



**MULTI-HAZARD EFFECTS OF SCOUR AND
EARTHQUAKE FOR SKEWED HIGHWAY
BRIDGES CONSIDERING GROUND MOTION
DIRECTIONALITY**

PhD Dissertation

Serenay ATEŞ

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PhD Dissertation

Department of Civil Engineering

Programme in Structure

Supervisor: Prof. Dr. Özgür AVŞAR

Eskişehir

Eskişehir Technical University

Institute of Graduate Programs

August 2024

FINAL APPROVAL FOR THESIS

This thesis titled MULTI-HAZARD EFFECTS OF SCOUR AND EARTHQUAKE FOR SKEWED HIGHWAY BRIDGES CONSIDERING GROUND MOTION DIRECTIONALITY has been prepared and submitted by Serenay ATEŞ in partial fulfillment of the requirements in “Eskişehir Technical University Directive on Graduate Education and Examination” for the Degree of PhD in Civil Engineering Department has been examined and approved on 15/08/2024.

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ABSTRACT

MULTI-HAZARD EFFECTS OF SCOUR AND EARTHQUAKE FOR SKEWED HIGHWAY BRIDGES CONSIDERING GROUND MOTION DIRECTIONALITY

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In literature, the earthquake incidence angle (θ) is taken into account using two different methods. In the first method, bridge principal axes are kept constant and ground motion components are rotated using linear transformation equations (Method-1). In the second method, the ground motion components are kept constant and the bridge principal axes are rotated (Method-2). The study aims to compare two methods and identify the most effective method in reflecting the effect of incidence angle of ground motion components to the nonlinear analysis of skew bridges. After deciding on the method, the most unfavorable earthquake incidence angle for various engineering demand parameters was determined.

In the next stage, the variation of seismic demands of the bridge elements was examined due to the effect of the scour, which occurs around the substructure elements due to the erosive effect of water over time, especially in bridges built on stream beds. Two different scour cases can be observed around bridge piles, which are uniform and non-uniform scour cases. To reflect the critical ground motion angle in the analyses, horizontal ground motion components were rotated from 0° to 180° in 15° increments. Considering the nonlinear analyses results, it is inferred that the scour case is an important parameter that greatly affects the seismic demands of bridges. Additionally, there is no specific critical earthquake incidence angle for each demand parameter. Lastly, a suggestion is made to improve the Caltrans recommendation for considering the critical earthquake excitation angles to achieve the most unfavorable seismic demands imposed on bridges.

Keywords: Ground motion incidence angle, Non-uniform scour, Residual displacement, Nonlinear response history analysis, Soil-structure interaction.

ÖZET

YER HAREKETİ DÖNDÜRÜLMESİ DİKKATE ALINARAK VEREV KARAYOLU KÖPRÜLERİNDE OYULMA VE DEPREMİN ÇOKLU TEHLİKE ETKİLERİ

Serenay ATEŞ

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Danışman: Prof. Dr. Özgür AVŞAR

Literatüre bakıldığında deprem etkime açısı olarak adlandırılan θ açısının 2 farklı yöntem kullanılarak dikkate alındığı anlaşılmaktadır. Bunlardan ilki köprü asal eksenlerinin sabit tutulup yer hareketi bileşenlerinin lineer dönüştürme denklemleri kullanılarak döndürülmesi (Yöntem-1), diğeri ise yer hareketi bileşenlerinin sabit tutulup köprü asal eksenlerinin döndürülmesi (Yöntem-2) yöntemidir. Çalışmada iki yöntemin karşılaştırılması ve yer hareketi bileşenleri etkime açısının vev köprülerin doğrusal olmayan analizlerine en etkin şekilde yansıtabilecek yöntemin belirlenmesi amaçlanmaktadır. Deprem etkime açısının uygulanmasında kullanılacak yöntem karar verildikten sonra, çeşitli mühendislik talep parametreleri için en elverişsiz deprem etkime açısı belirlenmiştir.

Sonraki aşamada ise, özellikle dere yatağına yapılan köprülerde zamanla suyun aşındırıcı etkisi nedeniyle altyapı elemanları etrafında meydana gelen oyulma durumunun köprü elemanlarının sismik taleplerine olan etkisi incelenmiştir. Köprü kazıkları etrafında meydana gelen oyulma, düzenli ve düzensiz oyulma olmak üzere iki farklı türde oluşabilmektedir. Kritik yer hareketi etkime açısını analizlere yansıtabilmek adına, yatay yer hareketi bileşenleri 0° 'den 180° 'ye kadar 15° 'lik arttırmalarla döndürülmüştür. Doğrusal olmayan analiz sonuçlarına bakıldığında, oyulma durumunun köprülerin sismik taleplerini etkileyen önemli bir parametre olduğu görülmektedir. Ayrıca, her bir talep parametresi için spesifik bir kritik deprem etkime açısı bulunmamaktadır. Son olarak, Caltrans'ın kritik yer hareketi etkime açısının belirlenmesi için önerdiği yöntemin geliştirilmesi için ilave öneriler getirilerek, köprü sismik taleplerinin gerçeğe daha yakın bir şekilde belirlenmesi sağlanmıştır.

Anahtar Sözcükler: Deprem etkime açısı, Düzensiz oyulma durumu, Kalıcı yer değiştirme, Doğrusal olmayan analiz, Zemin-yapı etkileşimi.

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Serenay ATEŞ

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Eskişehir Technical University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

AASHTO	: American Association of State Highway and Transportation Officials
ACI	: American Concrete Institute
ASCE	: American Society of Civil Engineers
Caltrans	: California Department of Transportation
CQC3	: Complete quadratic combination with three components
E_c	: Modulus of elasticity of concrete
f_c	: Compressive strength of concrete
f_y	: Yield strength of reinforcement
G_c	: Shear modulus of concrete
H_d	: Non-uniform scour depth
H_u	: Uniform scour depth
M_w	: Moment magnitude of earthquake
PGA	: Peak ground acceleration
PGD	: Peak ground displacement
PGV	: Peak ground velocity
SRSS	: Square root of the sum of squares
SSI	: Soil structure interaction
$V_{s,30}$	: Average shear wave velocity to a depth of 30 meters
α	: Skew angle
δ	: Gap distance
θ	: Ground motion incidence angle
γ	: Scour angle between downstream and upstream piles
ν	: Poisson's ratio

1. INTRODUCTION

1.1. General

Bridges are the critical part of the transportation network, which are vital and crucial systems that serve as the lifeline of a community. It is highly important for these structures to remain functional during and after an earthquake to ensure the survival of the community. Therefore, it is necessary to understand how bridges behave during earthquakes. To provide the earthquake resistance of highway bridges, they must be designed with a sufficient level of seismic capacity. Additionally, the current seismic performance of existing bridges must be accurately assessed to determine if any necessary precautions need to be taken to make them earthquake resistant.

The seismic performance of highway bridges is generally determined by conducting nonlinear response history analysis after generating their analytical models using the specified earthquake ground motion records (Ghobarah & Tso, 1974; Jónsson, Bessason, & Haflidason, 2010). Furthermore, fragility curves can be used to assess the seismic performance of highway bridges (Avşar, Yakut, & Caner, 2011; Mosleh, Jara, Razzaghi, & Varum, 2020). To obtain realistic performance assessment outcomes, it is critical to do proper modeling and accurately capture the nonlinear behavior of bridge components by means of the numerical model. The skew angle, which is one of the most important structural attributes of highway bridges, is the angle formed by the central axis of the bridge substructure and a line perpendicular to the bridge centerline. It causes irregularity on bridges and has a negative impact on the bridge's seismic performance. Therefore, researchers tried to figure out the vulnerability of skew bridges under the effects of major earthquakes, particularly utilizing fragility curves (Pottatheere & Renault, 2008; Huo & Zhang, 2013; Bhatnagar & Banerjee, 2014; Han, Chen, Du, & Huang, 2017).

In order to include the earthquake effect in the analysis, acceleration records of past earthquakes or artificially obtained ones are generally used. However, the angle at which earthquake components should be affected on structures is an important research topic when conducting nonlinear response history analysis. The most common approach is to apply ground motion components to the structure's principal axes without considering directionality of the ground motion components (Nielson & DesRoches, 2007). On the other hand, some researchers keep the structure unchanged and affect the earthquake components from different angles to achieve the most unfavorable situation. In these studies, linear transformation equations were used to rotate the ground motion orthogonal

components (Atak, Avşar, & Yakut, 2014; Roy, Bhattacharya, & Roy, 2017; Noori, Memarpour, Yakhchalian, & Soltanieh, 2019). As an alternative, an appropriate combination rule such as 30%, SRSS, CQC3, etc. can be used to determine the most critical case (Gao, Zhou, & Wang, 2004; Maleki & Bisadi, 2006; Bisadi & Head, 2011; Wang, Burton, & Dai, 2019). In some rare cases, researchers have rotated the bridge models with specific angle increments while maintaining the horizontal ground motion components fixed on the bridge global axes during nonlinear response history analysis.

Even if bridge-like structures are constructed in compliance with the regulations, they are still susceptible to damage from many external factors including aging, natural disasters etc. For bridges constructed on flood region areas, scour becomes a disastrous event as a result of erosion of flowing water. According to U.S. Department of Transportation (2012), 3 types of scour can exist in a flood region area; long term aggradation and degradation of the riverbed, contraction scour at the bridge and local scour at the piers or abutments. The most critical one in structural point of view is local scour for bridge type structures because it occurs around the bridge substructure and it may affect the seismic demand of members during earthquakes or any other natural hazards. AASHTO (2017) requires the design of bridge foundations for the scour caused by a 100-year flood and the stability of bridge foundations shall be investigated for 500-year flood. In recent years, researchers have concentrated on the assessment of bridges under the simultaneous effect of earthquake and scour by using experimental or analytical models of bridges. The effect of scour can be included to the bridge models by changing scour depth uniformly or non-uniformly around piers or piles. For each scour depth, nonlinear response history analysis is conducted and demands of bridge members are obtained to assess the seismic performance of bridge.

1.2. Object and Scope

There are two main objectives in this study. In the first part, it is aimed to reflect the incidence angle of the earthquake ground motion components acting on the bridges through the analytical models in the most accurate way. For this purpose, first of all, a reinforced concrete bridge with prestressed concrete I-beams and single column bents was modelled in the OpenSees program. The skew angle, which is regarded to be one of the key bridge feature that causes irregularity in bridges, is also included in analytical models. Nonlinear response history analyses are performed by using a considerable number of ground motion records. Two different methods are used to include the effect

of ground motion incidence angle to the nonlinear analysis. In the first method (Method-1), the bridge model is kept constant and the horizontal earthquake components are rotated with certain angle increments using linear transformation equations and affected on the bridge. In the second method (Method-2), nonlinear response history analyses are performed by keeping the horizontal ground motion components fixed on the global axes and rotating the bridge model for each incidence angle. As a result, the incidence angle of the horizontal ground motion components is applied separately with two different methods used in the literature, and the analysis results are compared with each other. Parameters such as displacements in the transverse and longitudinal directions of the bridge superstructure, curvature and shear force demand of the column piers and deformation demands of pounding elements are the engineering demand parameters examined within the scope of the thesis for the first part. As a result of the analyses to be performed with both methods, the changes in the relevant engineering demand parameters will be compared and the differences between the methods will be revealed. Considering both the numerical results and the ease of application of both methods, it will be determined by which method the earthquake incidence angle will be taken into account in a more effective way. Also, in the light of the results obtained with the determined method, the changes of the relevant engineering demand parameters for different incidence angles and different skew angles will be revealed. Furthermore, comparison of demands by using fixed based and soil structure interacted bridge model will be done to see the difference between modeling approaches.

In the second part of the PhD thesis, it is aimed to obtain seismic performance of bridges under the effect of scour around the bridge piers. Most of the researchers investigated uniform scour occurred on the bridge substructure. However, this phenomenon may occur around the bridge piers in a non-uniform elevation depending on the direction of flow. It is highly likely that the piers in the upstream may exposed to scour more than the piers in downstream. Unlike to the past studies, this study aims to examine the effect of non-uniform scour on the seismic demands of bridges. By using the bridge model, which is investigated in the first part of study, a soil structure interacted model is created in the OpenSees program. Afterwards, nonlinear response history analyses are conducted for a certain number of uniform and non-uniform scour cases and scour depths. By comparing the different scour cases, it is aimed to achieve the effect of scour shape on bridge member demands during earthquakes. Superstructure displacement

in the longitudinal and transverse directions of bridge, curvature and shear force demands of column piers, shear force demands of piles and residual displacements of superstructure and bridge column are the engineering demand parameters in this part of thesis. According to Caltrans (2019), ground motion components should be rotated at least three angular directions (i.e. 0° , 45° and 90°) to achieve maximum demands. In this regard, the maximum demands obtained according to Caltrans (2019) are compared to the maximum demands obtained within the scope of the study, and the adequacy of the earthquake rotation angle recommended in Caltrans (2019) is investigated in detail.

1.3. Organization of the Dissertation

This thesis is organized into six main chapters with the brief contents given as follows:

Chapter 1 is about the general overview of the main factors affecting bridge demands during nonlinear response history analysis and objective of the study.

Chapter 2 presents the studies in the literature on the evaluation of seismic demands of bridges under two subheadings: earthquake incidence angle and scour.

Chapter 3 explains the bridge analytical models used in the study. In the first model, a fixed supported bridge is defined into the OpenSees program and nonlinear response history analyses are performed. Calculation of ground motion incidence angle is taken into account by using two different methods. In the second bridge model, soil structure interaction is included to the analytical model and uniform and non-uniform scour cases are defined.

Chapter 4 deals with the calculation of ground motion incidence angle in nonlinear analysis. Firstly, the application methods of incidence angle are compared with each other and then critical ground motion incidence angle for bridges is researched. After that, comparison of member demands by using fixed based and soil structure interacted bridge is established.

Chapter 5 presents the scour effect for bridges considering uniform and non-uniform scour cases and comparison of scour cases with each other. Then, numerically obtained maximum demands for the considered incidence angle intervals are compared with maximum demands obtained according to Caltrans. Recommendations are made to improve the suggestions of Caltrans to obtain the most unfavorable seismic demands in nonlinear analysis.

Chapter 6 presents a brief summary and the conclusions obtained throughout the thesis. Recommendations for future studies are also provided.



2. LITERATURE

Bridges are the critical part of the transportation network, which are vital and crucial systems that serve as the lifeline of a community. They must remain functional during and after an earthquake to ensure the survival of the community. Because of this, it is crucial to understand how bridges behave during an earthquake. As a result, highway bridges must be designed with a high level of earthquake resistance, and the seismic performance of existing highway bridges should be accurately assessed to decide whether additional steps are required to make the bridge earthquake resistant. Ordinary highway bridges are generally composed of superstructure and substructure. Cap beam, abutments, piers and foundation form the substructure, while deck and prestressed beams form the superstructure. Many parameters affecting the seismic behavior of bridges have been examined in the literature from past to present. The thesis study consists of two main topics: the effect of earthquake ground motion incidence angle in nonlinear analysis and the effect of scour around bridge piles on seismic demands. For this reason, studies on these issues in the literature are given under subheadings below.

2.1. Incidence Angle

In the literature, nonlinear analysis methods are often used when evaluating the seismic performance of bridges. In the response history analysis, recorded ground motion records or artificially generated ones are used. As it is known, earthquake acceleration records consist of 3 main components: 2 orthogonal horizontal components and 1 vertical component. During the analysis carried out both for the new design and for the performance evaluation of structures, the earthquake horizontal components are generally applied in the global axis of the structures. However, as shown in Figure 2.1, it is not known exactly at what angle an earthquake affects a structure in real life. In recent years, researchers have started to focus on studies on how the earthquake incidence angle affects the analysis results and bridge performance.

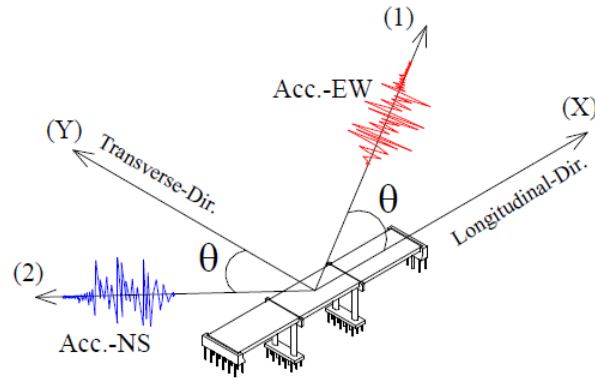


Figure 2.1. Ground motion pair acting with an angle of θ to the bridge transverse and longitudinal directions (Atak, Avcı, & Yakut, 2014)

Kalkan and Kwong (2014) performed a linear analysis of a 6-storey building using the two horizontal components of 20 different ground motion records. In the analyses carried out using the OpenSees program, the earthquake incidence angle was changed from 0° to 180° by using linear transformation equations with 5 degree increments and affected to the structure. In the studies conducted by Reyes and Kalkan (2015) and Kalkan and Reyes (2015), the effect of the earthquake incidence angle on the engineering demand parameters was investigated by using single-story and multi-story building models and it was questioned whether there was an optimum incidence angle for the demand parameters used. As a result, it has been emphasized that the demand parameters used in the studies are affected in terms of earthquake incidence angle, but the maximum values differ according to each ground motion and the engineering demand parameter examined, therefore it is not possible to determine a critical earthquake incidence angle for the structures.

The angle θ , which is called the earthquake incidence angle, is taken into account by using 2 different methods in the literature. The first one (Method-1) is to keep the bridge principal axes constant and rotate the ground motion components using linear transformation equations as shown in Figure 2.2(a), and the other method (Method-2) is to rotate the bridge principal axes by keeping the ground motion components constant as shown in Figure 2.2(b). In studies, the first method, which is easy to apply, was generally preferred. However, the most important drawback of this method is that it interferes with the content of the earthquake record due to the application of linear transformation to the recorded horizontal earthquake ground motion record. This means that the frequency content, intensity parameters and energy content of the earthquake record are changed to

move away from the real situation. Since the second method does not interfere with earthquake ground motion records, it is thought that this method will more accurately represent the real behavior. However, for each earthquake incidence angle, the reconstruction of the bridge numerical model to take this angle into account is the most important difficulty of this method.

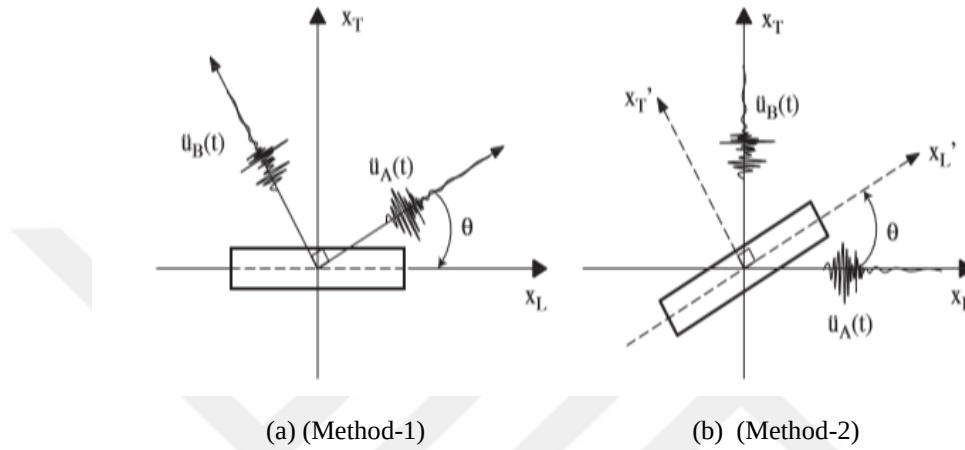


Figure 2.2. Application methods of ground motion incidence angle a) rotation of ground motion components b) rotation of bridge principal axes (Mackie, Cronin, & Nielson, 2011)

Bisadi and Head (2010) performed both linear and nonlinear analyses for 3 different span lengths using a single span bridge model. Parameters such as the deck displacement in the transverse and longitudinal directions, and the base shear force were investigated by applying 3 ground motions by using Method-1 from 0° to 180° with 30° increments. It is stated that the sensitivity of the time history analysis depends on both the bridge characteristics and the property of ground motion records.

Moschonas and Kappos (2011) investigated the variation of the earthquake incidence angle from 0° to 110° with a change of 15° in a 5 span and 20° skew bridge. In this study, the components of earthquake records were rotated using Method-1. First, as shown in Figure 2.3(a), a single horizontal component of the earthquake was used, then two horizontal components were used as in Figure 2.3(b) and fragility curves were obtained. It was concluded that, considering both horizontal components of the earthquake, the probability of damage increased by 40%, but the earthquake incidence angle was almost ineffective.

and affected on the structure using Method-1. According to the result obtained from the fragility curves of the two bridges, the probability of damage to the first model increased as the skew angle and earthquake incidence angle increased.

Atak et al. (2014) conducted a study on the effect of strong ground motion direction on skew bridges. Here, both the bridge skew angle was changed from 0° to 60° with 10-degree increments, and the horizontal components of the ground motion were changed by using Method-1 from 0° to 165° with 15-degree increments and it was aimed to determine the most unfavorable situation. As a model, two different types of bridges, one rigid and the other relatively less rigid, were used. As a result of nonlinear response history analyses, the moment and curvature demand occurring in the weak and strong axis of the columns were examined. It has been observed that the angle of attack of the ground motion components has a significant effect on the seismic behavior of the bridge, depending on the geometric and rigidity properties of the bridge members. Noori et al. (2019) examined the effect of ground motion direction acting on skew bridges by taking into account the soil structure interaction. The fragility curves of these models were obtained both by changing the bridge skew angle and by affecting the horizontal components of the ground motion at different angles. Here, as in most studies, the authors rotated the earthquake components using Method-1 and included it in the analysis. In addition, the case of accepting the bridge piers as fixed supports and considering the soil-structure interaction were compared. It has been concluded that the vulnerability of bridge members such as bridge piers, shear keys, elastomeric bearings will increase by 77% in cases where the earthquake angle is different from 0° .

It is known from the studies in the literature that the earthquake performance of bridges is affected by the earthquake ground motion characteristics of the bridges as well as the structural features of the bridge model considered. Parameters such as skew angle and pounding behavior are the most important parameters affecting the seismic performance of bridges. The skew angle represents the angle defined between the substructure and superstructure members in bridges. The substructure and superstructure are usually positioned perpendicular to each other. However, it may not be possible to meet this requirement in some bridges that pass over the railway or highway or cross the river, and there may be a skew angle between the substructure members and the superstructure as shown in Figure 2.4.

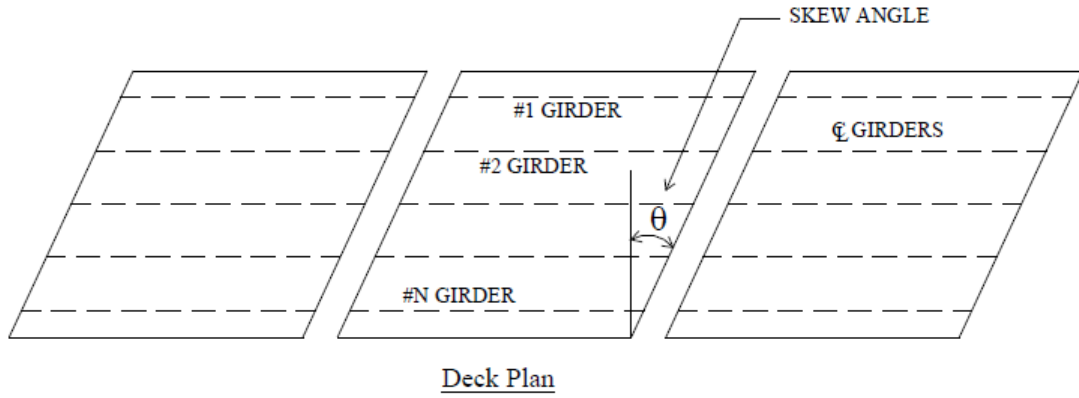


Figure 2.4. Bridge plan view and skew angle (Atak, Avşar, & Yakut, 2014)

There are many studies in the literature to show the effect of skew angle on earthquake performance. Ghobarah and Tso (1974) investigated the severe damage to the piers of a 55° skew bridge in California in 1971 San Fernando earthquake. The damages observed in the bridge piers and the results obtained from the analytical model were consistent with each other. Pottatheere and Renault (2008) performed a nonlinear response history analysis of 0°, 12.33° and 45° skew bridges based on a bridge model in Germany with a 12.33° skew angle. In line with these analyses, fragility curves of the mid-piers and elastomeric bearings, which are the most damaged members of the bridges, were obtained and it was observed that the damage to these members increased as the skew angle increased. Haque and Bhuiyan (2012) investigated the effects of bridge skew angle on base shear force, deck acceleration and axial forces in elastomeric bearings on a simple single span bridge model. As a result, it has been observed that the axial force, shear force and moment of the bridge piers increase due to the increase in the base shear force, deck acceleration and the responses in the bearings at large skew angles.

Kwon and Jeong (2013) observed that the bridges damaged in the 2010 Chile earthquake were especially skew bridges. For this reason, they investigated how the seismic performance of the bridge was affected by the change in skew angle over single and 2-span bridge models. Deepu et al. (2014) performed nonlinear response history analyses by increasing the skew angle of a 2-span bridge by 15 degrees from 0° to 60°. The analyses were performed for 3 different earthquake ground motion levels (earthquakes with 2%, 10% and 50% probability of exceedance in 50 years). As a result, the vulnerability of the bridge piers and deck was examined with the help of fragility curves, and it was observed that the damage increased as the skewness of the bridge

increased. Han et al. (2017) investigated variables such as the skew angle of a reinforced concrete bridge with prestressed box-section beam, the amount of space between the abutment and the superstructure, and the amount of space between the shear key and the superstructure. Using the two horizontal components of near-fault ground motions, nonlinear response history analyses were performed. As a result of these analyses, it has been seen that the amount of displacement in the bridge models depends on the characteristics of the bridge and the earthquake records used, but mostly on the bridge skew angle. Basnet and Suwal (2019) performed both linear and non-linear analyses by changing the skew angle of a 3-span and multi-pier continuous bridge from 0° , 15° , 30° , 45° and 60° , respectively. Fragility curves were obtained by affecting the strong component of the ground motion in the transverse direction of the bridge in response history analysis. It has been observed that the seismic vulnerability increases as the skew angle increases as a result of the combined effects of axial, bending and torsion effects.

Due to the lack of sufficient gap distance in both straight bridges and skew bridges, pounding is inevitable in the event of an earthquake, between the superstructure and the abutments, between the deck and deck or between the superstructure and shear keys. Relevant to this issue, Dimitrakopoulos (2011) examined the effect of the skew angle of the bridge model given in Figure 2.5 in terms of deck and abutment collision during an earthquake. As in similar studies, the skew angle was changed from 0° to 60° and a collision with the abutments occurred by turning the bridge deck with the effect of ground motion. It was concluded that the pounding event is not only dependent on the bridge skewness but also depends on the plan and geometry of the bridge.

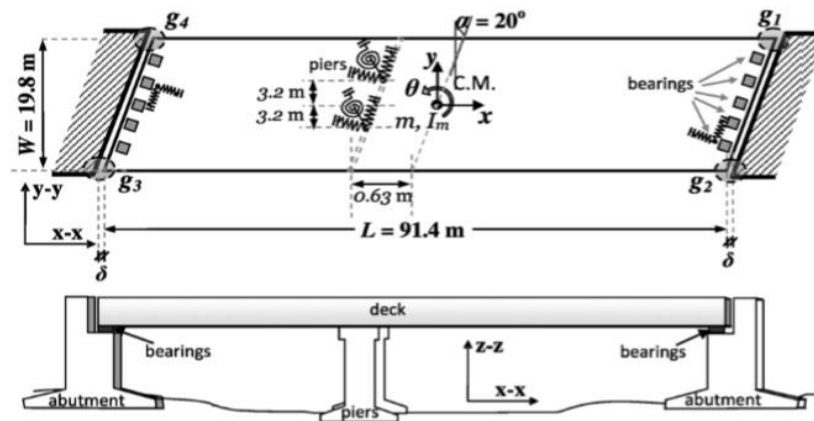


Figure 2.5. Bridge plan and side view, $g1$ - $g2$ - $g3$ - $g4$ possible collision zones (Dimitrakopoulos, 2011)

Kun et al. (2017) carried out an experimental study to fill the gap in the literature, unlike the analytical methods used in previous studies. A single span 1:20 scaled bridge model was subjected to shake table tests in the laboratory. The effect of the skew angle on the pounding behavior between the bridge deck and the abutments was investigated. As a result, the displacement and rotations in the transverse direction of the bridge deck were limited due to the collision in the 0° and 30° oblique models. However, larger displacements occurred in the model with 45° skew angle. In addition, it has been stated that the collision between the abutment and the deck in 0° and 30° skew bridges reduces the bending moment in the columns, but the demands increase in the 45° skew bridge. On the contrary, it was emphasized that the displacements in the transverse direction increased with pounding effect. Chen et al. (2017) firstly examined the case of deck-abutment collision in a single span 30° skew bridge. Then, by including the effect of skew angle, nonlinear analyses of a 2-span bridge were performed using 7 earthquake records. It has been observed that as the skew angle increases, the displacement and rotation demand in the longitudinal direction increases, but the pounding force decreases. However, the pounding force increases in the transverse direction. Kun et al. (2018), including soil-structure interaction in their studies, conducted shaking table experiments examining skew angle and pounding behavior. 0° (straight), 30° and 45° skew bridge models are prepared in 1:20 scale. As a result of the analysis, the pounding force was found to be smaller in the straight bridge model, in which the soil structure interaction was taken into account, compared to the one with the fixed support. On the contrary, in the 30° skew bridge, the pounding force was found to be greater in the model with SSI. Similar results were obtained in the 45° model, but the magnitude of the force generated in the 30° model is greater.

In the studies found in literature, while taking into account the angle of incidence of the ground motion components, Method-1 (keeping the bridge principal axes constant and rotating the ground motion components using linear transformation equations) was generally chosen and applied in the analyses. On the other hand, only 2 studies have been found in the literature using Method-2, in which the earthquake components are kept constant, and the bridge model is rotated. In the first part of thesis, it is aimed to determine the most appropriate method that can be used to reflect the earthquake incidence angle in nonlinear dynamic analysis of bridges. For this reason, the application methods of the earthquake incidence angle to be included in the calculations in the seismic analyses of

the bridges were compared over a reinforced concrete bridge model. In the analyses, a bridge model consisting of prestressed I-beams and a continuous reinforced concrete deck, which is commonly found in Turkey, was used. One of the parameters included in the study is its effect on the analysis by changing the skew angle at certain angles from 0° to 60° . The earthquake incidence angle was changed separately with the 2 different methods mentioned above, and the analyses results were compared. In this way, both the methods taken into account in determining the earthquake incidence angle in bridges were compared with each other and it was aimed to obtain the most unfavorable ground motion incidence angle for the bridge models used.

2.2. Scour

The main causes and mechanisms of bridge collapse classified into two categories, natural causes as seen in Figure 2.6 (flood, scour, earthquake hurricane etc.) and human factors (imperfect design, collision, fire etc.) (Deng, Wang, & Yu, 2015).



Figure 2.6. *The condition of substructure of Filyos Bridge due to scour (Avsar, Atak, & Caner, 2017)*

The analytical modeling of bridge type structures by using a finite element program is a common method and the demands of bridge elements in the effect of multi hazard framework can be easily achieved. For this purpose, significant research has been done in the literature. Banerjee and Prasad (2011) investigated 2 example reinforced concrete bridges under the combined effect of earthquake and scour. Scour depth was changed

with different levels, and it was obtained that bridge vulnerability may increase under multi hazard effect compared to discrete hazards. Wang et al. (2012) studied earthquake and scour hazards for bridges by using fragility surfaces. Two 3-span continuous bridge models were used and modeled with SAP2000 program. The first example of the bridge model is a concrete box girder bridge and the other one is steel girder bridge. According to the results, for concrete box girder bridge, collapse mode is controlled by ductility failures of column for no scour case. On the other hand, with increasing scour depth, collapse mode controlled by piles. For steel girder bridges, bridge collapse mode is controlled mainly by pier. Alipour and Shafei (2012) made a performance assessment of bridges under scour and earthquake. Firstly, they made a scour depth prediction by using the formula given HEC (Hydraulic Engineering Circular) No. 18 and then fragility curves were obtained for different scour depths. The results emphasize that the lateral load bearing capacity decreases with the increase in the scour depth and as a result, the probability of exceeding any damage state increases. Alipour et al. (2013) calibrated the scour load modification factors for the design of bridge. They suggested 1.42 and 1.12 factors for scour load modification for the moderate and major states of damage. For more important bridges, the factor should be taken as 1.42 and for regular bridges it should be taken as 1.12. Banerjee and Ganesh Prasad (2013) investigated two reinforced concrete bridges located in California. The p-y springs were used to simulate soil structure interaction and for scour cases springs were removed and nonlinear analysis were performed for different levels. The authors stated that consideration of only seismic hazard for the risk assessment of bridges may underestimate the maximum demand so the analysis with a combined seismic and flood hazard model is required. Prasad and Banerjee (2013) made fragility analysis and developed fragility curves for various scour depths for four representative reinforced concrete bridges. Nonlinear analysis results showed that the overall length of bridges has some effect on fragility characteristics, longer bridges have higher median fragility parameters which indicate higher vulnerability of these bridges due to seismic hazard.

Wang et al. (2014) studied 3 different bridges that have single column, olderly designed multi column and newly designed multi column models were created in the OpenSees program. Fragility curves were obtained for 6 different uniform scour depths. Results showed that scour has both beneficial and detrimental effects on column fragility. Because scour increases the flexibility of the pile foundation, which in turn increases the

period of the bridge, it has a favorable influence on the seismic response of the column by reducing curvature demands, because of the elongated period. However, scour may increase the potential seismic damage by transferring damage from column to pile and probability of deck unseating. Wang et al. (2014) used fragility surfaces as a function of earthquake seismic intensity level and scour depth. Then a multi hazard probabilistic seismic demand model was developed. Also, they determined load combination factors for design by comparing failure probability of the bridge for a certain scour depth. The study recommended a load factor of 0.59 for scour and 1.0 for earthquake to account for the combination of earthquake and scour hazards for single frame box girder bridges. According to the authors, first, the seismic hazard should be considered alone, then the bridge should be examined to ensure that its seismic response is still appropriate when subjected to the combined scour depth (i.e. design scour depth $\times$ scour load factor).

Klinga and Alipour (2015) made comprehensive research for assessment of bridges under scour conditions. Firstly, a detailed procedure was applied to calculate the scour depth then a detailed bridge model including soil pile structure interaction was created. Modal, buckling, and pushover analysis were done for different scour depths. The results show a reduction of shear force in the columns and increased shear force and bending moments of piles with increasing scour depths. Also, for increased scour depths, the deformations shift from columns to piles.

Guo and Chen (2016) researched a lifecycle multi hazard framework for considering earthquake and scour effects on bridge failure. A three span continuous concrete bridge supported by shallow foundations was investigated and nonlinear springs were used to reflect soil structure interaction. According to the obtained results, during the first 45 service years of the bridge, scour has no significant effect on the seismic vulnerability of the bridge in terms of system collapse. After 65 years, scour dominates the cause of system failure and between 45 and 65 years, bridge scour and earthquakes jointly contribute to system failure. Guo et al. (2016) investigated time dependent fragility analysis of bridges under scour and earthquake. They also used nonlinear springs to account for the nonlinear behavior of soil around a pile. For different scour levels, the springs were removed around the pile. The fragility curves implies that the seismic intensity affects the probability of collapse nonlinearly and when the ground motion intensity reaches at a certain level, it may cause significant damage to the structure.

A scour dependent empirical fragility modeling used by Guo et al. (2019) and the model parameters were associated with scour depths in terms of quadratic polynomials. A two span bridge model supported by one pile was used in the study and soil structure interaction was considered by using three kinds of nonlinear springs (p-y, t-z and q-z). The results indicate that, when scour depth is 10 m the probability of collapse is 17%, which is about 6 times of the no scour case. Wang et al. (2019) investigated the sensitivity of 14 structural and soil parameters by using fragility curves for seismic performance assessment of pile supported bridges in liquefiable ground. A fragility based Tornado Diagram Method was used for sensitivity analyses. According to the results, the effect of scour depth slightly influences the most sensitive parameters including column height and diameter, and pile diameter for the performance of bridge components. Li et al. (2020) studied the time dependent fragility of bridges under the action of scour and chloride ion corrosion. Based on the Duracrete model, which considers the characteristics of chloride ion diffusion rate with time and finds the influence of material and environment, the degradation of reinforced concrete performance with time was obtained by the Monte Carlo method under a chloride ion corrosion environment. The seismic fragility of the bridge shows nonlinear growth with the increasing scour depth and the fragility of the laminated rubber bearing is higher than that of the pier in the effect of an earthquake. Therefore, this makes the rubber bearing sustain more significant damage than the pier. He et al. (2020) used endurance time method (ETM) to evaluate the seismic fragility of bridges considering scour effect. A 2-span RC bridge supported by three different types of substructure (shaft foundation, two column bent foundation and pile group foundation) was examined in the study. For 6 different scour depths starting from 0 m to 5 m and different substructure design, fragility curves were obtained. The results show that the seismic fragility of bridges for different scour depths are influenced from the substructure design. He et al. (2020) made nonlinear static pushover analyses for bridges with different scour depths (from 0 m to 12 m). Numerical results demonstrate that the seismic demands of bending moments and the locations of maximum moments for piles vary significantly with increasing scour depth. Also, the initial lateral stiffness, yielding point, and ultimate strength of the pushover curves for scoured bridges depend on the scour depths and soil properties. Wei et al. (2021) used endurance time method for fragility analysis of cable-stayed bridges under scour and earthquake. The ETM framework was validated by comparing the calculated fragility curves with those calculated by incremental dynamic

analysis (IDA) framework. The results show that ETM reduces the computational effort without compromising the accuracy of fragility analysis results. Also, scour can produce either beneficial or adverse effects on the component and system seismic fragilities depending on the scour depth. Olmos et al. (2023) investigated engineering demand functions of reinforced concrete bridges which exposed to earthquake and scour in Mexico. First of all, a statistical analysis was done considering geometry, number of span, span length, pier height and shapes, and type of foundations of bridges in areas of high seismicity and high risk of scour. After that, nonlinear response history analyses were performed considering with and without scour conditions. According to the authors, the primary processes of bridge failure exposed to seismic activity are significantly affected by scour.

Furthermore, there are some studies, which were done to investigate real life bridges under scour and seismic effects. Yilmaz et al. (2016) examined 2 real life bridges located in California under multi hazard scenario. The multi hazard performance of the bridges was assessed by considering a flood event followed by a seismic event. Fragility curves and surfaces were obtained for different flood events with annual exceedance probabilities of 90%, 50%, 10%, 5%, 2%, and 1% (corresponding to 1.1-year, 2-year, 10-year, 20-year, 50-year, and 100-year floods). Obtained results show that flood events increase the seismic vulnerability and risk of bridges. Avsar et al. (2017) investigated Bahçeli Bridge which is located on Lapseki-Biga highway in Turkey. Twelve different scour depths from 0 m and 5.5 m were used in the study. It was observed that the horizontal superstructure displacements under earthquake loads were approximately doubled in the full scour case compared with the no scour case although the shear demand of the columns decreases with an increasing scour depth. Prendergast et al. (2018) monitor bridge health against scour and earthquake for performance assessment of bridges and focused on vibration-based damage identification methods. Again, this study demonstrates that scour can sometimes result in beneficial structural response due to increased flexibility that reduces the inertial forces transferred to the superstructure. Moreover, Zaky et al. (2020) investigated Boğaçay Bridge in Antalya, Turkey for different scour depths. The p-y curves were used to reflect the nonlinear soil structure interaction in SAP2000 program. A significant increase in pier displacement demands were obtained with increasing scour depth especially in the transverse direction of the bridge. Also, the spreading of plastic hinges was changed from piers to piles due to scour

effect. Shrestha et al. (2023) were done a case study of a reinforced concrete bridge over Bagmati River. According to the pushover analyses results, the damages are transferred from the bridge piers to the piles. Also, nonlinear response history analyses results show that, scour increases the probability of bearing failure and deck unseating because of the increased displacement demands.

Idealized 2 degree of freedom systems were also used by some researchers to model the bridge superstructure and substructure members. Song et al. (2015) modeled a 2 degree of freedom system to investigate the combined effects of earthquake and scour in bridges. The translational movement of the pile cap is assigned as the first DOF and the translational movement of the superstructure is assigned as the second DOF. The results of the idealized approach indicate that the seismic demand on the bridge column gradually decreases with increasing scour depth and reducing the damage potential for the bridge column. On the other hand, the lateral strength of the foundation can be reduced by pile exposure and seismic demand on the foundation may increase with the increase in scour depth. Moreover, Xu et al. (2016) studied dynamic interaction between bridge pier and its foundation considering scour depth based on a simplified 2 degree of freedom model. The authors emphasized that the effect of scour depth is strongly related to the fundamental vibration periods of both superstructure-pier system and the pile foundation itself.

In the literature, there are some significant experimental research studies about the bridges under the effect of scour and earthquake. Wang et al. (2015) made shake table tests to investigate the seismic behavior of scoured bridge pier with pile foundation. The bridge pier was subjected to uni-directional shaking by using earthquake records and the performance was discussed for different scour conditions. According to the experimental results, moment demand of pile increases with the increase of scour depth whereas the demand of bridge pier decreases, and this situation may induce the bridge failure mechanism transform from pier to pile. Also, Wang et al. (2019) studied the scoured pile group supported bridges in liquefiable and non-liquefiable soils. Authors carried out a series of shake table tests for 2-identical models each consisting of 2x2 reinforced concrete pile group embedded into saturated and dry sands with the same scour depth. The soil liquefaction tends to transfer failure modes of the bridges from piers to pile heads, so for scoured bridges under liquefaction potentials, pile heads are the primary concern for seismic design. Moreover, for 3 different scour scenarios (no scour, partial

scour and complete scour), shake table tests were done by Wang et al. (2020) to obtain the seismic behavior of pile supported bridges in liquefiable soils. The researchers demonstrated that scour can strongly affect failure mechanisms of pile supported bridges in liquefiable soils and again the pile heads were found as critical members in seismic designs for the consideration of scour. Zhou et al. (2021) investigated vertical load carrying capacity of scoured reinforced concrete pile group bridge foundations experimentally. Three identical 2x3 reinforced concrete (RC) pile group specimens were embedded in homogeneous medium density sand with an overall scour depth equal to five times the diameter of a single pile (5D), and then were subjected to lateral cyclic loads applied to the pile cap in order to produce a predetermined damage state in the piles. Pushover analysis in the vertical–downward direction (pushdown) was finally applied on these damaged specimens exhibiting a permanent lateral displacement to evaluate their residual load-carrying capacities. Experimental results show that the corner pile was more prone to seismic damage, as both the first aboveground and first belowground plastic hinges originally occurred on it.

Among all these studies, there is a different approach to consider scour effect on the seismic performance of bridges. All the above mentioned research considers scour cases uniformly changing along the bridge piers or piles. However, in real life, bridge substructure members stayed on the upstream are exposed to more scour than the downstream ones as given in Figure 2.7. For non-uniformly changed scour case, there are limited studies in the literature. Fioklou and Alipour (2019) studied uniform and non-uniform scour depth on the seismic performance of bridges. The non-uniform scour depth was defined as 25% more in the upstream called Case 1 and 50% more scour depth in the upstream called Case 2. These cases were compared with the uniform scour depth cases and results indicate that using a uniform distribution of scour depth to assess the seismic displacement demand of bridges will underestimate the demand that is expected to sustain. A numerical analysis was carried out by Hosseini et al. (2023) to examine the effect of random scouring on the seismic performance of a multi-span RC bridge. Four categories were used to categorize scouring scenarios in bridge foundations: intact, uniform, non-uniform, and uniform maximum credible scour pattern (UMCS). They pointed out that scouring around foundations has a significant impact on the response of bridge components because of the influence of scour on the structure's total base shear as

well as the pounding forces between superstructure elements after conducting non-linear seismic analyses based on selected seismic records for the scouring scenarios.



Figure 2.7. Examples of (a) uniform scour (Abd El Samee & Elsamny, 2019) (b) non-uniform scour (USGS)

It is important to detect damage to structures after severe earthquakes. Although some damage is repairable, irreparable damage may occur in various structural elements due to residual displacement demands. The residual displacement is defined as the deformation of structures or components that have undergone plasticity and cannot be returned to the initial state after unloading. Therefore, there are considerable studies in the literature on this subject. Christopoulos et al. (2003) made a framework for evaluating performance using residual deformations that takes into account both structural and non-structural elements. The response of SDOF oscillators, which exhibit distinct force-deflection behaviors in response to seismic input, is first examined in order to determine the properties of maximum and residual deformations. Five SDOF oscillators have been selected to symbolize 4, 8, 12, and 20-story reinforced concrete frame buildings. Residual deformations are found to be significantly influenced by hysteretic properties, maximum ductility, and post-yielding stiffness as influenced by $P-\Delta$ effects. In order to assess the mean residual displacement ratios for elastoplastic systems in existing structures constructed on firm soil locations, a simplified expression is proposed by Ruiz-Garcia and Miranda (2006). It is found that compared to mean inelastic displacement ratios, mean residual displacement ratios are more susceptible to changes in local site characteristics, earthquake magnitude, distance to the source range, and hysteretic behavior. Yazgan and Dazio (2011) made shake table tests to obtain maximum and residual displacements of reinforced concrete columns and compare the results with numerical models. Results

indicate that if stiffness degradation is taken into consideration in the chosen hysteresis model, maximum displacements can be approximated with a suitable degree of precision. However, reliable measurement of the residual displacements has been challenging to produce. In the second part of the study, the results show that simulated residual displacements are much more susceptible to model idealizations than maximum displacements (Yazgan & Dazio, 2011). Lioussatou and Fardis (2015) investigated how residual displacements for records with or without velocity pulses were affected by the hysteretic characteristics of SDOF systems. Peak inelastic displacements have been found to increase with pulses. It was discovered that pulses increased residual displacements generally, and that they did so nearly proportionately to peak displacements.

Cheng et al. (2016) used fiber-element models based on the OpenSees platform to build numerical models for the RC bridge columns and investigated factors affecting residual displacement of that columns. To capture the effects of strain penetration, the fiber components are coupled here with extra elements, i.e., the zero-length section elements. It is discovered that compared to far-fault ground motion, near-fault ground motion causes a higher residual drift ratio. The maximum lateral drift ratio, the displacement ductility factor, and the column aspect ratio increase, which causes the residual drift ratio to increase as well. Furthermore, because of the bar pulling out deformation, a bigger longitudinal reinforcement ratio may result in a larger residual drift ratio. Cai et al. (2019) researched residual displacement of precast segmental bridge columns with energy dissipation bars. They investigated four important factors such as including the post-tensioning force, gravity load, energy dissipation bar ratio, and shear span ratio and made some suggestions for the practical design procedure of the reinforced bridge columns with energy dissipation bar according to the cyclic analysis results. Moreover, Dong et al. (2024) examined the effects of ground motion characteristics, particularly the near-fault pulsed ground motion features, and structural properties on the residual displacements of the RC bridge columns. The findings demonstrate that the residual displacement responses of the RC bridge columns are strongly influenced by the structural attributes and ground motion features. There is inconsistency in the influence of structural properties on residual displacement responses of various models that are derived through the application of distinct methods of analysis. In addition, the residual displacement responses of the RC columns exposed to ground motions with near-fault

pulses are greater than those of ground motions without pulses, and they get higher as the pulse period is longer.



3. MATERIAL AND METHOD

Within the scope of the thesis, it is aimed to determine the most realistic method applied for the calculation of the rotation angle of the earthquake horizontal ground motion components used in the nonlinear analysis of the bridges as a first step. For this purpose, an analytical model of a 4-span RC bridge with prestressed I-beams and continuous RC deck was modeled using the OpenSees program. Then, the earthquake ground motion records selected for nonlinear response history analysis were rotated from 0° to 180° with 15° increments and applied on the bridge. Nonlinear analyses performed with earthquake records rotated using linear transformation equations are discussed as Method-1 in the study. On the other hand, under the name of Method-2, nonlinear response history analyses were performed by rotating the bridge models for each incidence angle. In the analyses, the horizontal earthquake components were kept constant on the global axes and no intervention was made to their content. The features of the bridge model used in this context, the analytical model created in the OpenSees platform, the selection and scaling of earthquake records, and the application of Method-1 and Method-2 are explained in the following subtitles.

In the second part, it is aimed to include scour effect to the bridge models, which were previously modeled with fixed supports at column base, by using soil structure interaction. Spring members were used to reflect lateral and axial resistance of soil around the piles. For this purpose, a group of piles were added under the columns with a pile cap and soil springs were defined at regular intervals on the pile nodes. Bridge model with soil structure interaction (SSI), properties of soil springs and scour cases are explained in the subtitles. The bridge is investigated under the effect of uniform and non-uniform scour effects.

3.1. Bridge Model for Incidence Angle

3.1.1. General properties of bridge members

The bridge used in the study is an RC highway bridge consisting of prestressed I-section beams and continuous deck, which was previously used by Atak et al. (2014). The bridge superstructure has 4 spans as seen in Figure 3.1, each span has 35 m length and 12 m width. The superstructure consists of 8 prestressed beams and a continuous reinforced concrete deck. Deck thickness is 22 cm. Concrete grade is C40 ($f_c=40$ MPa) for prestressed beams, C25 ($f_c=25$ MPa) for other members and reinforcing steel grade is S420 ($f_y=420$ MPa). In the parametric study, the bridge skew angle was changed from 0°

to 60° with 15° increments to consider the effect of skewness in the analysis. The bridge substructure consists of a cap beam, single column piers and abutments. Each of column piers has a height of $H=8.7$ m and consists of an oblong section of $B_c=1.2$ m and $D=4$ m as seen in Figure 3.2. End condition of the piers is considered to be fully restraint. The cap beam has a varying rectangular section with a width of 1.2 m and a depth of 1.75 m at the critical section, as shown in Figure 3.3. There are elastomeric bearings with a dimension of $450 \times 250 \times 40$ mm under each prestressed beam over the cap beam. These members transfer the vertical loads from the superstructure directly to the substructure members. In addition, since they are not connected to any member, they can move freely in all directions in the horizontal plane after the friction force is exceeded (Avşar, Yakut, & Caner, 2011). Therefore, it is assumed that the bridge superstructure will remain elastic in the event of an earthquake (Caltrans, 2019).

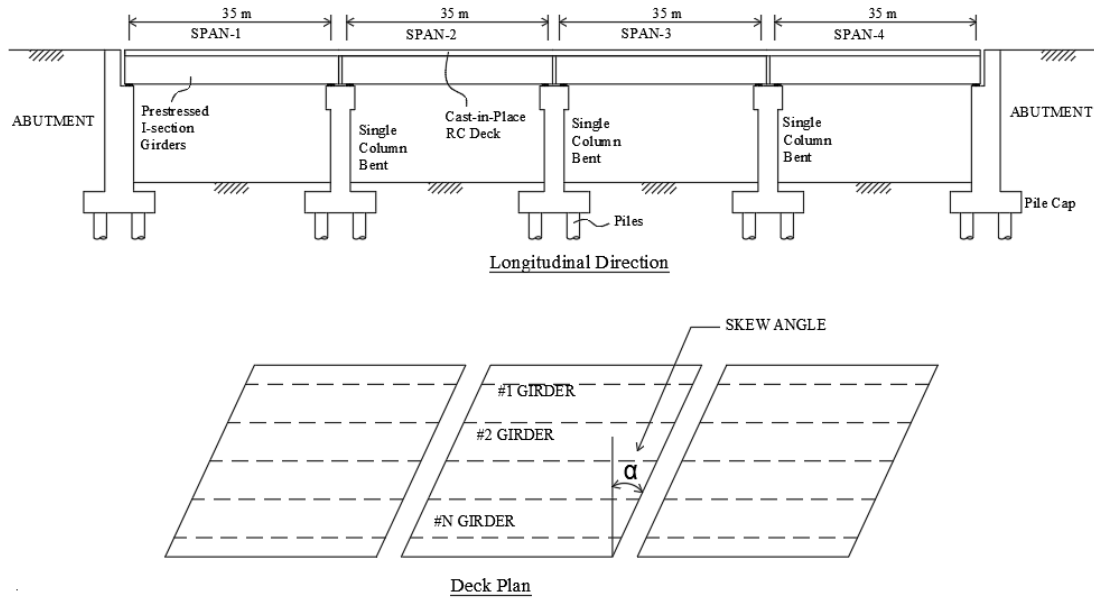


Figure 3.1. Reinforced concrete bridge consisting of prestressed I-section beams and continuous deck (Atak, Avşar, & Yakut, 2014)

Transverse Dir.

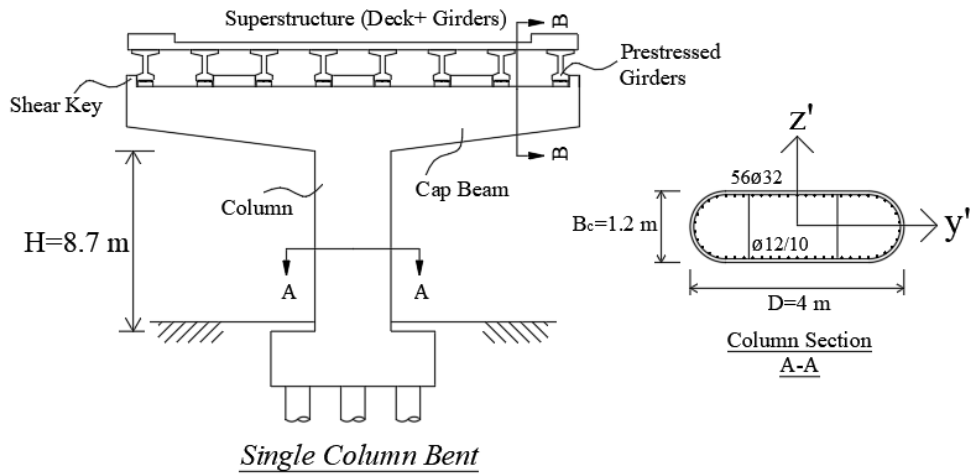


Figure 3.2. Bridge single column pier details (Atak, Avşar, & Yakut, 2014)

Longitudinal Dir.

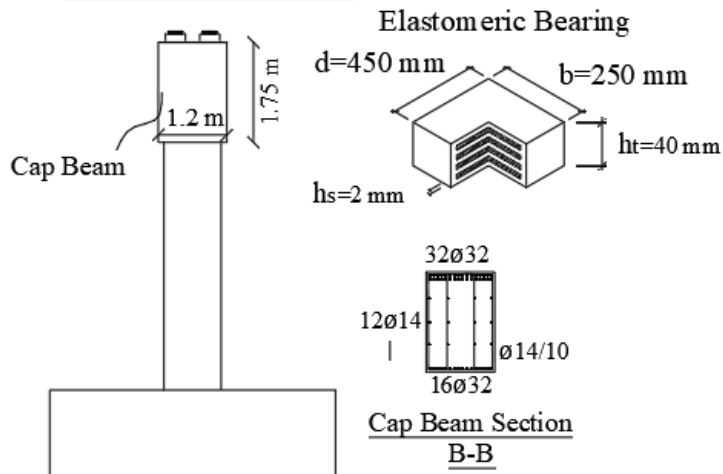


Figure 3.3. Bridge cap beam and elastomeric bearing details (Atak, Avşar, & Yakut, 2014)

In the bridge construction phase, which is widely practiced in Turkey, the prestressed beams are placed on elastomeric bearings located on the cap beams on the column pier and abutment. Then, the 22 cm reinforced concrete slab is continuously poured over the prestressed beams. This ensures that the bridge superstructure is continuous in the longitudinal direction. In this way, joints in the longitudinal direction are mostly formed between the superstructure and the abutments and the pounding event may occur during earthquake between these members. On the other hand, this event may

occur between superstructure and shear key both at the abutments and bents in transverse direction.

3.1.2. Analytical modeling in OpenSees

In order to obtain accurate results in nonlinear analysis, it is of great importance to reflect the properties of the structural members accurately to the analytical model. The 3-dimensional analytical model of the RC highway bridge used in the study was created using the frame elements in the OpenSees program, as seen in Figure 3.4. RC deck and prestressed beams form the superstructure members. As explained in the previous section, the elastomeric bearings between the bridge superstructure and the substructure transfer vertical forces generated during the earthquake directly from the superstructure members to the substructure members such as the abutments or the bent columns. For this reason, it is assumed that the bridge superstructure will remain within the elastic limits during the earthquake and the elastic beam column element in the program is used for superstructure members. The concrete grade was C25 for the reinforced concrete deck, and the modulus of elasticity was calculated as 23500 MPa using Equation (3.1) (ACI 318-14, 2014), and the C40 concrete grade was defined for the prestressed beams and the modulus of elasticity was calculated as 29725 MPa.

$$E_c = 4700\sqrt{f_c} \quad (3.1)$$

Since the bridge superstructure consists of a composite structure formed by reinforced concrete deck and prestressed beams, 2 different concrete classes must be reduced to one while defining the program. As Avşar (2009) suggested, the cross-sectional area of the reinforced concrete slab was reduced with a coefficient of $23500/23725=0.79$ and a single modulus of elasticity was introduced to the program for the entire superstructure. The shear modulus is calculated using Equation (3.2) for $\nu=0.2$.

$$G_c = \frac{E_c}{2(1 + \nu)} \quad (3.2)$$

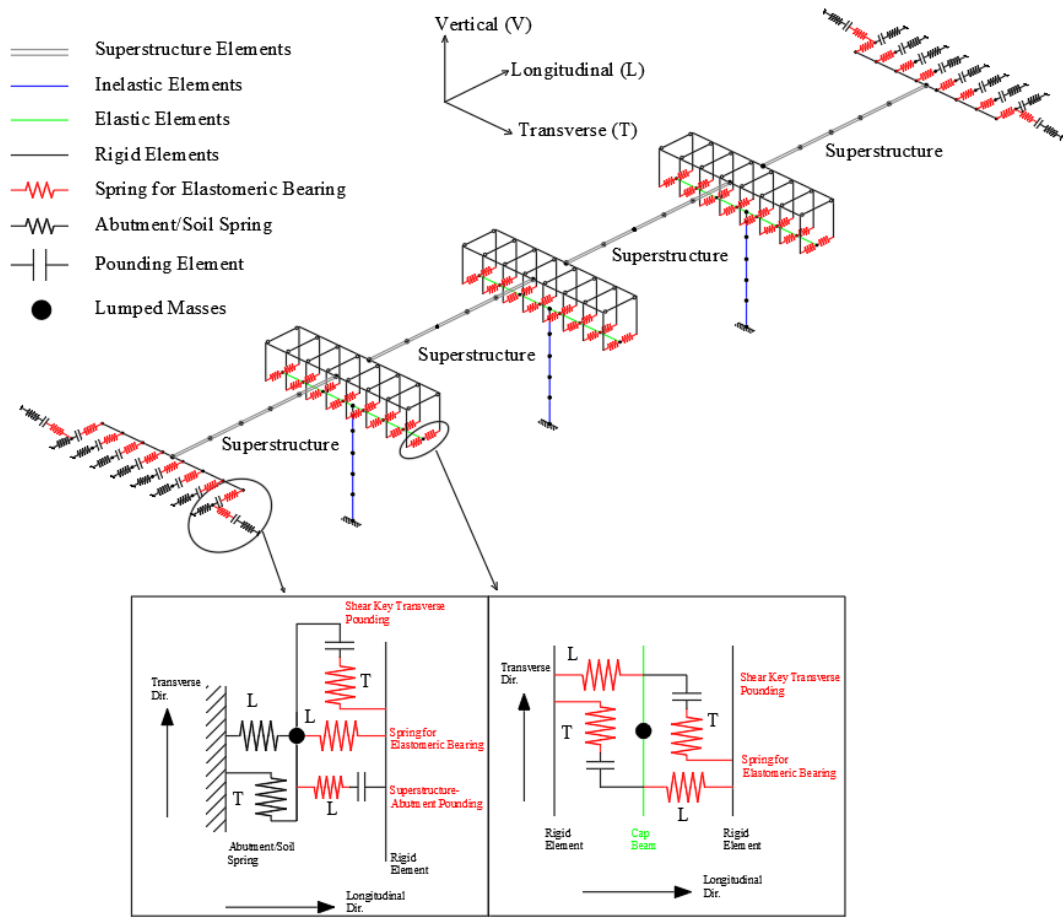


Figure 3.4. Bridge analytical model created with OpenSees program (Avşar, 2009)

The total reinforced concrete area and the transformed section properties calculated according to the principal axes given in Figure 3.5 are given in Table 3.1. The total area was used in the mass and load calculations of the superstructure members, and the converted concrete area was used in the axial stiffness calculations. In the analytical model, each bridge span consists of equally spaced nodes, and the total superstructure mass is divided equally and defined to these nodes.

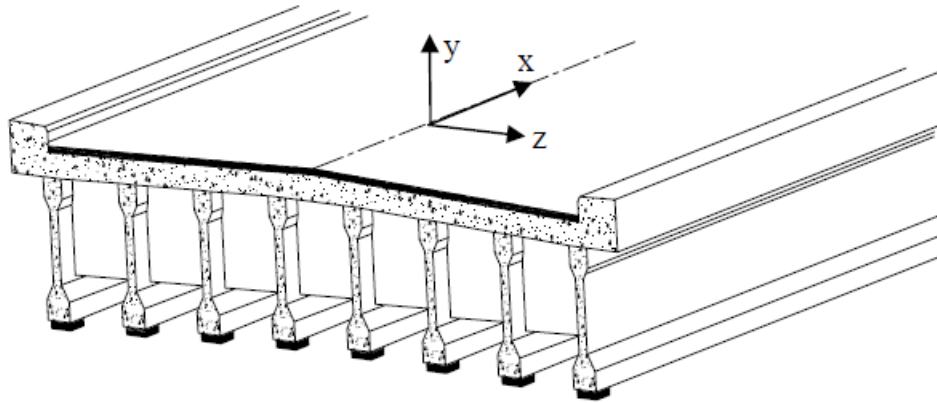


Figure 3.5. Bridge superstructure (Avşar, 2009)

Table 3.1. Transformed section properties for bridge superstructure (Avşar, 2009)

Total Concrete Area (m ²)	Transformed Section Properties			
	Conc. Area (m ²)	I _{zz} (m ⁴)	I _{yy} (m ⁴)	J (m ⁴)
6.988	6.209	2.003	103.963	0.1992

In RC bridges, the forces that arise during earthquakes are transferred from the superstructure to the abutment and column piers by means of elastomeric bearings. In bridges with a single bent column model, since the cap beam exhibits cantilever behavior, no moment occurs in these members due to the earthquake force. Therefore, as seen in Figure 3.6, the cap beam elements are introduced in the analytical program using the linear elastic element model. By using rigid elements in the joints of the members, the definition of the rigid joint zone was used. The mass of the cap beam was calculated and defined to the node where the column and beam meet.

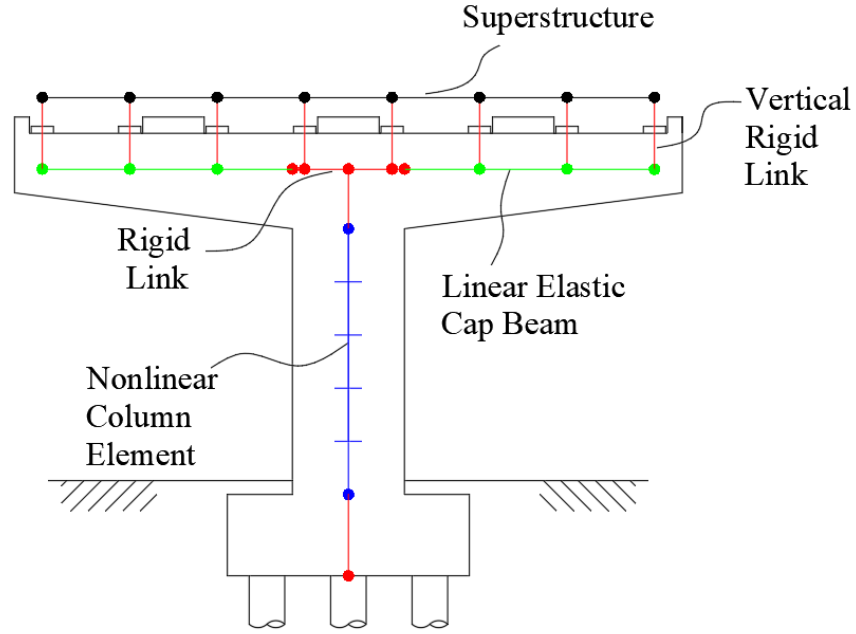


Figure 3.6. Definition of bridge bent column and cap beam with frame elements in OpenSees

Between the cap beam and each prestressed I-section beam, there are 450x250x40 mm elastomeric bearing elements as shown in Figure 3.3. In addition, there are $n=4$ steel plates with $h_s=2$ mm thickness in elastomeric bearings in order to prevent lateral bulging under axial loading and to increase vertical rigidity. Elastomeric bearings do not have any connection with the superstructure members and substructure members, and they can move freely in horizontal directions during an earthquake if the friction force between concrete elastomer surfaces exceeded. Initial stiffness for elastomeric bearing element is calculated by Equation (3.3) given below.

$$K_{bearing} = \frac{G * A}{h_{rt}} \quad (3.3)$$

In this equation, “G” is the shear modulus of the elastomeric bearing, which is taken as approximately 1.04 MPa (AASHTO, 2017). In addition, “A” represents the area of the bearing element ($A=dxb$), and “ h_{rt} ” represents the clear height of the elastomer rubber ($h_{rt}=h_t-nxh_s$). According to Caltrans (2019), the horizontal shear capacity of elastomeric bearings depends on the frictional capacity between the bearing and concrete. In this case, the elastomeric bearings will behave as linear elastic until the friction force between elastomer and concrete is overcome. After the friction force is overcome, the force will remain constant, and they continue to make displacement. The material properties of the

elastomeric bearing elements were defined to the OpenSees program as elastic-full plastic as shown in Figure 3.7.

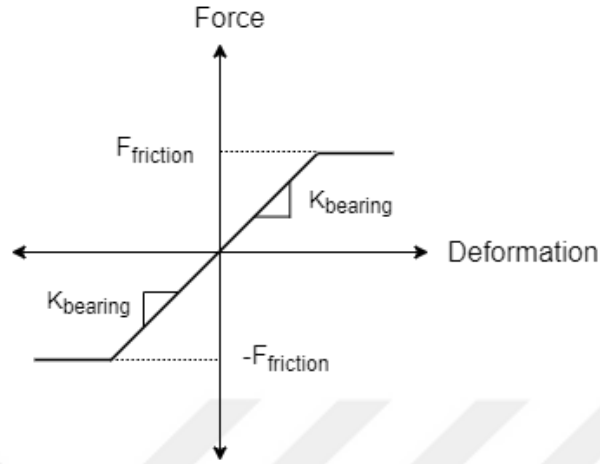


Figure 3.7. Force-deformation relationship of elastomeric bearing

Bridge members that do not show linear behavior in the event of an earthquake, such as column piers, are introduced to the numerical model with nonlinear fiber elements. For this purpose, three different material definitions were used while modeling the column sections: unconfined concrete, confined concrete and reinforcement steel. The reinforcement grade is S420 as mentioned in the previous sections. The modulus of elasticity is 2×10^5 MPa for the reinforcing steel, and the characteristic yield strength is $\sigma_{sy}=420$ MPa, the ultimate strength $\sigma_{su}=550$ MPa and the ultimate strain $\epsilon_{su}=0.1$. The reinforcing steel was defined using the Steel01 material model in the OpenSees program as shown in Figure 3.8.

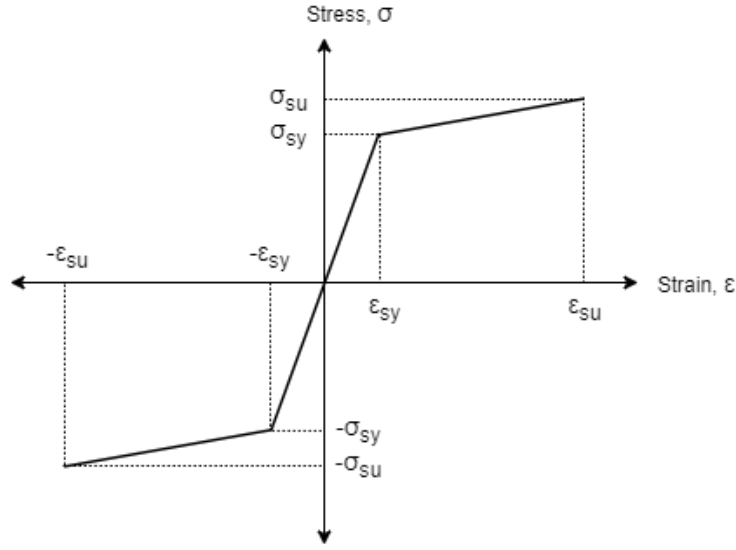


Figure 3.8. Stress-strain diagram for reinforcing steel

Unconfined concrete and confined concrete are defined using the Concrete01 material model included in the program for the C25 concrete class. As seen in Figure 3.9(a), the maximum compressive stress for unconfined concrete is $\sigma_{co}=25$ MPa and the strain corresponding to this stress is $\epsilon_{co}=0.002$, and it is assumed that the unconfined concrete is crushed when $\epsilon_{cu}=0.005$. For the confined concrete, the graph given in Figure 3.9(b) is the material model defined in Kent and Park (1971), and the parameters given in the graph are obtained by using Equations (3.4), (3.5), (3.6) and (3.7) given below. Here, “K” is a coefficient for the confinement effect that increases the concrete strength, “ ρ_s ” represents the volumetric ratio of the stirrup, “ f_{yh} ” is the stirrup yield strength, “Z” is strain softening slope, “h” is the confined concrete width and “ s_h ” is the stirrup spacing.

$$K = 1 + \frac{\rho_s f_{yh}}{\sigma_{co}} \quad (3.4)$$

$$\epsilon_{cco} = 0.002 \cdot K \quad (3.5)$$

$$\sigma_{cco} = \sigma_{co} \cdot K \quad (3.6)$$

$$Z = \frac{0.5}{\frac{3 + 0.29\sigma_{co}}{145\sigma_{co} - 1000} + 0.75\rho_s \sqrt{\frac{h'}{s_h}} - \epsilon_{cco}} \quad (3.7)$$

According to Kent and Park (1971), the residual strength for the confined concrete shown in the graph is taken as $\sigma_{cu}=0.2 \times \sigma_{co}$ and the strain (ϵ_{cu}) of the concrete at this strength is obtained using the Z slope calculated above.

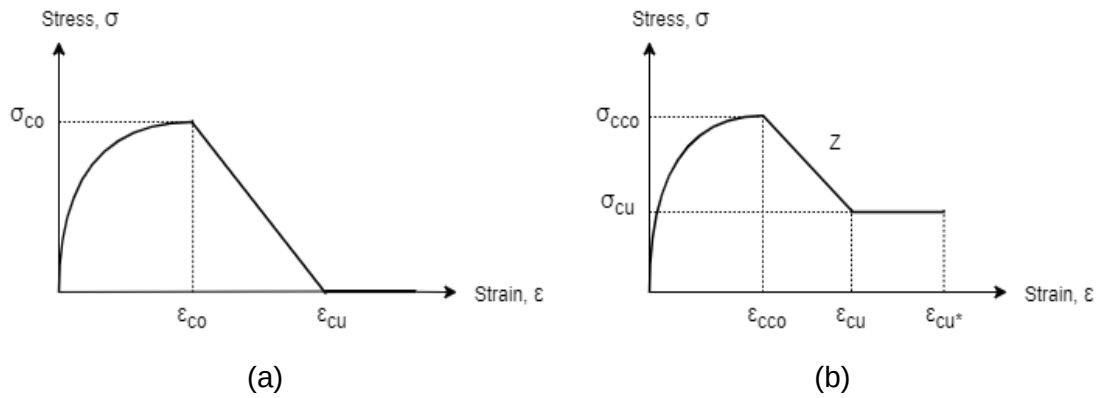


Figure 3.9. Stress-strain diagram for concrete (a) unconfined concrete (b) confined concrete

The mass of the pier is defined by dividing it equally into the 2 end nodes shown in Figure 3.6. In addition, the soil-structure interaction is not taken into account in the analytical model, and the bottom of the column piers is defined as fixed supported, with the assumption that the bridge piers are completely on solid ground.

In addition, moment-curvature analyses were performed according to the strong axis and weak axes shown in Figure 3.10 using the XTRACT section analysis program for the bridge column piers. In order to determine the axial load on the bridge column piers, static analysis was carried out by applying only vertical loads to the model of the bridge created in OpenSees. The column axial load was obtained as a result of this analysis were used in the section analysis. The resulting graphs were made bilinear as shown in Figure 3.11 and Figure 3.12. The curvature demands of the column piers obtained from the response history analysis are compared with the ultimate curvature limit values given in these graphs.

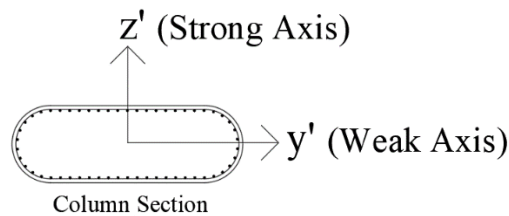


Figure 3.10. Strong and weak axis of bridge bent column

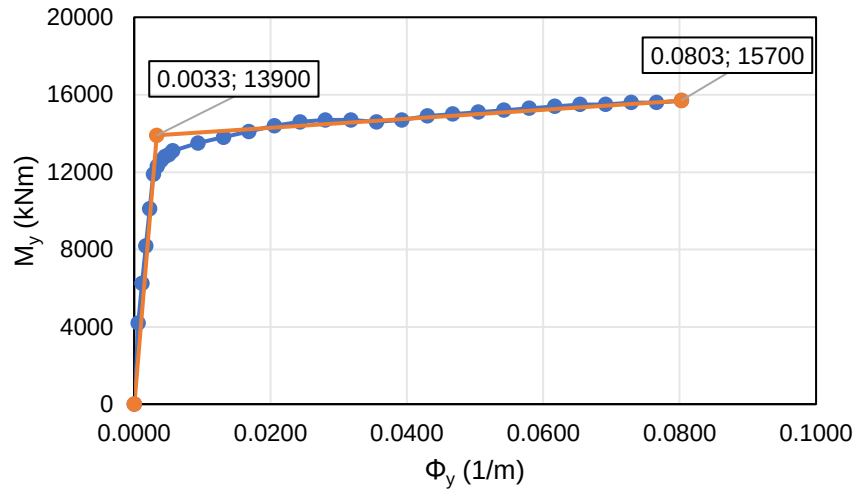


Figure 3.11. Moment-curvature graph of the weak axis (y') of bridge bent column

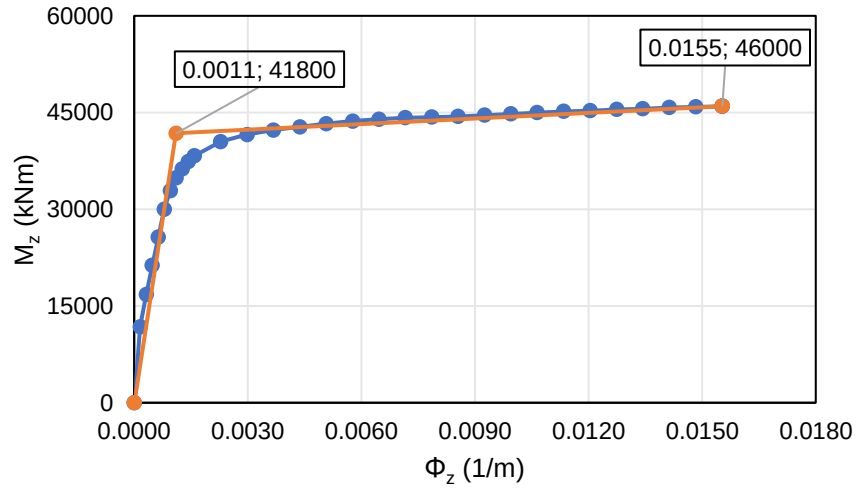


Figure 3.12. Moment-curvature graph of the strong axis (z') of bridge bent column

The modern earthquake codes enforce to prevent brittle type of damage for structural members by limiting the seismically induced shear demands lower than their shear force capacity. For this reason, within the scope of the study, the shear force capacities of the bridge column piers were calculated according to TS500 (2000) for each local axis shown in Figure 3.10, and it was aimed that the shear demands obtained from nonlinear response history analysis would remain below the shear capacity, V_r , given in Equation (3.8). V_r is the shear strength of the section and is obtained by adding the contribution of concrete (V_c) and shear reinforcement (V_w). Contribution of concrete (V_c) is calculated using (3.9), contribution of stirrup (V_w) is calculated using (3.10). V_{cr} in the equations is the oblique crack strength of concrete and is calculated by (3.11). “ A_{sw} ”

represents total cross-sectional area of shear reinforcement, “s” stirrup spacing, “ f_{ywd} ” design yield strength of transverse reinforcement, “d” height, “ f_{ctd} ” design axial tensile strength of concrete, “ b_w ” width, “ N_d ” design axial force and “ A_c ” represents concrete area in these equations. In addition, “ γ ” is the coefficient that reflects the effect of axial force on the cracking resistance, and it is taken as 0.07 in case of axial compression. The shear force capacities obtained for each local axis and bridge column pier are given in Table 3.2.

$$V_r = V_c + V_w \quad (3.8)$$

$$V_c = 0.8V_{cr} \quad (3.9)$$

$$V_w = \frac{A_{sw}}{s} \cdot f_{ywd} \cdot d \quad (3.10)$$

$$V_{cr} = 0.65 \cdot f_{ctd} \cdot b_w \cdot d \cdot \left(1 + \gamma \cdot \frac{N_d}{A_c}\right) \quad (3.11)$$

Table 3.2. Bent column shear capacities of local y' and z' axes

Col No	N_d (kN)	$V_{cy'}$ (kN)	$V_{wy'}$ (kN)	$V_{ry'}$ (kN)	$V_{cz'}$ (kN)	$V_{wz'}$ (kN)	$V_{rz'}$ (kN)
3101	7734	3216.4	1982.6	5199.1	3216.4	3304.4	6520.8
3201	7715	3215.6	1982.6	5198.2	3215.6	3304.4	6519.9
3301	7734	3216.4	1982.6	5199.1	3216.4	3304.4	6520.8

While defining the abutments, one of the bridge substructure members, in the analytical model, it is necessary to make a correct approach to consider the interaction with the soil. Although there are various studies in the literature in which the abutment-soil interaction is described in detail, the abutment-soil interaction is modeled using a simple approach that is suggested in Caltrans (2019) and used by Avşar (2009) because of the excess of parameters to be examined within the scope of this study and the aim of eliminating convergence problems that may arise in nonlinear analyses. According to this approach, as it can be seen in Figure 3.13, when the abutment is in the passive region at the time of the earthquake, a passive pressure is created due to the soil fill and piles. In the case where the abutment passes into the active region, it is assumed that the pier and the earth fill are separated from each other, and it is assumed that the pressure in this region is only due to the piles and there is no soil fill pressure. In the analytical model, the interaction between the abutment and soil is defined by using the spring elements with the bilinear force-displacement relationship separately for the active and passive pressure

situations, as shown in Figure 3.14. Abutment stiffness ($K_{abutment}$) was calculated using (3.12).

$$K_{abutment} = K_i \cdot w \cdot \frac{h}{1.7} \quad (3.12)$$

The “ K_i ” in this equation represents the earth fill stiffness and is taken as 11.5 kN/mm/m according to Caltrans (2019). “ w ” and “ h ” represent the width and height of the abutment wall. The yield force F_y given in Figure 3.14 was calculated using (3.13).

$$F_y = A_e \cdot 368kPa \cdot \frac{h}{1.7} ; A_e = h \cdot w \quad (3.13)$$

In addition, the lateral stiffness of the piles under the abutment was chosen as 7 kN/mm/pile according to Caltrans (2019).

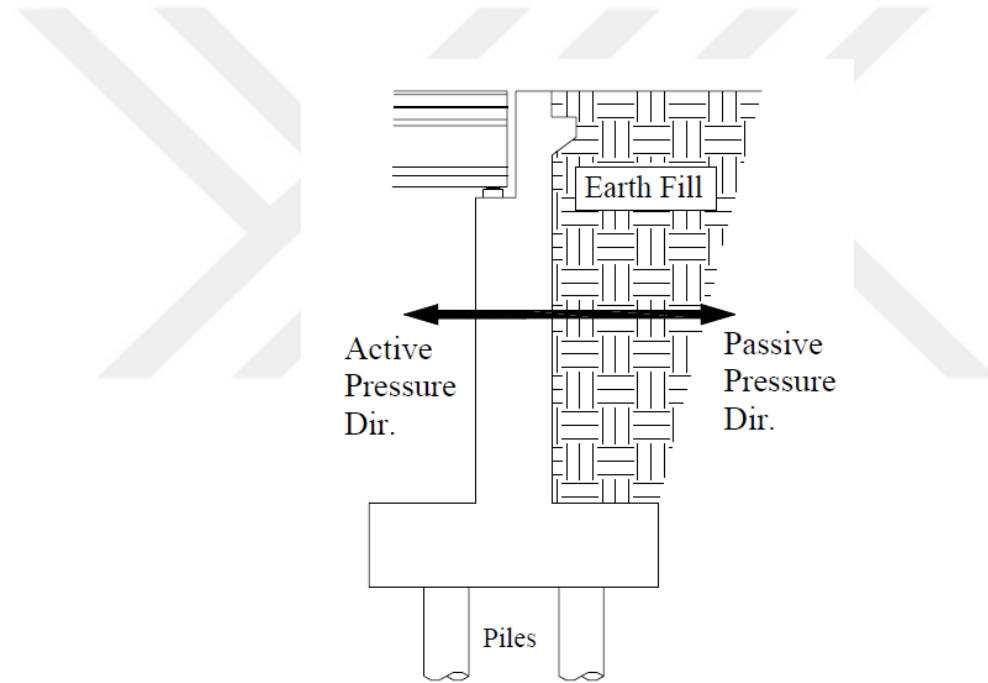


Figure 3.13. Active and passive earth pressures occurring at the abutment in the longitudinal direction of the bridge (Avşar, 2009)

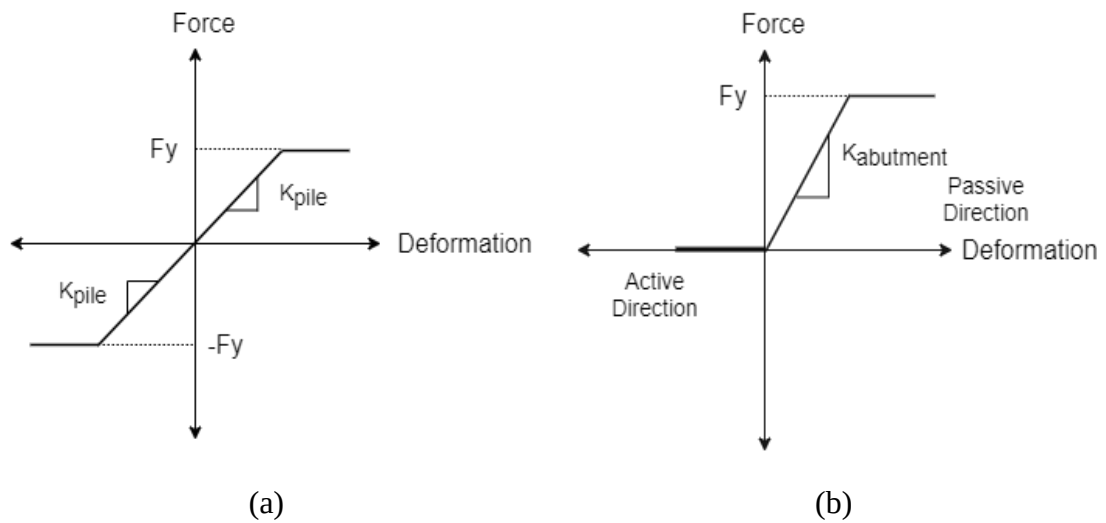


Figure 3.14. Force-deformation curves in the longitudinal direction of the abutment (a) Pile contribution (b) Soil fill contribution

In transverse direction of the abutment, the effect of the wing walls is neglected, and the resulting demand is assumed to be met only by the piles. In the analytical model, the abutment force-displacement relationship in transverse direction is as shown in Figure 3.14(a).

There are expansion joints between various bridge elements. These joints are between the superstructure and the abutment in the longitudinal direction of the bridge, and between the superstructure and the shear keys in the transverse direction, both at the abutments and at the piers. In cases where the expansion joints are wide enough, the bridge members can displace in the horizontal plane during earthquake. However, soil, garbage, etc. may fill into these gaps over time. As the materials fill, the effective working width of the expansion joints decreases. In such a case, due to the lack of sufficient joint distance or in cases where there are large displacement demands in severe earthquakes, pounding occurs between the bridge members during the earthquake and it becomes inevitable for the structural members to be damaged. In the analytical model, bilinear spring elements are defined between the members that may collide in the longitudinal and transverse directions of the bridge. In the spring model, when the bridge members move away from each other during the earthquake, there will be no force transfer, but when the elements get closer each other, there will be a force transfer between the members by the closure of the expansion joint. As shown in Figure 3.15, when the existing bridge members, where collision can occur, reach their maximum capacity, the spring element will continue to deform without taking any additional force. The gap distance (δ_{gap})

between the members in longitudinal direction of the bridge is defined as 50 mm and 25 mm in transverse direction in the analytical model.

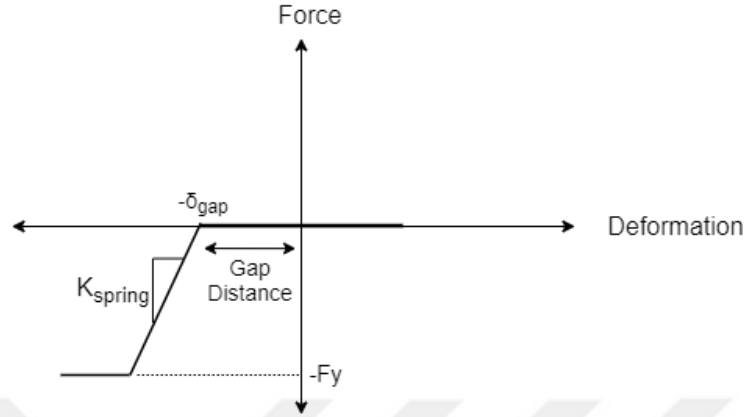


Figure 3.15. Spring model defined between bridge members

The properties of the springs used in the OpenSees program were obtained from Avşar (2009) and are as given in Table 3.3. The spring stiffness (K_{spring}) used here is the shear and bending stiffness of the abutment in the longitudinal direction and shear key in the transverse direction. Yield force (F_y) is the maximum shear and bending capacity of the abutment in the longitudinal direction and the capacity value of the shear key in the transverse direction.

Table 3.3. Spring elements used in the analytical model for pounding and their properties (Avşar, 2009)

	Superstructure-Abutment	Superstructure-Shear Key
Direction	Longitudinal	Transverse
δ (mm)	50	25
K_{spring} (kN/m)	1.5×10^5	3.4×10^6
F_y (kN)	250	1600

After defining all the members of the bridge, eigenvalue analysis of the straight bridge model ($\alpha=0^\circ$) is done in the OpenSees program and as seen in Figure 3.16, first three mode shapes are constructed by using a MATLAB code. It is clearly seen that, the

first mode belongs to the longitudinal direction of the bridge, the second mode belongs to the transverse direction of the bridge and the third mode is a rotational mode.

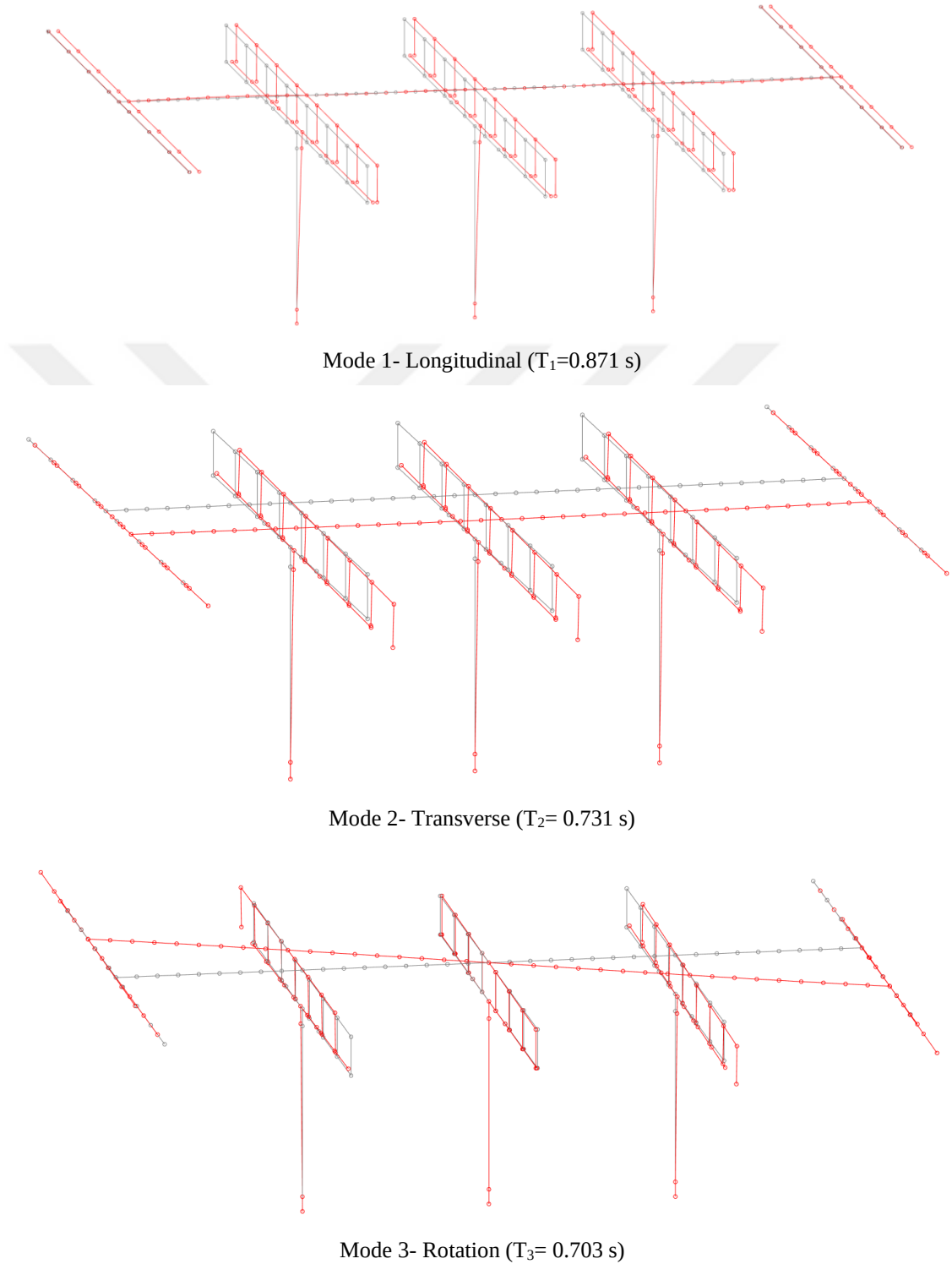


Figure 3.16. Mode shapes of straight ($\alpha=0^\circ$) bridge model

3.1.3. Selection and scaling of ground motion records

Nonlinear response history analysis is often used to determine the behavior and demands of structures during earthquakes. In the analysis, either the acceleration records of the earthquakes in the past or the artificially created records are used. However, selection of records and station is of great importance in order to obtain consistent results for the bridge of interest. While selecting the ground motion records, it is necessary to pay attention to parameters such as the magnitude of the earthquake, distance from the fault, soil class, PGA, PGV etc. Nonlinear response history analysis of the bridge analytical model created in Section 3.1 were performed using the OpenSees program. In Principles for the Design of Highway and Railway Bridges and Viaducts Under the Impact of Earthquakes (Ministry of Transport and Infrastructure of The Republic of Turkey, 2020), it is recommended to use at least 7 ground motion record sets for three-dimensional calculation in response history analysis. For this purpose, ground motion records were selected using the Pacific Earthquake Engineering Research Center (PEER, 2021) database. The magnitude of the selected earthquakes has been chosen as $M_w > 5.5$ and the faulting mechanism is strike slip. The properties of ground motion recordings are given in Table 3.4.

Table 3.4. Properties of ground motion records used in the study

No.	Earthquake	Station	M_w	Fault Mechanism	Component	PGA (g)	PGV (cm/s)	PGD (cm)
1	Coyote Lake	Gilroy	5.74	Strike Slip	230	0.42	44.34	12.44
		Array #6			320	0.31	25.39	4.38
2	Morgan Hill	Anderson	6.19	Strike Slip	250	0.42	25.40	4.43
		Dam			340	0.28	27.80	6.43
3	Imperial Valley	El Centro	6.53	Strike Slip	140	0.48	39.64	25.13
		Array #4			230	0.37	80.41	74.26
4	Landers	Lucerna	7.28	Strike Slip	260	0.72	133.40	113.92
					345	0.78	28.10	25.53
5	Düzce	Düzce	7.14	Strike Slip	180	0.40	71.15	49.69
					270	0.51	84.23	48.03
6	Superstition Hills	El Centro	6.54	Strike Slip	0	0.35	48.07	19.27
		Imp. Co.			90	0.25	41.79	21.85
7	Kocaeli	İzmit	7.51	Strike Slip	90	0.23	38.29	24.29
					180	0.16	22.33	11.84

Assuming that the bridge used in the study is located in Eskisehir, Turkey with latitude of 39.756762°N and longitude of 30.94864°E as shown in Figure 3.17, from Turkey Earthquake Hazard Map (AFAD, 2021) web interface. The soil class was assumed as ZD which has an average shear wave velocity (V_{s30}) between 180-360 m/s and elastic design spectrum is obtained for DD-2 (earthquake ground motion level with 10% probability of exceedance in 50 years) level for this location.



Figure 3.17. Data from Turkey Earthquake Hazard Map

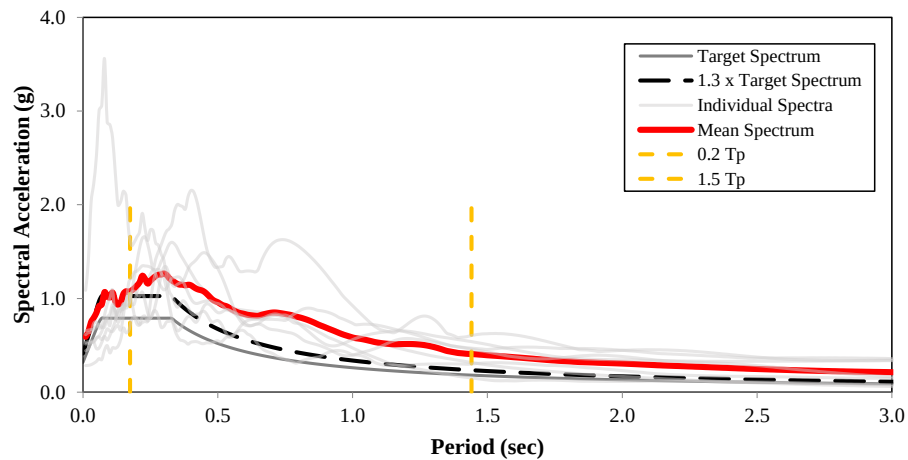


Figure 3.18. Elastic response spectra for the selected ground motions with 5% damping ratio

According to the Principles for the Design of Highway and Railway Bridges and Viaducts Under the Impact of Earthquakes (Ministry of Transport and Infrastructure of The Republic of Turkey, 2020), it is stated that the earthquake ground motions to be used in the calculation in the response history should be obtained by simple scaling method from the selected earthquake records. Accordingly, “The resultant horizontal spectrum will be obtained by taking the square root of the sum of the squares of the spectra of the two horizontal components of each earthquake record set selected for the three-dimensional calculation. The amplitudes of the earthquake ground motion components will be scaled according to the rule that the ratio of the mean amplitudes of the resultant spectra of all selected records between the $0.2 T_p$ and $1.5 T_p$ periods to the amplitudes in the same period interval of the design spectrum defined should not be less than 1.3”. In Figure 3.18, scaled elastic response spectra for 5% damping in accordance with the above mentioned section of the location determined and selected earthquake records are given. In order not to interfere with the content of ground motion records, the scale coefficients of the horizontal components of all selected earthquakes were taken as 1.0. The T_p period given in the graph is the natural vibration period of the 1st mode of the bridge. It has an increasing demand when the skew angle increases and it is given in Table 3.5 as a result of the modal analysis. In order to comprise the $0.2 T_p$ and $1.5 T_p$ period interval for all bridge models, the values of the 1st mode of the 0° skew bridge with the smallest period for the lower limit and the 60° skew bridge with the largest period for the upper limit were used.

Table 3.5. Natural vibration periods of the 1st mode depending on the bridge skew angle

Skew Angle	0°	15°	30°	45°	60°
T (s)	0.872	0.877	0.891	0.915	0.961

3.1.4. Sensitivity analysis for bridge column

When defining nonlinear column elements in the analytical model, it is necessary to use the correct number of integration points. In Avşar (2009), 5 integration points for column elements were used in the bridge analytical model. With this number, the length of the plastic hinge in the end regions of the column element could be obtained with a correct approach. In order to examine the effect of the number of integration points used in this study on the demand parameters, nonlinear analysis was performed for the Landers

earthquake by choosing 4 different number of integration points as 3, 4, 5 and 6. The longitudinal and transverse displacement demands of the bridge superstructure are given in Figure 3.19 and Figure 3.20 for each integration points. In addition, the curvature demands occurred at the end point of the column are given in Figure 3.21 and Figure 3.22. Considering the obtained results, all number of integration points give approximately same results in terms of maximum displacement demands. In curvature demands, the largest curvature occurs at the 6 integration points. However, the integration numbers 5 and 6 give approximately the same results in terms of curvature demands. As a result, it is appropriate to use 5 integrations since the use of 5 and 6 integration points for the nonlinear bridge column elements does not affect the analysis results much.

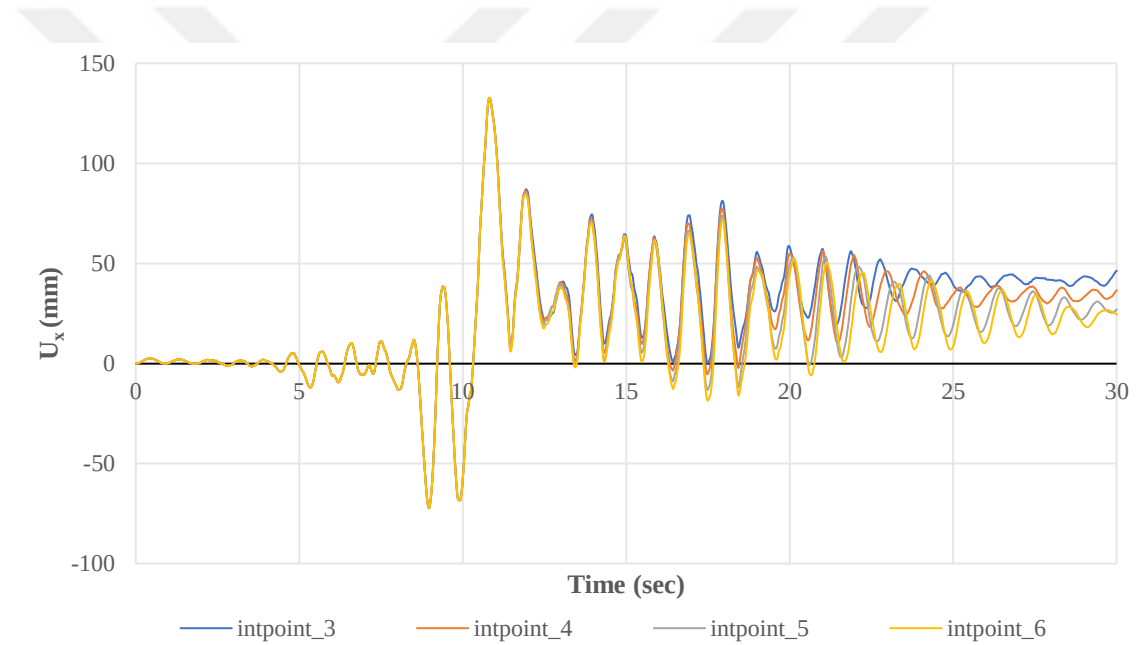


Figure 3.19. Superstructure displacement in longitudinal direction for different number of integration points on bridge column

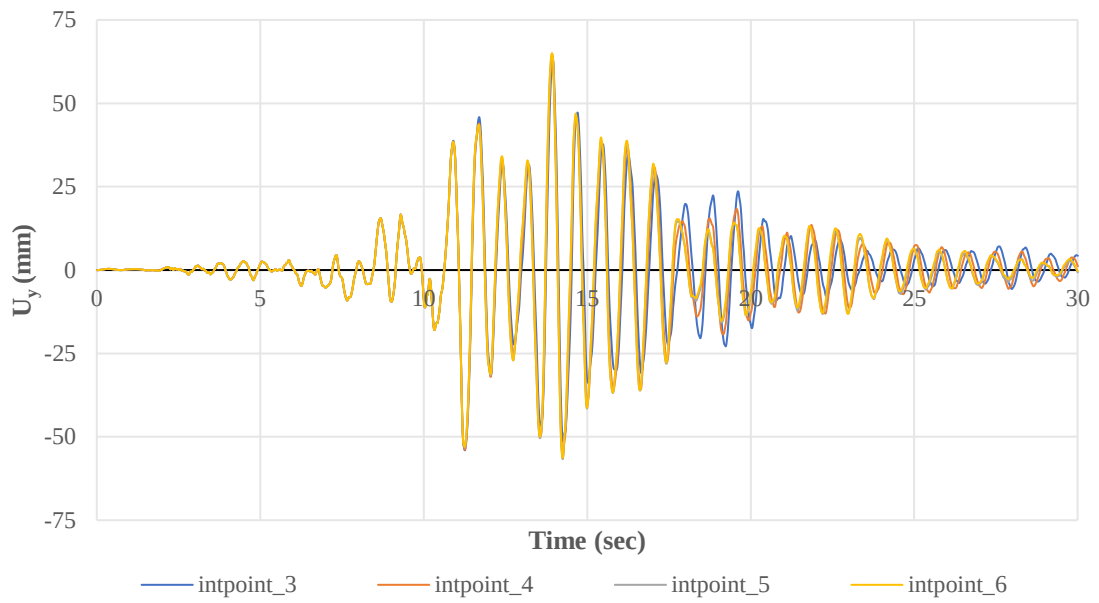


Figure 3.20. Superstructure displacement in transverse direction for different number of integration points on bridge column

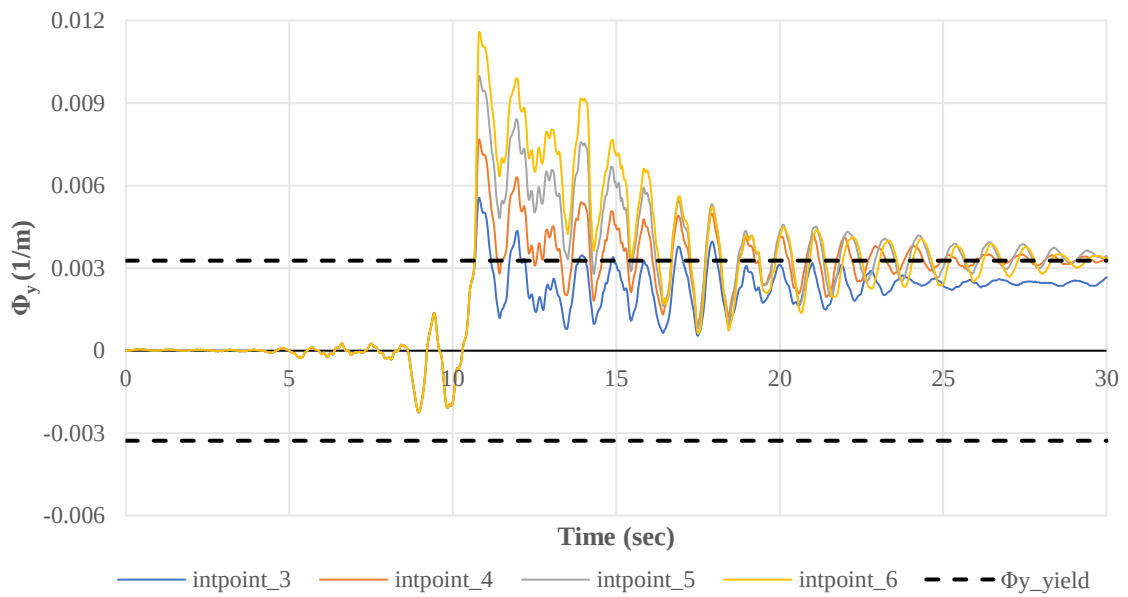


Figure 3.21. Curvature demand in the weak axis (y') of column for different number of integration points

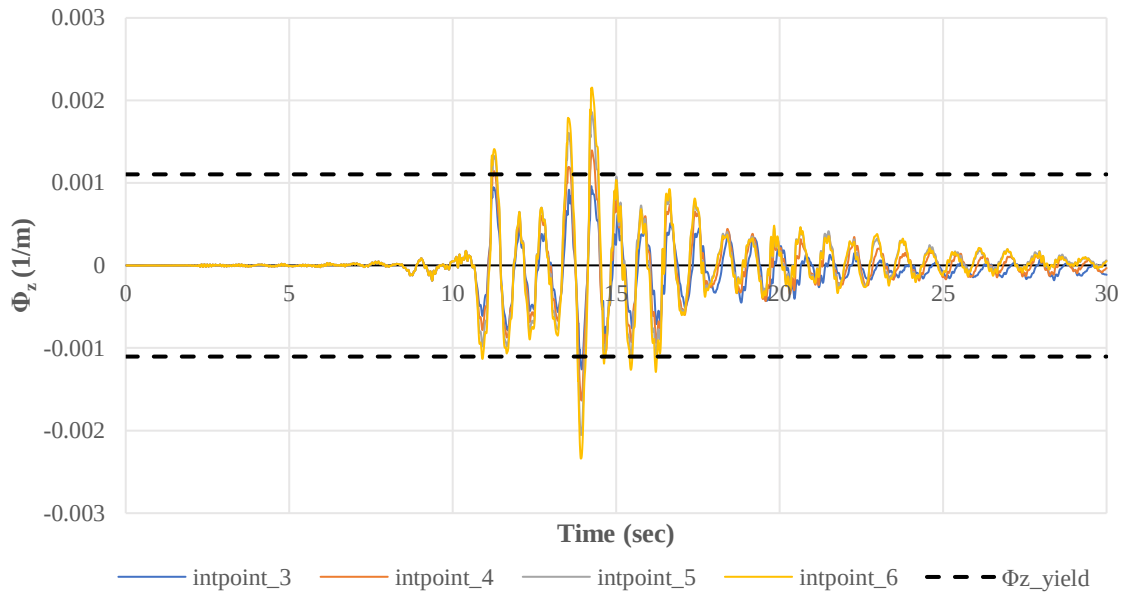


Figure 3.22. Curvature demand in the strong axis (z') of column for different number of integration points

3.1.5. Calculation of ground motion incidence angle by using 2 different methods

Nonlinear response history analysis of the bridge analytical models created in Section 3.1.2 was performed in the OpenSees program using the horizontal components of the ground motion records obtained from Section 3.1.3. However, the subject that forms the basis of the thesis is how the earthquake incidence angle should be affected on the bridge. It is a general assumption that the ground motion components affect the global axis of the structure in response history analysis. However, in reality, it is not known at what angle the earthquake affected a structure. For this reason, in recent years, researchers have carried out several studies on the effect of critical incidence angle on bridge performance. There are 2 different methods to include the incidence angle of the earthquake components in the analysis. The first one is the method of keeping the bridge global axes constant and rotating the ground motion components, and it is named as Method-1 in this study. The other is to keep the earthquake ground motion components constant on the global axes and rotate the bridge model with certain angle increments, and it is called Method-2. These methods are explained in detail in the sub-headings.

3.1.5.1. Method-1: Keeping the bridge global axes constant and rotating the ground motion components

In the literature, this method is based on the rotation of the ground motion components at certain angle intervals by keeping the global axes of the bridge model

constant. Ground motion components are recalculated using the linear transformation equations given in Equation (3.14) and the new orthogonal earthquake components are applied to the bridge global axis as shown in Figure 3.23.

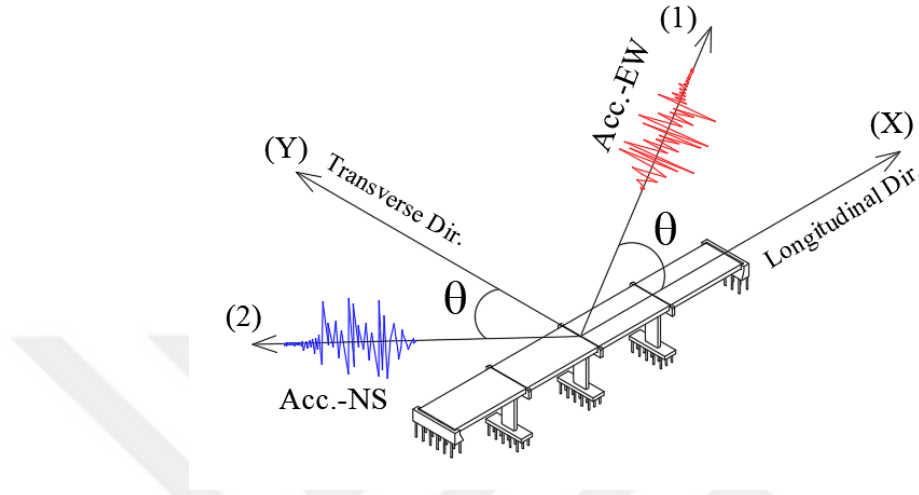


Figure 3.23. The rotation of the horizontal ground motion pair and its application to the bridge (Atak, Avşar, & Yakut, 2014)

The most important advantage of this method is that the earthquake incidence angle is easily taken into account by simply transforming the ground motion components in the principal axes of the bridge. $a_1(t)$ and $a_2(t)$ specified in Equation (3.14) are the original horizontal earthquake records that should be applied to the local axes (1) and (2) determined by the angle θ . However, to be used in the analysis, $a_x(t)$ and $a_y(t)$ which are their equivalents on the global axes are converted by linear transformation using Equation (3.14). With this method, analyses are performed by rotating the original components of ground motion from 0° to 360° at regular intervals. If the bridge model used in the analysis is symmetrical, it is sufficient to calculate up to 180° (Bhatnagar & Banerjee, 2014; Roy, Bhattacharya, & Roy, 2017; Jeon, Choi, & Noh, 2017).

$$\begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{Bmatrix} a_1(t) \\ a_2(t) \end{Bmatrix} \quad (3.14)$$

Due to the symmetry of the bridge model, the horizontal components of 7 strong ground motions selected within the scope of the thesis were rotated from 0° to 180° . The choice of how many degrees to increase is an important parameter when changing the angle of incidence from 0° to 180° . In the studies carried out, it is a common use to make increments of 15 degrees each, and the same application was adopted in the study.

3.1.5.2. Method-2: Rotating the bridge model by keeping the ground motion components constant on the global axis

Although not very often, some researchers used the method of keeping the ground motion components fixed and rotating the bridge model instead of rotating the earthquake components (Mackie, Cronin, & Nielson, 2011; Torbol & Shinozuka, 2012). In this case, the original ground motion records are kept constant on the global axes and the axes of the bridge members are rotated counterclockwise as shown in Figure 3.24. Although this method is thought to be more compatible with real behavior, the main drawback is that the bridge analytical model must be reconstructed for each incidence angle and a considerable effort is required when a detailed 3D bridge analytical model including too many nodes, elements, nonlinear springs, etc. is constructed. Through a code created in the MATLAB program, all the bridge element coordinates are rotated at the desired angle. One of the benefits of this method is that the content of earthquake records is not interfered with, and the original features of the records are preserved. In order to compare Method-1 and Method-2, bridge models with different skew angles are rotated from 0° to 180° with 15° increments. According to the results of nonlinear response history analysis using both methods, engineering demand parameters such as bridge superstructure displacement, column curvature and shear force demands, deformation demands of collision members were examined and compared with each other.

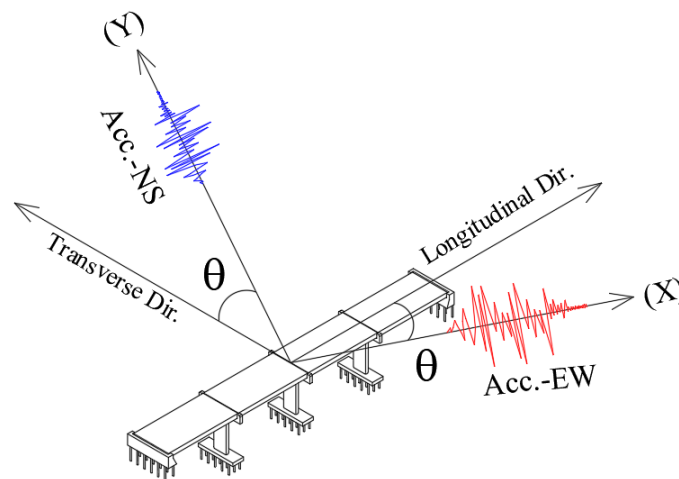


Figure 3.24. Rotation of bridge members

3.2. Bridge Model with Soil Structure Interaction

For the bridges, which were built on riverbeds, defining the column pier end as fixed support cannot realistically represent the actual behavior of the bridge due to the flexibility of soil. In such cases, including soil-structure interaction in the analysis can give more realistic results. Therefore, within the scope of thesis, it is aimed to include scour effect to the bridge models, which were previously modeled with fixed supports at column base, by using soil structure interaction. For this purpose, a group of piles were added under the columns with a pile cap and soil springs were defined at regular intervals on the pile nodes. As seen in Figure 3.25 and Figure 3.26, a group of pile (3x2 Φ 100) with a pile cap was included to the bridge model, which was used in the previous part of the thesis. Pile cap has a rectangular section with dimensions $B_{cap}=2.5$ m, $L_{cap}=5$ m and a height of $H_{cap}=1.5$ m. Six circular piles with a diameter of $D_{pile}=1$ m and a height of $H_{pile}=20$ m supports the pile cap. Concrete grade is taken as C25 and steel grade is S420 for these elements.

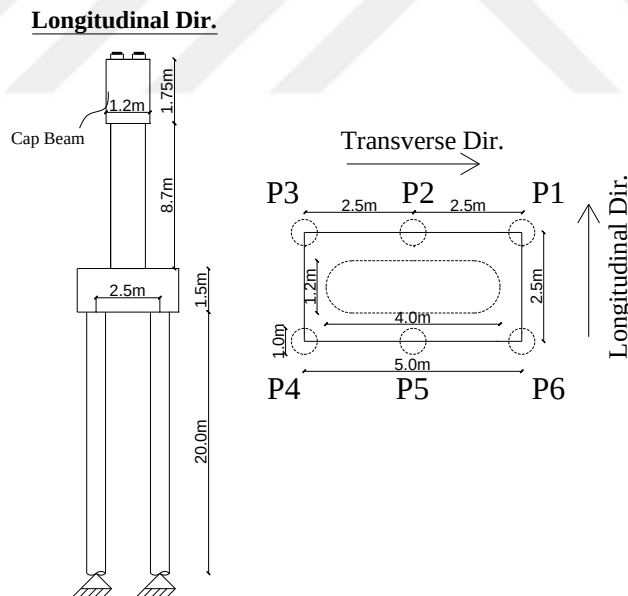
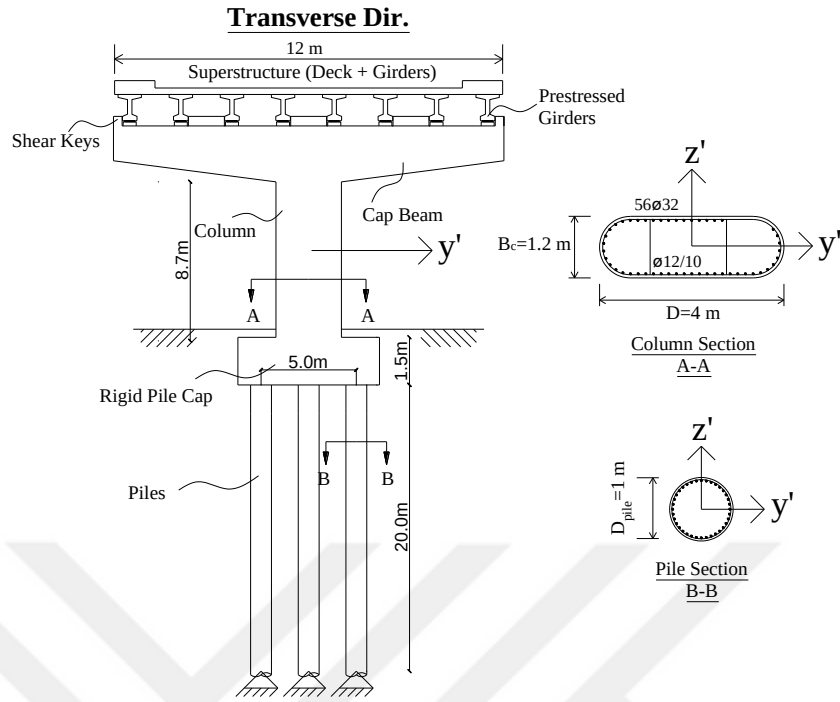


Figure 3.25. Bridge pile cap and pile member details



While defining the pile cap, rigid elastic beam column elements were used in the OpenSees platform. Column pier and piles were connected to the pile cap with also rigid elements. For the piles, force based nonlinear elements were used to reflect the nonlinear behavior. Finally, the base of the piles was defined as pin supported assuming they extended into solid ground (Figure 3.27). All the superstructure and substructure (abutments and piers) member properties were kept same as the previous part of the study.

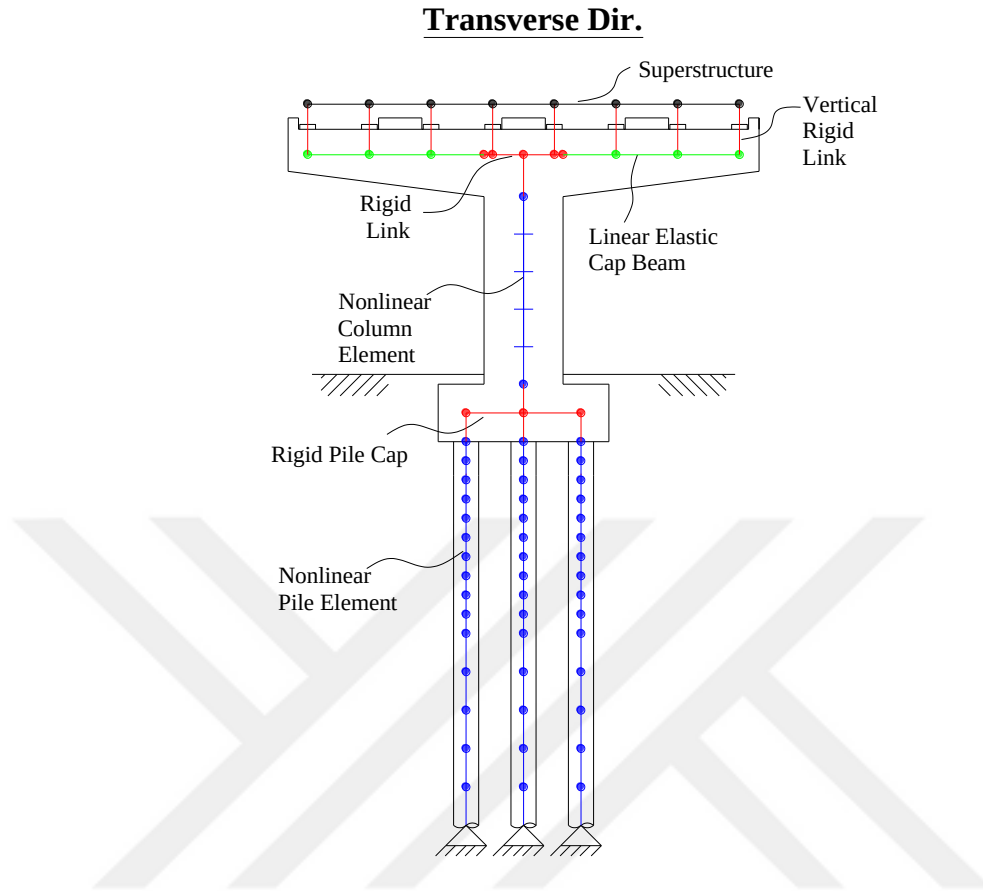


Figure 3.27. Representation of bridge column and pile elements

3.2.1. P-y and t-z soil springs

The interaction between piles and surrounding soil in lateral and axial direction influence on pile foundation especially during earthquake. While modeling the structure, it is important to consider soil structure interaction for bridges to obtain realistic results. In the literature, many of the researchers used soil springs to reflect this interaction (Banerjee Basu & Shinozuka, 2011; Alipour & Shafei, 2012; Yilmaz, Banerjee, & Johnson, 2016; Avsar, Atak, & Caner, 2017). During the modeling process in the OpenSees program, “Py Simple1” material was used for lateral soil resistance and “Tz Simple1” material was used for axial resistance. They were defined at the nodes on the pile. The soil around the piles was chosen as sand with a unit weight $\gamma_{\text{sand}}=18 \text{ kN/m}^3$ and angle of internal friction $\phi=25^\circ$. Uniaxial material properties of p-y springs were calculated according to the American Petroleum Institute (API, 2000).

The relationship between lateral soil resistance (P) and deflection (y) can be calculated by using Equation (3.15);

$$P = A \cdot P_u \cdot \tanh \left[\frac{k \cdot H}{A \cdot P_u} \cdot y \right] \quad (3.15)$$

where, A= factor to account for cyclic or static loading condition and evaluated by A=0.9 for cyclic loading. P_u (kN/m) is the ultimate bearing capacity at depth H (m), k is the initial modulus of subgrade reaction, and it is determined from Figure 3.28(a) as function of internal friction ϕ . H (m) is the depth from ground level and y (m) is the lateral deflection. The ultimate lateral capacity for sand can be calculated by using Equation (3.16) and (3.17) for shallow and deep depths, respectively. At a given depth the smallest value of the given equation should be used as P_u .

$$P_{us} = (C_1 \cdot H + C_2 \cdot D) \cdot \gamma \cdot H \quad (3.16)$$

$$P_{ud} = C_3 \cdot D \cdot \gamma \cdot H \quad (3.17)$$

In these equations, P_u is the ultimate resistance (kN/m) for s=shallow and d=deep. γ is the effective soil weight (kN/m³), H is depth (m), C_1 , C_2 and C_3 are the coefficients determined from Figure 3.28(b) as function of ϕ . And D is the average pile diameter from surface to depth (m).

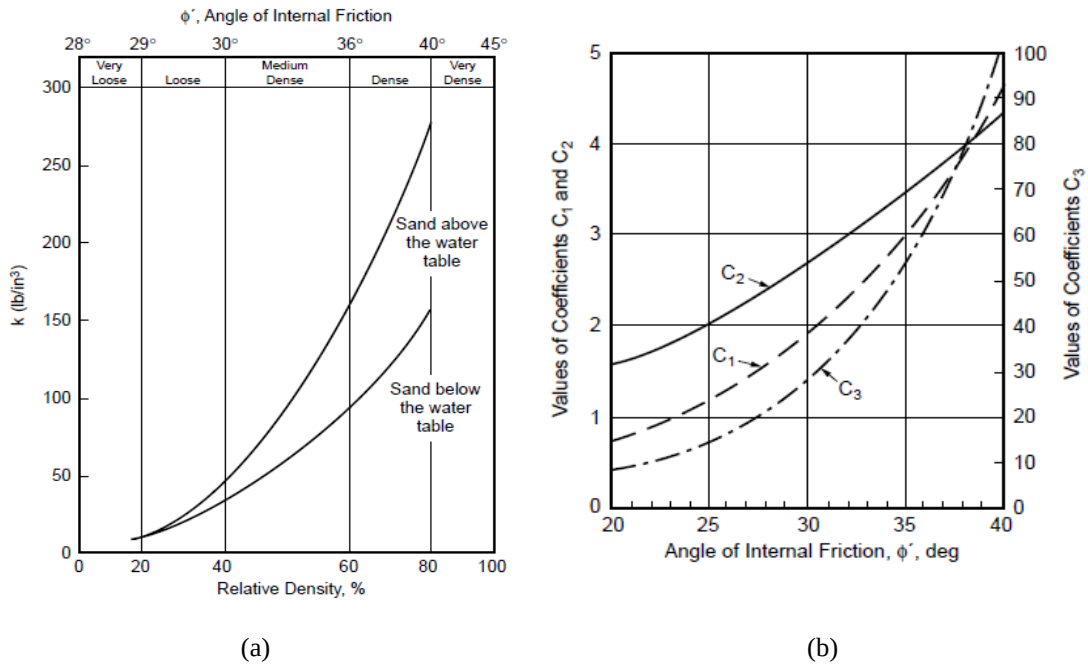


Figure 3.28. Soil spring modelling parameters (a) initial of subgrade reaction, k and (b) coefficients as function of ϕ (API, 2000)

The uniaxial material properties of t-z spring were calculated by using equations given in Kulhawy (1991) for sand type soil. Ultimate axial soil resistance was calculated by using Equation (3.18);

$$T_{ult1} = K_0 \cdot \gamma \cdot H \cdot P_{Perimeter} \cdot \tan \delta \quad (3.18)$$

$$T_{ult} = T_{ult1} \cdot L \quad (3.19)$$

$$Z_{50} = \frac{t_{ult}}{K_f} \quad (3.20)$$

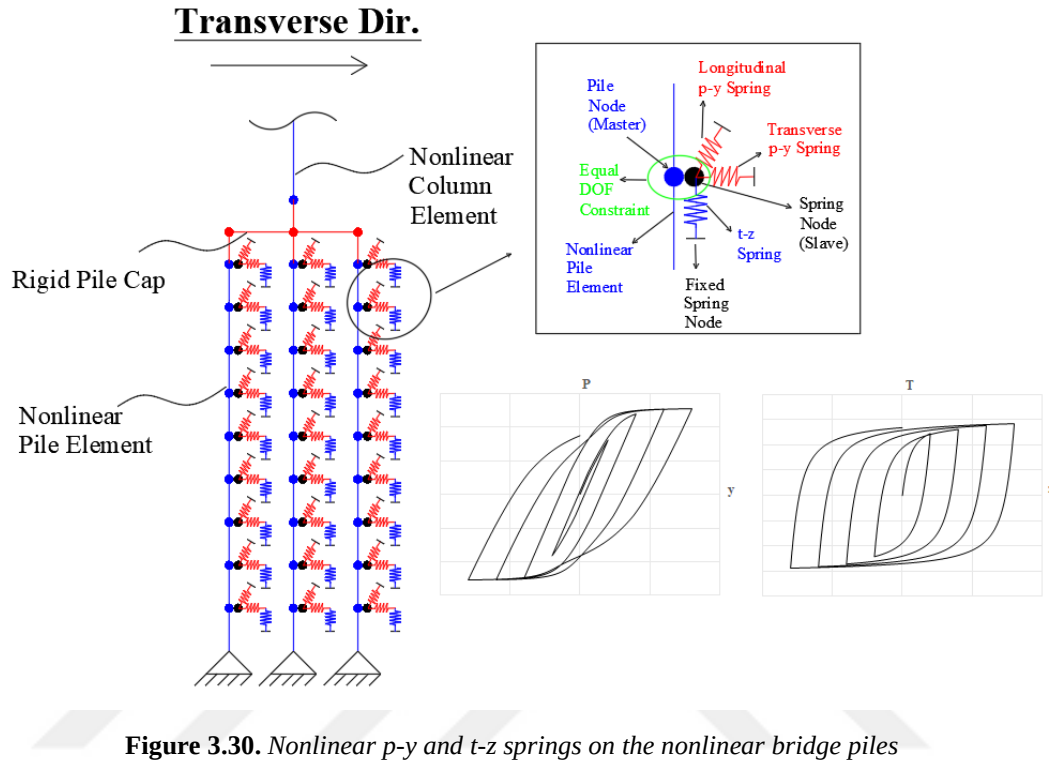
where, T_{ult1} is the ultimate axial bearing capacity of pile with a unit of kN/m. K_0 is the coefficient of the lateral earth pressure at rest, taken as $K_0=0.4$, H is the depth (m), P is the perimeter of pile surface and δ is interface friction between soil and pile, taken as $\delta=0.8\phi$ to be representative of a smooth precast concrete pile according to Kulhawy (1991). After calculating T_{ult1} , it should be converted to the force unit (T_{ult}) by multiplying length of the pile section (3.19). Z_{50} represents displacement at 50% of T_{ult} . It can be calculated by using Equation (3.20). K_f is initial modulus of side resistance, and it can be gathered from Figure 3.29 according to Mosher (1984).

<u>Initial Modulus of Side Resistance</u>		
<u>Relative Density</u>	<u>ϕ</u>	<u>Initial Modulus of Side Resistance, E_f, psf/in.</u>
Loose	28°-31°	6,000-10,000
Medium	32°-34°	10,000-14,000
Medium-Dense	35°-38°	14,000-18,000

Figure 3.29. Initial modulus of side resistance (Mosher, 1984)

After calculating all the parameters for p-y and t-z springs, they were defined in the OpenSees program. For the first 10 m below the pile cap, the pile elements were divided into 0.5 m length segments, and for the last 10 m, they were divided into 1 m length segments and springs were assigned to the nodes of these small elements. P-y springs

were defined in both longitudinal and transverse direction of the bridge and t-z springs were assigned in the vertical direction as seen in Figure 3.30.



3.2.2. Sensitivity analysis for piles

The distributed plasticity model is frequently used when modeling nonlinear elements in the Opensees program. The distances at which the plastic hinge can occur are approximately obtained by dividing the elements into various integration points. Then, the yield and ultimate curvature limit values obtained from the section analysis are compared with the curvature demands at the element ends obtained from the nonlinear analysis, and it can be seen whether the examined element is damaged or not. For this reason, it is necessary to calculate the plastic hinge length correctly and to use a realistic number of integration points.

In this section, nonlinear pile elements were defined by using number of integration points as 3, 4, 5 and 6. Nonlinear response history analysis was done for uniform scour case study which has the uniform scour depth equal to 3 m for all piles. Pile curvature was investigated for outer 4 piles as given in Figure 3.31. In addition, moment-curvature analysis was performed for the bridge pile shown in Figure 3.32 using the XTRACT

section analysis program. In order to determine the axial load on the bridge piles, static analysis was carried out by applying only vertical loads to the model of the bridge created in OpenSees. The pile axial load obtained as a result of static analysis and used in the section analysis. The resulting graph was made bilinear as shown in Figure 3.33. The curvature demands of the piles for each number of integration point model are compared with the yield curvature limit value given in this graph.

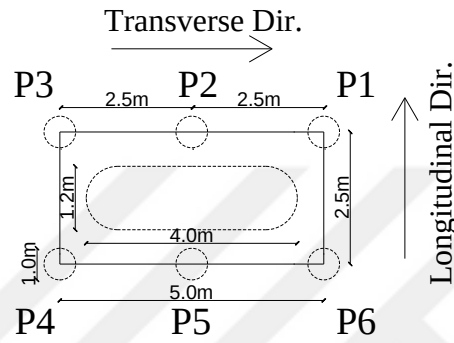


Figure 3.31. Plan view of bridge piles

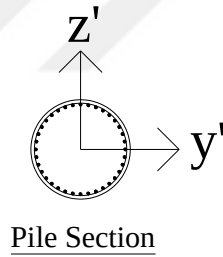


Figure 3.32. Local y' and z' axis of bridge pile

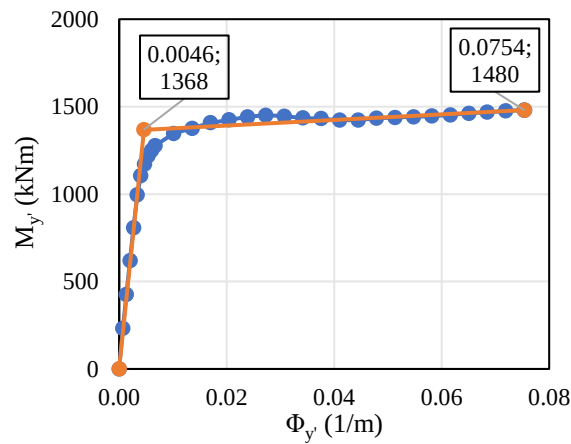


Figure 3.33. Moment-curvature graph of the y' axis of bridge pile

The curvature demands occurred along the first 7 meters of pile element 1 (P1) as a result of the analyses carried out for 3 m scour depth using the Landers Earthquake record are given in the Figure 3.34. Accordingly, the curvature demands do not exceed the yield curvature for all number of integration points and the same results were obtained for all of the corner piles (Figure 3.35). In this case, due to the fact that the pile elements remain within elastic limits, it was deemed appropriate to define these elements using the elastic beam column element model in the final analyses performed in OpenSees program. In addition, according to Caltrans (2019), it is aimed that the damages in the event of an earthquake should be on the bridge substructure elements such as column pier, and the pile elements should not be damaged and remained within the elastic limits. The results obtained from the sensitivity analyzes show that bridge model provides this condition.

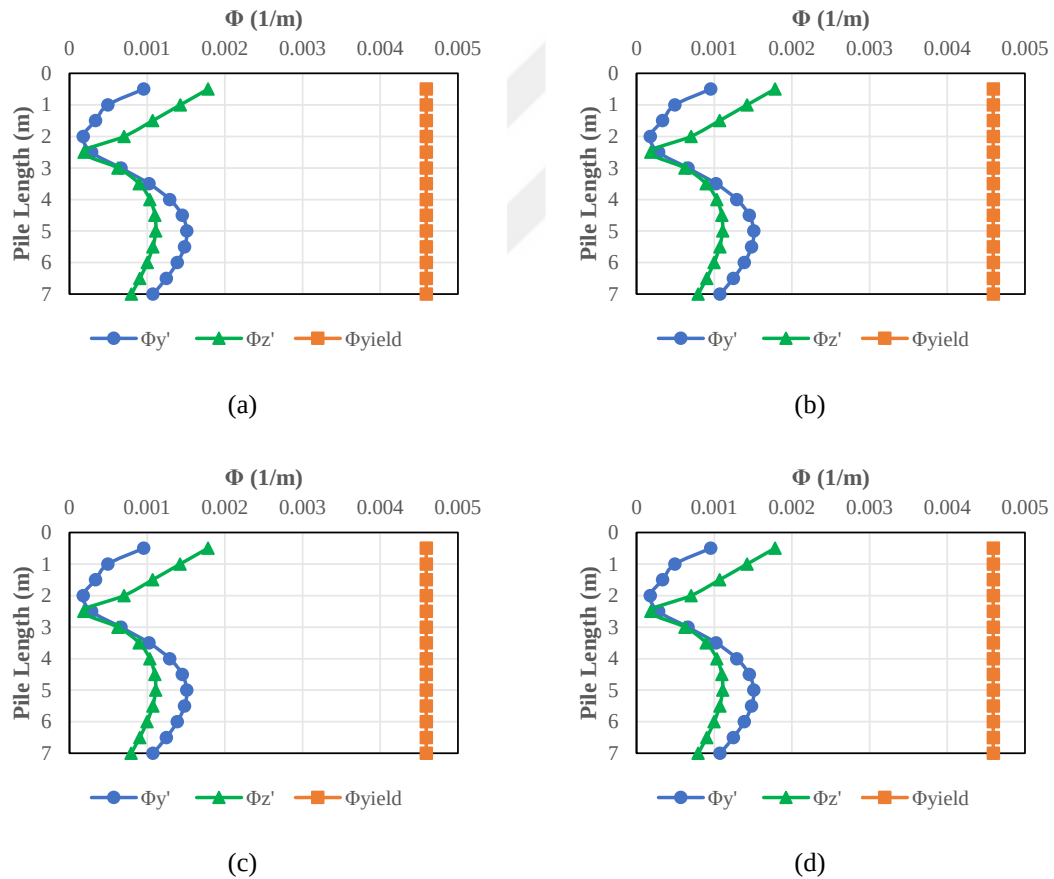


Figure 3.34. Curvature demands along the pile element 1 (P1) with the Landers Earthquake (a) 3 integration point (b) 4 integration point (c) 5 integration point (d) 6 integration point

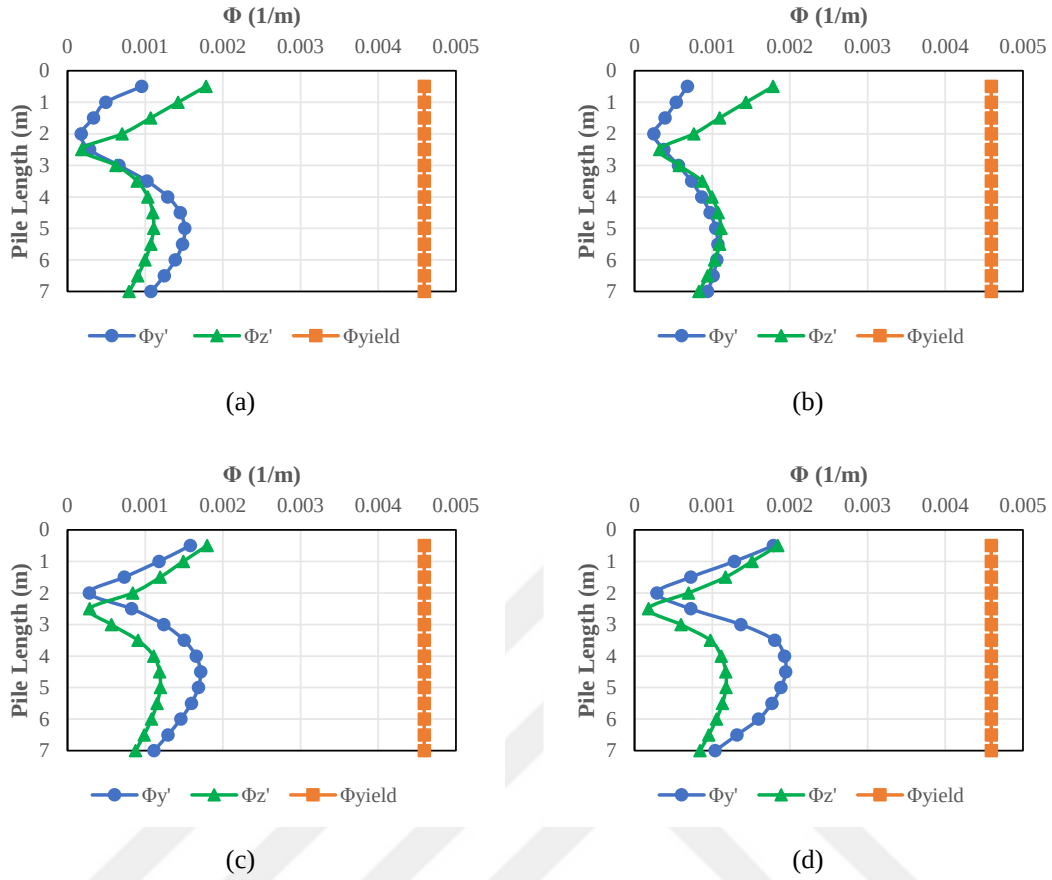


Figure 3.35. Curvature demands on pile elements due to Landers Earthquake (a) Pile 1 (b) Pile 3 (c) Pile 4 (d) Pile 6

3.2.3. Construction of final bridge model with SSI

According to the sensitivity analysis results, pile elements don't reach their yield curvature capacity and behave as elastic members. For this reason, the definition of pile elements in the OpenSees platform is provided by using the elastic beam column element model. In this way, analysis durations are shortened considerably. The final analytical model of the bridge column and pile elements are given in Figure 3.36.

Concrete grade is taken as C25 and steel grade is S420 for pile elements. While defining the pile cap, rigid elastic beam column elements were used in the OpenSees platform. Column pier and piles were connected to the pile cap with also rigid elements. Piles were defined by using elastic beam column element model and the base of the piles was defined as pin supported. All the superstructure and substructure (abutments and piers) member properties were kept same as the previous part of the study. Skew angle was selected as $\alpha=0^\circ$ (non-skewed) and $\alpha=45^\circ$ skewed and bridge models defined in the program according to these properties.

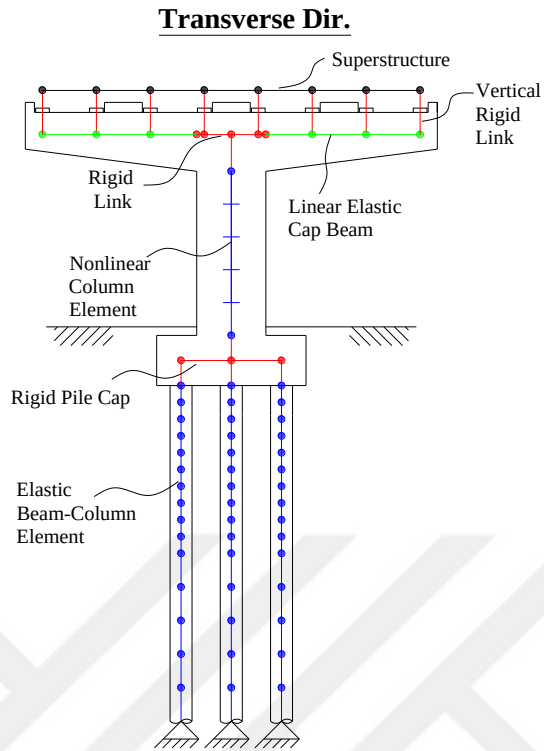


Figure 3.36. Representation of bridge column and elastic pile elements

P-y and t-z springs were defined on the piles to reflect soil structure interaction. For the first 10 m below the pile cap, the pile elements were divided into 0.5 m length segments, and for the last 10 m, they were divided into 1 m length segments and soil springs were assigned to the nodes of these small elements. P-y springs were defined in both longitudinal and transverse direction of the bridge and t-z springs were assigned in the vertical direction as seen in Figure 3.37.

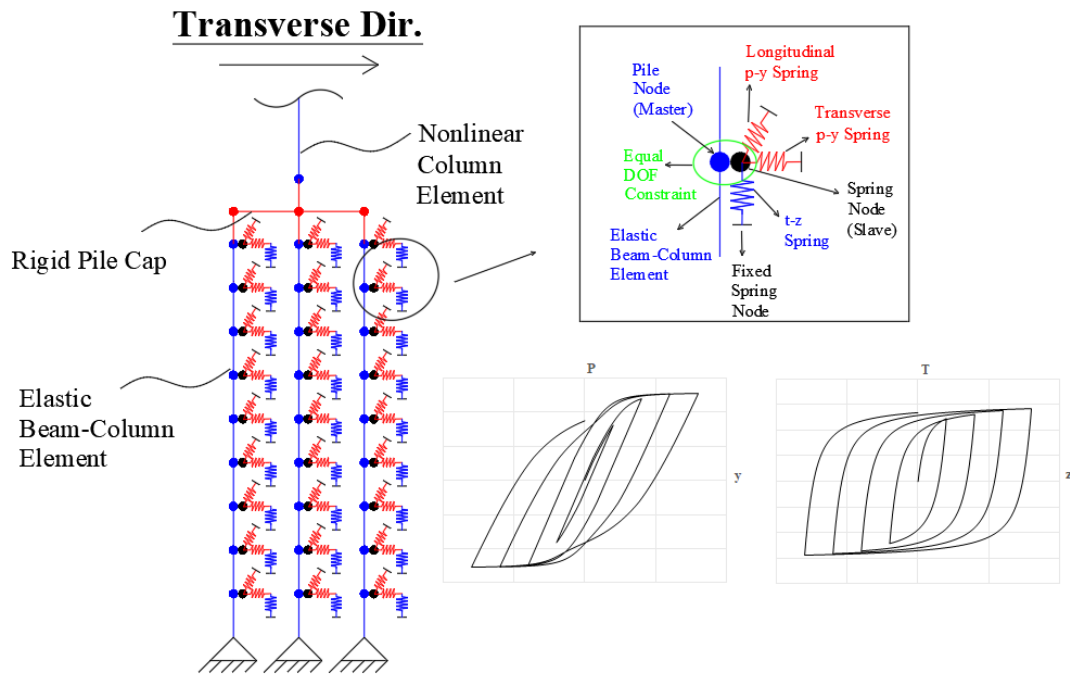
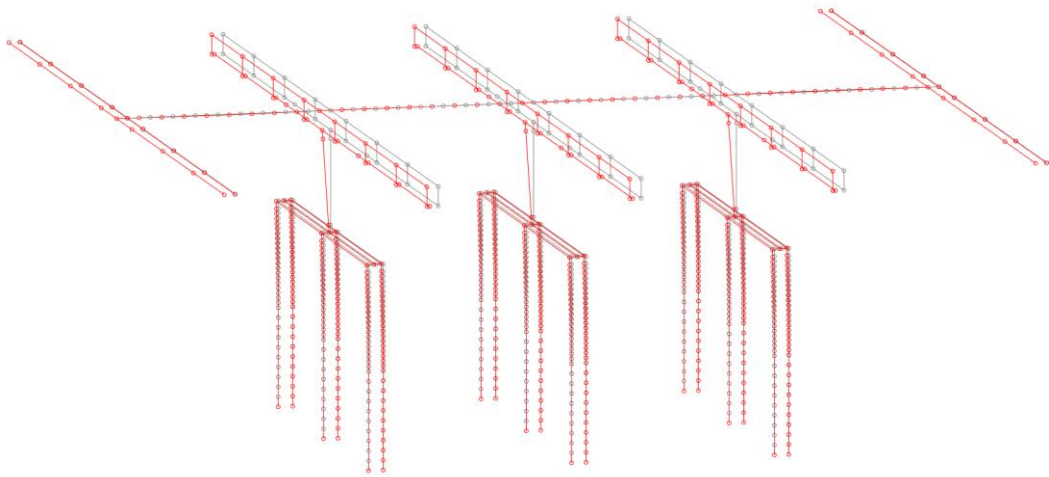
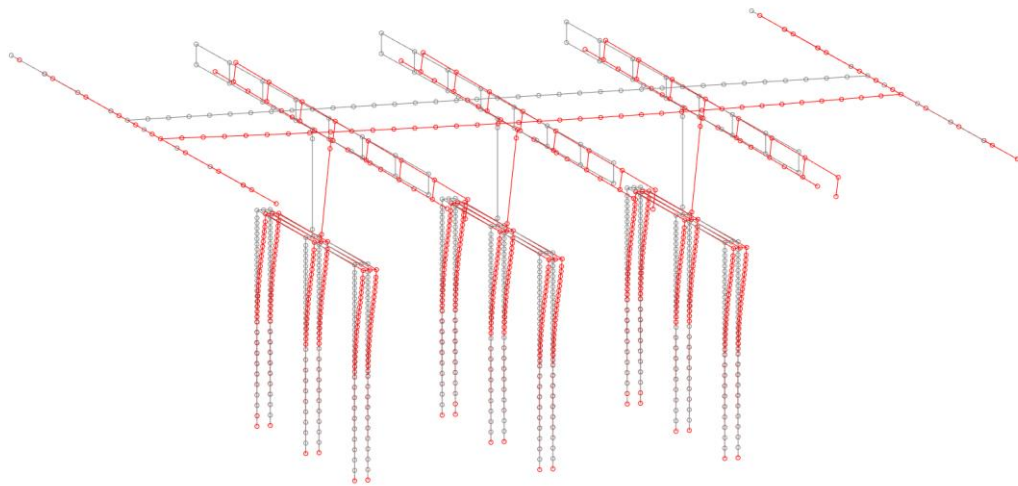


Figure 3.37. Nonlinear p-y and t-z springs on the elastic bridge piles

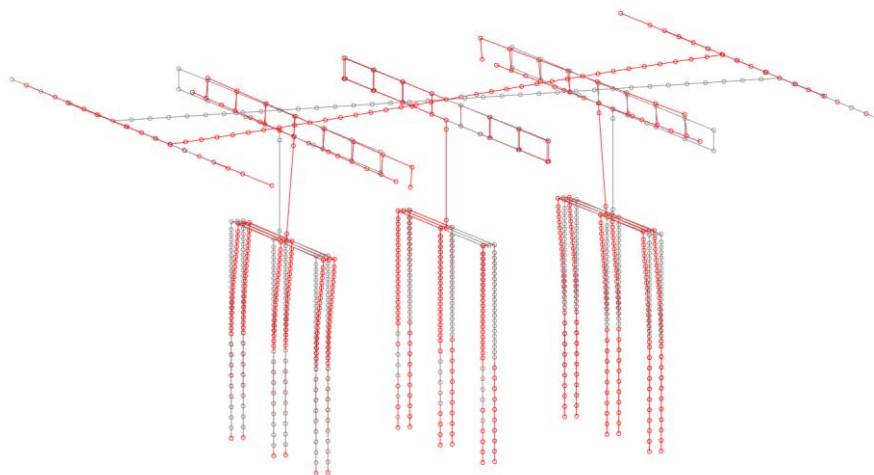
After defining all the members and elements of the bridge, eigenvalue analysis of the soil structure interacted bridge model without any skewness ($\alpha=0^\circ$) is done in the OpenSees program and as seen in Figure 3.38, first three mode shapes are constructed by using a MATLAB code. It is clearly seen that, the first mode belongs to the longitudinal direction of bridge, the second mode belongs to the transverse direction of bridge and the third mode belongs to rotational mode in the vertical axis.



Mode 1- Longitudinal direction ($T_1=1.006$ s)



Mode 2- Transverse direction ($T_2= 0.906$ s)



Mode 3- Rotation direction ($T_3= 0.770$ s)

Figure 3.38. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge model with soil structure interaction

Pile elements may be more vulnerable to earthquake forces and brittle type of failure may occur at these elements. Therefore, within the scope of the study, the shear force capacities of the pile section were calculated according to ASCE-ACI 426 (1973), and it was aimed that the shear demands obtained from nonlinear response history analysis would remain below the capacity. The shear capacity of the pile elements was calculated as 735 kN by using Equation (3.21) and the results obtained from nonlinear analyses were compared with this shear capacity to identify the brittle type of shear damage on the piles.

$$V_d = \Phi_s(V_c + V_s) \quad (3.21)$$

where V_d is the shear strength, V_c and V_s the nominal strength of concrete and transverse reinforcement shear resisting mechanisms and $\Phi_s=0.85$ is the shear strength reduction factor (ASCE-ACI 426, 1973). V_c is concrete contribution and calculated according to Equation (3.22) where v_c is the strength of concrete and A_e is the effective shear area which is equal to $0.628D^2$ for circular columns of diameter D . In Equation (3.23), the formula of concrete strength, v_c is given where v_b is the nominal shear stress, P is the axial load, f_c' is the compressive stress of concrete, A_g is the gross area of column and ρ_t is the tension steel ratio. Transverse reinforcement contribution is calculated according to Equation (3.24) where A_v is the total area of transverse reinforcement in a layer in the direction of the shear force, f_{yh} is the yield strength of steel, d is the effective depth and s is the spacing along the member axis of the layers of stirrups (Priestley, Seible, & Calvi, 1996).

$$V_c = v_c \cdot A_e ; A_e = 0.628D^2 \quad (3.22)$$

$$v_c = v_b \left(1 + \frac{3P}{f_c' \cdot A_g}\right) ; v_b = (0.066 + 10\rho_t)\sqrt{f_c'} \quad (3.23)$$

$$V_s = \frac{A_v \cdot f_{yh} \cdot d}{s} \quad (3.24)$$

3.2.4. Scour cases

Scour is an important phenomenon, which may affect the seismic demands of bridge members as explained before. Most of the researchers considered uniform scour depth around bridge substructure members and made their response history analysis accordingly. This is an easy and practical way during modeling process. However, in reality this may not be the case. In the content of thesis, it is aimed to consider 2 types of

scour case for the bridge which is modeled in the above section with SSI. In the first case, which will be mentioned as Case-1 in the next sections, the scour depth will be changed uniformly starting from 0 m to 5 m with an increment of 1 m (Figure 3.39).

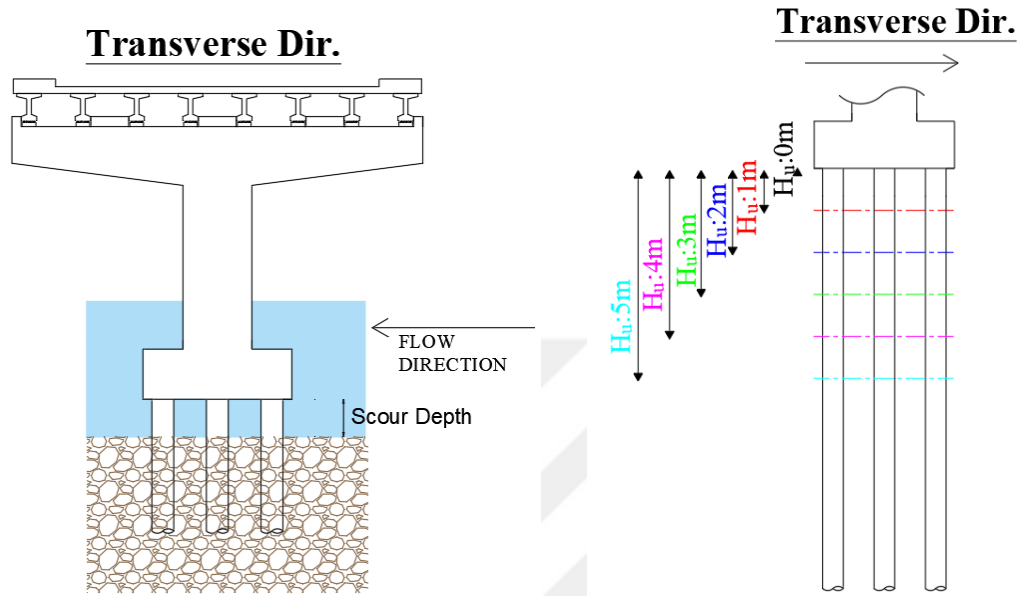


Figure 3.39. Uniform scour Case-1 and the change of scour depth (H_u)

In Case-2, the non-uniform shape of scour will be considered to reflect the uneven distribution of soil removal around the piles. Case-2 is further divided into 2 subgroups, Case 2-1 is the condition which may cause more scour around the upstream piles than the downstream according to the direction of flow (Figure 3.40). In this case, scour depth is changed from downstream starting from 0 m to 5 m. The scour angle between downstream and upstream piles is taken as a variable and two further cases are adopted for this angle, which is taken as $\gamma=0.6$ and $\gamma=1.0$ for mild and severe non-uniform scour cases, respectively.

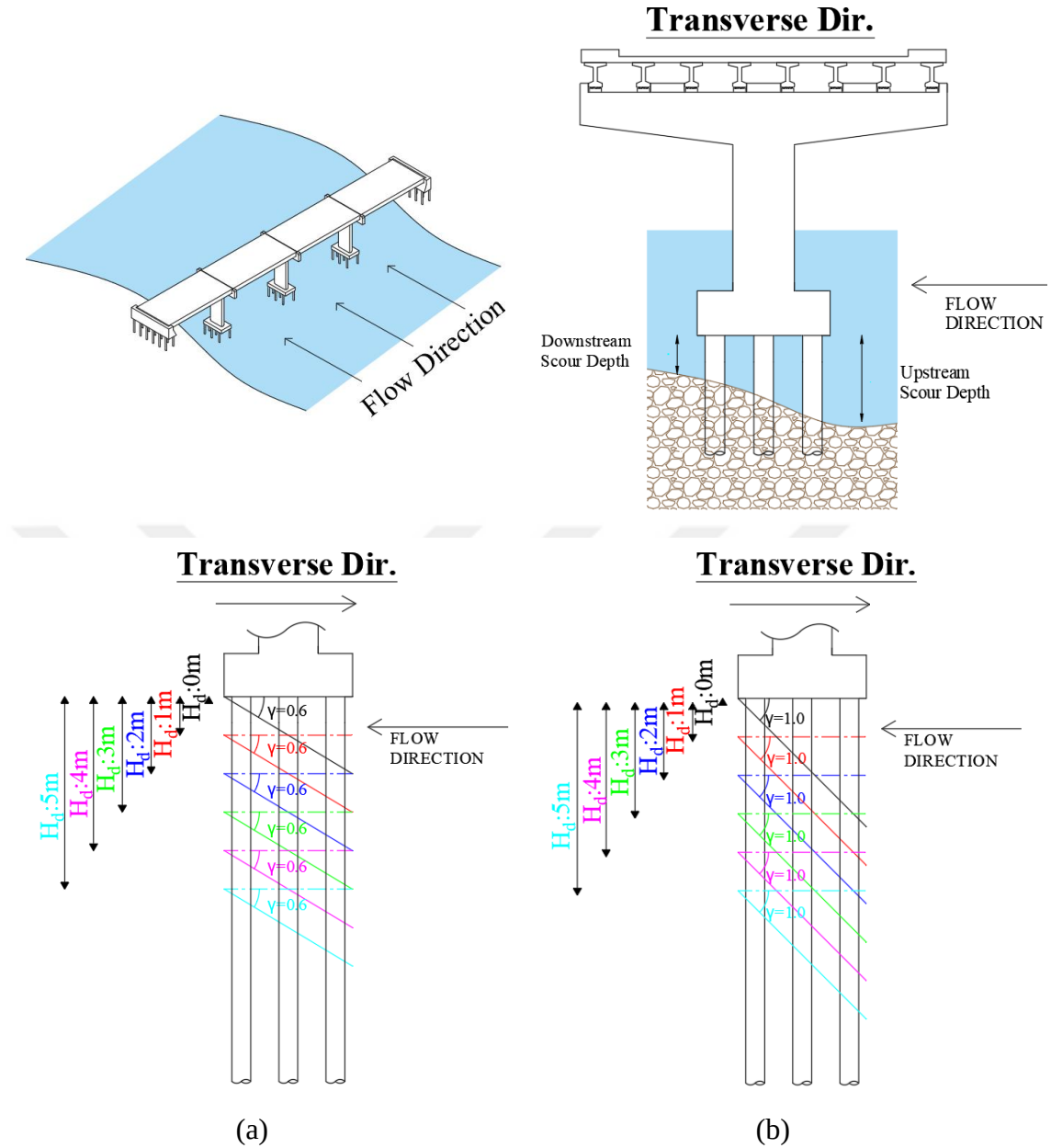


Figure 3.40. Non-uniform scour Case-2-1 and the change in scour depth from downstream pile (a) when angle is $\gamma=0.6$ (b) when angle is $\gamma=1.0$

On the other hand, in Case 2-2, the situation where the piles in the middle span have more scour than those in the outer spans is investigated as seen in Figure 3.41. Case 2-2 is obtained by taking the scour depth varying as 25%, 50% and 75% more around middle column piles than side column piles as given in Figure 3.42, Figure 3.43 and Figure 3.44, respectively. Scour depth is taken as 2 m, 4 m and 6 m (H_d) at side piles and the depth around middle piles are calculated according to the adopted scour depth variation ratios (25%, 50% and 75%).

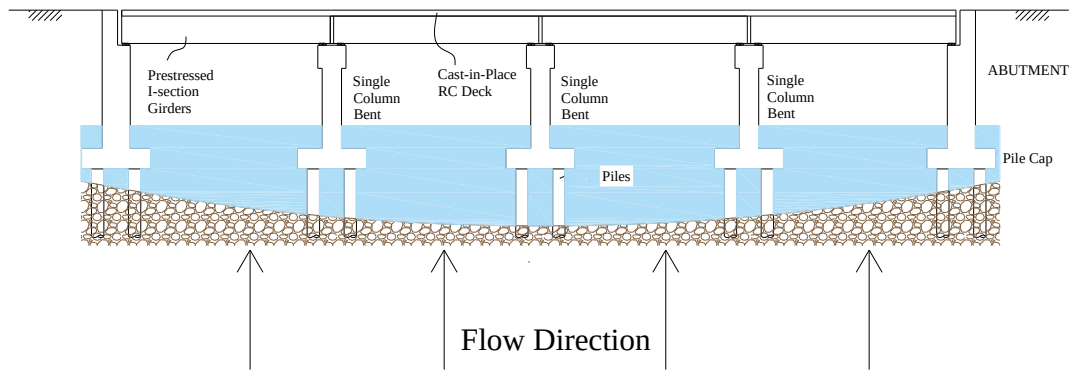


Figure 3.41. Non-uniform scour Case 2-2

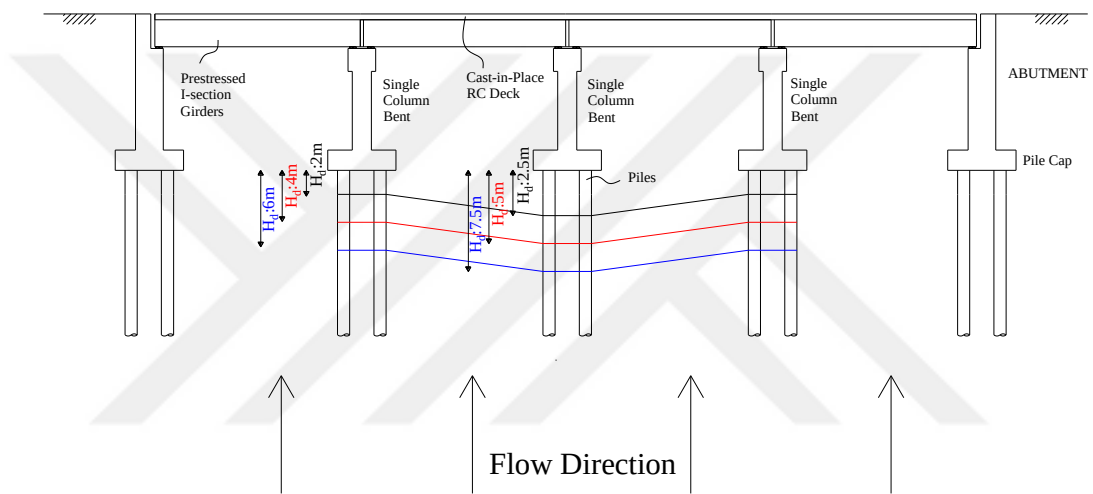


Figure 3.42. The change of non-uniform scour depth in the longitudinal direction of bridge when scour is 25% more around middle piles (Case 2-2a)

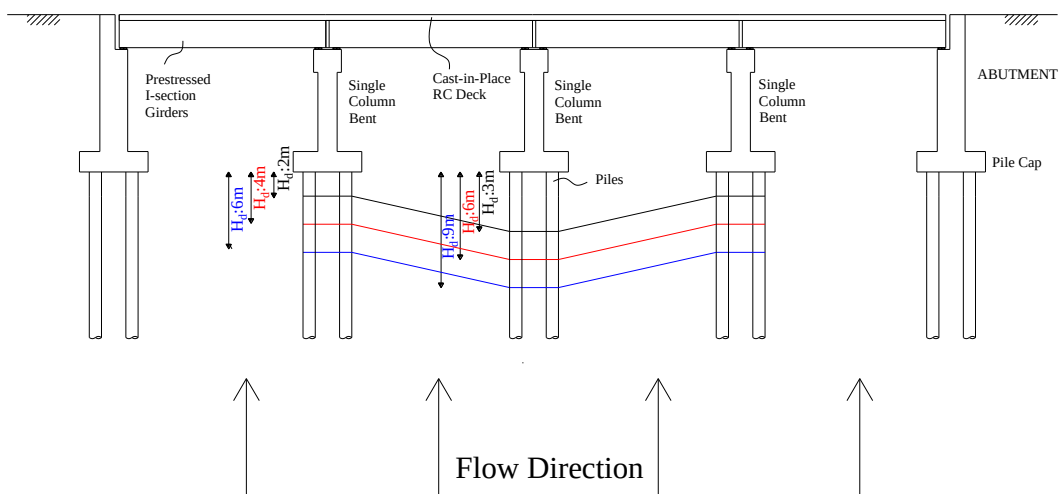


Figure 3.43. The change of non-uniform scour depth in the longitudinal direction of bridge when scour is 50% more around middle piles (Case 2-2b)

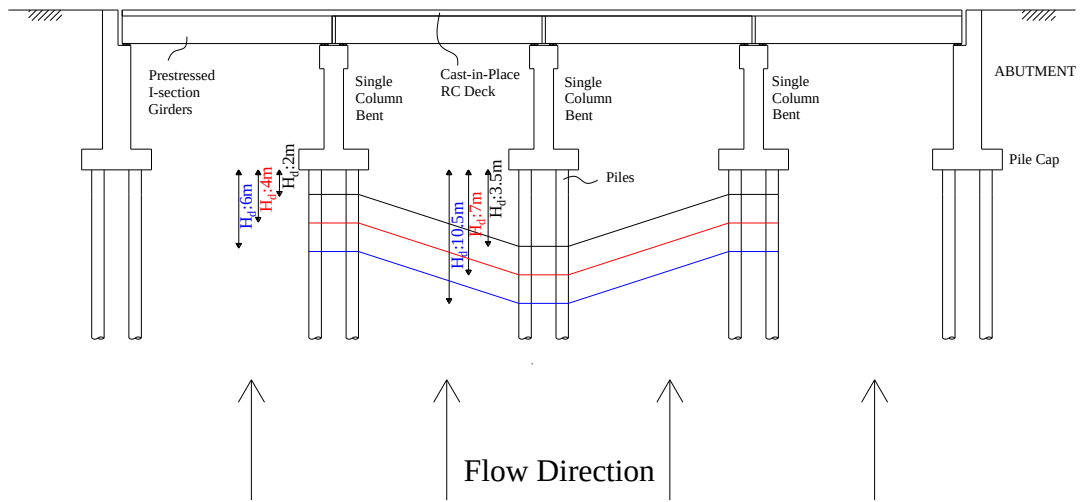


Figure 3.44. The change of non-uniform scour depth in the longitudinal direction of bridge when scour is 75% more around middle piles (Case 2-2c)

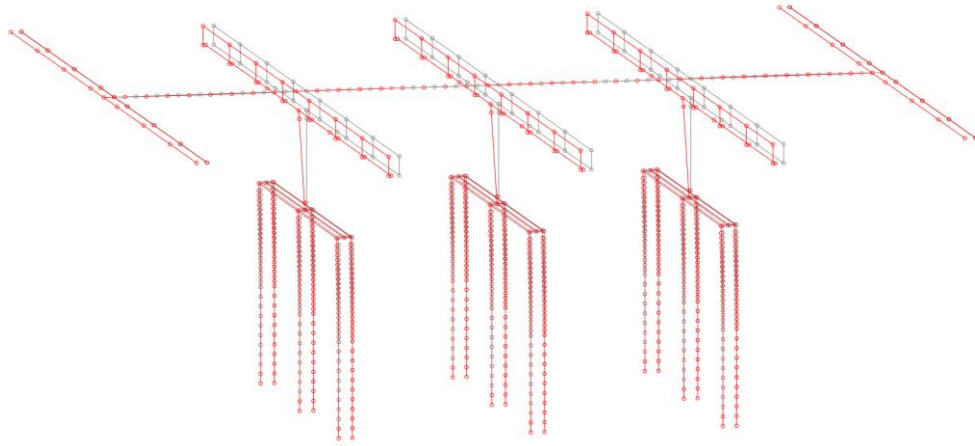
3.2.5. Mode shapes

Before starting the dynamic analysis of the bridge models, it is primarily aimed to obtain the first 3 mode shapes of the bridge by performing modal analysis. Each of the analysis are done by using non-skewed ($\alpha=0^\circ$) and 45° skewed bridges for each scour cases in the OpenSees program. Scour depth is assumed as 0 m and 5 m for the bridges to investigate the most critical situations for uniform scour case (Case 1) and non-uniform scour case occurred in transverse direction (Case 2-1). Also, scour depth is chosen as 2 m and 6 m for non-uniform scour case occurred in longitudinal direction of bridge (Case 2-2) to obtain the most critical situation. After modal analysis, mode shapes are constructed in the MATLAB program by using eigenvectors obtained from the analysis for each nodes. The first 3 periods of the investigated bridges are given in Table 3.6. Also, mode shapes of bridges for each skew angle and scour case given in detail Appendix-A.

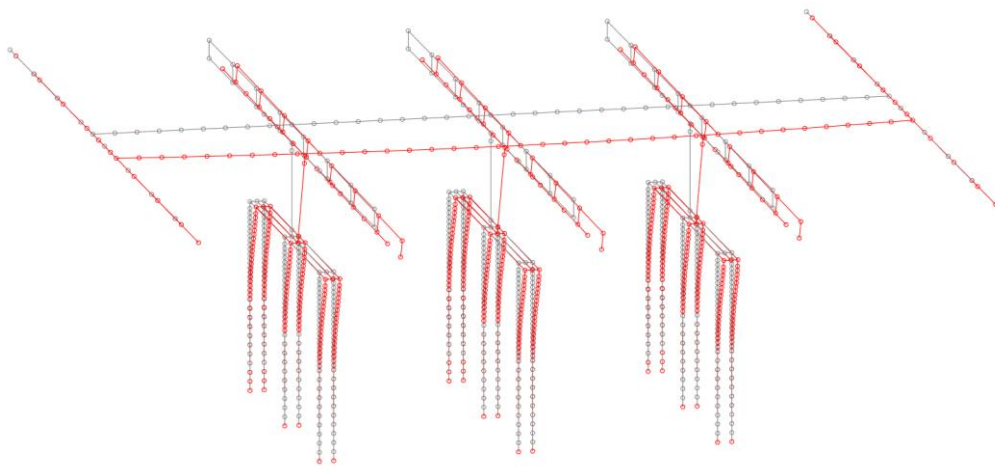
In Figure 3.45 and Figure 3.46, mode shapes belong to non-skewed bridge ($\alpha=0^\circ$) are given when uniform scour depth equals to 0 m and 5 m respectively. Also, in Figure 3.47 and Figure 3.48, the mode shapes belong to the skewed bridge ($\alpha=45^\circ$) when uniform scour depth is 0 m and 5 m is shown. It is clearly seen that, the first mode belongs to the longitudinal direction of bridge, the second mode is in the transverse direction of bridge and the third mode belongs to rotation for non-skewed and skewed bridges when uniform scour depth is equal to 0 m and 5 m.

Table 3.6. *Periods of the investigated bridges according to skew angle and scour depth*

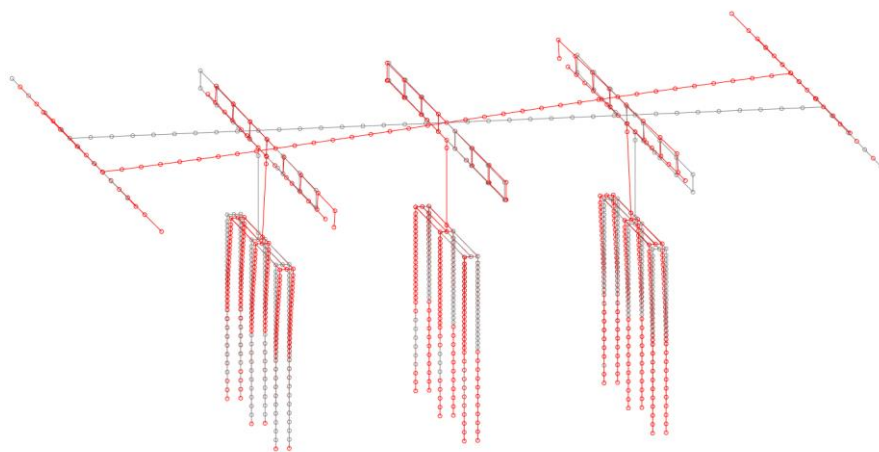
Scour Case	Skew Angle (°)	Scour Depth (m)	T ₁ (s)	T ₂ (s)	T ₃ (s)
Case 1	0°	0	1.007	0.906	0.770
	0°	5	1.093	1.064	0.817
	45°	0	1.074	0.871	0.799
	45°	5	1.191	0.998	0.835
Case 2-1a	0°	0	1.028	0.937	0.780
	0°	5	1.120	1.116	0.830
	45°	0	1.100	0.897	0.807
	45°	5	1.230	1.037	0.845
Case 2-1b	0°	0	1.040	0.953	0.785
	0°	5	1.143	1.134	0.836
	45°	0	1.115	0.911	0.811
	45°	5	1.251	1.057	0.850
Case 2-2a	0°	0	1.040	0.963	0.787
	0°	5	1.127	1.123	0.827
	45°	0	1.118	0.919	0.812
	45°	5	1.237	1.043	0.843
Case 2-2b	0°	0	1.043	0.969	0.787
	0°	5	1.148	1.132	0.827
	45°	0	1.122	0.923	0.812
	45°	5	1.253	1.057	0.843
Case 2-2c	0°	0	1.046	0.975	0.787
	0°	5	1.165	1.139	0.826
	45°	0	1.127	0.928	0.812
	45°	5	1.267	1.068	0.842



Mode 1- Longitudinal ($T_1=1.007$ s)

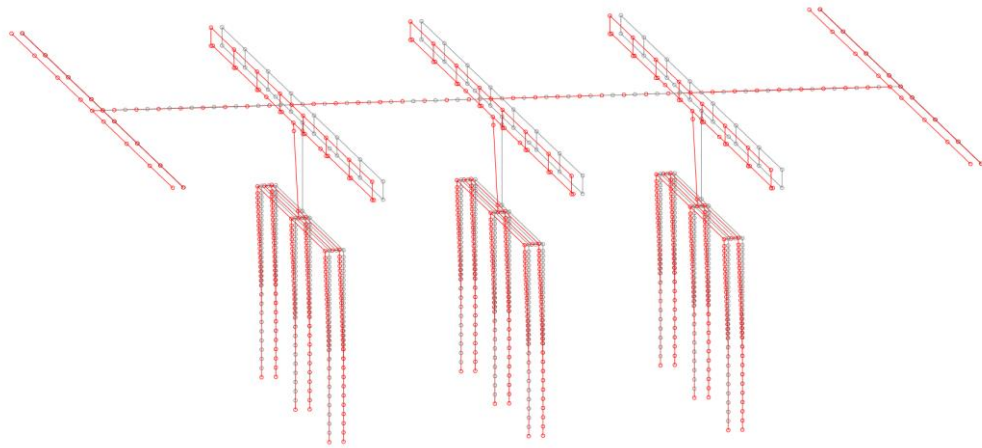


Mode 2- Transverse ($T_2= 0.906$ s)

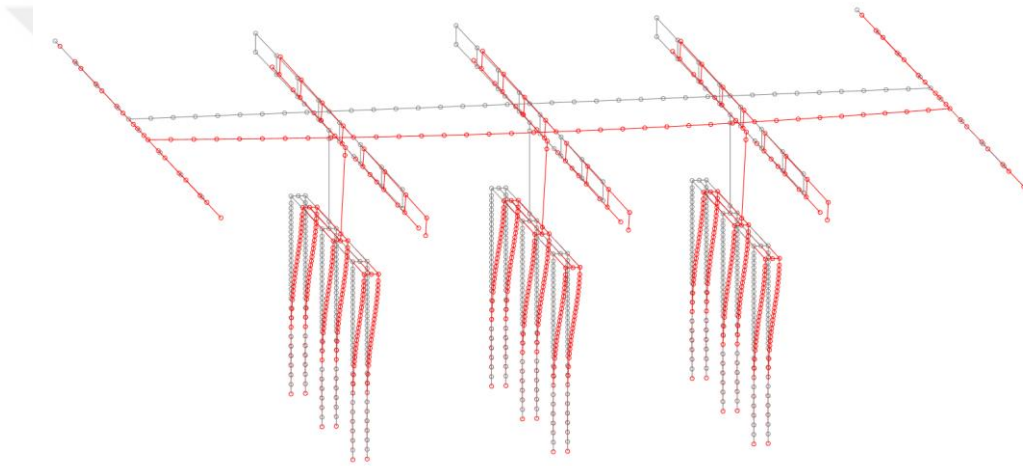


Mode 3- Rotation ($T_3= 0.770$ s)

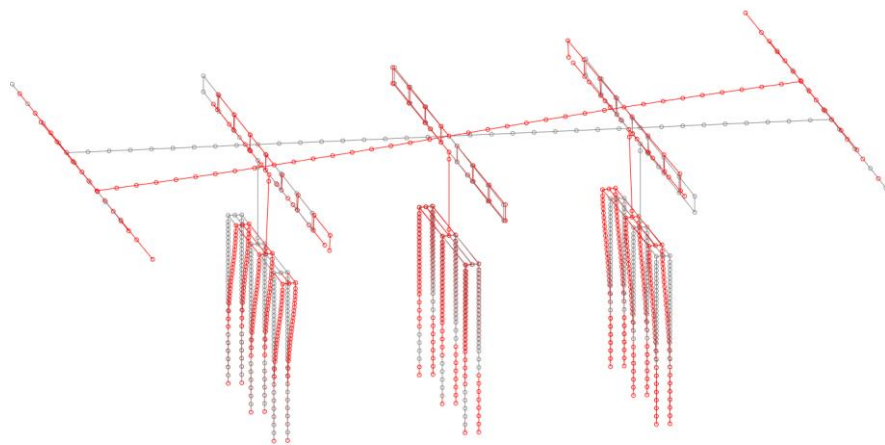
Figure 3.45. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 0 m uniform scour depth



Mode 1- Longitudinal ($T_1=1.093$ s)

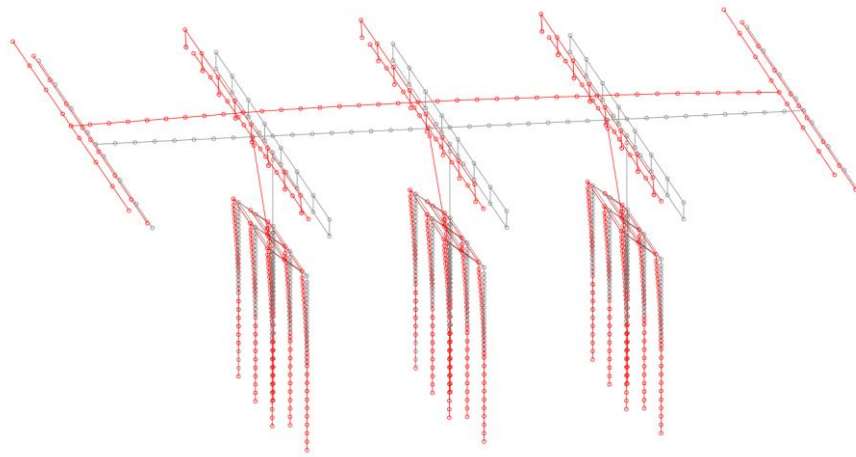


Mode 2- Transverse ($T_2= 1.064$ s)

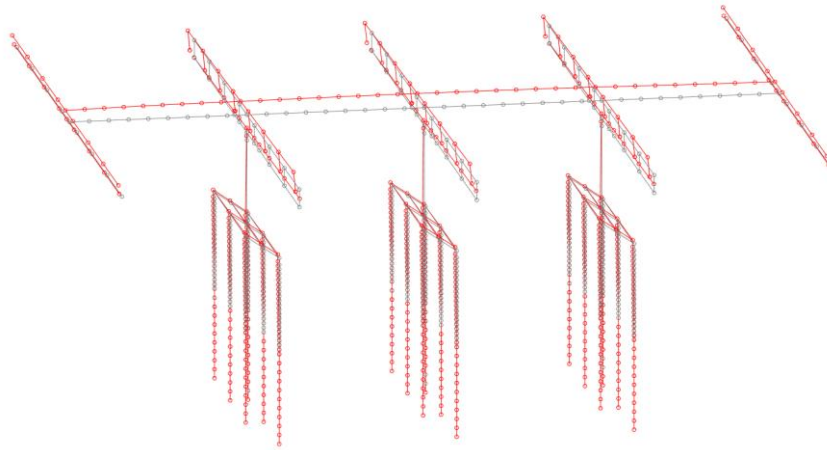


Mode 3- Rotation ($T_3= 0.817$ s)

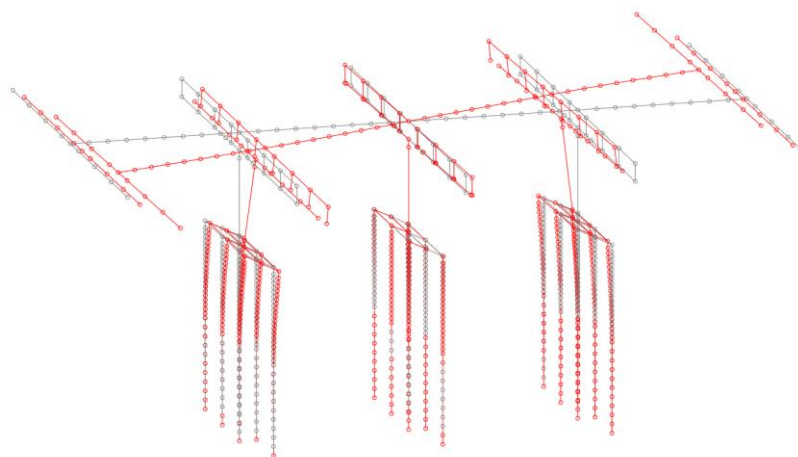
Figure 3.46. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 5 m uniform scour depth



Mode 1- Longitudinal ($T_1=1.074$ s)

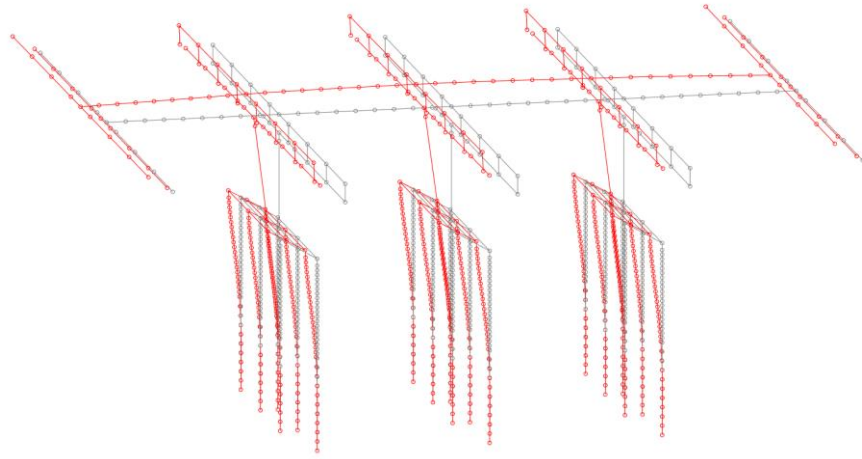


Mode 2- Transverse ($T_2= 0.871$ s)

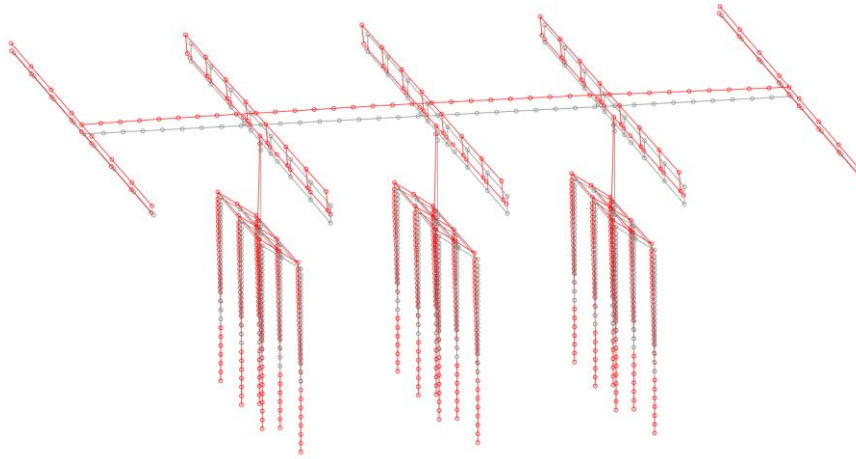


Mode 3- Rotation ($T_3= 0.799$ s)

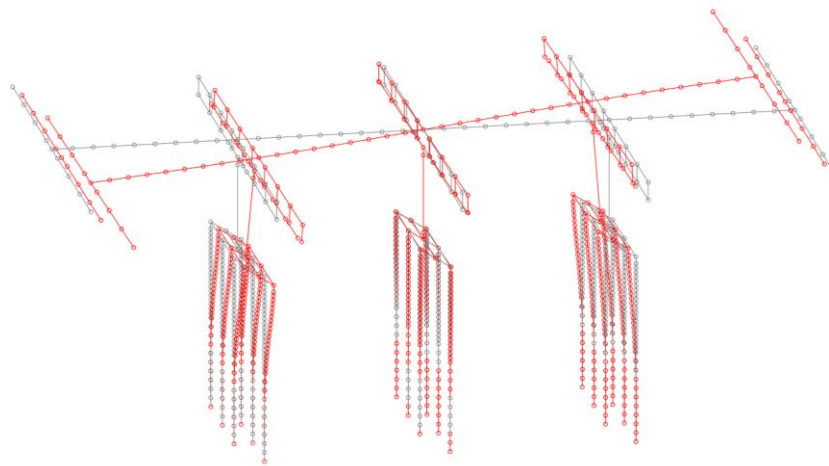
Figure 3.47. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 0 m uniform scour depth



Mode 1- Longitudinal ($T_1=1.191$ s)



Mode 2- Transverse ($T_2= 0.998$ s)



Mode 3- Rotation ($T_3= 0.835$ s)

Figure 3.48. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 5 m uniform scour depth

3.2.6. Selection and scaling of ground motion records

Nonlinear response history analysis of the bridge analytical model created in Section 3.2.3 within the scope of the study were performed using the OpenSees program. The same earthquake record sets that were selected in Section 3.1.3 were used in analyses. Because the bridge is assumed to be located on weak ground and its substructure is modeled with piles, the soil class was chosen as ZD which has an average shear wave velocity (V_{s30}) between 180-360 m/s in this section. The location was again chosen as in Eskisehir, Turkey with latitude of 39.756762°N and longitude of 30.94864°E as shown in Figure 3.49, from Turkey Earthquake Hazard Map (AFAD, 2021) web interface and spectral acceleration-period graph was obtained for DD-2 (earthquake ground motion level with 10% probability of exceedance in 50 years) level of this location.



Figure 3.49. Data from Turkey Earthquake Hazard Map

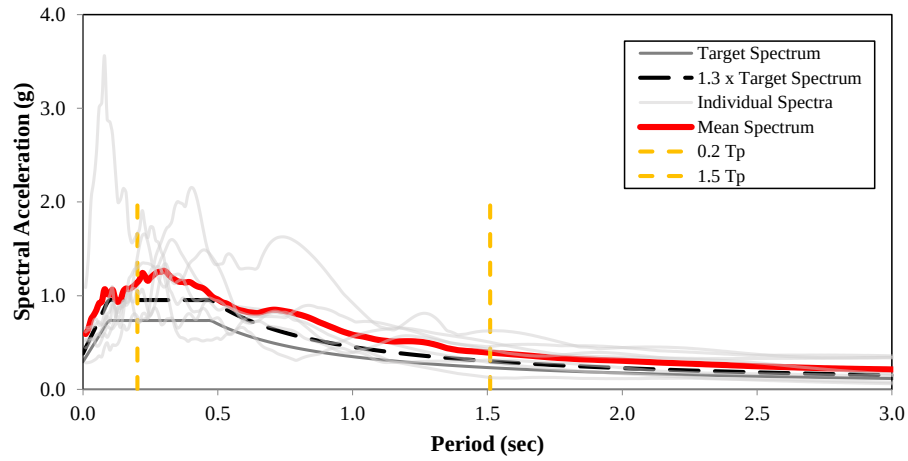


Figure 3.50. Elastic response spectra for the selected ground motions with 5% damping ratio

In Figure 3.50, the target design spectrum for 5% damping of the selected location in Eskisehir and the scaled response spectra of the selected earthquake records are given. In order not to interfere with the content of ground motion records, the scale coefficients of the horizontal components of all selected earthquakes were taken as 1.0. The T_p period given in the graph is the natural vibration period of the 1st mode of the non-skewed bridge without scour. Both the horizontal components and the vertical component of the ground motion recordings were taken into account when applying the chosen scale factor. Also, the horizontal component of ground motion which has the highest PGV was affected to the bridge transverse direction to be consistent for all selected ground motions.

4. CALCULATION OF GROUND MOTION INCIDENCE ANGLE

In this part of the thesis, it is aimed to obtain the most favorable method for considering the ground motion incidence in nonlinear response history analysis of bridges. In this context, nonlinear analyses are performed by using 2 different methods in literature for bridges with different skew angles. First of all, seismic demands of bridge members acquired from 2 different ground motion incidence angle application methods are compared with each other. After that, critical ground motion incidence angle is researched for the same bridges. As mentioned above sections, in the analytical model of bridge, support condition is assumed as fixed for column piers. In the last part of this section, the bridge is modeled with soil structure interaction (SSI) and member demands are compared to demands of fixed based bridge. The engineering demand parameters for this part of the study is superstructure displacement, curvature and shear force demand of column pier and deformation demands of pounding elements.

4.1. Comparison of Ground Motion Incidence Angle Application Methods

Before creating the analytical model of a complex structure such as a bridge, a single column model with fixed support was created in the OpenSees program. Then, nonlinear response history analyses were carried out under the effect of the Coyote Lake earthquake, and 2 different methods used to reflect the earthquake incidence angle into nonlinear response history analyses were investigated for various demand parameters.

4.1.1. Single column model

In order to check the accuracy of the analysis results, first of all, a nonlinear model of a cantilever column with distributed plasticity was created in the OpenSees program, and bidirectional nonlinear analyses were carried out. In the analyses, the earthquake incidence angle was changed from $\theta=0^\circ$ to 180° with an increment of 30° . The cantilever column has dimensions of $b=100$ mm, $h=200$ mm and $L=1000$ mm, as shown in Figure 4.1. The material class has been chosen as S420, with $\sigma_y=420$ MPa and modulus of elasticity $E=200$ GPa. The column model is formed with fiber elements consisting of a sufficient number of small parts. In addition, a mass of 50 tons is defined at the upper node of the element.

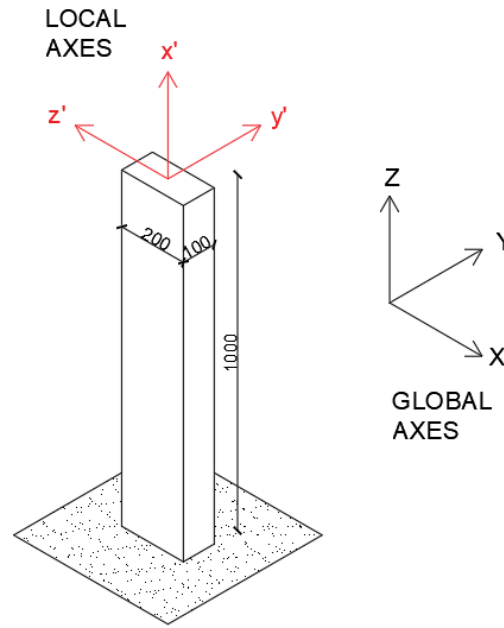


Figure 4.1. Properties of single column and the definition of axes used in the OpenSees (units are in mm)

In order to reflect the incidence angle of the Coyote Lake earthquake (No. 1, Table 3.4) to the program, Method-1 and Method-2 used in the study were applied in the same way in the cantilever column analysis. First of all, horizontal ground motion components were rotated using linear transformation equations, as explained in Method-1, by keeping the column fixed on the global axes. In Method-2, the cantilever column was rotated counterclockwise by keeping the ground motion components constant on the global axes and nonlinear analyses were performed. By looking at the results of the analysis, various engineering demand parameters were examined in the column such as column peak displacement demand, strong (y') and weak (z') axis curvature and shear demands. In Figure 4.2, the peak results obtained by using Method-1 and Method-2 are given for each incidence angle of the examined demands. As can be seen from the graphs, the methods used to reflect the earthquake incidence angle to the analytical models give the same results for the cantilever column model.

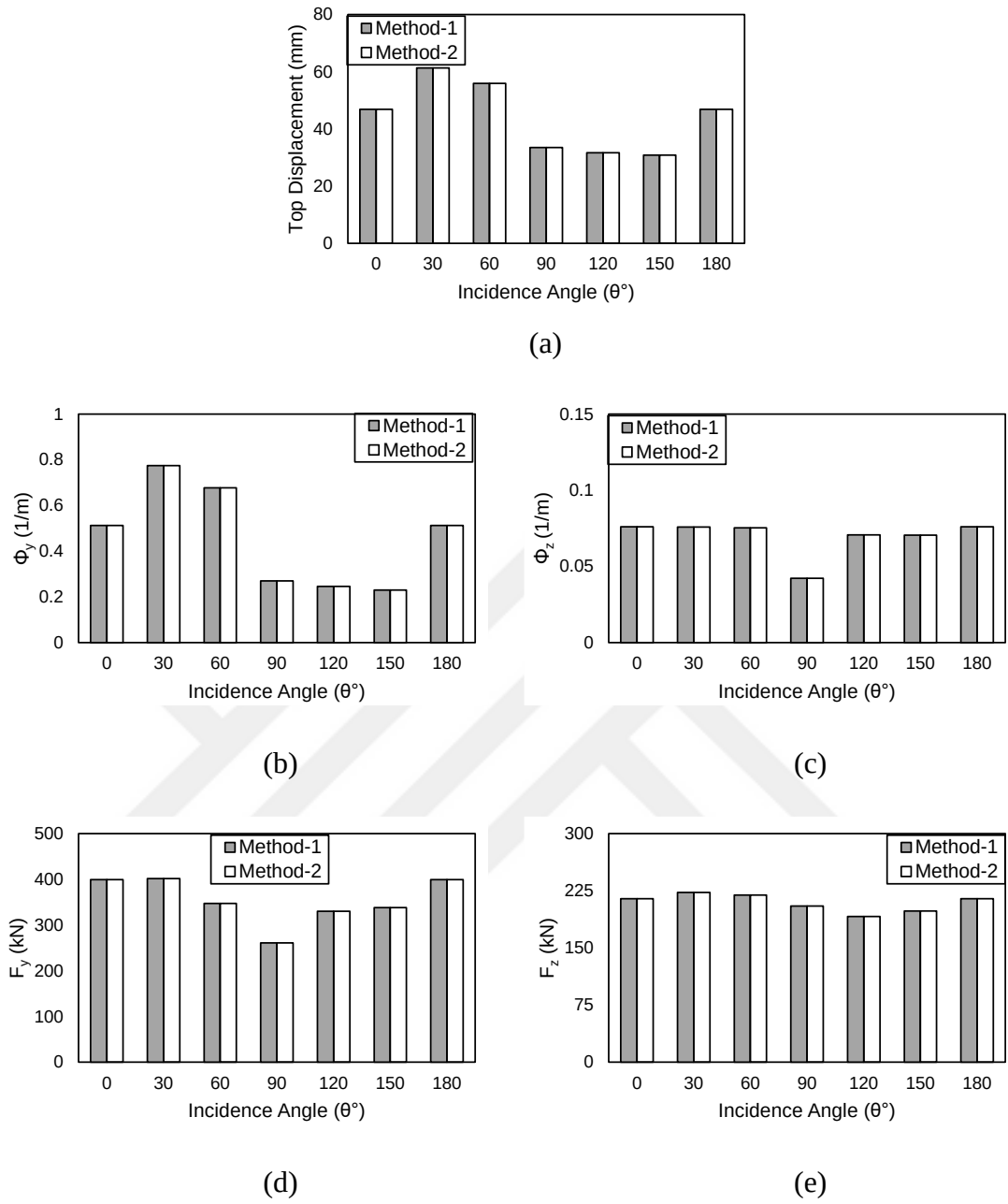


Figure 4.2. Maximum demands on the cantilever column for different incidence angles of the Coyote Lake earthquake (a) Top Displacement (b) Strong axis (y') curvature (c) Weak axis (z') curvature (d) Local y'axis shear force (e) Local z' axis shear force demands

4.1.2. 3D bridge model

After that, analytical models of the bridges, which are explained in detail in the Material and Method section, were created in the OpenSees and nonlinear response history analyses were performed under the effect of 7 strong ground motions. Analyses were made using two different methods (Method-1 and Method-2) and the results obtained from both methods were compared with each other. The engineering demand

parameters examined within the scope of the study are superstructure displacement, bent column curvature and shear force, and deformations of the pounding elements. In Figure 4.3, the analysis results of the evaluated elements and the locations of the nodes are shown. The comparison of the nonlinear analysis results obtained by two different methods of these elements is given in detail in the sub-headings.

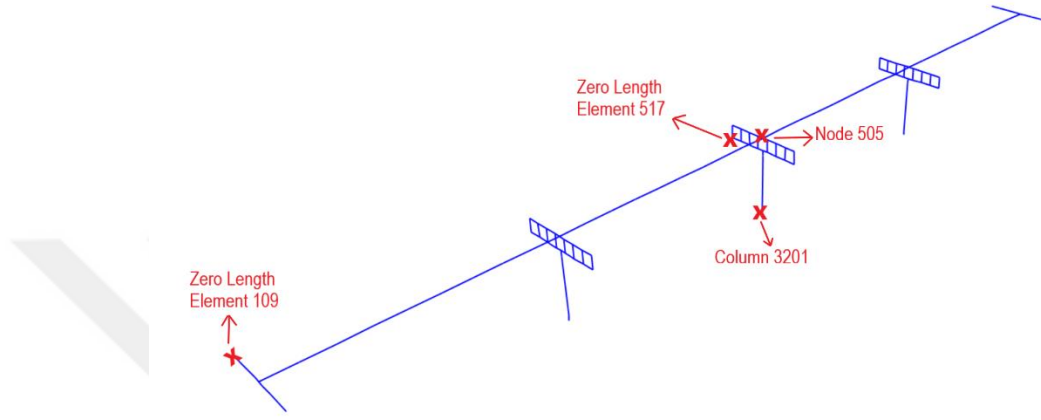


Figure 4.3. Investigated bridge elements and nodes

4.1.2.1. Superstructure displacement

One of the important parameters taken into consideration when evaluating the seismic performance of bridges is superstructure displacement. These displacements can be both in the longitudinal and transverse direction of the bridge. In Figure 4.4 the maximum resultant displacements in the longitudinal and transverse directions are given for bridges with different skew angles (α). When calculating the resultant displacements, the square root of the sum of the squares (SRSS) of the displacements in the longitudinal direction and the transverse direction is taken. The values belong to node 505 located at the midpoint of the bridge. The average of the maximum demands was obtained using 7 ground motion records in nonlinear analysis. It is seen that average superstructure displacement demands have almost same value for each incidence angle in both methods. The average superstructure displacement of the bridge with a 60° skew angle and a 75° ground motion incidence angle was one example of a situation where there was little difference between the two approaches. However, this insignificant difference was considered to be issues resulting from convergence of numerical computations in the nonlinear analysis. Moreover, the maximum displacement occurs at $\alpha=0^\circ$ skewed bridge

when earthquake incidence angle is $\theta=105^\circ$ and is obtained as 122.5 mm. For $\alpha=15^\circ$ and $\alpha=30^\circ$ skewed bridges, the maximum demand is obtained as 125.4 mm and 129.3 mm at $\theta=135^\circ$, respectively. When skew angle is $\alpha=45^\circ$, the maximum displacement is 130.2 mm and occurs at $\theta=150^\circ$ earthquake incidence angle. Finally, when earthquake incidence angle is $\theta=75^\circ$ on $\alpha=60^\circ$ skewed bridge, a maximum average displacement demand of 137.4 mm occurs.

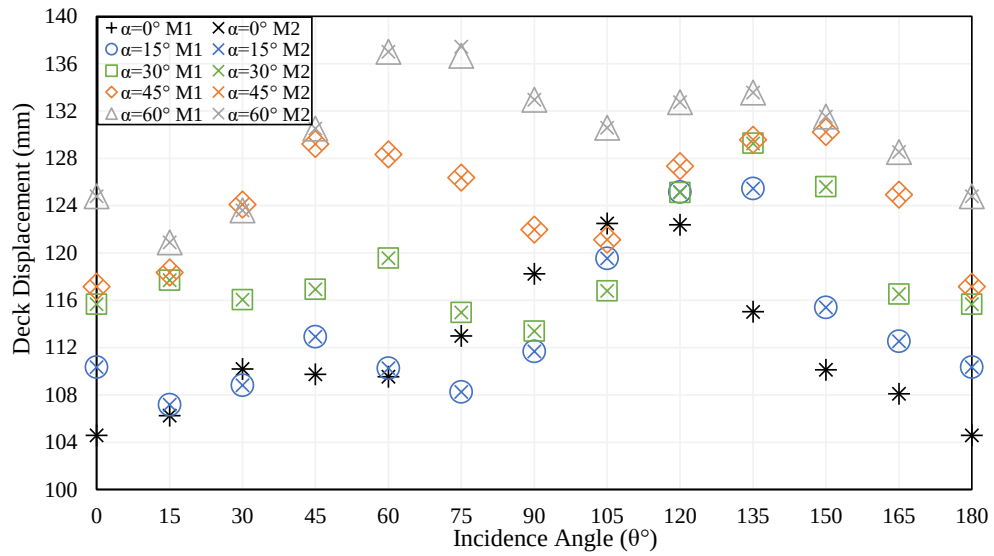


Figure 4.4. Average maximum superstructure displacements obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

4.1.2.2. Curvature demands of column pier

The assumption that the bridge superstructure will behave elastically during an earthquake, by means of the elastomeric bearings between the bridge superstructure elements and the substructure, was explained in the previous sections. However, with the transfer of the forces from the superstructure to the column pier, especially with the pounding in the transverse direction and the friction force between the elastomeric bearings and the concrete surface, the column pier can attain the yield limit state and undergo permanent deformation. Consequently, they can exhibit a nonlinear behavior due to the earthquake effect. Comparing the curvature demands of elements exhibiting this type of behavior makes an important contribution when evaluating the seismic performance of bridges. Within the scope of the study, the curvature demands of the column 3201 shown in Figure 4.3 were obtained both for the strong and weak axes

defined in Figure 3.10. The results represent the average of maximum curvature demands, which were obtained from 7 ground motion records used in the analyses. The values obtained depended on the methods used to reflect the earthquake incidence angle in the analyses. Figure 4.5 and Figure 4.6 show the values obtained for each bridge skew angle (α). The average maximum curvature demands were not affected by the methods used to reflect the earthquake incidence angle to nonlinear analyses, and both methods gave the same results.

Considering the maximum average curvatures occurred in the column weak axis, the maximum demand for $\alpha=0^\circ$ and $\alpha=15^\circ$ skewed bridges emerge at $\theta=135^\circ$ earthquake incidence angle and is obtained as 0.0086 1/m and 0.0094 1/m. In a $\alpha=30^\circ$ skewed bridge, the maximum curvature is 0.0095 1/m when incidence angle is $\theta=150^\circ$, and for skew angle $\alpha=45^\circ$, it is 0.0101 1/m when incidence angle is $\theta=45^\circ$. When bridge skew angle is $\alpha=60^\circ$, the maximum curvature is 0.0125 1/m at incidence angle of $\theta=60^\circ$.

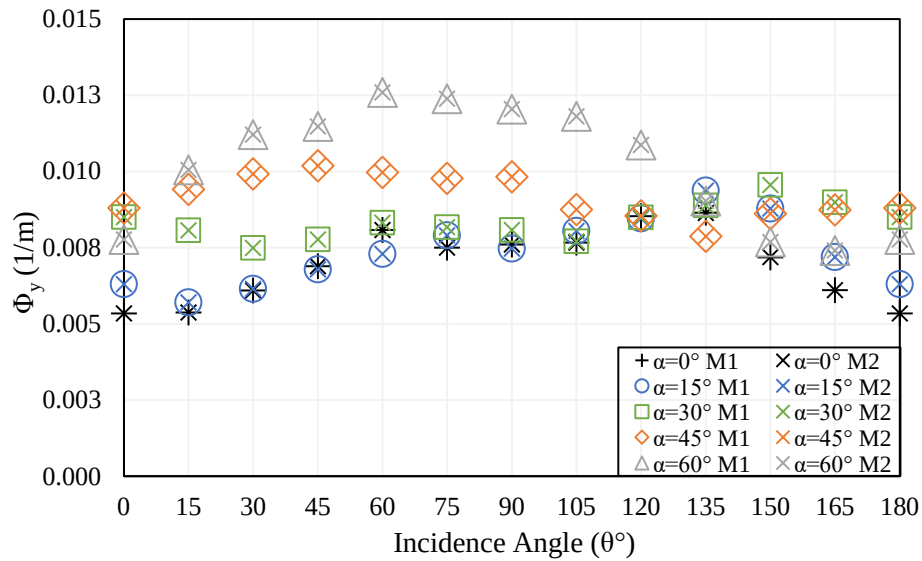


Figure 4.5. Average maximum curvature demands (Φ_y) of column weak axis (y') obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

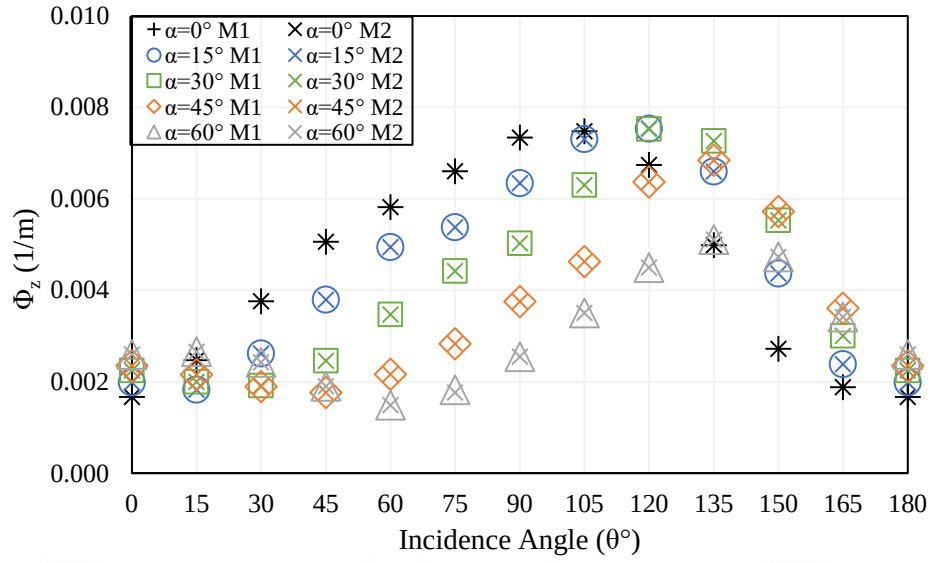


Figure 4.6. Average maximum curvature demands (Φ_z) of column strong axis (z') obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

Considering the maximum average curvatures occurred in the column strong axis, the maximum demand in $\alpha=0^\circ$ skewed bridge emerges at $\theta=105^\circ$ earthquake incidence angle as 0.0074 1/m and for $\alpha=15^\circ$ and $\alpha=30^\circ$ skewed bridges it is 0.00754 1/m and 0.00752 1/m respectively at $\theta=120^\circ$ incidence angle. In bridges where the skewness is $\alpha=45^\circ$ and $\alpha=60^\circ$, the maximum curvature is 0.0068 1/m and 0.0051 1/m, respectively at the $\theta=135^\circ$ earthquake incidence angle.

4.1.2.3. Shear force demands of column pier

Shear force demand, which is one of the force-based engineering demand parameters, is an important parameter in terms of examining the behavior of structures during an earthquake. The modern earthquake design codes ensure that reinforced concrete elements are designed to exhibit ductile behavior under the influence of strong ground motions, in accordance with capacity design principles. Within the scope of thesis, the shear force demands of the critical column piers of the bridges were obtained from the nonlinear analysis results using Method-1 and Method-2. The shear forces given in Figure 4.7 and Figure 4.8 belong to column 3201 and were obtained for each skew angle (α) and incidence angle (θ). The results represent the average of maximum shear force demands, which were obtained from 7 ground motion records used in the analyses. The shear forces obtained by using Method-1 and Method-2 have the same value and the earthquake incidence angle is not affected by the application method.

Considering the shear force demands of the column local y' axis according to Figure 4.7, the maximum average shear force obtained as 3397 kN and 3357 kN at $\theta=75^\circ$ earthquake incidence angle for $\alpha=0^\circ$ and $\alpha=15^\circ$ skewed bridge, respectively. The maximum average shear force is 3283 kN at $\theta=90^\circ$ incidence angle when the bridge skew angle is $\alpha=30^\circ$, and 3251 kN at $\theta=120^\circ$ incidence angle when the skewness is $\alpha=45^\circ$. In the $\alpha=60^\circ$ skewed bridge, the maximum demand is found to be 3201kN at $\theta=135^\circ$ incidence angle.

When Figure 4.8 examined, for the shear force demands of the local z' axis of the column, the maximum value of the average shear force occurred at $\theta=0^\circ$ earthquake incidence angle and is 1192 kN for $\alpha=0^\circ$ skewed bridge. When bridge skew angle is $\alpha=15^\circ$, the maximum average shear force is 1226 kN at $\theta=45^\circ$ incidence angle and when the skewness is $\alpha=30^\circ$, it becomes 1263 kN at $\theta=60^\circ$ incidence angle. In $\alpha=45^\circ$ skewed bridge, the maximum demand is 1286 kN when incidence angle is $\theta=75^\circ$, and in $\alpha=60^\circ$ skewed bridge, it is 1335 kN when the incidence angle is $\theta=90^\circ$.

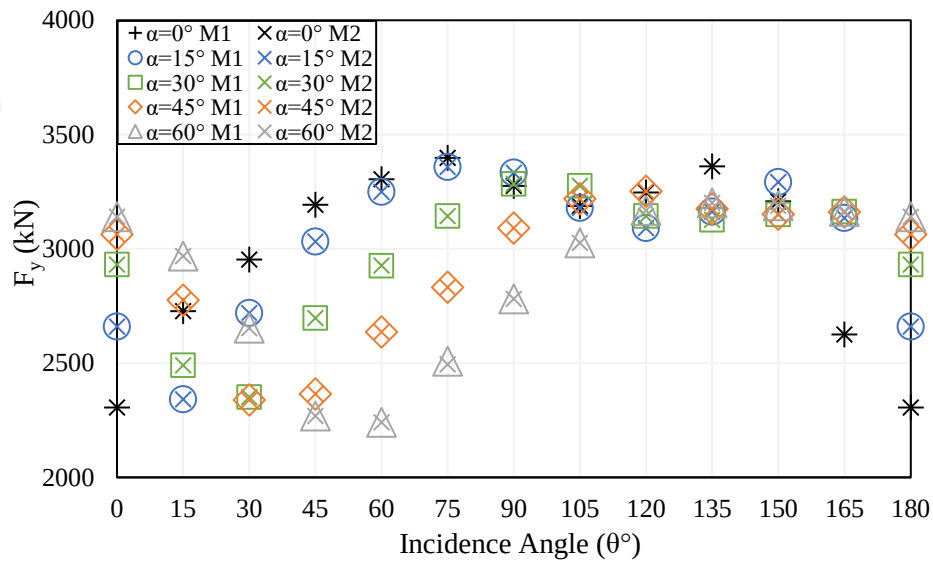


Figure 4.7. Average maximum shear force demands of column local y' axis obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

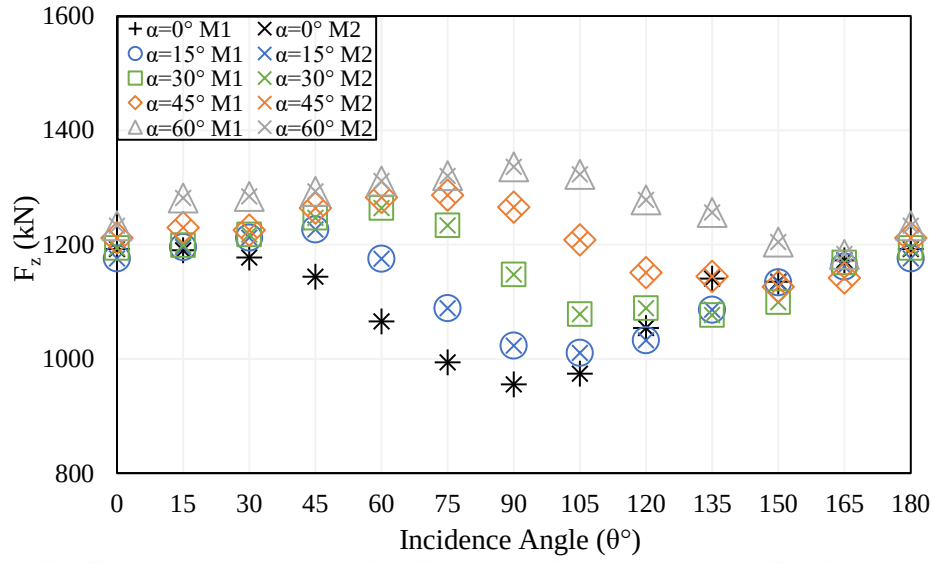


Figure 4.8. Average maximum shear force demands of column local z' axis obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

4.1.2.4. Deformation demands of pounding elements

Sufficient gap distance should be left in order to prevent a possible collision that may occur between the bridge elements in the event of an earthquake. These gaps exist between the abutment and the superstructure in the longitudinal direction of the bridge, and between the superstructure and shear keys in the abutment, and between superstructure and the shear keys in the bent columns in the transverse direction. Within the scope of the study, the spring model given in Figure 3.15 was defined to the OpenSees program and the pounding that may occur between the bridge elements during an earthquake was examined. The spring model used works as an element that can start to transfer force between the elements and deform linearly after exceeding the gap distance defined in the program, and after reaching the capacity, the force remains constant, and the deformation continues to increase. For this reason, it is a more accurate approach to evaluate the pounding elements as deformation-based rather than force-based. For the pounding elements shown in Figure 4.3, the average of the maximum deformation demands investigated from nonlinear response history analyses using 7 ground motion records. The graphs given in Figure 4.9 and Figure 4.10 for the pounding element at node 109 show the average maximum deformation between the abutment and the superstructure in the longitudinal direction of the bridge, and between the superstructure and the shear key in the transverse direction. In Figure 4.11, the average maximum

deformation occurred between the superstructure and the shear key at the bent column in transverse direction of the bridge is given for the pounding element at node 517. It is seen that the results are not affected by both earthquake incidence angle application methods used in nonlinear analyses.

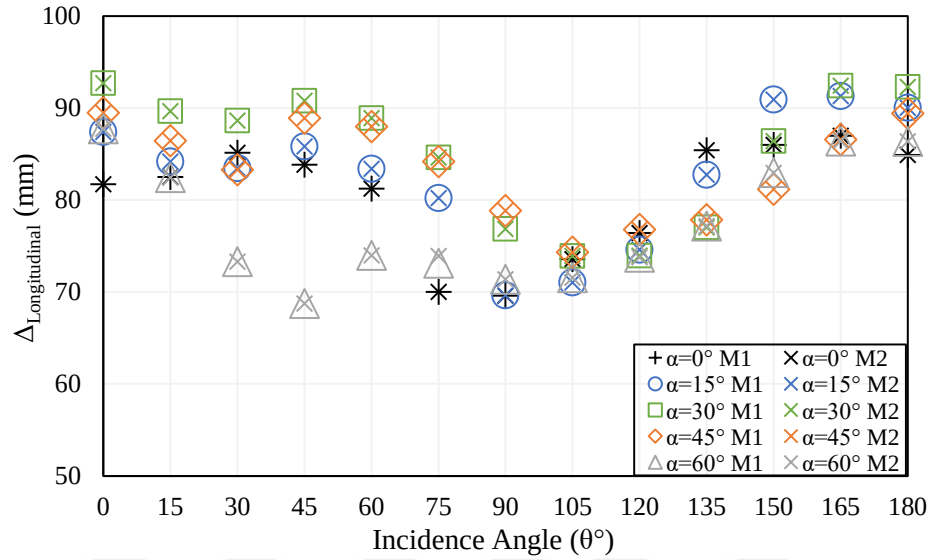


Figure 4.9. Average maximum deformation demands of pounding element defined in the bridge longitudinal direction between superstructure and abutment obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

The maximum average deformation occurred between the abutment and the superstructure in the longitudinal direction of the bridge is obtained as 86 mm and 91 mm, respectively, when earthquake incidence angle is $\theta=165^\circ$ in $\alpha=0^\circ$ and $\alpha=15^\circ$ skewed bridges. When bridge skew angle is $\alpha=30^\circ$ and $\alpha=45^\circ$, the maximum deformation is 92 mm and 89 mm, respectively, at $\theta=0^\circ$ earthquake incidence angle. In $\alpha=60^\circ$ skewed bridge, the maximum average demand is 87 mm, again at the $\theta=0^\circ$ incidence angle.

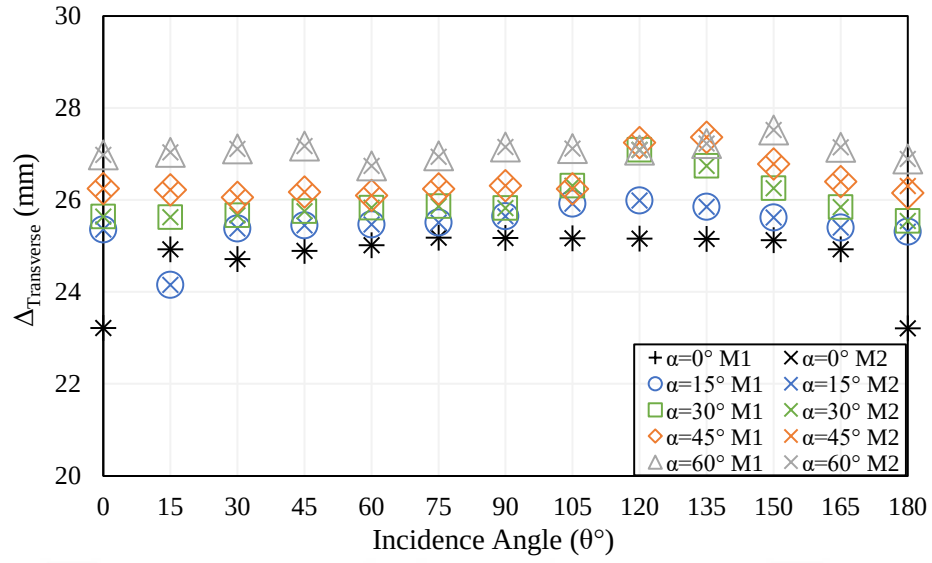


Figure 4.10. Average maximum deformation demands of pounding element defined in the bridge transverse direction between superstructure and shear key at the abutments obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

The maximum average deformation occurred in the transverse direction between the superstructure and the shear keys at the abutment is obtained as 25.2 mm for $\alpha=0^\circ$ skewed bridge when earthquake incidence angle is $\theta=75^\circ$. When bridge skew angle is $\alpha=15^\circ$ and $\alpha=30^\circ$, the maximum deformation is 26 mm and 27 mm, respectively, at the incidence angle of $\theta=120^\circ$. For $\alpha=45^\circ$ and $\alpha=60^\circ$ skewed bridges, the maximum demand occurs at incidence angles of $\theta=135^\circ$ and $\theta=150^\circ$, and are 27.4 and 27.5 mm, respectively.

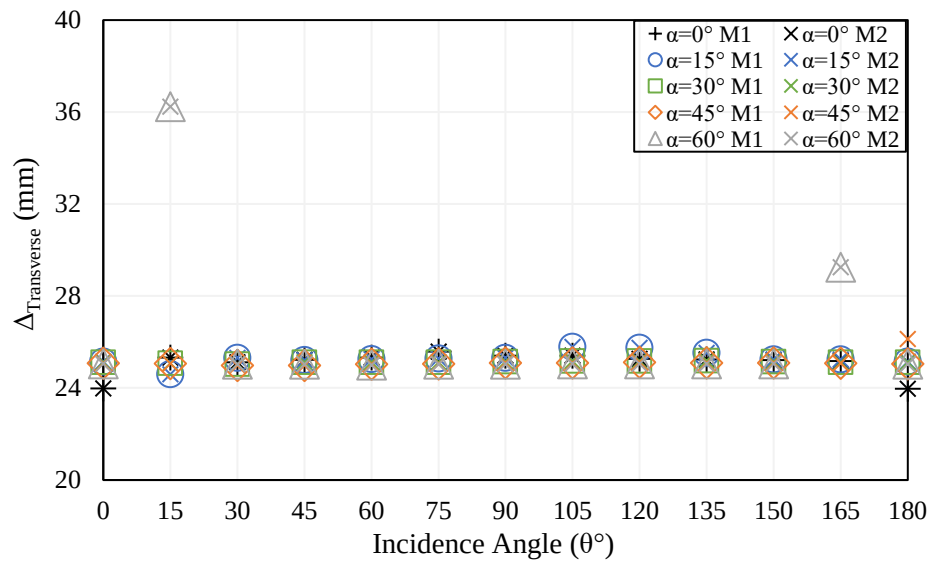


Figure 4.11. Average maximum deformation demands of pounding element defined in the bridge transverse direction between superstructure and shear key obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles

The maximum average deformation occurred in the transverse direction between the superstructure and the shear key is obtained as 25.6 mm for the $\alpha=0^\circ$ skewed bridge when earthquake incidence angle is $\theta=75^\circ$. When bridge skew angle is $\alpha=15^\circ$, the maximum average deformation is 25.8 mm at the incidence angle of $\theta=105^\circ$, and when skew angle is $\alpha=30^\circ$, the maximum average deformation is 25.2 mm at the $\theta=135^\circ$ incidence angle. For $\alpha=45^\circ$ and $\alpha=60^\circ$ skewed bridges, the maximum demand occurs at $\theta=120^\circ$ and $\theta=15^\circ$ incidence angles and is 25.1 mm and 36.2 mm respectively. In all above mentioned cases pounding took place between superstructure and shear keys in transverse direction.

4.1.3. Comparison of two methods for a second set of GM records

When the engineering demand parameters obtained from the previous sections were examined, it was seen that the results were not affected by the methods used to reflect the earthquake incidence angle to the nonlinear analysis of bridges. In this case, a second set of ground motion records were selected and the nonlinear response history analyses were repeated. Acceleration records and characteristics of the new earthquakes selected were obtained using the Pacific Earthquake Engineering Research Center (PEER, 2021) database, as given in Table 4.1. The faulting type of the earthquakes used in the first stage was chosen as strike slip. At this stage, earthquakes with different faulting types were selected and evaluated whether they would have an impact on the earthquake incidence angle application method used in nonlinear response history analyses.

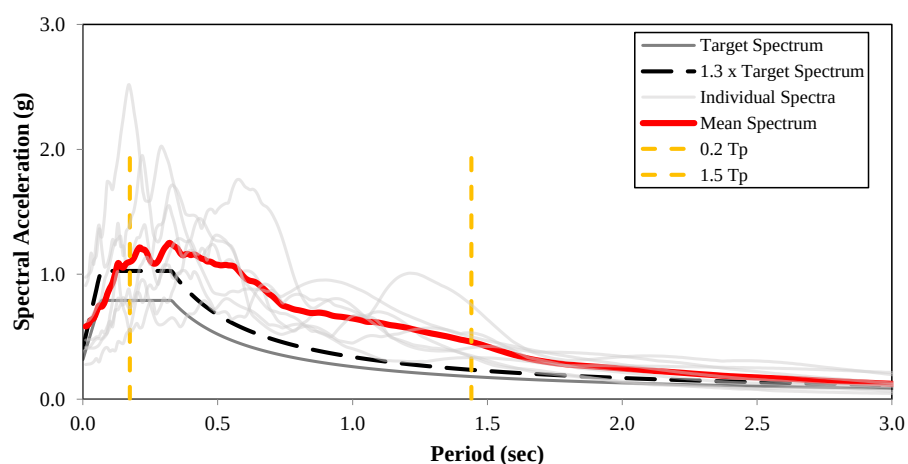
Table 4.1. Properties of second set ground motion records

No	Earthquake	Station	M_w	Fault Mechanism	Component	PGA (g)	PGV (cm/s)	PGD (cm)
1	Victoria Mexico	Cerro	6.33	Strike Slip	45	0.64	33.59	6.62
		Prieto			315	0.63	17.60	3.19
2	Loma Prieta	Gilroy	6.93	Reverse	0	0.41	40.14	7.98
		Array #4		Oblique	90	0.21	38.85	17.74
3	North Palm Springs	North Palm	6.06	Reverse	210	0.69	65.99	16.17
		Springs		Oblique	300	0.66	27.93	4.91
4	Northridge	Canyon	6.69	Reverse	0	0.40	44.38	11.26
		Country			270	0.47	41.12	14.57

Table 4.1. *Properties of second set ground motion records (continued)*

5	Kobe	Kobe University	6.90	Strike Slip	0	0.27	55.29	15.15
					90	0.31	30.88	7.47
6	Coalinga	Pleasant Valley P.P	6.36	Reverse	45	0.30	39.40	6.38
					135	0.27	21.53	3.02
7	West Morland	Parachute Test Site	5.90	Strike Slip	225	0.23	55.58	37.09
					315	0.14	32.70	21.86

The selected ground motion records were scaled with the simple scaling method according to the Principles for the Design of Highway and Railway Bridges and Viaducts Under the Effect of Earthquakes (Ministry of Transport and Infrastructure of The Republic of Turkey, 2020). In Figure 4.12, elastic response spectra scaled for 5% damping are given for the same location and selected earthquake records in Eskisehir province. In order not to interfere with the content of the ground motion records, the scale coefficients of the horizontal components of all selected earthquakes were taken to be 1.0. Since the scaling conditions defined in the Principles for the Design of Highway and Railway Bridges and Viaducts Under the Effect of Earthquakes (Ministry of Transport and Infrastructure of The Republic of Turkey, 2020) are met with this scale factor, nonlinear response history analyses have been carried out by using the selected earthquake records in their current form.

**Figure 4.12.** *Elastic response spectra for the second set of ground motions with 5% damping ratio*

4.1.3.1. Superstructure displacement (Second set GM records)

According to the nonlinear analysis results carried out by using second set of GM records, it can be seen in the graph given in Figure 4.13 that, the average maximum displacement demands occurred on the bridge superstructure is not affected by the application method of earthquake incidence angle used in nonlinear analysis.

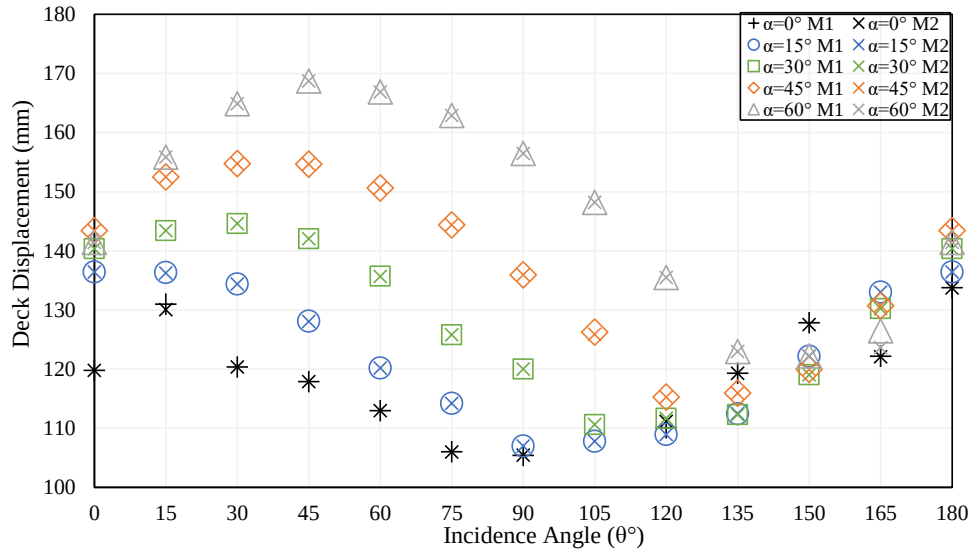


Figure 4.13. Average maximum superstructure displacements obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

4.1.3.2. Curvature demands of column pier (Second set GM records)

When the average curvature demands of bridge column piers checked for weak and strong axis, as can be seen from Figure 4.14 and Figure 4.15, the results are same for Method-1 and Method-2 when different ground motion records are used. Although small demand differences that occur at some earthquake incidence angles correspond to numerical values less than 1%, they are negligible.

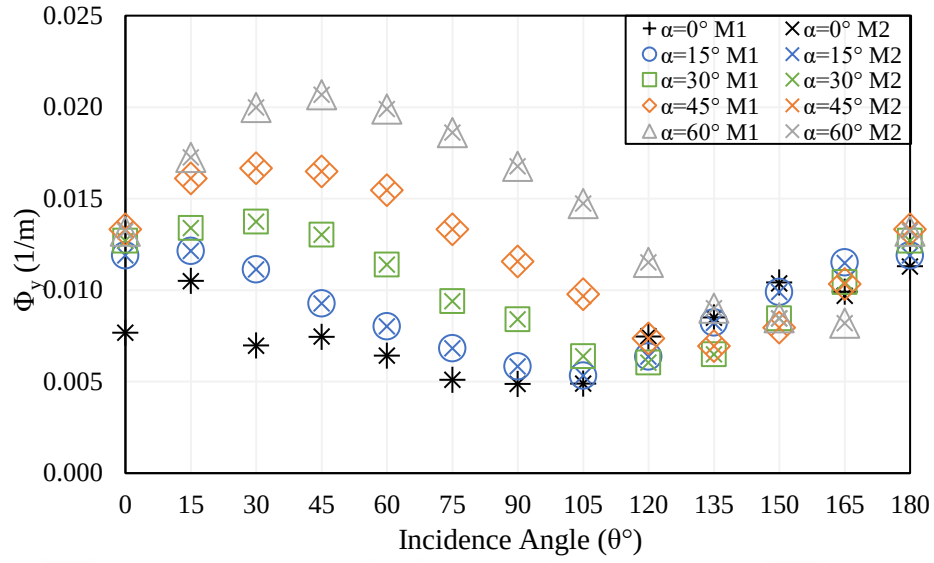


Figure 4.14. Average maximum curvature demands (Φ_y) of column weak axis (y') obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

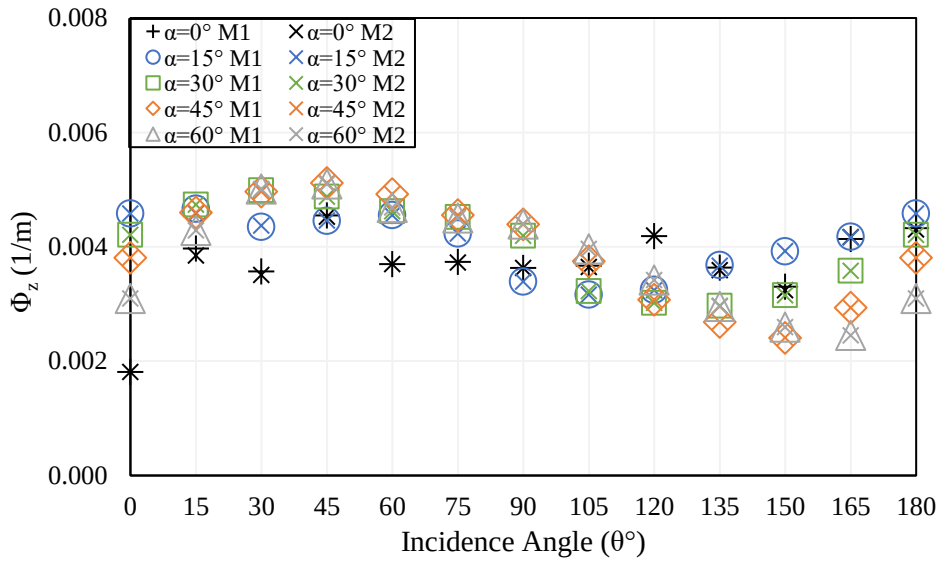


Figure 4.15. Average maximum curvature demands (Φ_z) of column strong axis (z') obtained using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

4.1.3.3. Shear force demands of column pier (Second set GM records)

According to the results of the nonlinear analysis repeated for a second set of GM records, the average maximum column shear force demands are obtained as given in Figure 4.16 and Figure 4.17 for both local y' and z' axis of column pier. It is seen that both methods used to reflect the earthquake incidence angle in terms of shear force give the same results.

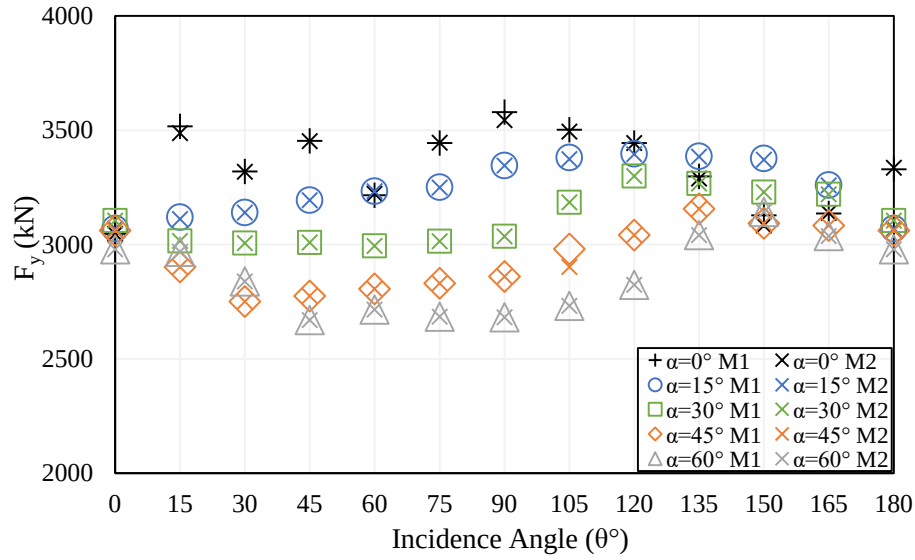


Figure 4.16. Average maximum shear force demands of column local y' axis obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

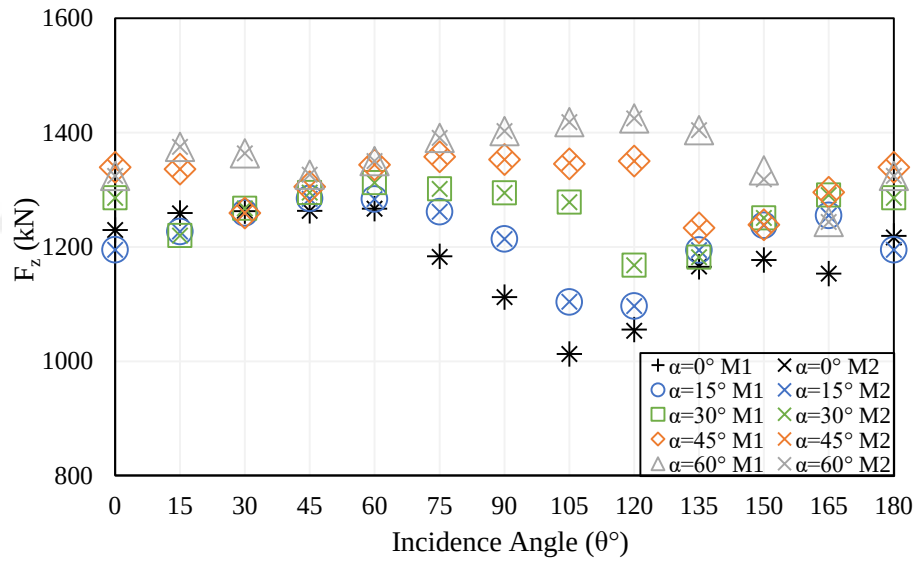


Figure 4.17. Average maximum shear force demands of column local z' axis obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

4.1.3.4. Deformation demands of pounding elements (Second set GM records)

The average maximum deformations of the pounding elements occurring in longitudinal and transverse direction of the bridge during earthquake are given in Figure 4.18, Figure 4.19 and Figure 4.20. When the results are examined, Method-1 and Method-2 used to apply the earthquake incidence angle for both directions give the same deformations.

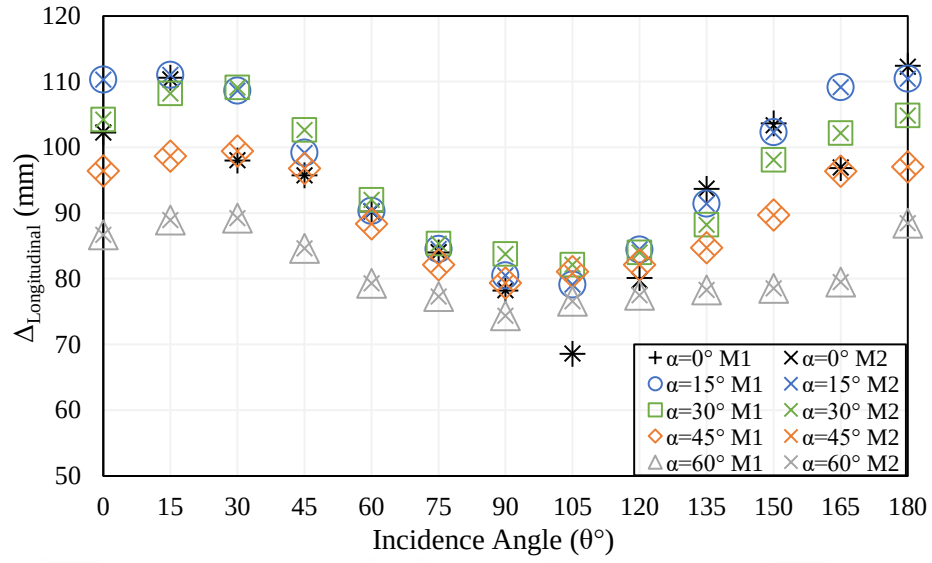


Figure 4.18. Average maximum deformation demands of pounding element defined in the bridge longitudinal direction between superstructure and abutment obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

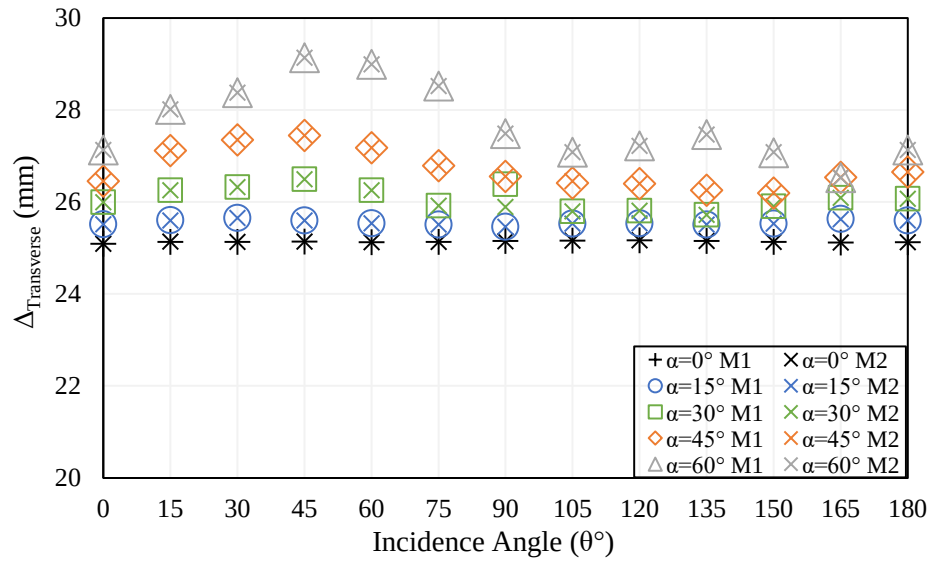


Figure 4.19. Average maximum deformation demands of pounding element defined in the bridge transverse direction between superstructure and shear key at the abutment obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

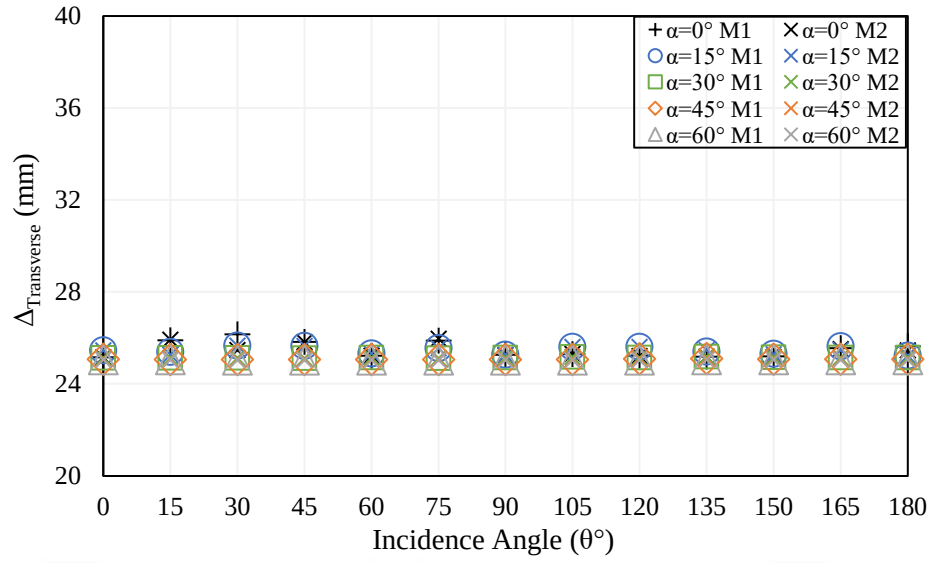


Figure 4.20. Average maximum deformation demands of pounding element defined in the bridge transverse direction between superstructure and shear key obtained by using Method-1 and Method-2 for different bridge skew angles and earthquake incidence angles (Second set GM records)

4.2. Critical Ground Motion Incidence Angle for Bridges

In seismic performance evaluation of bridges, it is crucial to assess the impact of earthquake components on the structure. Method-1 and Method-2, which were explained in detail in the previous sections, were used to reflect the effect of strong ground motion components, which is the main purpose of the first part of the doctoral thesis, to the nonlinear analysis of bridges. When the results obtained from the analyses are examined, it is seen that the methods used have no effect on the analysis results and both methods give the same results. At this stage, it is aimed to determine the critical incidence angle that will cause the maximum demands on the structural components of the bridge. Considering the studies in the literature, it is emphasized that the critical earthquake incidence angle varies from structure to structure and a critical incidence angle cannot be determined for all structures in general (Kalkan & Reyes, 2015; Reyes & Kalkan, 2015). For this reason, critical earthquake incidence angles affecting various engineering demand parameters were investigated only for the bridge model used in the study. The bridge elements and nodes whose analysis results were evaluated are shown in Figure 4.3. The results of demand parameters obtained by using Method-1 are given in detail in the sub-headings.

4.2.1. Superstructure displacement

The superstructure and substructure members that make up bridges can suffer various damages during an earthquake. In particular, displacement of the superstructure consisting of slabs and prestressed beams gives information about the behavior of the bridge during earthquake. This displacement can be both in longitudinal direction of the bridge and in transverse direction. In addition, bridge skew angle, which is one of the important parameters affecting the seismic performance of bridges, plays a major role in the superstructure displacement. In previous studies, it was emphasized that as skew angle increases, the displacement in the bridge superstructure increases (Chen, Han, Liang, & Du, 2017; Han, Chen, Du, & Huang, 2017; Kun, Jiang, & Chouw, 2017). Maximum displacement results occurred in the bridge longitudinal and transverse directions and resultant displacements of the node 505 for each bridge skew angle (α) and earthquake incidence angles (θ) are given in Figure 4.21, Figure 4.22 and Figure 4.23 respectively. The maximum displacements of all earthquakes are given separately in the graphs on the left, and the average maximum values of the 7 earthquakes used are shown with a thick red line. In the graphs on the right, the maximum displacements and average maximum values of all earthquakes are given in radar graph format for the bridge skew angles and earthquake incidence angles examined. In the last bar chart graph, when the average maximum displacements are considered, the mutual effects of the bridge skew angle and the earthquake incidence angle are presented together.

According to Figure 4.21, the superstructure displacement variation does not exhibit a clear trend in the longitudinal direction of the bridge with regard to either the ground motion incidence angle or the bridge skew angle. As a result, the bridge skew angle affects the critical incidence angle for deck longitudinal displacement. The maximum average displacement in longitudinal direction of bridge occurs at the earthquake incidence angle of $\theta=135^\circ$ for $\alpha=0^\circ$ skewed bridge and it is 98 mm. In $\alpha=15^\circ$ and $\alpha=30^\circ$ skewed bridges, the maximum average displacement occurs as 101 mm and 102 mm at the incidence angle of $\theta=165^\circ$. When the bridge skew angle is $\alpha=45^\circ$, the maximum average demand is 98 mm at the earthquake incidence angle of $\theta=60^\circ$. Finally, in the $\alpha=60^\circ$ skewed bridge, the maximum mean displacement in the longitudinal direction becomes 97 mm at the $\theta=165^\circ$ incidence angle.

When maximum average displacements occurred in the transverse direction of the bridge investigated, according to Figure 4.22, it is evident that the shift in the skew angle

has a greater impact on the superstructure displacement of the bridge in the transverse direction. The demands for bridge transverse displacement increase with the bridge skew angle. For all skewed bridges, the superstructure displacement in the transverse direction exhibits an increasing trend between 30° and 120° earthquake incidence angles. The maximum average demand for $\alpha=0^\circ$ and $\alpha=15^\circ$ skewed bridges is 97 mm and 101 mm, respectively, at $\theta=105^\circ$ seismic incidence angle. For $\alpha=30^\circ$ and $\alpha=45^\circ$ skewed bridges, the maximum displacement is 109 mm and 118 mm at $\theta=120^\circ$ incidence angle. In the $\alpha=60^\circ$ skewed bridge, the maximum mean displacement in the transverse direction is again at the $\theta=120^\circ$ incidence angle and it is 128 mm.

Figure 4.23 shows the resultant displacements obtained from longitudinal and transverse directions of the bridge. The resultant displacements are calculated by taking the square root of the sum of the squares of the displacements in the longitudinal and transverse directions occurring at each ground motion step, and the maximum value is taken as the maximum demand. When resultant displacements are considered, in general, there is an increasing trend with increasing skew angle. Accordingly, when average displacement demands studied, the maximum demand for the $\alpha=0^\circ$ skewed bridge emerges as 122 mm when the earthquake incidence angle is $\theta=105^\circ$. When the bridge skew angle is $\alpha=15^\circ$ and $\alpha=30^\circ$, the maximum average demand occurs at the incidence angle $\theta=135^\circ$ and it is 125 mm and 129 mm, respectively. At $\alpha=45^\circ$ skewed bridge, the maximum average demand is 130 mm at $\theta=150^\circ$ seismic incidence angle. Finally, when the bridge skewness is $\alpha=60^\circ$, the maximum mean resultant displacement occurs as 136 mm when the earthquake incidence angle is $\theta=60^\circ$.

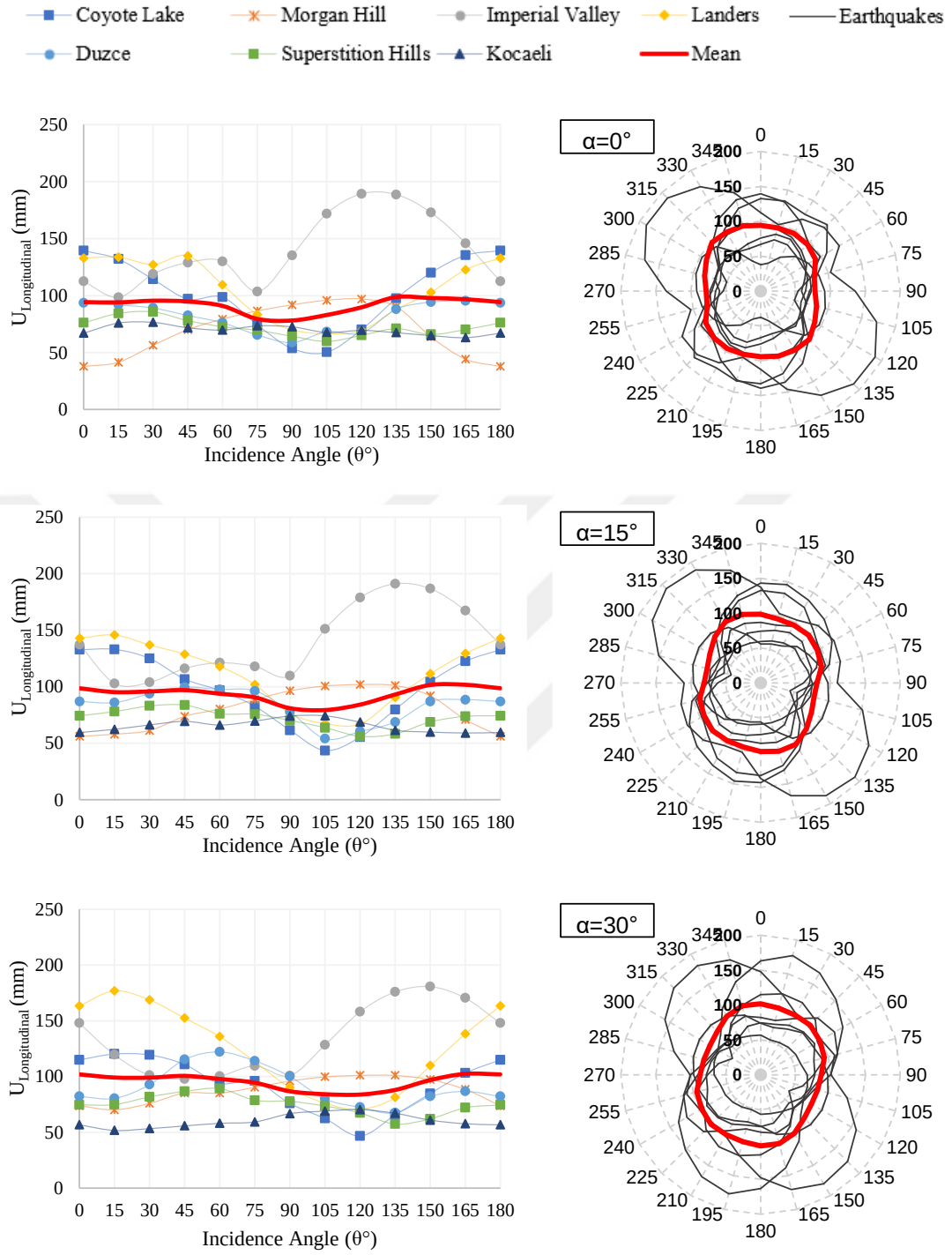


Figure 4.21. Maximum displacement demands occurred in longitudinal direction of bridge for different bridge skew angles and earthquake incidence angles

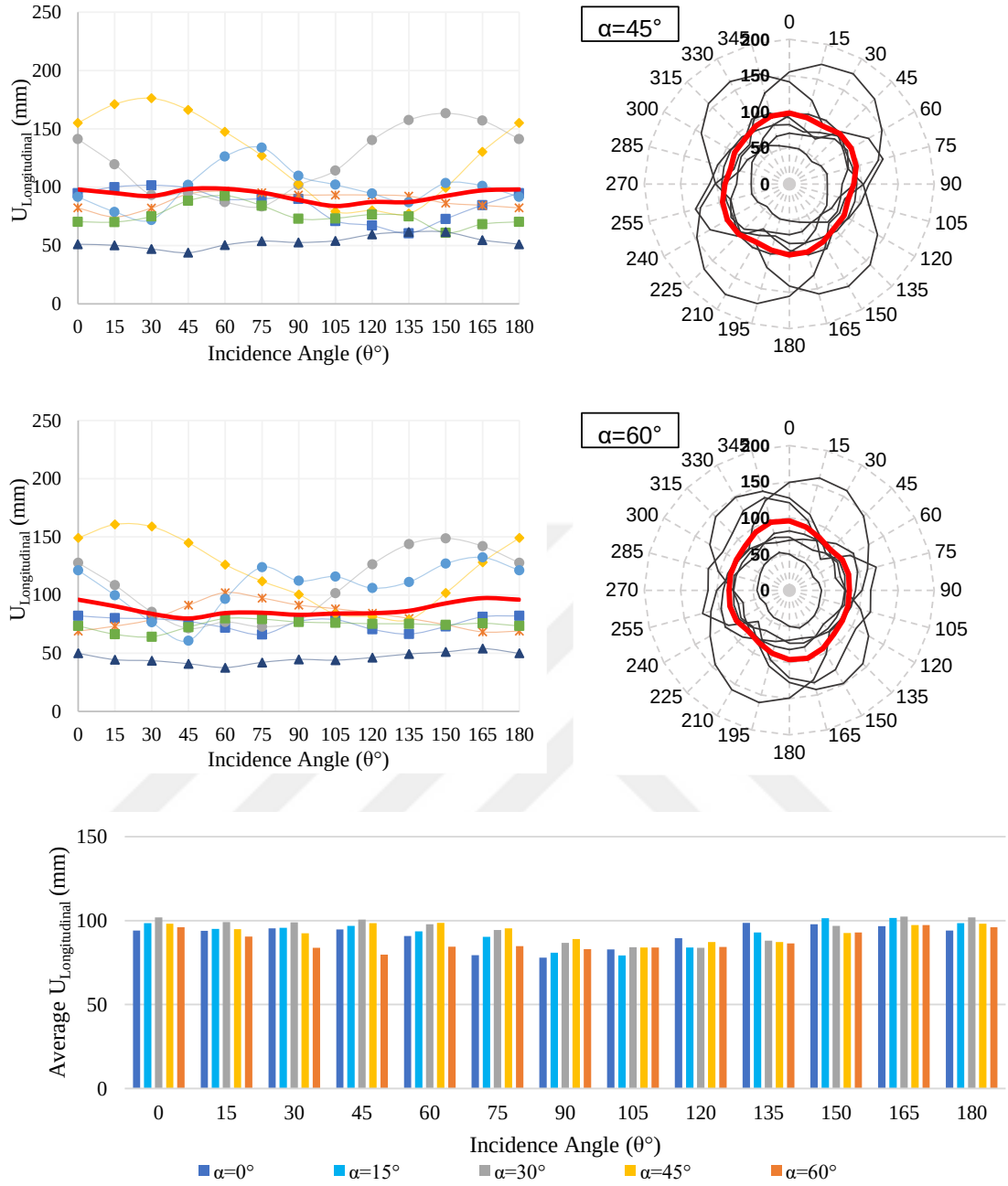


Figure 4.21. Maximum displacement demands occurred in longitudinal direction of bridge for different bridge skew angles and earthquake incidence angles (continued)

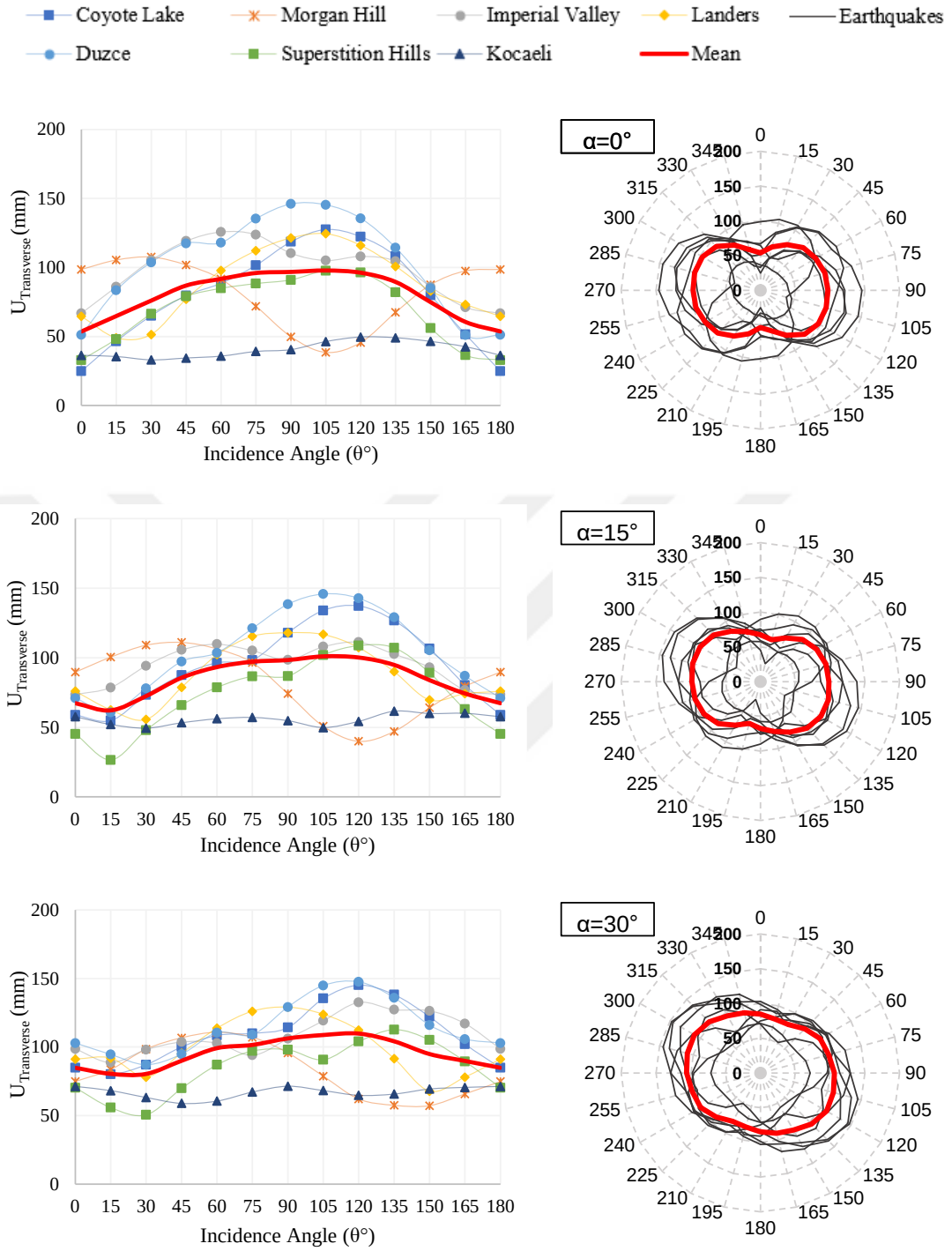


Figure 4.22. Maximum displacement demands occurred in transverse direction of bridge for different bridge skew angles and earthquake incidence angles

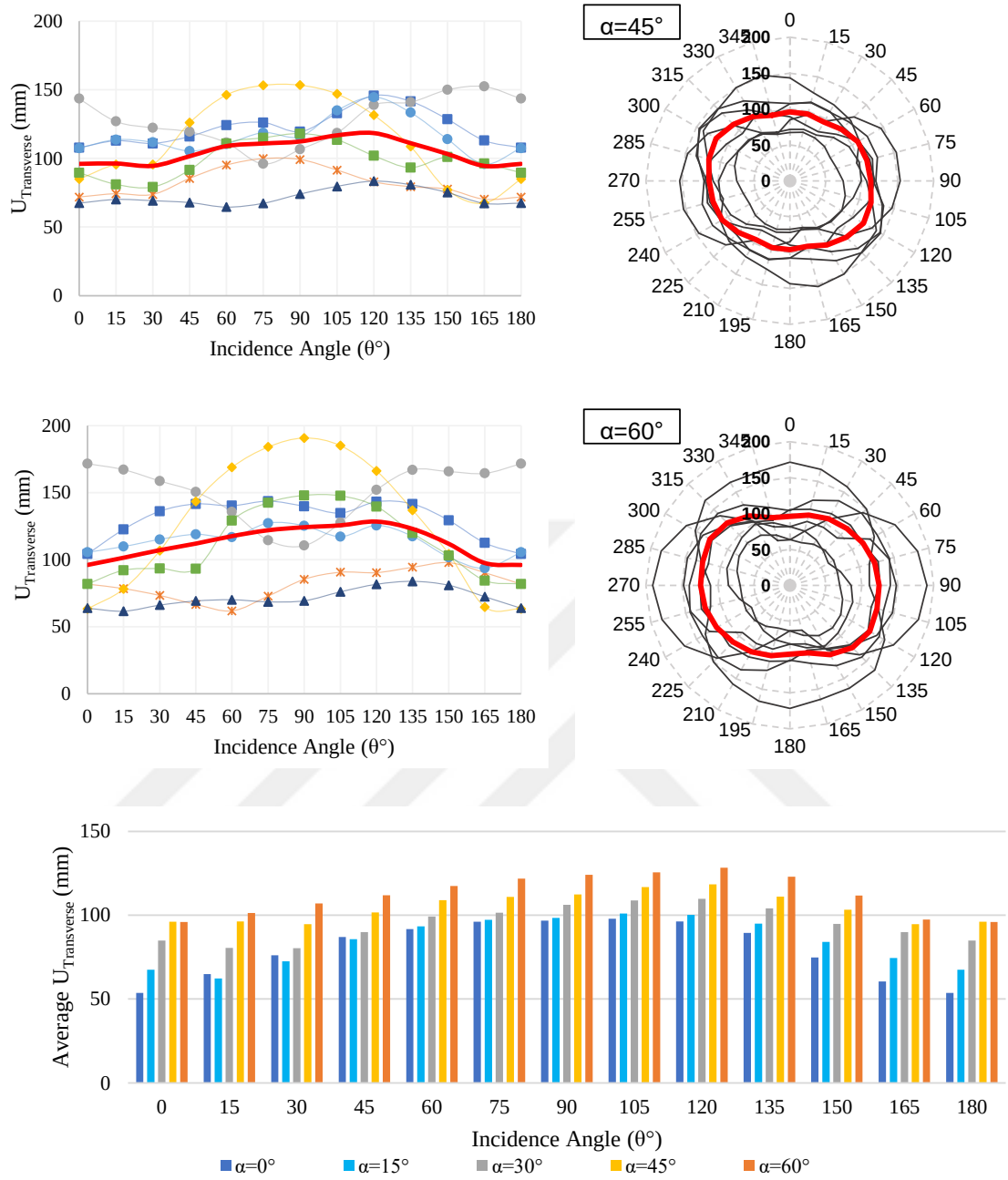


Figure 4.22. Maximum displacement demands occurred in transverse direction of bridge for different bridge skew angles and earthquake incidence angles (continued)

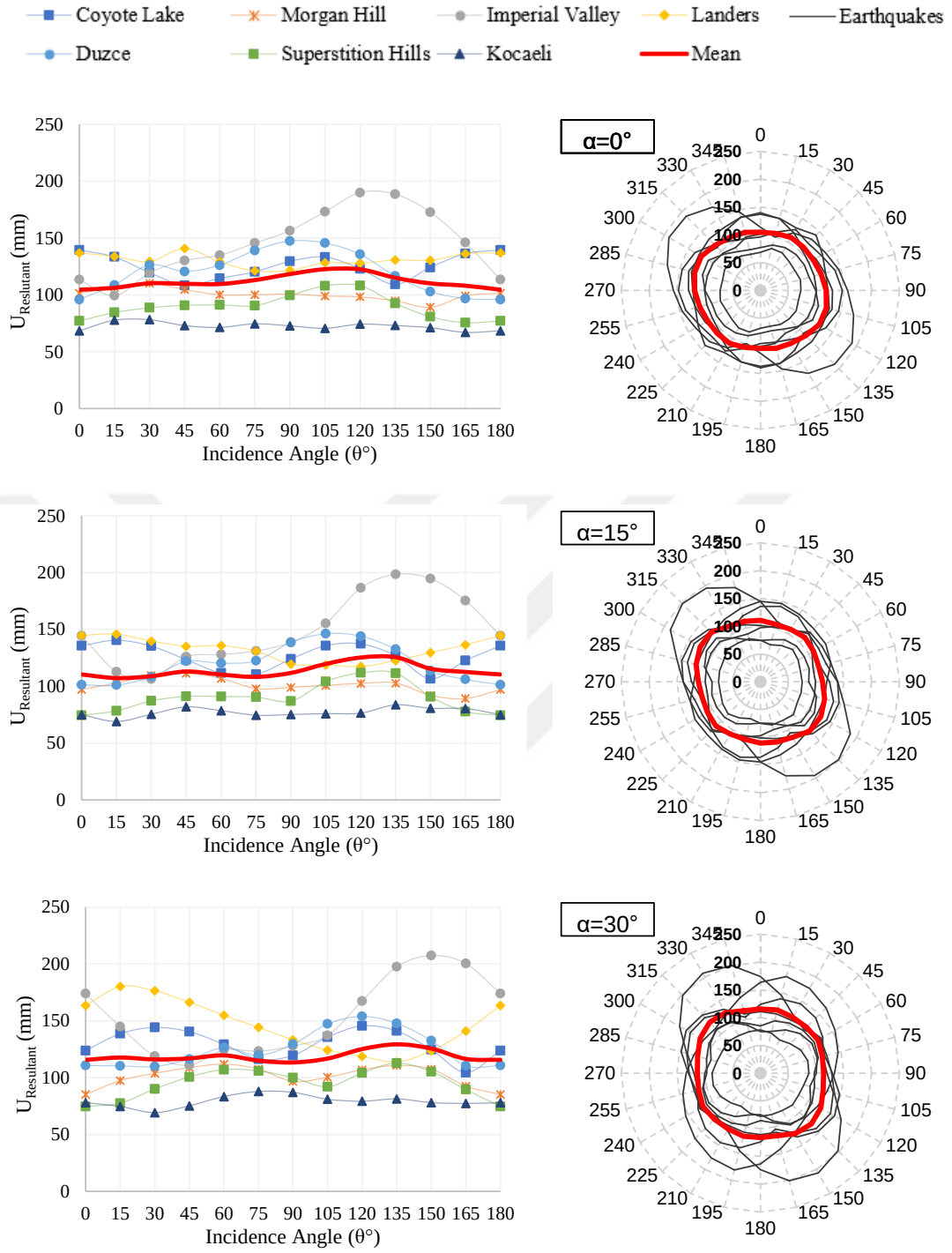


Figure 4.23. Maximum resultant displacement demands of bridge for different bridge skew angles and earthquake incidence angles

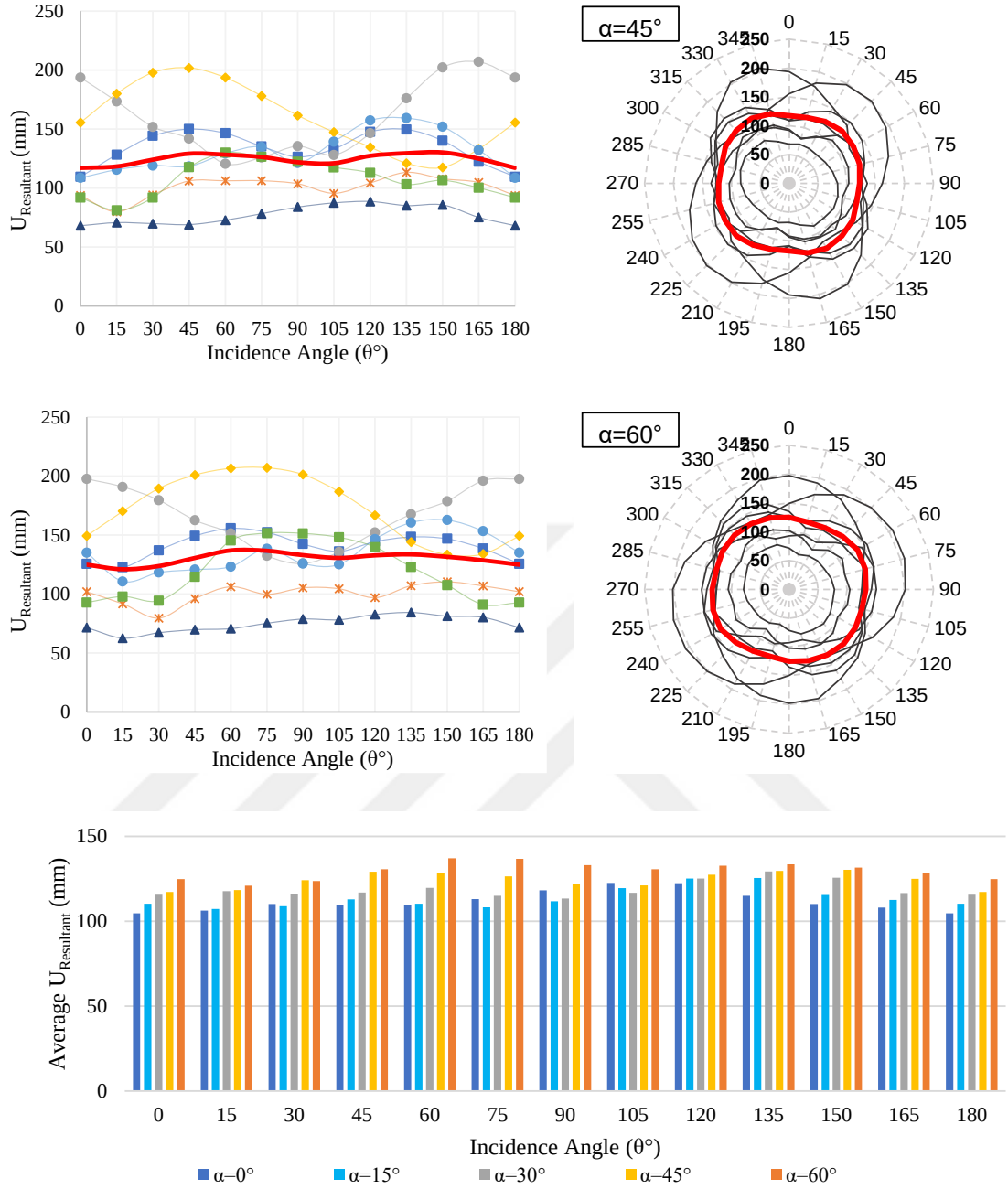


Figure 4.23. Maximum resultant displacement demands of bridge for different bridge skew angles and earthquake incidence angles (continued)

4.2.2. Curvature demands of column pier

Considering that bridge superstructure will behave elastically through the elastomeric bearings during an earthquake, it can be said that the most critical elements are the substructure members. Various damages may occur, especially in the column piers, due to earthquakes. Within the scope of the study, it has been explained in the previous sections that the members are defined using nonlinear fiber elements in the

analytical model in order to evaluate the seismic behavior of the piers. In this way, the curvature demands for the strong and weak axes of the column shown in Figure 3.10 were examined, and the effect on the change of both the bridge skew angle and the earthquake incidence angle was examined. For each bridge skew angle (α) and earthquake incidence angles (θ), the maximum curvature demands occurring in the strong (z') and weak (y') axes of the column 3201 located in the middle of the bridge span is given in Figure 4.24 and Figure 4.25, respectively. In the graphs on the left, the maximum curvatures of all earthquakes are given separately, and the average maximum demands of the 7 earthquakes used are shown with a thick red line. In the radar graphs on the right, the maximum curvature and average maximum values of all earthquakes can be seen more clearly for the bridge skew angles and earthquake incidence angles examined. In addition, the values shown with the red dashed line in the graphs are the yield curvatures obtained from Figure 3.11 and Figure 3.12 and calculated from the XTRACT section analysis program for the weak and strong axes of the column pier. In the last bar chart, when the average maximum demands are considered, the mutual effects of the bridge skew angle and the earthquake incidence angle are presented together.

In Figure 4.24, the maximum curvature demands occurred in weak axis of the column during earthquake are given for different skew angles and earthquake incidence angles. It is shown that the curvature demands of the column weak axis increases as the skew angle increases when the earthquake incidence angle is between 0° and 120° . The demand in the weak axis is larger in the 60° skew bridge than in the other skew bridges. The bridge skew angle has less of an impact on the curvature demands on the weak axis after an earthquake incidence angle of 120° . It is generally observed that changes in the earthquake incidence angle have a significant impact on the curvature demands on the weak axis. The demand for column curvature in the weak axis increases with the skew angle, particularly for large skew angles. The curvature demand of bridge column in weak axis reaches its maximum value when ground motion incidence angle is 60° for each skewed bridges.

Moreover, in cases where the bridge skew angle is $\alpha=0^\circ$ and $\alpha=15^\circ$, the maximum average curvature occurred in the weak axis is 0.0086 1/m and 0.0093 1/m, respectively at the earthquake incidence angle of $\theta=135^\circ$. In the $\alpha=30^\circ$ skewed bridge, the maximum average curvature occurs as 0.0095 1/m at the $\theta=150^\circ$ incidence angle. When the bridge skew angle is $\alpha=45^\circ$, the maximum average demand is 0.0101 1/m at the $\theta=45^\circ$

earthquake incidence angle, and when the skewness is $\alpha=60^\circ$, the maximum average demand is 0.0125 1/m at the $\theta=60^\circ$ incidence angle. It is seen that the maximum average curvature demands for the column weak axis exceed the yield curvature at all bridge skew angles and earthquake incidence angles.

In Figure 4.25, the maximum curvature demands occurred in the column strong axis are given for different skew angles and earthquake incidence angles. It was evident that the shift in the skew angle and earthquake incidence angle has a significant impact on the curvature demands in the column's strong axis. The average peak curvature in the column strong axis of a bridge with a 0° skew tends to increase from 0° to 120° earthquake incidence angle, and then to decrease beyond 120° . Similarly, this rise exists between 15° and 135° earthquake incidence angles in the 15° skew bridge model. The curvature demands on the strong axis increases significantly in the range from 90° to 135° incidence angles when the skew angle is 30° and 45° . In the 60° skew bridge, the average curvature demand decreases when the earthquake incidence angle is between 0° and 60° and increases between 60° and 135° .

When the bridge skew angle is $\alpha=0^\circ$, the maximum average curvature occurred in the strong axis is 0.0074 1/m at the earthquake incidence angle of $\theta=105^\circ$. In the $\alpha=15^\circ$ and $\alpha=30^\circ$ skewed bridges, the maximum average curvature occurs as 0.00754 1/m and 0.00752 1/m, respectively, at the $\theta=120^\circ$ incidence angle. When the bridge skew angle is $\alpha=45^\circ$ and $\alpha=60^\circ$, the maximum demand emerges as 0.0068 1/m and 0.0051 1/m at the earthquake incidence angle of $\theta=135^\circ$. It is seen that the average maximum curvature demands for the column strong axis exceed the yield curvature at all bridge skew angles and earthquake incidence angles.

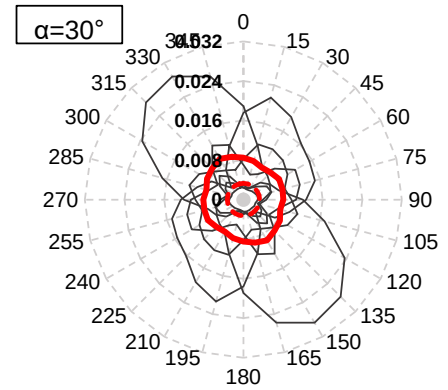
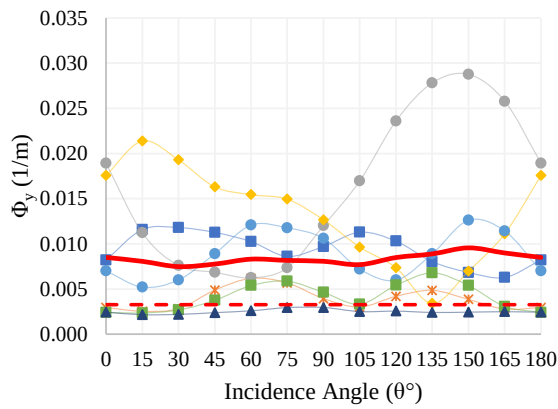
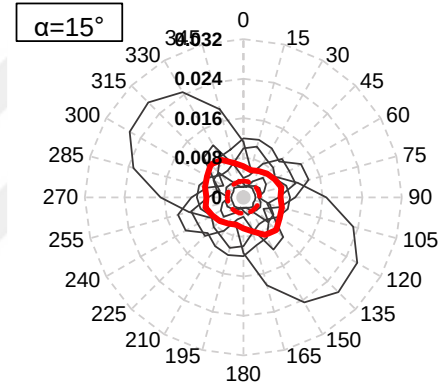
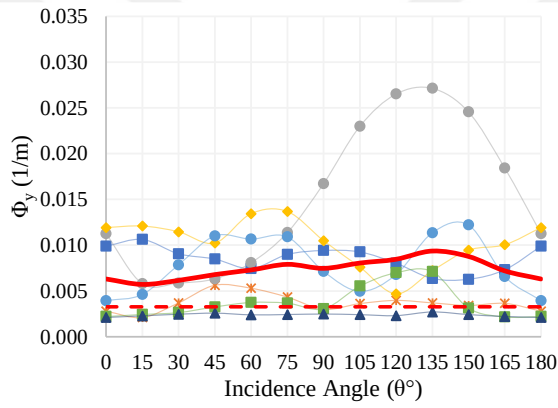
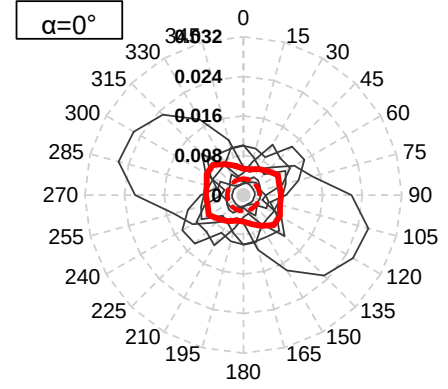
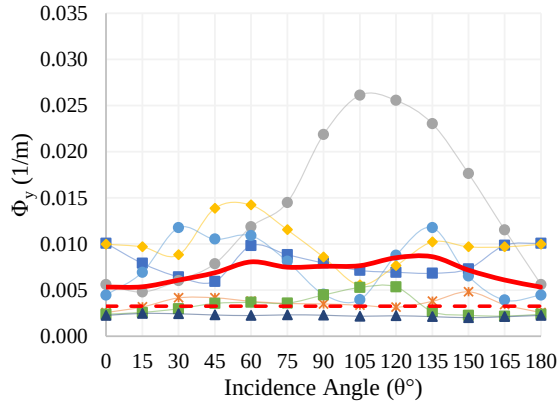


Figure 4.24. Maximum curvature demands of column weak axis (y') for different bridge skew angles and earthquake incidence angles

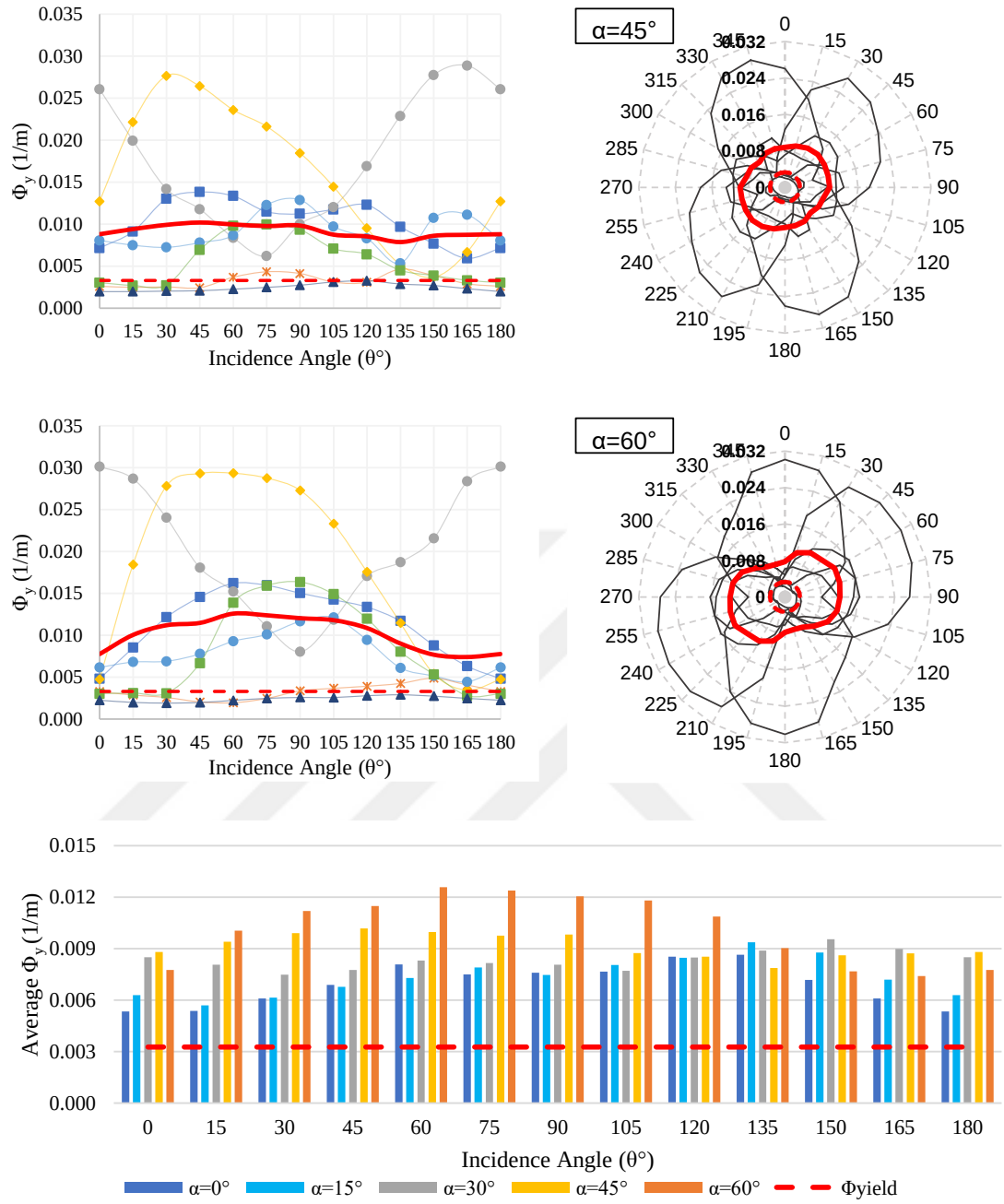


Figure 4.24. Maximum curvature demands of column weak axis (y') for different bridge skew angles and earthquake incidence angles (continued)

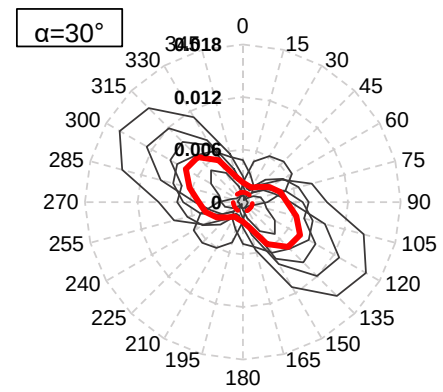
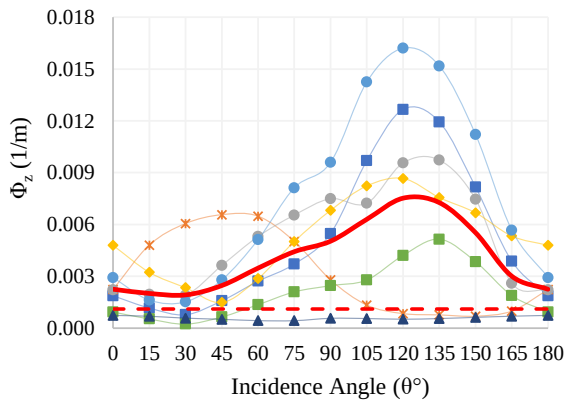
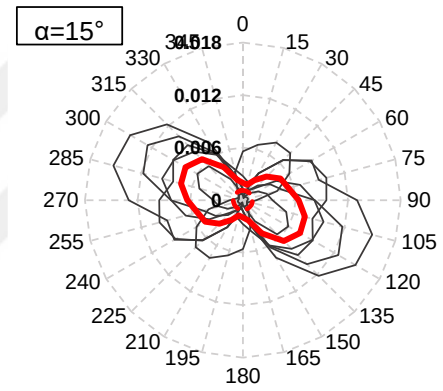
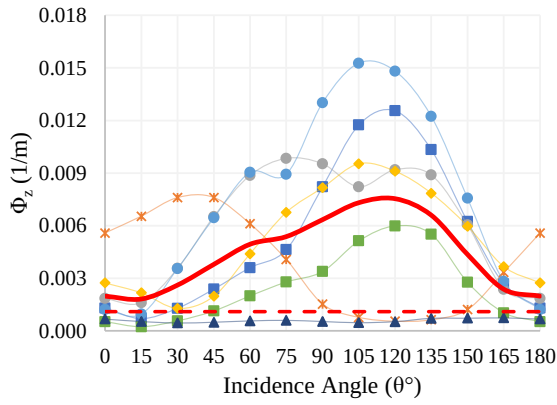
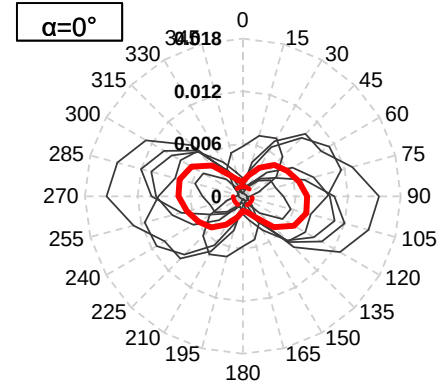
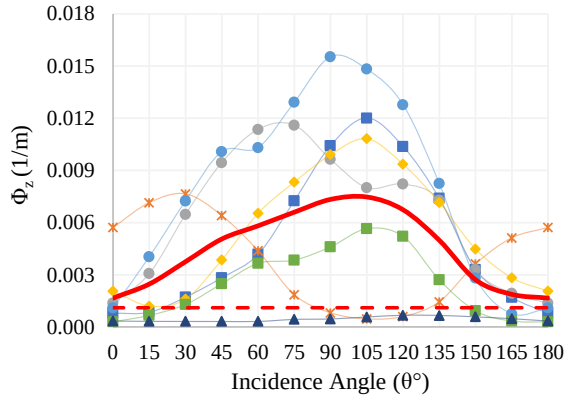


Figure 4.25. Maximum curvature demands of column strong axis (z') for different bridge skew angles and earthquake incidence angles

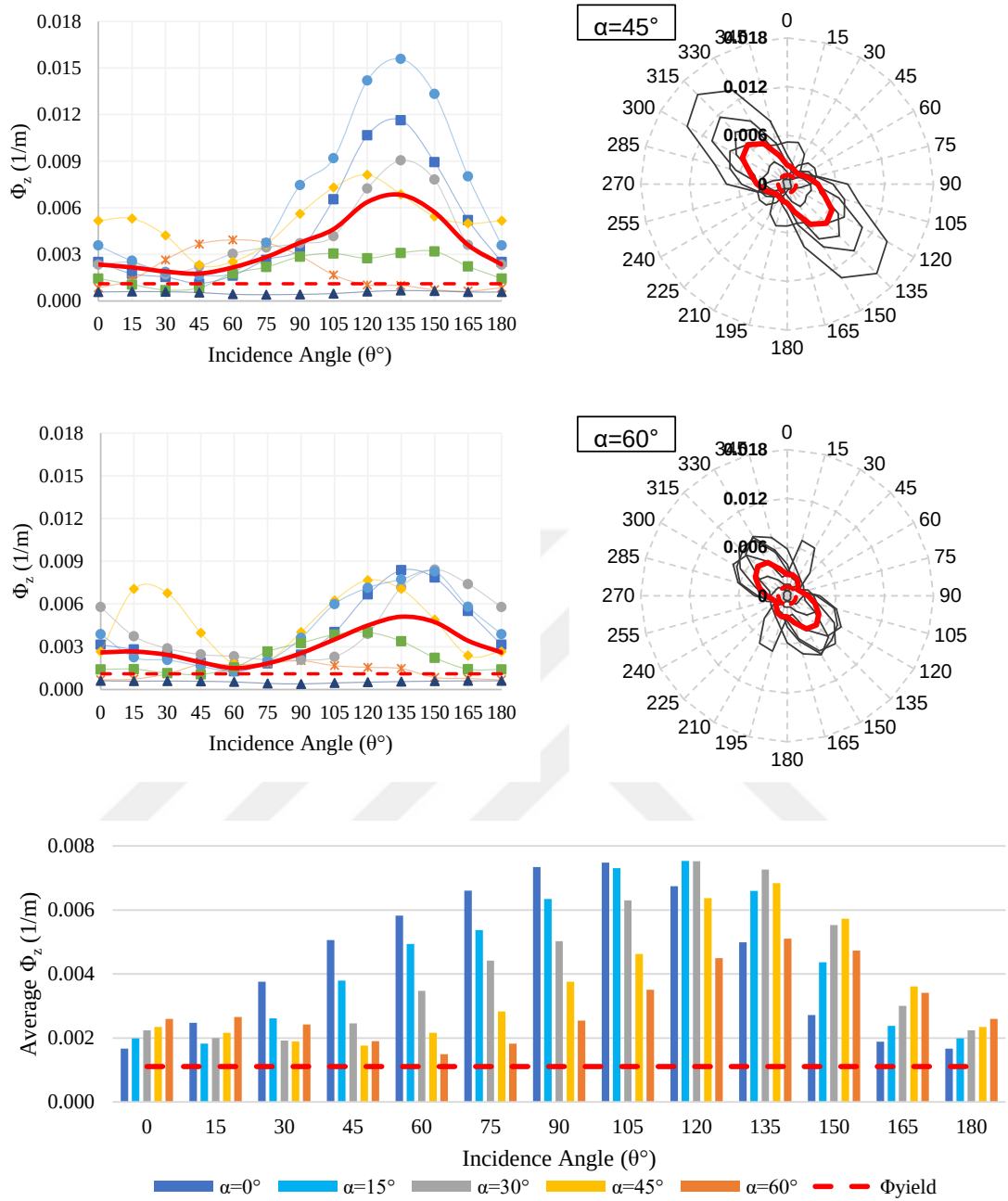


Figure 4.25. Maximum curvature demands of column strong axis (z') for different bridge skew angles and earthquake incidence angles (continued)

4.2.3. Shear force demands of column pier

Shear force is a force-based engineering demand parameter and is used when evaluating whether the members exceed their shear capacity. If the bridge columns reach the shear capacity during an earthquake, severe damage or even collapse may occur in the structure. Therefore, within the scope of the study, shear force demands of the bridge column piers due to earthquake effect were obtained separately for the local y' and local

z' axes of the column shown in Figure 3.10, and their effects on change of both the bridge skew angle and the earthquake incidence angle were examined. For each bridge skew angle (α) and earthquake incidence angles (θ), the maximum shear force demands occurred in the local y' and local z' axes of the column 3201 located in the middle of the bridge span are shown in Figure 4.26 and Figure 4.27, respectively. In graphs on the left, the maximum shear forces of all earthquakes are given separately, and the average maximum demands of the 7 earthquakes are shown with a thick red line. In radar graphs on the right, the maximum forces and average maximum values of all earthquakes can be seen more clearly for the bridge skew angles and earthquake incidence angles. In the bar chart given at the end, the mutual effects of the bridge skew angle and the earthquake incidence angle are presented together by considering the average maximum shear force demands.

In Figure 4.26, maximum shear force demands occurred in the local y' axis of the column are given for different skew angles and earthquake incidence angles. Accordingly, for every ground motion incidence angle in a 0° skew bridge, the average of the peak shear force in the column's local y' axis does not exhibit a trend. But as soon as the models account for the bridge skew angle, demands begin to decline. Shear force demands for 15° and 30° skew bridges typically rise between 30° and 105° incidence angles. This rise happens on the local y' axis of bridge columns with 45° and 60° skewness at incidence angles between 60° and 150° . In cases where the bridge skew angle is $\alpha=0^\circ$ and $\alpha=15^\circ$, the maximum average shear force occurred in the local y' axis emerges at the earthquake incidence angle of $\theta=75^\circ$ as 3397 kN and 3357 kN, respectively. In $\alpha=30^\circ$ skewed bridge, the maximum average shear force occurs as 3283 kN at $\theta=90^\circ$ incidence angle. When the bridge skew angle is $\alpha=45^\circ$, the maximum average demand is 3251 kN at $\theta=120^\circ$ ground motion incidence angle, and when the skewness is $\alpha=60^\circ$, the maximum average demand is 3201 kN at $\theta=135^\circ$ incidence angle.

In Figure 4.27, maximum shear force demands occurred in the local z' axis of the column are given for different skew angles and earthquake incidence angles. The average of the peak shear force in column local z' axis tends to decrease at earthquake incidence angles between 45° and 90° in 0° and 15° skew bridges. The demands on the z' axis decrease after the incidence angle of 75° when the skew angle is 30° . Conversely, in 45° and 60° skew bridges, the variation in the earthquake incidence angle has no effect on the average shear force demands in the local z' axis. The average shear force in the local z'

axis at other incidence angles is not significantly affected by the change in skew angle, but when the average shear forces in column z' axis is evaluated in terms of bridge skewness, it found that the demands increase as the skew angle increases in the range of 45° to 135° earthquake incidence angle. In addition, when the bridge skew angle is $\alpha=0^\circ$, the maximum average shear force occurred in the local z' axis occurred at $\theta=0^\circ$ and $\theta=180^\circ$ earthquake incidence angles as 1192 kN. In the $\alpha=15^\circ$ skewed bridge, the maximum average shear force occurs as 1226 kN at the $\theta=45^\circ$ incidence angle. When the bridge skew angle is $\alpha=30^\circ$, the maximum demand emerges as 1263 kN at earthquake incidence angle of $\theta=60^\circ$. In the $\alpha=45^\circ$ skewed bridge, the maximum average shear force occurs as 1286 kN at $\theta=75^\circ$ earthquake impact angle. In $\alpha=60^\circ$ skewed bridge, the maximum average shear force demand is 1335 kN at $\theta=90^\circ$ incidence angle.

The shear capacity demands of column was calculated in Section 3.1.2 as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the maximum average shear force demands are compared to these capacities, it is seen that demands are below the limits for all skewed bridges. Therefore, it can be said no shear damage occurred in the bridge column during earthquakes.

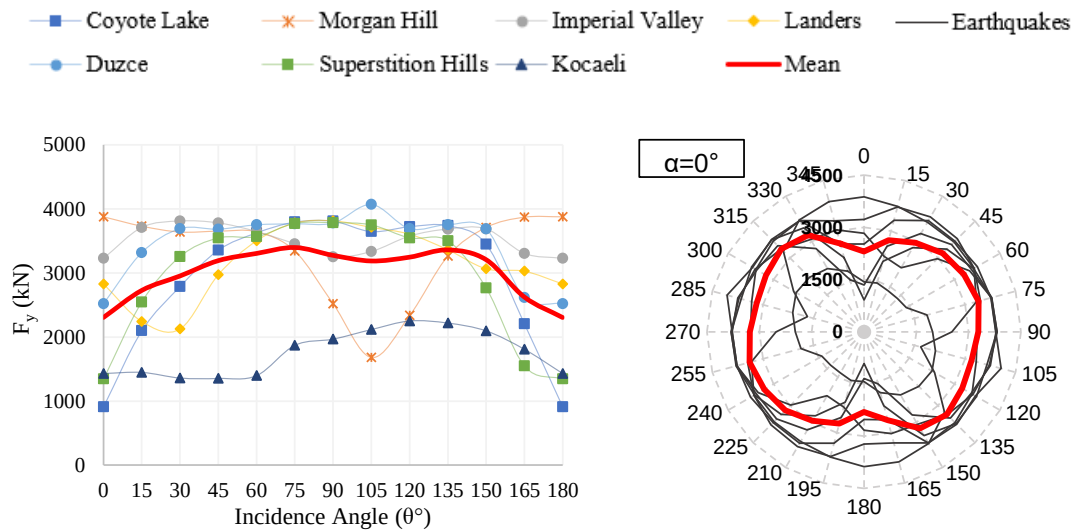


Figure 4.26. Maximum shear force demands of column local y' axis for different bridge skew angles and earthquake incidence angles

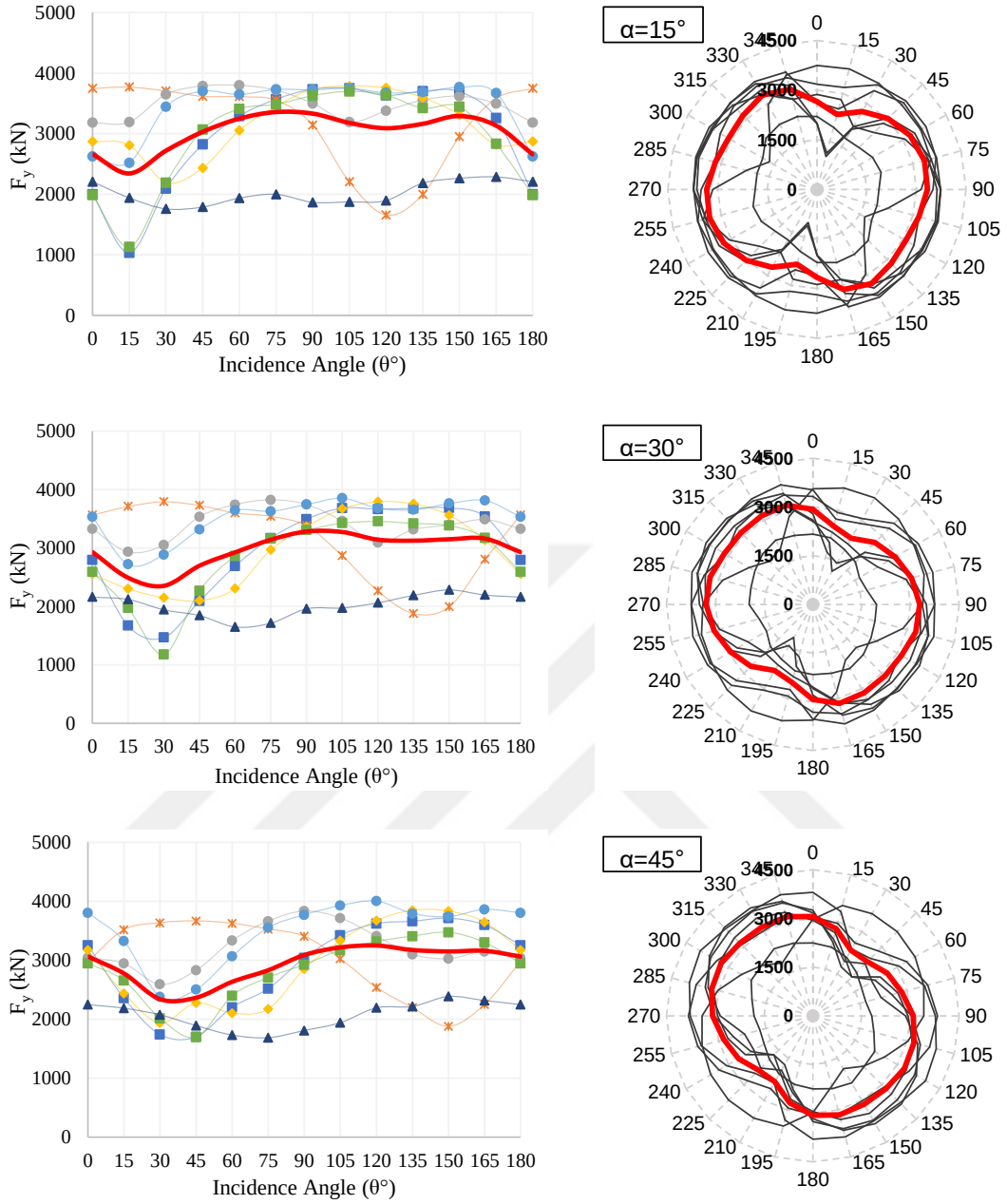


Figure 4.26. Maximum shear force demands of column local y' axis for different bridge skew angles and earthquake incidence angles (continued)

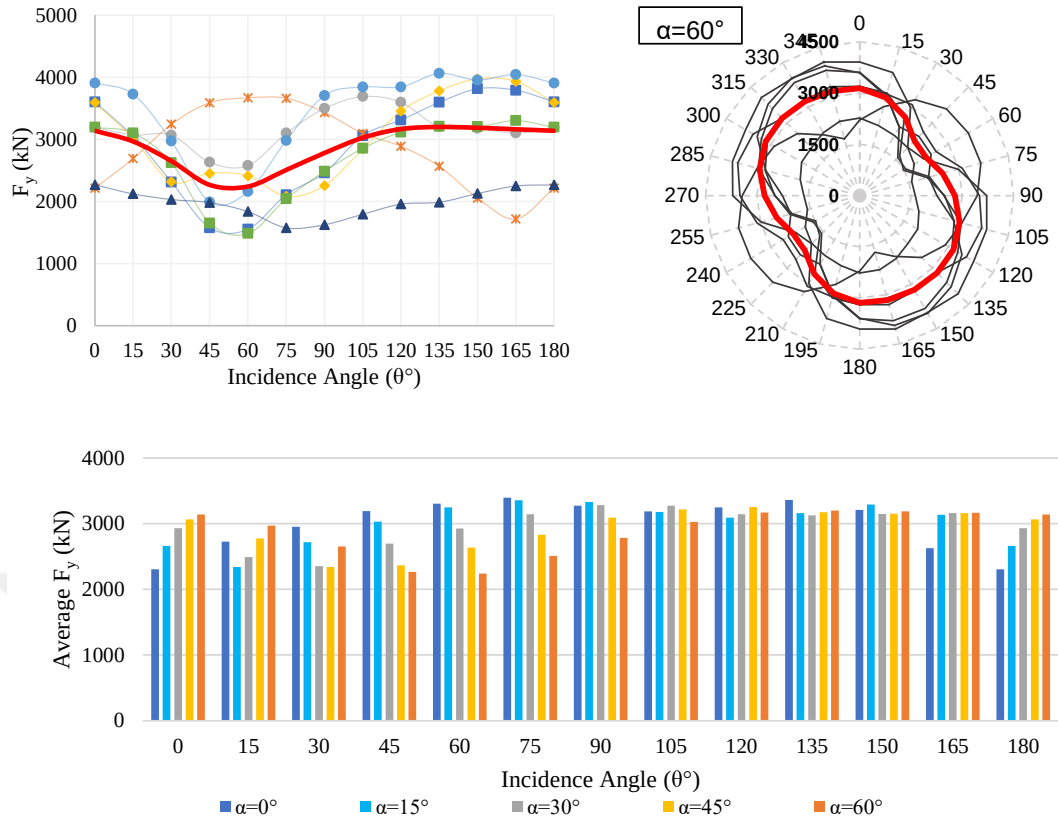


Figure 4.26. Maximum shear force demands of column local y' axis for different bridge skew angles and earthquake incidence angles (continued)

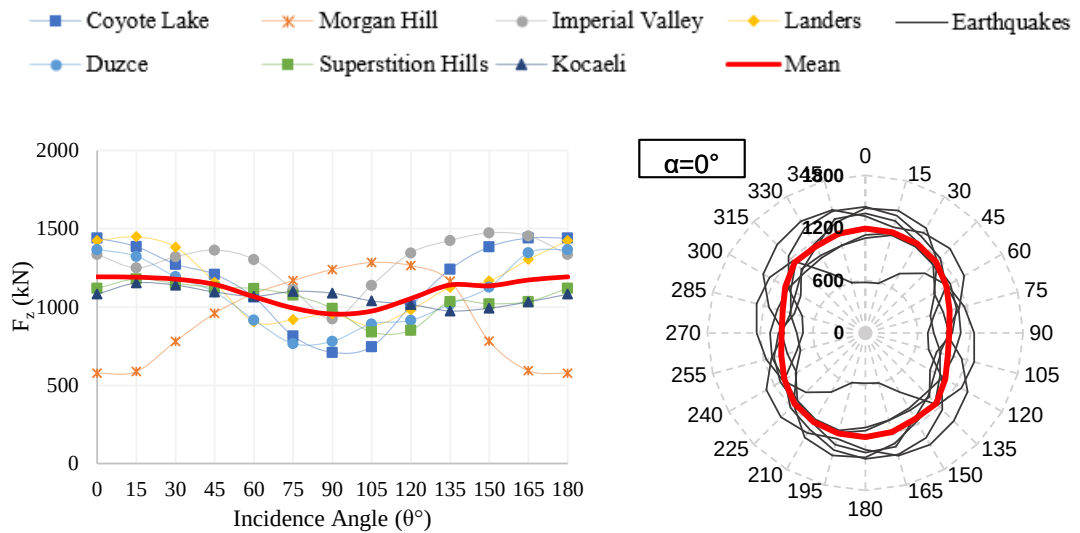


Figure 4.27. Maximum shear force demands of column local z' axis for different bridge skew angles and earthquake incidence angles

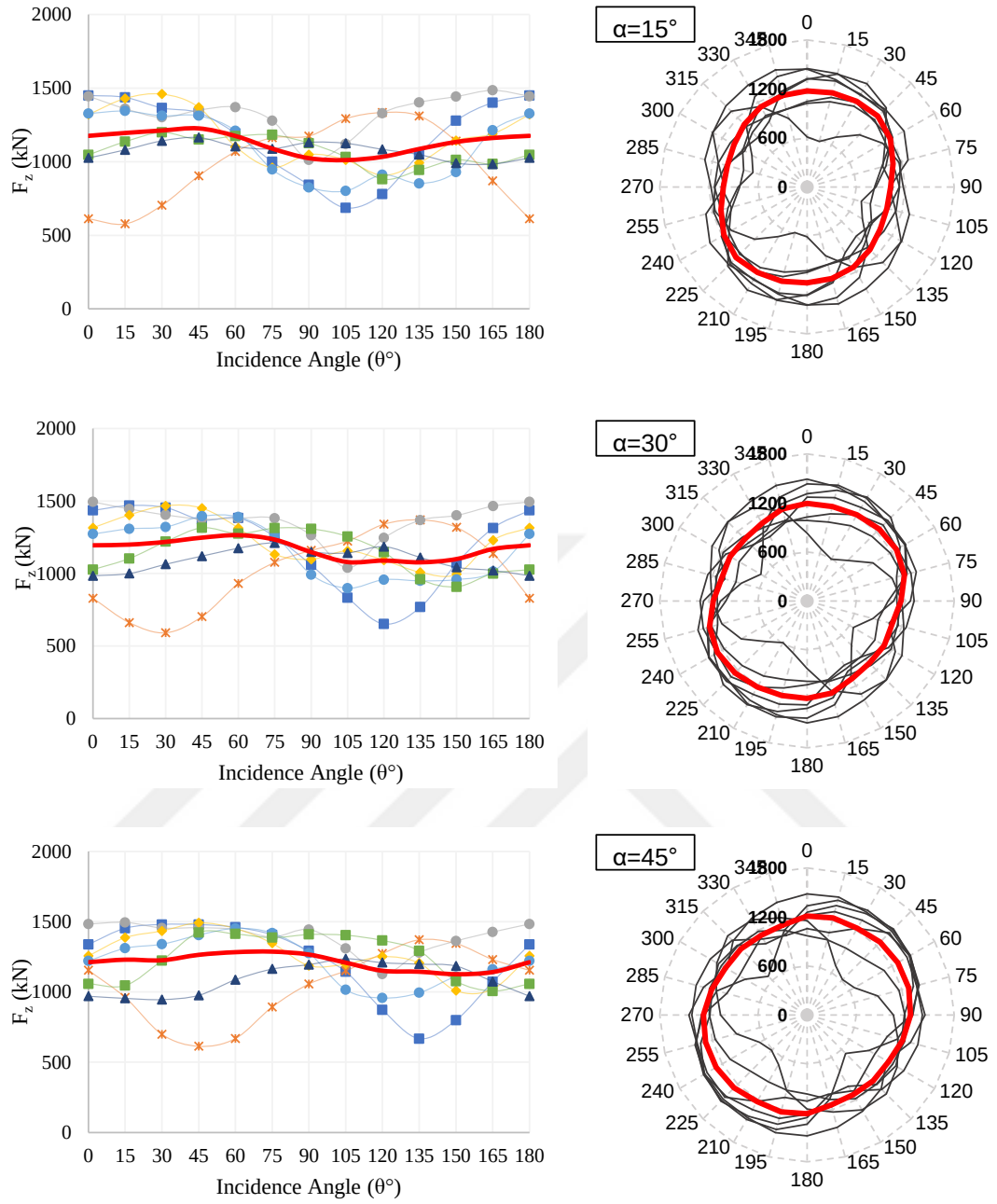


Figure 4.27. Maximum shear force demands of column local z' axis for different bridge skew angles and earthquake incidence angles (continued)

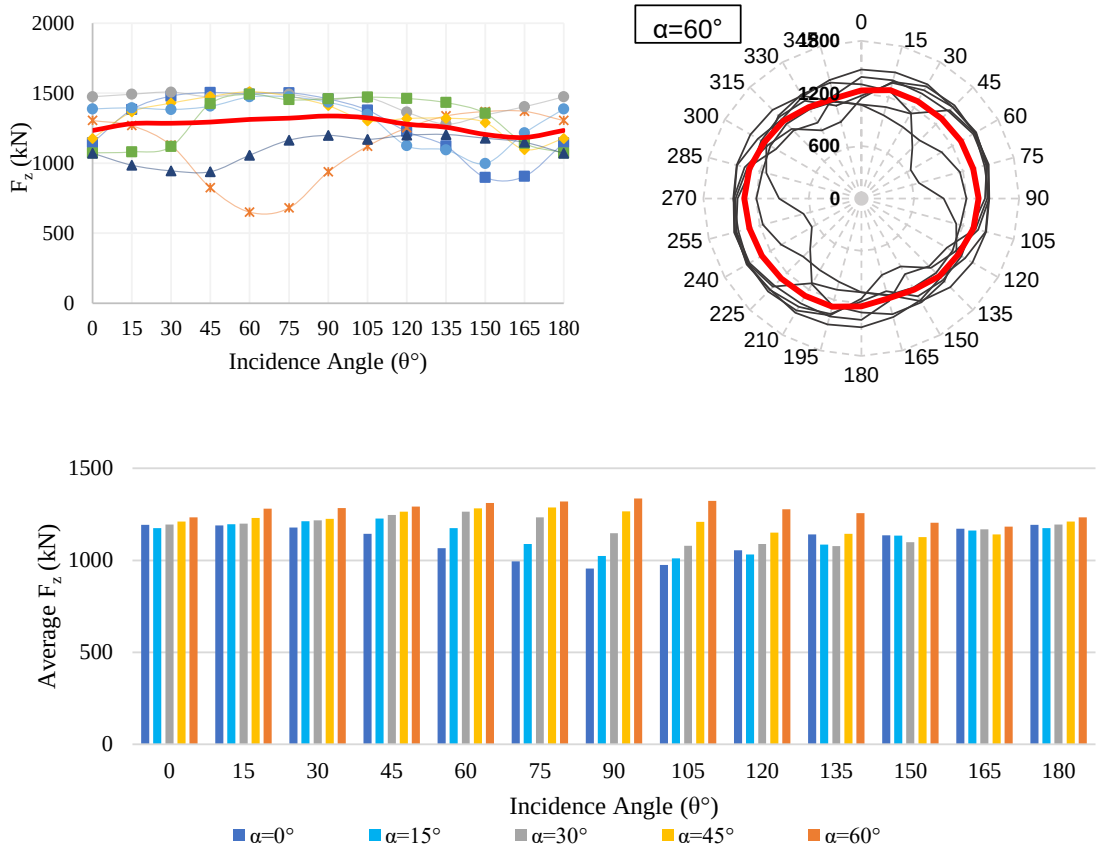


Figure 4.27. Maximum shear force demands of column local z' axis for different bridge skew angles and earthquake incidence angles (continued)

4.2.4. Deformation demands of pounding elements

In order to prevent pounding between bridge members during earthquakes, gap distance should be left between various members. As explained in the previous sections, within the scope of the thesis, the effect of pounding on the seismic behavior of the bridges was investigated by defining certain gap distances both between bridge superstructure and abutments and between superstructure and shear keys. The pounding elements defined in the bridge analytical model are defined as bilinear model, as shown in Figure 3.15, and transfer forces between the elements when the gap distances are closed during earthquake. The spring element, which works linearly elastic until it reaches the capacity, does not take any more force after exceeding the limit value and continues to deform. For this reason, it is thought that evaluating the deformation in the spring instead of the pounding force would be a more accurate approach for the pounding behavior. The possible collision zones whose deformation demands are examined are the nodes 109 on the abutment and 517 on the mid pier given in Figure 4.3. According to that, the

longitudinal and transverse deformations of the spring element at node 109 between the abutment and the bridge superstructure for different skew angles (α) and earthquake incidence angles (θ) are given in Figure 4.28 and Figure 4.29, respectively. In Figure 4.30, there are deformation graphs of spring element at node 517 at the column pier defined in transverse direction of the bridge between superstructure and shear key.

In Figure 4.28, maximum deformation demands in longitudinal direction occurred between abutment and superstructure are given for different skew angles and earthquake incidence angles. Accordingly, in cases where the bridge skew angle is $\alpha=0^\circ$ and $\alpha=15^\circ$, maximum average deformation in longitudinal direction occurs at the earthquake incidence angle of $\theta=165^\circ$ as 86.9 mm and 91.3 mm, respectively. In $\alpha=30^\circ$ and $\alpha=45^\circ$ skewed bridges, maximum average deformation occurs as 92.7 mm and 89.5 mm at the incidence angle of $\theta=0^\circ$. When the bridge skew angle is $\alpha=60^\circ$, the maximum average demand again emerges as 87.7 mm at $\theta=0^\circ$ earthquake incidence angle.

In Figure 4.29, maximum average deformation demands in transverse direction occurred between superstructure and shear key at abutment are given for different skew angles and earthquake incidence angles. When bridge skew angle is $\alpha=0^\circ$, the maximum average deformation in the transverse direction occurs at the incidence angle of $\theta=75^\circ$ and is 25.2 mm. In $\alpha=15^\circ$ and $\alpha=30^\circ$ skewed bridges, maximum average deformation occurs as 25.9 mm and 27.1 mm at the incidence angle of $\theta=120^\circ$. When bridge skew angle is $\alpha=45^\circ$, maximum average demand is 27.4 mm at $\theta=135^\circ$ earthquake incidence angle, and when skewness is $\alpha=60^\circ$, maximum deformation in the transverse direction is 27.5 mm at $\theta=150^\circ$ seismic incidence angle.

The maximum deformation demands in transverse direction occurred between bridge superstructure and shear key at the column pier are shown in Figure 4.30 for different skew angles and earthquake incidence angles. When bridge skew angle is $\alpha=0^\circ$, maximum average deformation in transverse direction occurs at earthquake incidence angle of $\theta=75^\circ$ as 25.6 mm. In $\alpha=15^\circ$ skewed bridge, maximum average deformation occurs as 25.7 mm at the $\theta=120^\circ$ incidence angle. When bridge skew angle is $\alpha=30^\circ$, maximum average demand is 25.2 mm at $\theta=135^\circ$ seismic incidence angle, and when skew angle is $\alpha=45^\circ$, maximum deformation in transverse direction is 25.1 mm at $\theta=120^\circ$ incidence angle. In $\alpha=60^\circ$ skewed bridge, the maximum average deformation demand is 36.2 mm at the earthquake incidence angle of $\theta=15^\circ$.

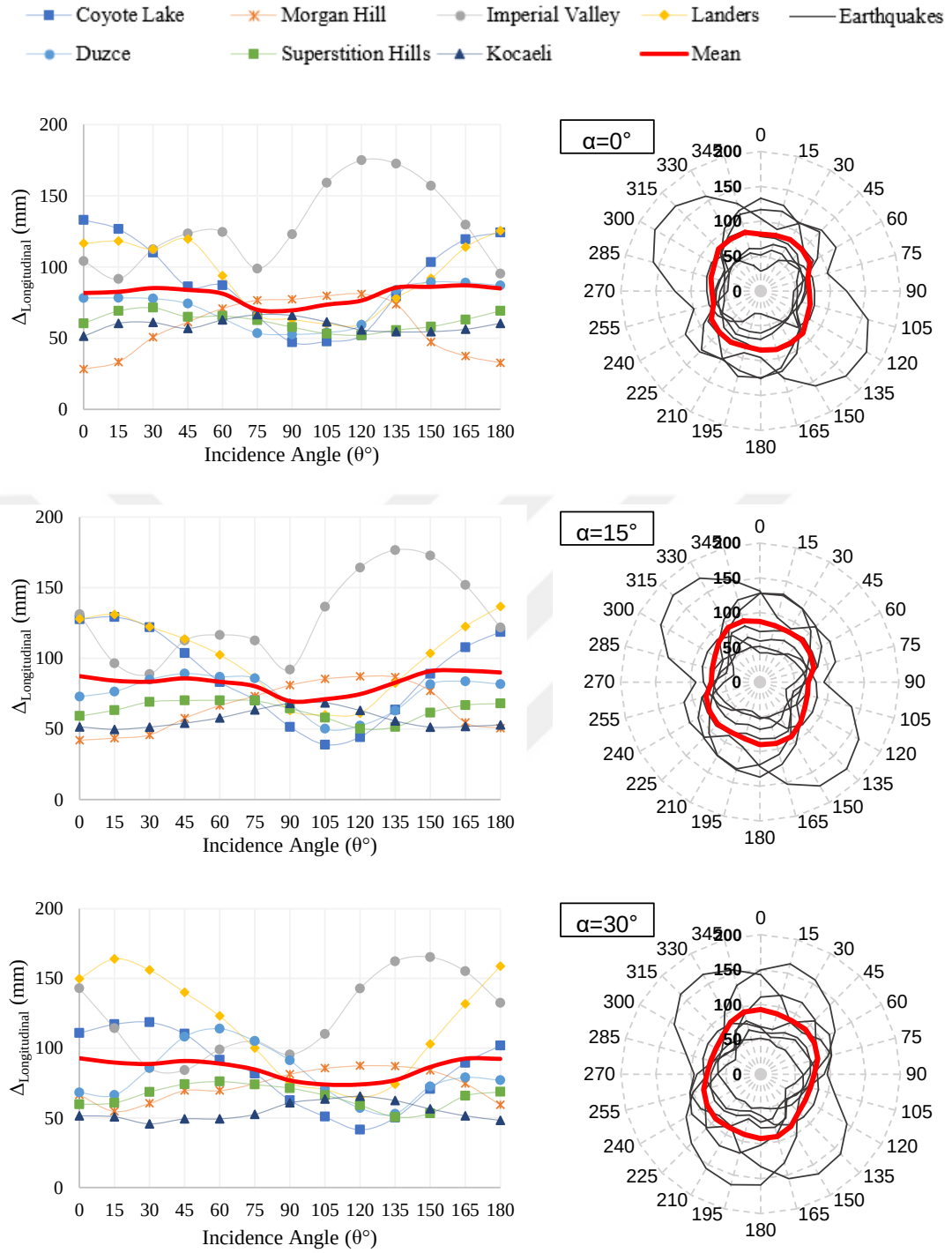


Figure 4.28. Maximum deformation demands of pounding element defined in bridge longitudinal direction between superstructure and abutment

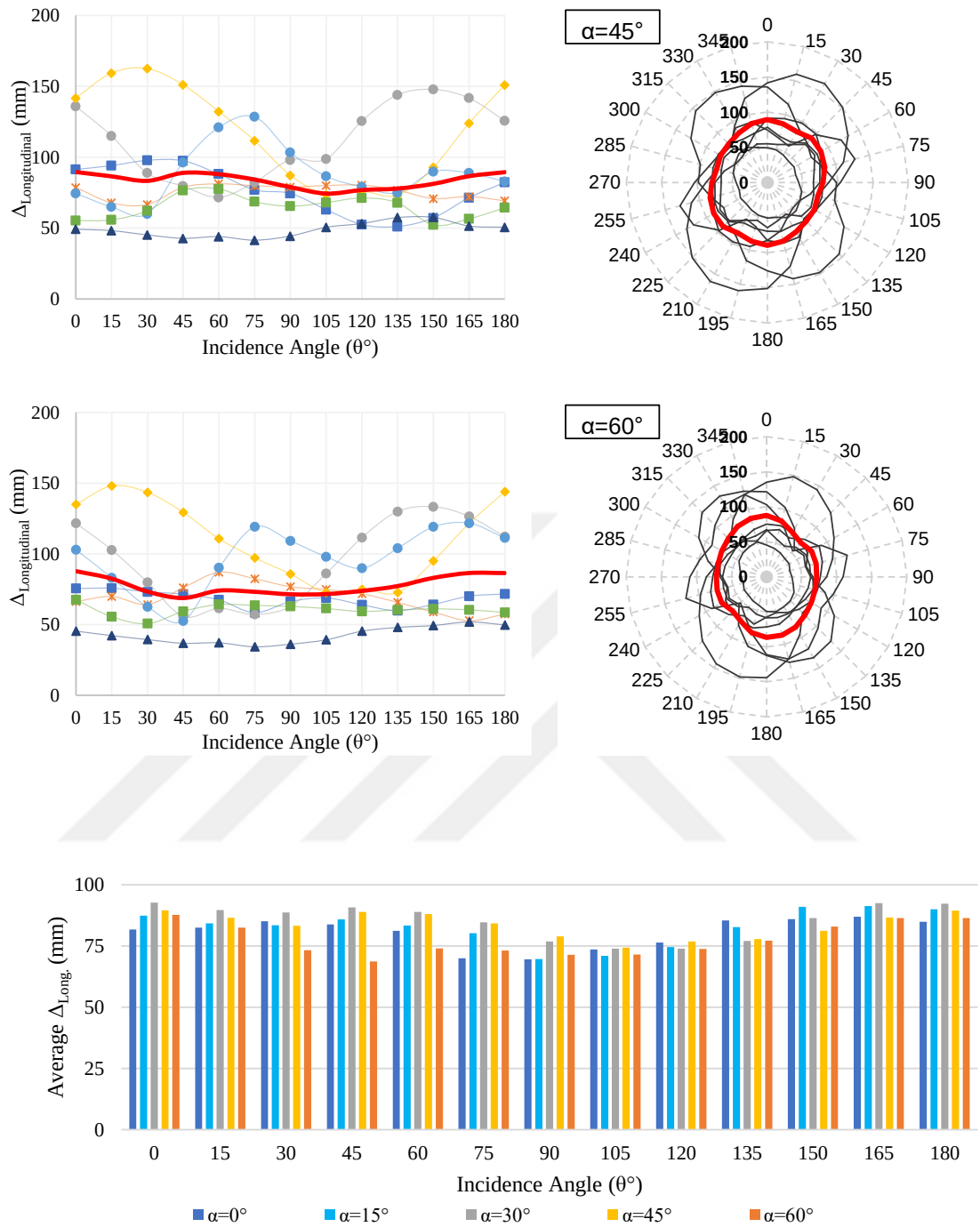


Figure 4.28. Maximum deformation demands of pounding element defined in bridge longitudinal direction between superstructure and abutment (continued)

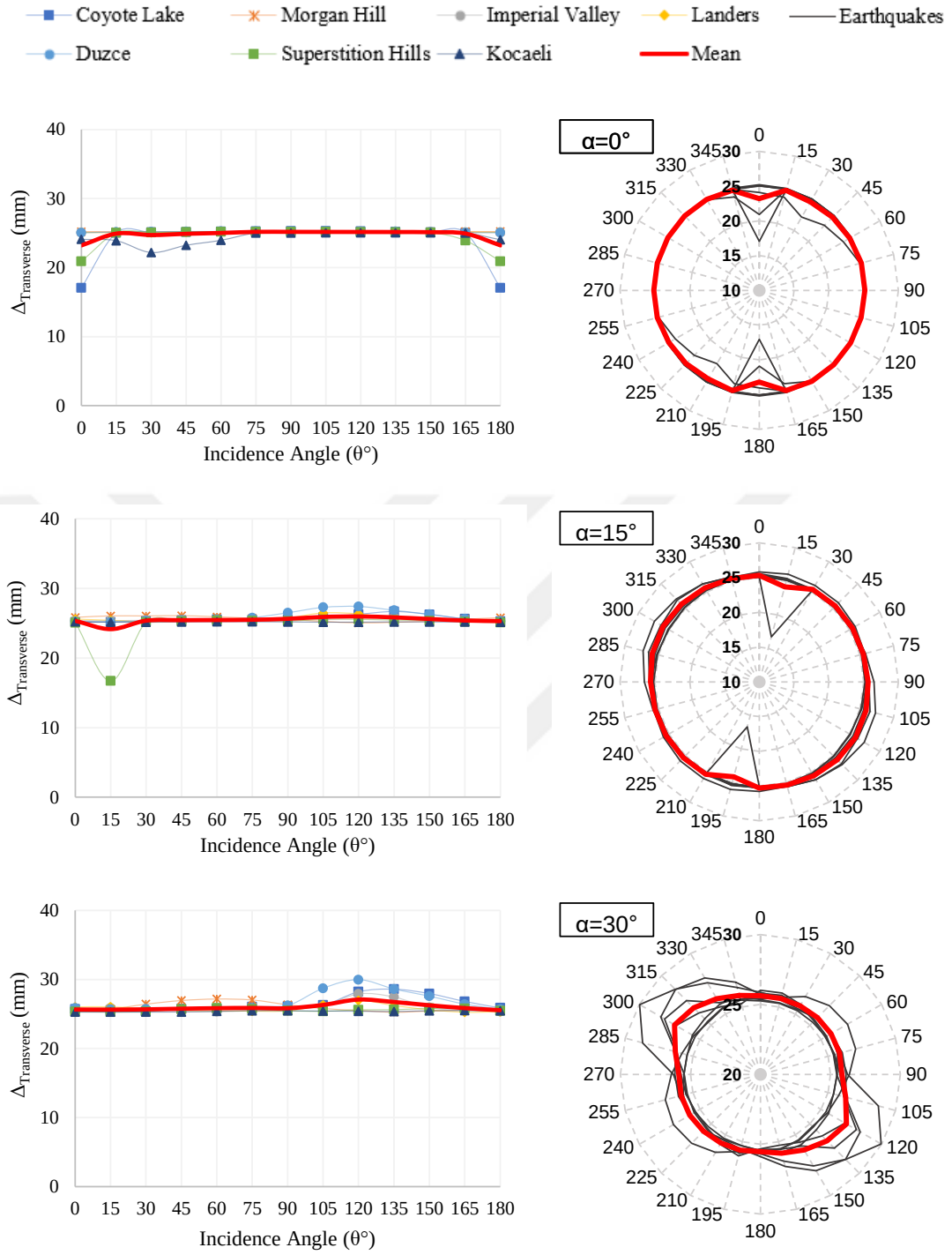


Figure 4.29. Maximum deformation demands of pounding element defined in bridge transverse direction between superstructure and shear key at the abutment

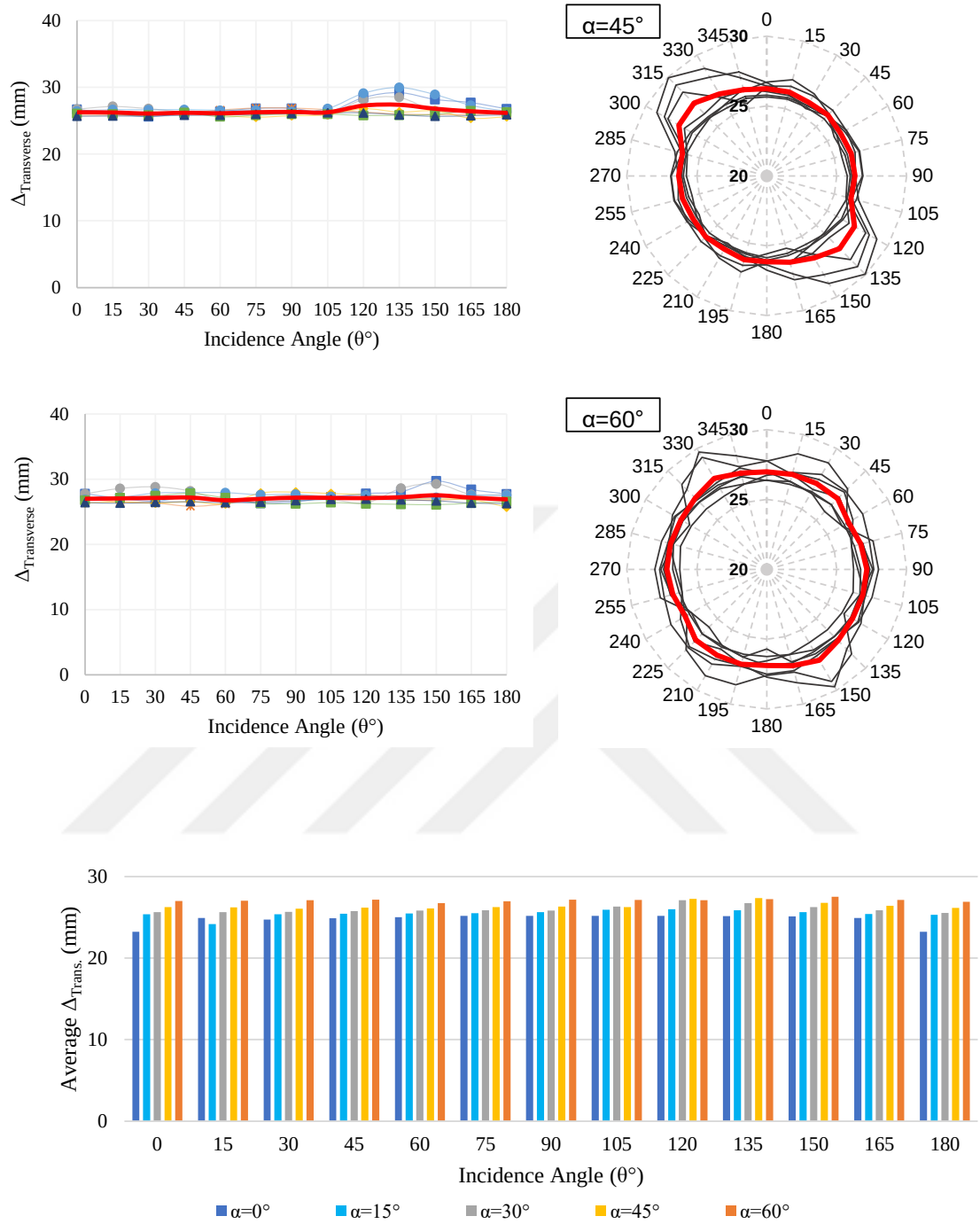


Figure 4.29. Maximum deformation demands of pounding element defined in bridge transverse direction between superstructure and shear key at the abutment (continued)

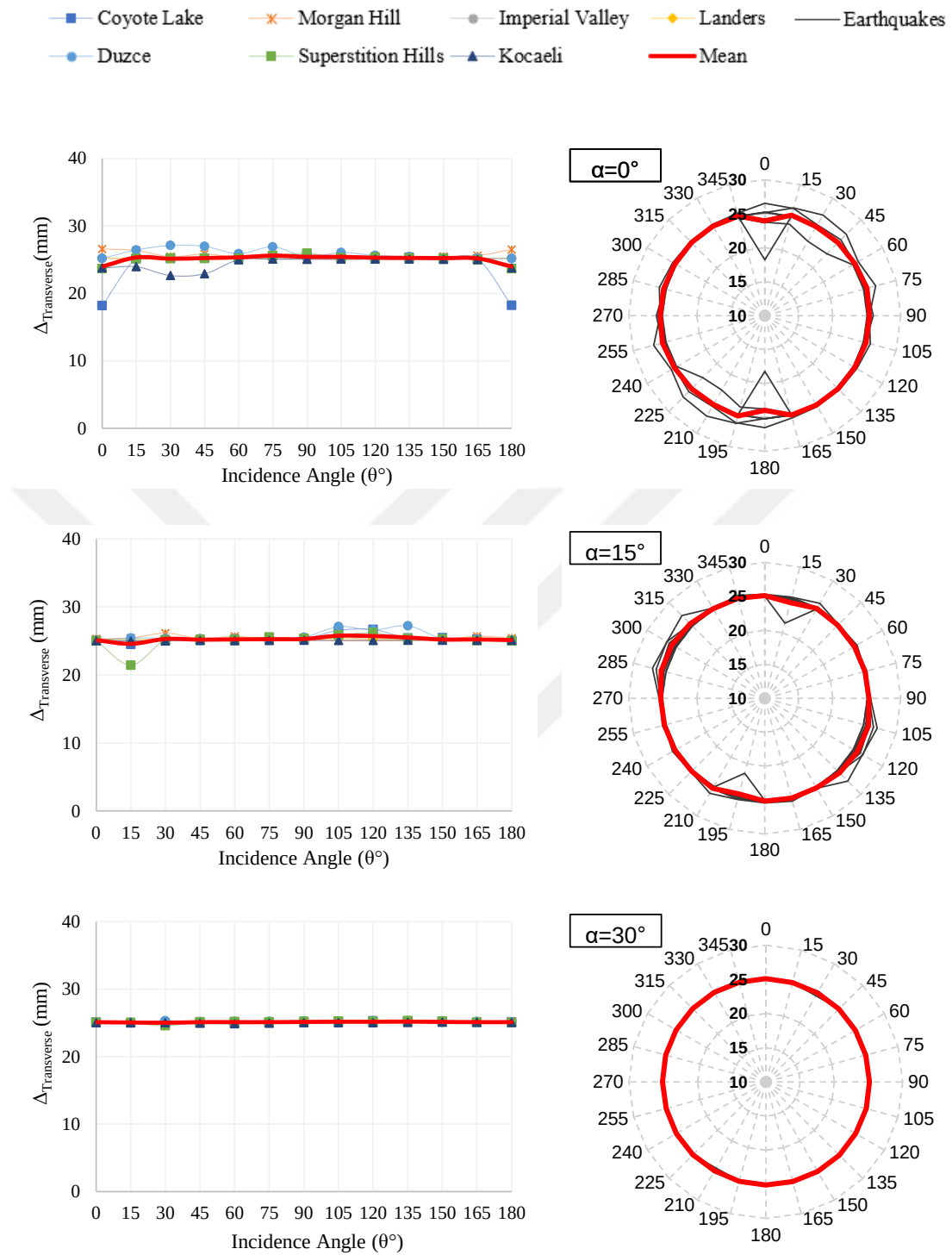


Figure 4.30. Maximum deformation demands of pounding element defined in bridge transverse direction between superstructure and shear key

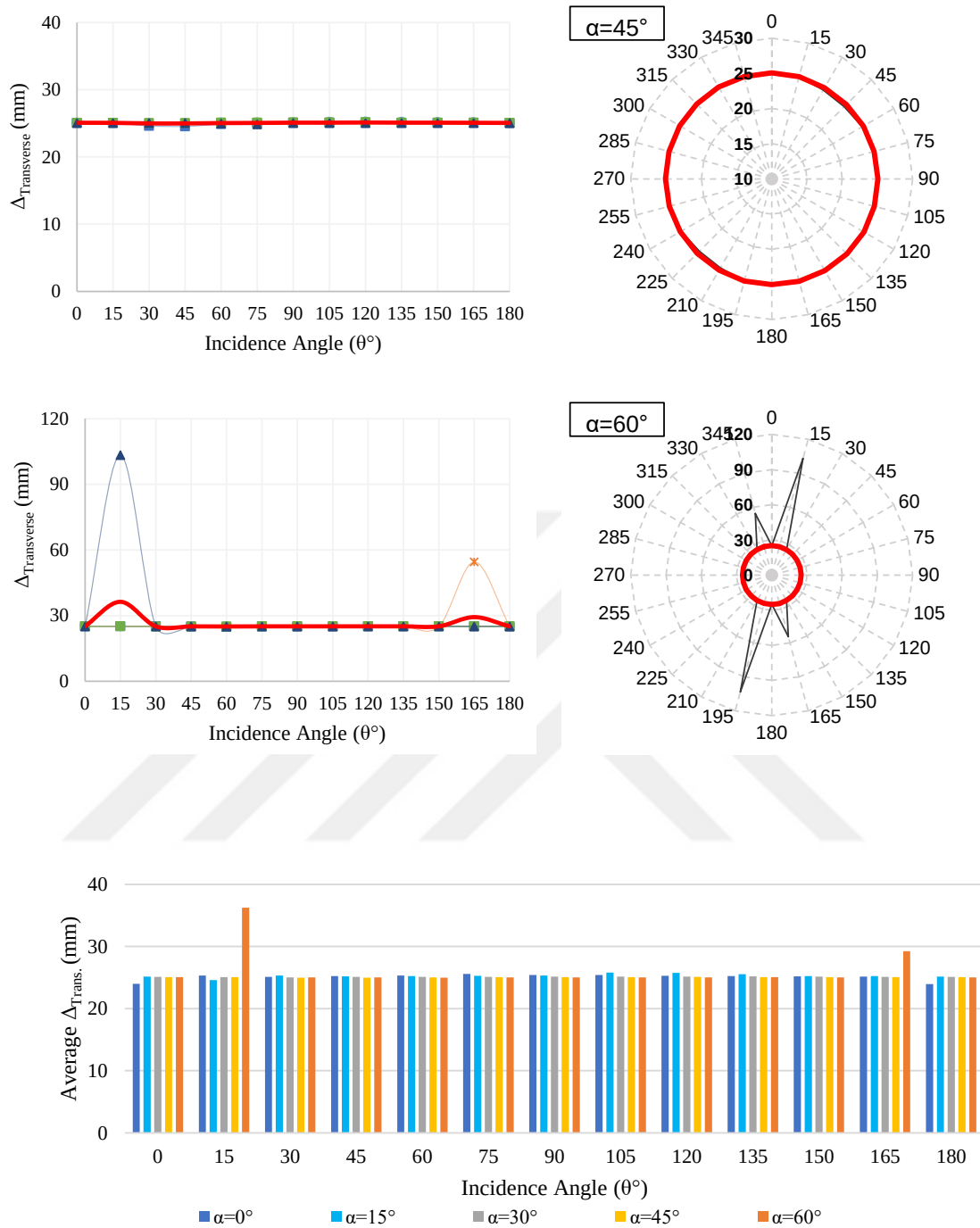


Figure 4.30. Maximum deformation demands of pounding element defined in bridge transverse direction between superstructure and shear key (continued)

4.3. Comparison of Fixed Based and Soil Structure Interacted Bridges

Defining support conditions of a structure as fixed is an easy method for applying to the analytical programs. However, it is thought that this approach will significantly affect the analysis results in cases where the interaction between soil and structure is high,

for example, in bridges built on the riverbed. Therefore, within the scope of the study, soil structure interaction (SSI) was added to the non-skewed ($\alpha=0^\circ$) bridge model without any scour which was researched in previous sections and the fixed based approach and soil structure interacted model was compared by using nonlinear response history analysis results. Engineering demand parameters such as superstructure displacement, curvature and shear force demand of column pier is investigated for this part of study.

4.3.1. Superstructure displacement

In Figure 4.31, the 1st and 2nd vibration periods of fixed based and soil structure interacted bridges are given. It is shown that, when soil-structure interaction is taken into account, the bridge becomes more flexible and thus, its natural vibration period increases compared to the bridge that is supported fully restraint.

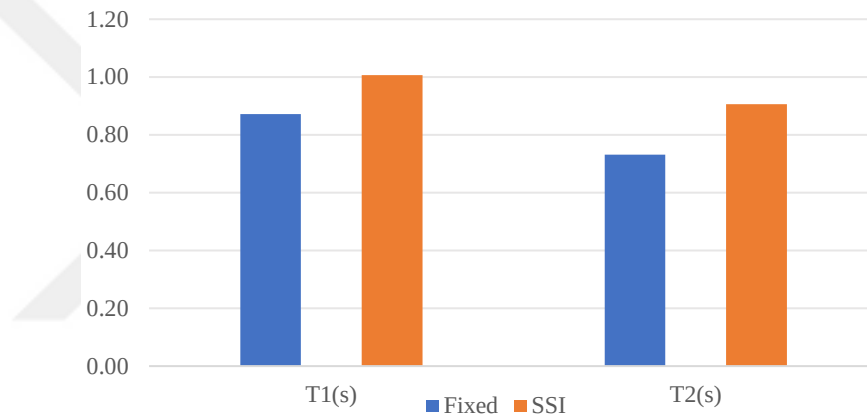
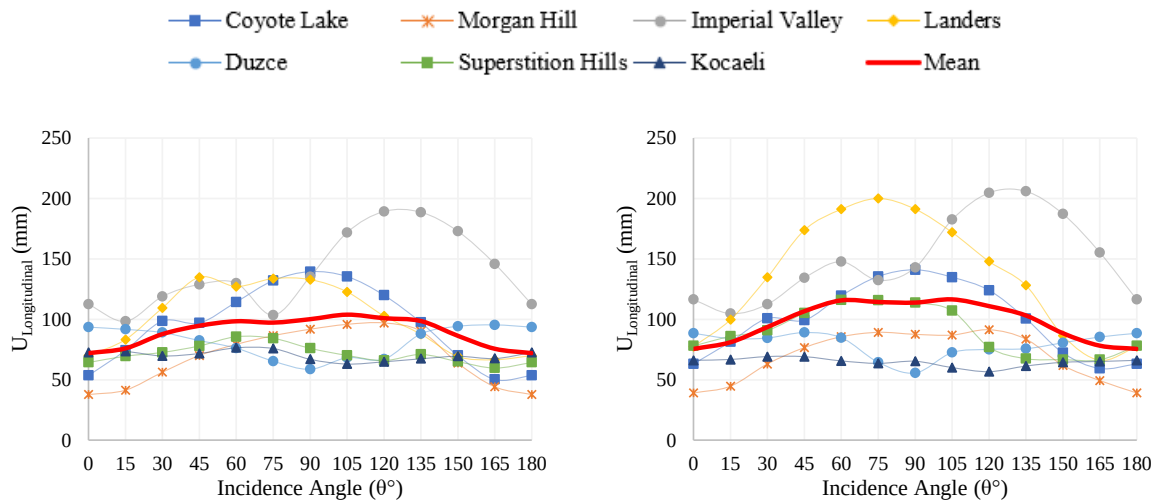


Figure 4.31. The variation of 1st and 2nd vibration period of bridge depending on support condition

Superstructure displacement demands obtained from nonlinear analysis results belong to the midpoint of the bridge deck. In Figure 4.32 and Figure 4.33, maximum displacement demand occurred in longitudinal and transverse direction of bridges are given. Also, Figure 4.34 shows the maximum resultant displacement that is calculated by taking maximum of the square root of sum of squares of these directions at each time step. The results are obtained for 7 earthquakes and 13 ground motion incidence angles varying from 0° to 180° with an increment of 15° as explained in previous sections. When results examined in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge which is shown with red line has an increasing trend between 0° and 105° although in transverse direction it has vice versa. Also, radar and bar charts present that superstructure displacement increases when SSI is

considered in the analytical model because, soil makes the bridge more flexible, and this causes an increase in the superstructure displacements. The maximum difference of average displacement demand in longitudinal direction between fix based and SSI bridge is occurred at 60° incidence angle as nearly 18%. In transverse direction, it is 36% at 105° incidence angle. If it is checked for resultant displacement, maximum difference becomes 28% at 60° incidence angle.





(a) Fixed

(b) SSI

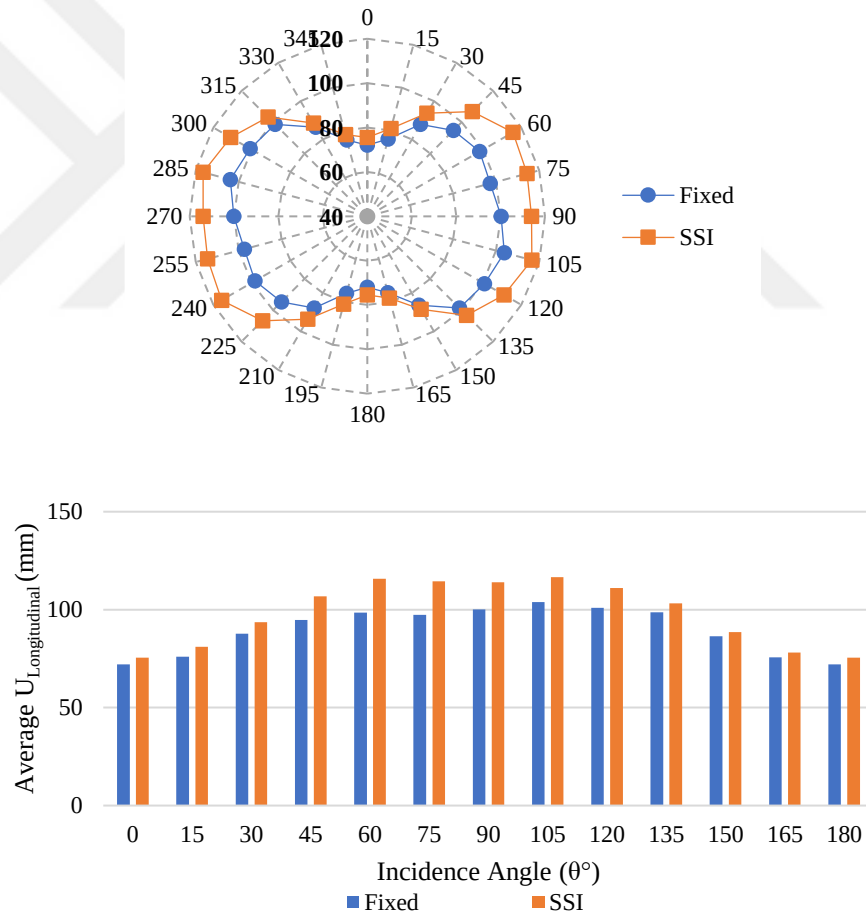


Figure 4.32. Maximum displacement demands occurred in longitudinal direction of bridge for different support conditions and earthquake incidence angles

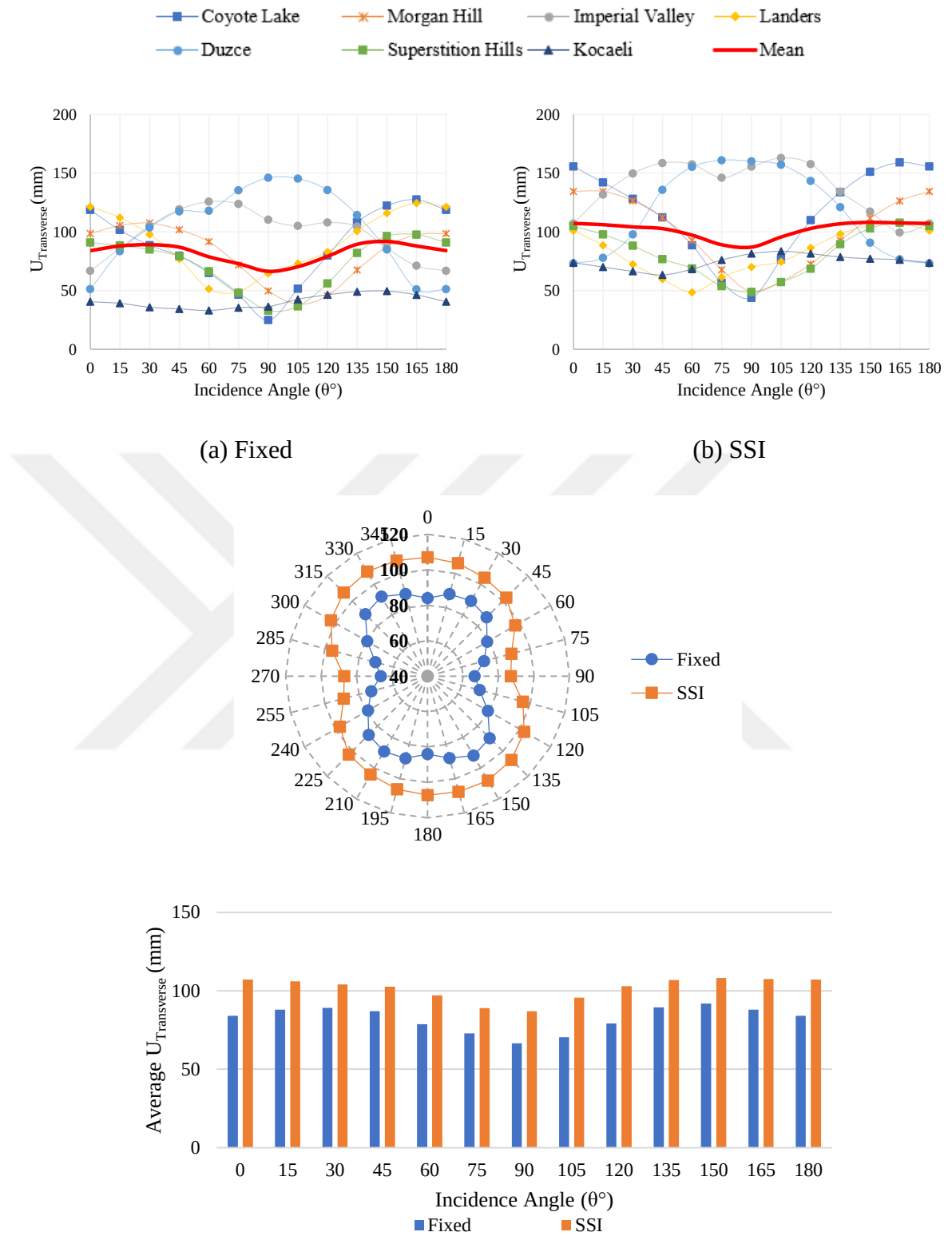


Figure 4.33. Maximum displacement demands occurred in transverse direction of bridge for different support conditions and earthquake incidence angles

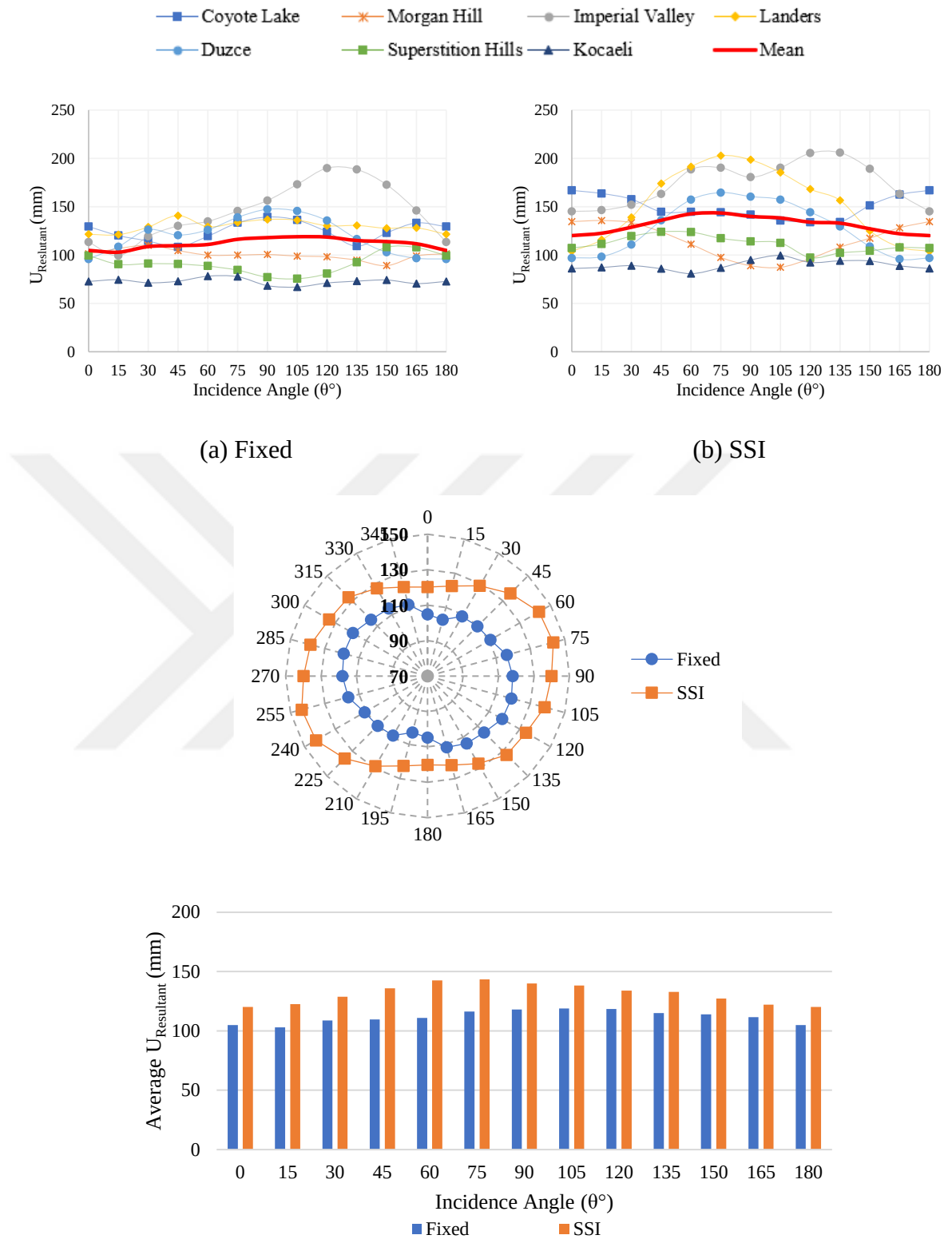
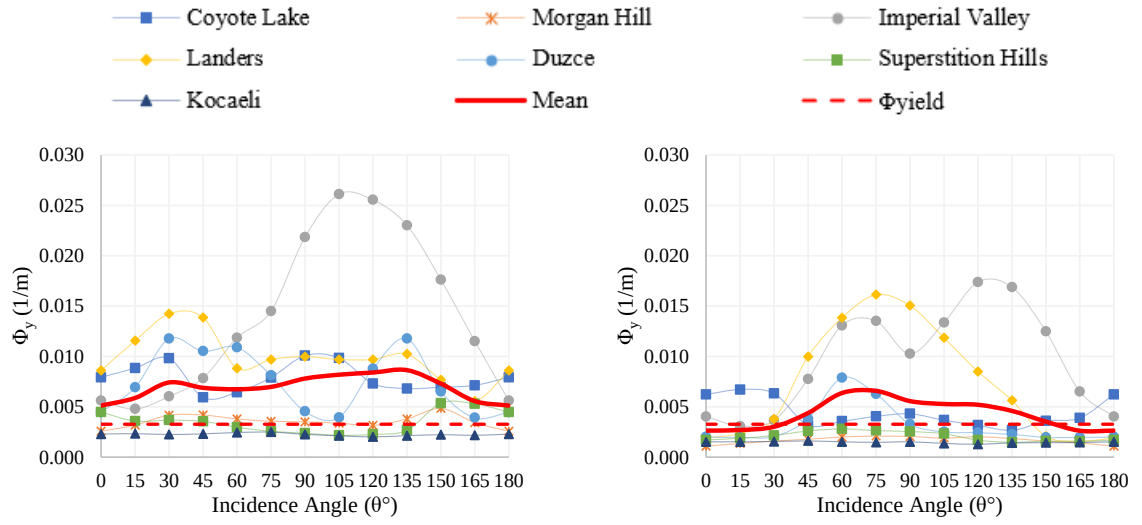


Figure 4.34. Maximum resultant displacement demands of bridge for different support conditions and earthquake incidence angles

4.3.2. Curvature demands of column pier

In Figure 4.35 and Figure 4.36, maximum curvature demands of the middle column of bridges in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. The average maximum column curvature demand in fixed base bridge is much more than in SSI bridge in both axes and most of the ground motion incidence angles according to the radar and bar charts. The reason of this, fixed based approach makes bridge column more rigid and this causes to increase in curvature. If bridge is modeled with soil structure interacted, soil relieves seismic demands imposed on the bridge column, and hence the seismic demands decrease. Also, average demands in both axes exceed yield curvature for all earthquake incidence angles in fixed based bridge. On the other hand, SSI bridge column curvature is below the yield curvature which means the column is in the elastic limit at some earthquake incidence angles. In the weak axis (y') of column, the average demands are nearly same at 60° and 75° incidence angles although the difference in demands reach their maximum values as nearly 59% at 30° incidence angle. The gap is more obvious and nearly 72% at 150° in the column strong axis (z').



(a) Fixed

(b) SSI

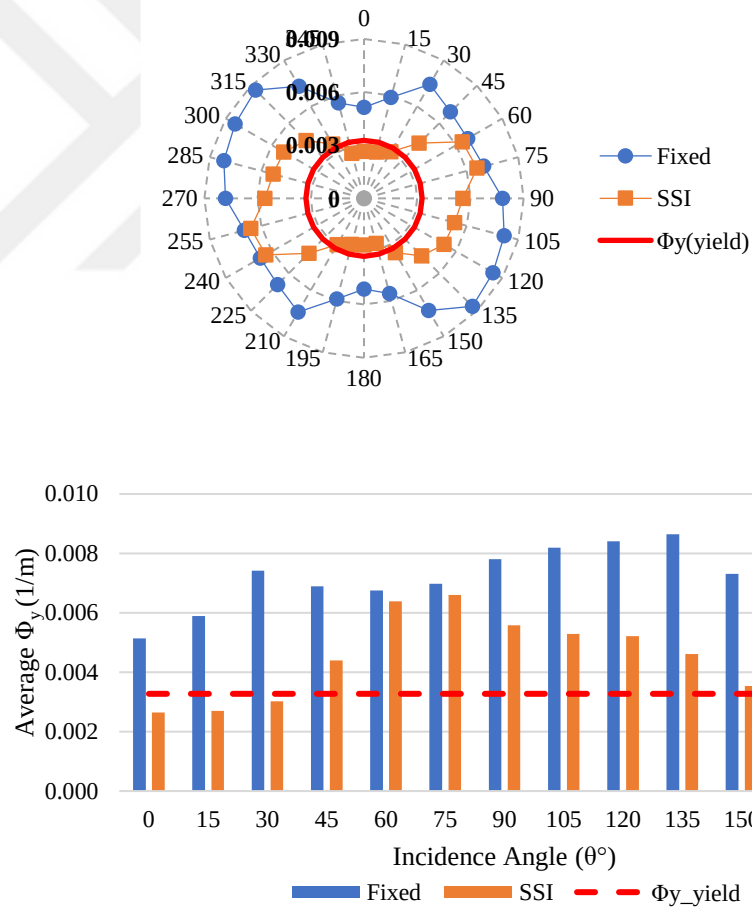
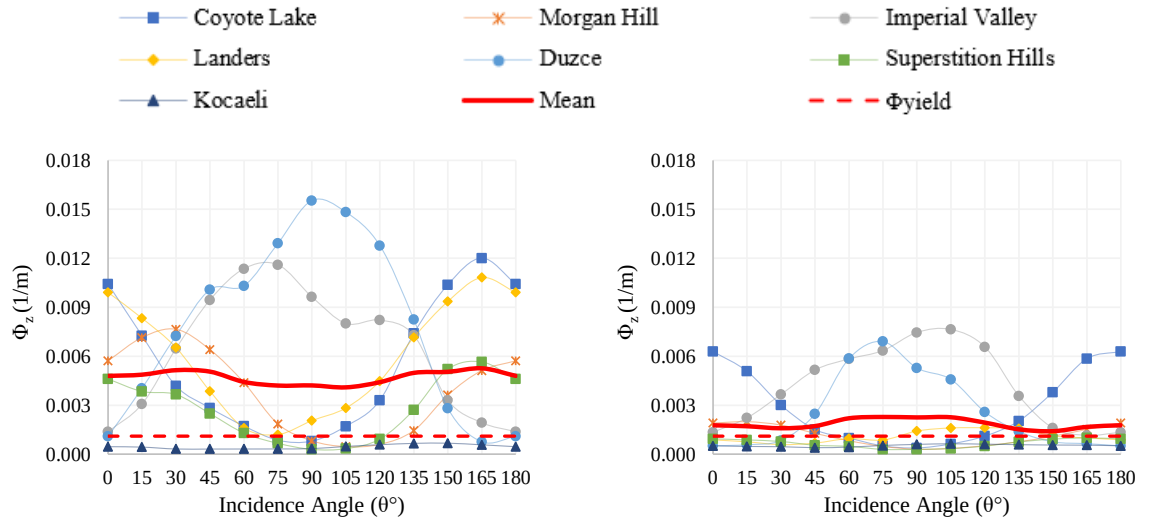


Figure 4.35. Maximum curvature demands of column weak axis (y') for different support conditions and earthquake incidence angles



(a) Fixed

(b) SSI

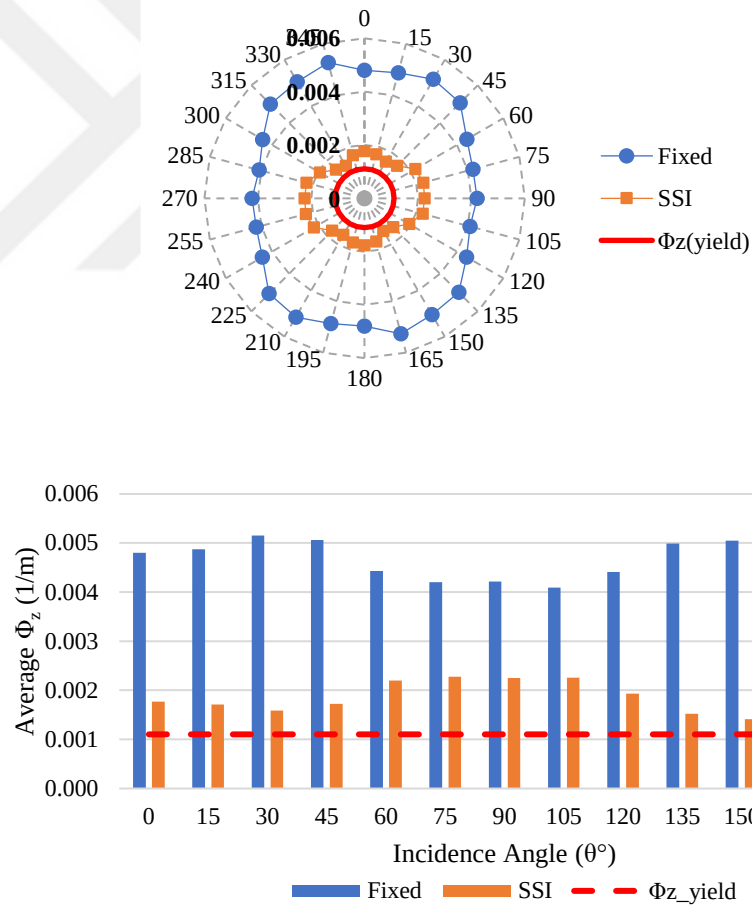
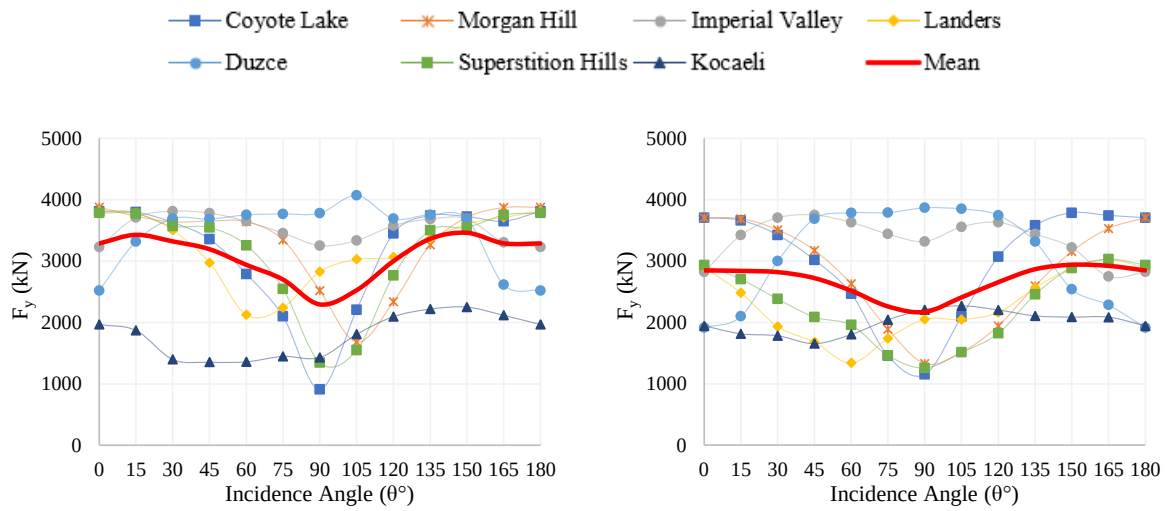


Figure 4.36. Maximum curvature demands of column strong axis (z') for different support conditions and earthquake incidence angles

4.3.3. Shear force demands of column pier

In Figure 4.37 and Figure 4.38, maximum shear force demands of the middle column of bridges in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. The average maximum shear force is shown with red line, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, it is shown that average maximum column shear demand in fixed base bridge is more than in SSI bridge in both axes, but the difference is not as much as in the curvature demands. The maximum difference in local y' axis of fixed and SSI bridge columns occurs at 15° incidence angle and nearly as 17%. Also, it is about 16% at 0° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the maximum average shear force demands are compared to these capacities, it is seen that demands are below the limits for both fixed and SSI models. Therefore, it can be said no shear damage occurred in the bridge column during earthquakes.



(a) Fixed

(b) SSI

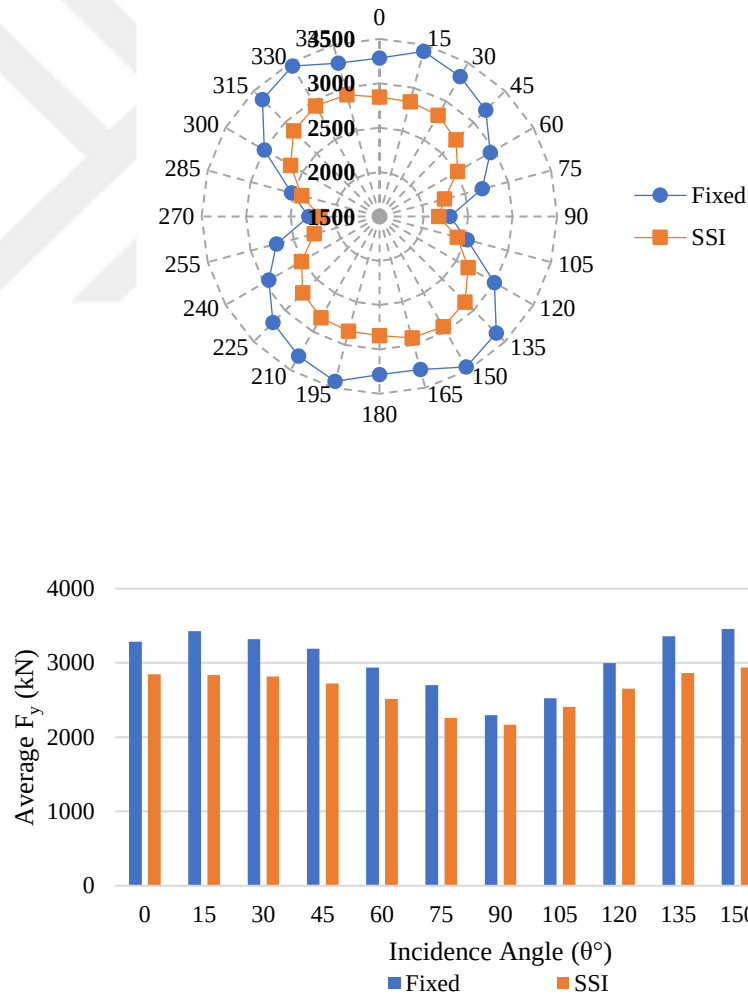


Figure 4.37. Maximum shear force demands of column local y' axis for different support conditions and earthquake incidence angles

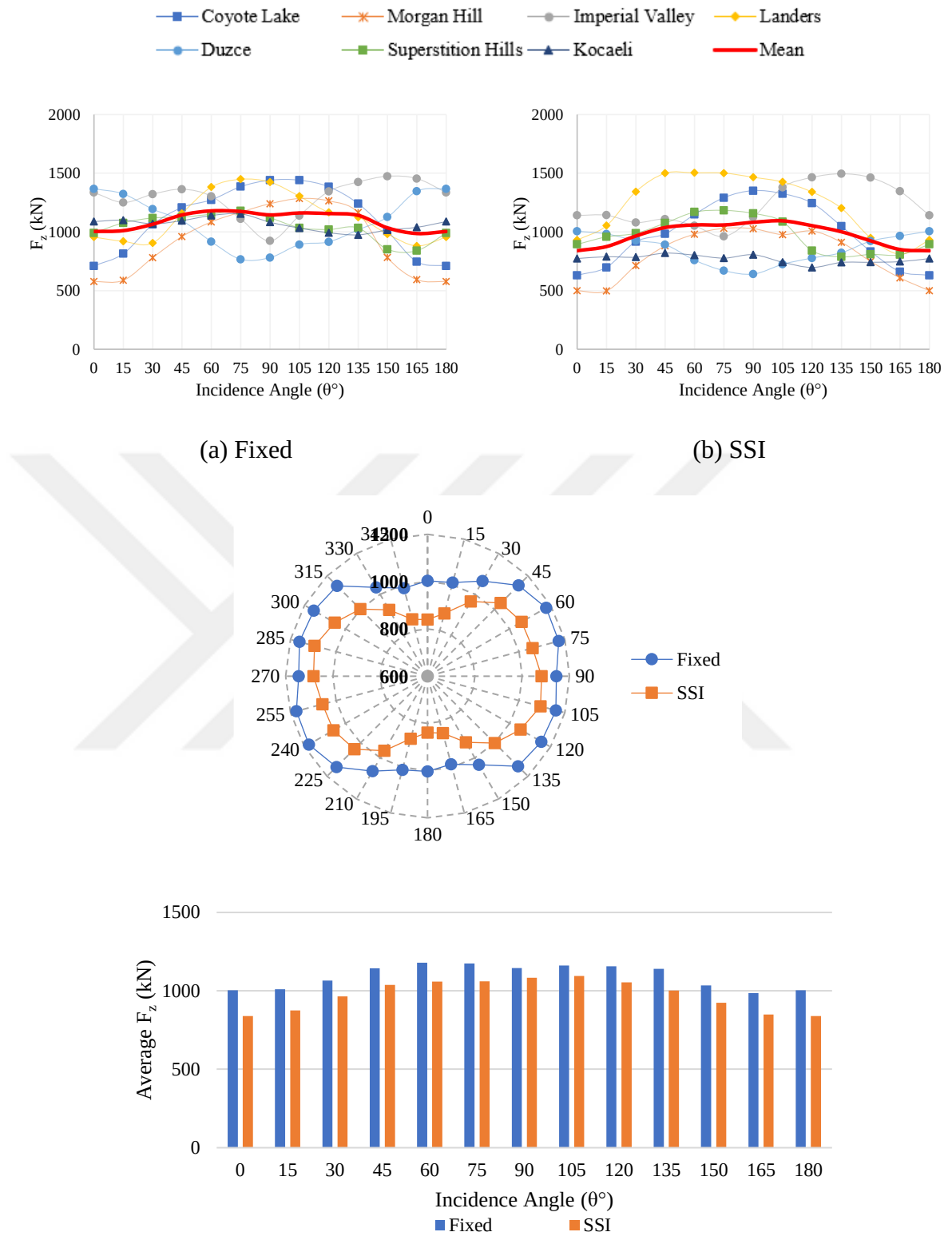


Figure 4.38. Maximum shear force demands of column local z' axis for different support conditions and earthquake incidence angles

5. SCOUR EFFECT

The combined effect of flood induced scour and earthquakes on existing highway bridges is one of the most critical issues for the safety of transportation network. To investigate safety of bridges under the multi hazard effects, analytical models of the non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are created in the OpenSees program and nonlinear response history analyses are performed for 7 strong ground motions. Analyses are done for two different scour cases, uniform scour (Case-1) and non-uniform scour (Case-2) and earthquake incidence angle is changed for each ground motion and scour cases. The engineering demand parameters (EDPs) examined within the scope of the study are superstructure displacement, bent column curvature and shear force and pile shear. In addition, residual displacement demand of bridge superstructure and column which is an important parameter for the assessment of bridge after earthquake is evaluated in this section of the thesis. The EDPs are peak values for the investigated analysis results and they will be mentioned as maximum demands in the following sections. The comparison of analysis results is given in detail in the sub-headings.

5.1. Uniform Scour (Case 1)

The scour phenomenon occurred in bridge column piers or pile elements has been examined by many researchers, and the performances of such bridges during earthquakes have constituted an important field of study. In the studies carried out, the scour depth is increased uniformly around all piles and the change in the seismic demands of the bridge elements depending on the scour depth is examined. In this part of the thesis, the changes in various demand parameters depending on the uniform change in the scour depth are examined by using non-skewed ($\alpha=0^\circ$) and 45° skewed bridge models. The depth of scour around the pile elements is changed starting from 0 m up to 5 m with 1 m increment.

As seen in Figure 5.1, the 1st and 2nd vibration periods of the bridge increase when scour depth increases. This is because, the clear height of the bent piles increases when the soil around piles is removed. This situation increases the flexibility of the bridge and so do the periods. While the 1st period values of 45° skewed bridge model are higher than the non-skewed bridge, the 2nd period values are less. This is due to the fact that the stiffness in longitudinal direction of the bridge decreases with increase of the skew angle, while it increases in the transverse direction of the bridge.

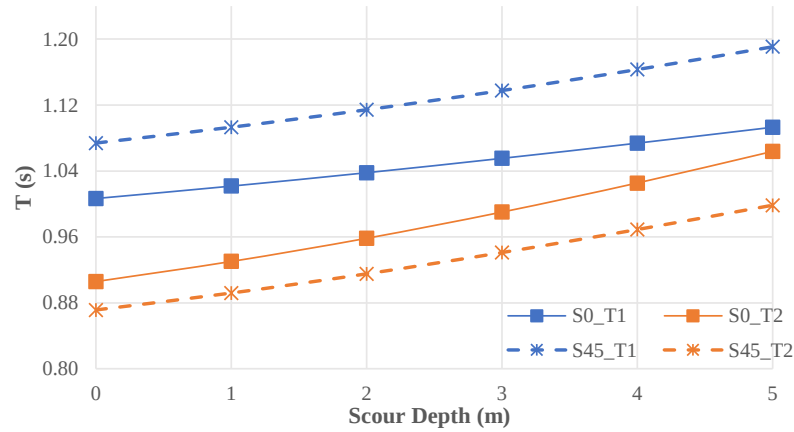


Figure 5.1. The variation of 1st and 2nd vibration period of non-skewed ($\alpha=0^\circ$) and 45° skewed bridge depending on uniform scour depth

5.1.1. Superstructure displacement

Consideration of uniform scour depth change is a practical way while modeling soil structure interaction in bridges. For each scour depth, nonlinear springs were removed from the pile nodes therefore, the scoured bridge models were obtained easily. In this section of the thesis, scour depth was changed from 0 m (no scour) to 5 m with an increment of 1 m for all the piles uniformly and soil properties were recalculated for each depth in non-skewed ($\alpha=0^\circ$) and 45° skewed bridges.

Superstructure displacement demands obtained from nonlinear analysis results belong to the midpoint displacement of the bridge deck. In Figure 5.2 and Figure 5.3, maximum displacement demands in longitudinal and transverse direction of the non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.4 shows maximum resultant displacement that is calculated by taking the maximum of square root of the sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained in previous sections. When the results examined in terms of the change of the earthquake incidence angle, the average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 75° although in transverse direction it is decreasing between 0° and 90° . Therefore, the resultant displacement is not much affected from the change of scour depth. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_u) increases uniformly around piles. Because as the depth of scour increases, the effective height of the bridge pier increases, which causes more

superstructure displacement. The maximum difference of average displacement demands in longitudinal direction between no scoured ($H_u=0\text{m}$) and 5 m scoured ($H_u=5\text{m}$) bridge is occurred at 75° incidence angle as nearly 12.4%. In transverse direction, it is at 165° as 18.1%. If it is checked for resultant displacement, maximum difference becomes 13% at 0° incidence angle.

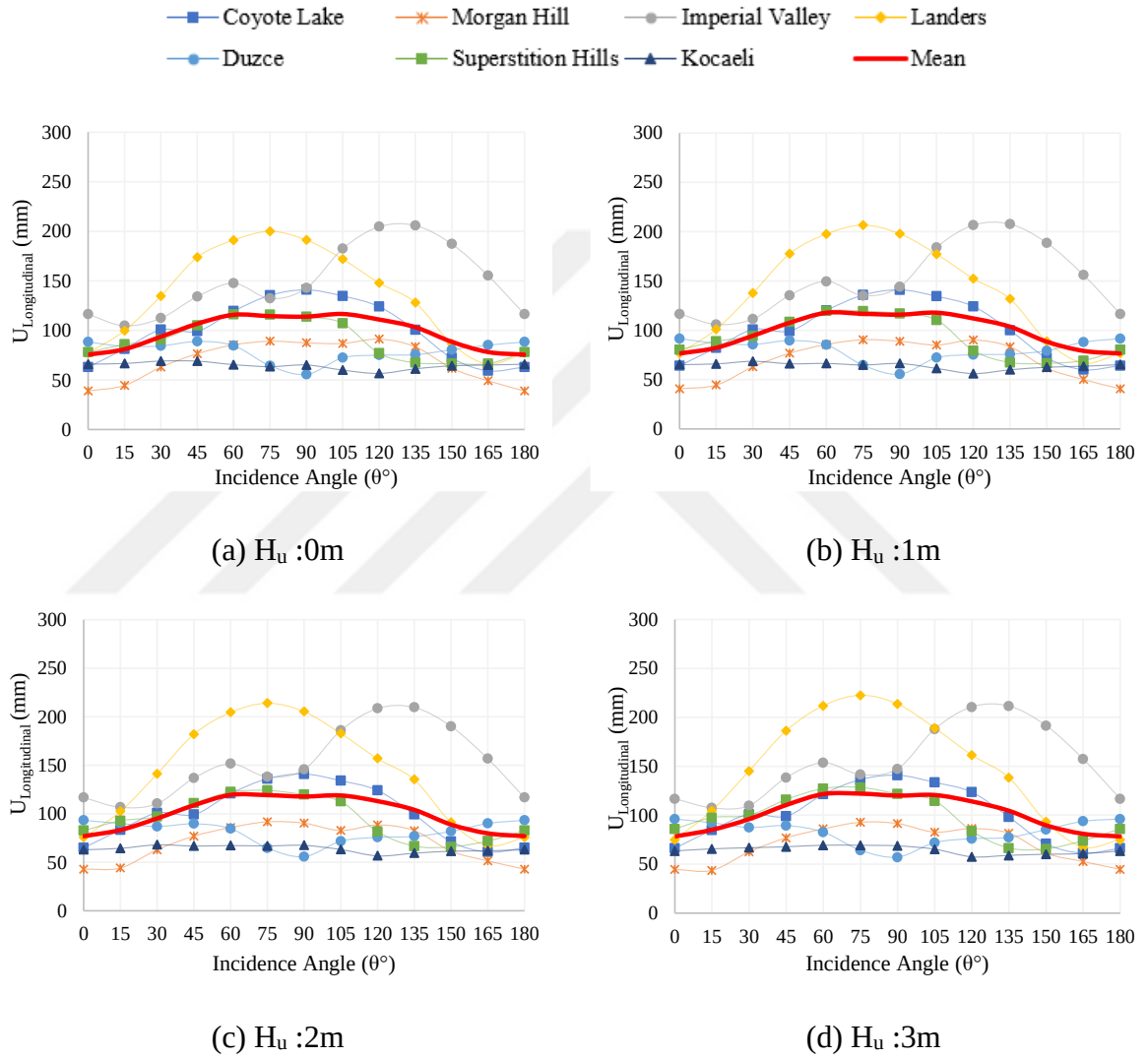
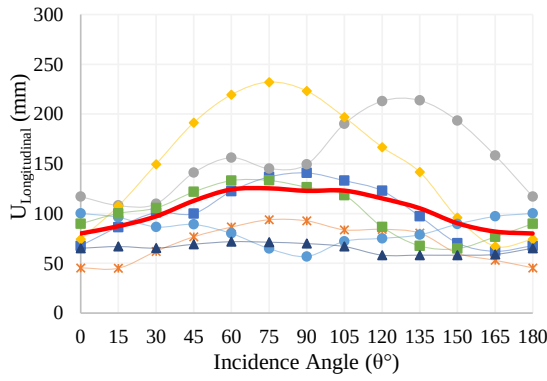
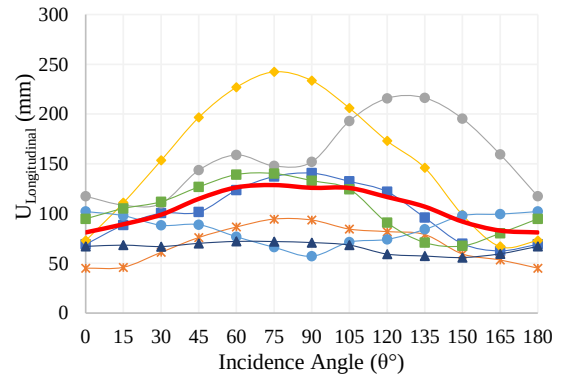


Figure 5.2. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles



(e) $H_u : 4m$



(f) $H_u : 5m$

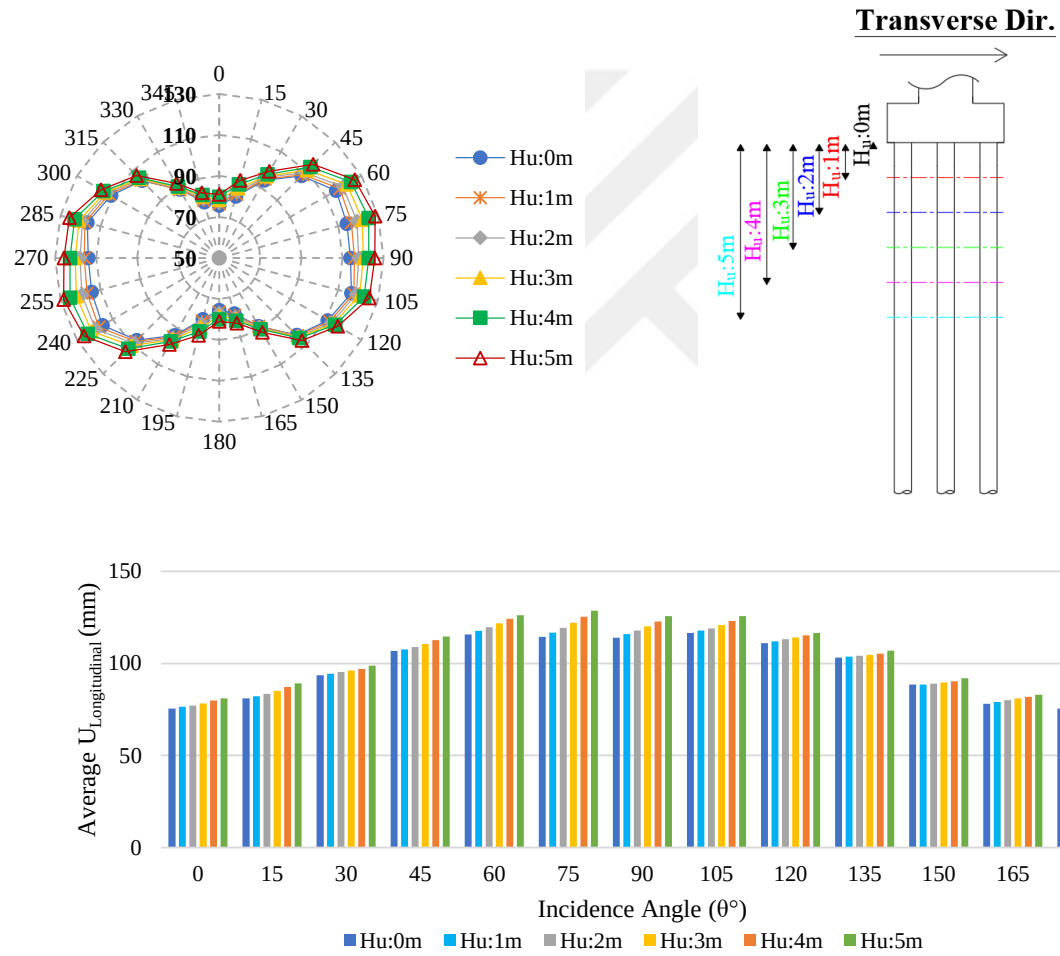


Figure 5.2. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles (continued)

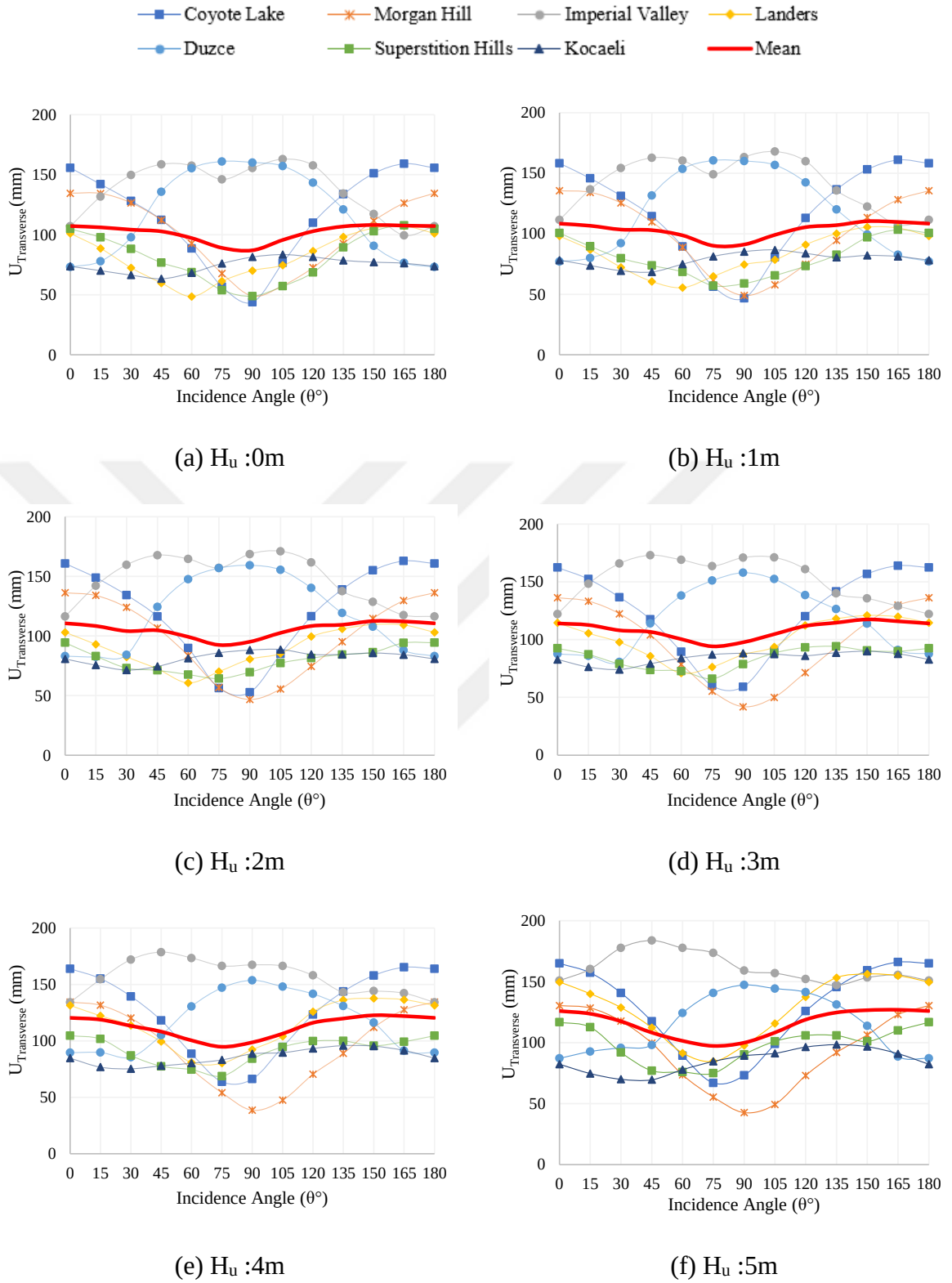


Figure 5.3. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles

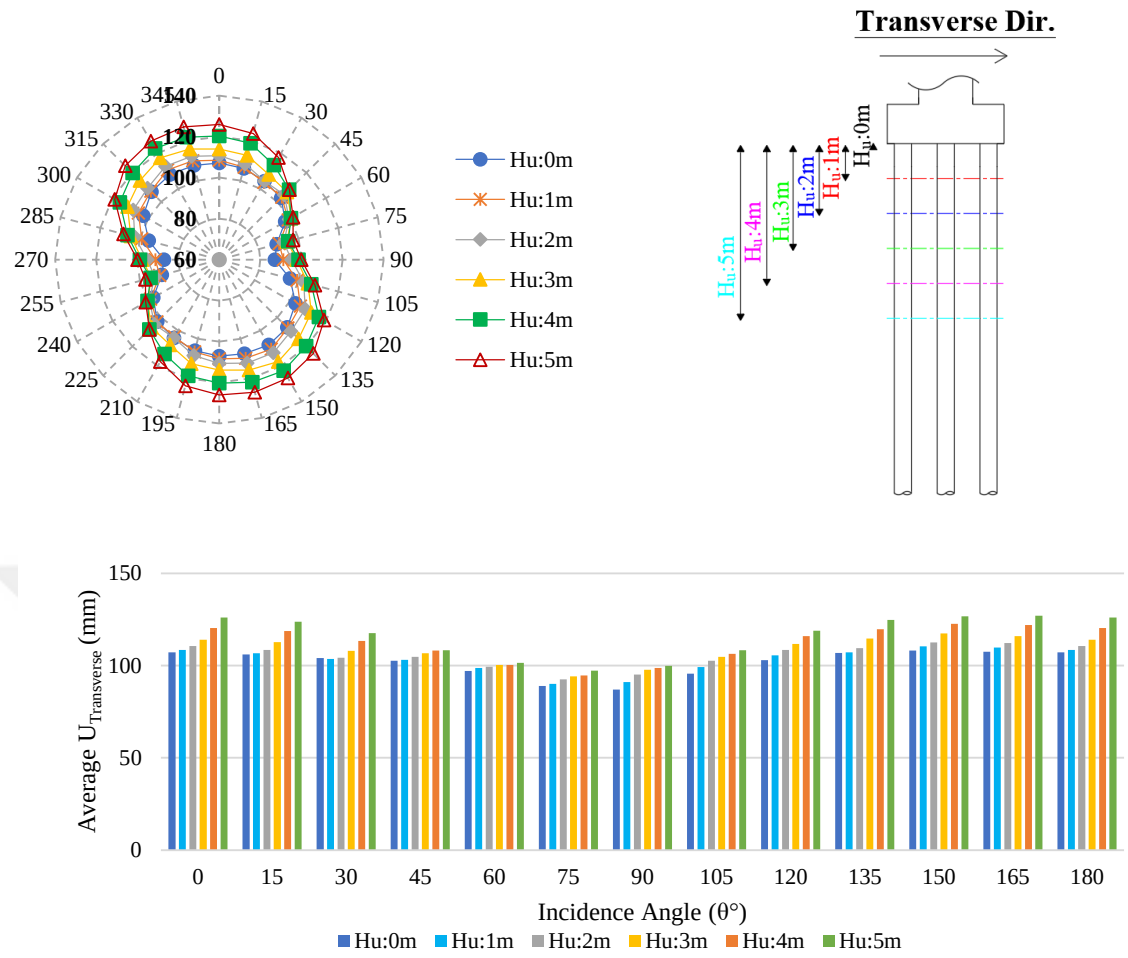


Figure 5.3. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles (continued)

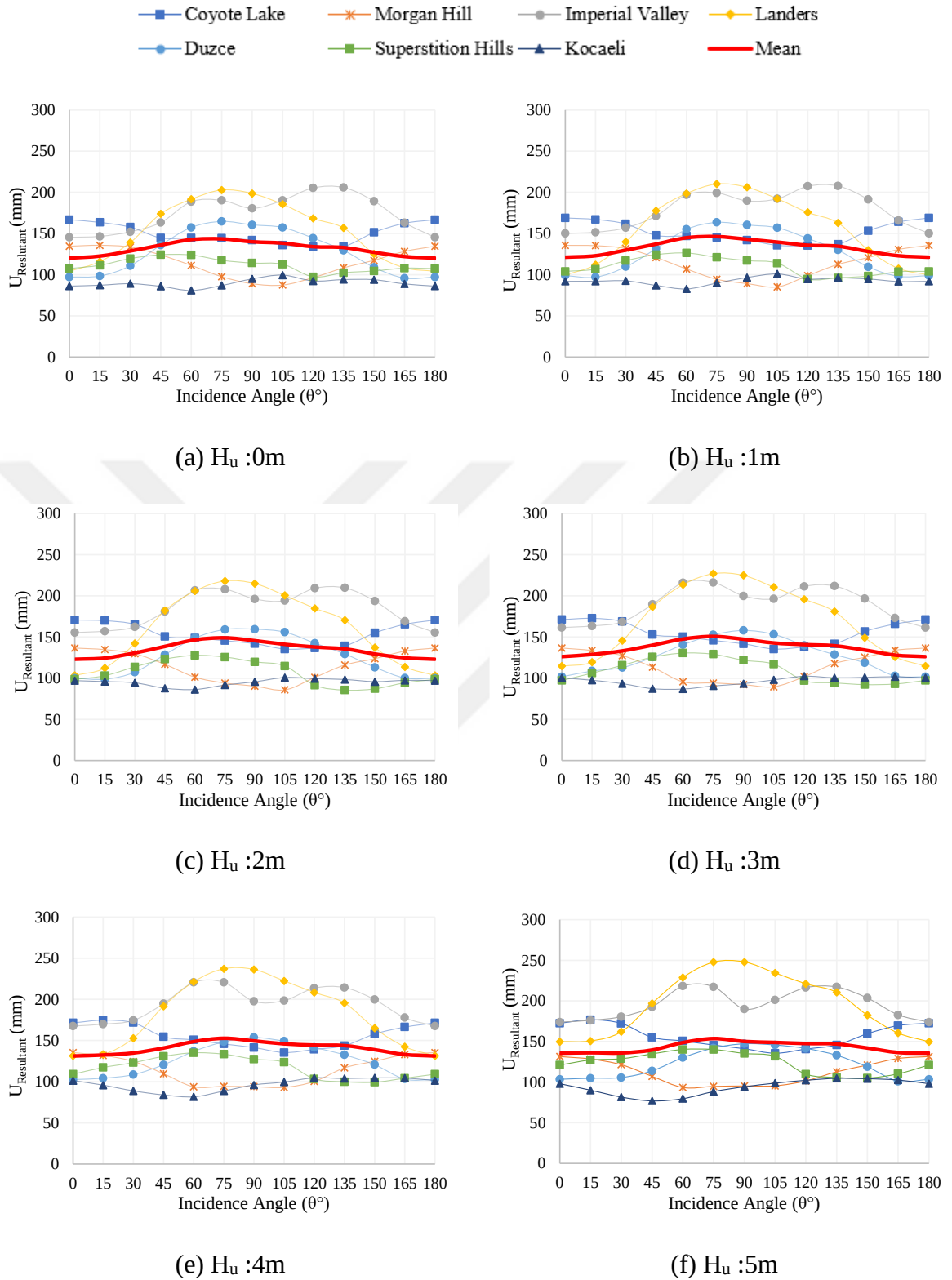


Figure 5.4. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles

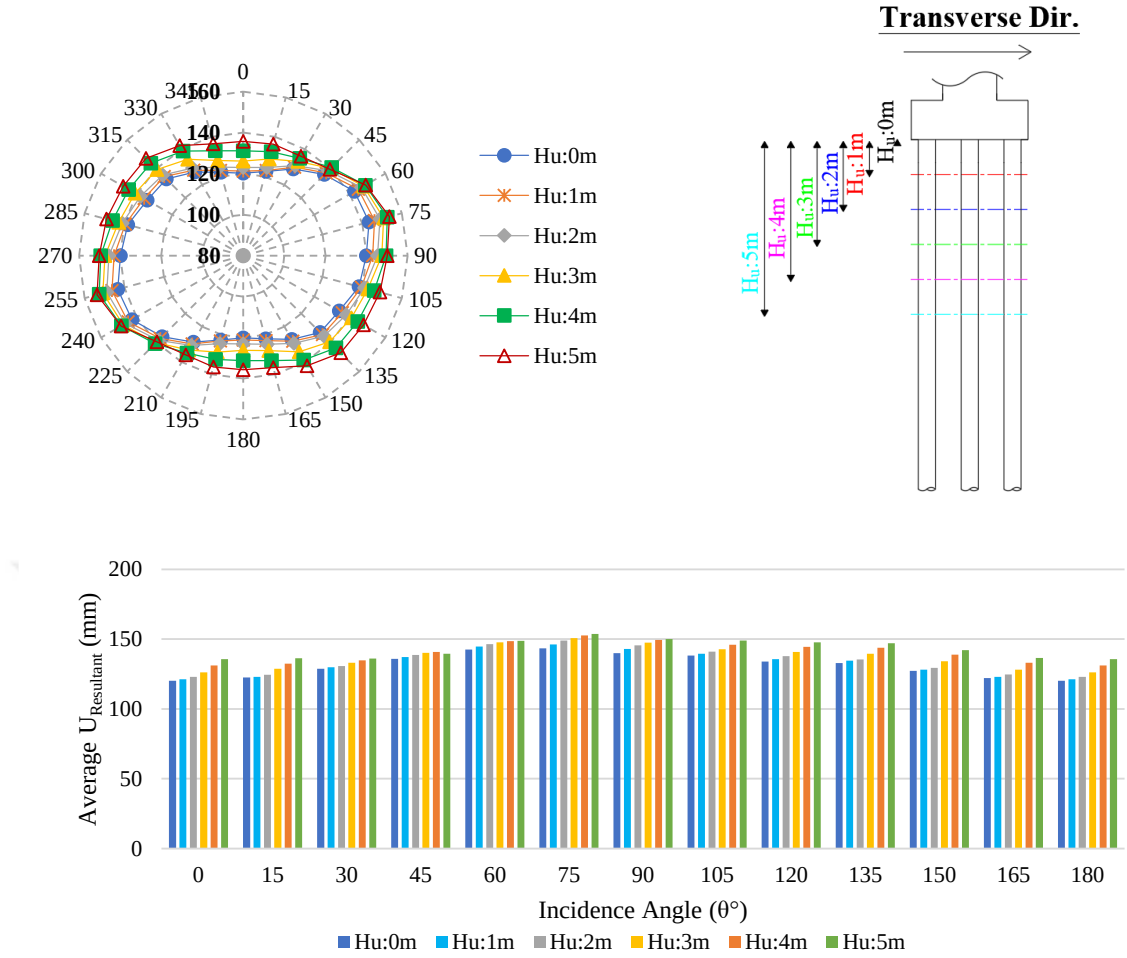


Figure 5.4. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.5 and Figure 5.6, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge are given. Also, Figure 5.7 shows maximum resultant displacement that is calculated by taking maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When we examine the results in terms of the change of the earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° and in transverse direction it is increasing between 90° and 135° . Therefore, the resultant displacement is also increasing between 90° and 135° incidence angles. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_u) increase uniformly around piles. The

maximum difference of average displacement demands in longitudinal direction between no scoured ($H_u=0m$) and 5 m scoured ($H_u=5m$) bridge is occurred at 45° incidence angle as nearly 8.1%. In transverse direction, it is at 15° as 17.6%. If it is checked for resultant displacement, maximum difference becomes 13.6% at 75° incidence angle.

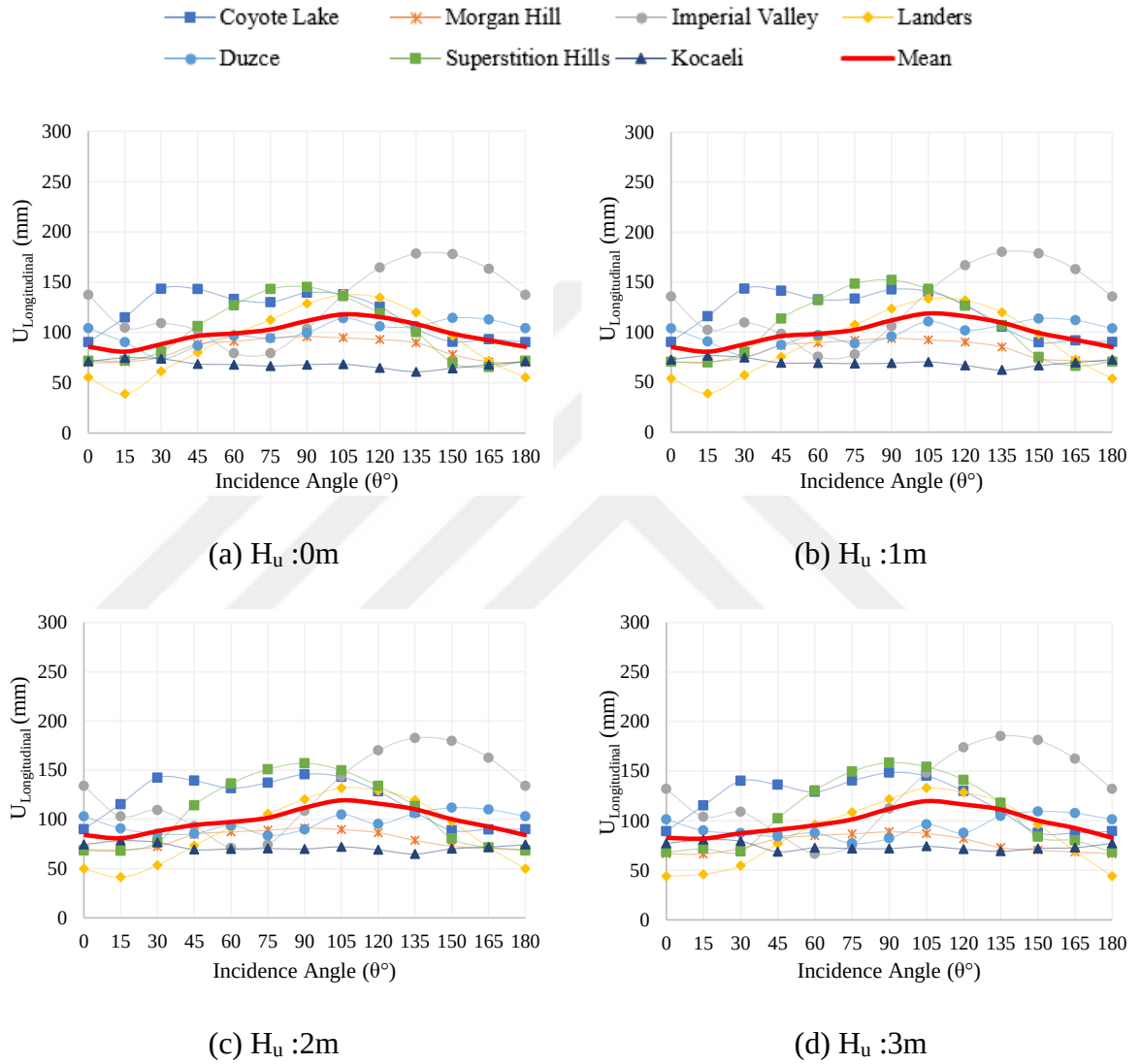
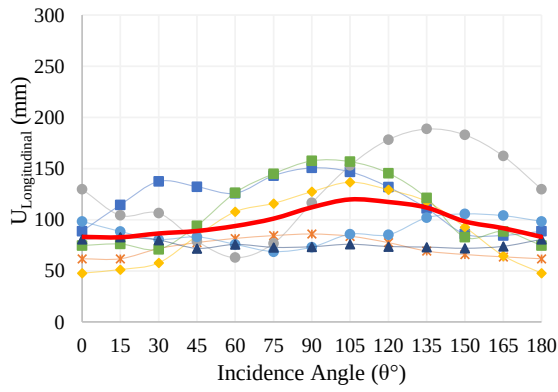
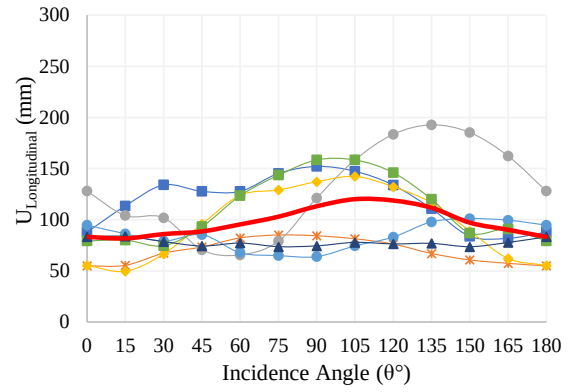


Figure 5.5. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different uniform scour depths and earthquake incidence angles



(e) $H_u : 4m$



(f) $H_u : 5m$

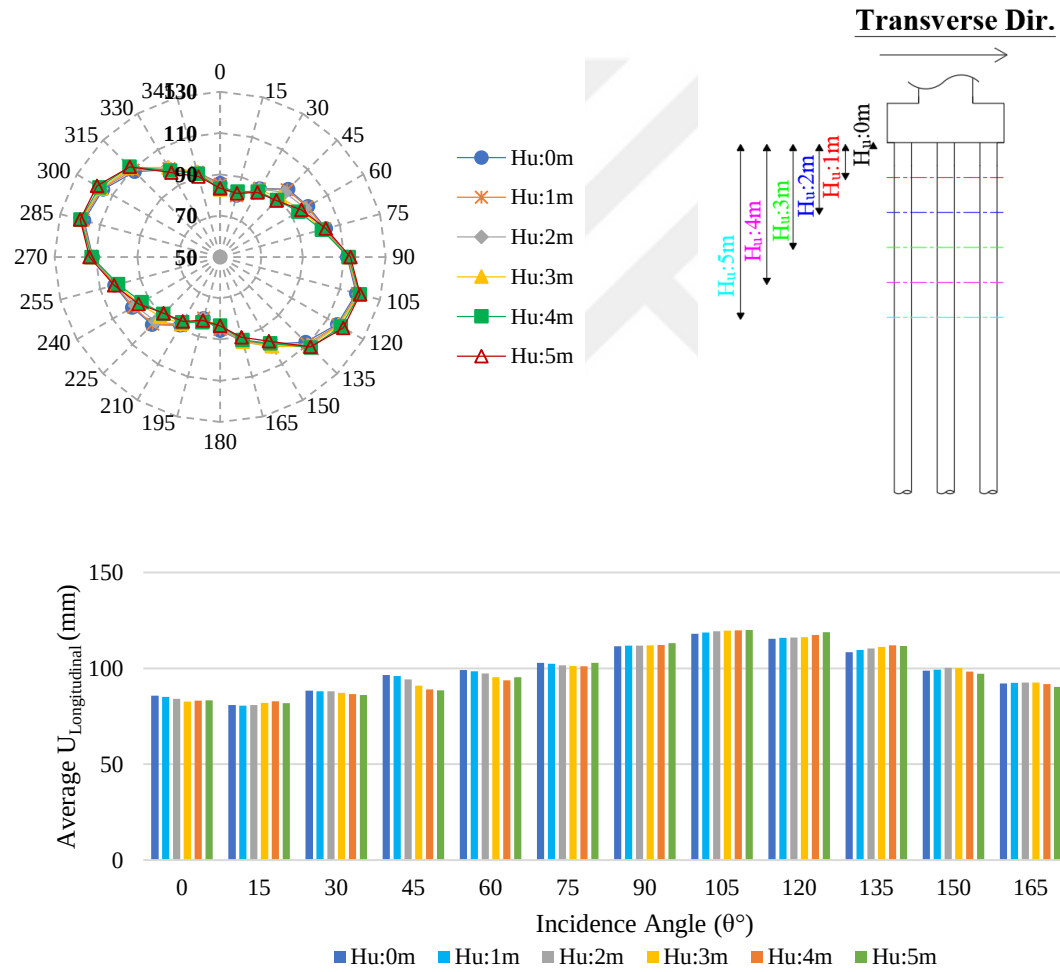


Figure 5.5. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different uniform scour depths and earthquake incidence angles (continued)

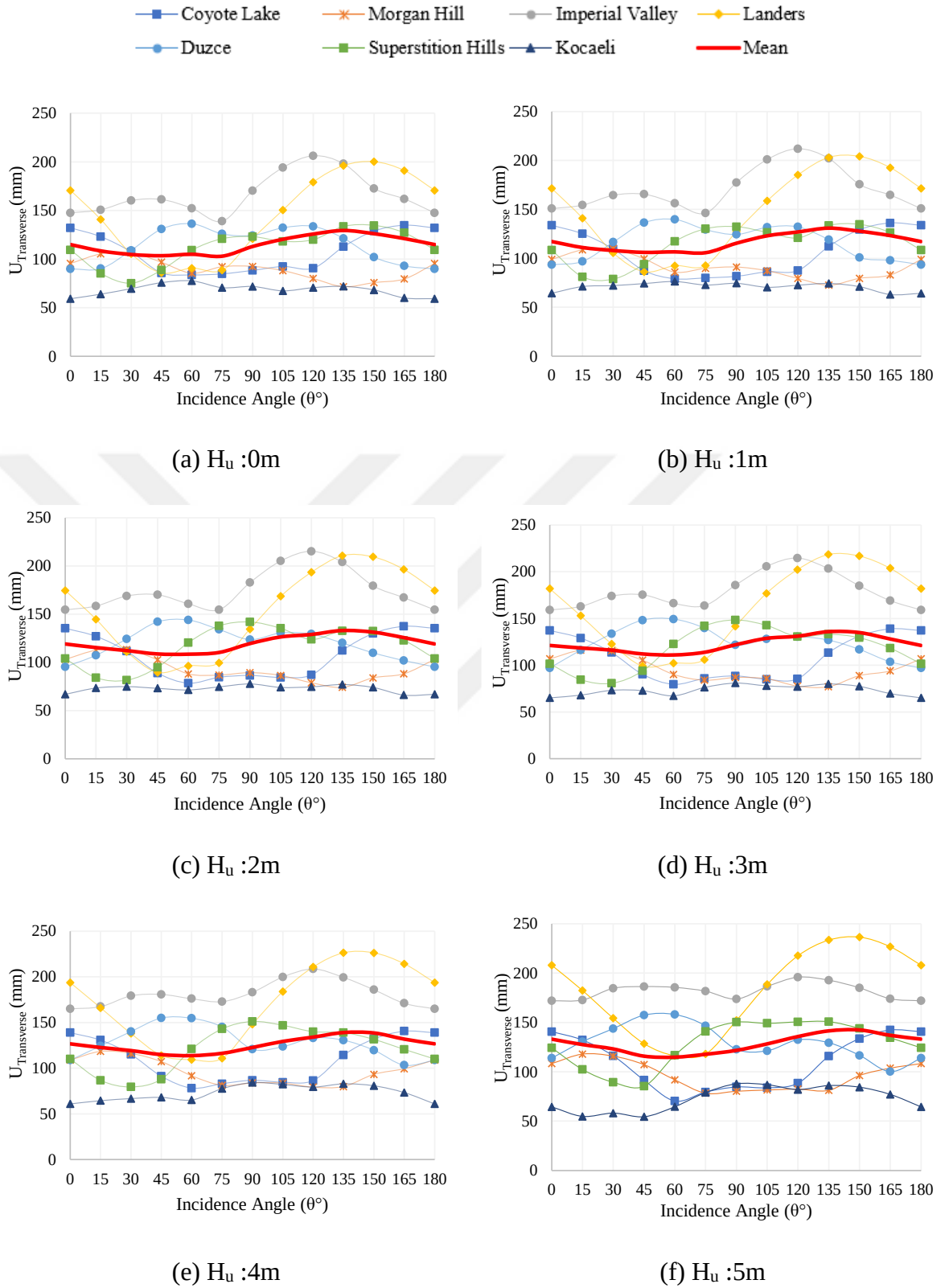


Figure 5.6. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different uniform scour depths and earthquake incidence angles

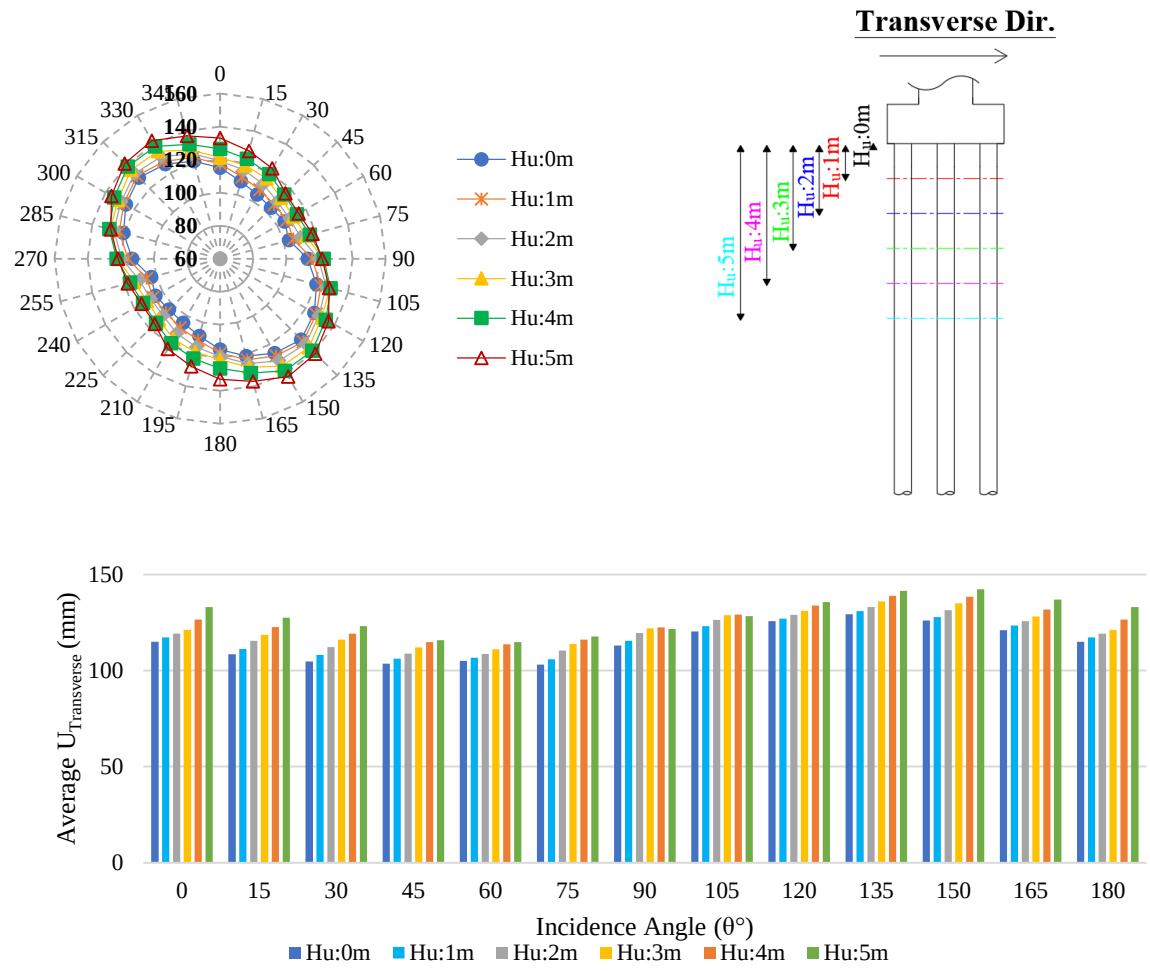


Figure 5.6. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different uniform scour depths and earthquake incidence angles (continued)

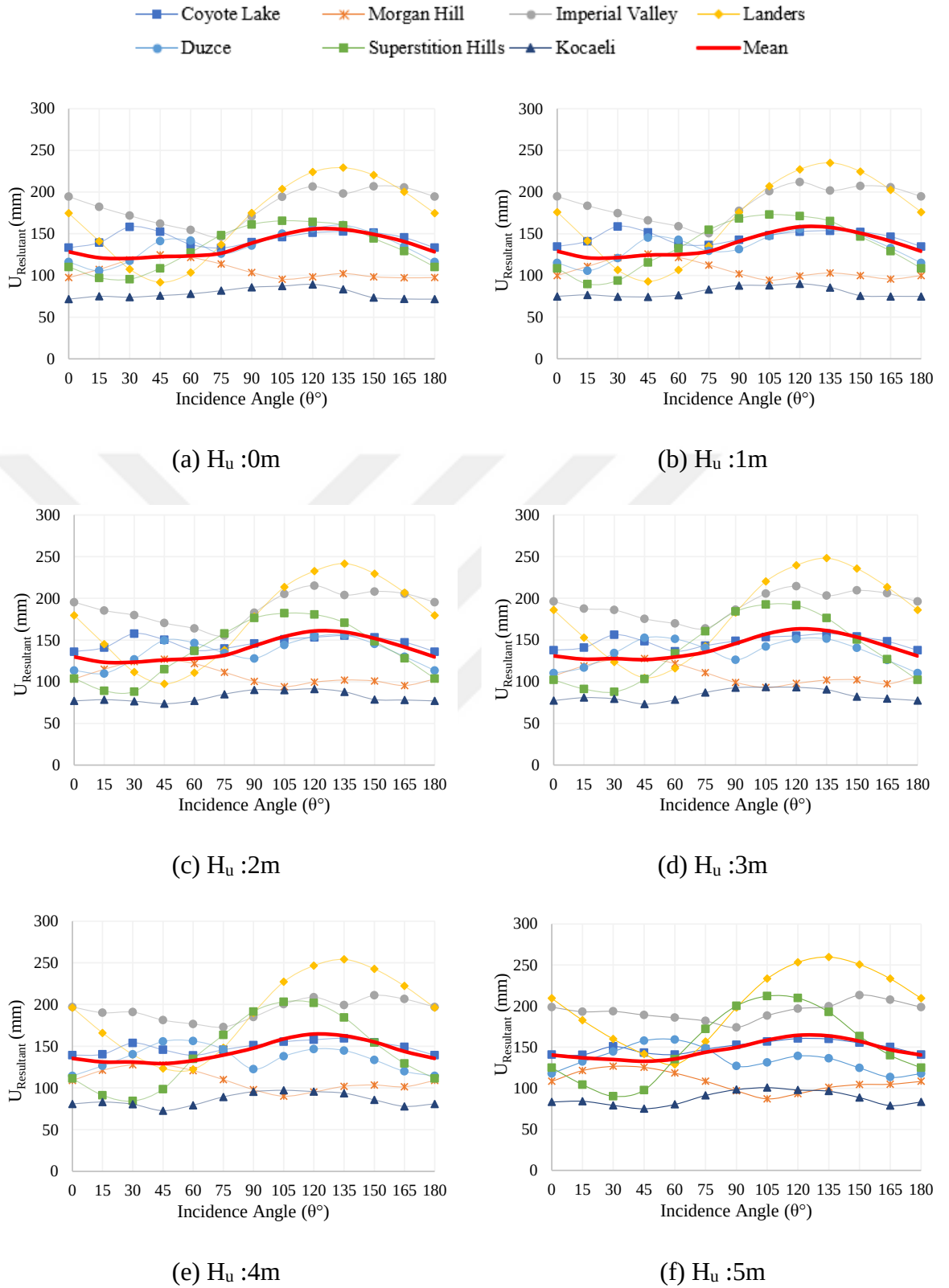


Figure 5.7. Maximum resultant displacement demands of 45° skewed bridge for different uniform scour depths and earthquake incidence angles

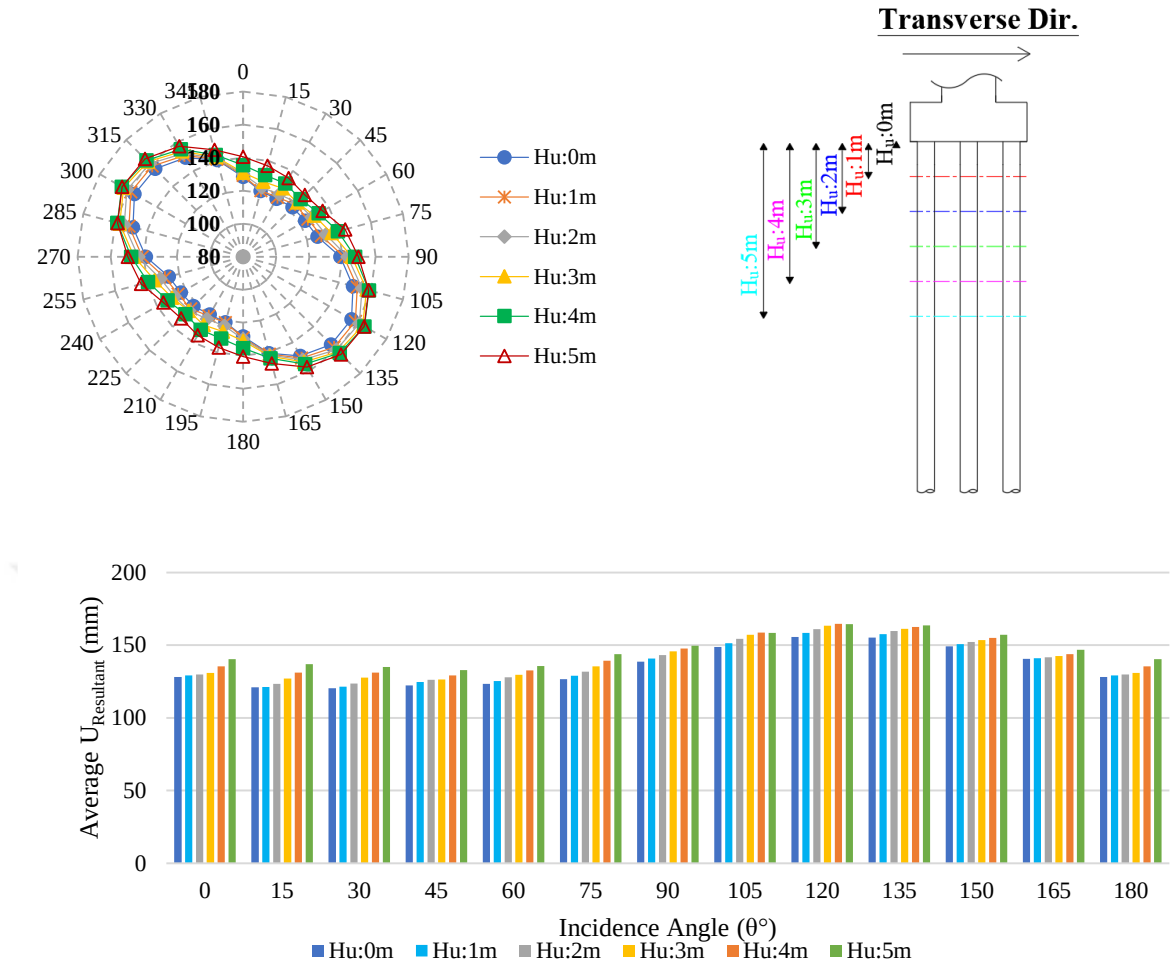


Figure 5.7. Maximum resultant displacement demands of 45° skewed bridge for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.8 and Figure 5.9, maximum average displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges and resultant displacements are compared. In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge. On the other hand, this situation is vice versa in transverse direction. For both skewed and non-skewed bridges, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 60° incidence angle and 5m scour depth as nearly 32%. In transverse direction, it is at 90° and 0m scour depth as 23%. If it is checked for resultant displacement, maximum difference becomes 15.6% at 60° incidence angle and 2m scour depth.

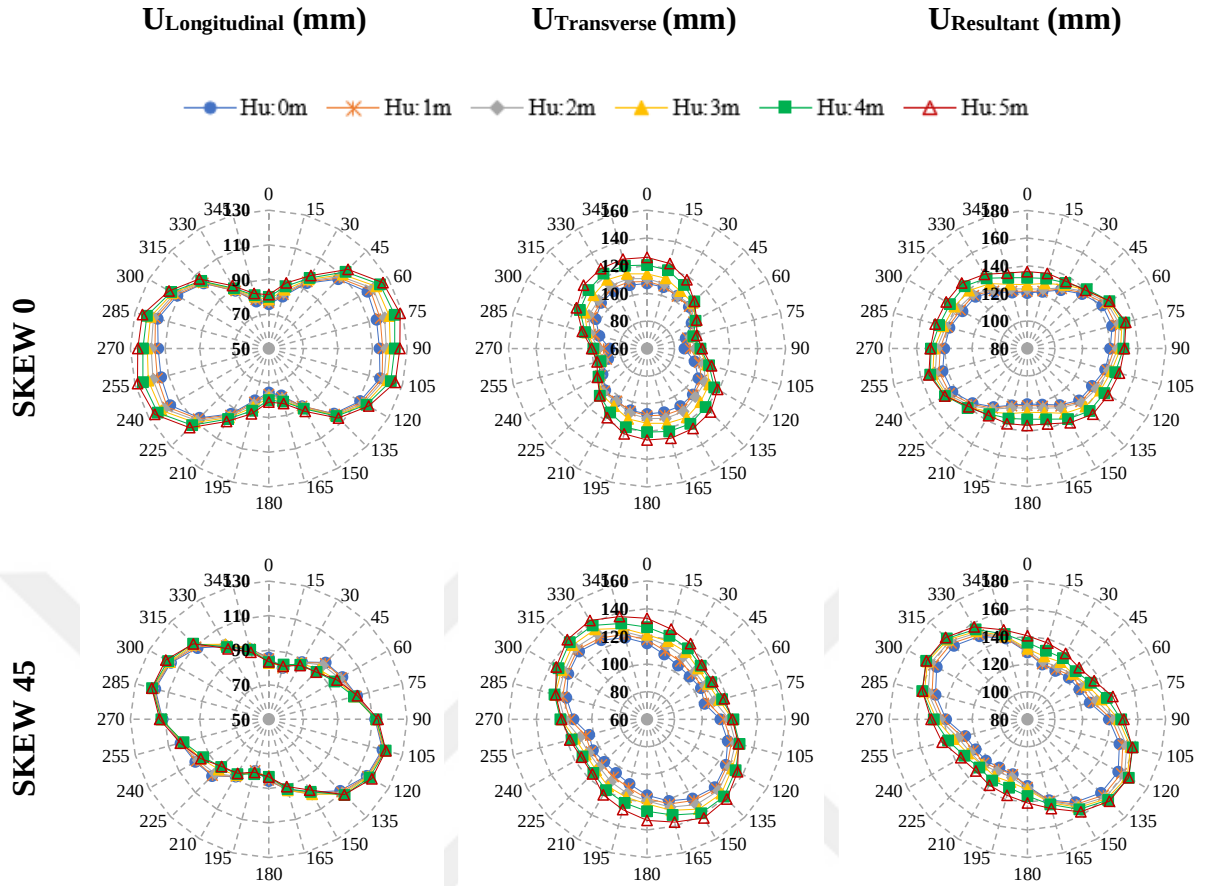


Figure 5.8. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different uniform scour depths and earthquake incidence angles

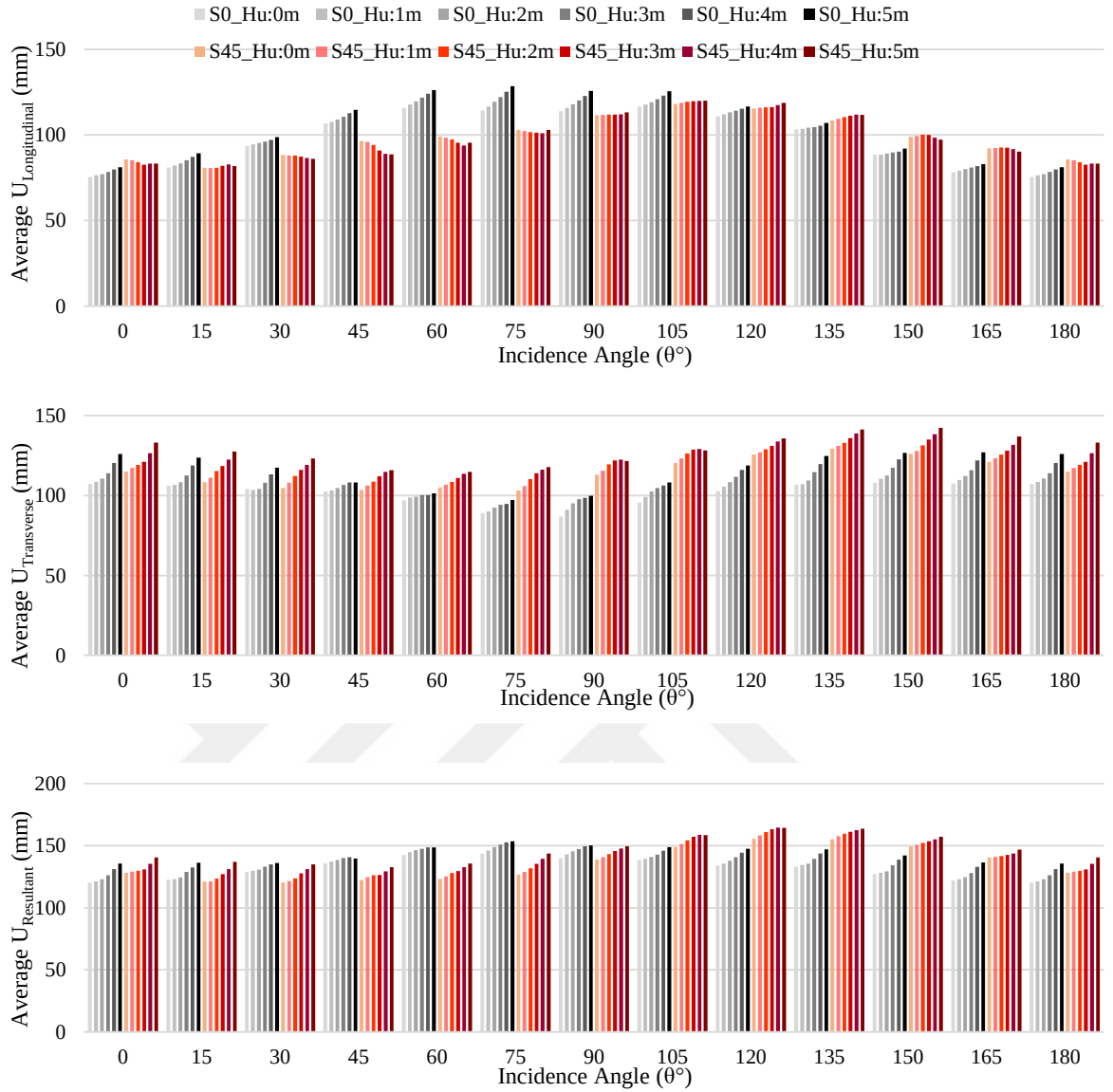


Figure 5.9. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different uniform scour depths and earthquake incidence angles

5.1.2. Curvature demands of column pier

In Figure 5.10 and Figure 5.11, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). Also, it is increasing between 0° and 105° in strong axis (z'). When the radar and bar chart are checked, they show that average maximum column curvature demand has a decreasing trend when uniform scour depth (H_u) increases in both

axes and for all ground motion incidence angles. The reason of such a behaviour is based on the fact that the bridge column becomes more flexible as the scour depth increases and this causes a reduction in curvature. Especially in strong axis (z'), the average maximum curvature demand of column is under the yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes 4 and 5 m. The maximum difference of curvature demands in weak axis (y') of column between no scoured ($H_u=0m$) and 5 m scoured ($H_u=5m$) bridge is 45.5%, which occurred at 0° incidence angle. Also, in strong axis (z'), the difference becomes 68.7% at 60° incidence angle. These results show that scour around piles has a positive contribution to curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

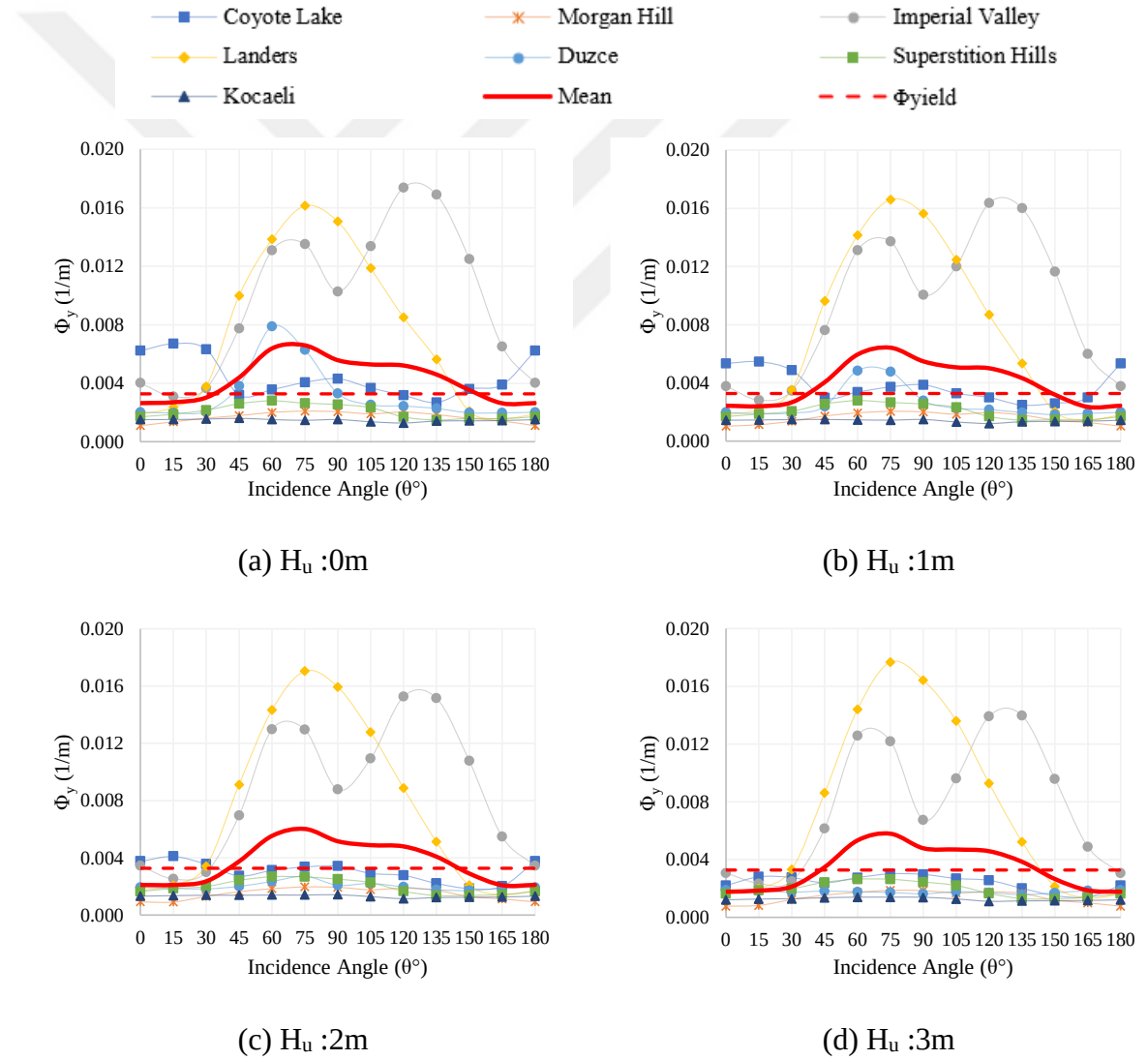
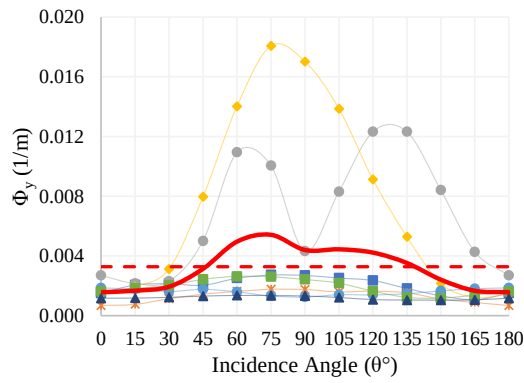
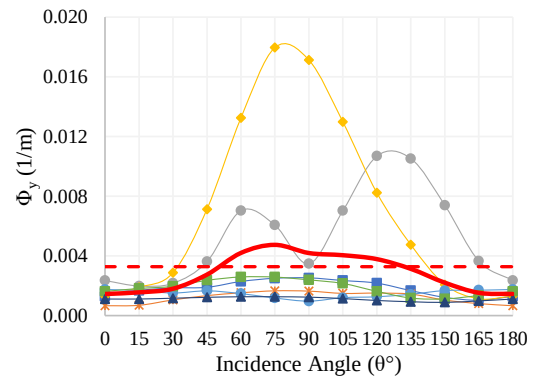


Figure 5.10. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles



(e) H_u :4m



(f) H_u :5m

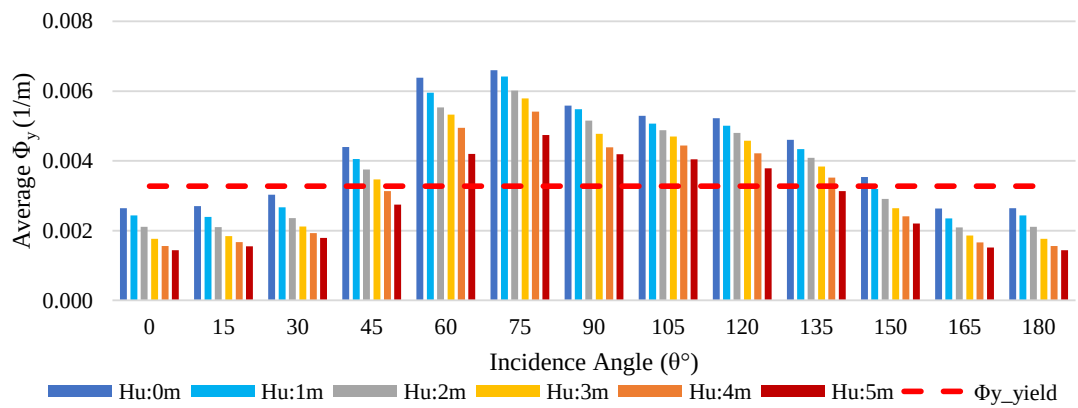
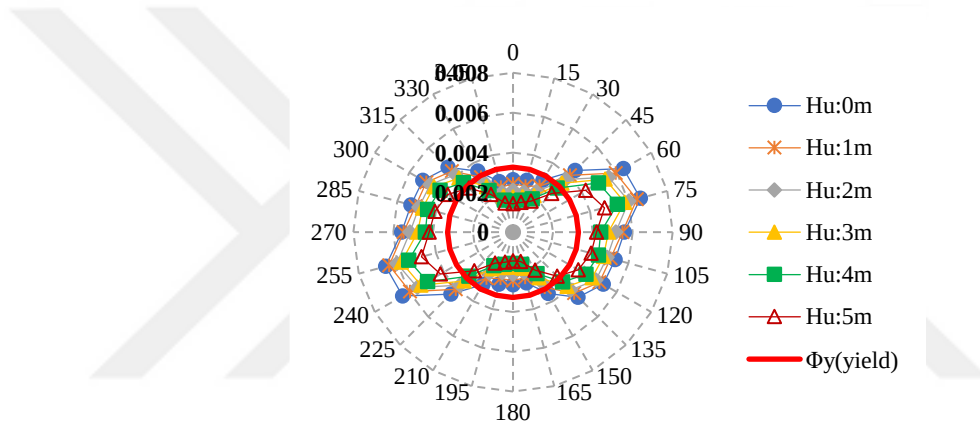


Figure 5.10. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles (continued)

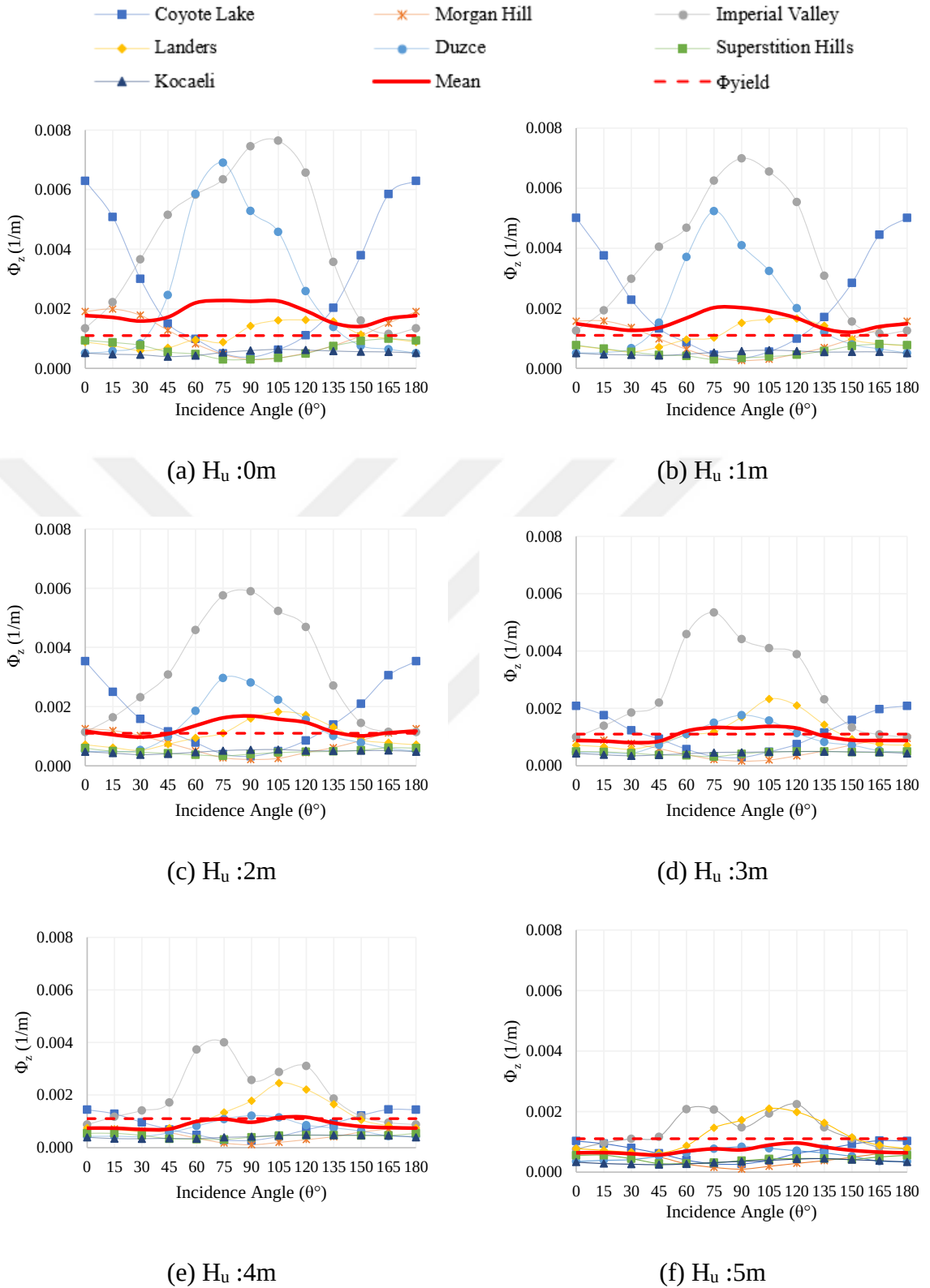


Figure 5.11. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles

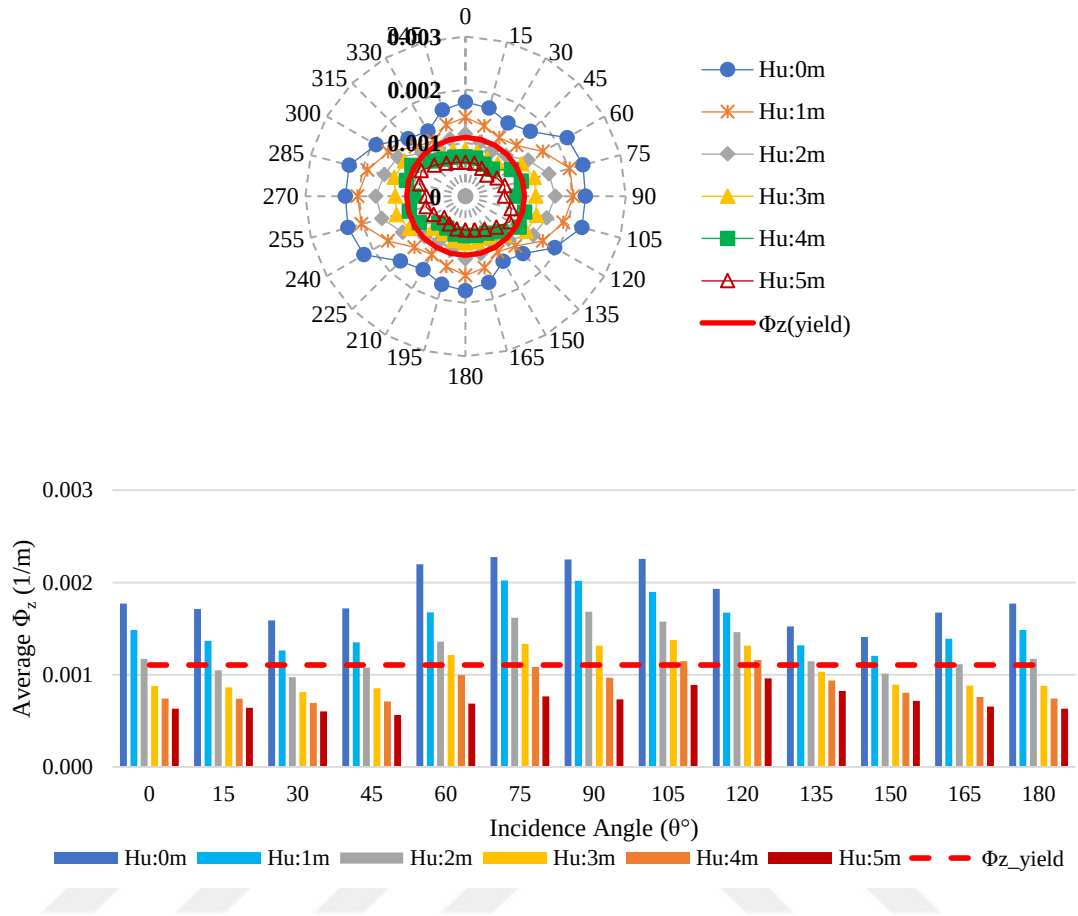


Figure 5.11. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.12 and Figure 5.13, the maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 150° in weak axis (y'). Also, it is increasing between 90° and 135° in strong axis (z'). When the radar and bar chart is checked, they show that average maximum column curvature demand has a decreasing trend when scour depth (H_u) increases in both axes and for all ground motion incidence angles. Especially in strong axis (z'), the average maximum curvature demand of column is under the yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes 5 m. The maximum difference of curvature demands in the weak axis (y') of column between no scoured ($H_u=0\text{m}$) and 5 m scoured ($H_u=5\text{m}$) bridge is occurred at 45° incidence angle as nearly 40.9%. Also, in strong axis

(z'), it becomes 51.9% at 120° incidence angle. These results show that scour around piles has a positive contribution to curvature demands of 45° skewed bridge column piers.

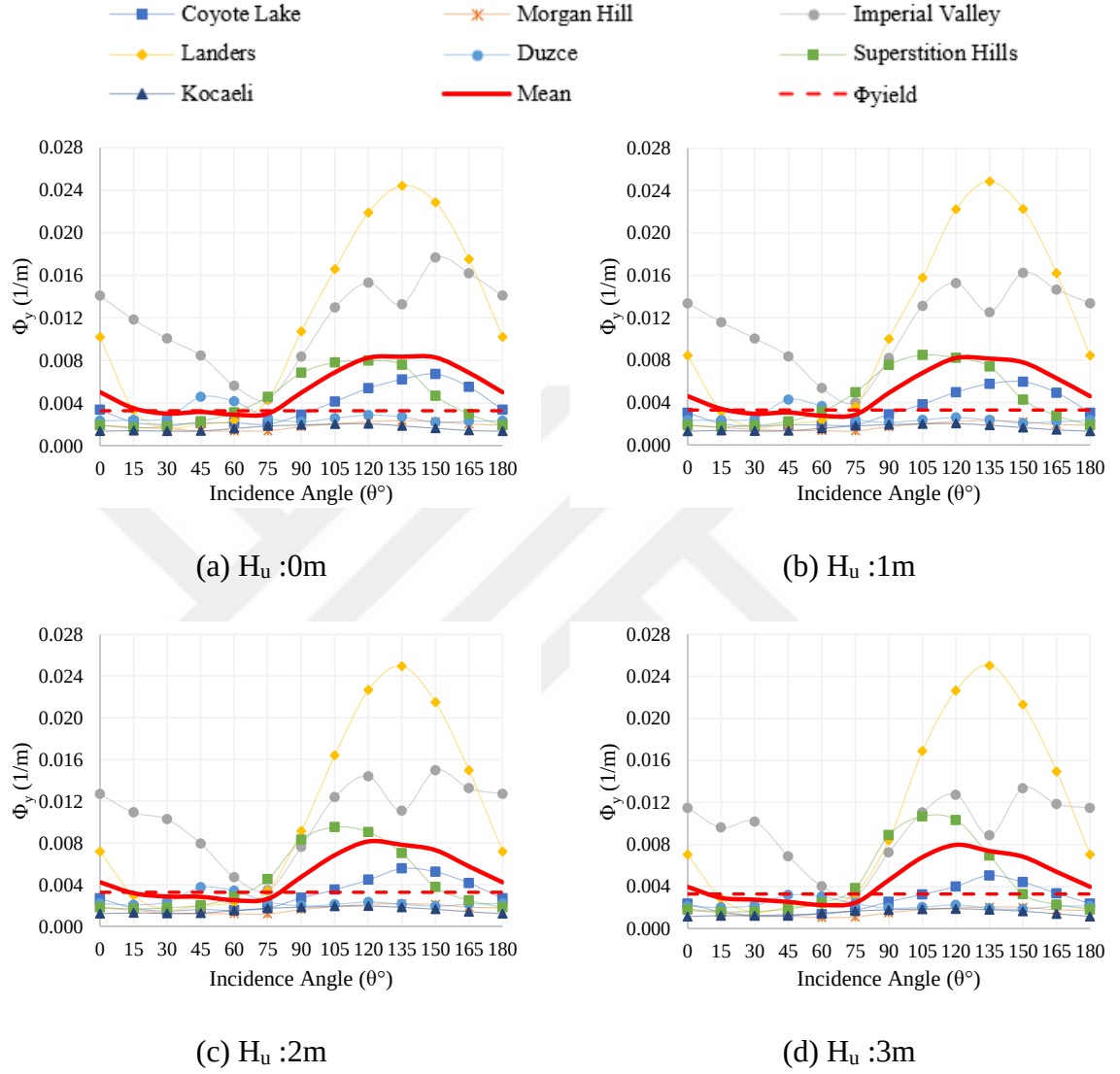
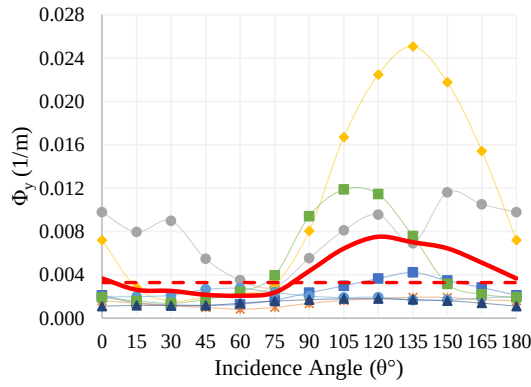
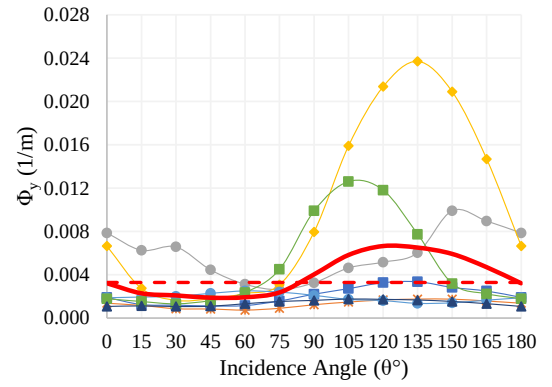


Figure 5.12. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles



(e) H_u :4m



(f) H_u :5m

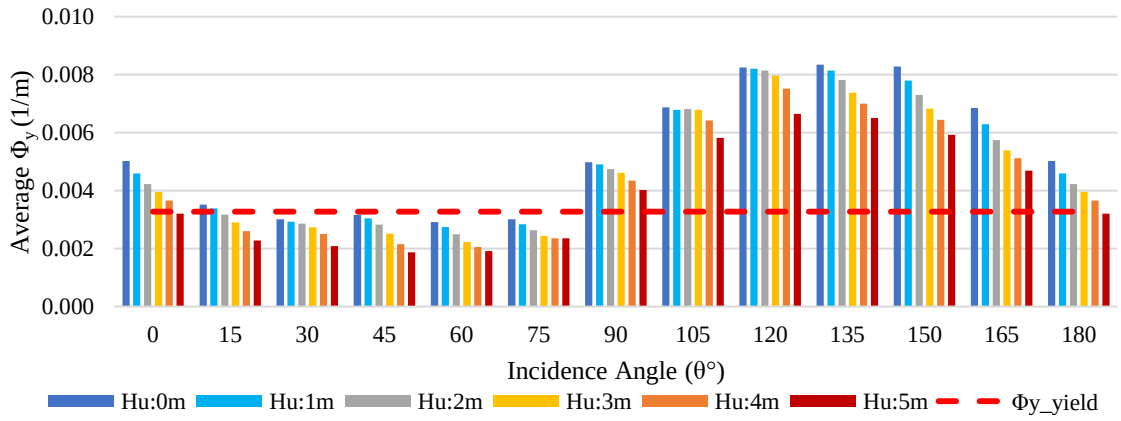
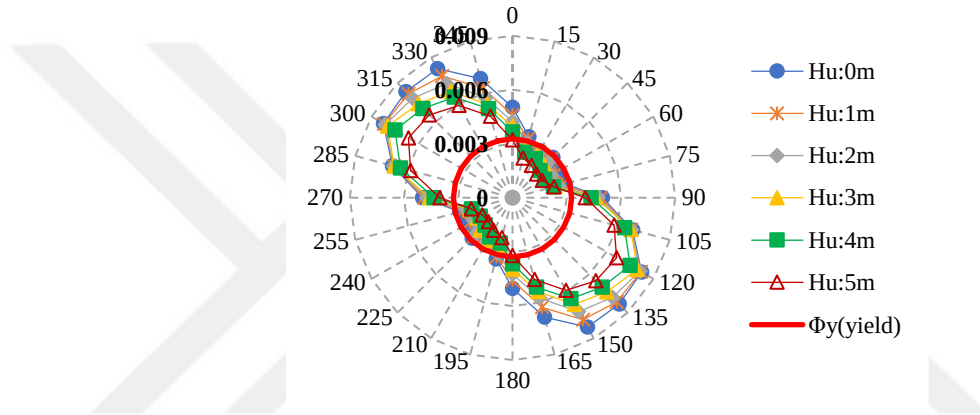


Figure 5.12. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles (continued)

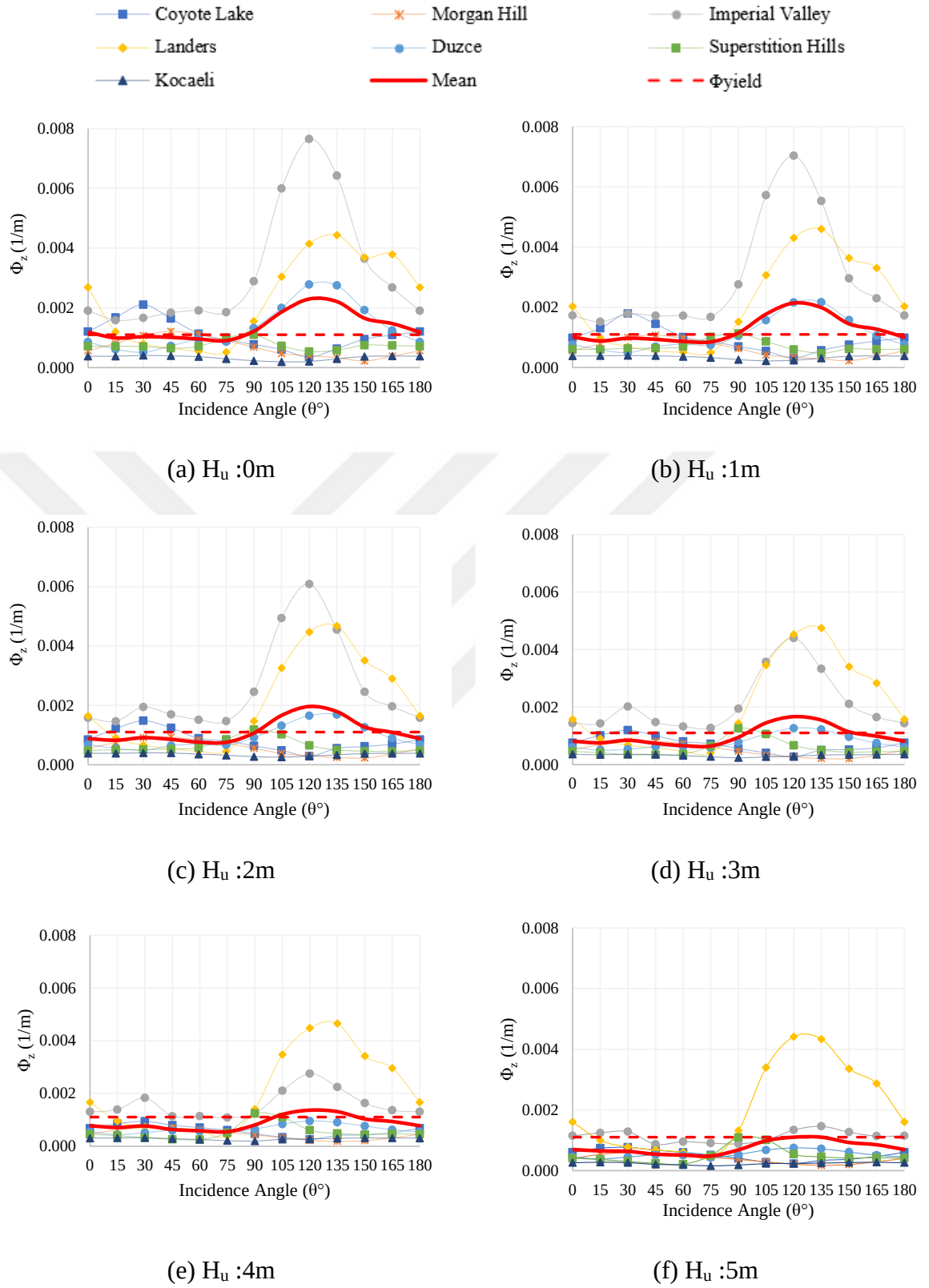


Figure 5.13. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles

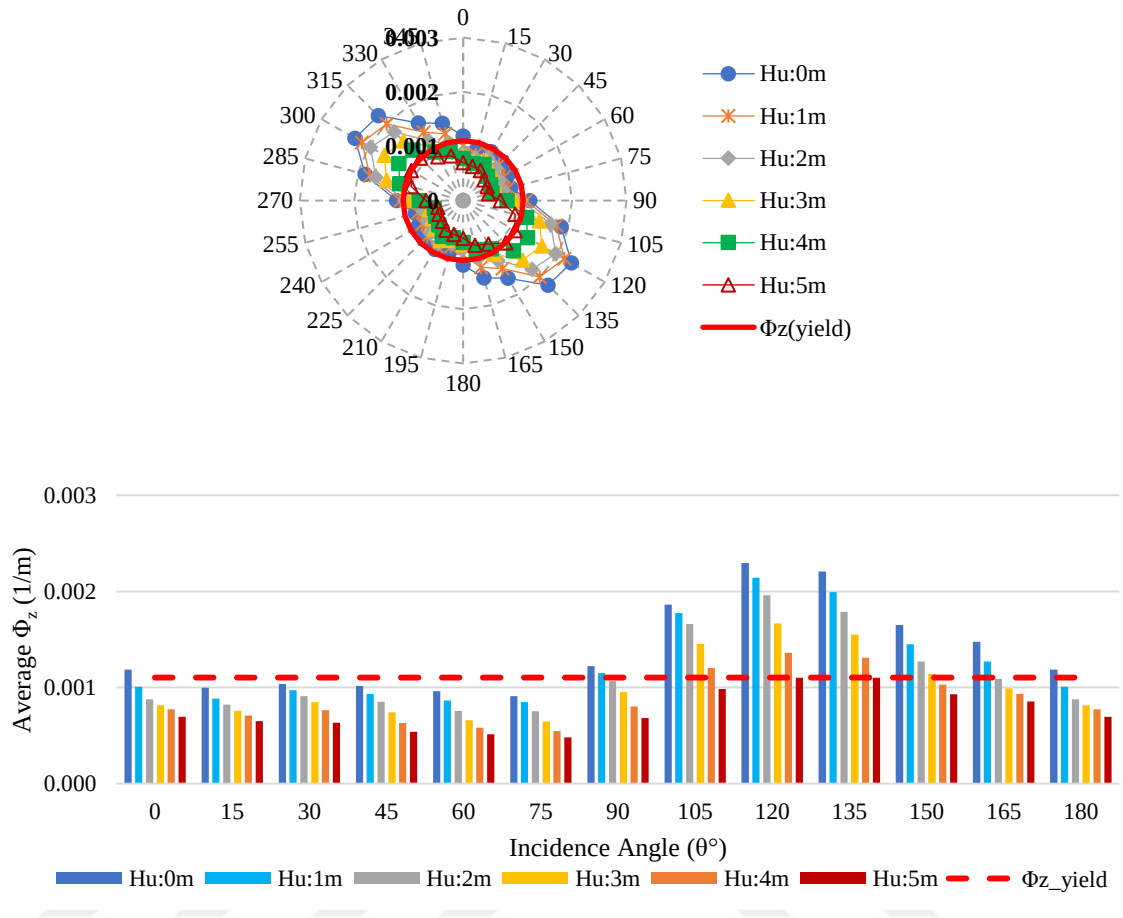


Figure 5.13. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.14 and Figure 5.15, the maximum average curvature demands of column weak (y') and strong (z') axes of the non-skewed ($\alpha=0^\circ$) and 45° skewed bridges are compared. In column weak axis (y'), the column curvature demands are higher in non-skewed bridge at 75° incidence angle. However, it becomes much higher in skewed bridge at 135° incidence angle. Moreover, this situation is similar in strong (z') axis of column. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 5m scour depth as nearly 209%. In strong axis, it is at 75° and 0m scour depth as 60.1%.

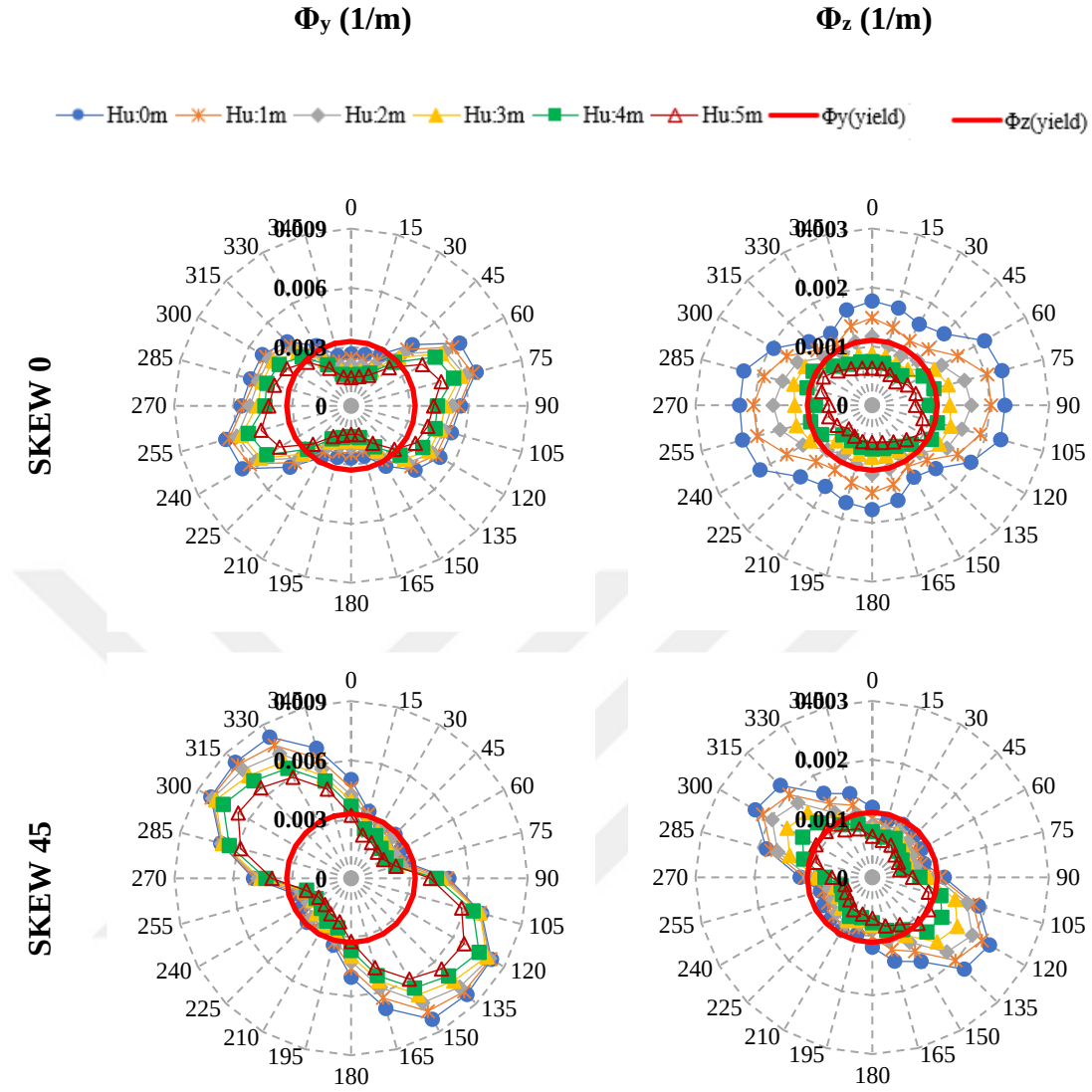


Figure 5.14. Average maximum curvature demands of the non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different uniform scour depths and earthquake incidence angles

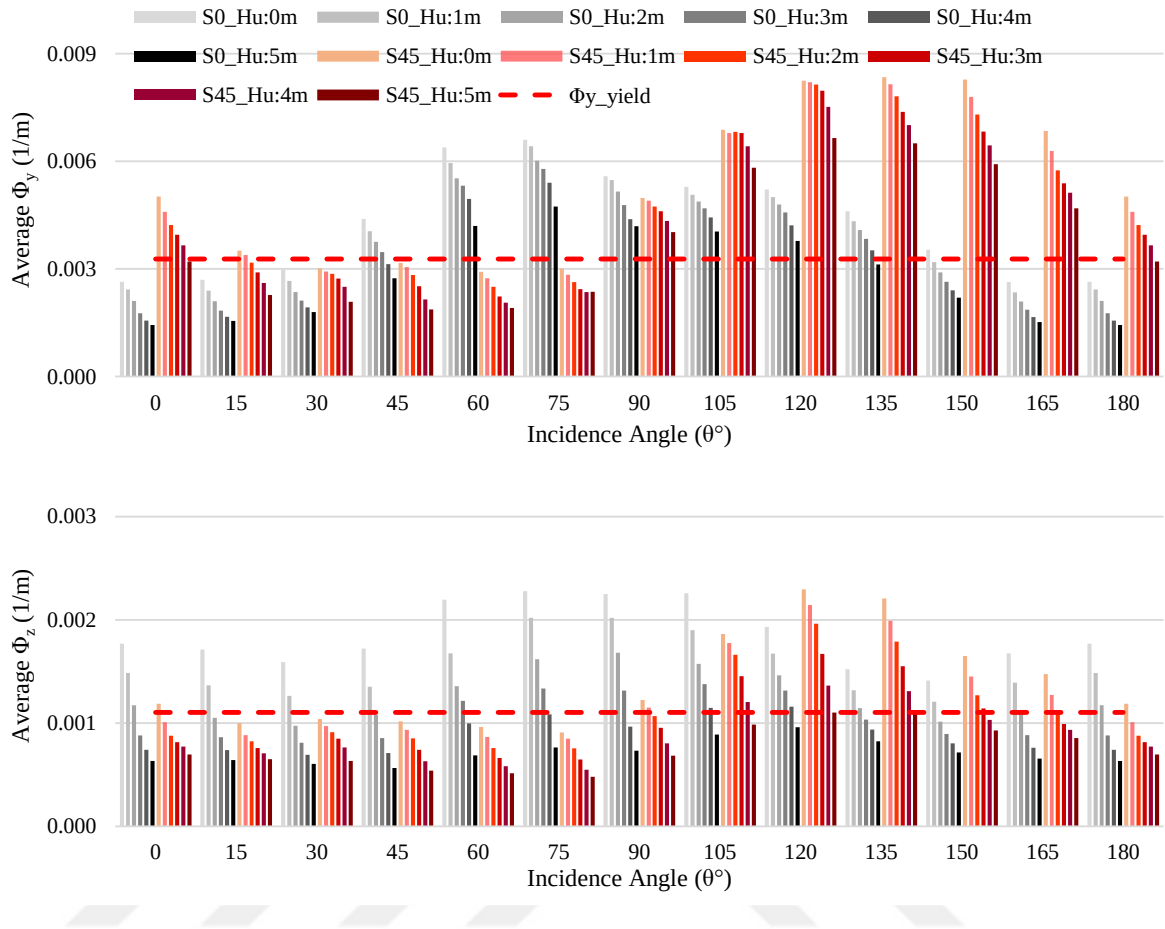


Figure 5.15. Average maximum curvature demands of the non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different uniform scour depths and earthquake incidence angles

5.1.3. Shear force demands of column pier

In Figure 5.16 and Figure 5.17, the maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of uniform scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_u=0\text{m}$) and 5m scoured ($H_u=5\text{m}$) bridges occurs as nearly 27.7% at 60° incidence angle. Also, it is about 14.2% at 150° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When average maximum shear force demands are compared to these capacities, it is seen that demands are below

the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis.

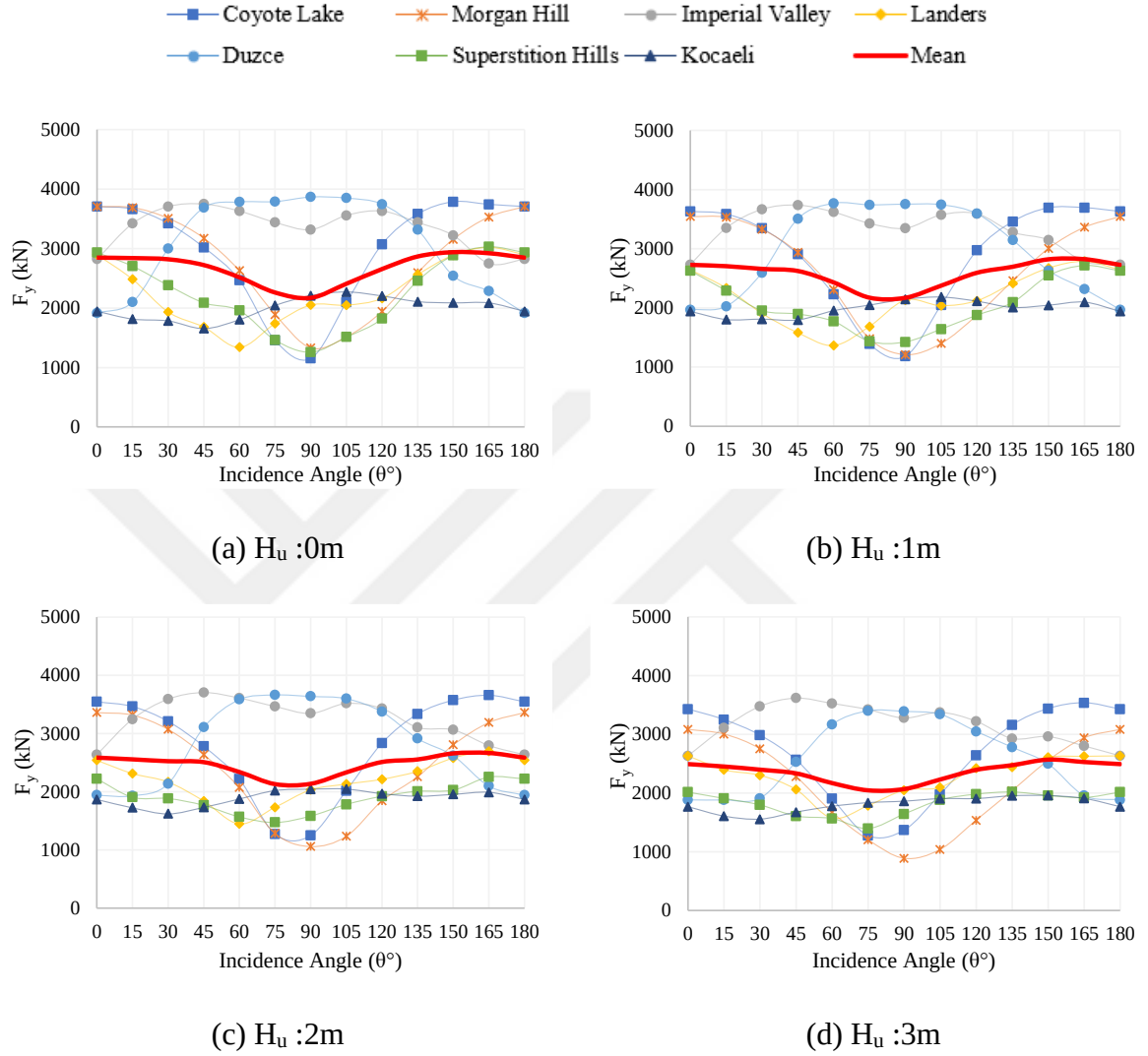
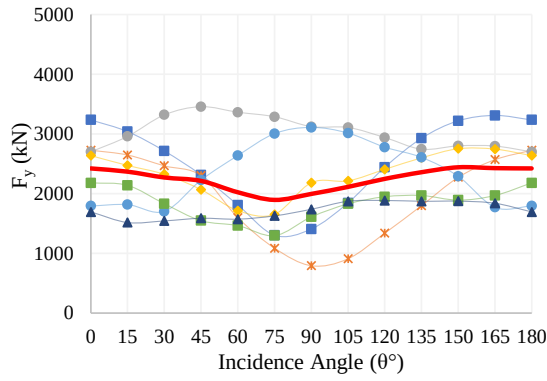
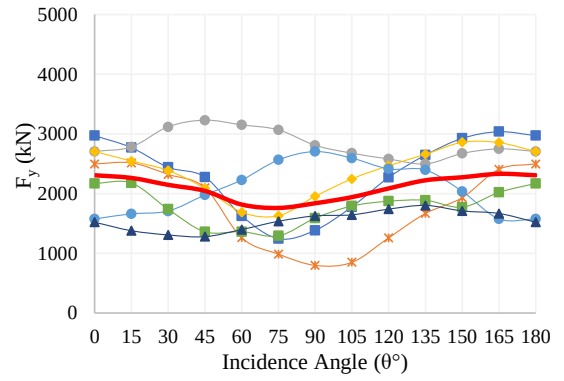


Figure 5.16. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles



(e) H_u :4m



(f) H_u :5m

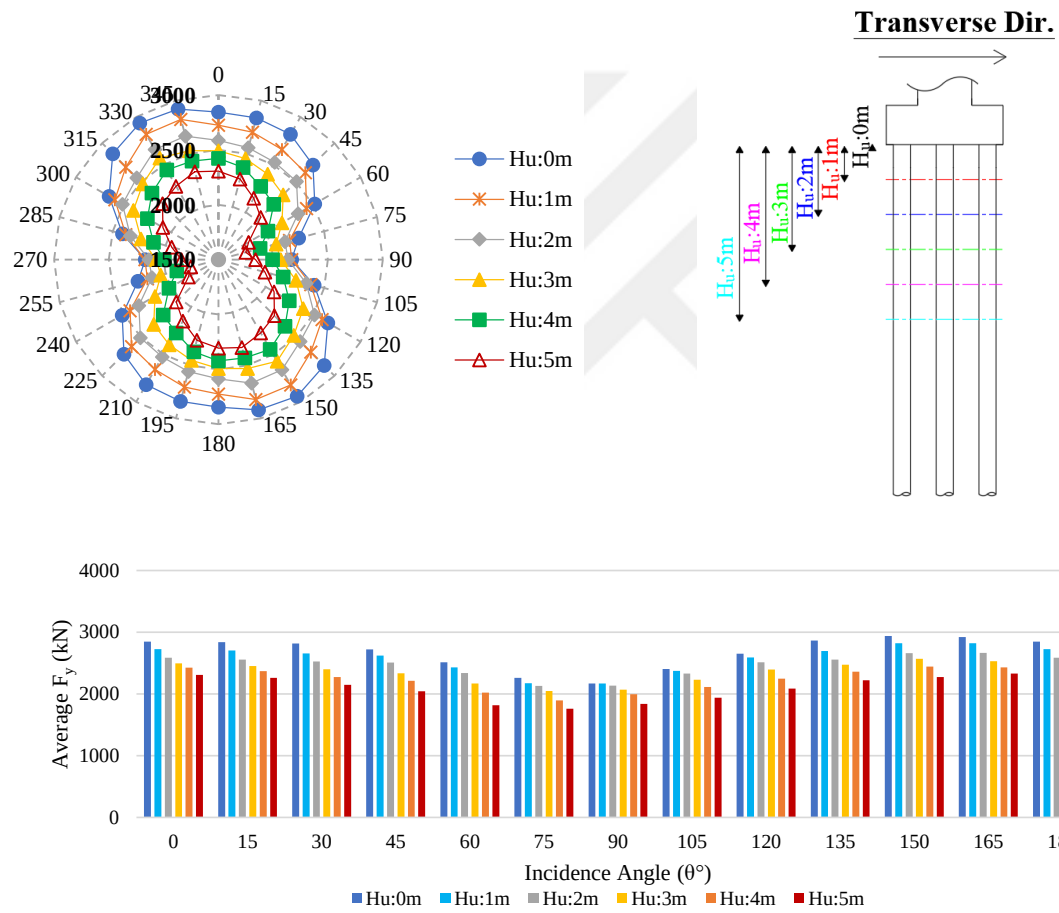


Figure 5.16. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles (continued)

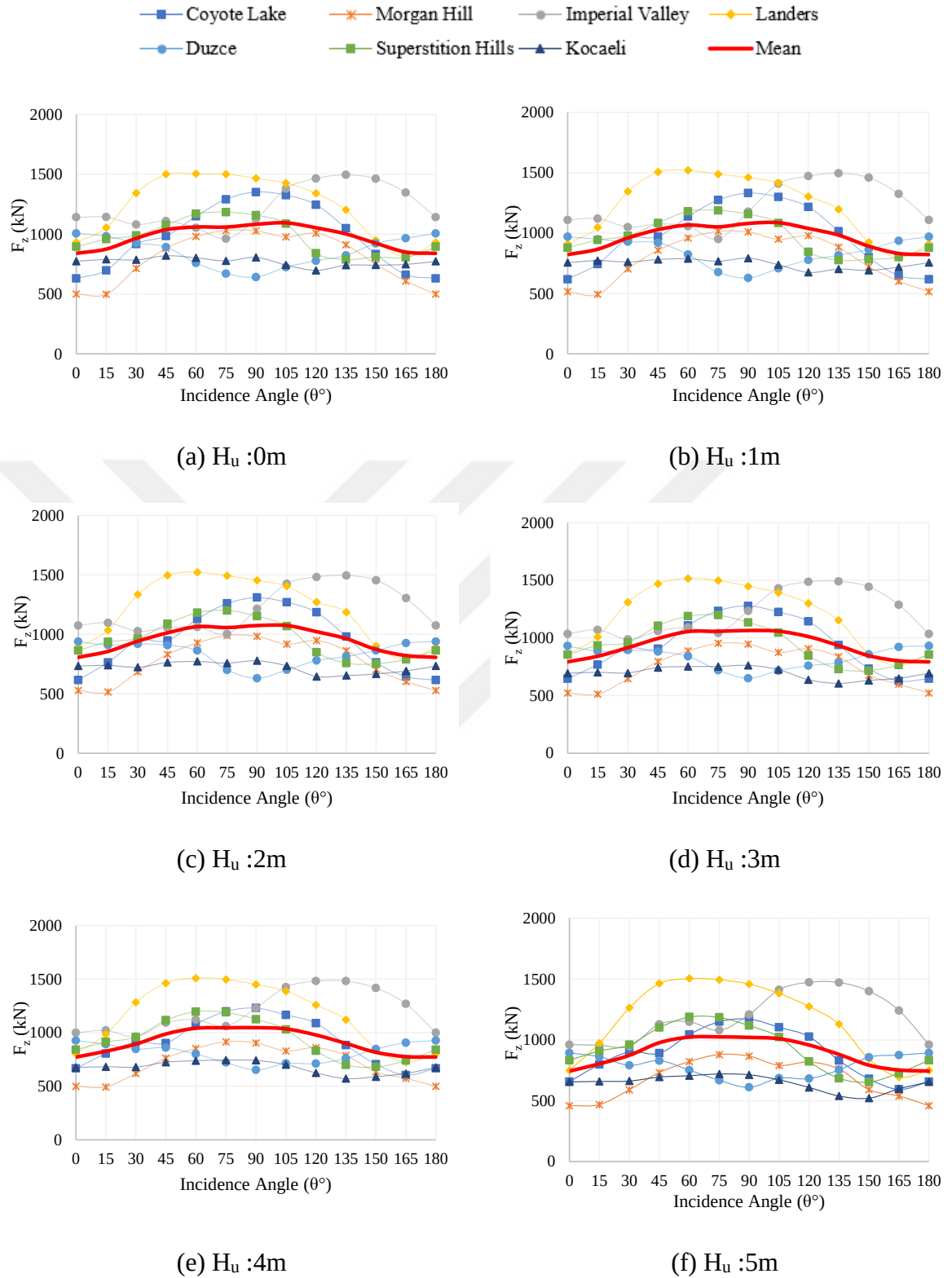


Figure 5.17. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles

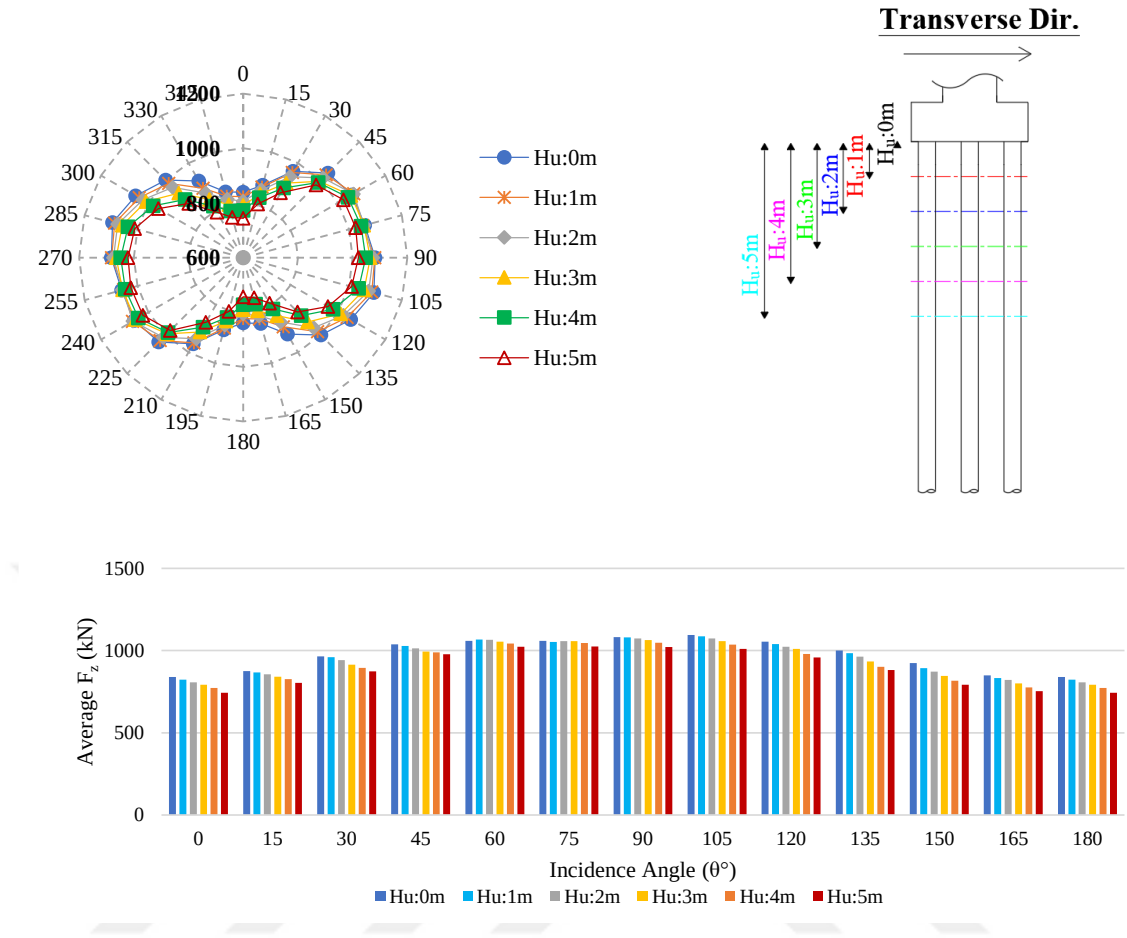


Figure 5.17. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.18 and Figure 5.19, the maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 75° to 135° in local y' axis. Besides, it has an increasing trend between 30° and 135° incidence angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as depth of scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_u=0m$) and 5m scoured ($H_u=5m$) bridges occurs at 75° incidence angle as nearly 26.2%. Also, it is about 14.4% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands

are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in 45° skewed bridge column during nonlinear analysis.

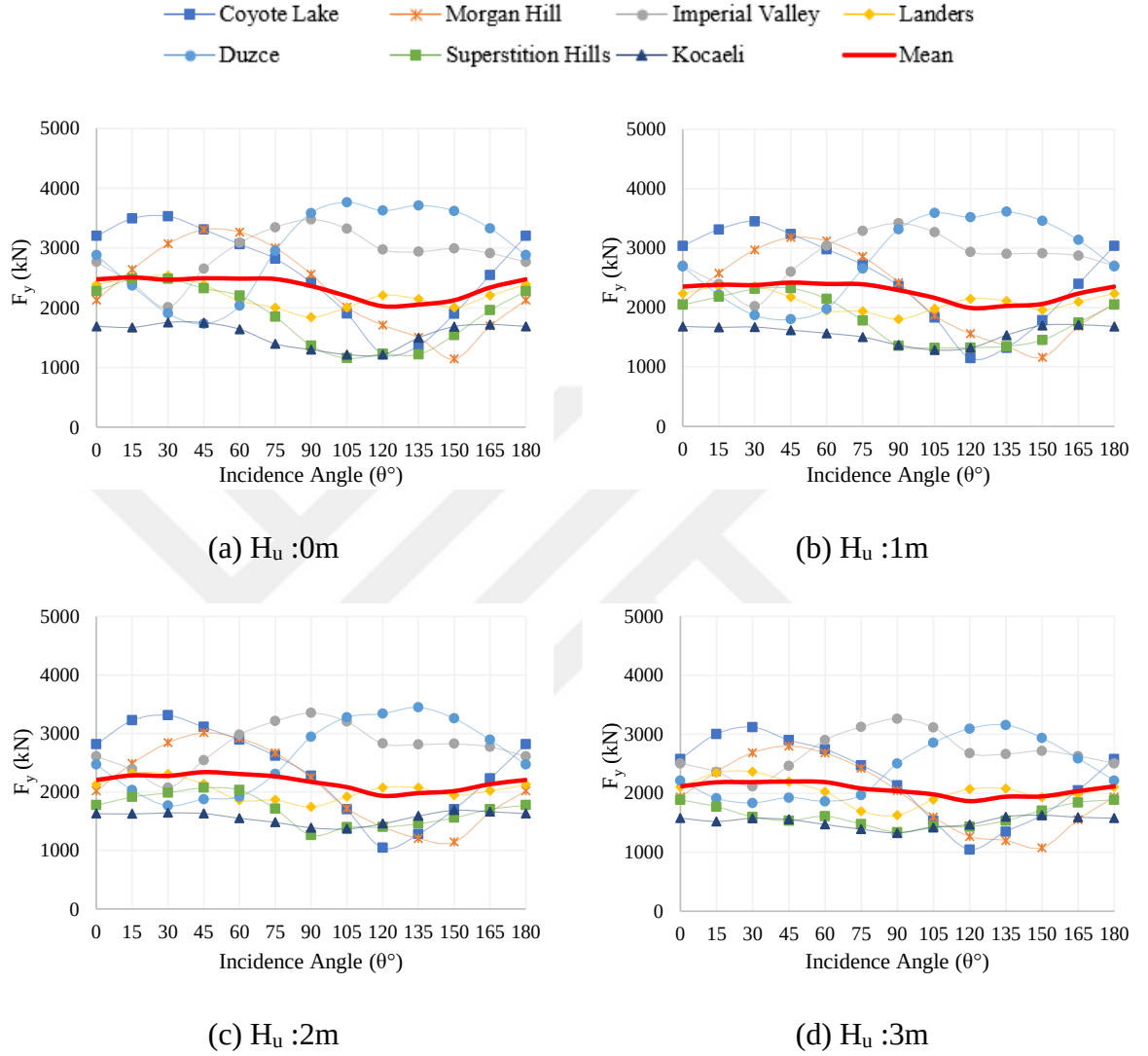
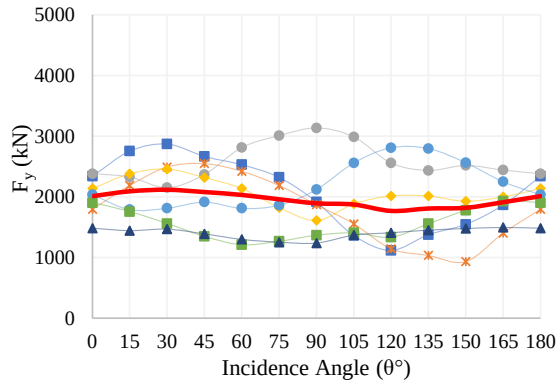
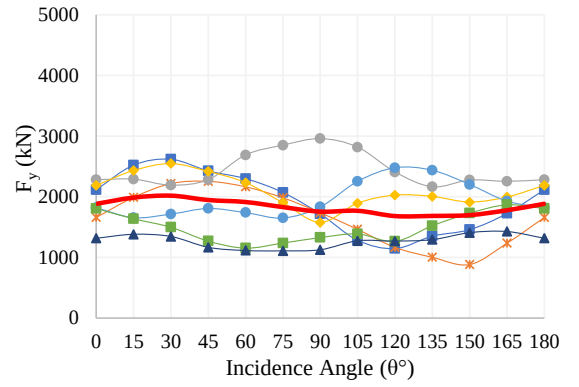


Figure 5.18. Maximum shear force demands in local y' axis of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles



(e) H_u :4m



(f) H_u :5m

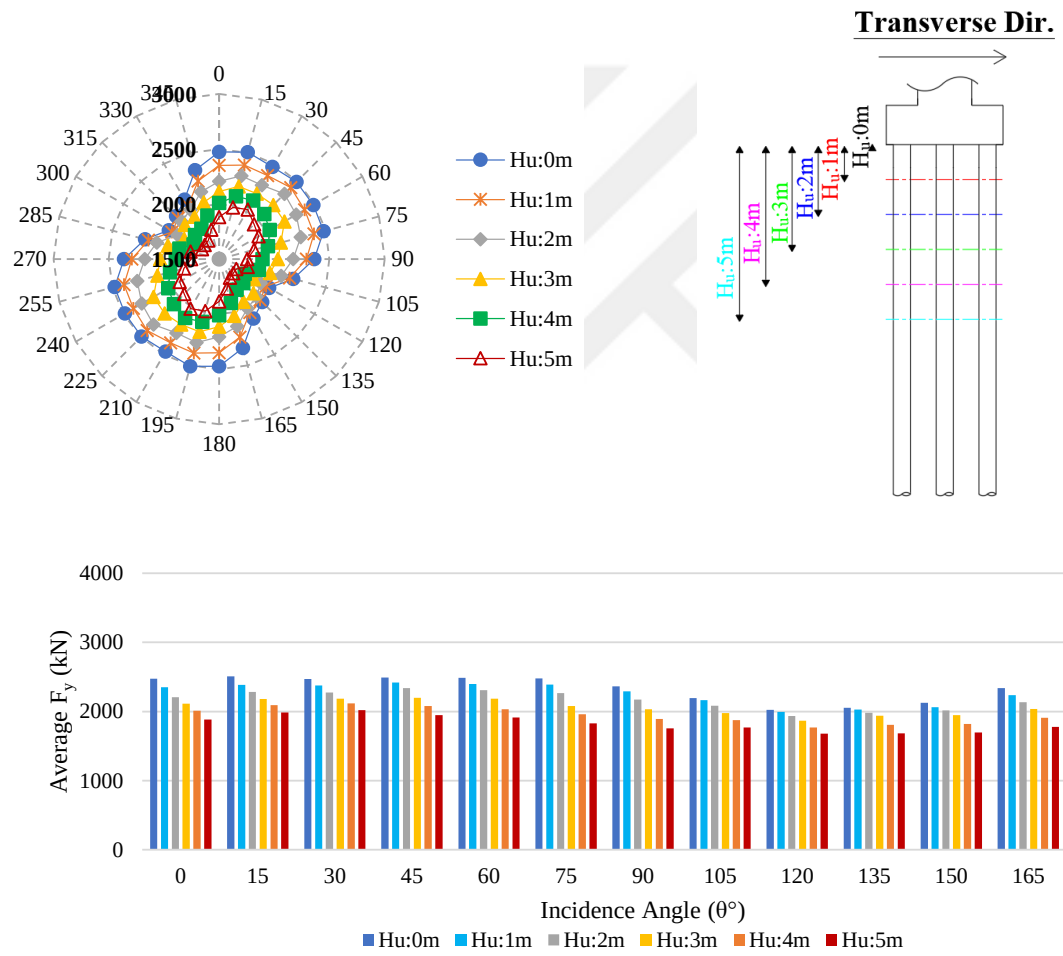


Figure 5.18. Maximum shear force demands in local y' axis of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles (continued)

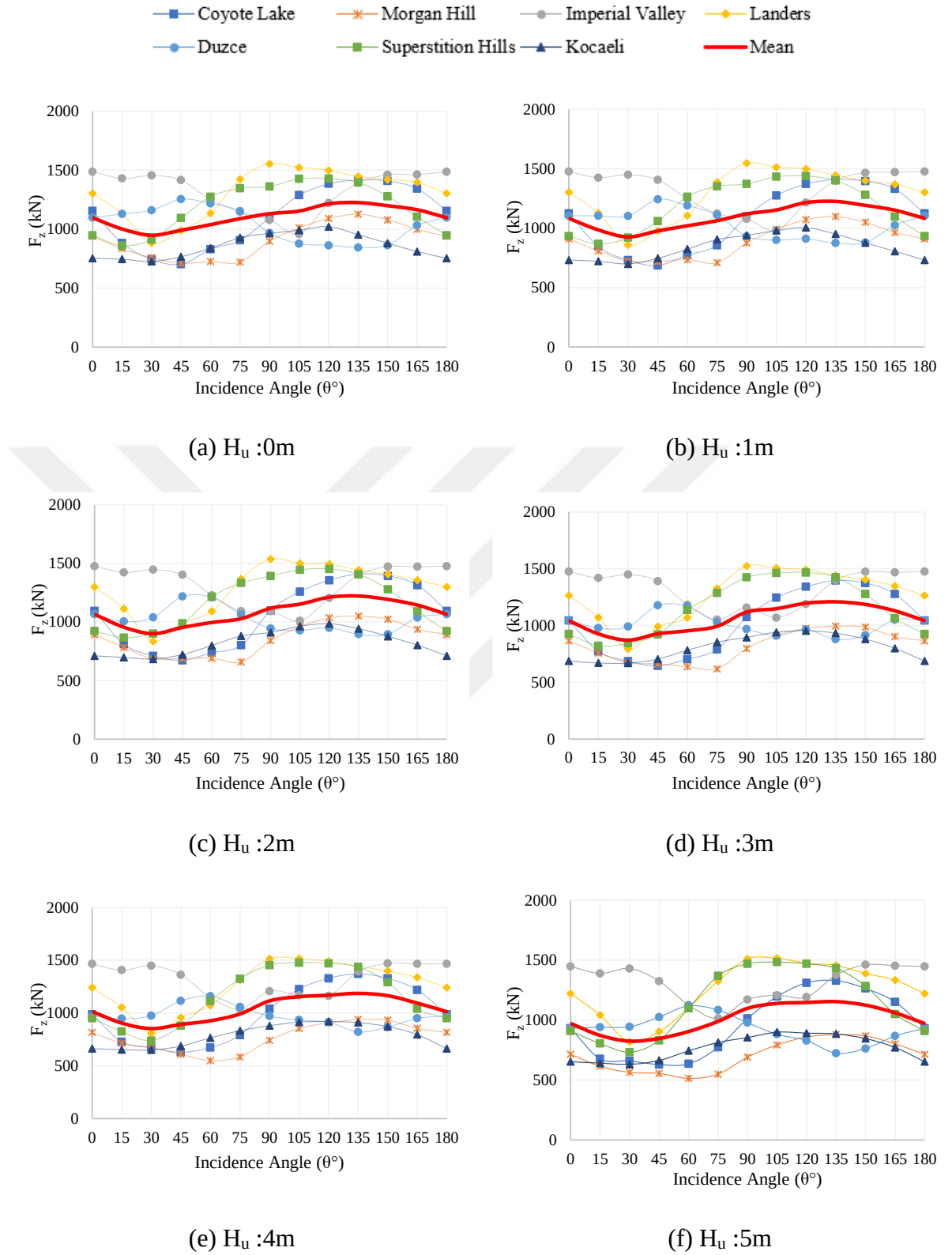


Figure 5.19. Maximum shear force demands in local z' axis of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles

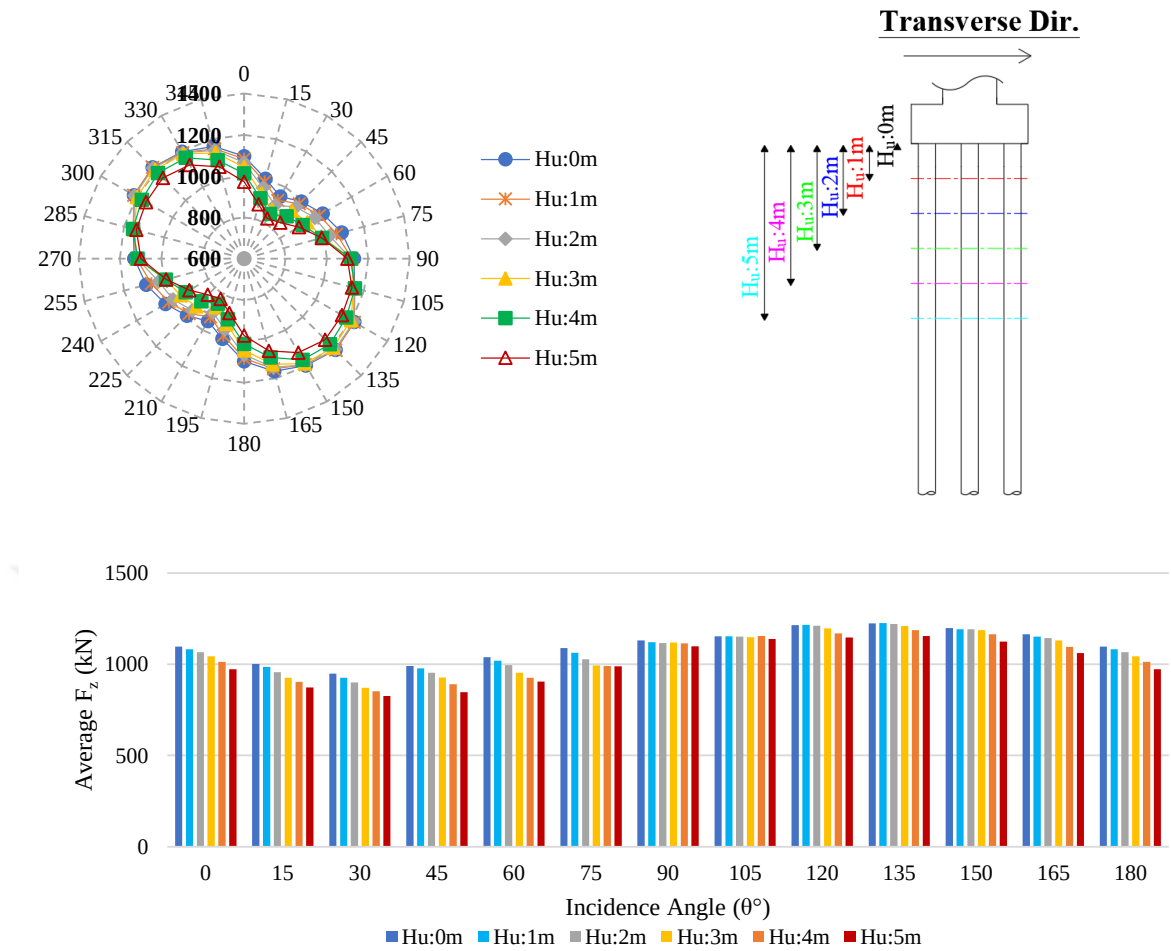


Figure 5.19. Maximum shear force demands in local z' axis of 45° skewed bridge column for different uniform scour depths and earthquake incidence angles (continued)

In Figure 5.20 and Figure 5.21, the maximum shear force demands of column local y' and z' axes of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges are compared. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The reduction in shear force demands with the increasing scour depth is more evident in local y -direction of the column compared to the local z -direction. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 135° incidence angle and 0m scour depth as nearly 39.6%. In local z' axis, it is at 150° and 5m scour depth as 42%.

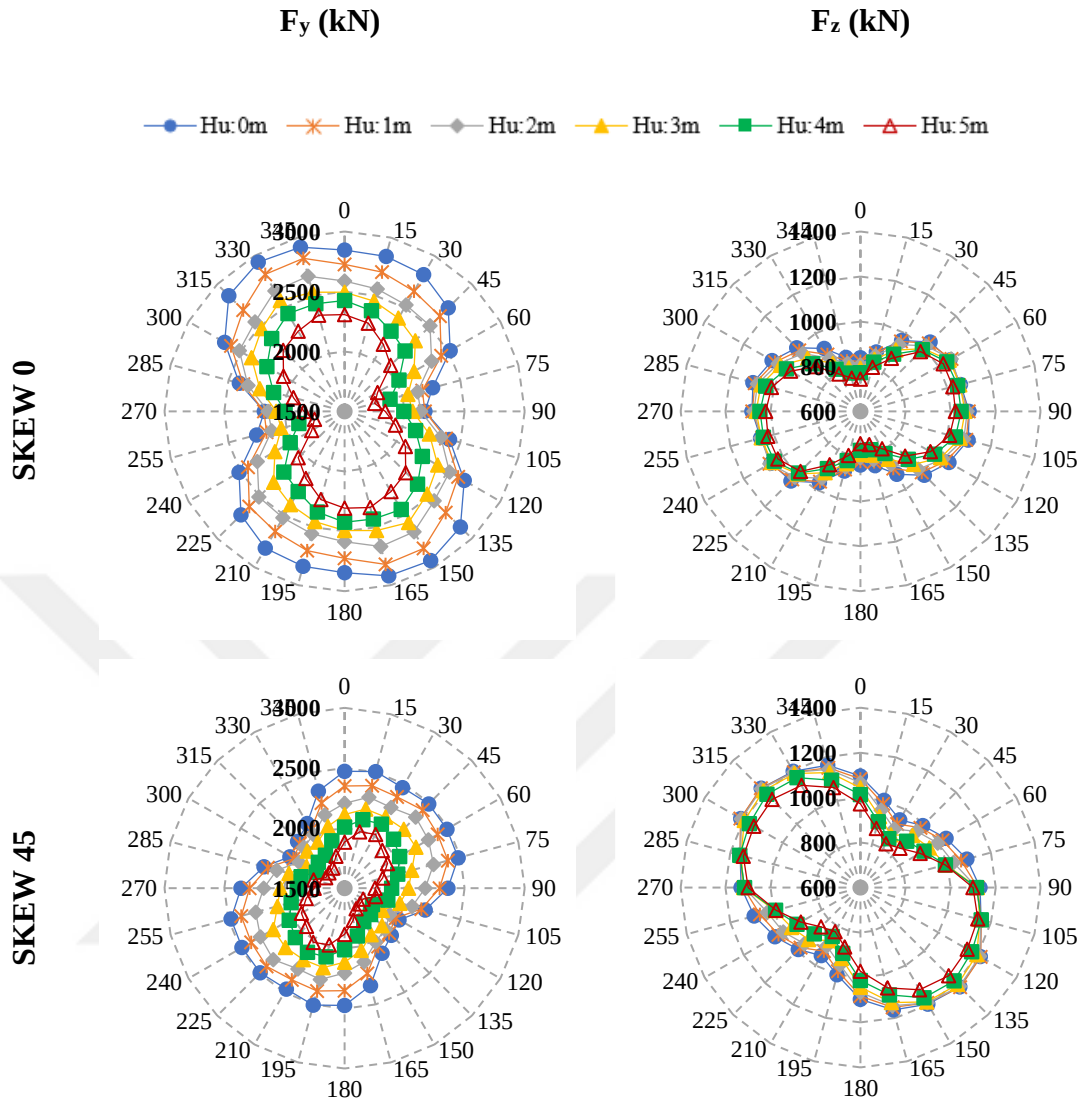


Figure 5.20. Average maximum shear force demands of non-skewed and 45° skewed bridge column for different uniform scour depths and earthquake incidence angles

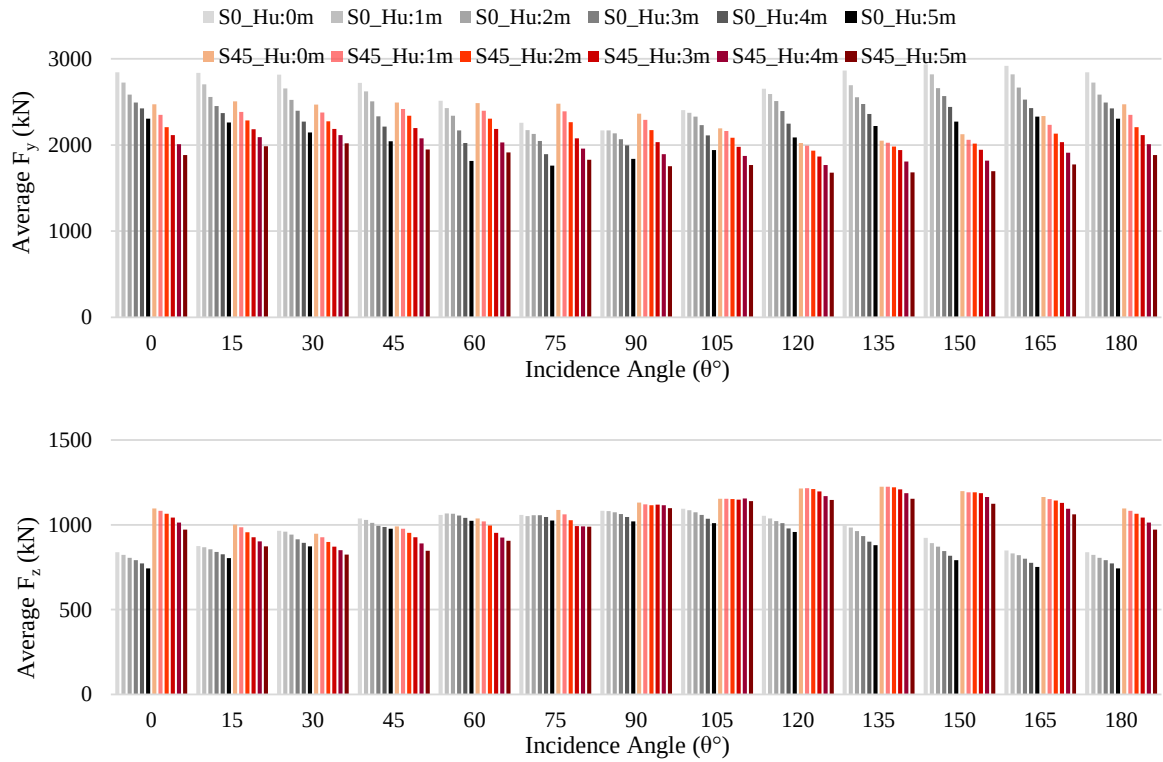


Figure 5.21. Average maximum shear force demands of non-skewed and 45° skewed bridge column for different uniform scour depths and earthquake incidence angles

5.1.4. Shear force demands of piles

In Figure 5.22 and Figure 5.23, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. For all scour depths shear force demands are below the pile shear capacity of 735.2 kN. Also, demands are nearly the same for all corner piles and they are much higher in local y' axis than z' axis. Therefore, shear force demands of local y' axis of pile number 1 (P1) is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.24. P1 pile shear demand is higher in non-skewed bridge and it has a maximum value at 0m scour depth. It is decreasing when scour depth increases and don't reach the shear capacity.



Figure 5.22. Maximum shear force demands of local y' and z' axis of corner piles for different uniform scour depths and earthquake incidence angles ($\alpha=0^\circ$ non-skewed bridge)



Figure 5.23. Maximum shear force demands of local y' and z' axis of corner piles for different uniform scour depths and earthquake incidence angles ($\alpha=45^\circ$ skewed bridge)

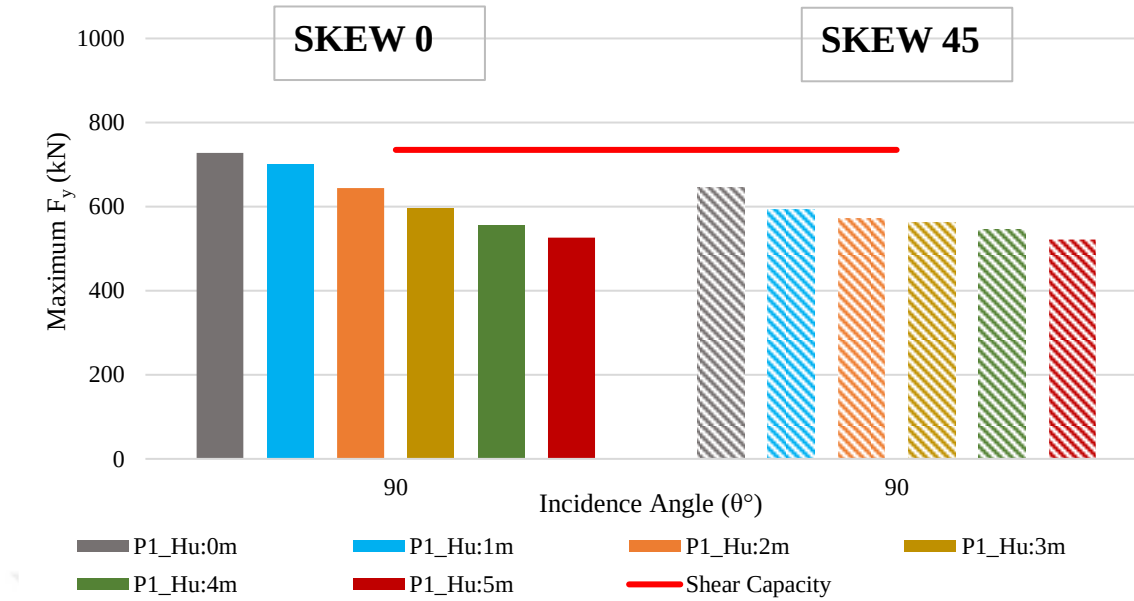


Figure 5.24. Average maximum shear force demands of local y' axis of pile (P1) for different uniform scour depths and 90° earthquake incidence angle

5.1.5. Residual displacements

Residual displacements of bridges may occur after severe earthquakes. Therefore, it is necessary to take residual displacements into consideration when evaluating the results obtained from nonlinear response history analysis. Within the scope of the study, it was aimed to obtain residual displacement demands in the bridge column and superstructure. Residual displacement demands were obtained by taking the average of the peak and through displacement demands in the last displacement cycle of the bridge under the influence of earthquake ground motion. Then, the average of the demands obtained from 7 earthquake records was taken. In addition, the maximum displacement demands of the node at the top of the column pier and the middle node of the superstructure under the influence of each earthquake were also obtained. The demands were obtained by using 7 ground motion records and 13 different ground motion incidence angles. Also scour depth was uniformly changed for each bridge model and residual displacements of middle column and superstructure were investigated for non-skewed ($\alpha=0^\circ$) and 45° skewed bridges. In Figure 5.25, the average residual displacement demands of middle column for the non-skewed and skewed bridges are given when scour depth is uniformly changed. Also, in Figure 5.26, the ratio of residual displacement demand to maximum displacement of middle column for the non-skewed and 45° skewed bridge is shown when scour depth change is uniform (Case-1). Furthermore, the same

demands are evaluated for the superstructure and shown in Figure 5.27 and Figure 5.28, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal direction for both column and superstructure residual displacements. However, in transverse direction the situation becomes vice versa.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when uniform scour depth is 5m at 75° incidence angle for non-skewed bridge as 21.4mm. In transverse direction it is maximum at 90° incidence angle and 5m scour depth as 6.4mm for 45° skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 3m scour depth as 0.18 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 2m scour depth when incidence angle 180° in transverse direction of skewed bridge.

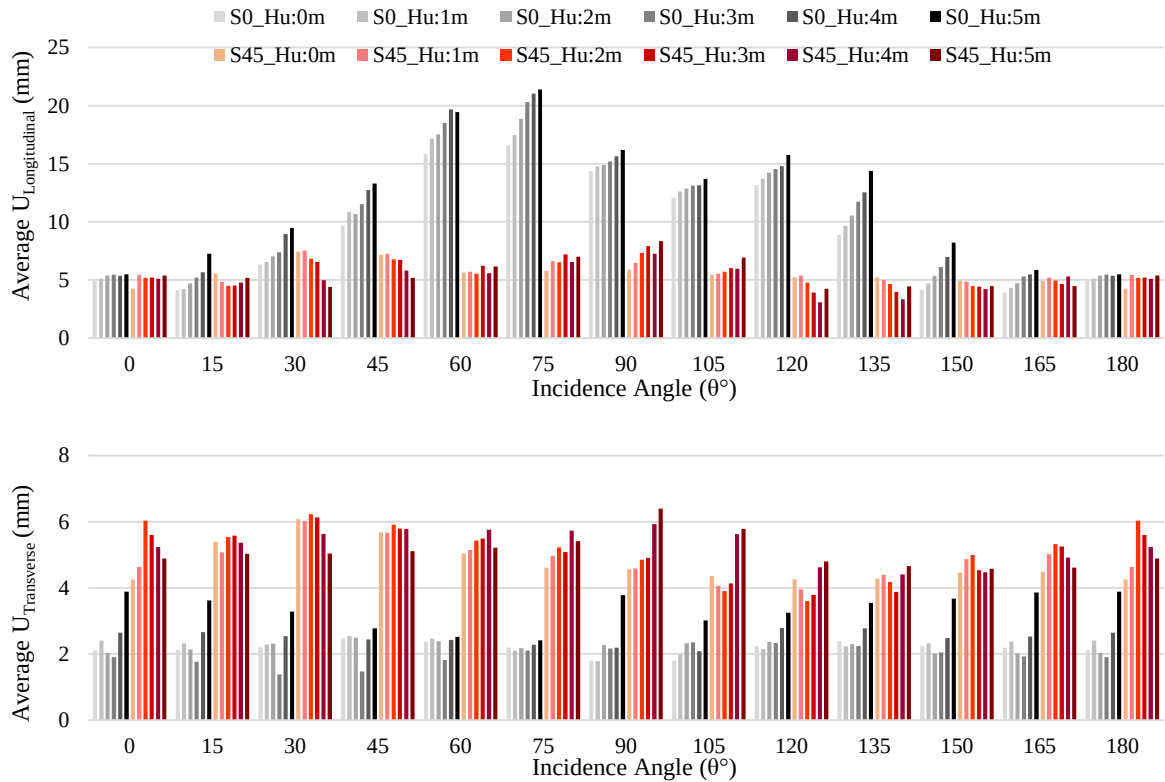


Figure 5.25. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is uniform (Case-1)

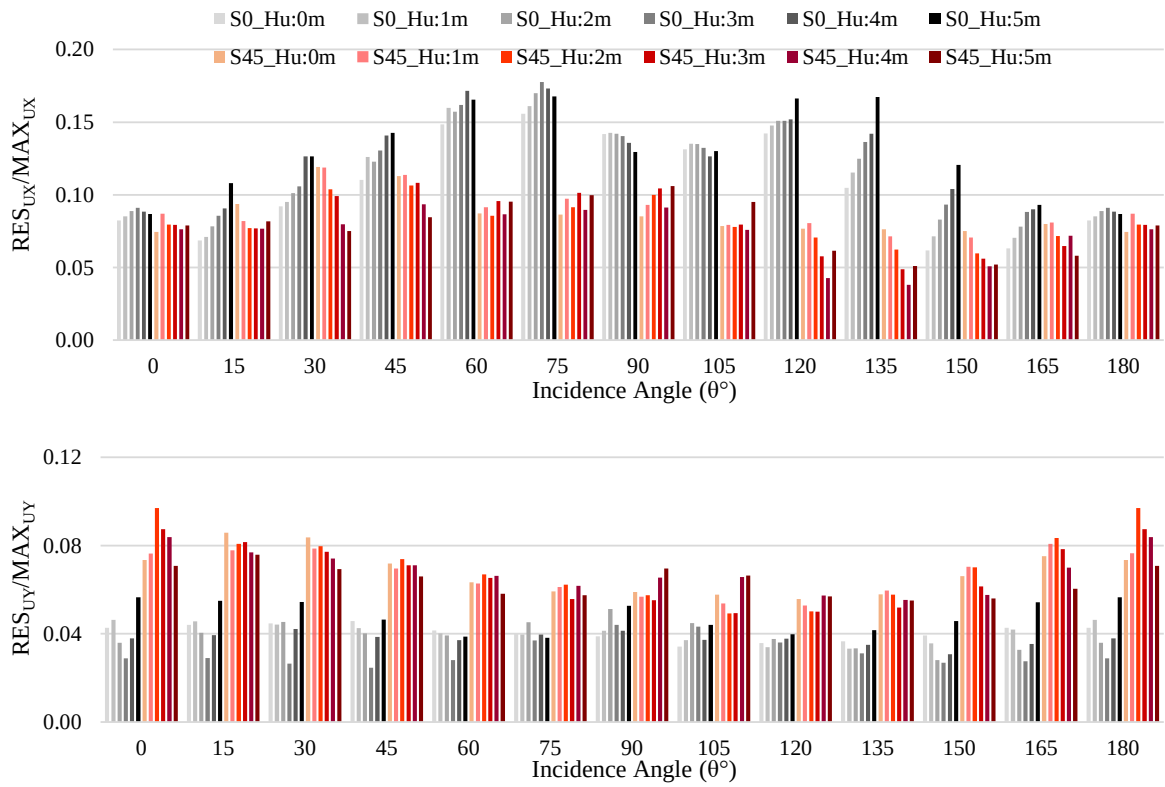


Figure 5.26. The ratio of residual displacement demand to maximum displacement of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is uniform (Case-1)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when uniform scour depth is 5m at 75° incidence angle for non-skewed bridge as 25.8mm. In transverse direction it is maximum at 180° incidence angle and 2m scour depth as 8.9mm for skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands, the maximum ratio occurs at an incidence angle of 75° and 3m scour depth as 0.18 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 2m scour depth when incidence angle 180° in transverse direction of skewed bridge.

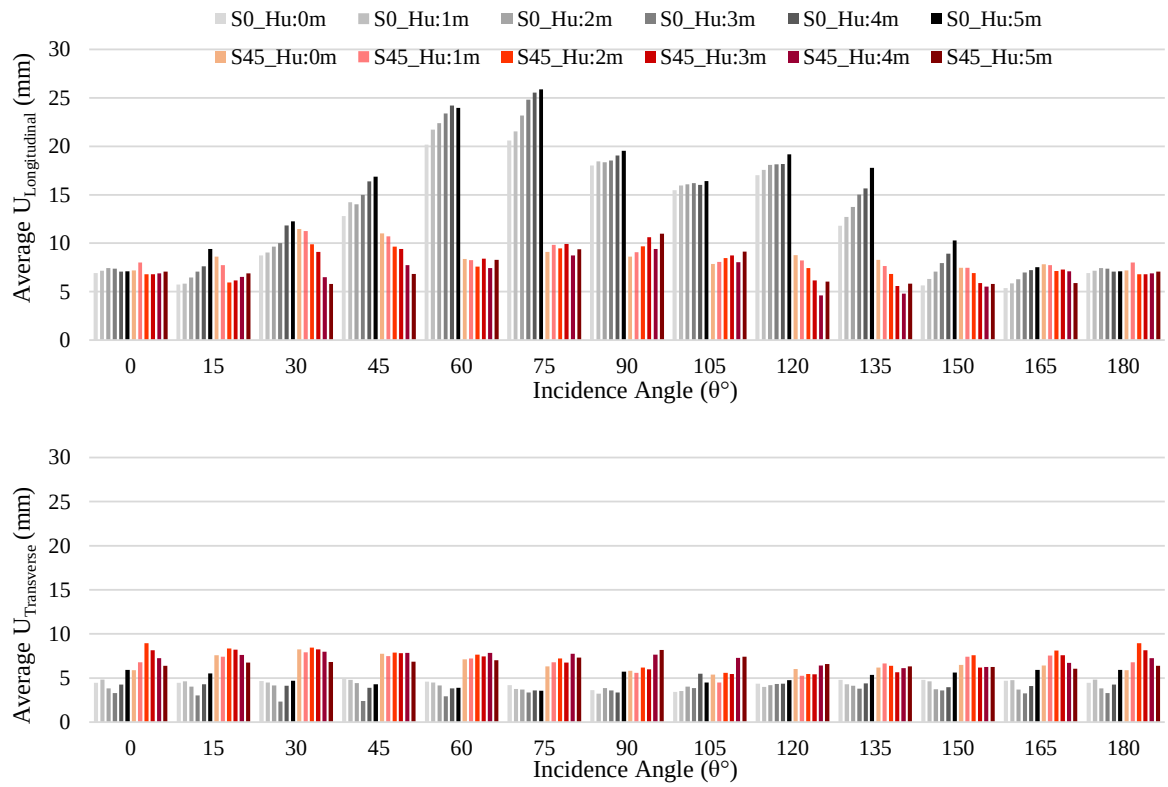


Figure 5.27. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is uniform (Case-1)

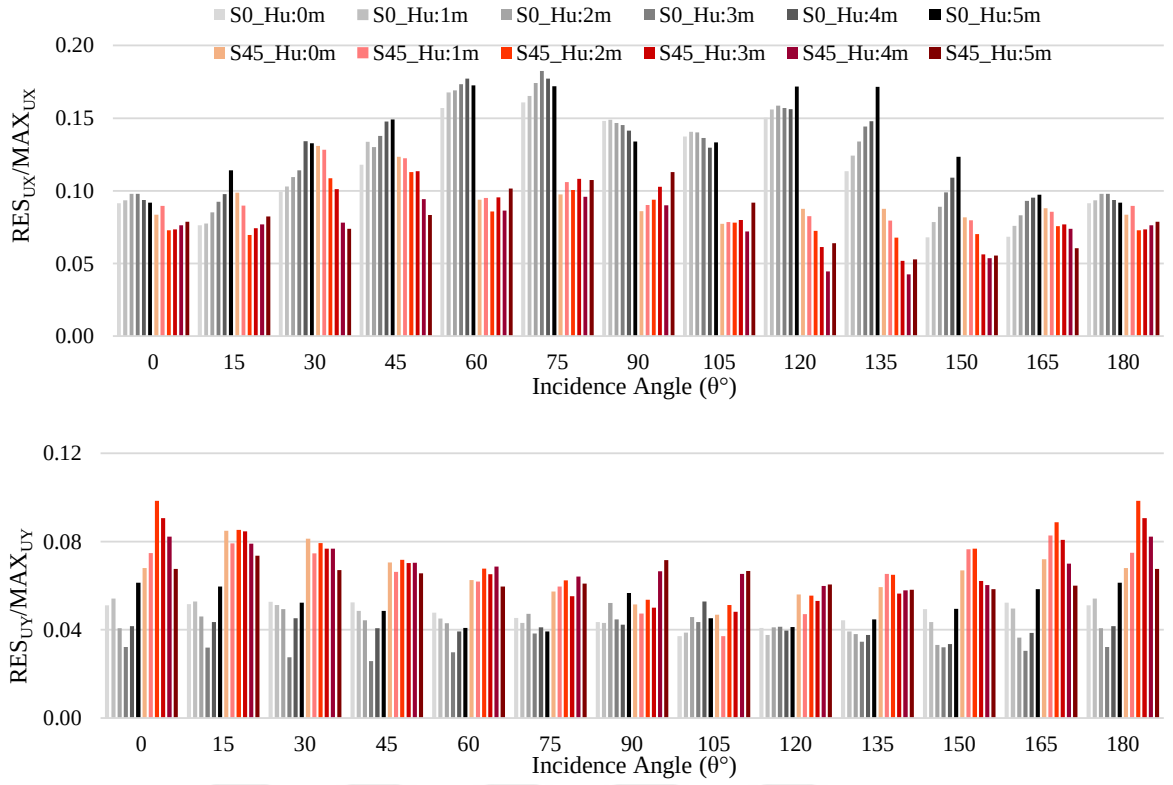


Figure 5.28. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is uniform (Case-1)

5.2. Non-Uniform Scour in Transverse Direction of Bridge (Case 2-1)

In literature, consideration of uniform scour depth is a common way and seismic response of highway bridges under the effect of uniform scour was investigated in many studies. However, in reality, the scour depth may be emerged differently around each pier or pile. This situation is called as non-uniform scour case (Case-2) in the content of thesis. This non-uniformity may occur in both longitudinal and transverse direction of bridges. The non-uniform scour which occurred more in upstream according to the flow direction of the pile in transverse direction is called as Case 2-1 in the study. The irregularity was created by changing the scour depth angle between upstream and downstream piles as $\gamma=0.6$ and $\gamma=1.0$ as given in Figure 3.40. Seismic response of the investigated highway bridge under the effect of Case 2-1 scour was investigated for various variable parameters such as scour depth, scour type ($\gamma=0.6$ and $\gamma=1.0$), skew angle (0° and 45°), and incidence angle.

5.2.1. Non-uniform scour when $\gamma=0.6$ (Case 2-1a)

Non-uniform scour can occur in transverse direction of bridge according to direction of flow as mentioned before. However, it is not easy to determine the scour depth difference that occur between downstream and upstream piles. Also, there is only one research study which takes non-uniform scour into consideration in literature. Fioklou and Alipour (2019) investigated seismic performance of bridges with non-uniform scour by taking downstream scour depth as 20% more around upstream piles. In the content of thesis, 2 different scour depth angles are discussed, $\gamma=0.6$ and $\gamma=1.0$, and analytical models of bridge is constructed accordingly. Scour depth is changed starting from 0 m (no scour) to 5 m with 1 m increment around downstream pile (H_d). The results given below belong to the bridge with non-uniform scour when $\gamma=0.6$.

As seen in Figure 5.29, the 1st and 2nd vibration period of the bridge increases when scour depth increases. Because the clear height of the piles increases when the soil around piles is removed. This situation increases the flexibility of the bridge and so do the periods. While the 1st period values of 45° skewed bridge model are higher than the straight bridge, the 2nd period values are less similar to uniform scour case (Case-1). This is because the stiffness in longitudinal direction of the bridge decreases with increase of the skew angle, while it increases in the transverse direction of the bridge.

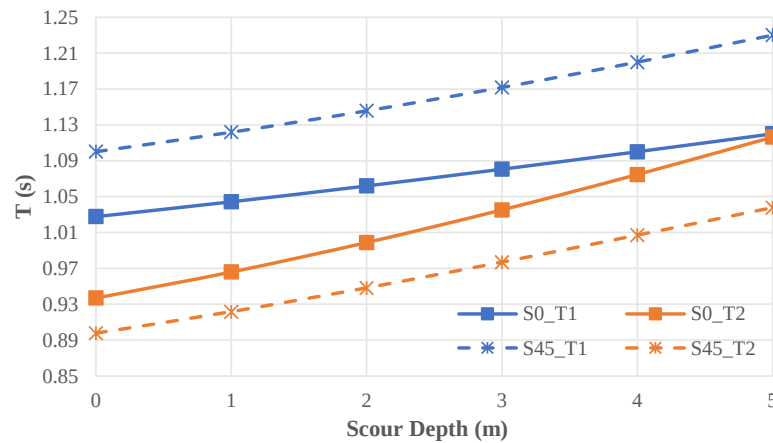


Figure 5.29. The variation of 1st and 2nd vibration period of non-skewed ($\alpha=0^\circ$) and 45° skewed bridge depending on non-uniform scour depth when $\gamma=0.6$

5.2.1.1. Superstructure displacement

Superstructure displacement demands obtained from nonlinear analysis results belong to midpoint of the bridge deck as mentioned above. In Figure 5.30 and Figure

5.31, maximum displacement demands in longitudinal and transverse direction of the non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.32 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When we examine the results in terms of change of earthquake incidence angle, the average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 60° incidence angles although in transverse direction it is decreasing between 0° and 75° incidence angles. Therefore, the resultant displacement becomes nearly the same for each earthquake incidence angle. According to the radar and bar charts, the average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in transverse direction is more obvious than in longitudinal direction of bridge in some incidence angles. The maximum difference of average displacement demands in longitudinal direction between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 75° incidence angle as nearly 11.8%. In transverse direction, it is at 15° as 21.5%. If it is checked for resultant displacement, maximum difference becomes 16.2% at 0° incidence angle.

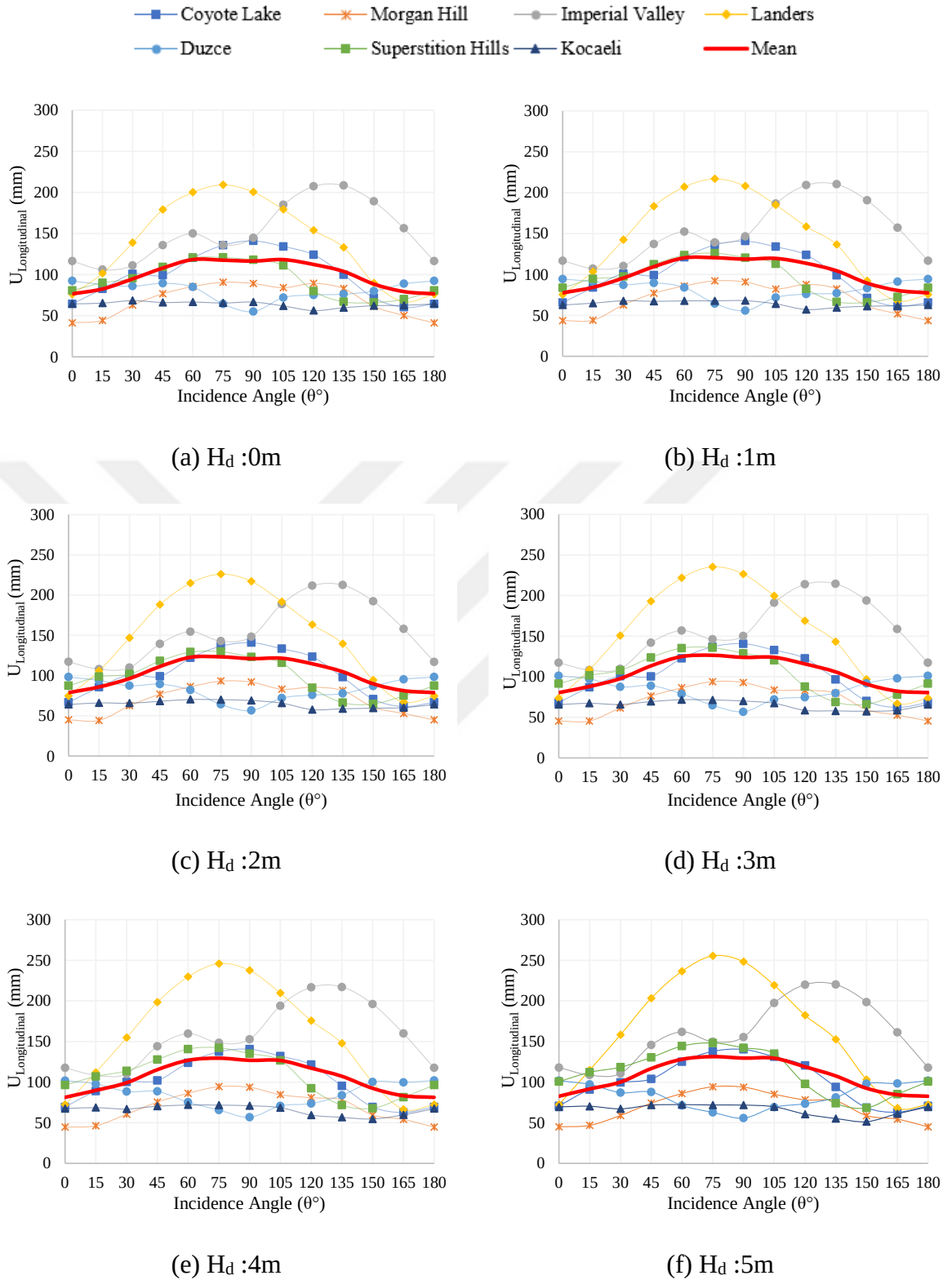


Figure 5.30. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

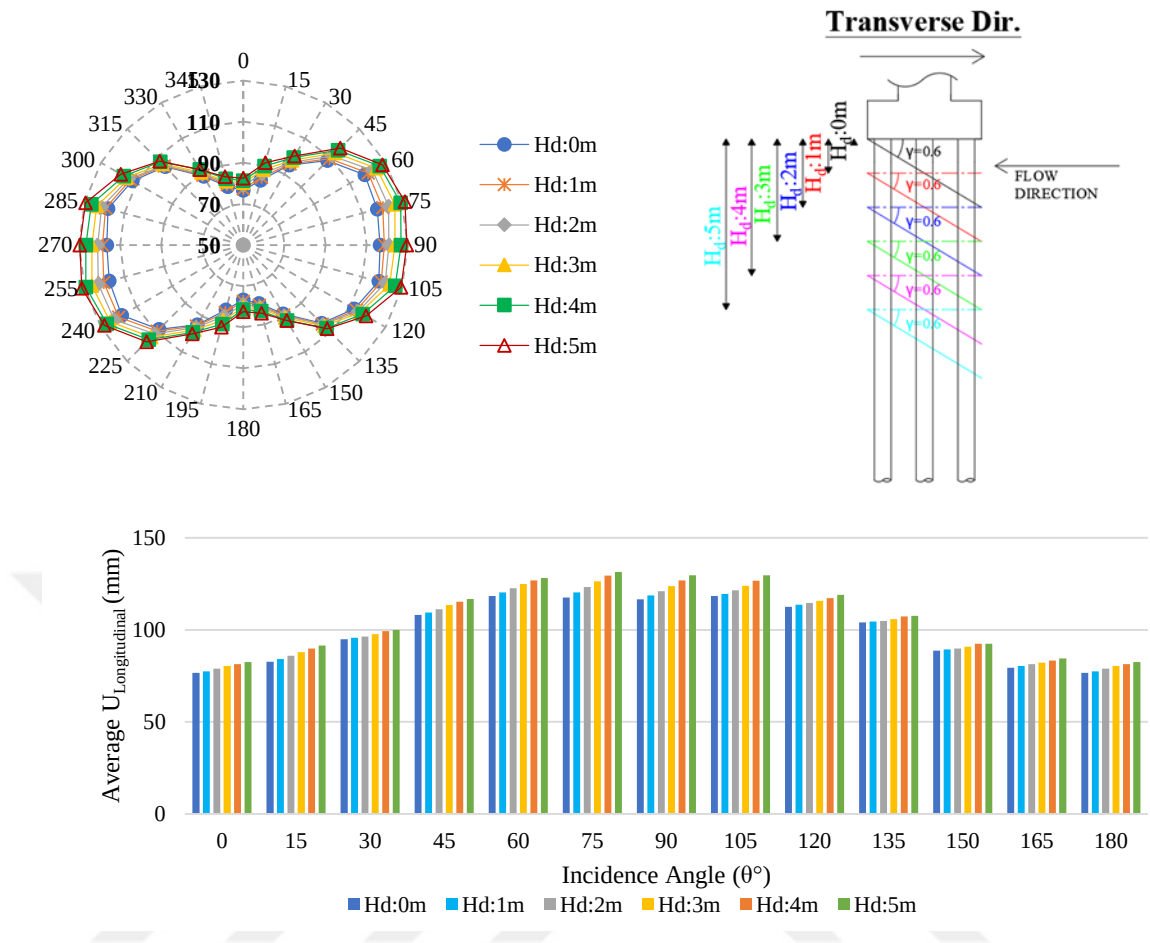


Figure 5.30. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

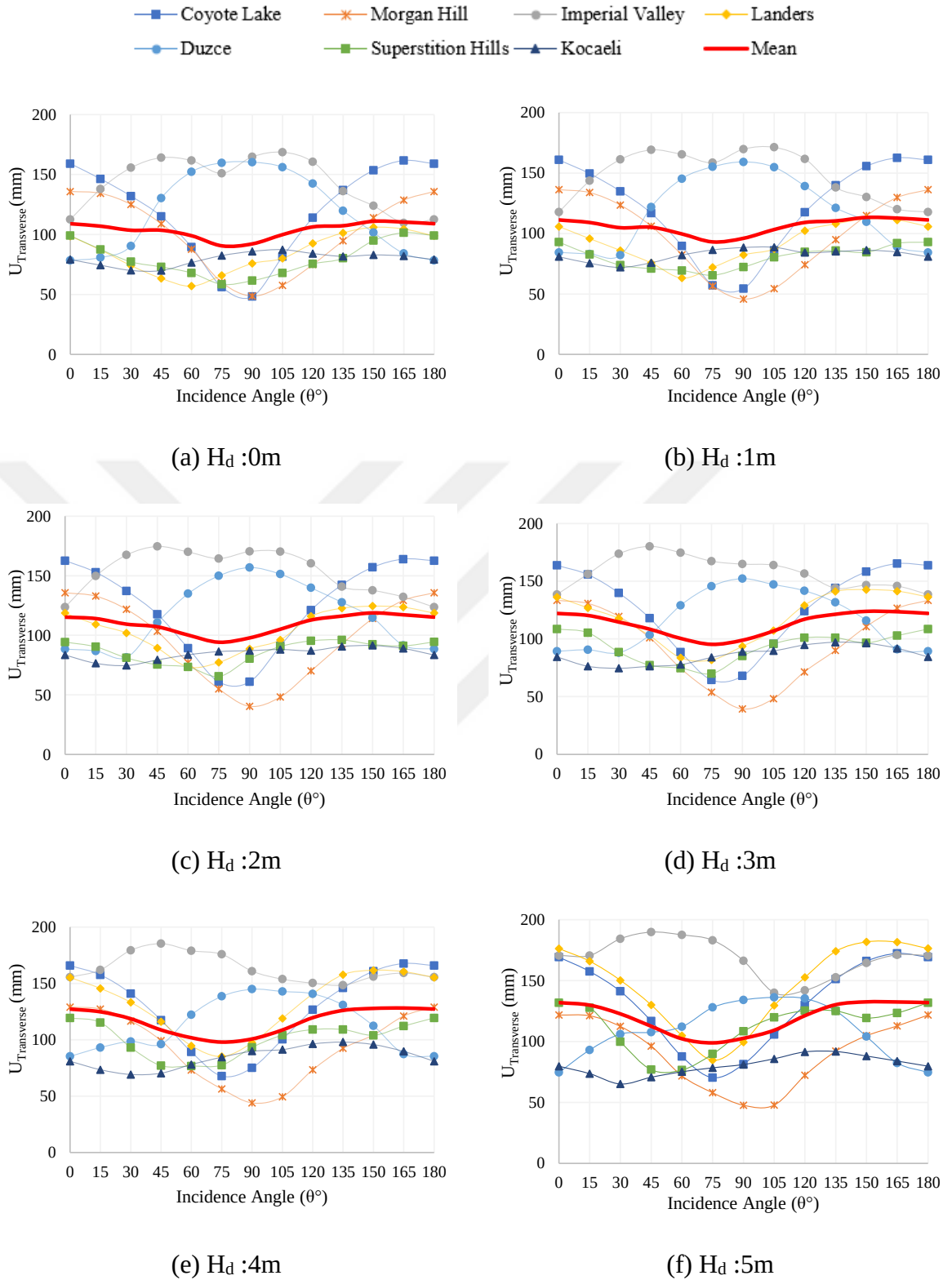


Figure 5.31. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

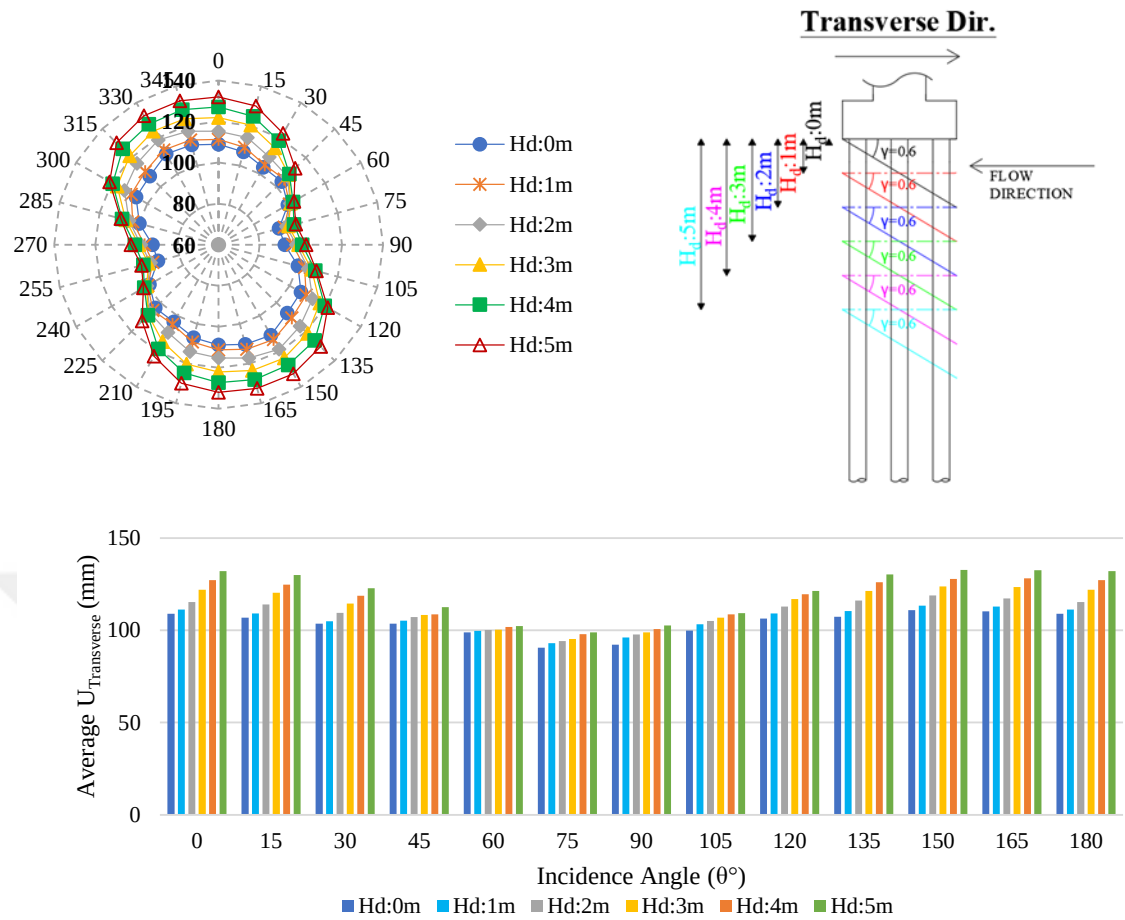


Figure 5.31. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

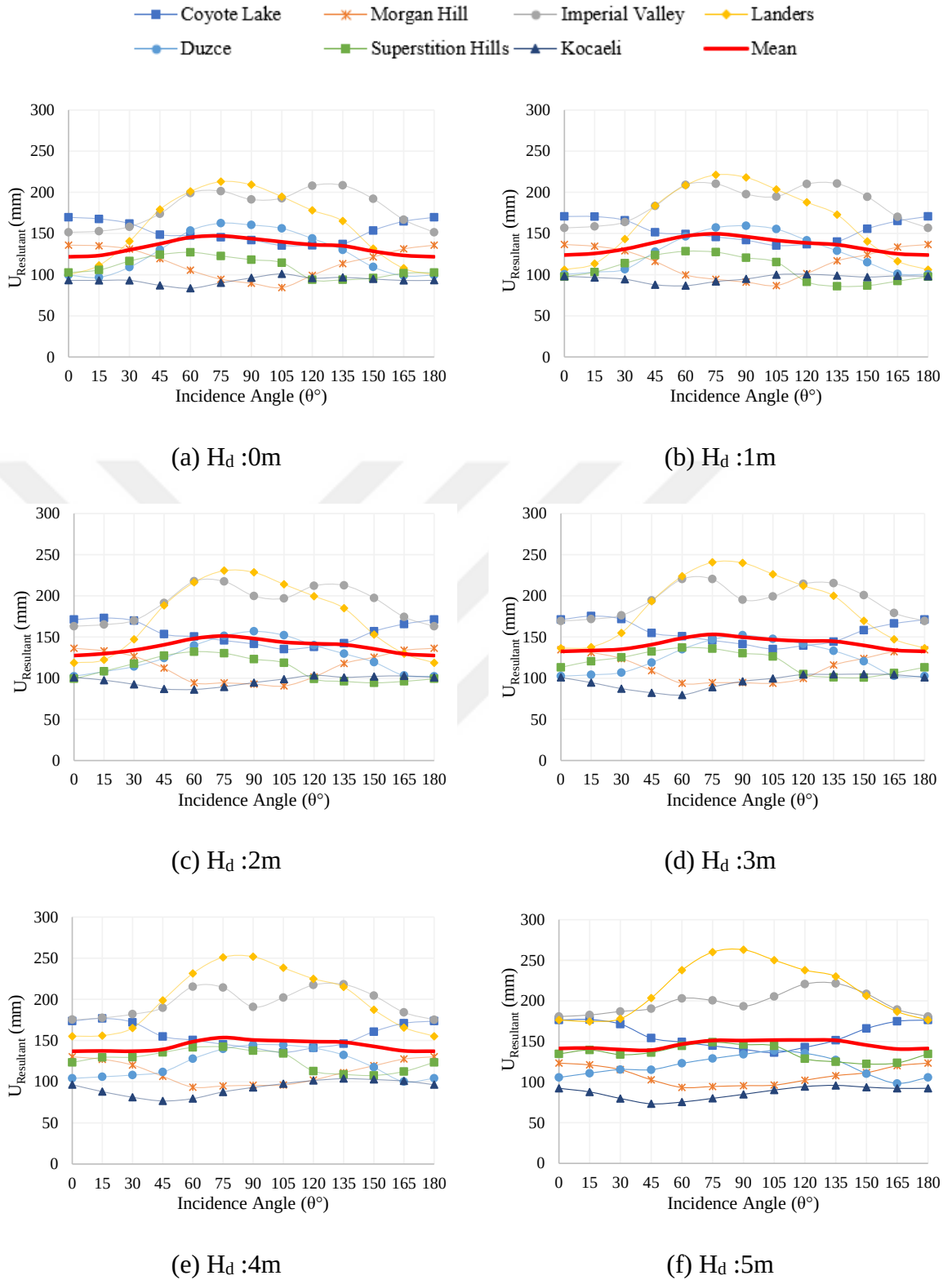


Figure 5.32. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

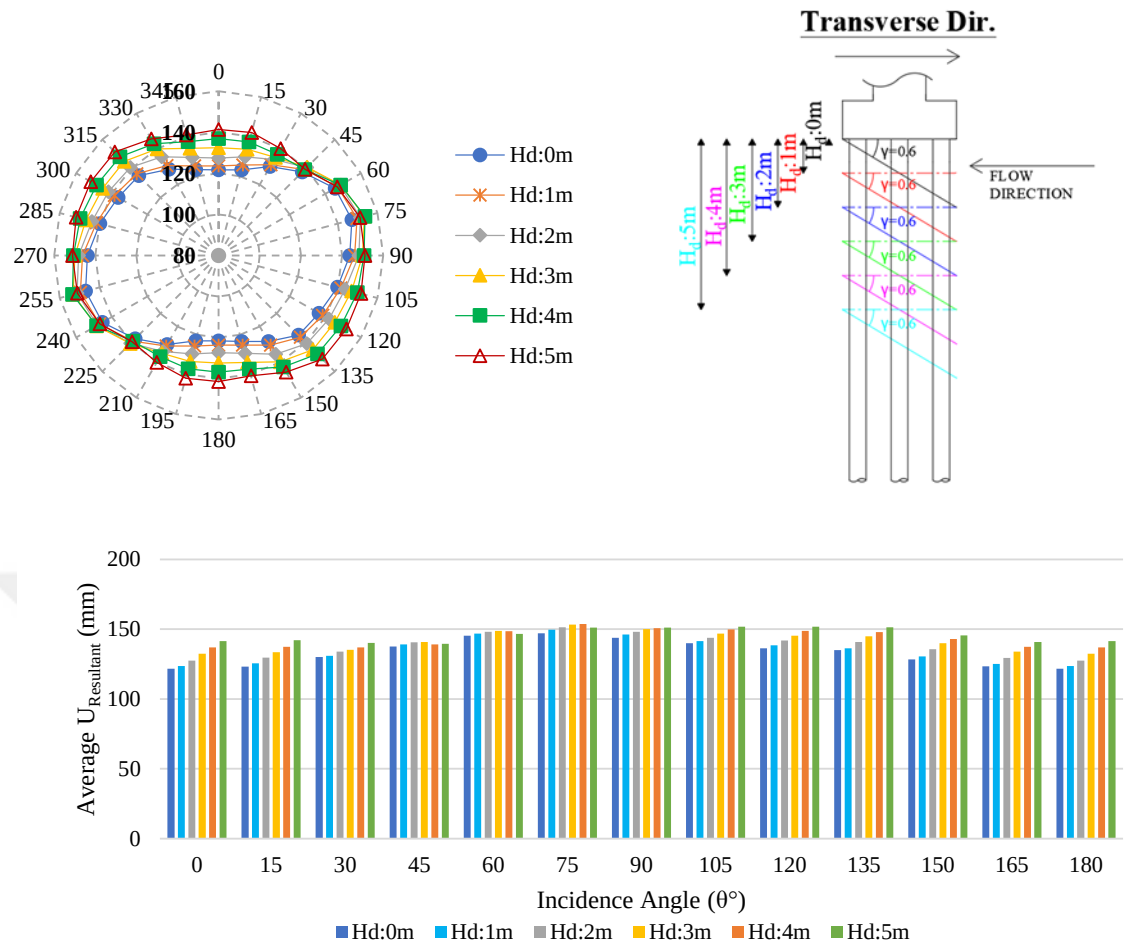


Figure 5.32. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.33 and Figure 5.34, maximum displacement demands in longitudinal and transverse direction of the 45° skewed bridge are given. Also, Figure 5.35 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results examined in terms of change in earthquake incidence angle, the average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° although in transverse direction it is decreasing between 0° and 90° . Therefore, the resultant displacement becomes nearly the same for each earthquake incidence angle. According to the radar and bar charts, the average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly

around piles. The increase of displacement in transverse direction is more obvious than in longitudinal direction of bridge in some incidence angles. The maximum difference of average displacement demands in longitudinal direction between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 45° incidence angle as nearly 5.4%. In transverse direction, it is at 15° as 18.8%. If it is checked for resultant displacement, maximum difference becomes 17.9% at 15° incidence angle.

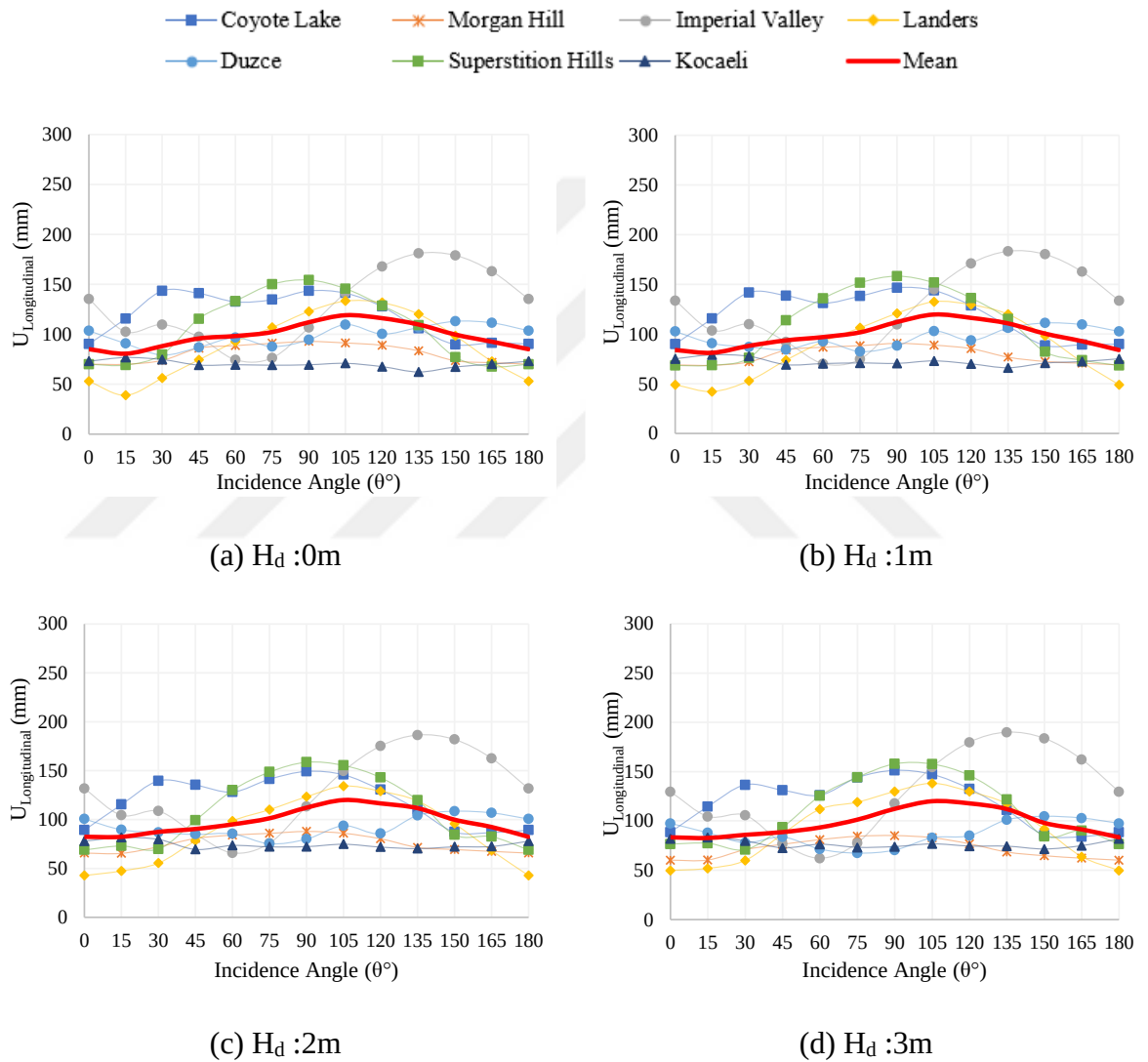
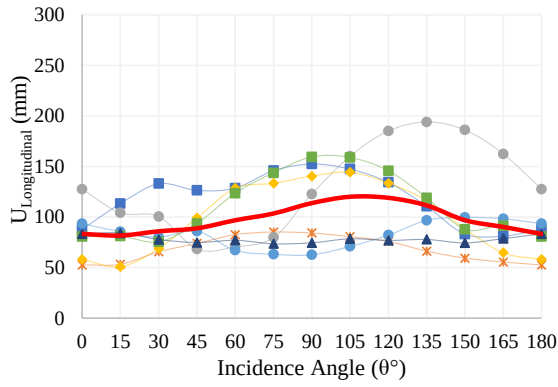
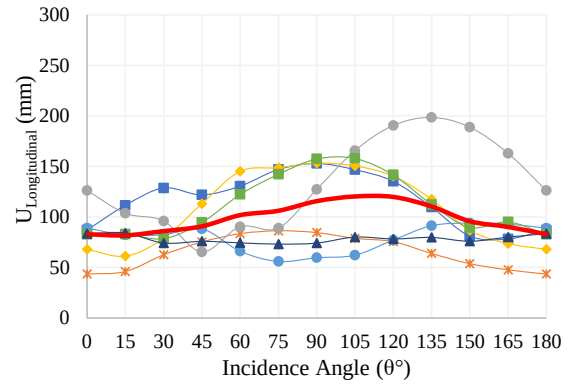


Figure 5.33. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$



(e) $H_d : 4m$



(f) $H_d : 5m$

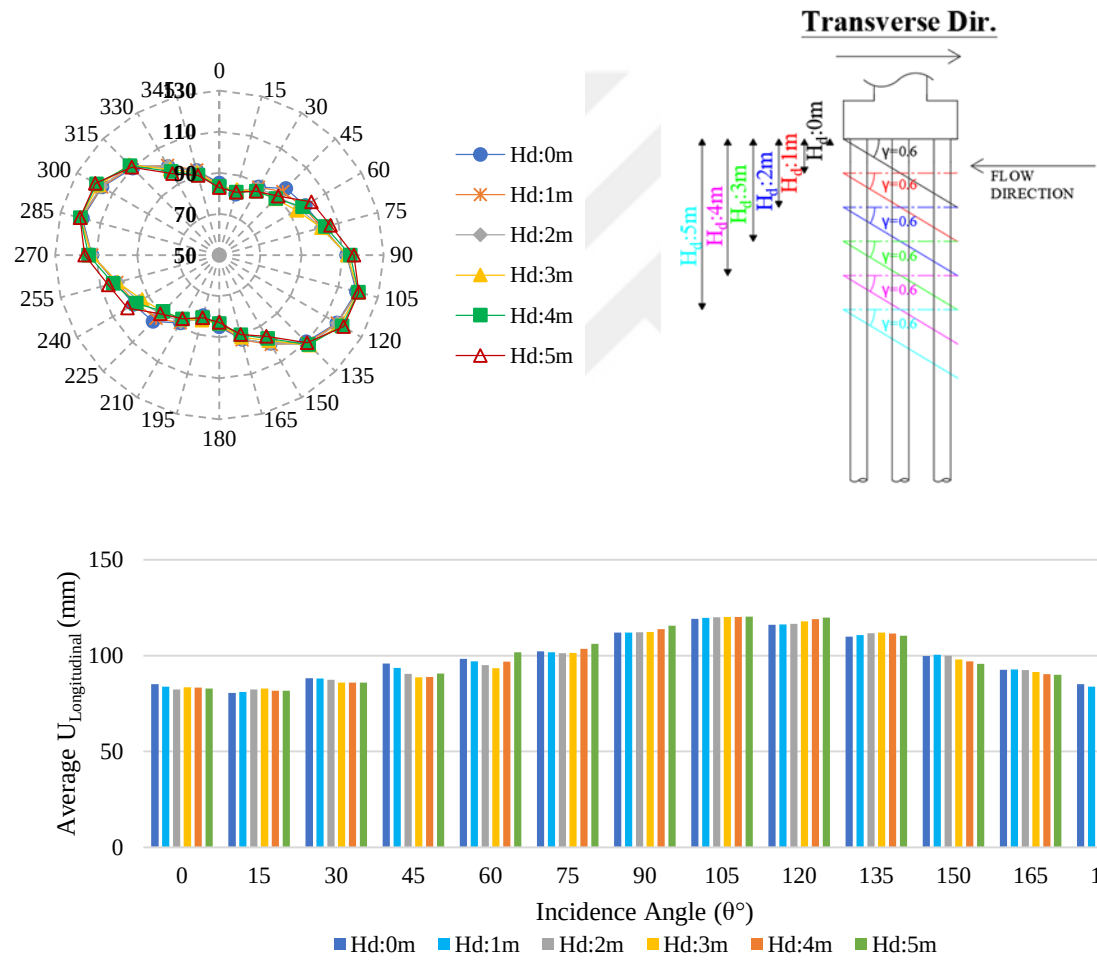


Figure 5.33. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

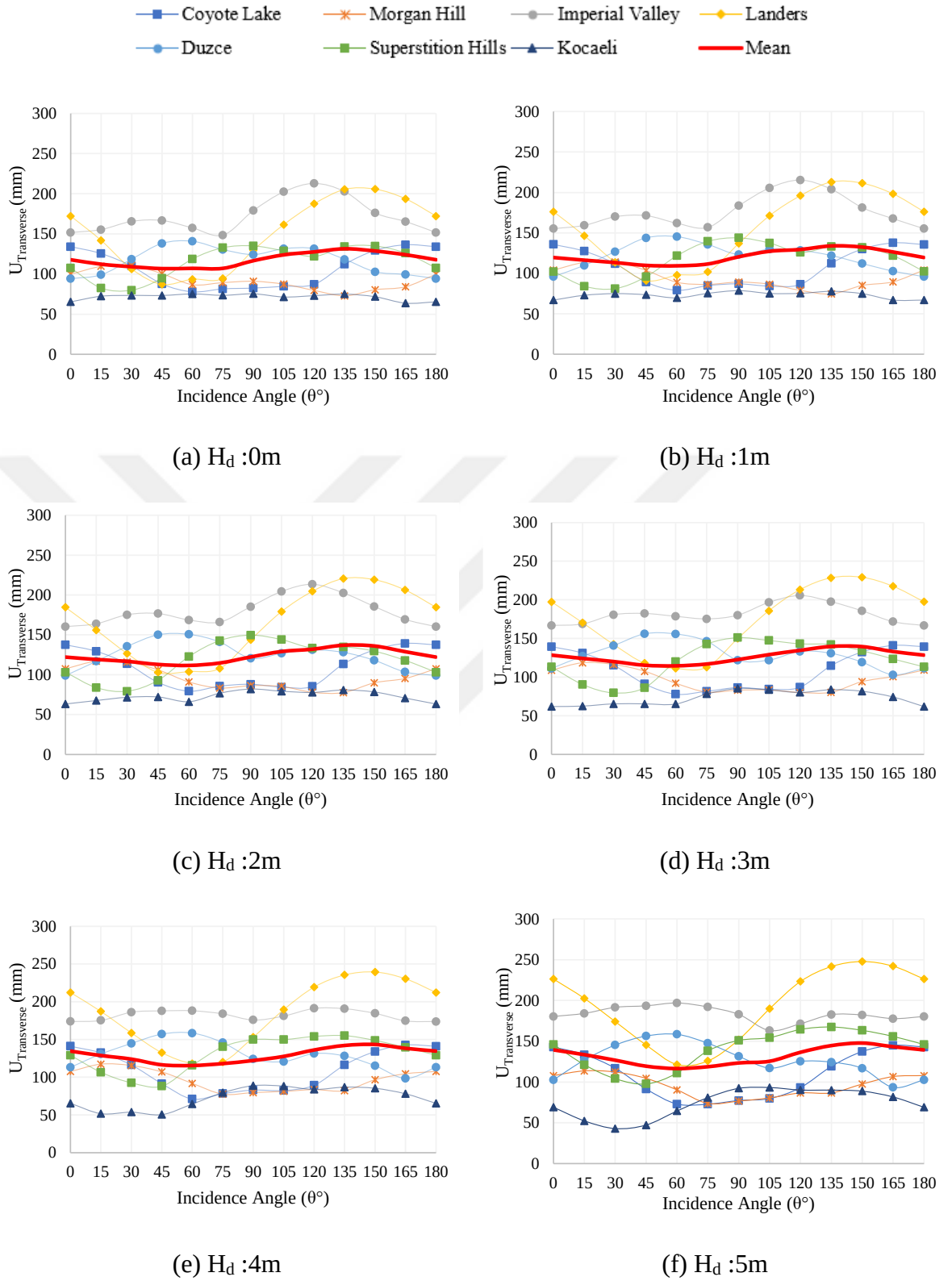


Figure 5.34. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

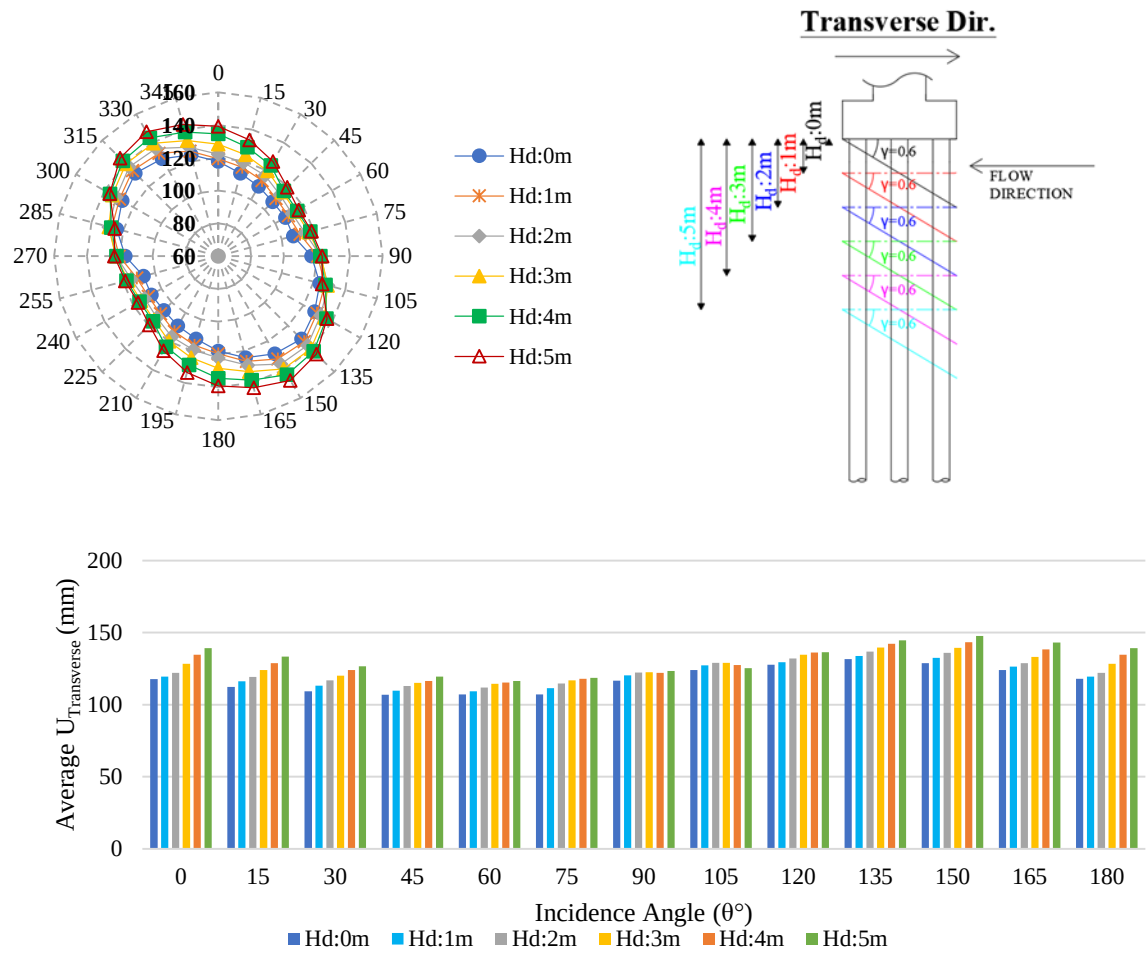


Figure 5.34. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

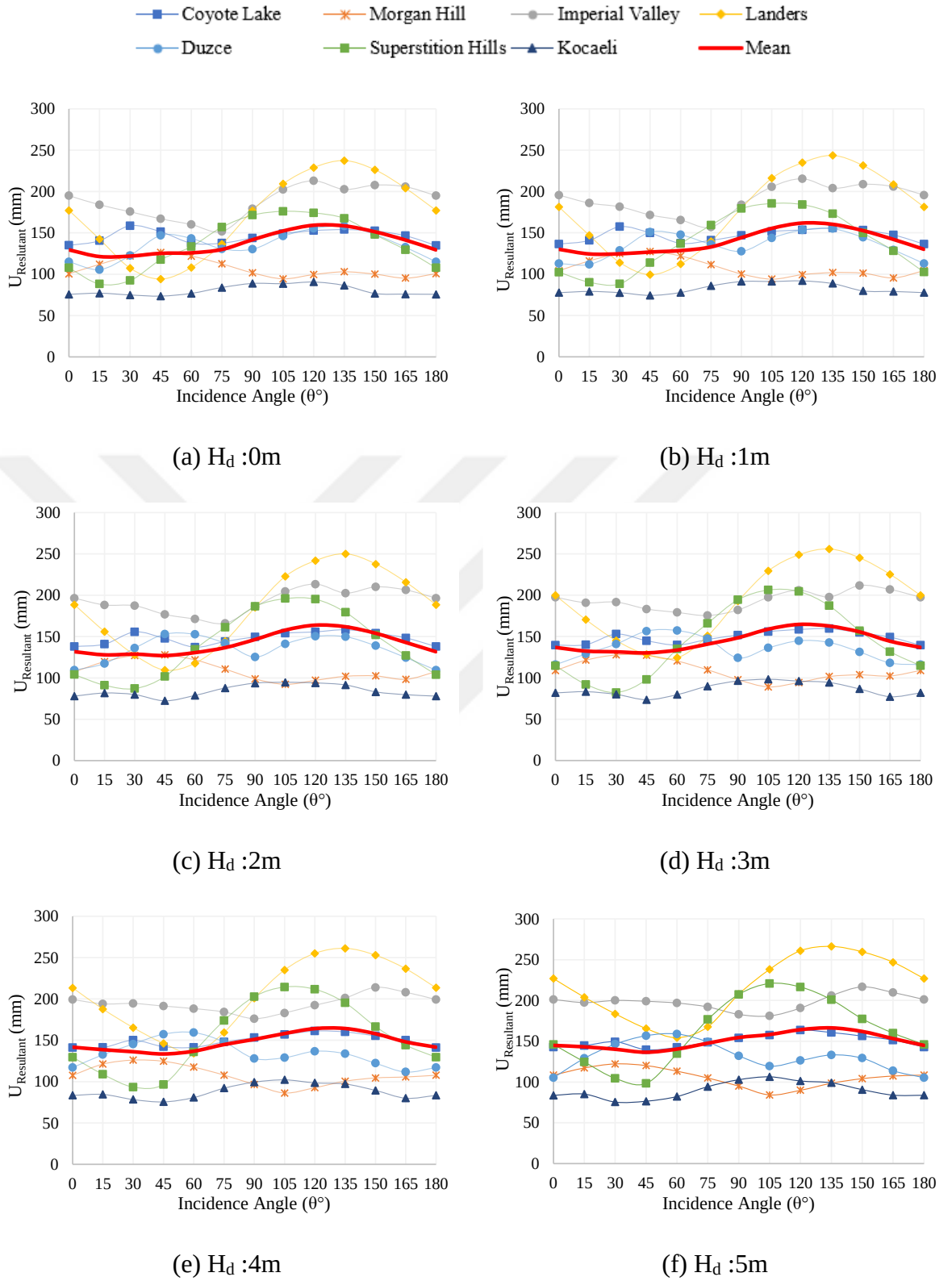


Figure 5.35. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

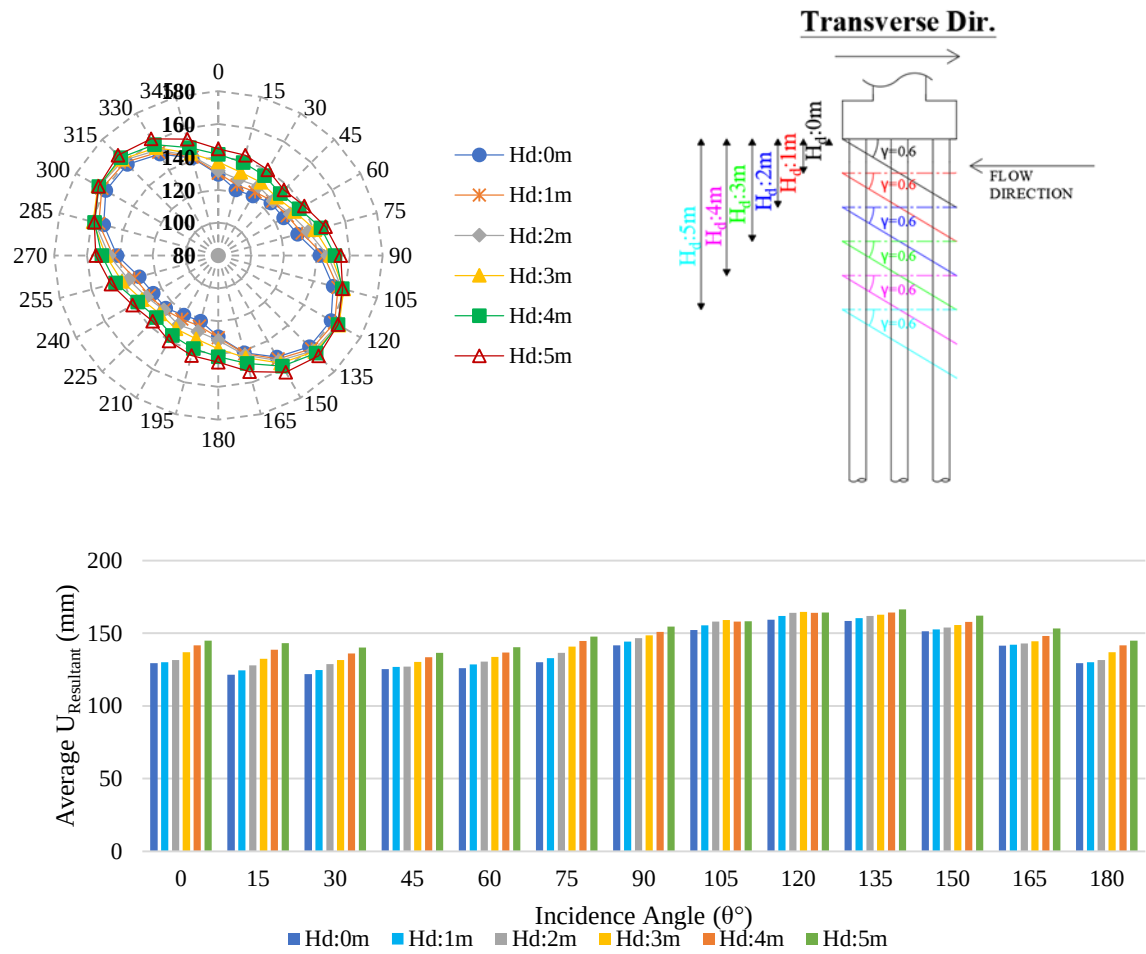


Figure 5.35. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.36 and Figure 5.37, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges and resultant displacements are compared. In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge. On the other hand, this situation is vice versa in transverse direction. For both skewed and non-skewed bridges, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 60° incidence angle and 5m scour depth as nearly 30.9%. In transverse direction, it is at 90° and 0m scour depth as 21%. If it is checked for resultant displacement, maximum difference becomes 15.5% at 60° incidence angle and 0m scour depth.

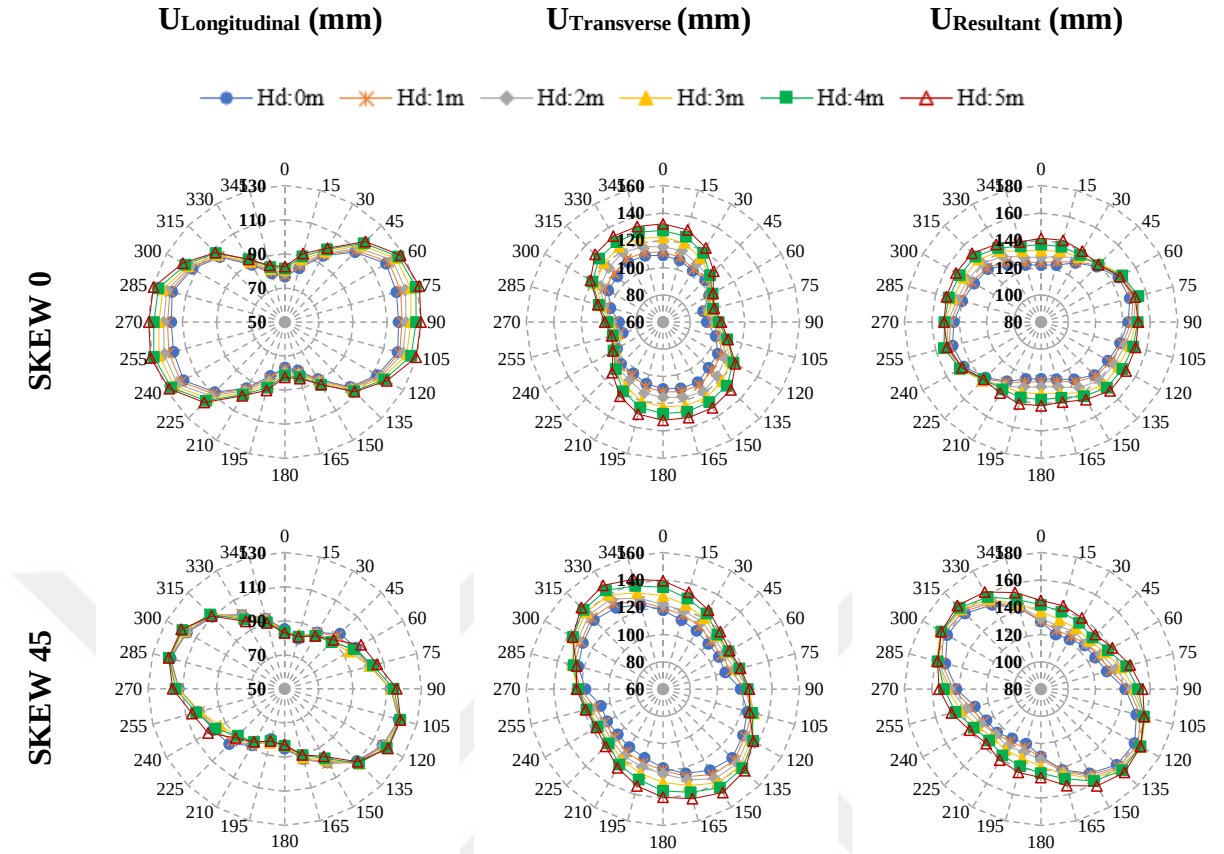


Figure 5.36. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

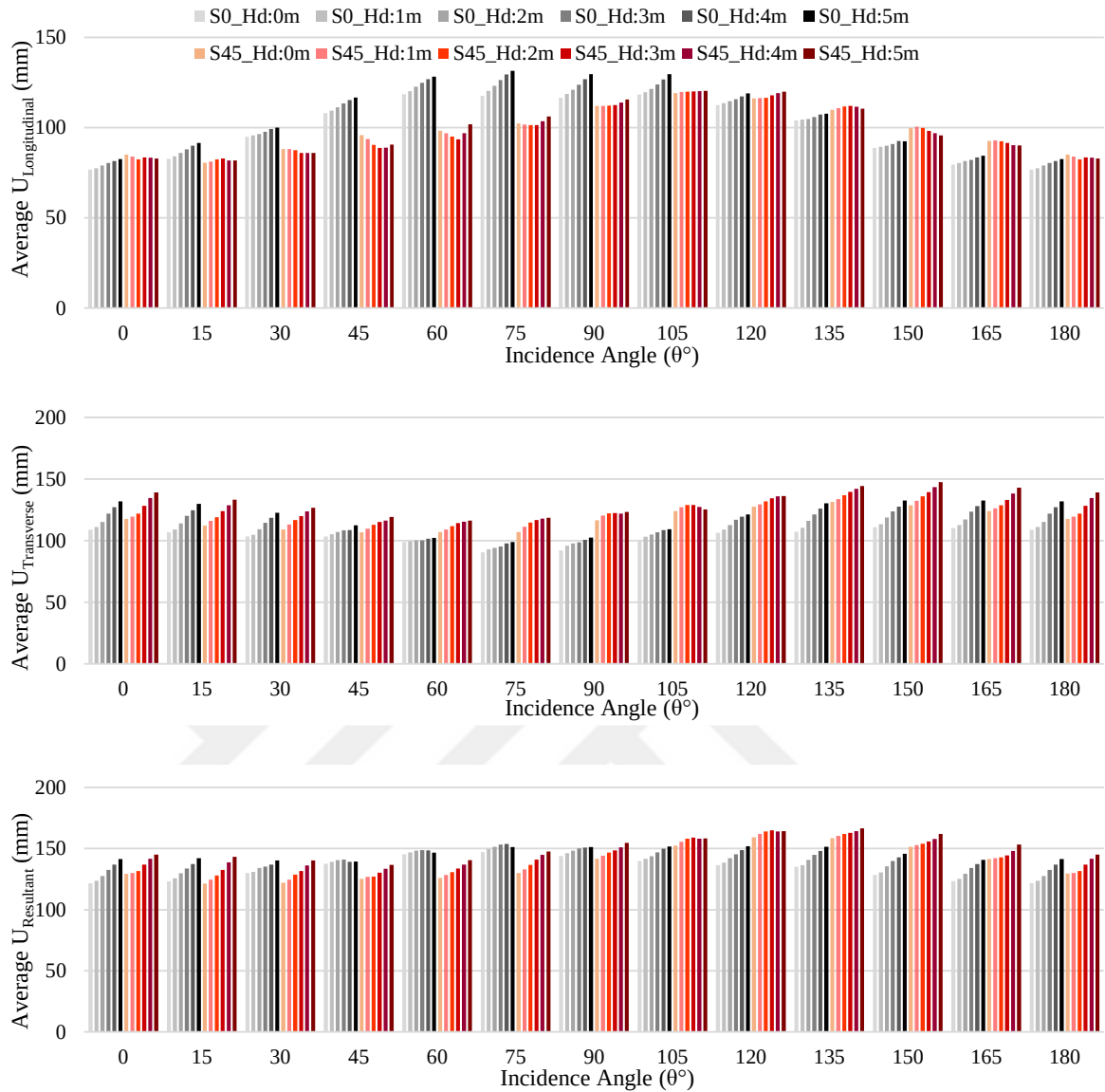


Figure 5.37. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

5.2.1.2. Curvature demands of column pier

In Figure 5.38 and Figure 5.39, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). In strong axis (z'), it has a decreasing trend between 0° and 30° and it starts to increase between 45° and 90° incidence angles. When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend

when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is the same as uniform scour case as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. Especially in strong axis (z'), the average maximum curvature demand of column is under the yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes more than 3 m. The maximum difference of curvature demands in weak axis (y') of column between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 0° incidence angle as nearly 44.3%. Also, in strong axis (z'), it becomes 71.9% at 75° incidence angle. These results show that scour around piles has a positive contribution to curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

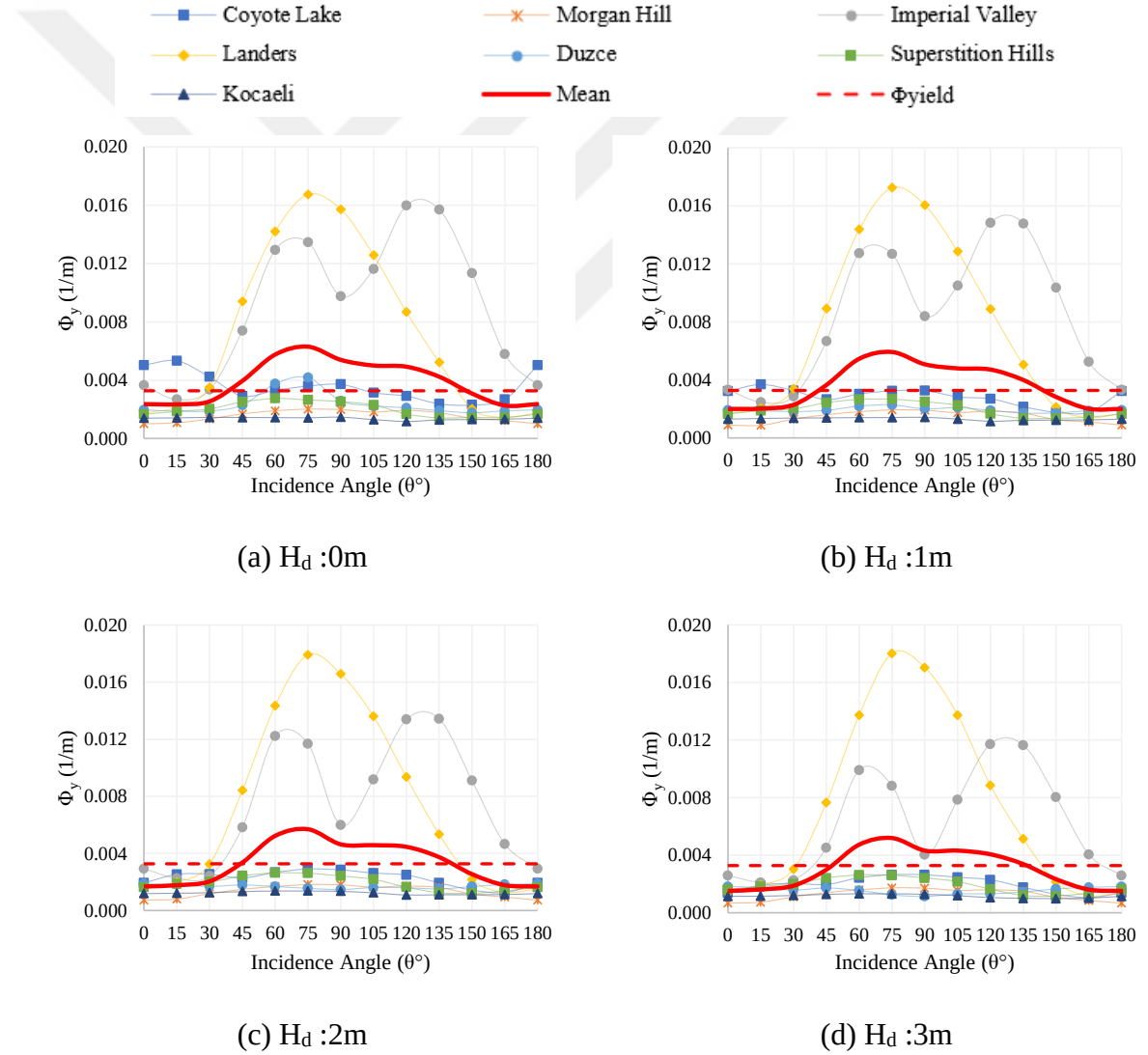
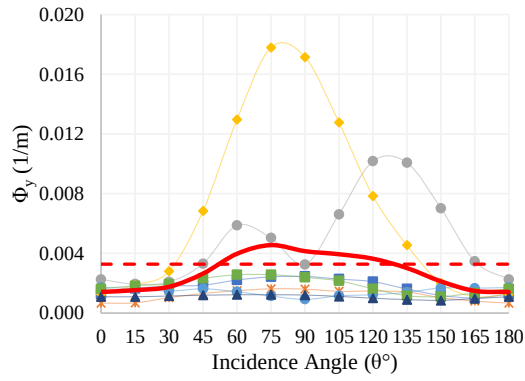
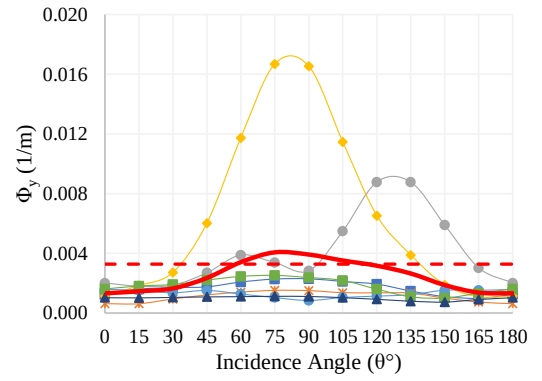


Figure 5.38. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$



(e) $H_d : 4m$



(f) $H_d : 5m$

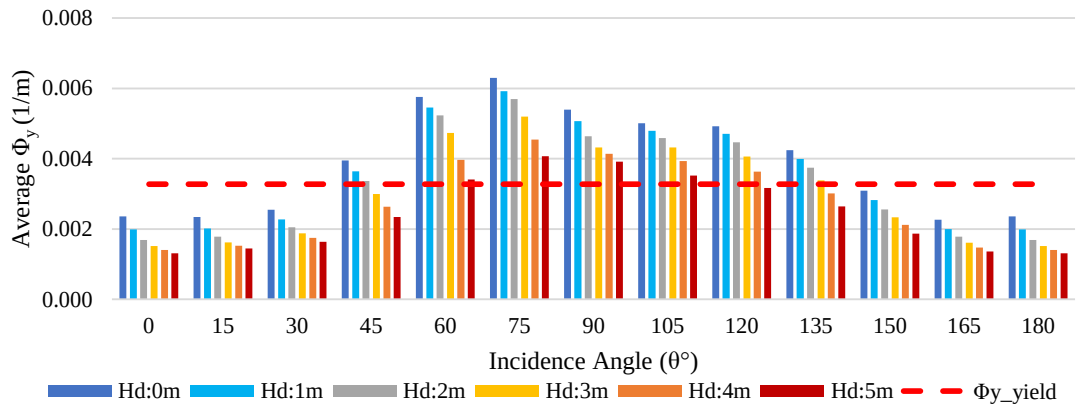
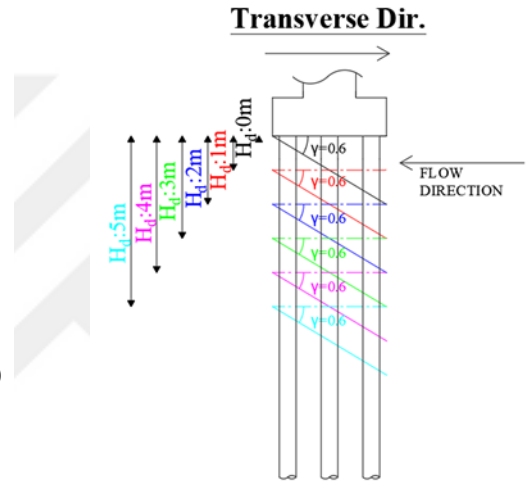
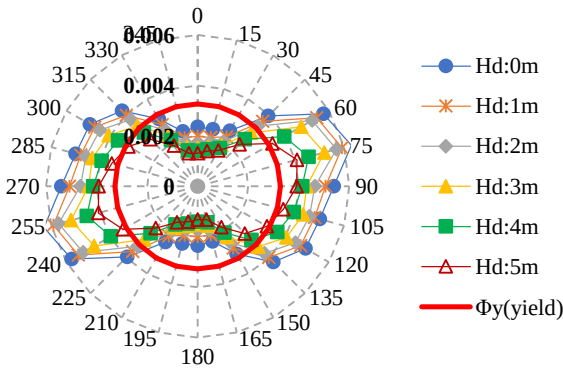


Figure 5.38. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

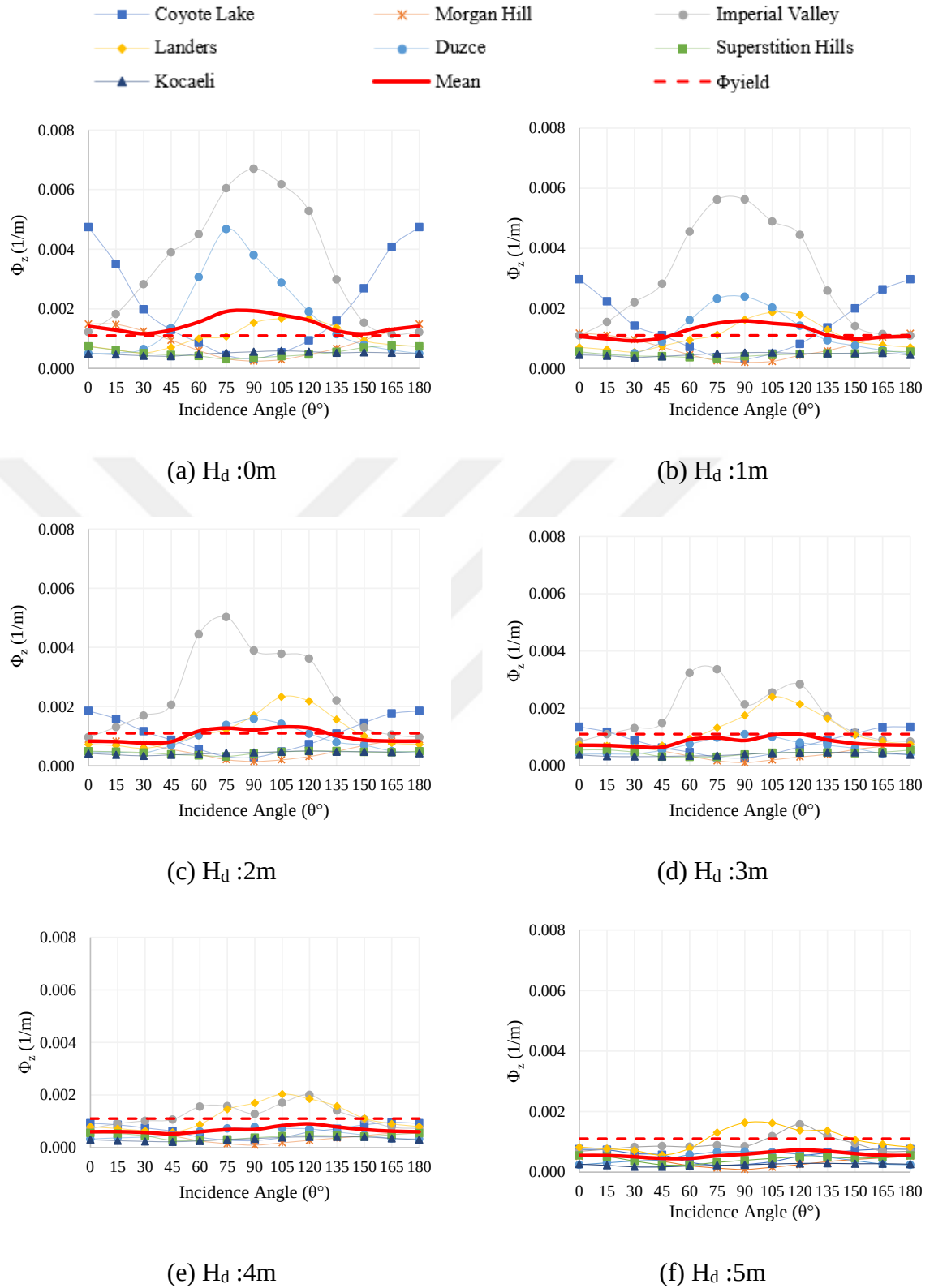


Figure 5.39. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

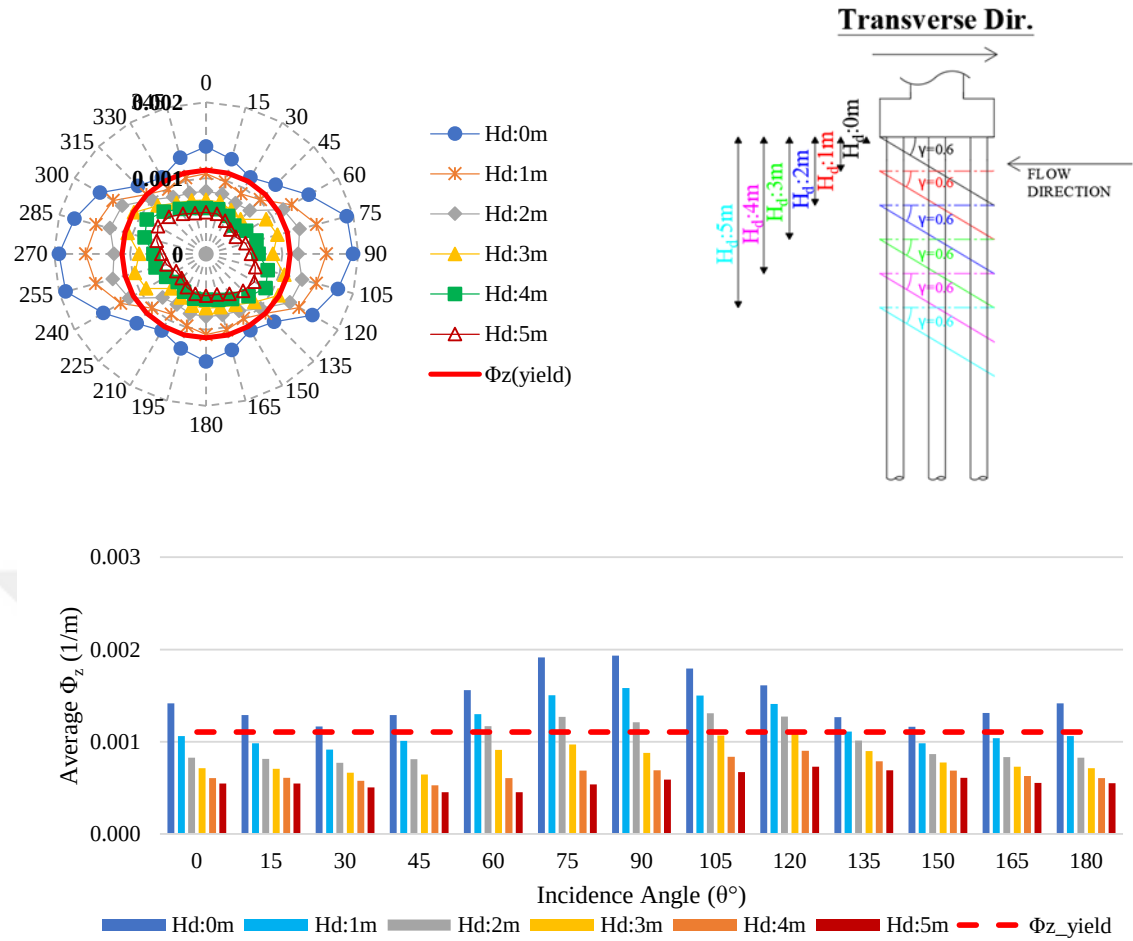


Figure 5.39. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.40 and Figure 5.41, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 120° in weak axis (y'). In strong axis (z'), it has also an increasing trend between these incidence angle. When the radar and bar chart is checked, they show that average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is the same as uniform scour case as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. Especially in strong axis (z'), the average maximum curvature demand of column is under yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes 4m and 5m. The maximum difference of

curvature demands in weak axis (y') of column between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 45° incidence angle as nearly 46.9%. Also, in strong axis (z'), it becomes 56.2% at 105° incidence angle. These results show that scour around piles has a positive contribution to curvature demands of 45° skewed bridge column piers.

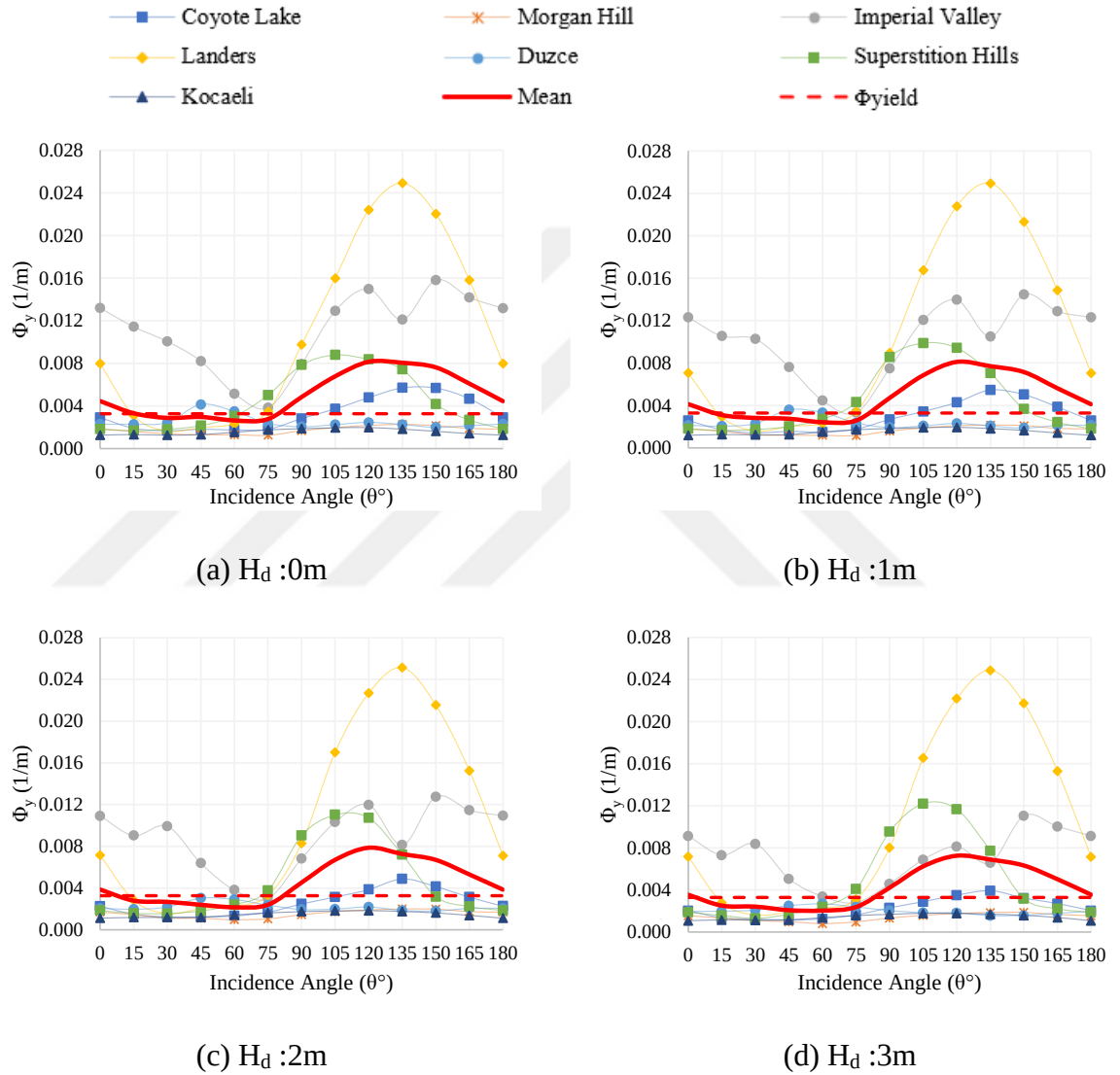
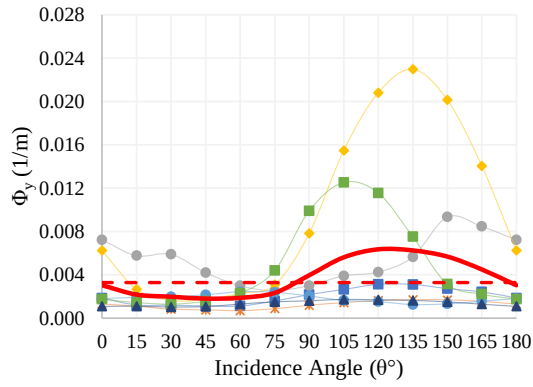
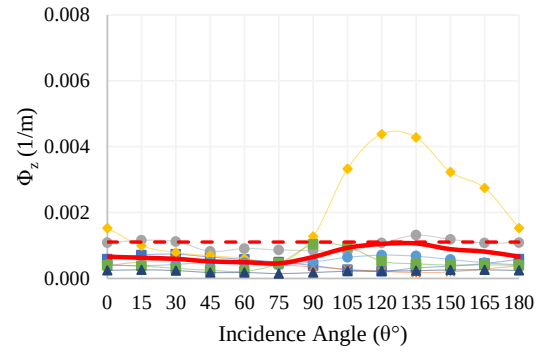


Figure 5.40. Maximum curvature demands in weak axis (y') of skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$



(e) $H_d : 4m$



(f) $H_d : 5m$

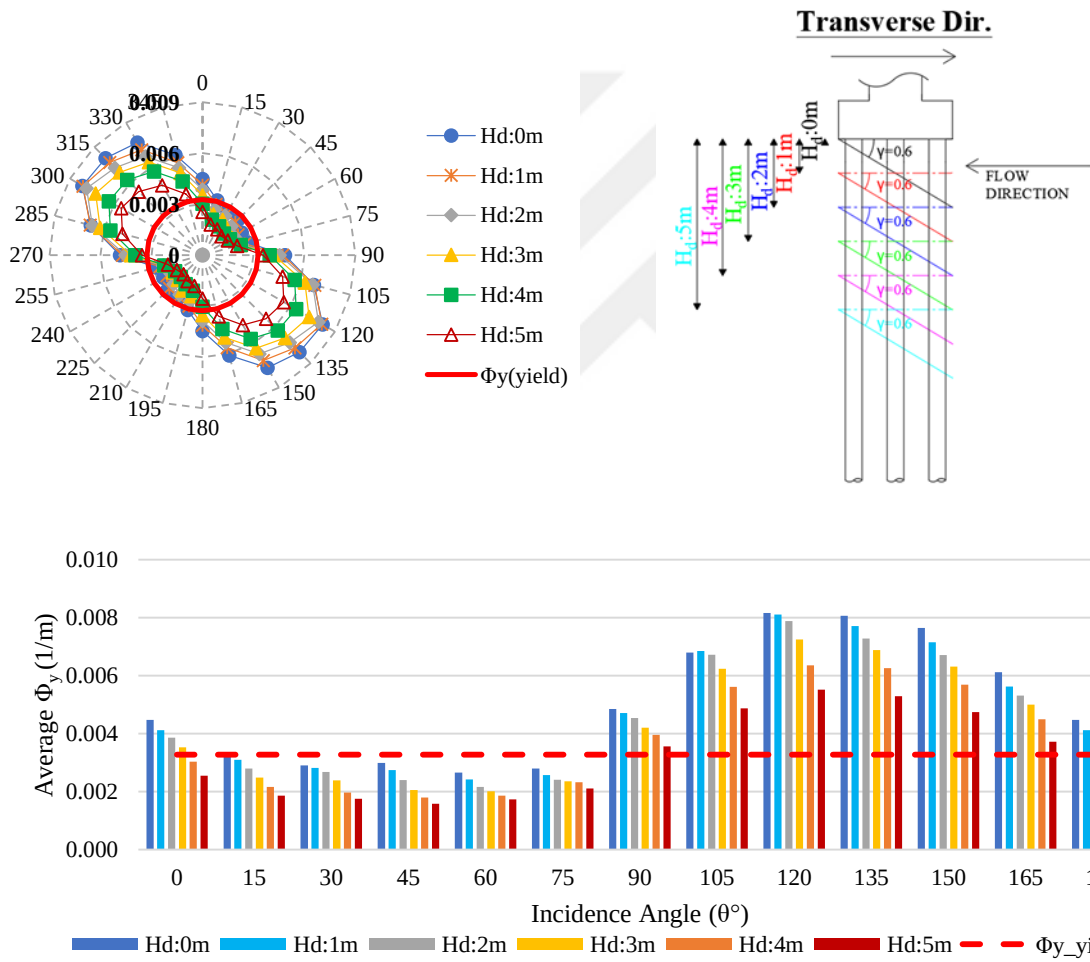


Figure 5.40. Maximum curvature demands in weak axis (y') of skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)



Figure 5.41. Maximum curvature demands in strong axis (z') of skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

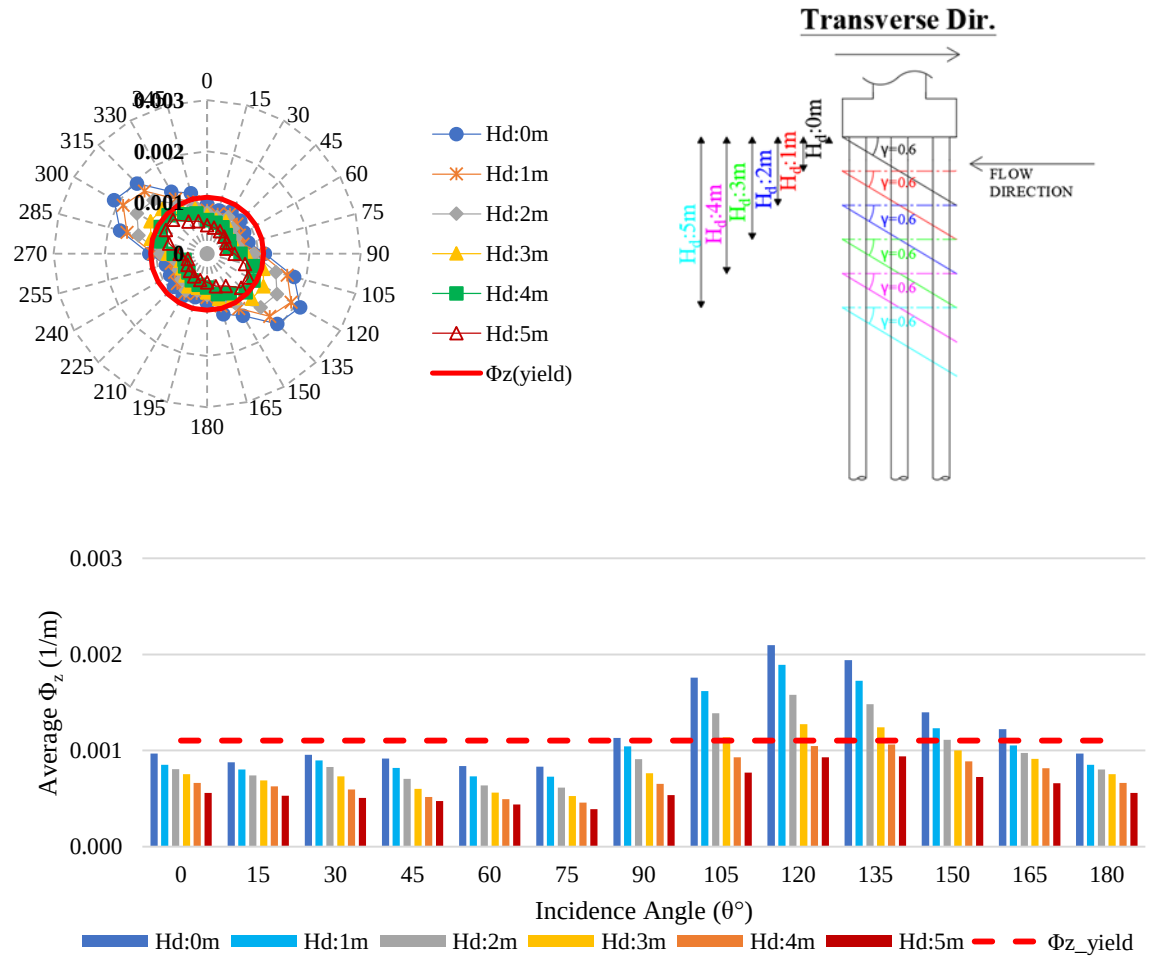


Figure 5.41. Maximum curvature demands in strong axis (z') of skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.42 and Figure 5.43, maximum curvature demands of column weak (y') and strong (z') axes of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges are compared. In column weak axis (y'), curvature demands are higher in non-skewed bridge at 75° incidence angle. However, it becomes much higher in skewed bridge at 135° incidence angle. Moreover, this situation is similar in strong (z') axis of column at 90° and 120° incidence angles respectively. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 5m scour depth as nearly 170.1%. In strong axis, it is at 75° and 0m scour depth as 56.4%.

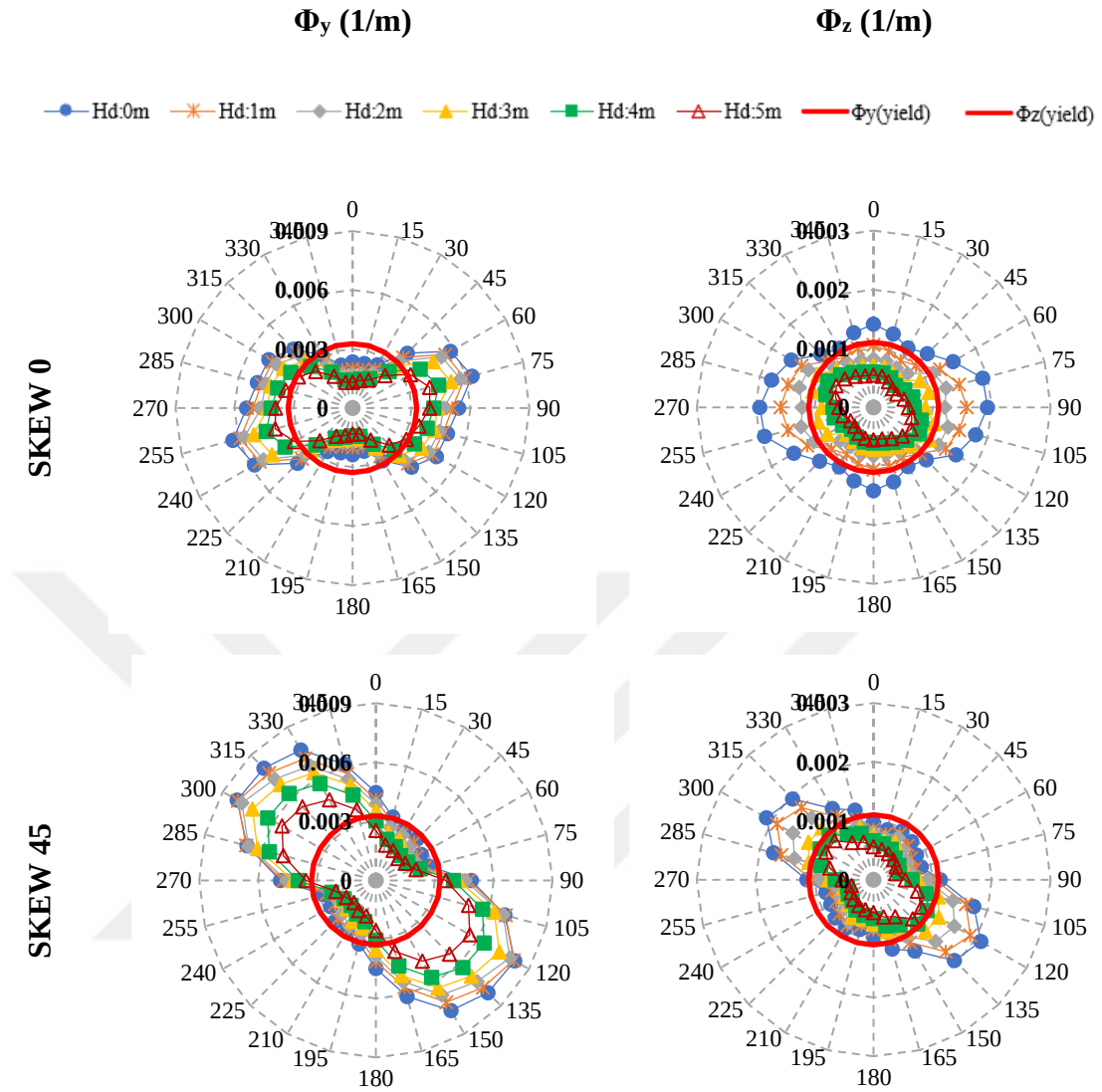


Figure 5.42. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

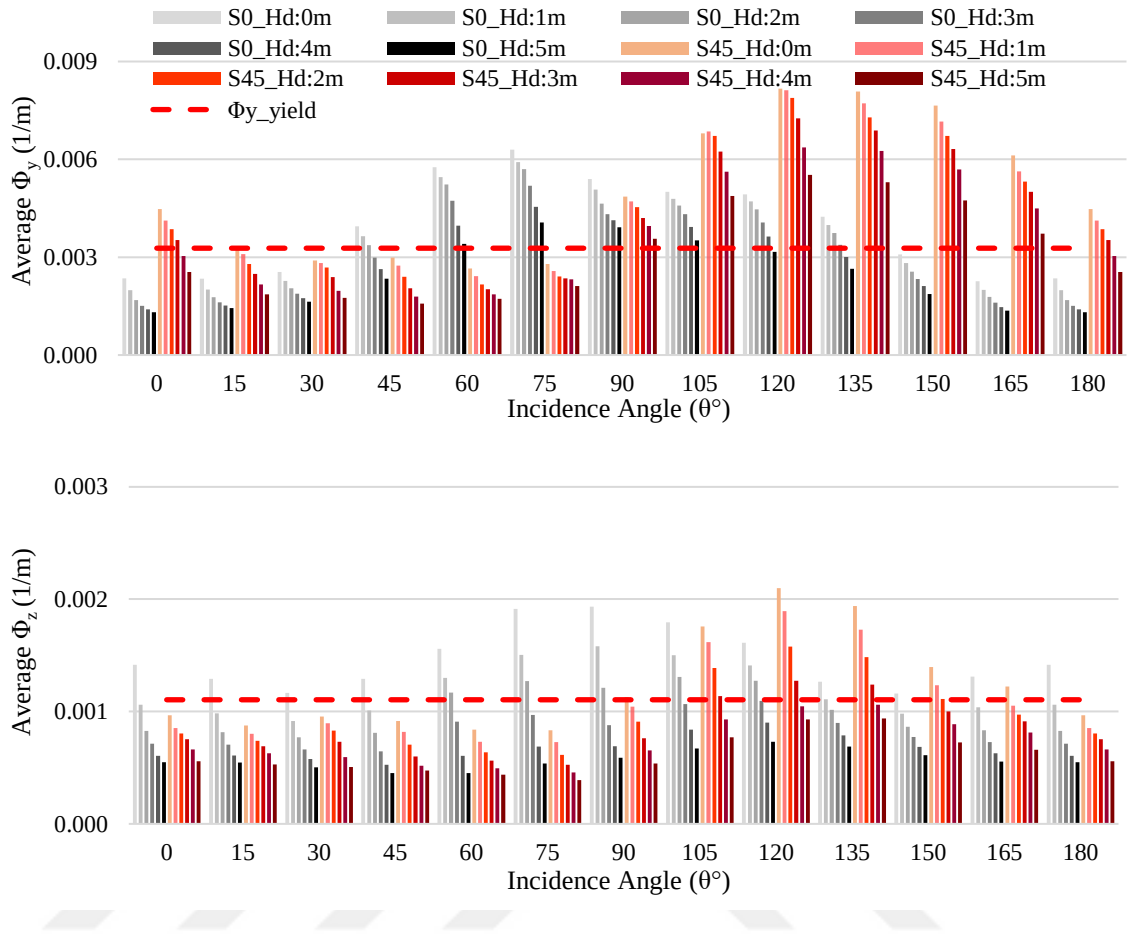


Figure 5.43. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

5.2.1.3. Shear force demands of column pier

In Figure 5.44 and Figure 5.45, the maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between those angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_d=0\text{m}$) and 5m scoured ($H_d=5\text{m}$) models occurs at 60° incidence angle as nearly 31.8%. Also, it is about 14.3% at 165° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When average maximum shear force demands are compared to these capacities, demands are below the limits for all

scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis.

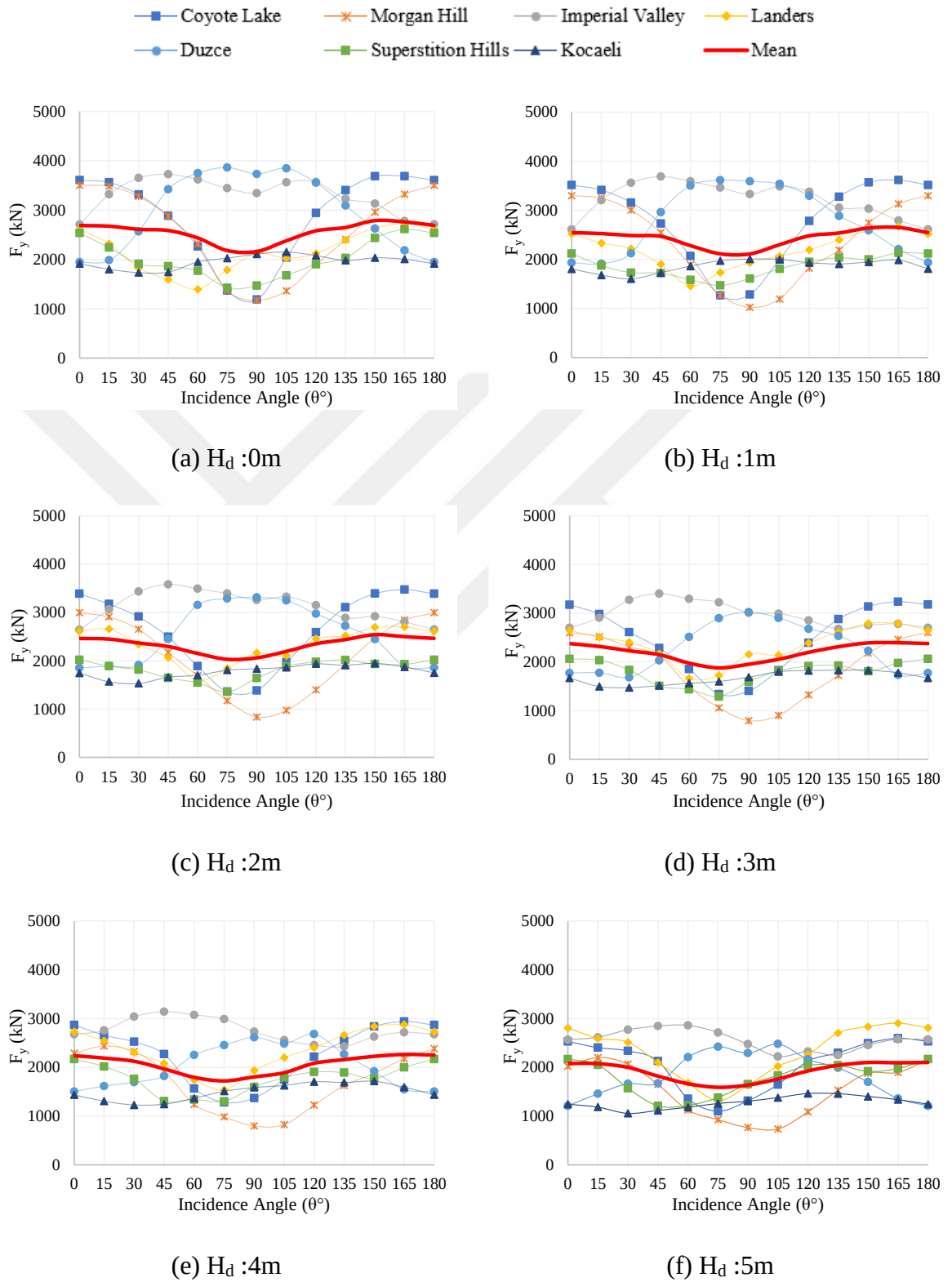


Figure 5.44. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

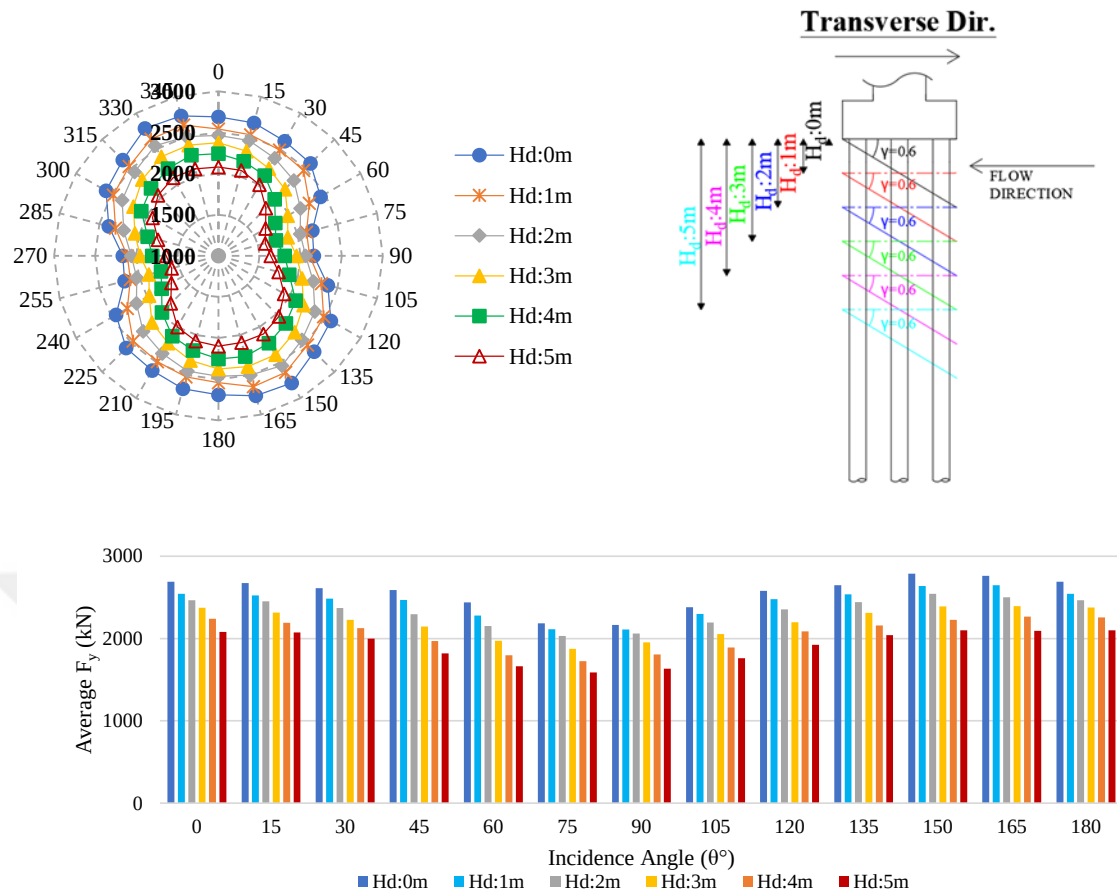


Figure 5.44. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

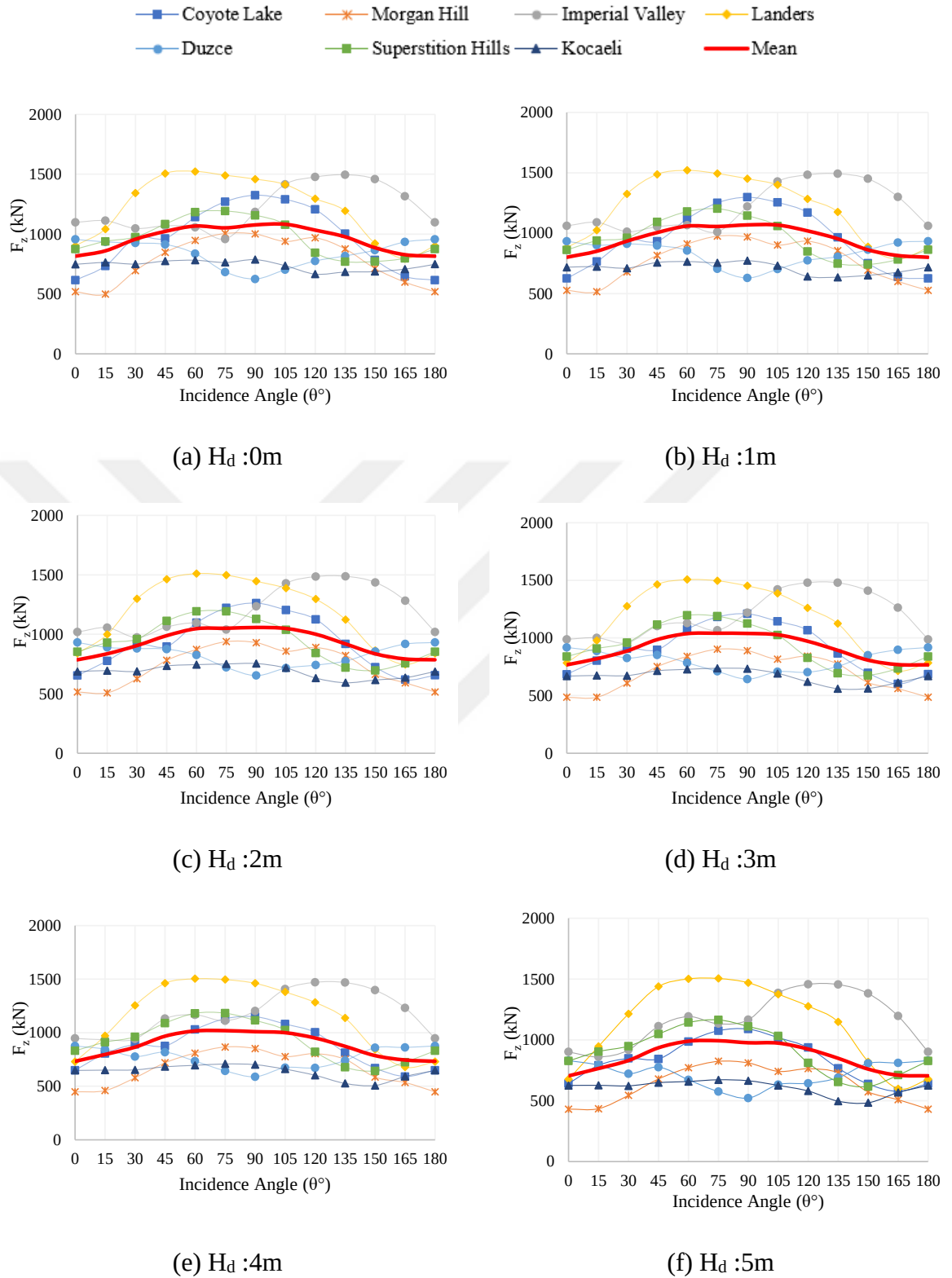


Figure 5.45. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

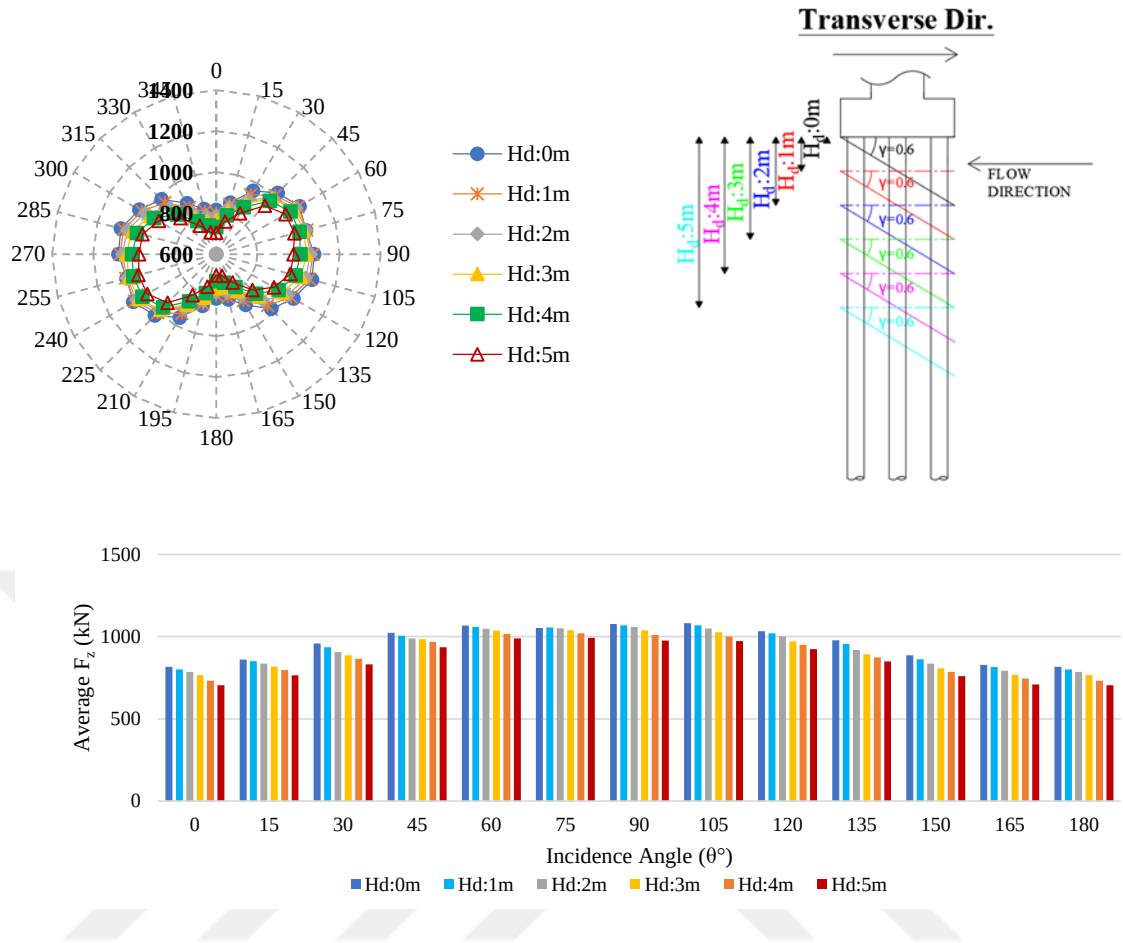


Figure 5.45. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.46 and Figure 5.47, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 120° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_d=0m$) and 5m scoured ($H_d=5m$) models occurs at 90° incidence angle as nearly 30.2%. Also, it is about 19.3% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour

depths and incidence angles. Therefore, it can be said no shear damage occurred in the 45° skewed bridge column during nonlinear analysis.

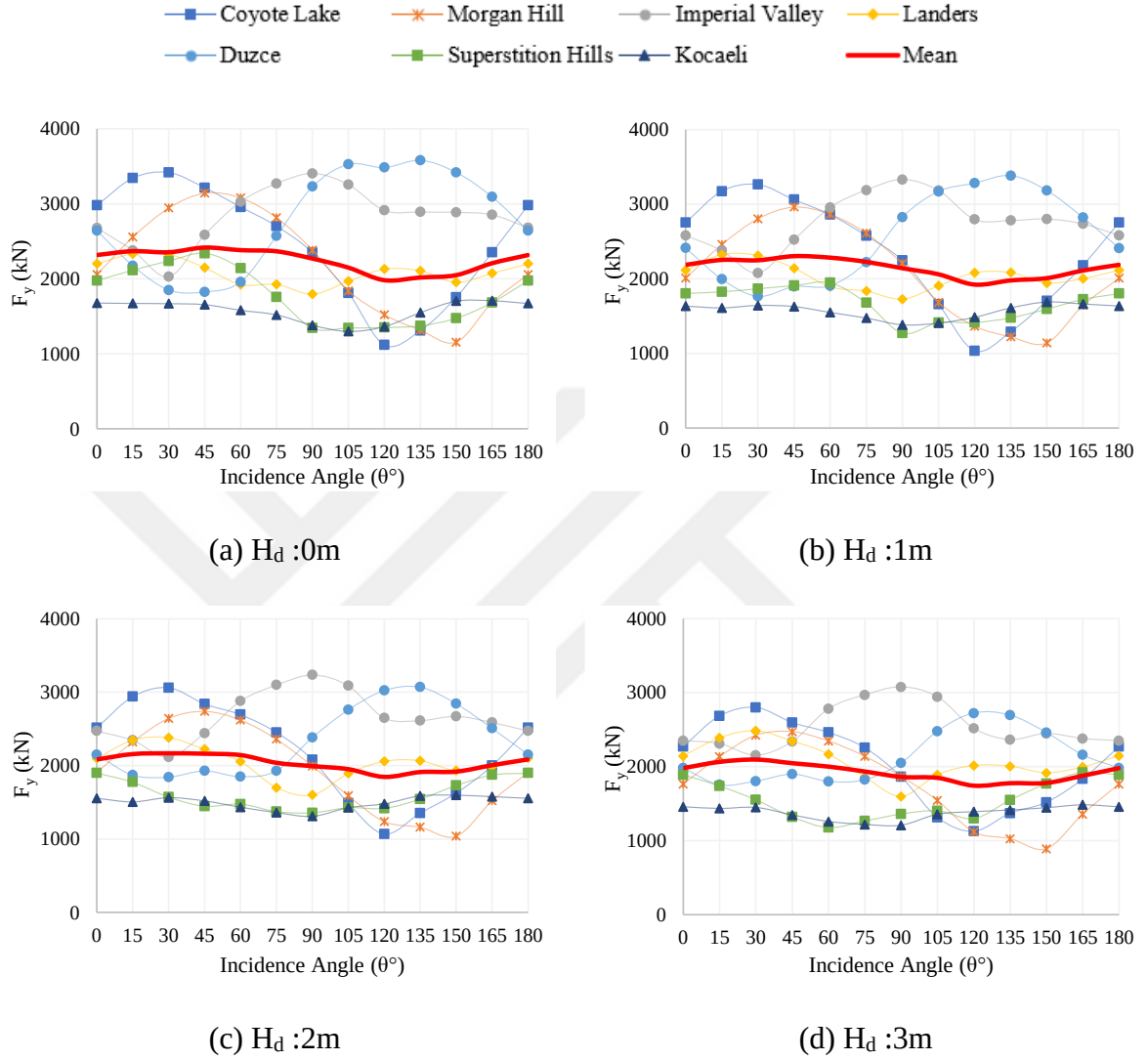
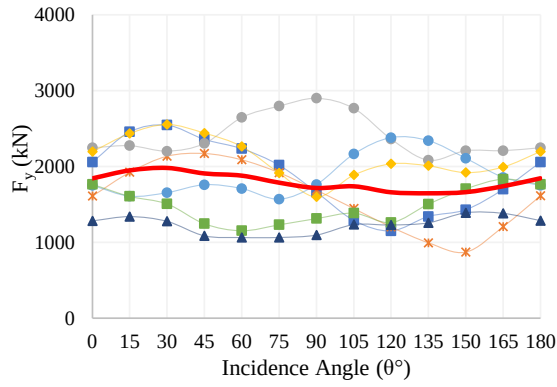
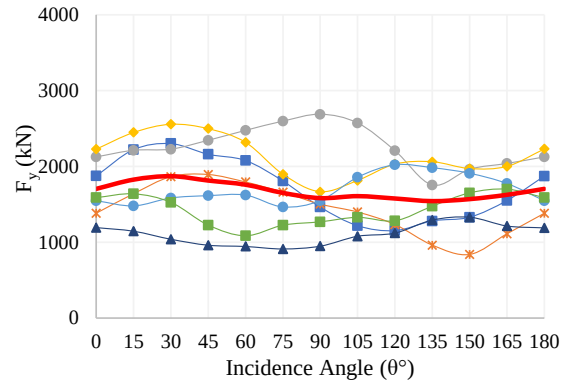


Figure 5.46. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$



(e) $H_d : 4m$



(f) $H_d : 5m$

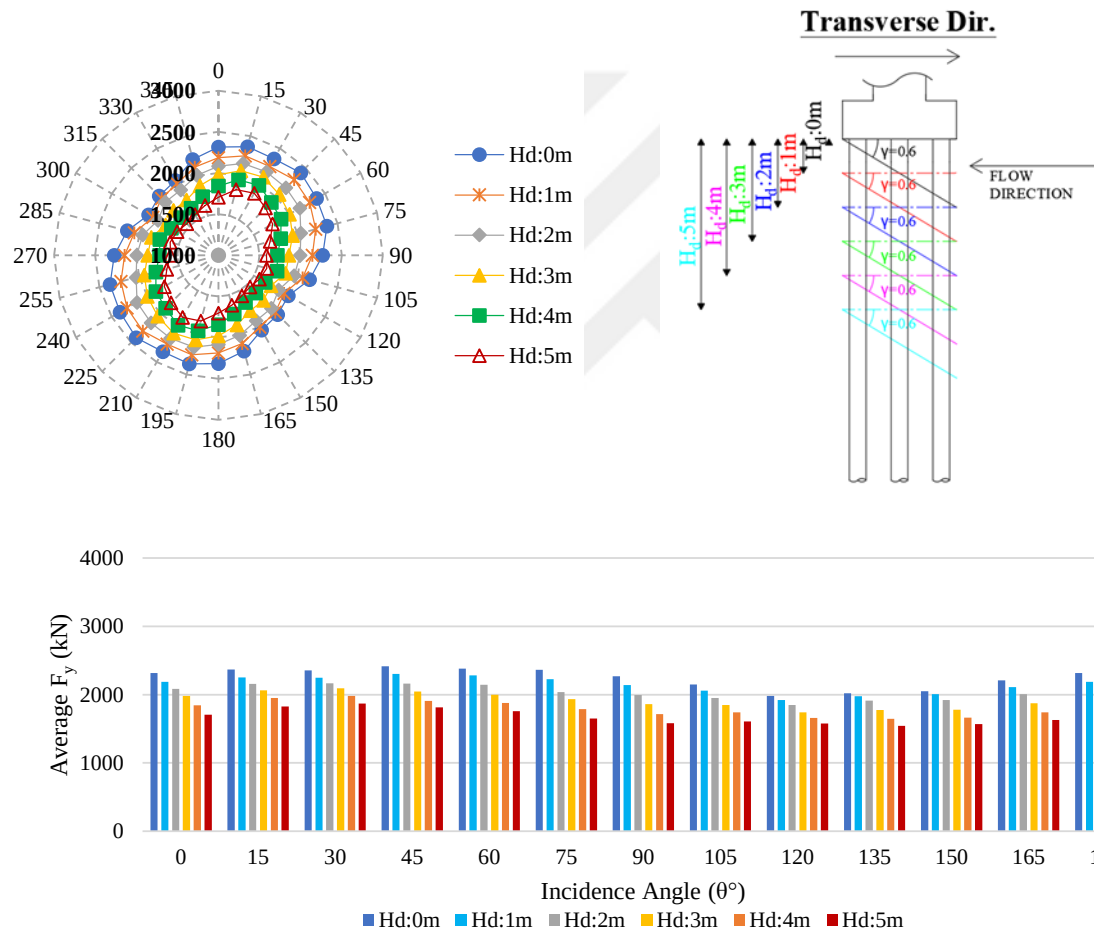


Figure 5.46. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

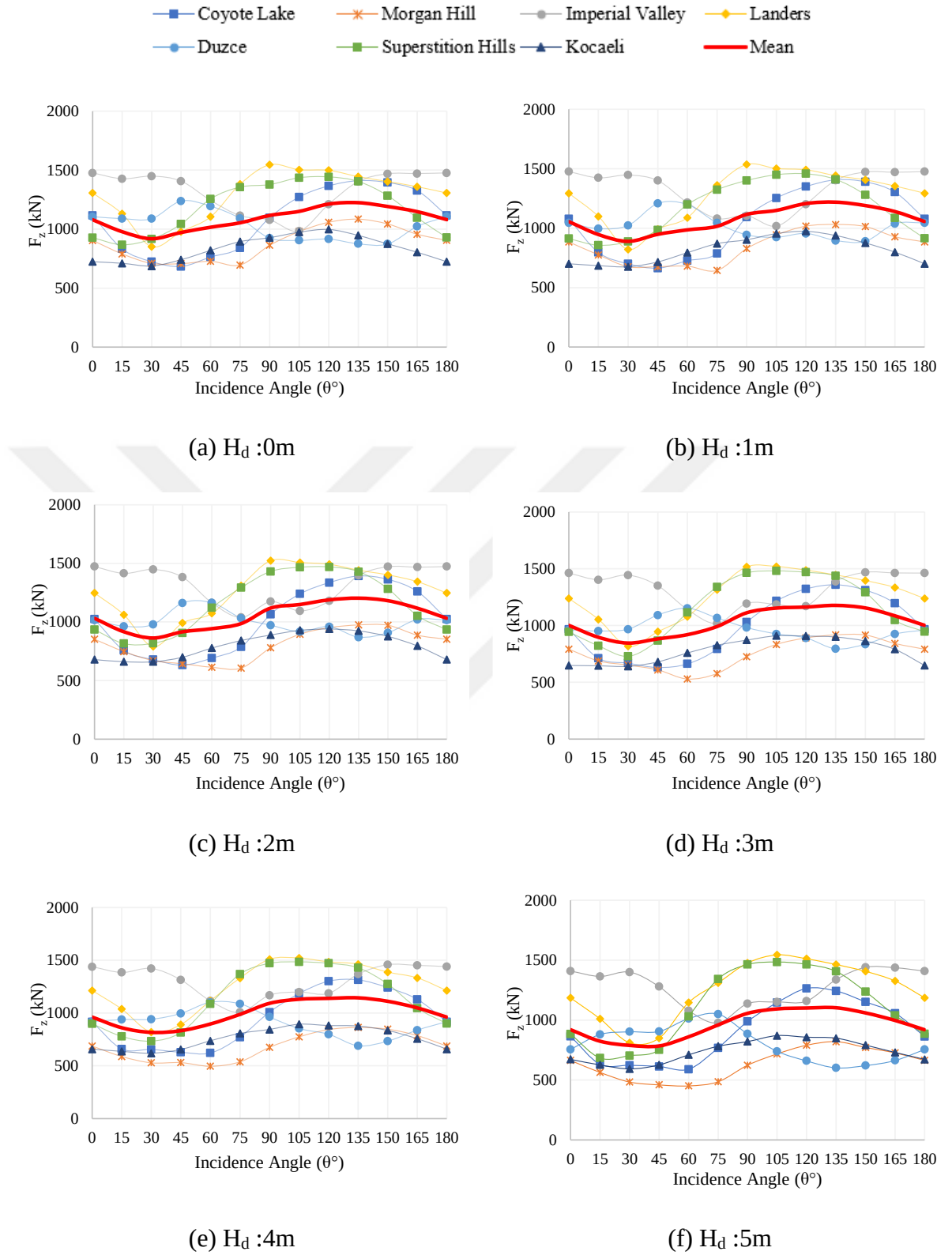


Figure 5.47. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

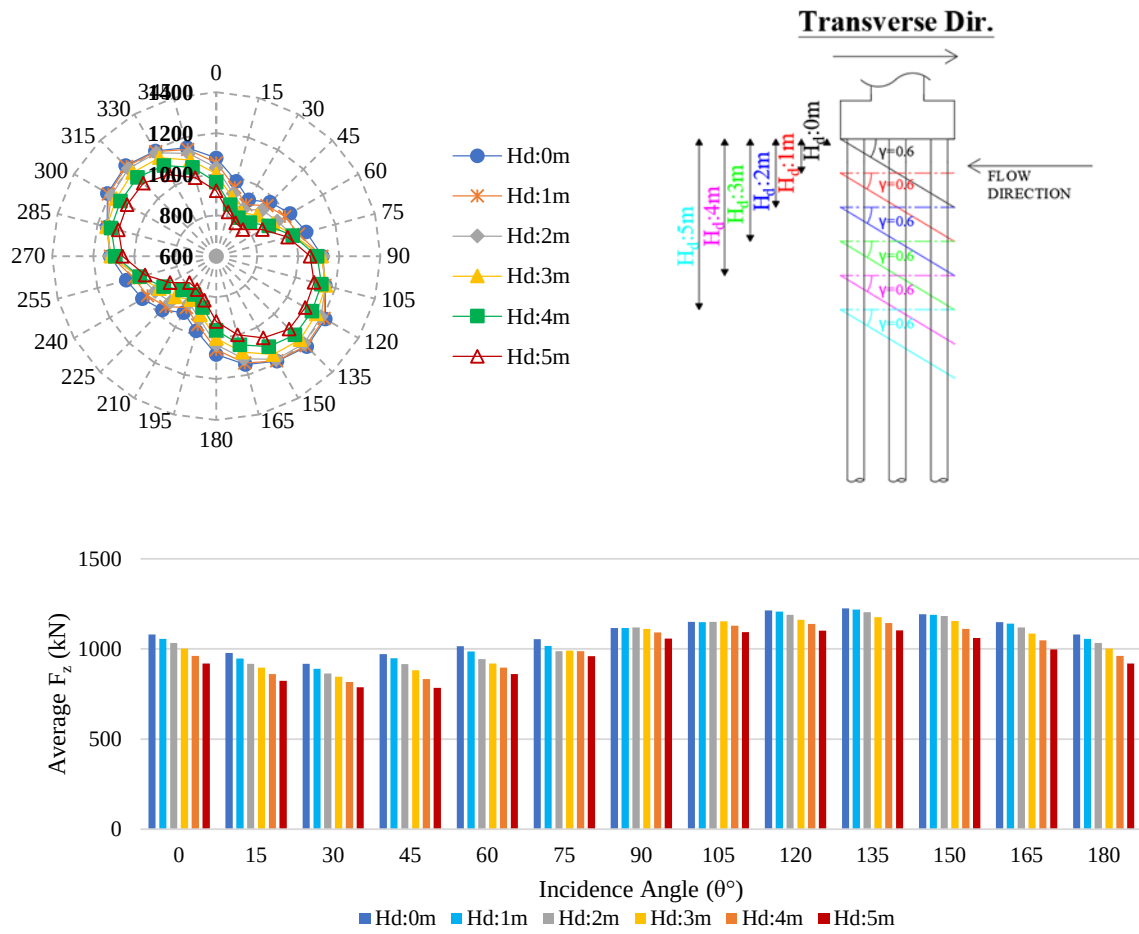


Figure 5.47. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (continued)

In Figure 5.48 and Figure 5.49, maximum shear force demands of column local y' and z' axes of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges are compared. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 150° incidence angle and 0m scour depth as nearly 26.4%. In local z' axis, it is at 150° and 3m scour depth as 42.9%.

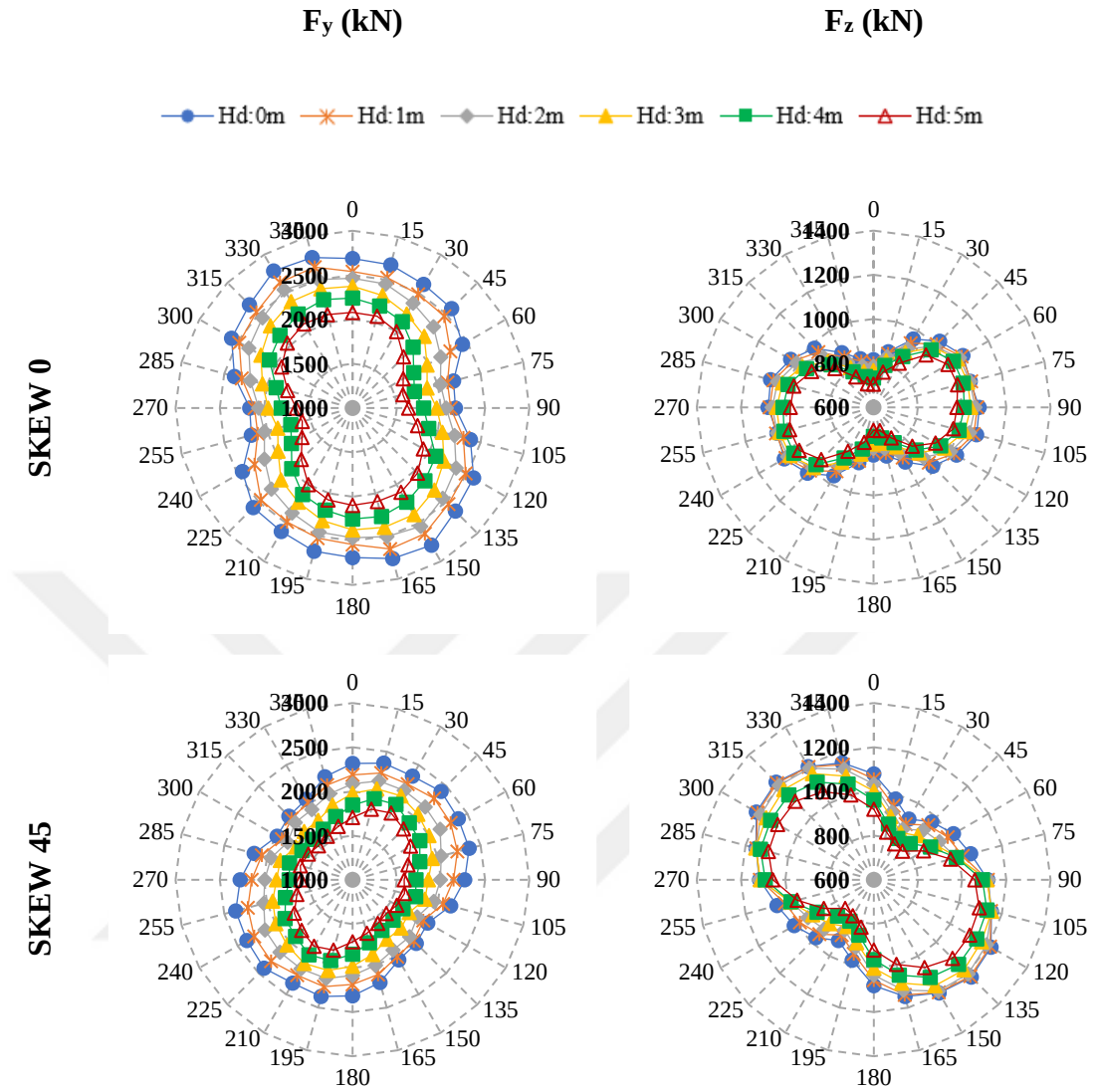


Figure 5.48. Average maximum shear force demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

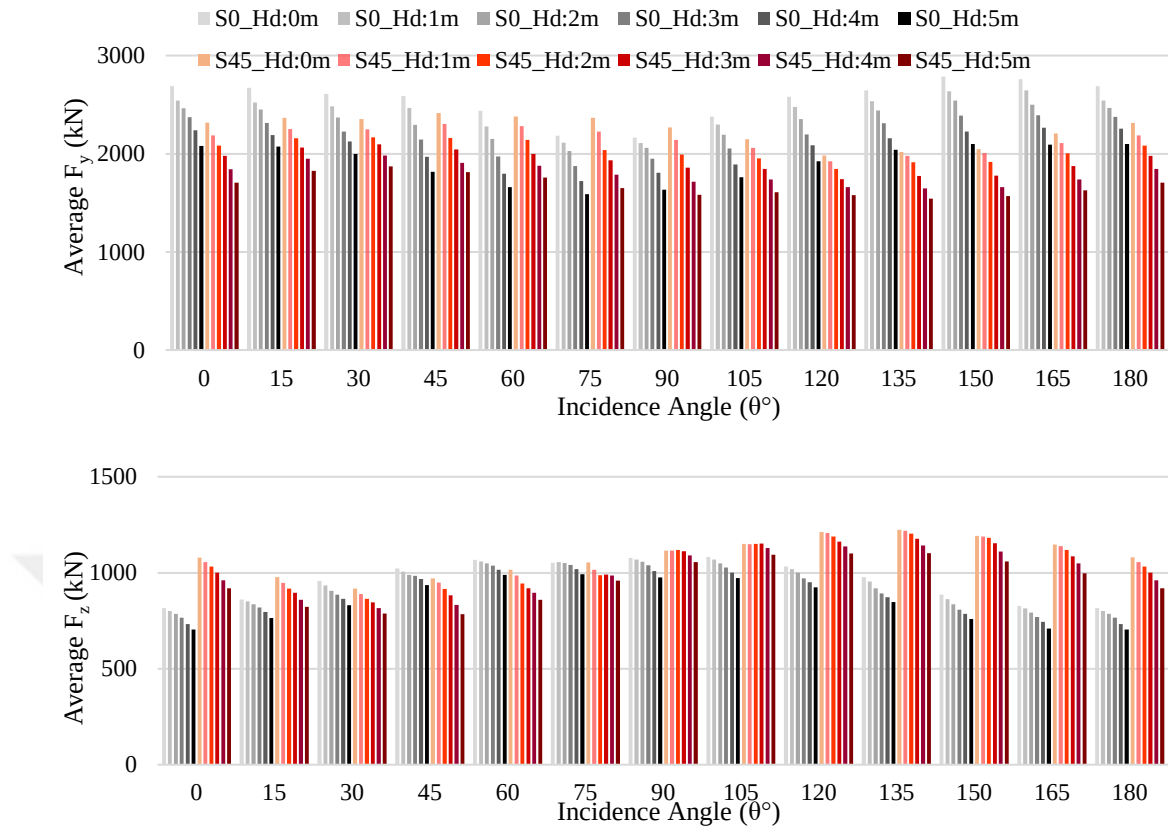


Figure 5.49. Average maximum shear force demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$

5.2.1.4. Shear force demands of piles

In Figure 5.50 and Figure 5.51, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. As it can be seen from the graphs, shear force demands occurred in downstream piles are more than demands occurred in upstream ones in both axes. For scour depths 0m, 1m, 2m and 3m of local y' axis of downstream piles, shear force demands are exceeding pile shear capacity of 735.2 kN in both non-skewed and skewed bridges. It means, shear failure occurs on piles in downstream during earthquake. Also, demands are below the shear capacity in local z' axis for all piles. Therefore, shear force demands of local y' axis of pile number 4 (P4) which is placed at downstream is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.52. P4 pile shear demand is higher in non-skewed bridge and it has a maximum value at 0m scour depth. It is decreasing when scour depth increases and don't reach the shear capacity at 4 m and

5m depths for both bridges. This means that non-uniform scour in transverse direction of bridge becomes more critical for pile elements at shorter scour depths.





Figure 5.50. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ ($\alpha=0^\circ$ non-skewed bridge)

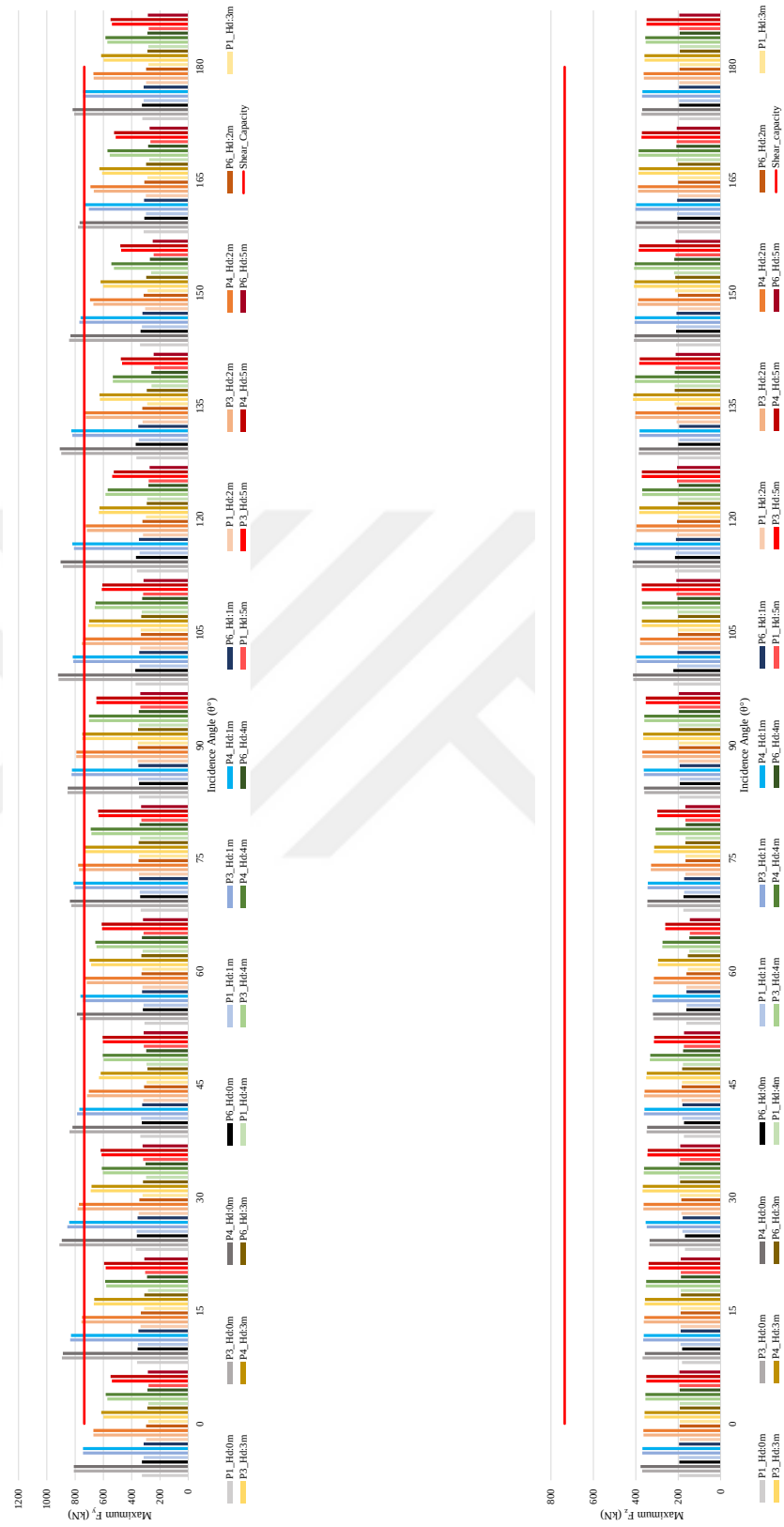


Figure 5.51. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles when $\gamma=0.6$ (45° skewed bridge)

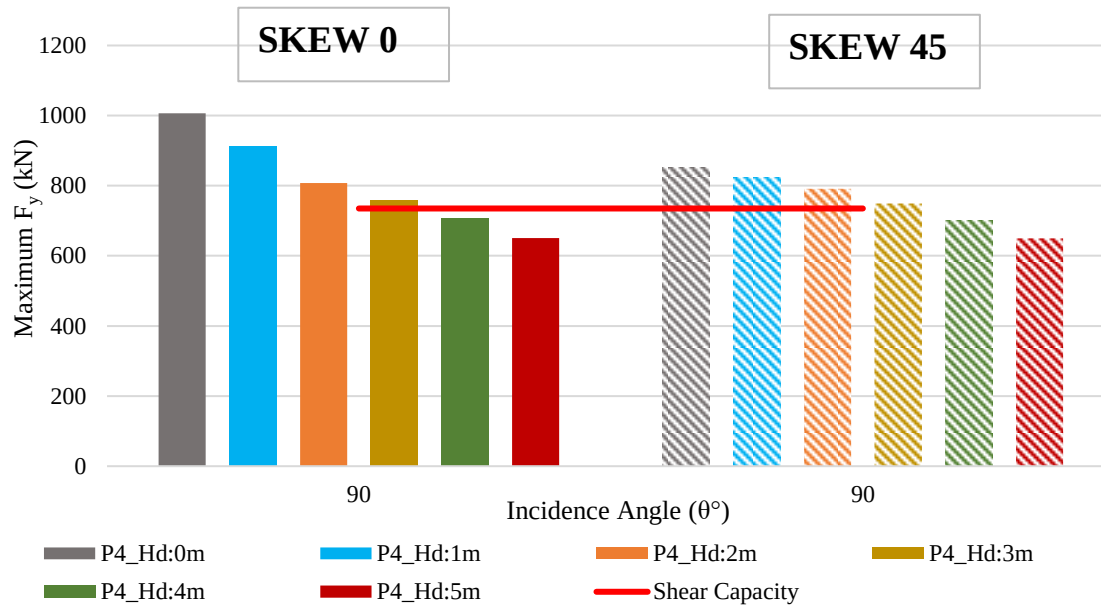


Figure 5.52. Average maximum shear force demands of local y' axis of pile (P4) for different nonuniform scour depths and 90° earthquake incidence angle when $\gamma=0.6$

5.2.1.5. Residual displacements

Residual displacements were calculated for middle column and superstructure by using non-skewed and skewed bridges for non-uniformly ($\gamma=0.6$) changed scour depths and different ground motion incidence angles. In Figure 5.53, the average residual displacement demands of middle column for the non-skewed and skewed bridges are given when scour depth is non-uniformly changed. Also, in Figure 5.54, the ratio of residual displacement demand to maximum displacement of middle column for the non-skewed and 45° skewed bridge is shown when scour depth change is non-uniform (Case 2-1a). Furthermore, the same demands are evaluated for the superstructure and shown in Figure 5.55 and Figure 5.56, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal direction for both column and superstructure. However, in transverse direction the situation becomes vice versa.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when non-uniform scour depth is 5m at 75° incidence angle for non-skewed bridge as 22.7mm. In transverse direction it is maximum at 30° incidence angle and 1m scour depth as 6.3mm for skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 5m scour depth as 0.18 in longitudinal

direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 1m scour depth when incidence angle 0° in transverse direction of skewed bridge.

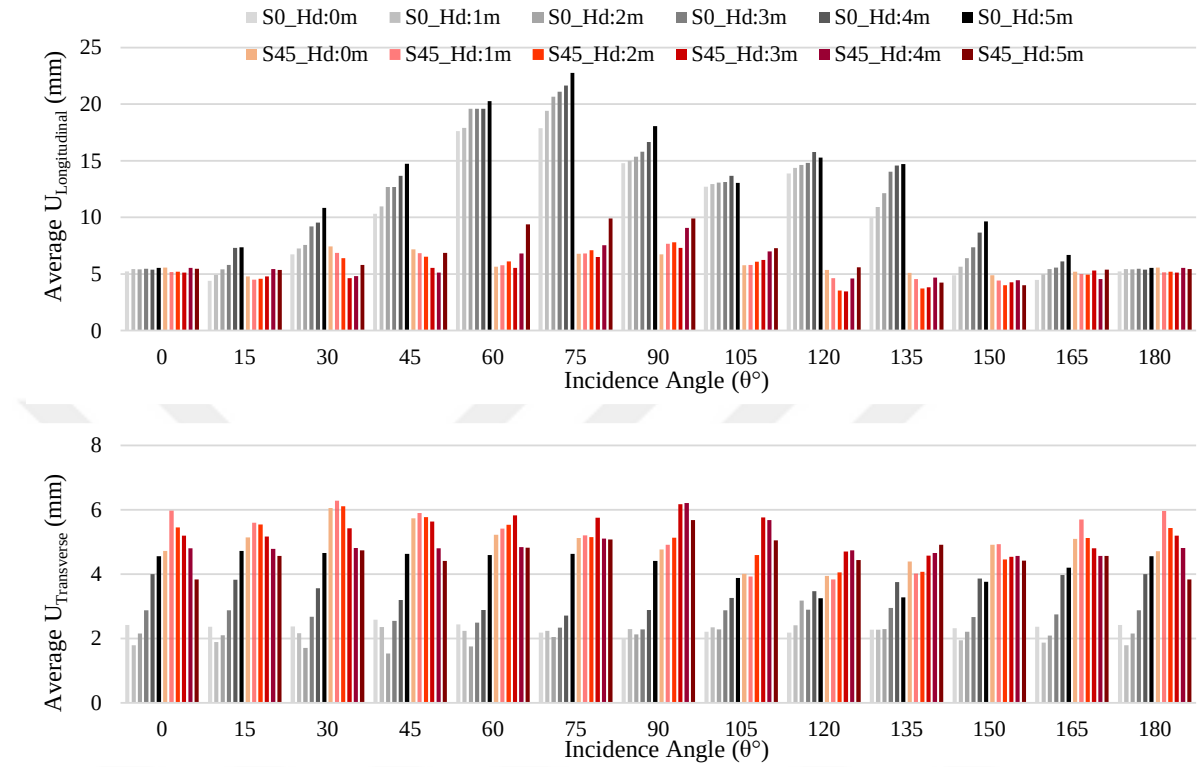


Figure 5.53. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1a)

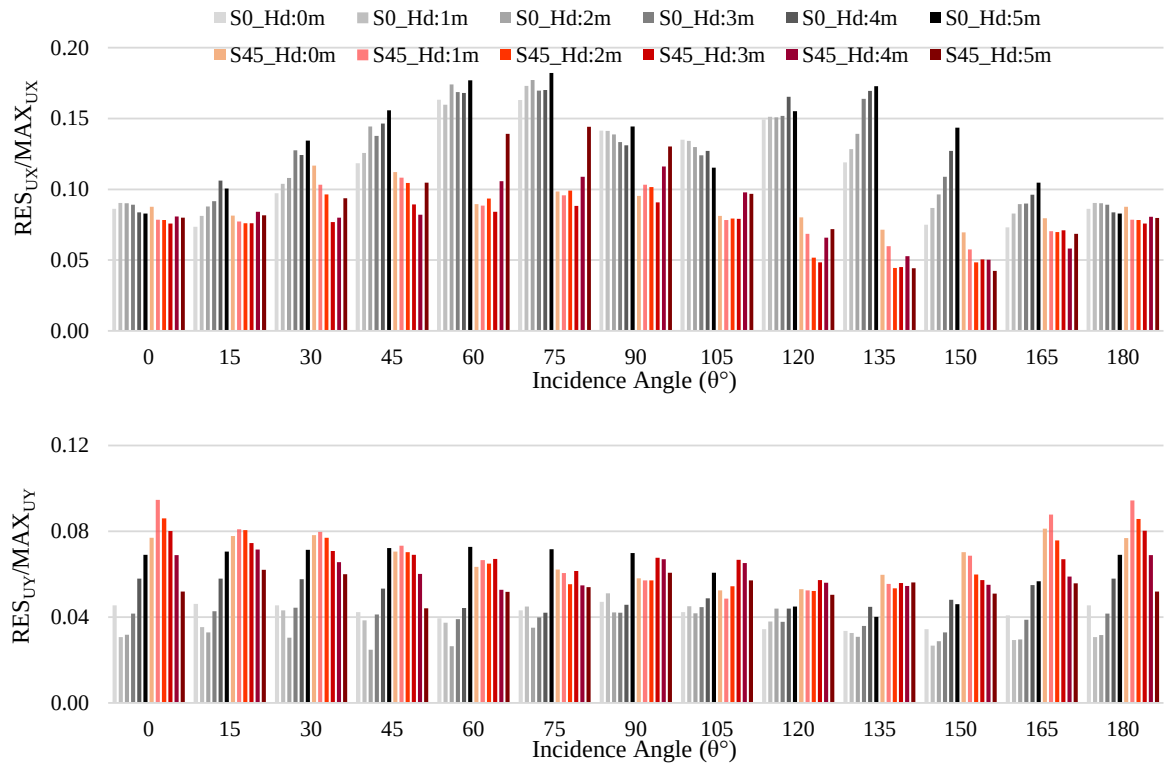


Figure 5.54. The ratio of residual displacement demand to maximum displacement of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1a)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when non-uniform scour ($\gamma=0.6$) depth is 5m at 75° incidence angle for non-skewed bridge as 27.5mm. In transverse direction it is maximum at 0° incidence angle and 1m scour depth as 8.9mm for skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 5m scour depth as 0.19 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 1m scour depth when incidence angle 180° in transverse direction of skewed bridge.

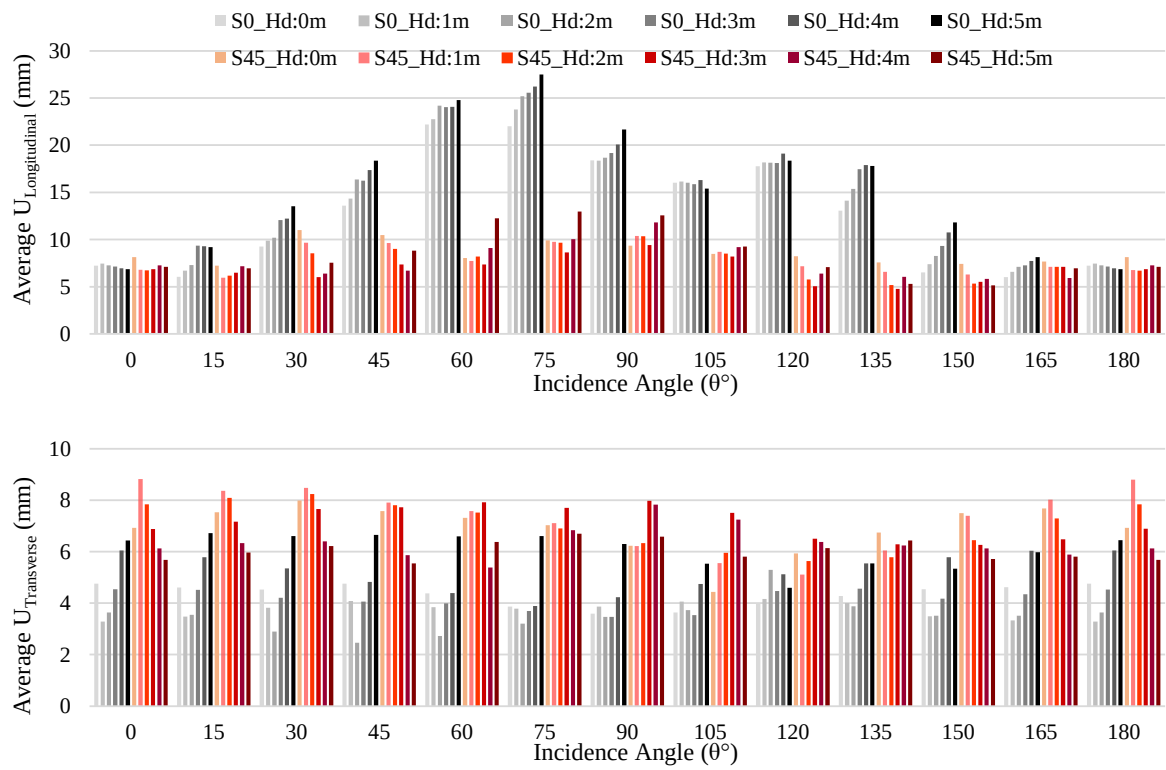


Figure 5.55. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1a)

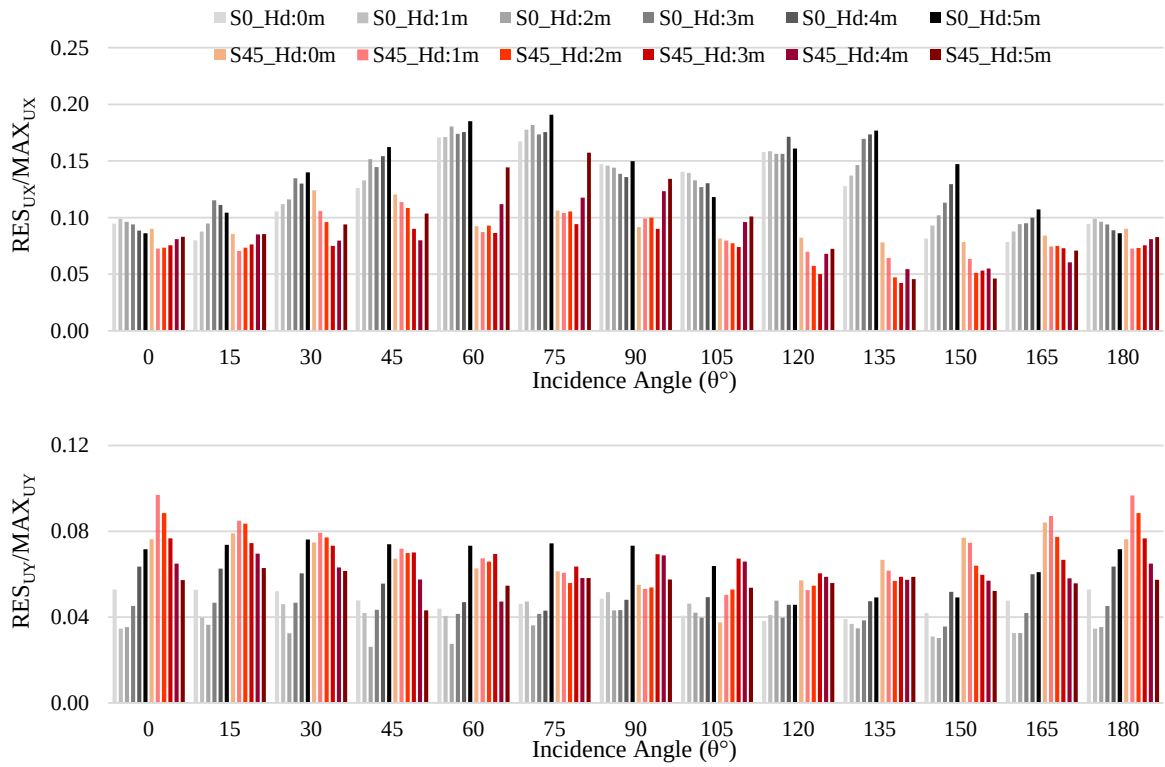


Figure 5.56. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1a)

5.2.2. Non-uniform scour when $\gamma=1.0$ (Case 2-1b)

In this part of thesis, non-uniformly scoured bridge models are constructed by taking the angle between downstream and upstream piles as $\gamma=1.0$. Scour depth is changed starting from 0 m (no scour) to 5 m with 1 m increment around downstream pile (H_d). The demands obtained from nonlinear analysis results are given below.

As seen in Figure 5.57, the 1st and 2nd vibration period of the bridge increases when scour depth increases. Because the clear height of the piles increases when the soil around piles is removed. This situation increases the flexibility of the bridge and so do the periods. While the 1st period values of 45° skewed bridge model are higher than the straight bridge, the 2nd period values are less similar to uniform scour case (Case-1) and non-uniform scour in transverse direction of bridge when $\gamma=0.6$. This is because the stiffness in longitudinal direction of the bridge decreases with increase of the skew angle, while it increases in the transverse direction of the bridge.

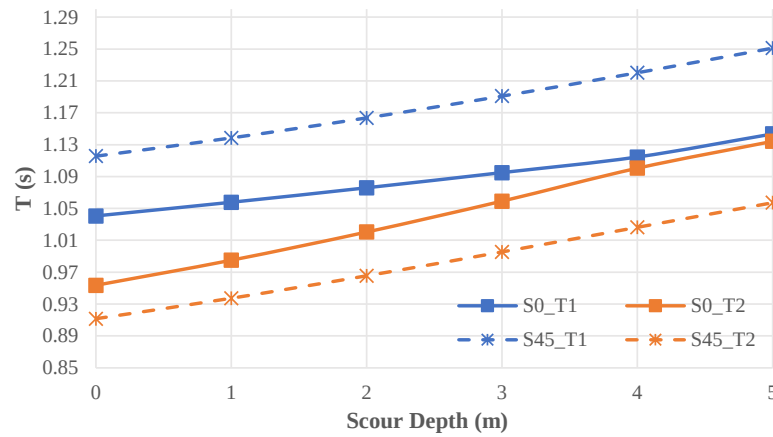


Figure 5.57. The variation of 1st and 2nd vibration period of bridge depending on non-uniform scour depth when $\alpha=1.0$

5.2.2.1. Superstructure displacement

Superstructure displacement demands obtained from nonlinear analysis results belong to midpoint of bridge deck as mentioned above. In Figure 5.58 and Figure 5.59, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.60 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results examined in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 60° although in transverse direction it is decreasing between 0° and 75° . Therefore, the resultant displacement becomes nearly same for each earthquake incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in transverse direction is more obvious than in longitudinal direction of bridge in some incidence angles. The maximum difference of average displacement demands in longitudinal direction between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 90° incidence angle as nearly 11.4%. In transverse direction, it is at 15° as 24.3%. If it is checked for resultant displacement, maximum difference becomes 18% at 180° incidence angle.

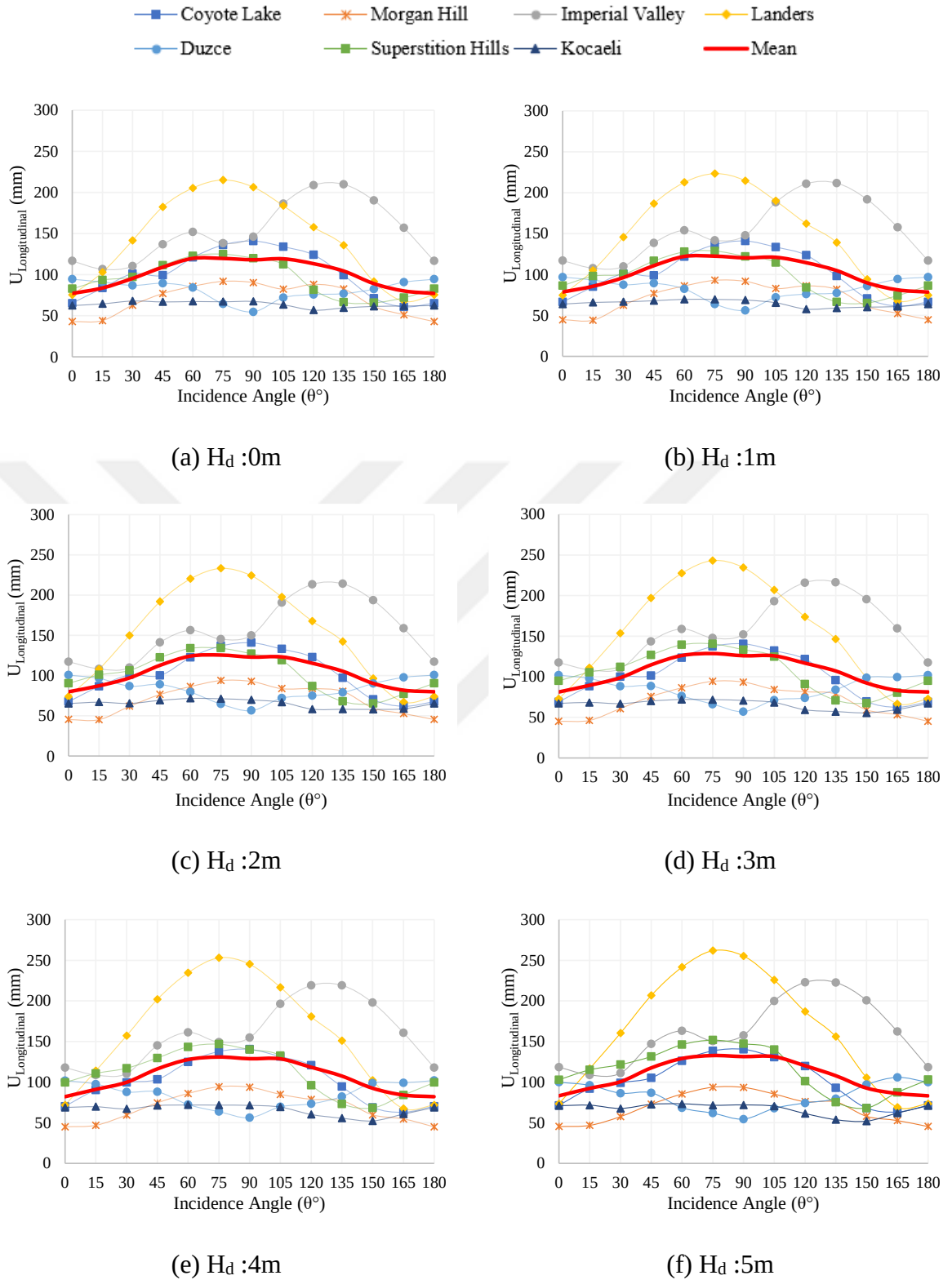


Figure 5.58. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

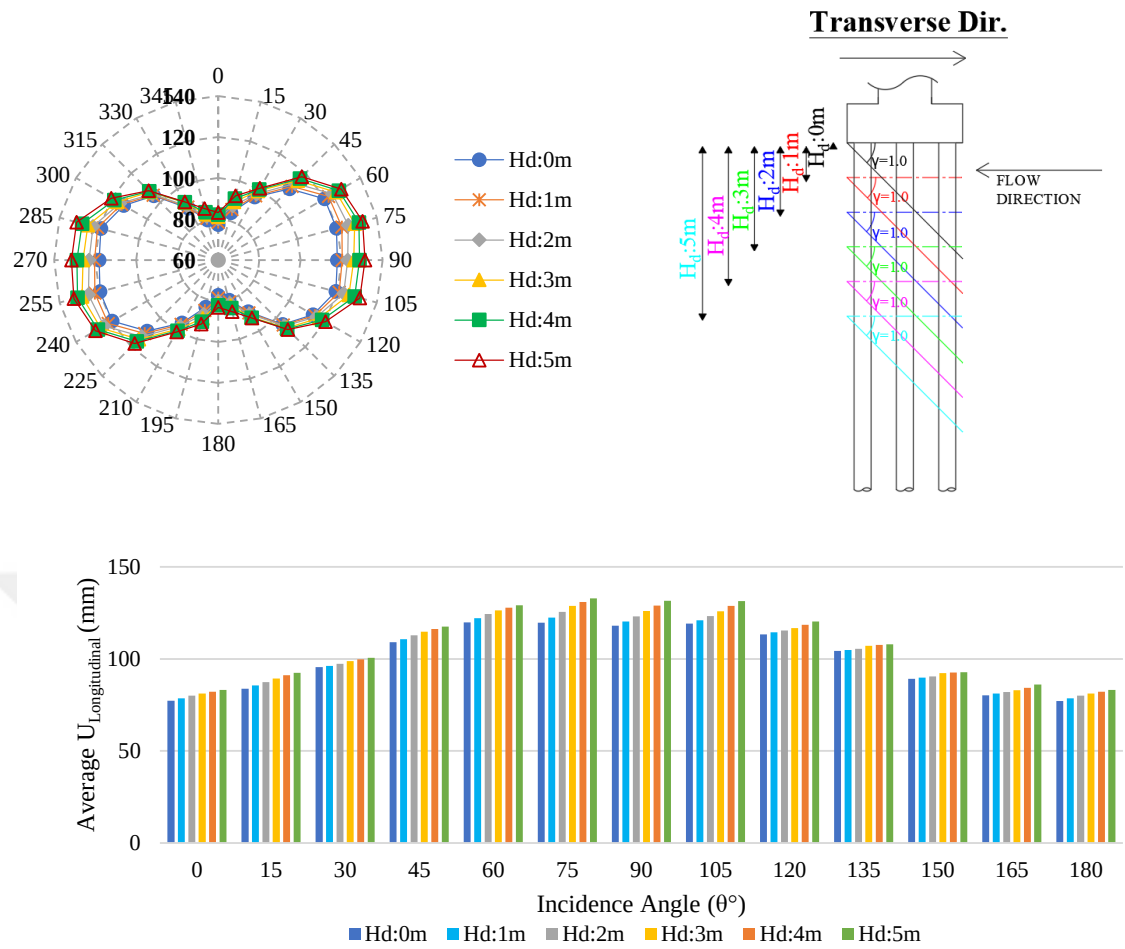


Figure 5.58. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

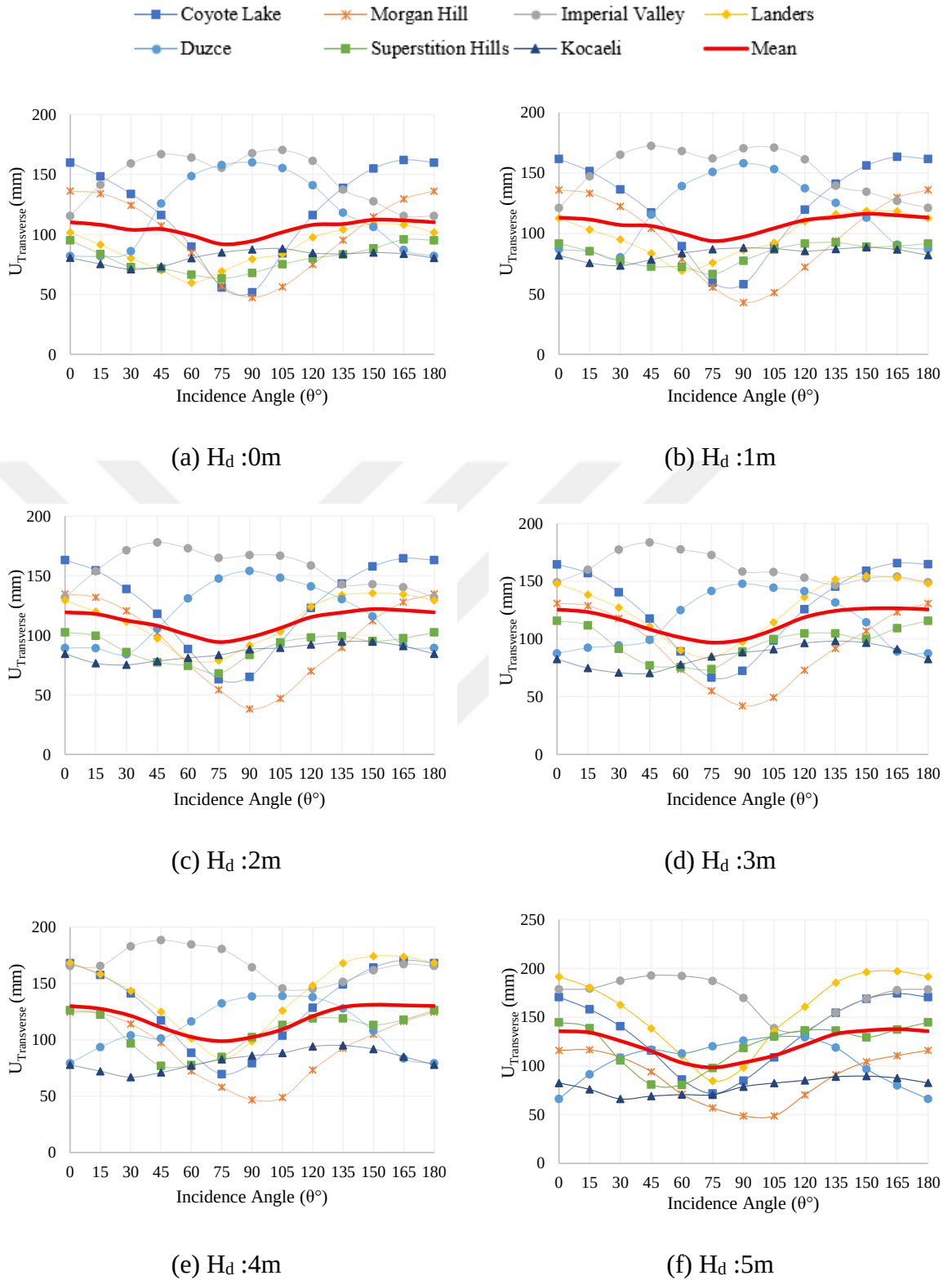


Figure 5.59. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

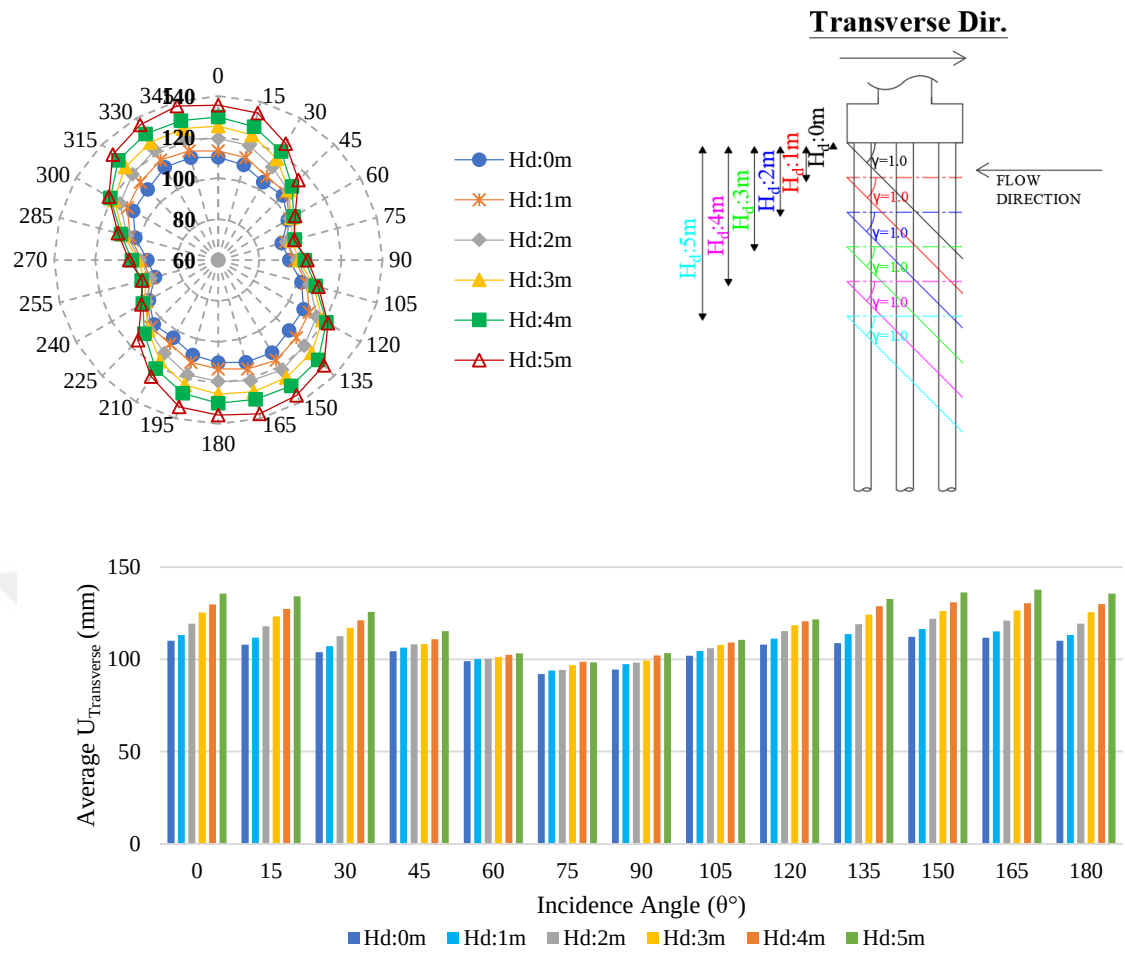


Figure 5.59. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

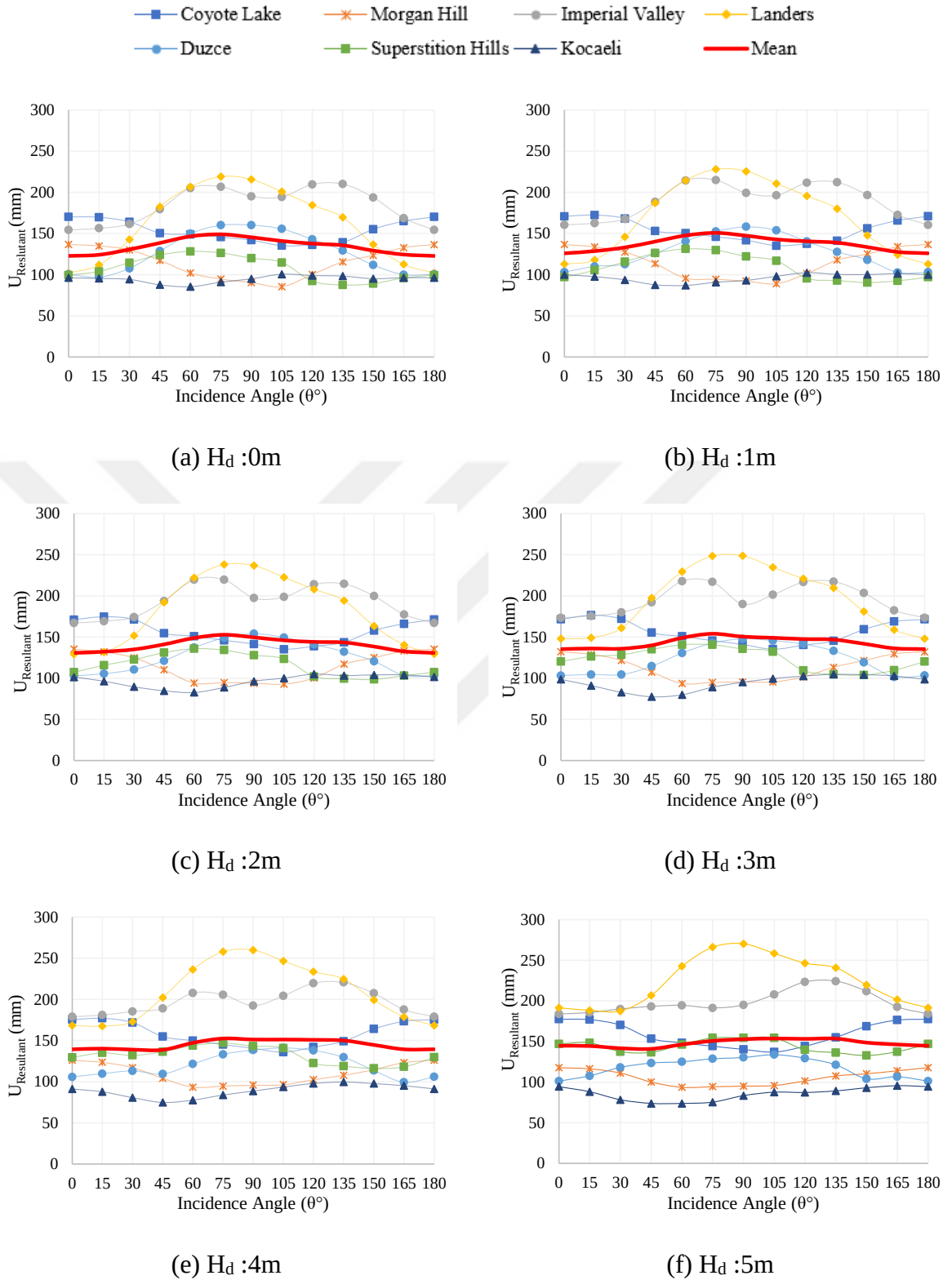


Figure 5.60. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

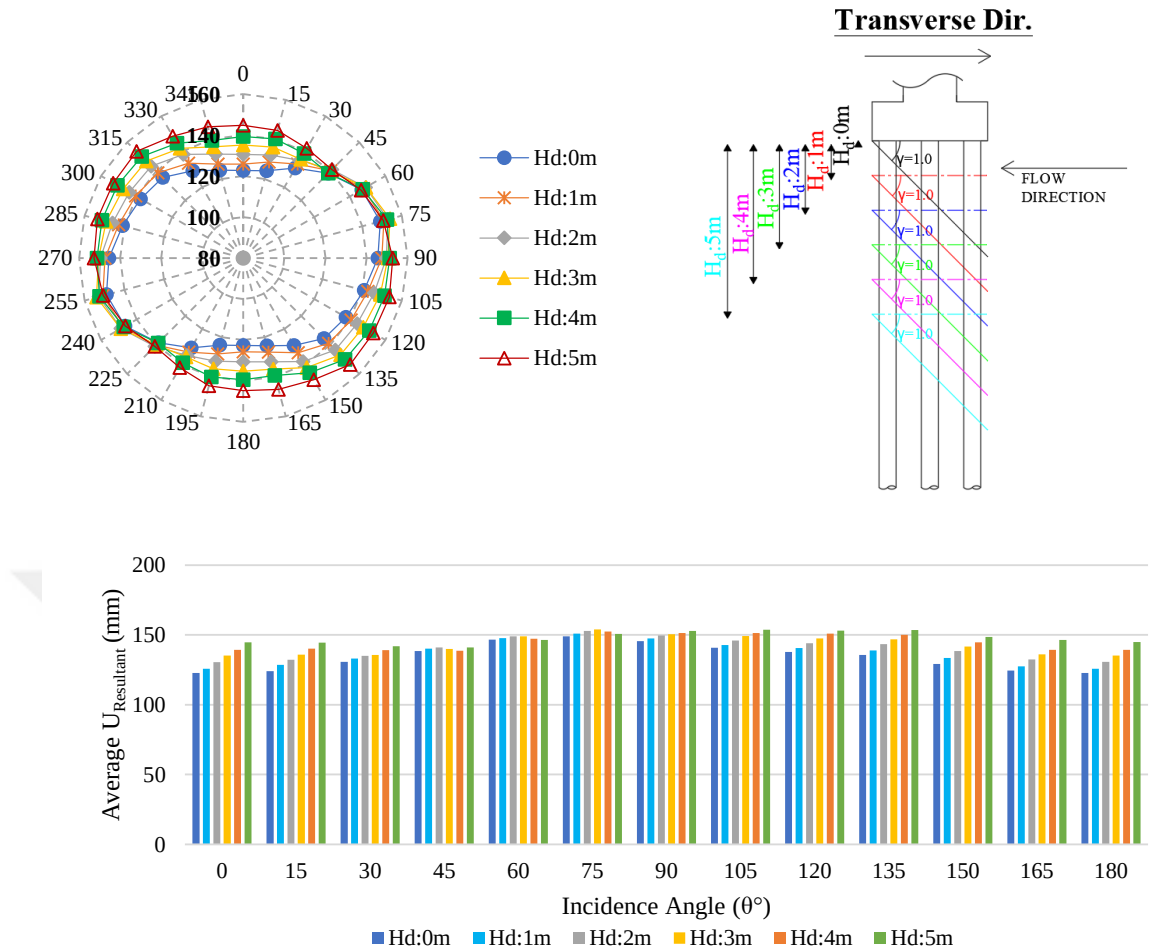


Figure 5.60. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.61 and Figure 5.62, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge are given. Also, Figure 5.63 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results assessed in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° although in transverse direction it is decreasing between 0° and 75° . Therefore, the resultant displacement becomes nearly same for each earthquake incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly

around piles. The increase of displacement in longitudinal direction is more obvious than in transverse direction of bridge in some incidence angles unlike previous scour cases. The maximum difference of average displacement demands in longitudinal direction between no scoured ($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 60° incidence angle as nearly 7.2%. In transverse direction, it is at 0° as 18.5%. If it is checked for resultant displacement, maximum difference becomes 17.3% at 15° incidence angle.

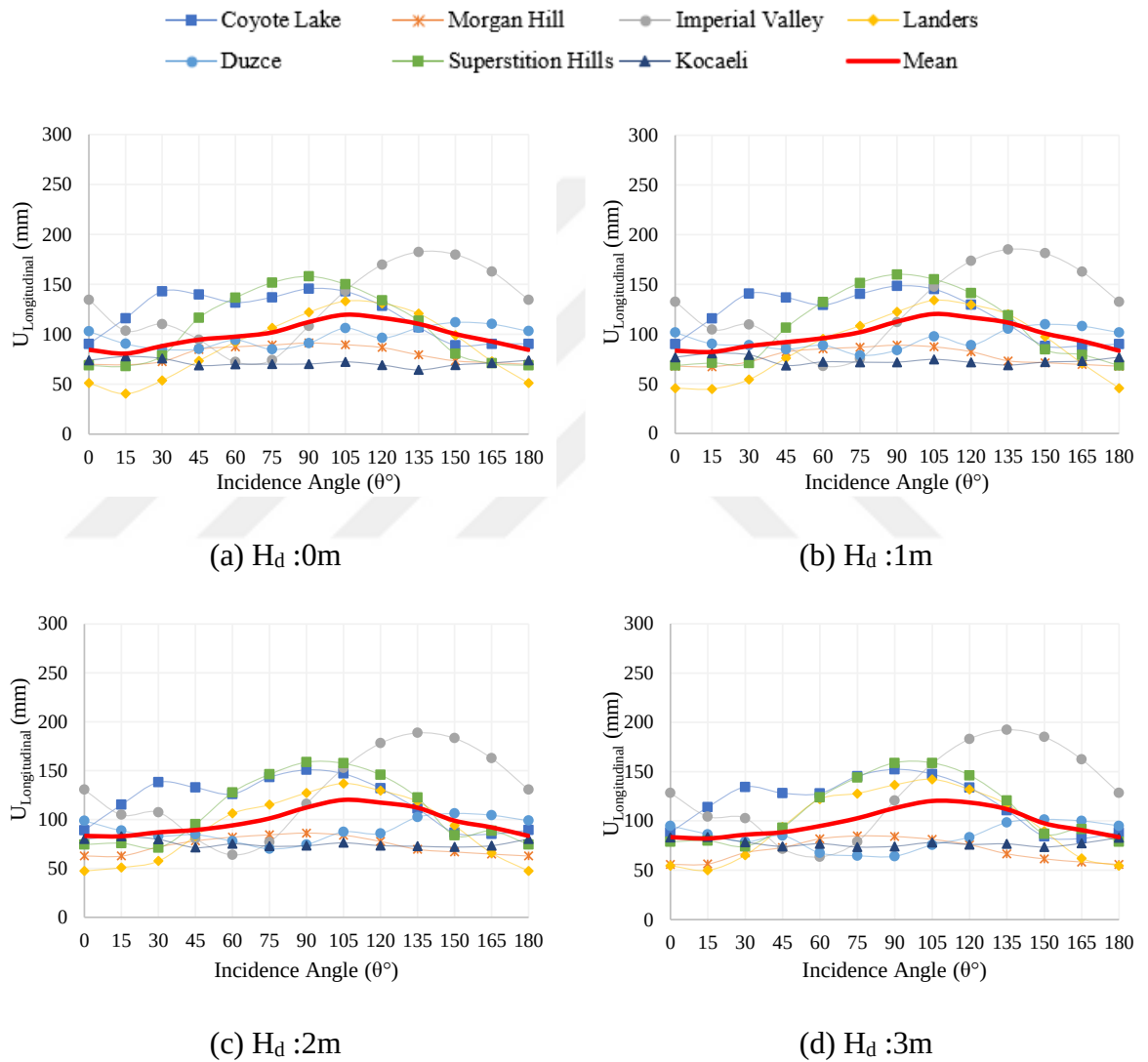
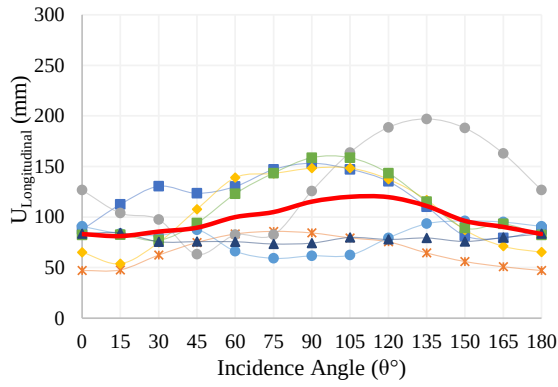
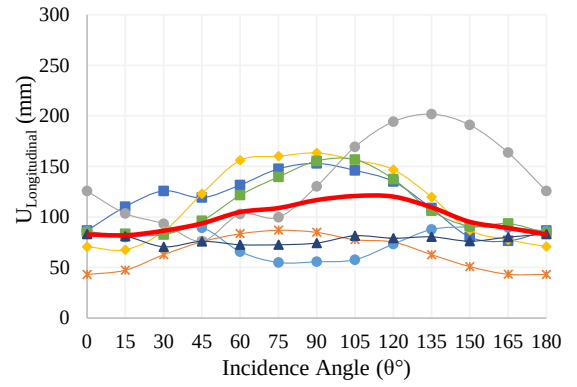


Figure 5.61. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$



(e) $H_d : 4m$



(f) $H_d : 5m$

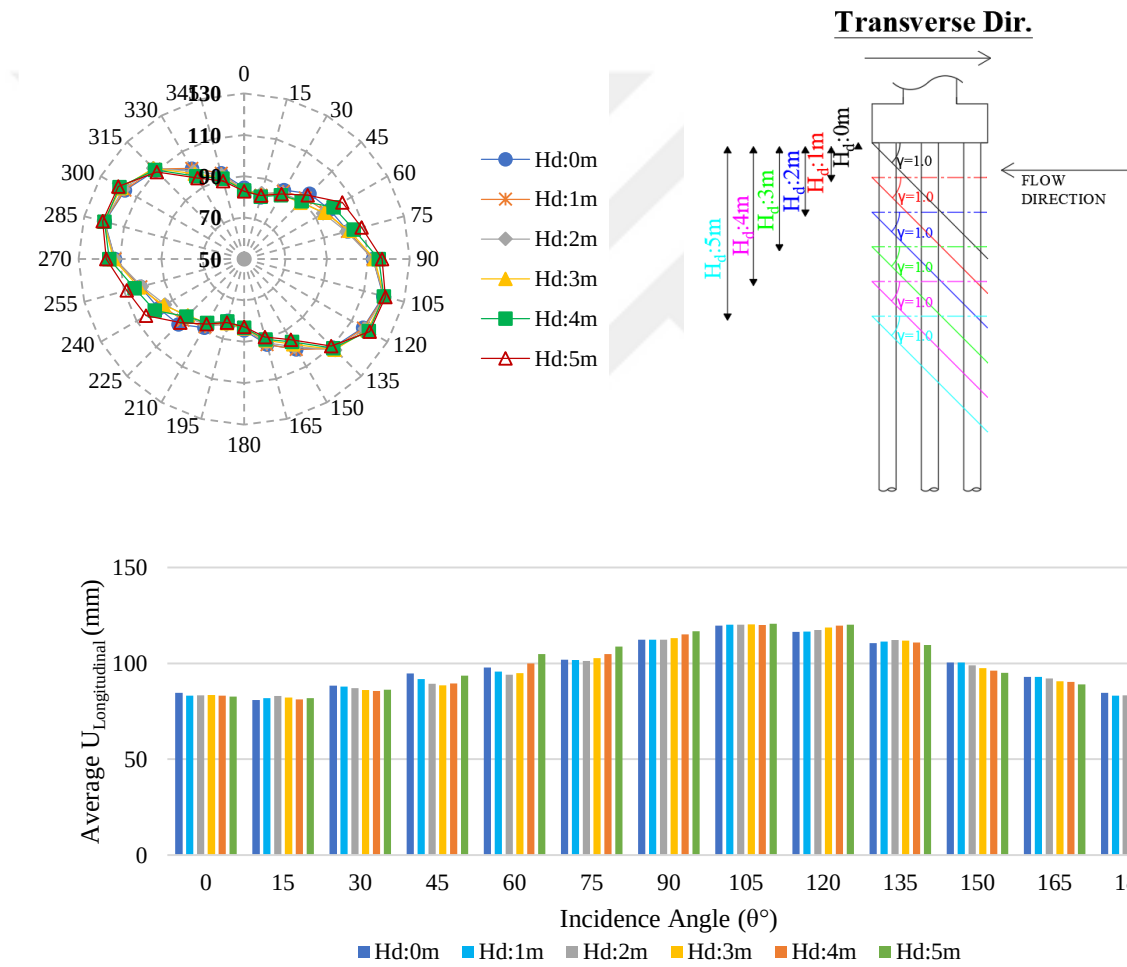


Figure 5.61. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

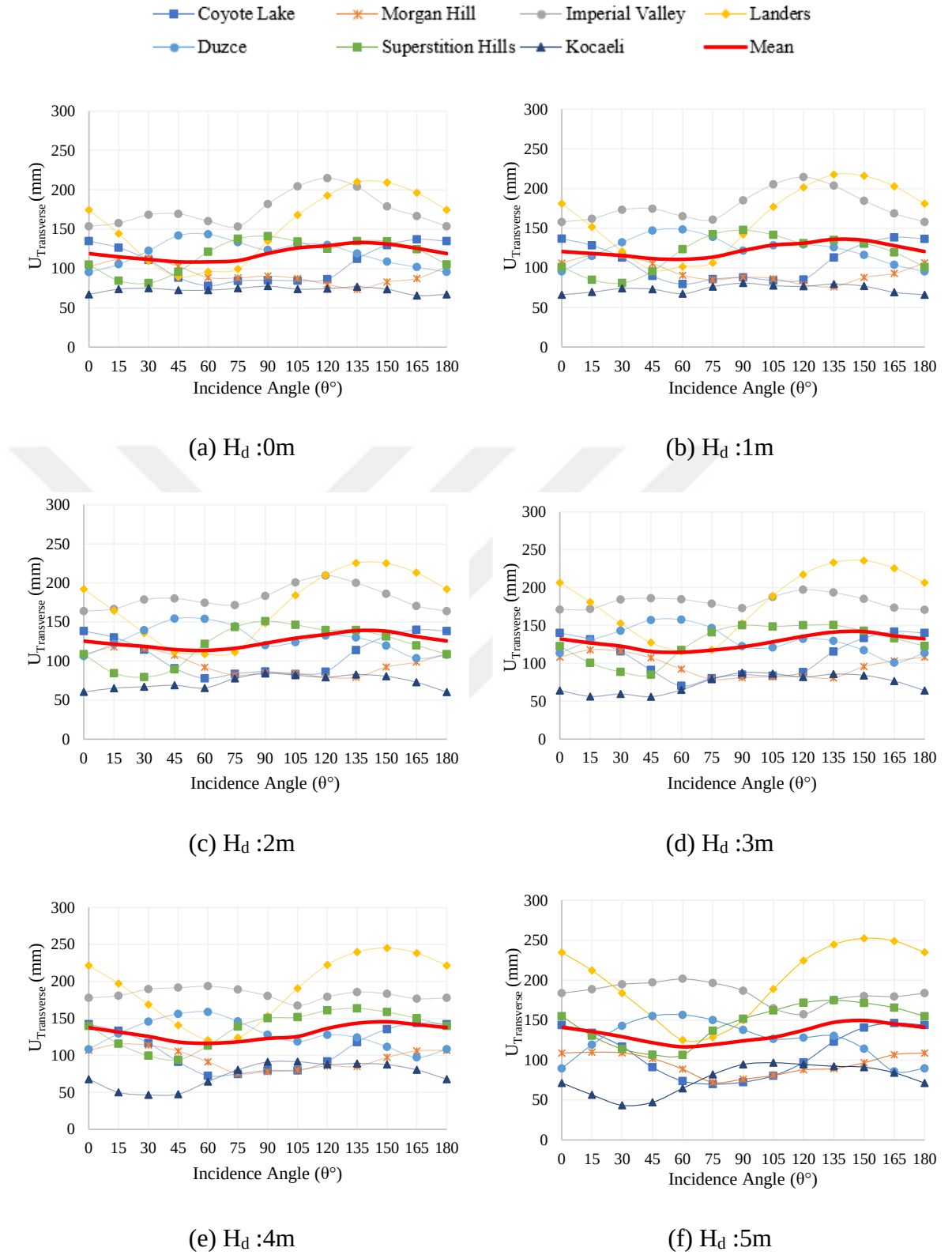


Figure 5.62. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

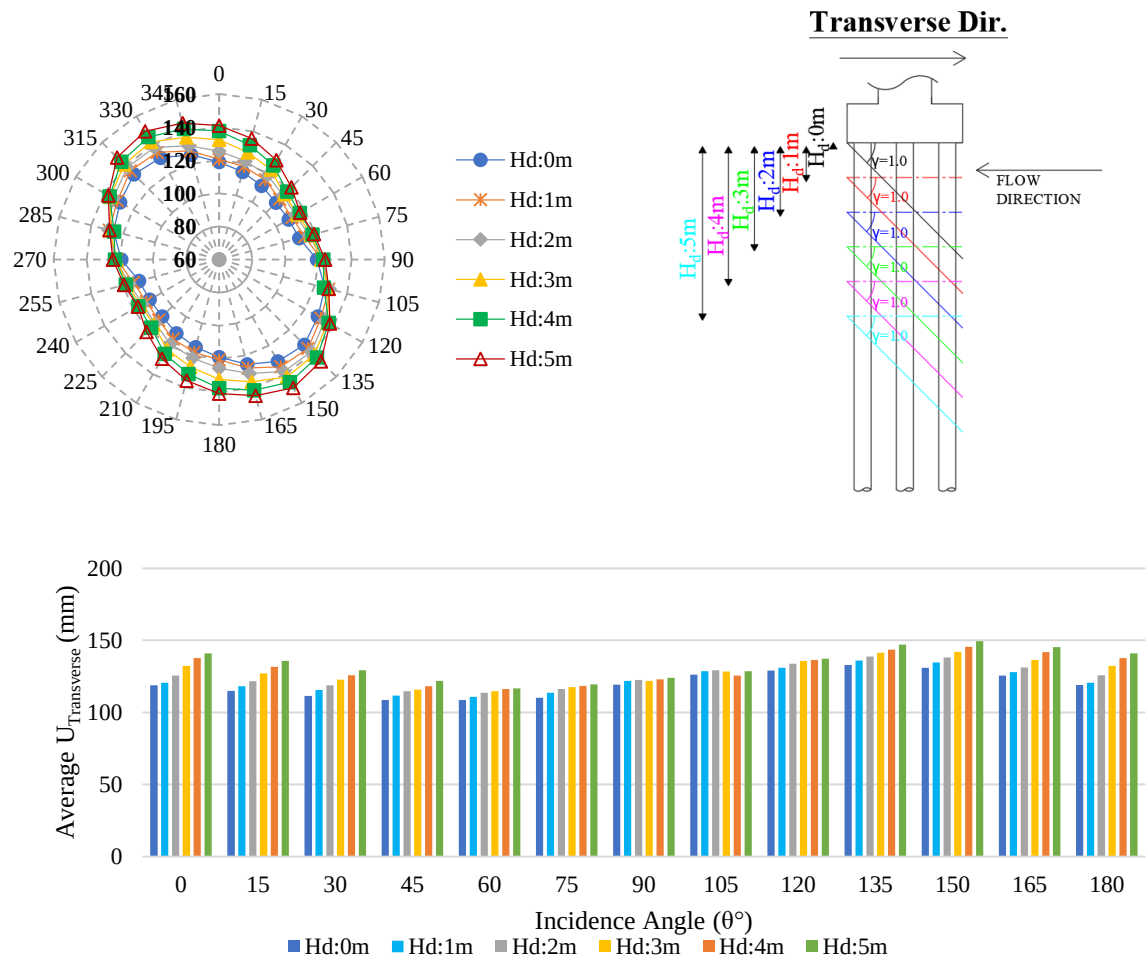


Figure 5.62. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

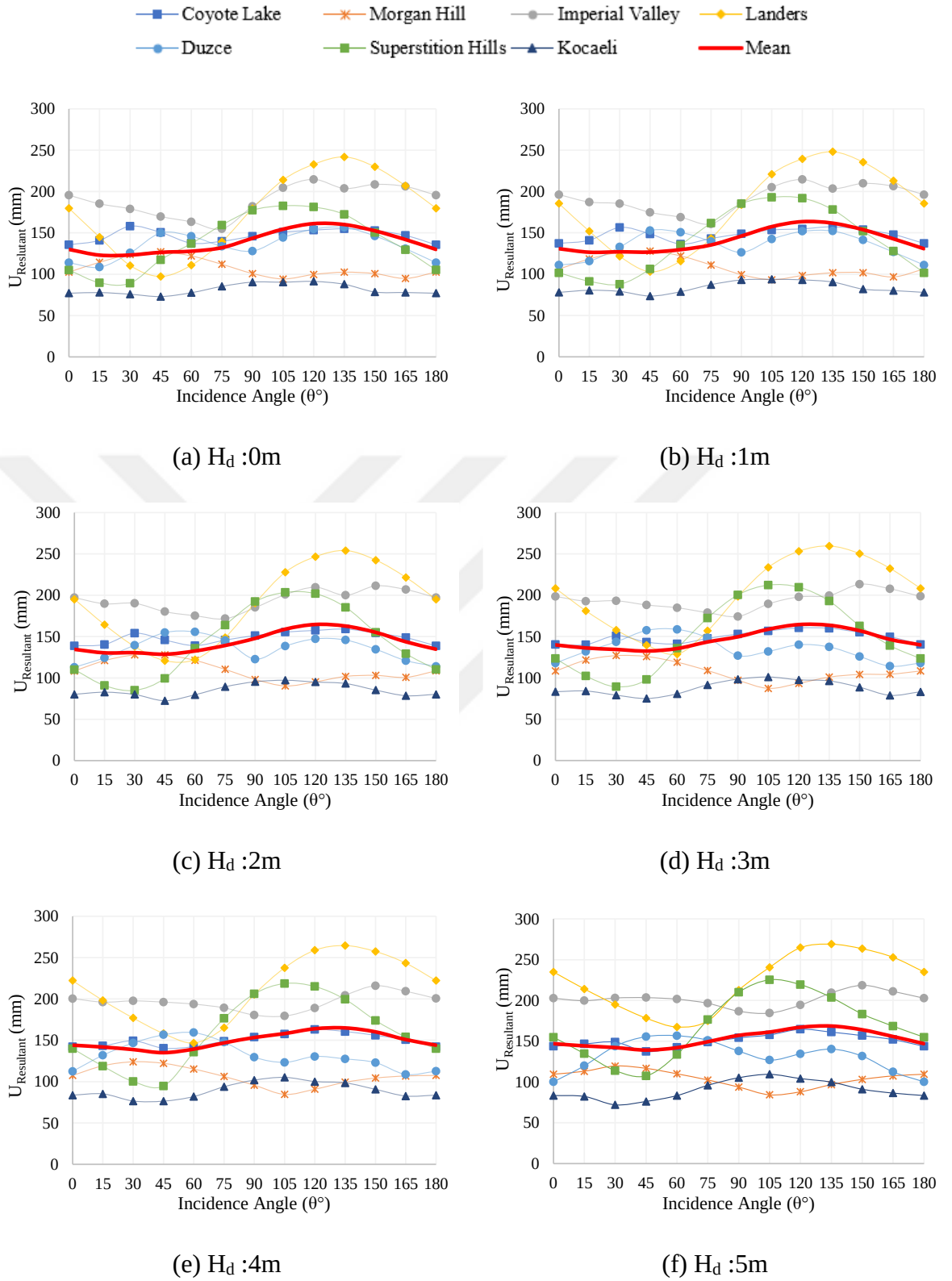


Figure 5.63. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

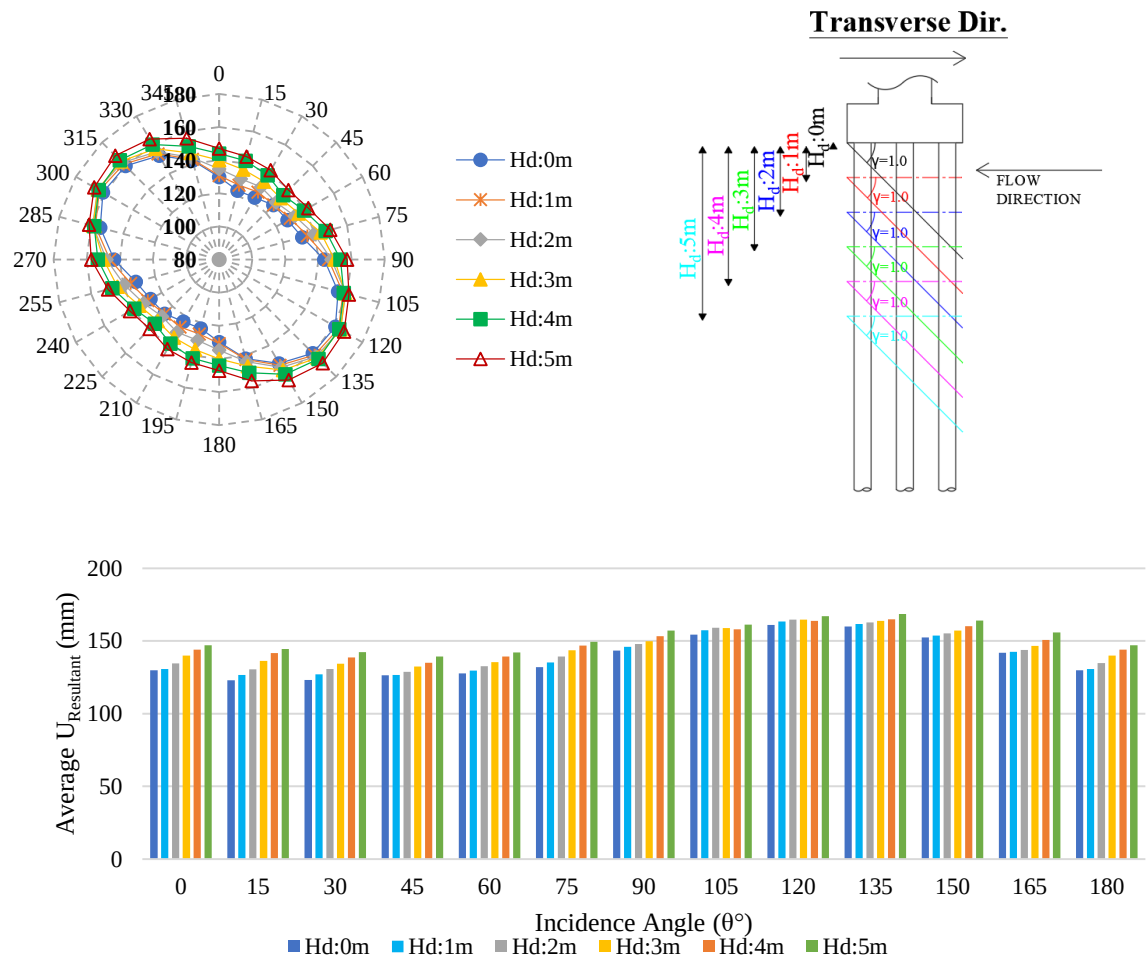


Figure 5.63. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.64 and Figure 5.65, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges and resultant displacements are compared. In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge. On the other hand, this situation is vice versa in transverse direction. For both skewed and non-skewed bridges, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 45° incidence angle and 5m scour depth as nearly 30%. In transverse direction, it is at 90° and 0m scour depth as 20.6%. If it is checked for resultant displacement, maximum difference becomes 15.2% at 150° incidence angle and 0m scour depth.

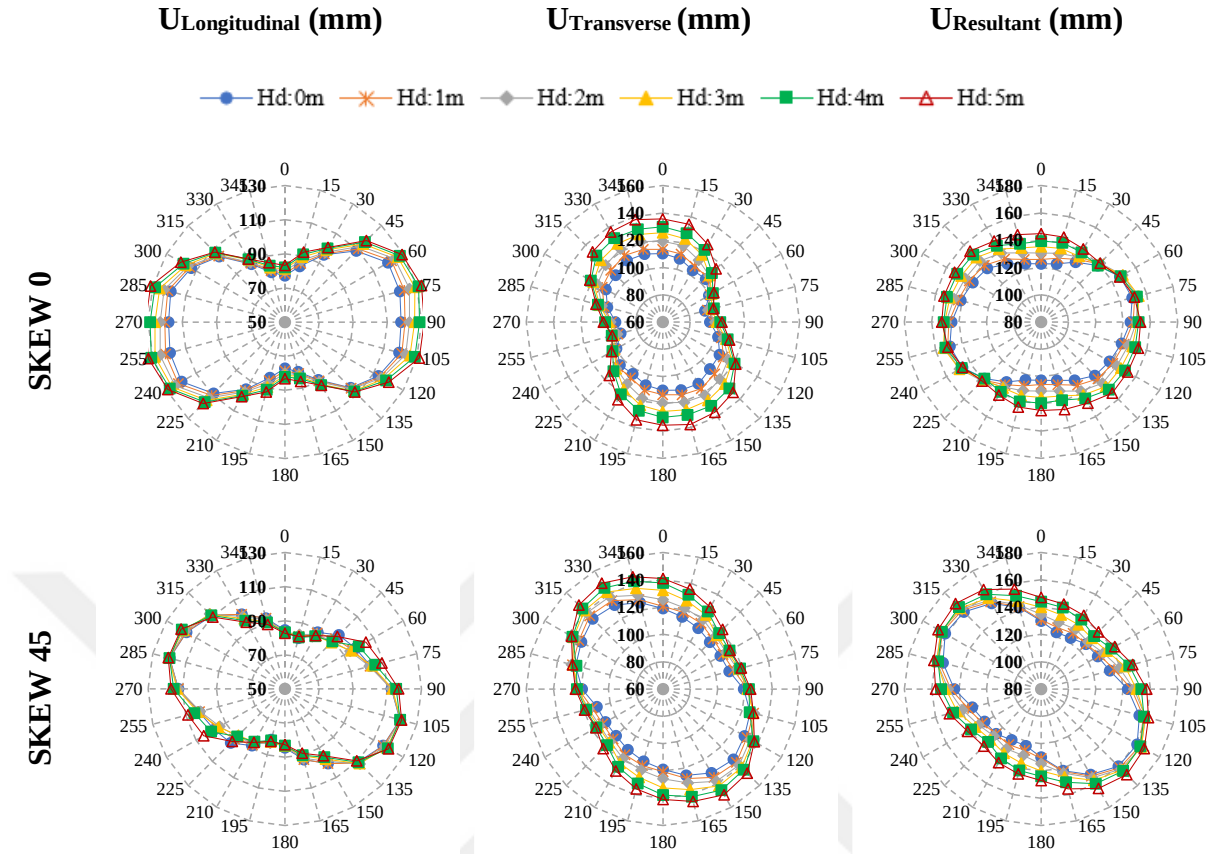


Figure 5.64. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

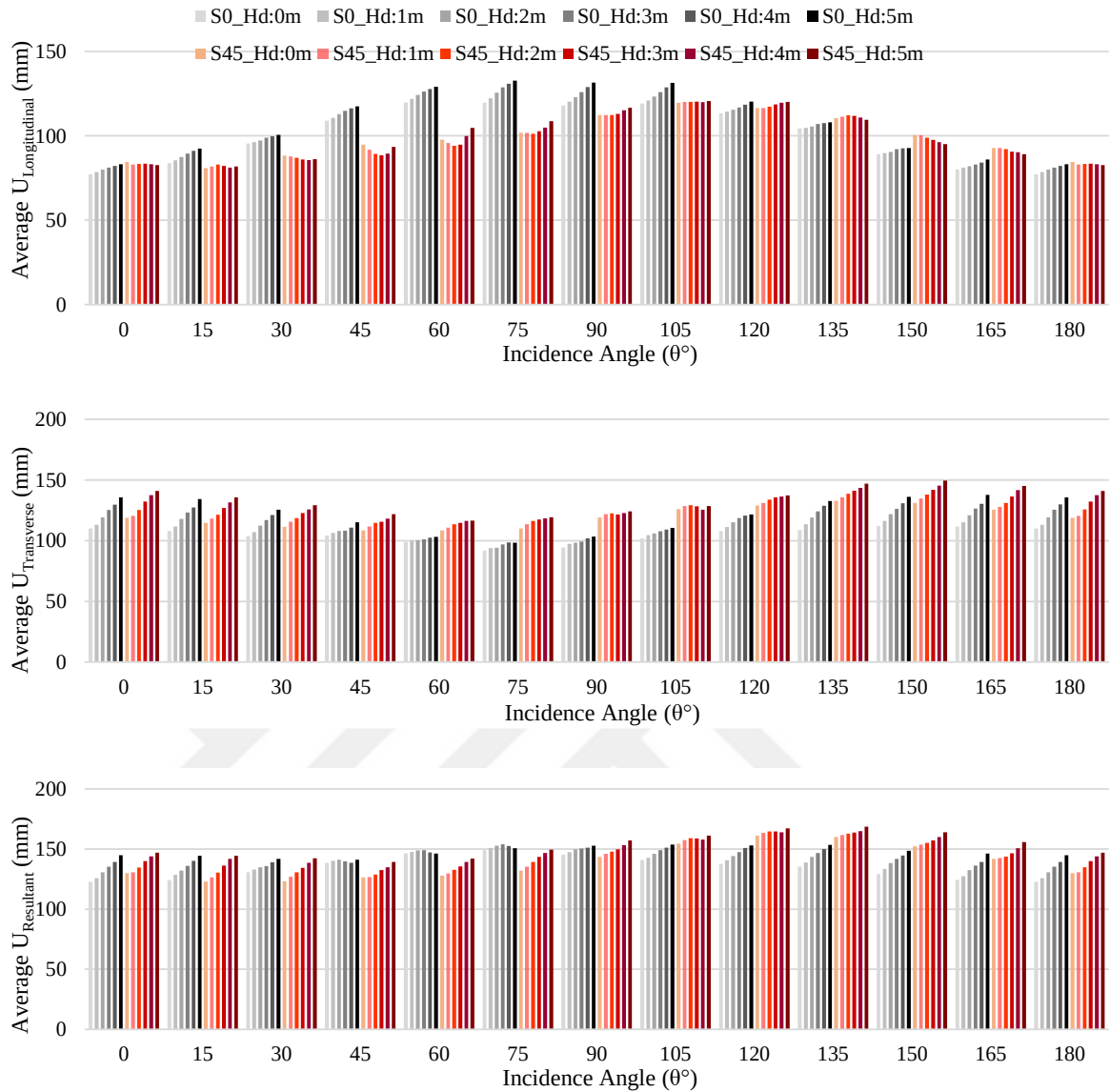


Figure 5.65. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

5.2.2.2. Curvature demands of column pier

In Figure 5.66 and Figure 5.67, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). In strong axis (z'), it has a decreasing trend between 0° and 30° and it starts to increase between 45° and 90° incidence angles. When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend

when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is same as uniform scour case as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. Especially in strong axis (z'), the average maximum curvature demand of column is under the yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes more than 3 m. The maximum difference of curvature demands in weak axis (y') of column between no scoured ($H_d=0m$) and 5 m scoured ($H_d=5m$) bridge is occurred at 60° incidence angle as nearly 43.5%. Also, in strong axis (z'), it becomes 71.5% at 75° incidence angle. These results show that scour around piles has a positive contribution to the curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

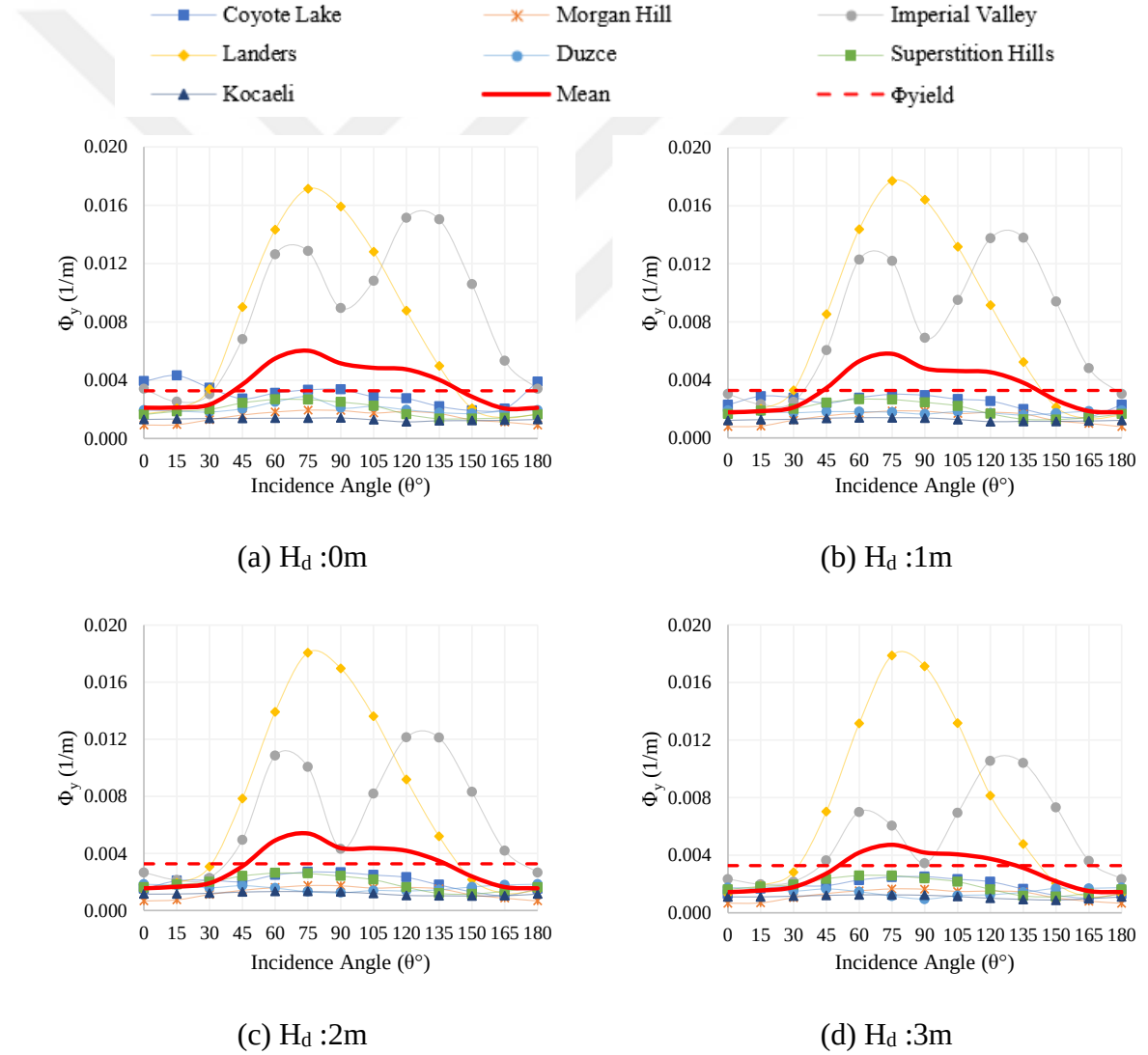
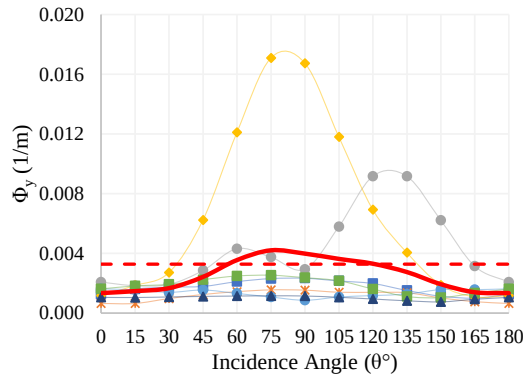
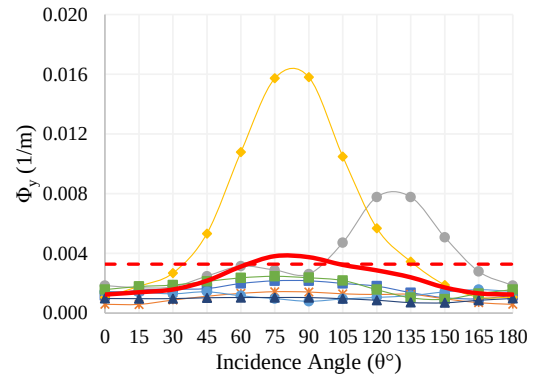


Figure 5.66. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$



(e) $H_d : 4m$



(f) $H_d : 5m$

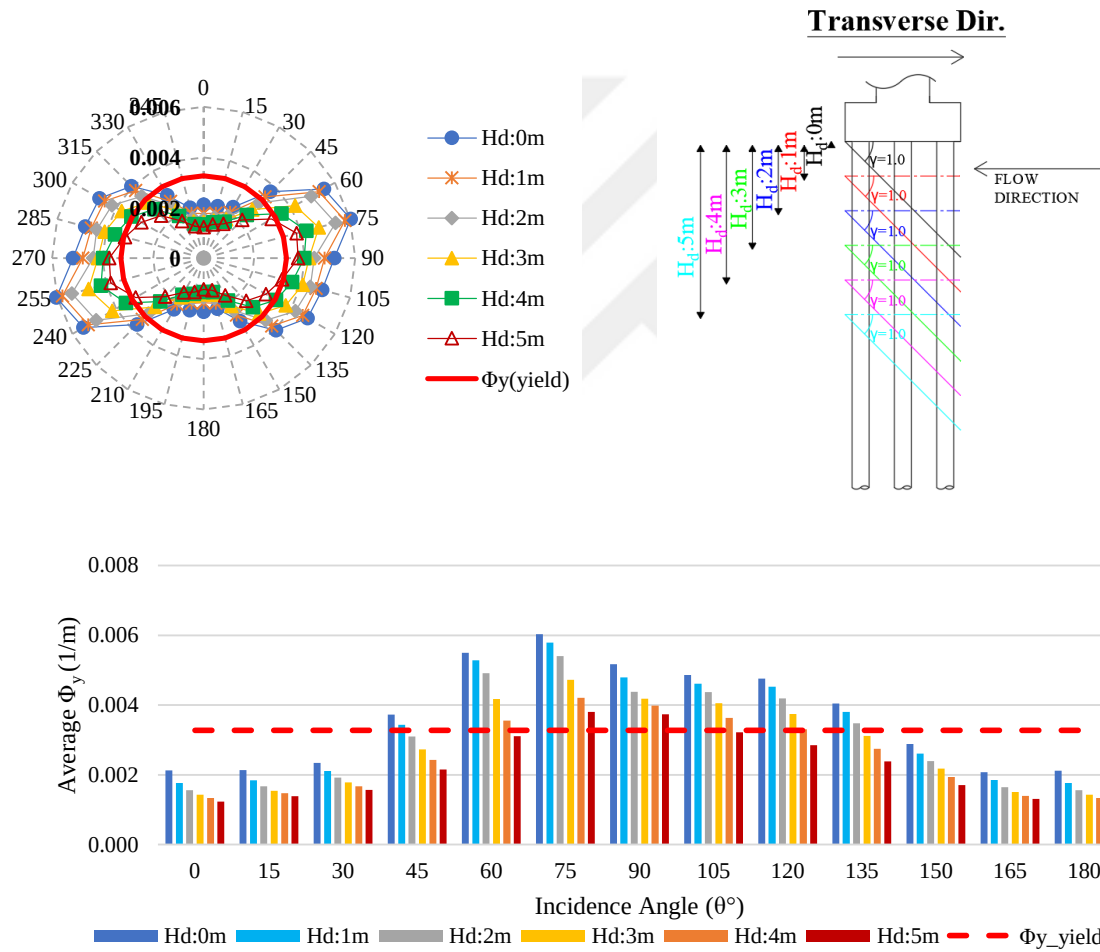


Figure 5.66. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

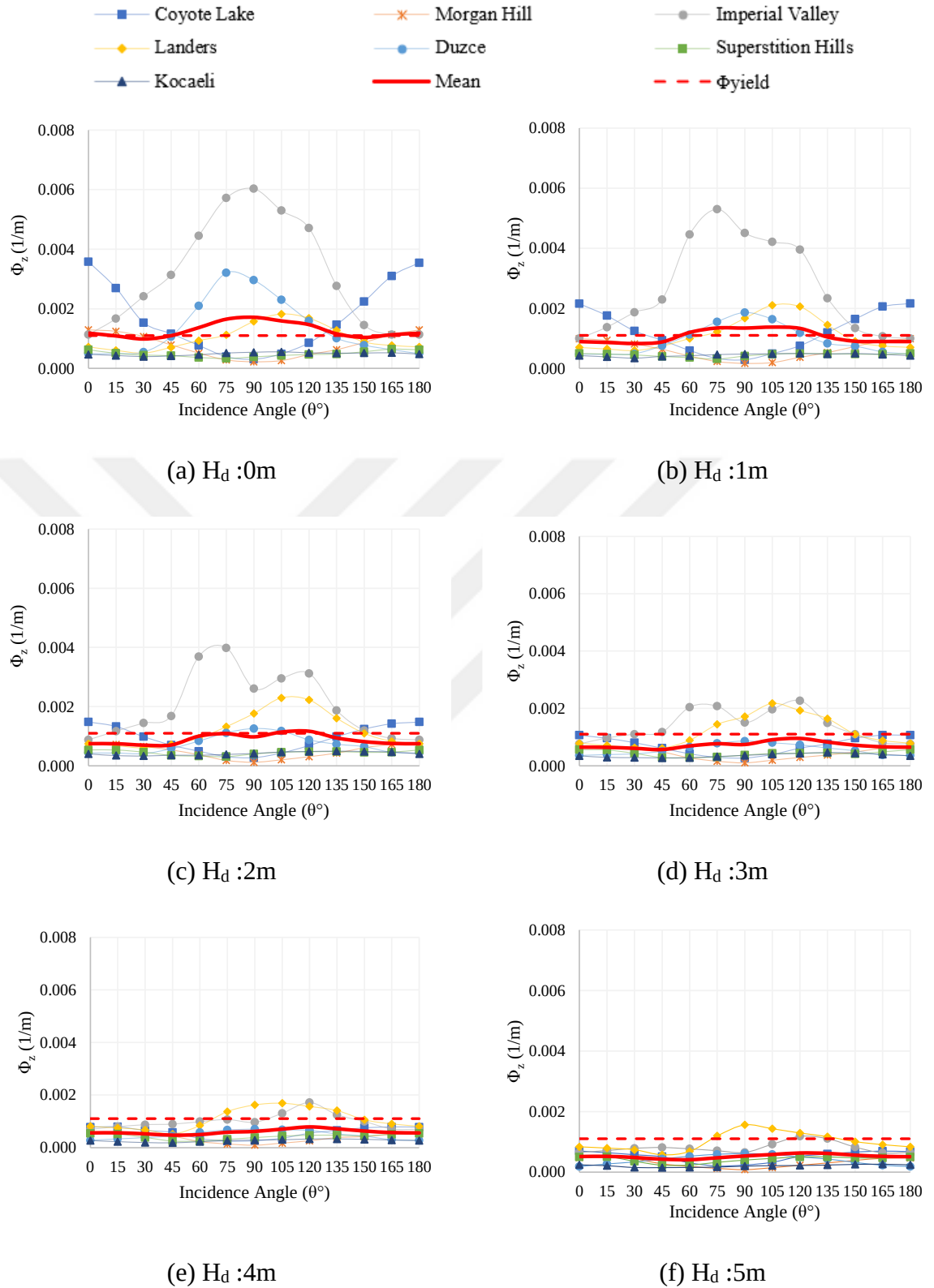


Figure 5.67. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

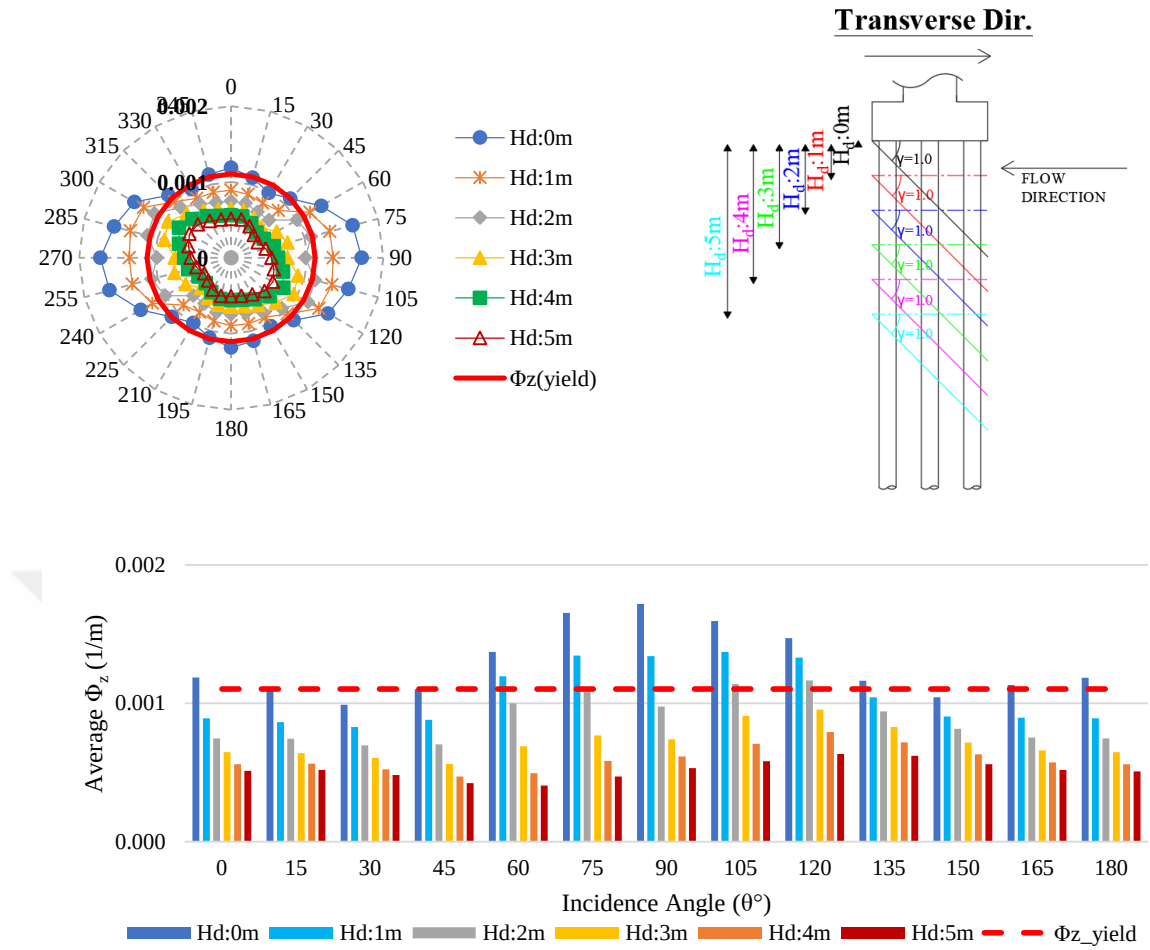


Figure 5.67. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.68 and Figure 5.69, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 135° in weak axis (y') and strong axis (z'). When the radar and bar chart is checked, they show that average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is same as uniform scour case as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. Especially in strong axis (z'), the average maximum curvature demand of column is under the yield curvature (Φ_{z_yield}) for all incidence angles when scour depth becomes 4m and 5m. The maximum difference of curvature demands in weak axis (y') of column between no scoured

($H_d=0\text{m}$) and 5 m scoured ($H_d=5\text{m}$) bridge is occurred at 180° incidence angle as nearly 48.2%. Also, in strong axis (z'), it becomes 61.5% at 105° incidence angle. These results show that scour around piles has a positive contribution to the curvature demands of 45° skewed bridge column piers.

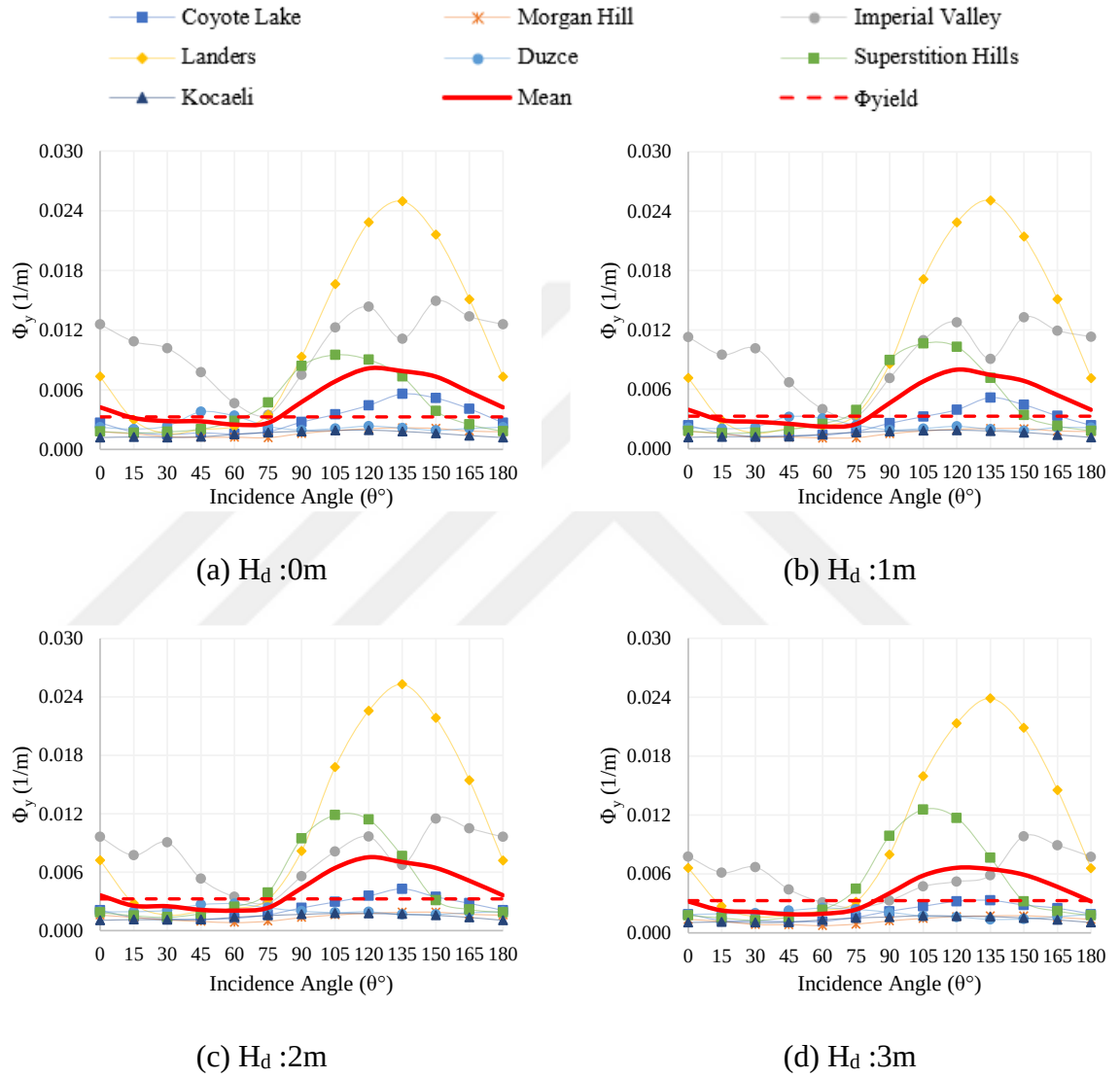
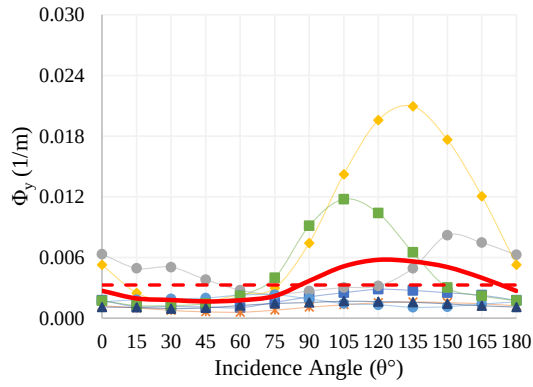
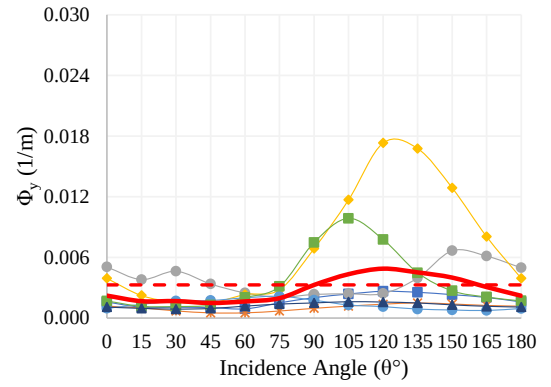


Figure 5.68. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$



(e) $H_d : 4m$



(f) $H_d : 5m$

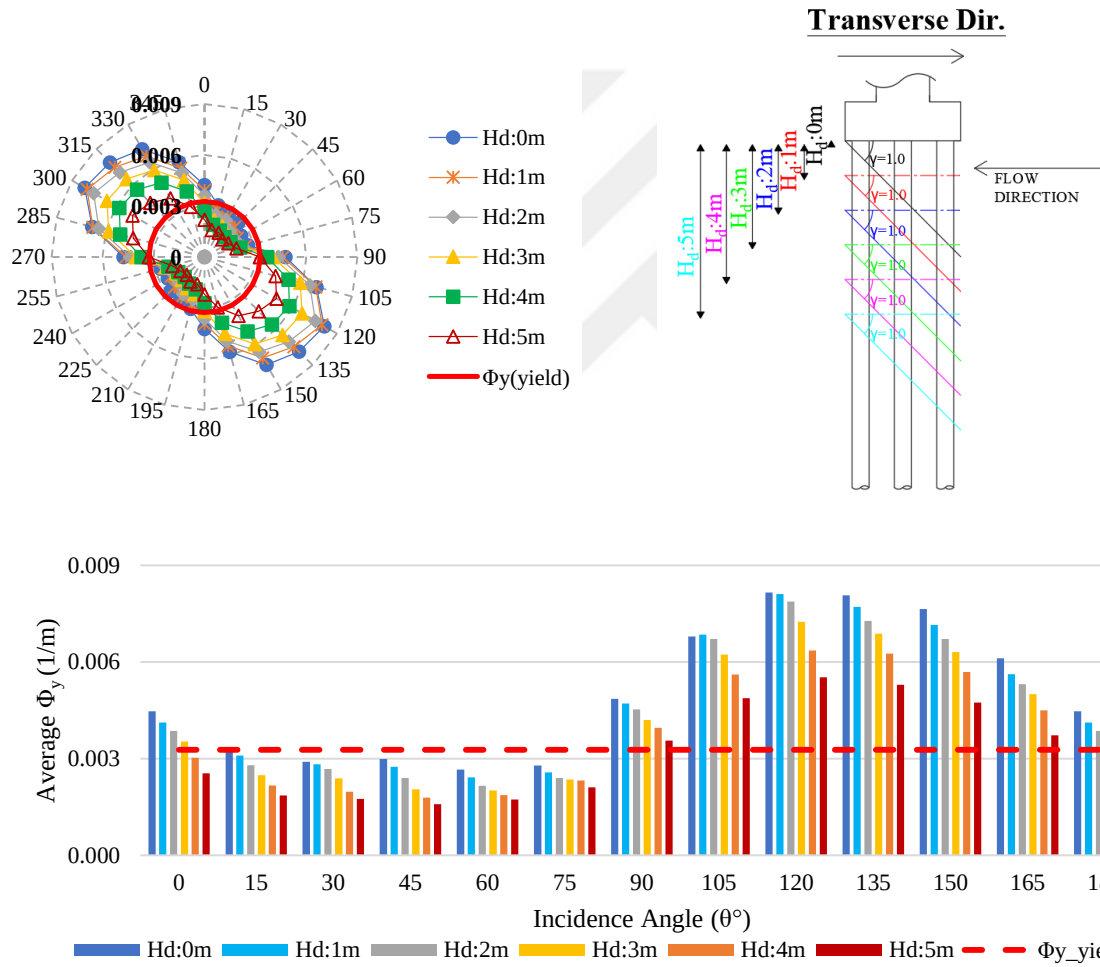


Figure 5.68. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)



Figure 5.69. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

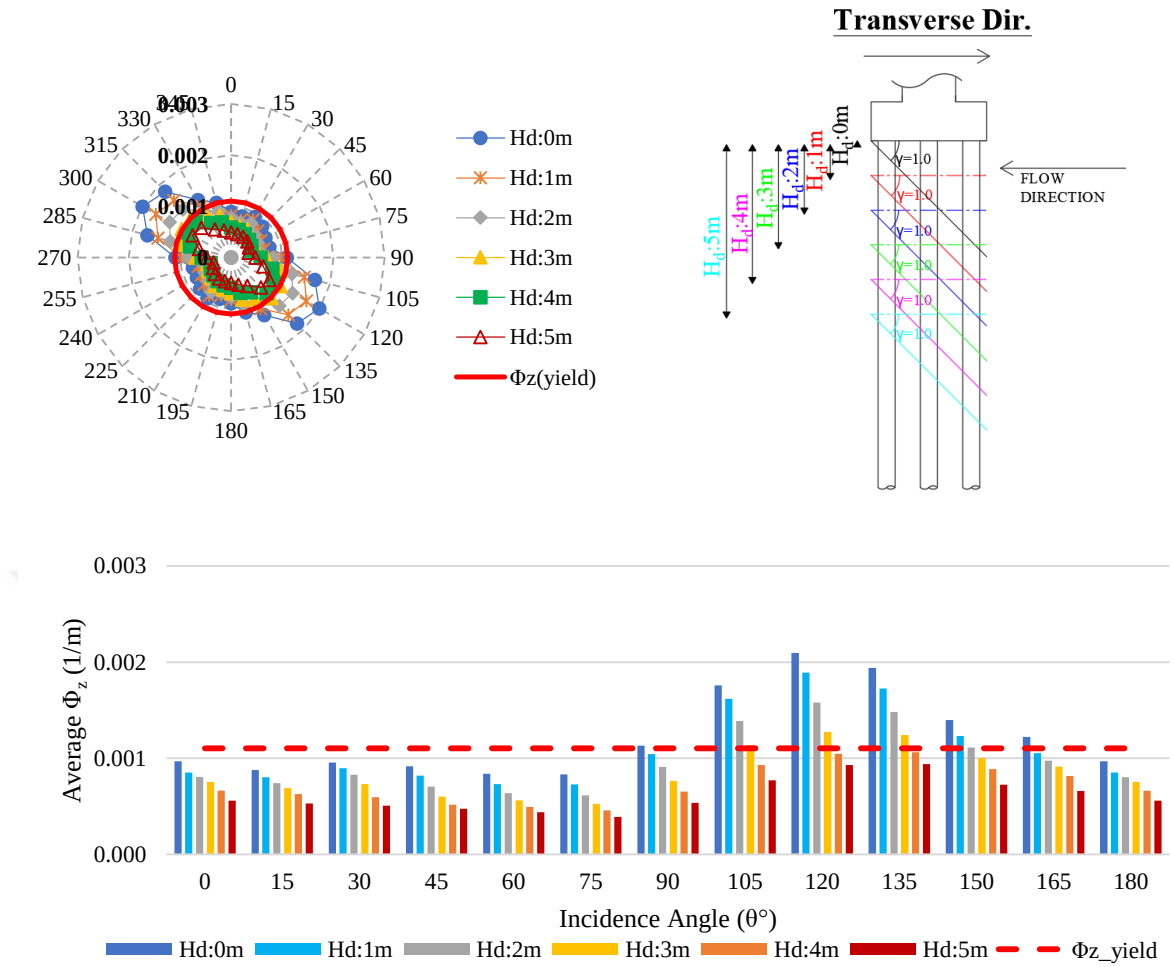


Figure 5.69. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.70 and Figure 5.71, maximum curvature demands of column weak (y') and strong (z') axes of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges are compared. In column weak axis (y'), curvature demands are higher in non-skewed bridge at 75° incidence angle. However, it is become much higher in skewed bridge at 120° incidence angle. Moreover, this situation is similar in strong (z') axis of column. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 3m scour depth as nearly 210%. In strong axis, it is at 135° and 0m scour depth as 56.6%.

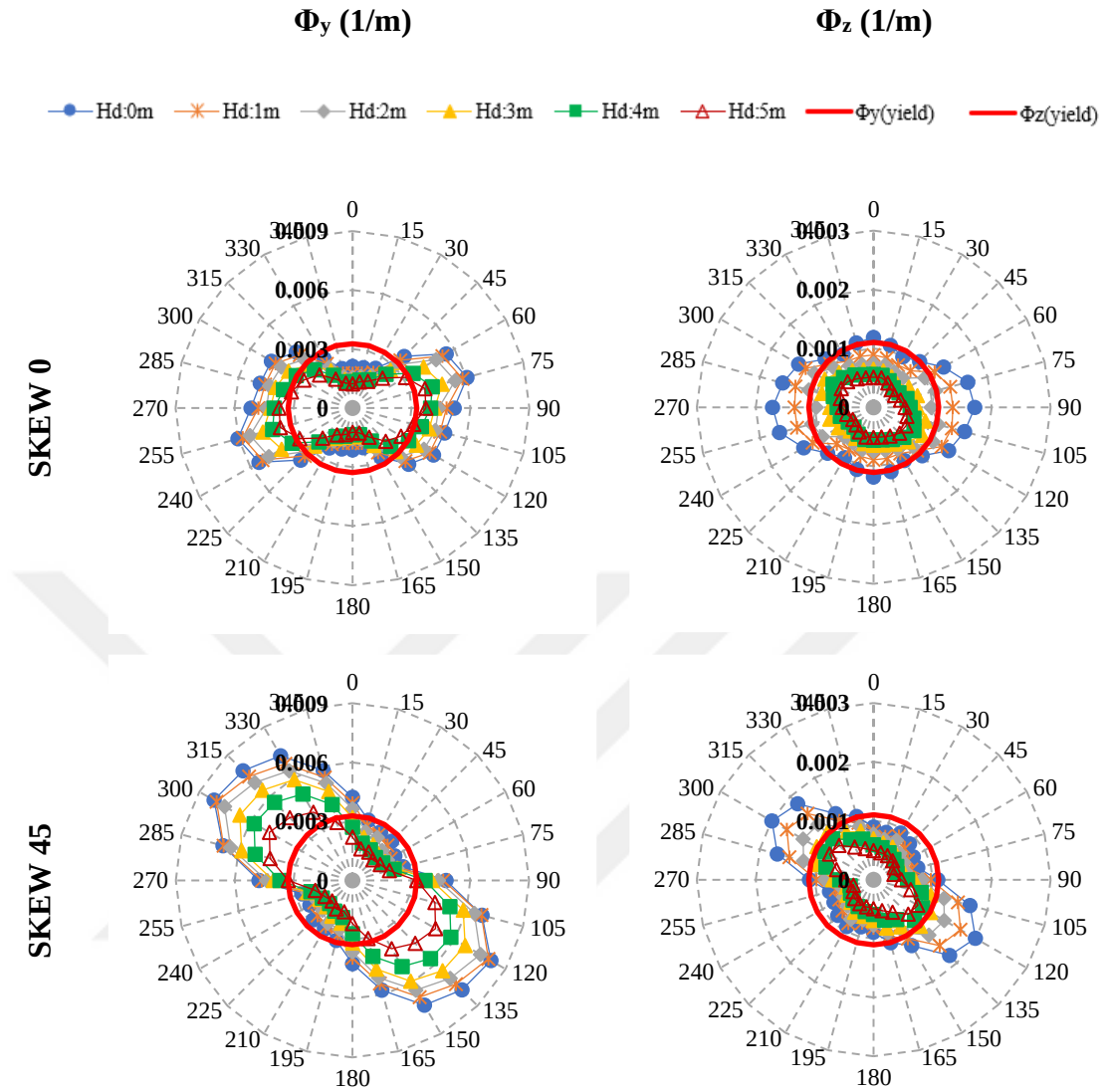


Figure 5.70. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

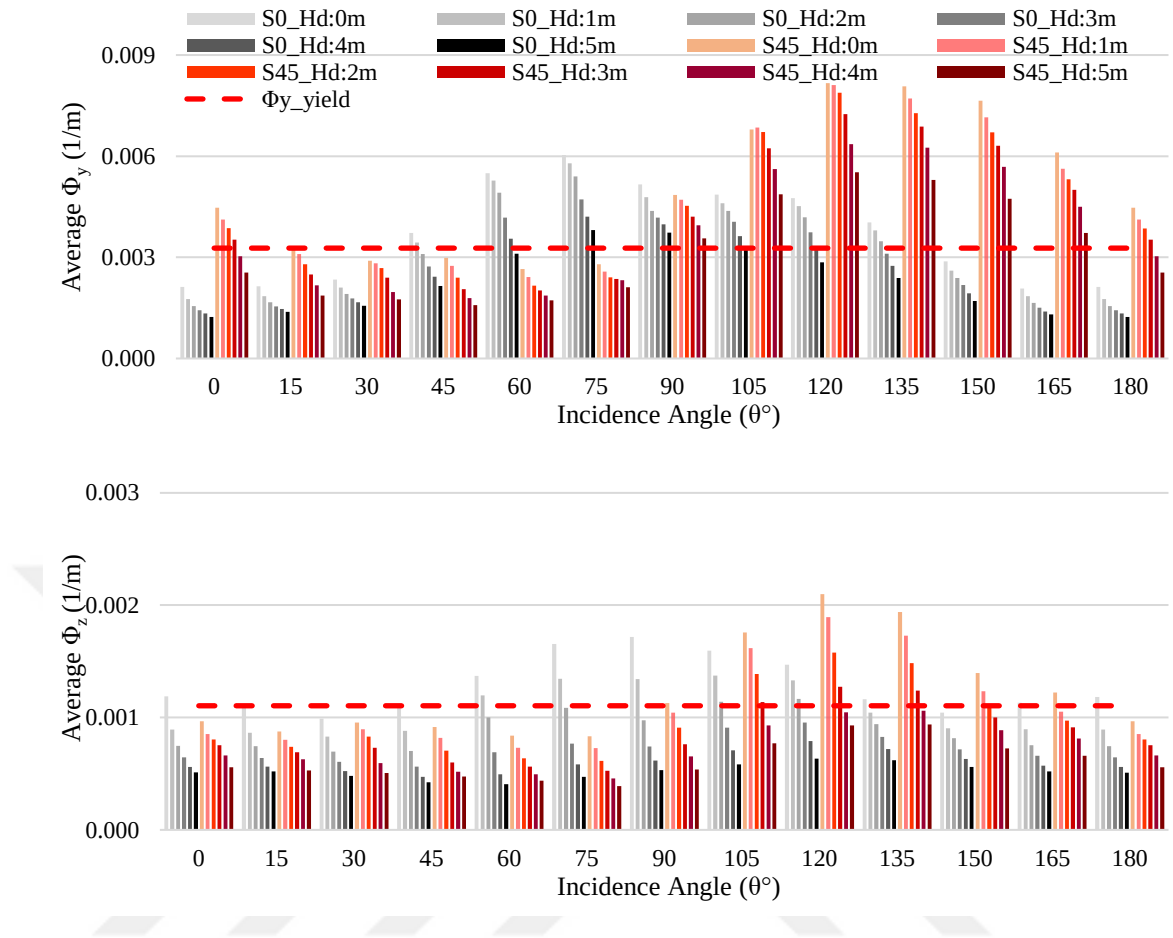


Figure 5.71. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

5.2.2.3. Shear force demands of column pier

In Figure 5.72 and Figure 5.73, maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_d=0m$) and 5m scoured ($H_d=5m$) models occurs at 60° incidence angle and nearly 32.9%. Also, it is about 15.3% at 165° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below

the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis.

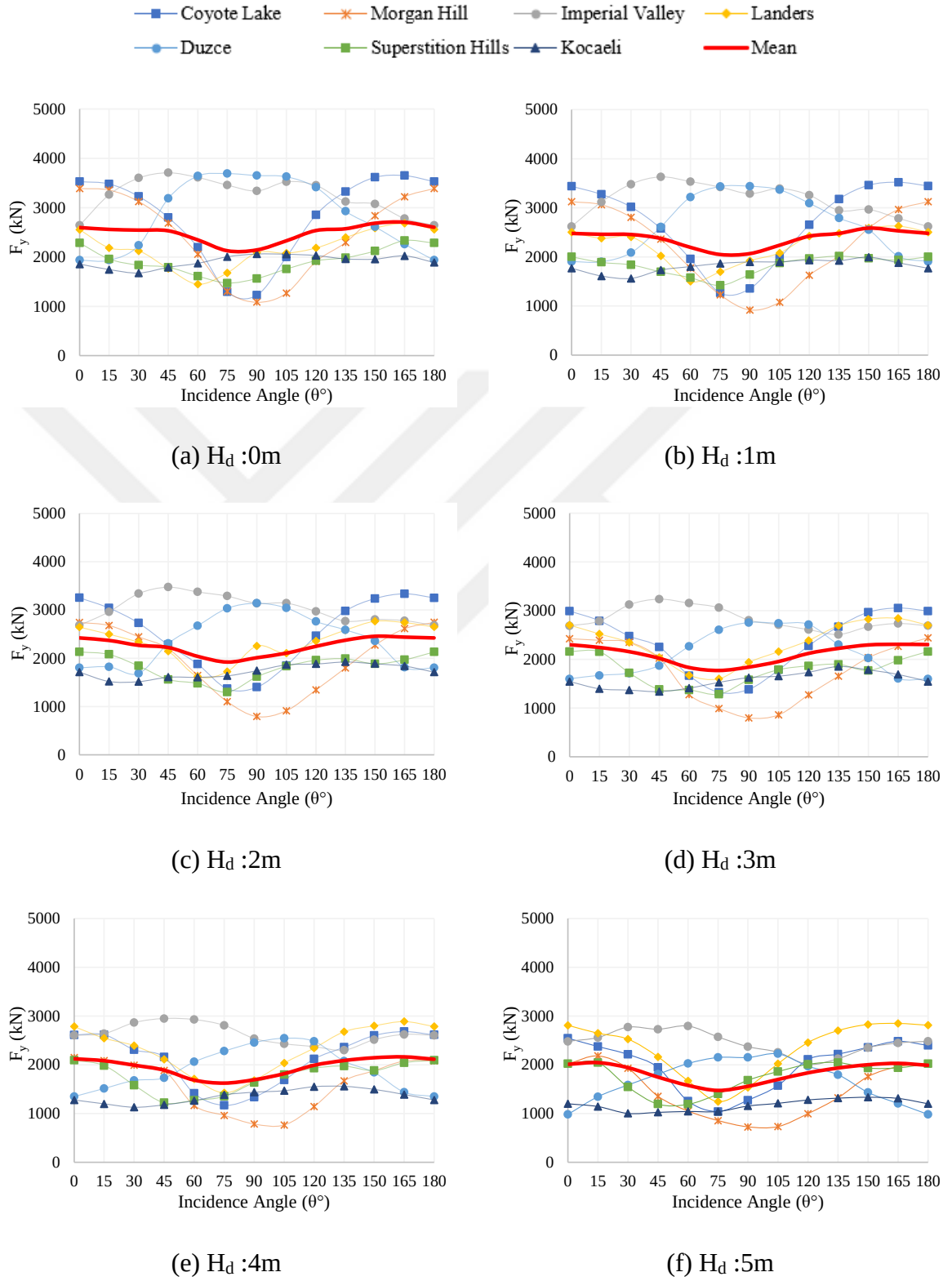


Figure 5.72. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

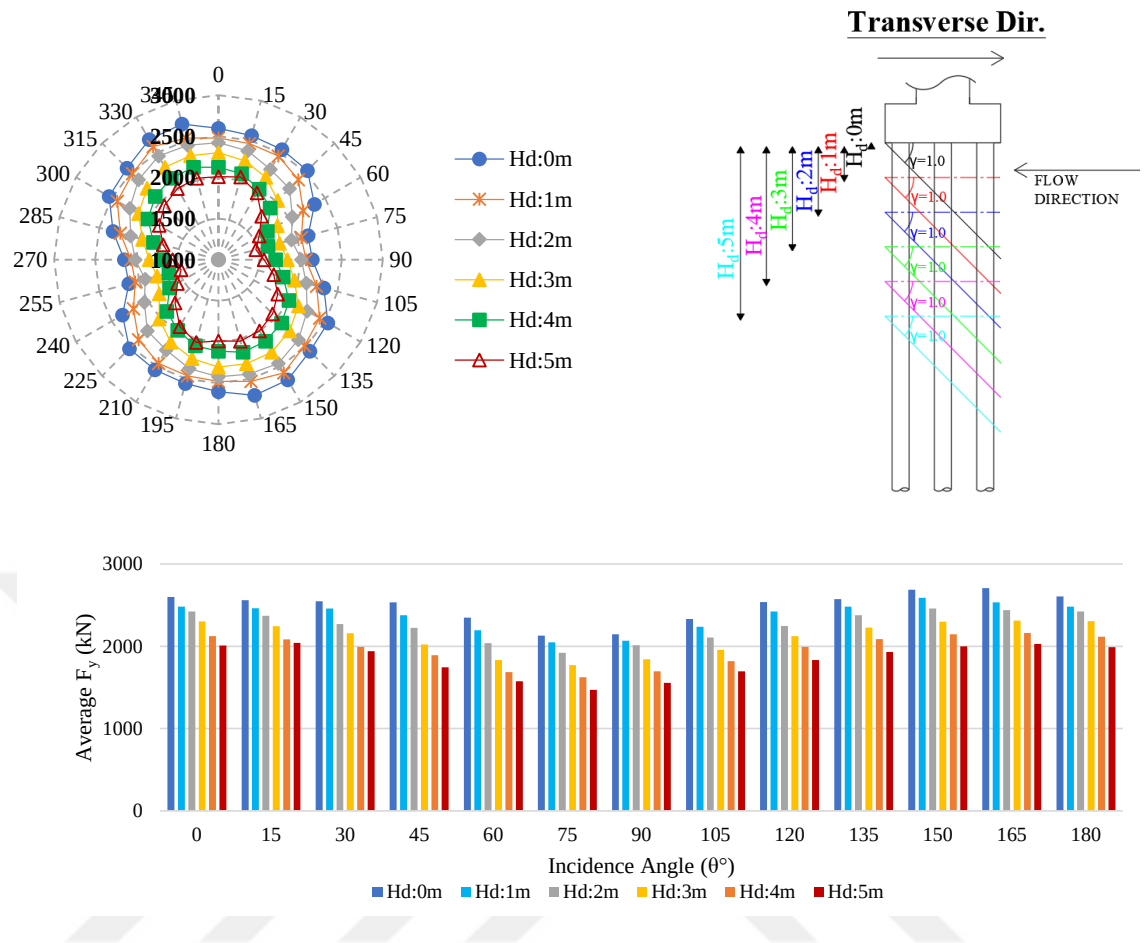


Figure 5.72. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

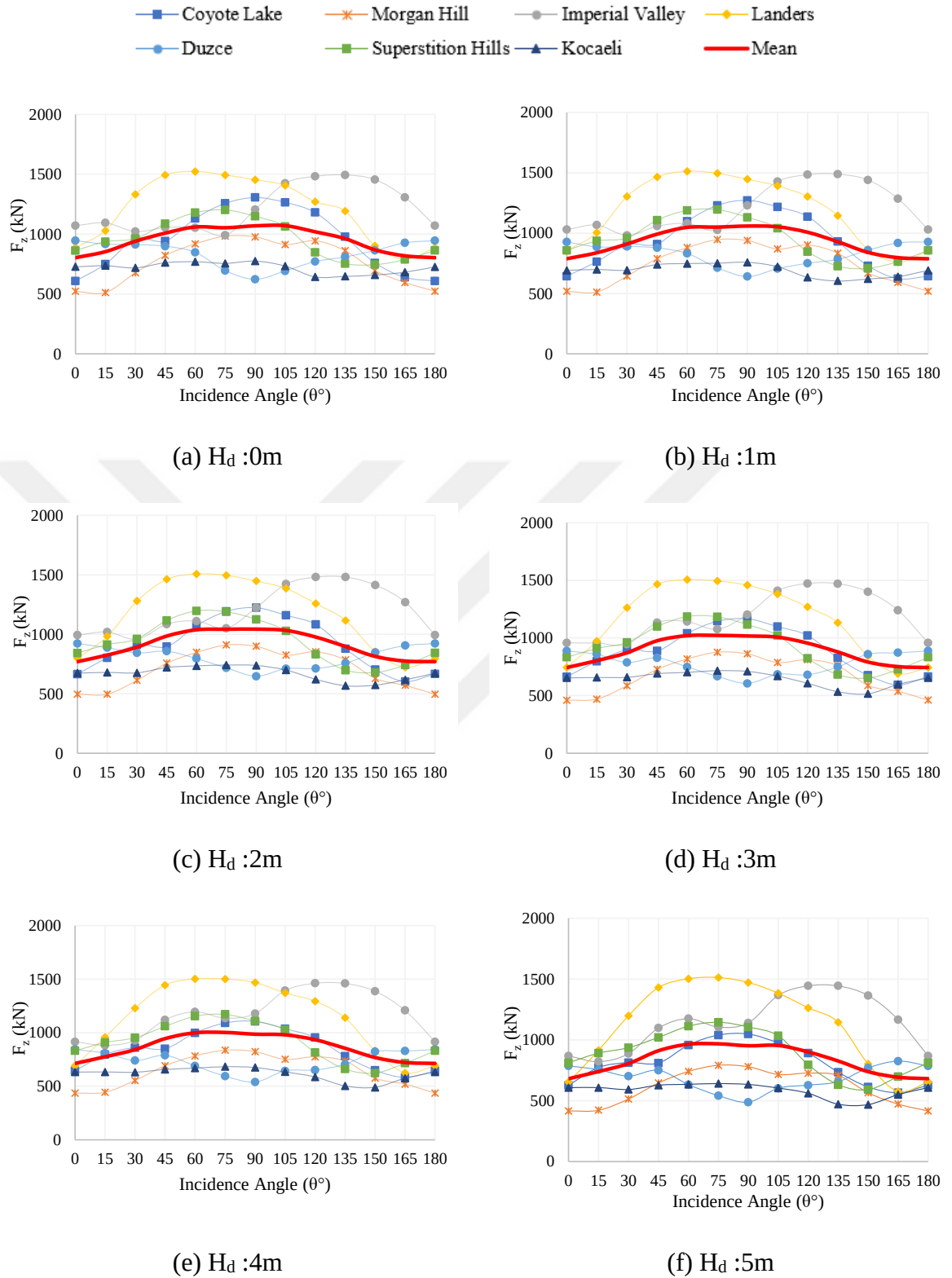


Figure 5.73. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

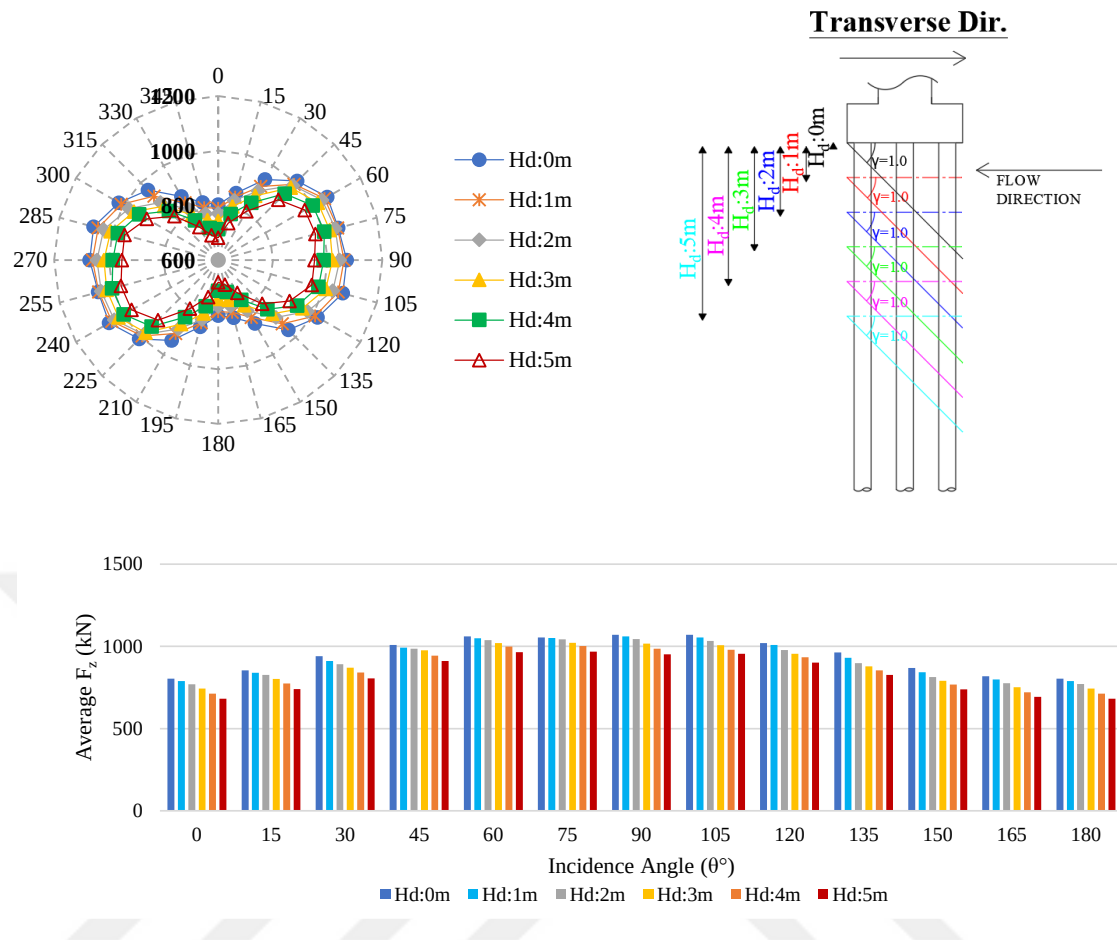


Figure 5.73. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.74 and Figure 5.75, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 75° to 120° in local y' axis. Besides, it has an increasing trend between 30° and 135° incidence angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. The maximum difference of average demands in local y' axis of no scoured ($H_d=0m$) and 5m scoured ($H_d=5m$) models occurs at 90° incidence angle and nearly 32%. Also, it is about 20.6% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below

the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in 45° skewed bridge column during nonlinear analysis.

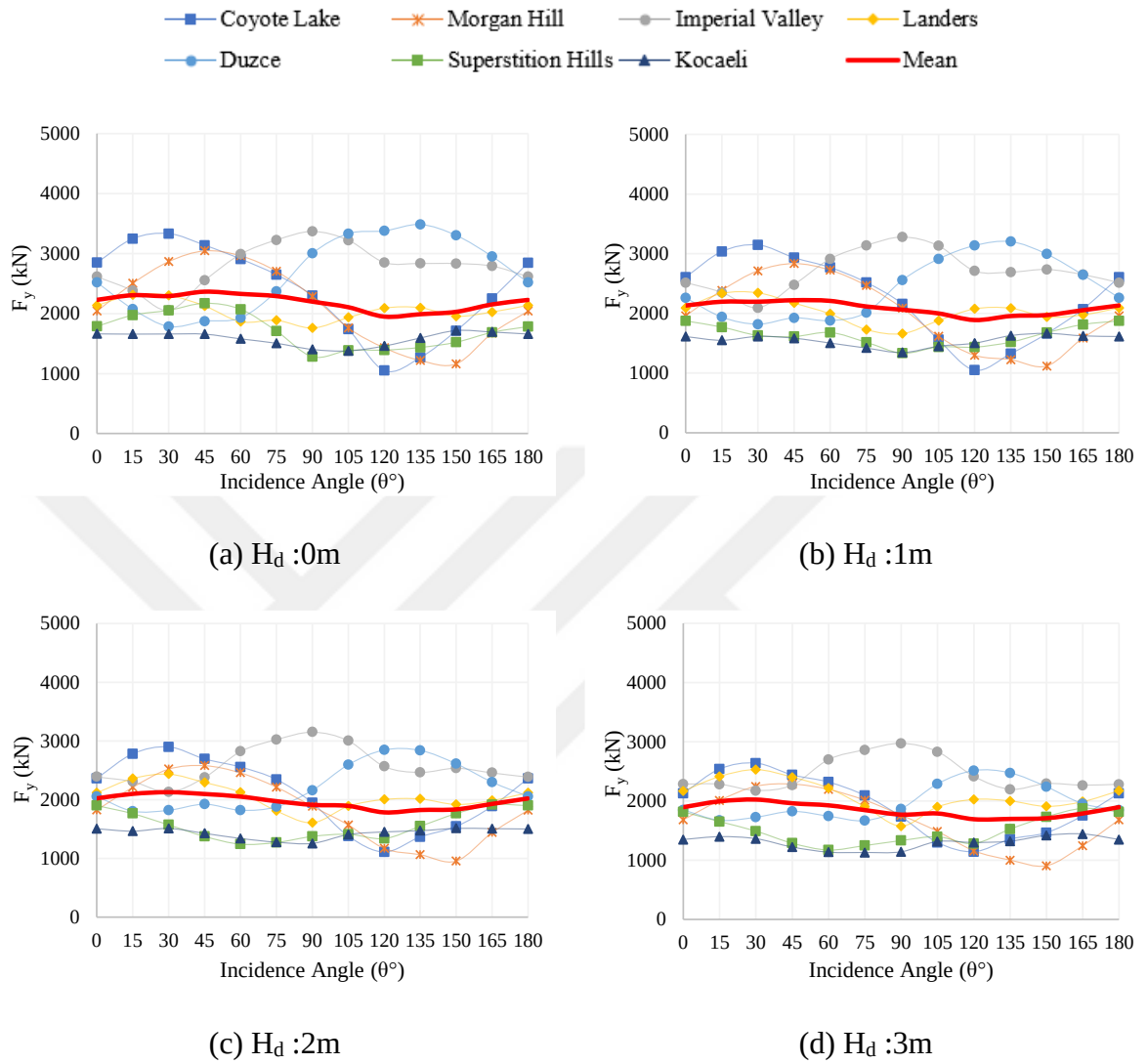
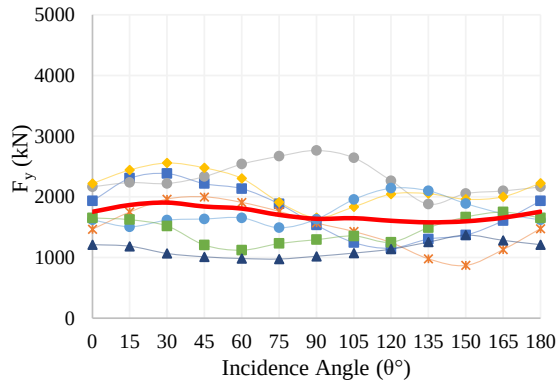
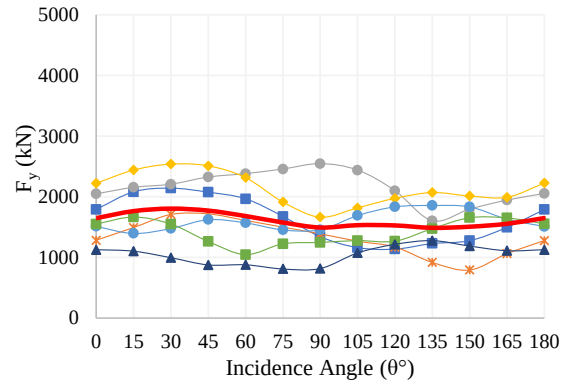


Figure 5.74. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$



(e) $H_d : 4m$



(f) $H_d : 5m$

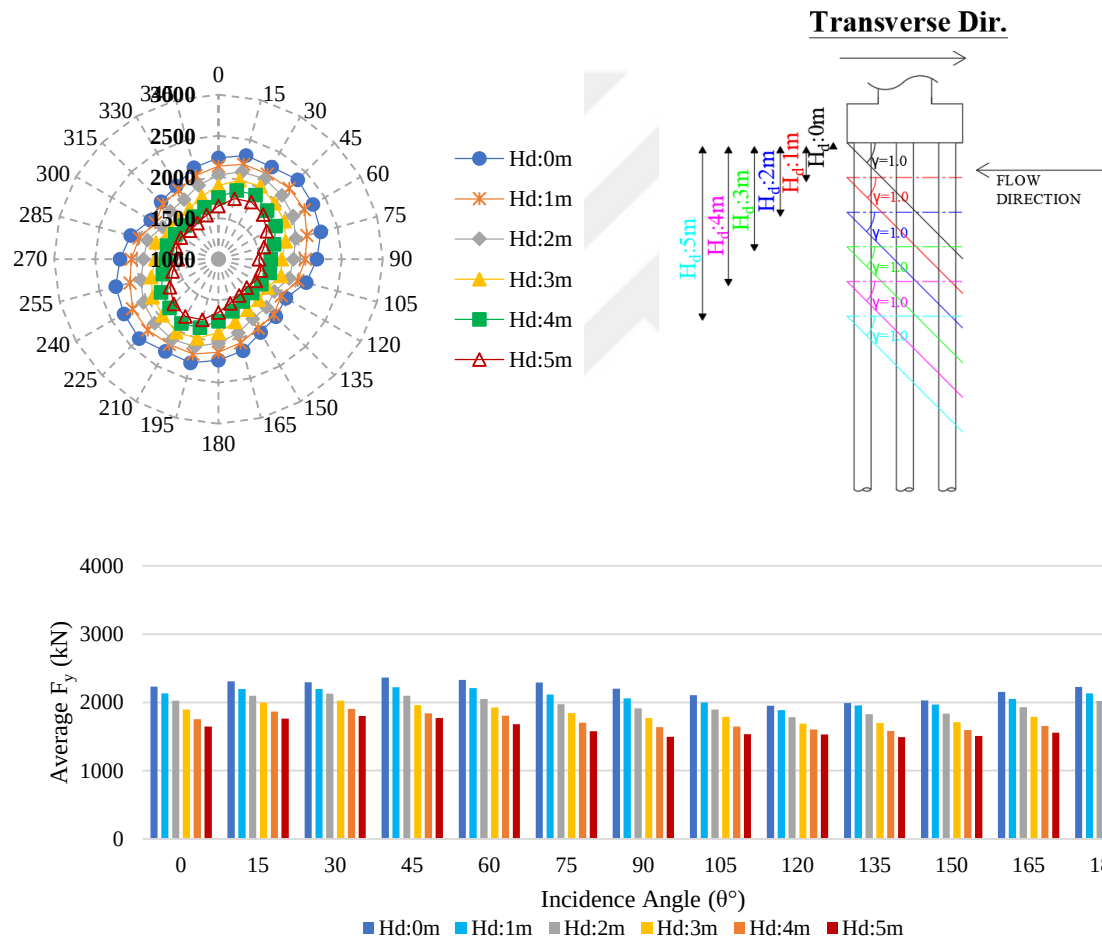


Figure 5.74. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

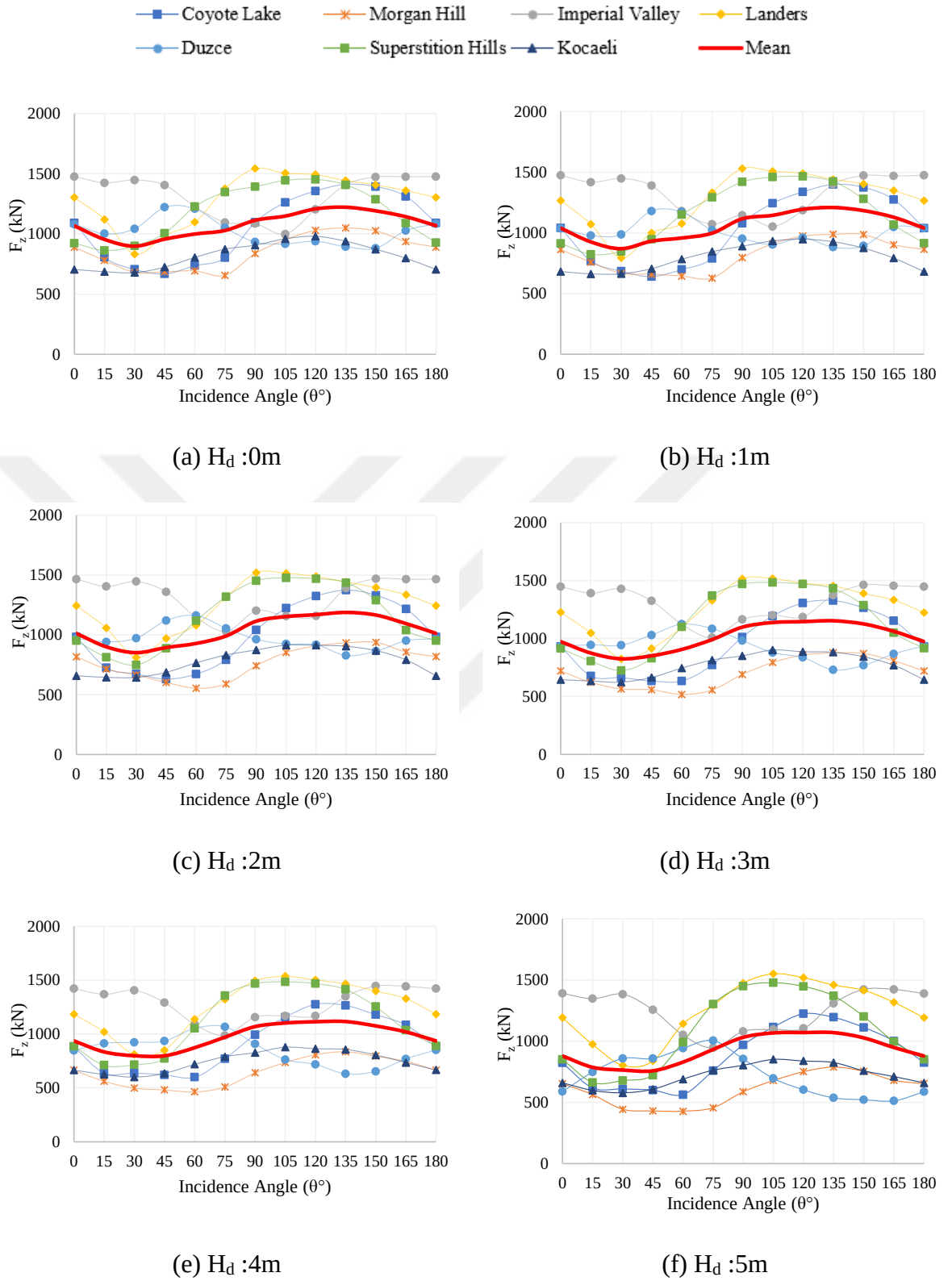


Figure 5.75. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

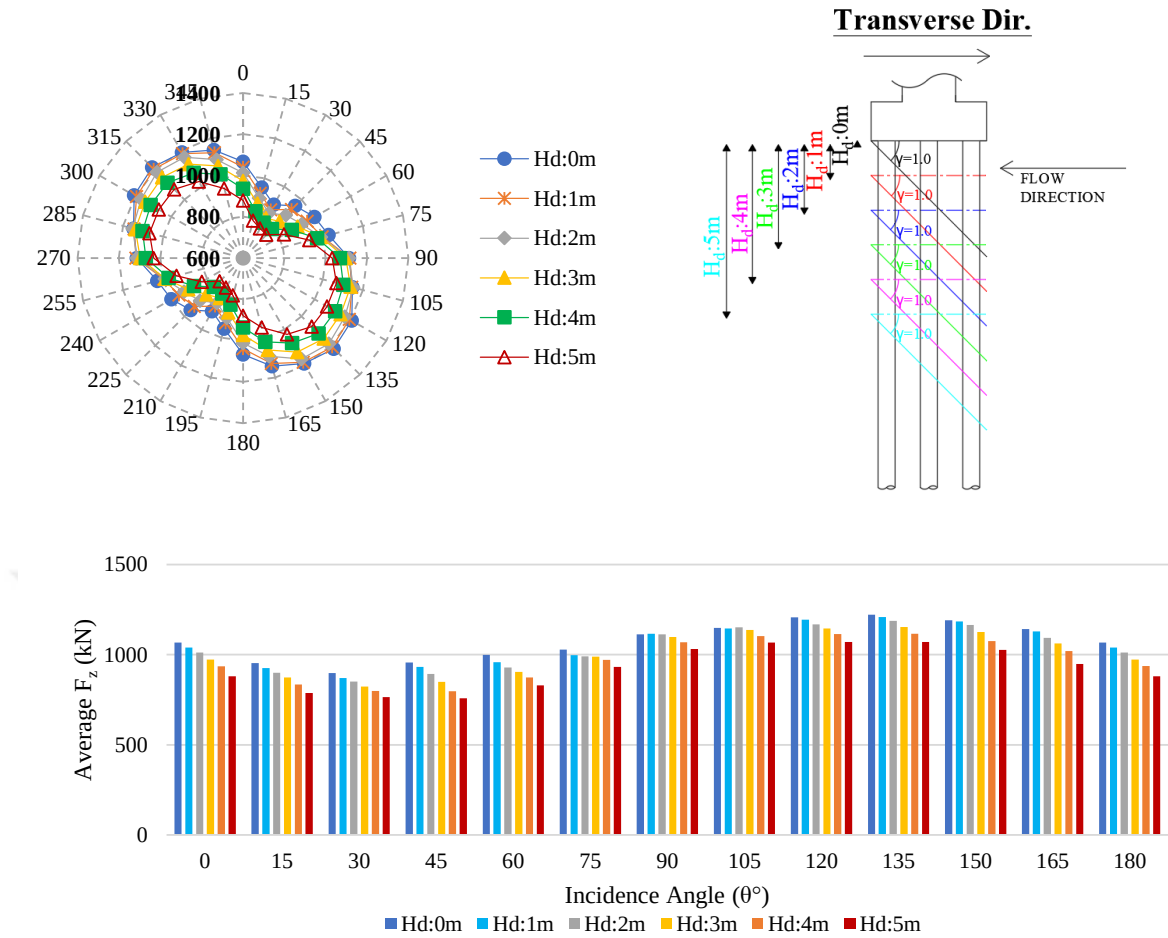


Figure 5.75. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ (continued)

In Figure 5.76 and Figure 5.77, maximum shear force demands of column local y' and z' axes of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridges are compared. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 150° incidence angle and 3m scour depth as nearly 25.6%. In local z' axis, it is also at 150° and 2m scour depth as 43.1%.

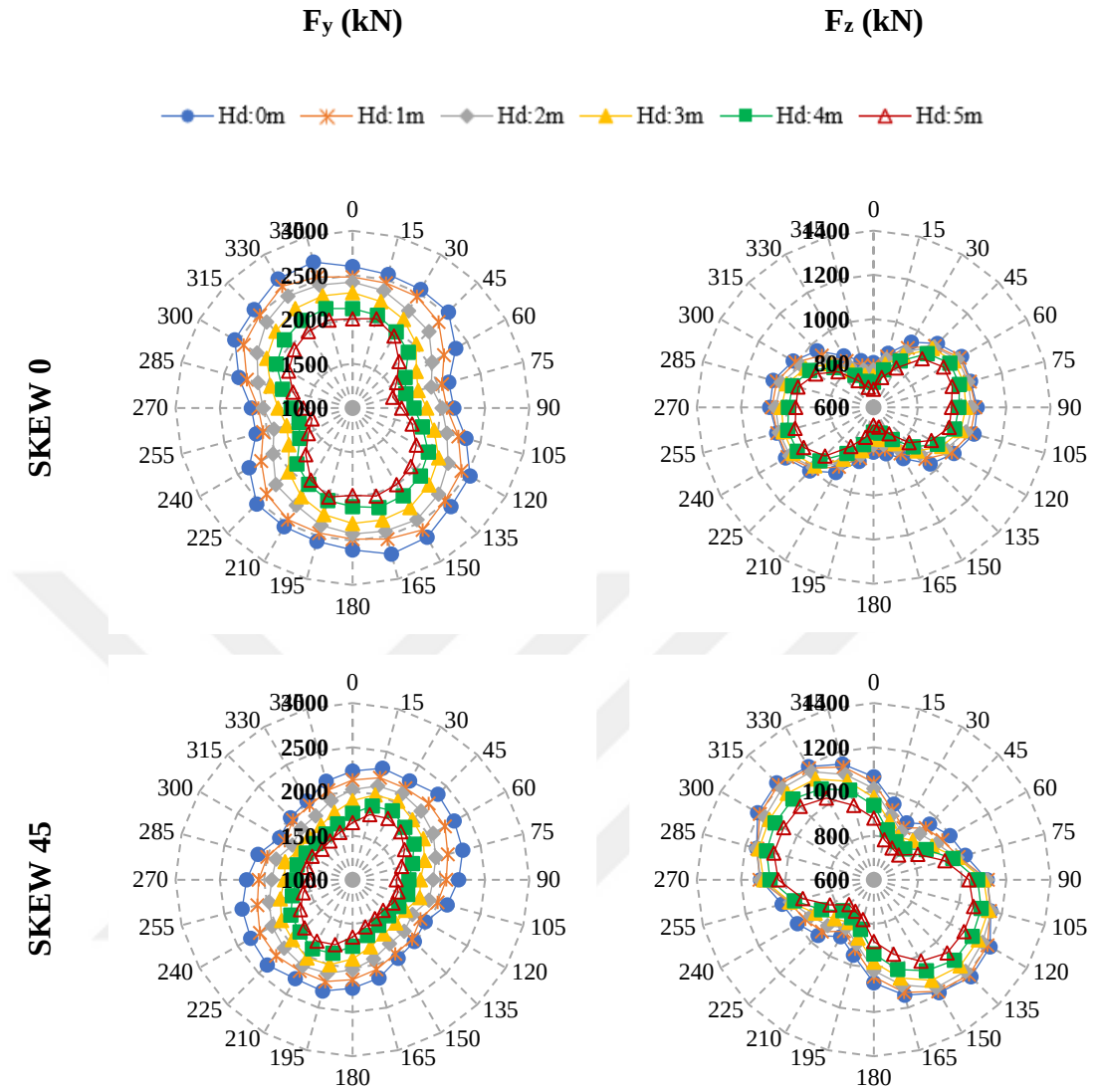


Figure 5.76. Average maximum shear force demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

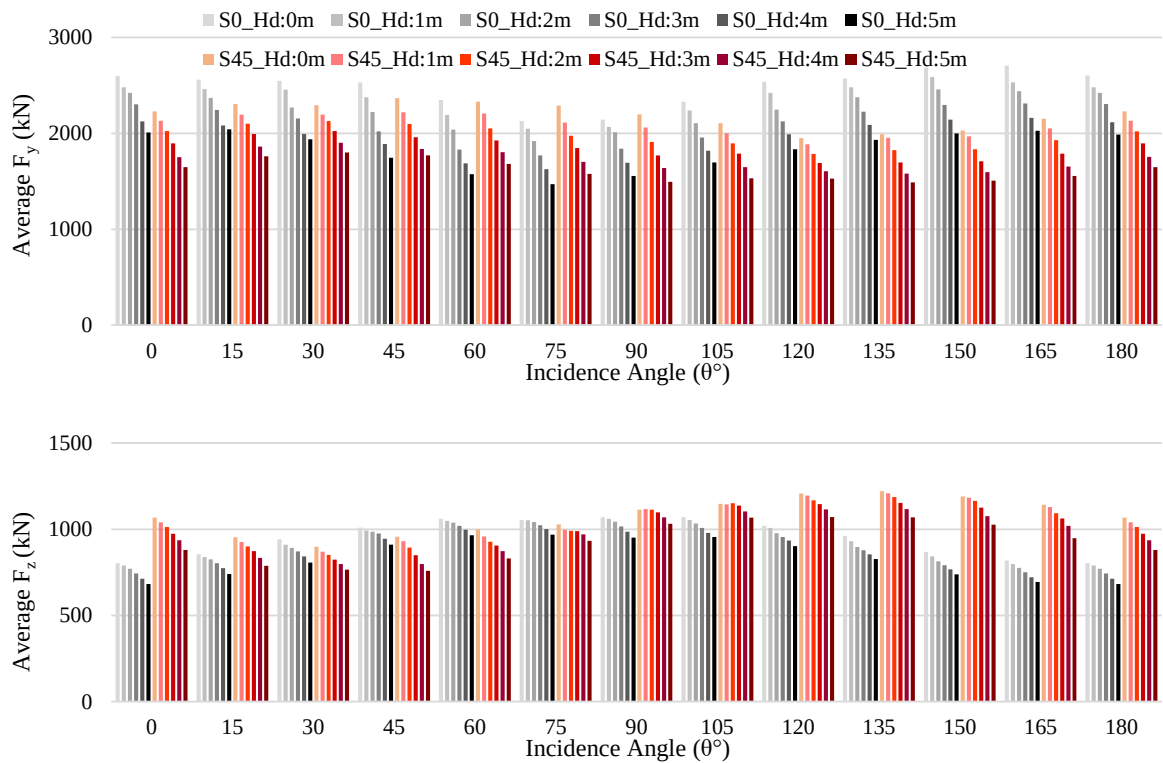


Figure 5.77. Average maximum shear force demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$

5.2.2.4. Shear force demands of piles

In Figure 5.78 and Figure 5.79, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. As it can be seen from the graphs, shear force demands occurred in downstream piles are more than demands occurred in upstream ones in both axes. For all scour depths except 5m, shear force demands are above the pile shear capacity of 735.2 kN. It means, shear failure occurs on piles in downstream during earthquake. Also, demands are below the shear capacity in local z' axis for all piles. Therefore, shear force demands of local y' axis of pile number 4 (P4) which places at downstream is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.80. P4 pile shear demand is higher in non-skewed bridge and it has a maximum value at 0m scour depth. It is decreasing when scour depth increases and don't reach the shear capacity at 5m depths for both bridges. This means that non-uniform scour in transverse direction of bridge becomes more critical for pile elements at shorter scour depths.



Figure 5.78. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ ($\alpha=0^\circ$ non-skewed bridge)

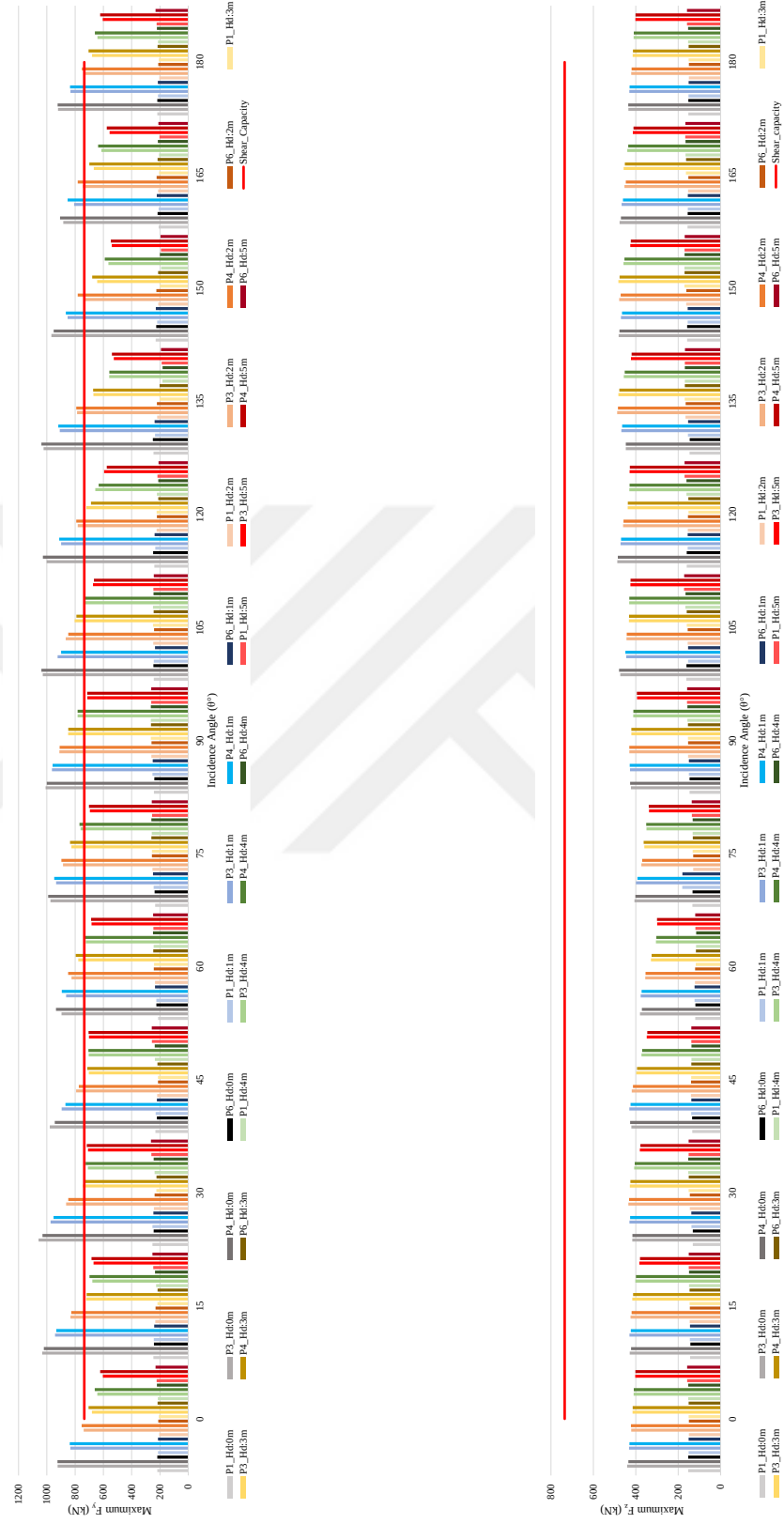


Figure 5.79. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles when $\gamma=1.0$ ($\alpha=45^\circ$ skewed bridge)

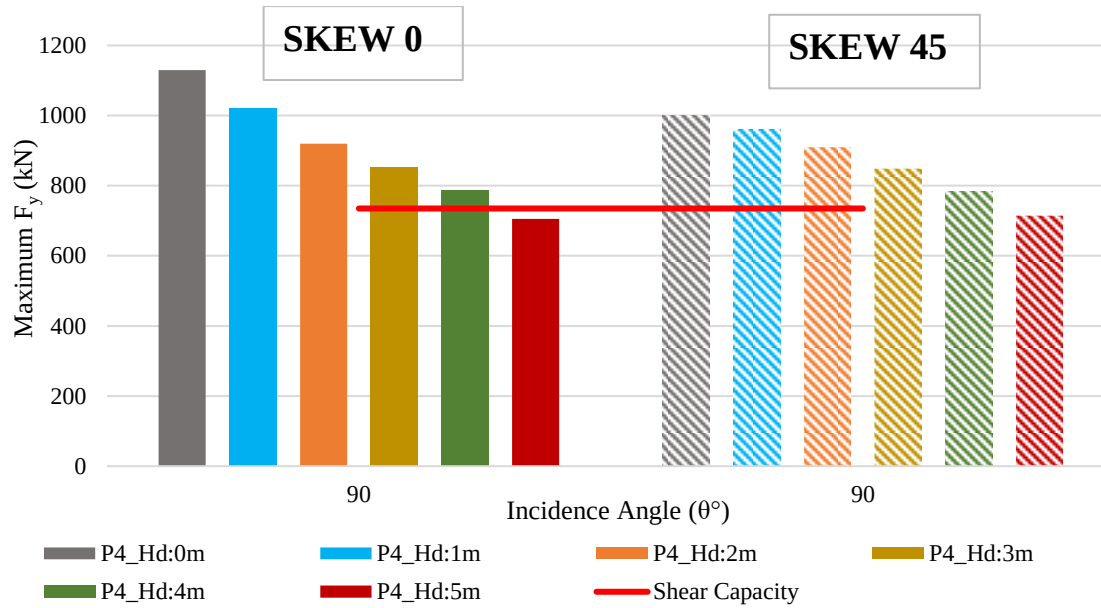


Figure 5.80. Average maximum shear force demands of local y' axis of pile (P4) for different nonuniform scour depths and 90° earthquake incidence angle when $\gamma=1.0$

5.2.2.5. Residual displacements

Residual displacements were calculated for middle column and superstructure by using non-skewed and skewed bridges for non-uniformly ($\gamma=1.0$) changed scour depths and different ground motion incidence angles. In Figure 5.81, the average residual displacement demands of middle column for non-skewed and skewed bridges are given when scour depth is non-uniformly changed. Also, in Figure 5.82, the ratio of residual displacement demand to maximum displacement of middle column for non-skewed and 45° skewed bridge is shown when scour depth change is non-uniform (Case 2-1b). Furthermore, the same demands are evaluated for superstructure and shown in Figure 5.83 and Figure 5.84, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal and transverse direction for middle column of bridge. However, superstructure demands are higher in longitudinal direction for non-skewed bridge and in transverse direction the situation becomes vice versa for skewed bridge.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when non-uniform scour depth is 5m at 75° incidence angle for non-skewed bridge as 23.4mm. In transverse direction it is maximum at 90° incidence angle and 5m scour depth as 6.5mm for non-skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the

maximum ratio occurs at an incidence angle of 75° and 5m scour depth as 0.18 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 0m scour depth when incidence angle 0° in transverse direction of skewed bridge.

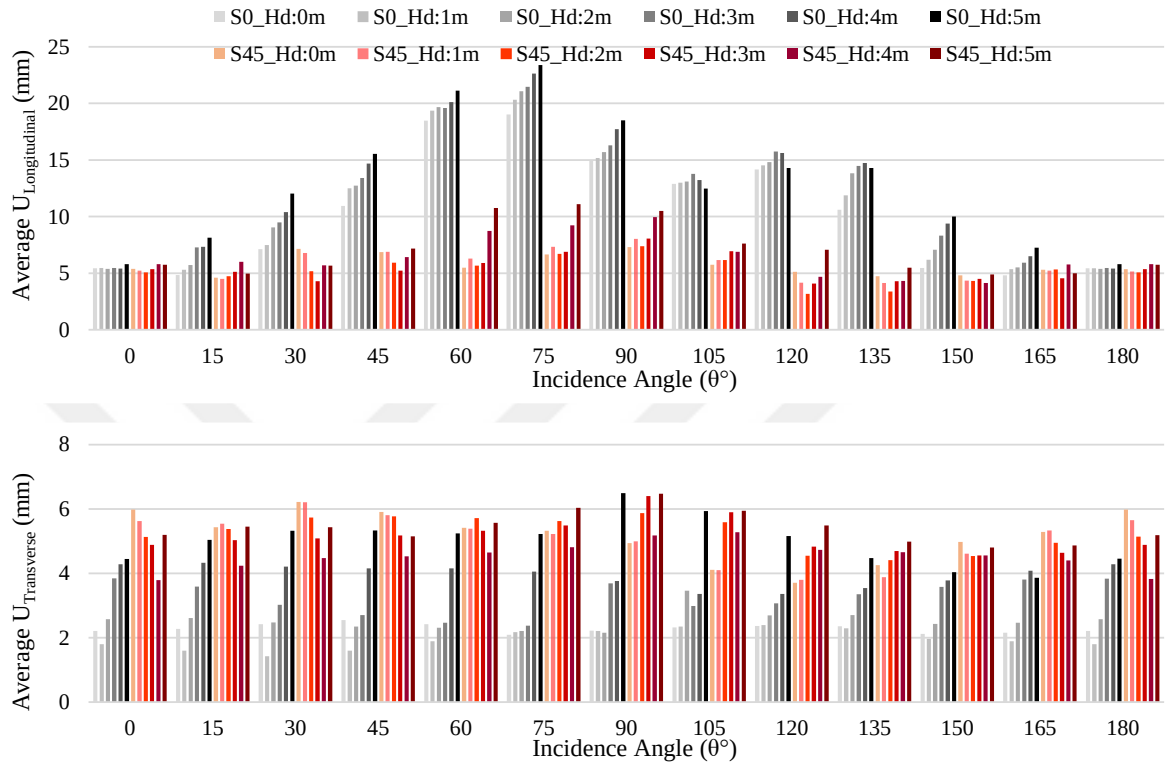


Figure 5.81. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1b)

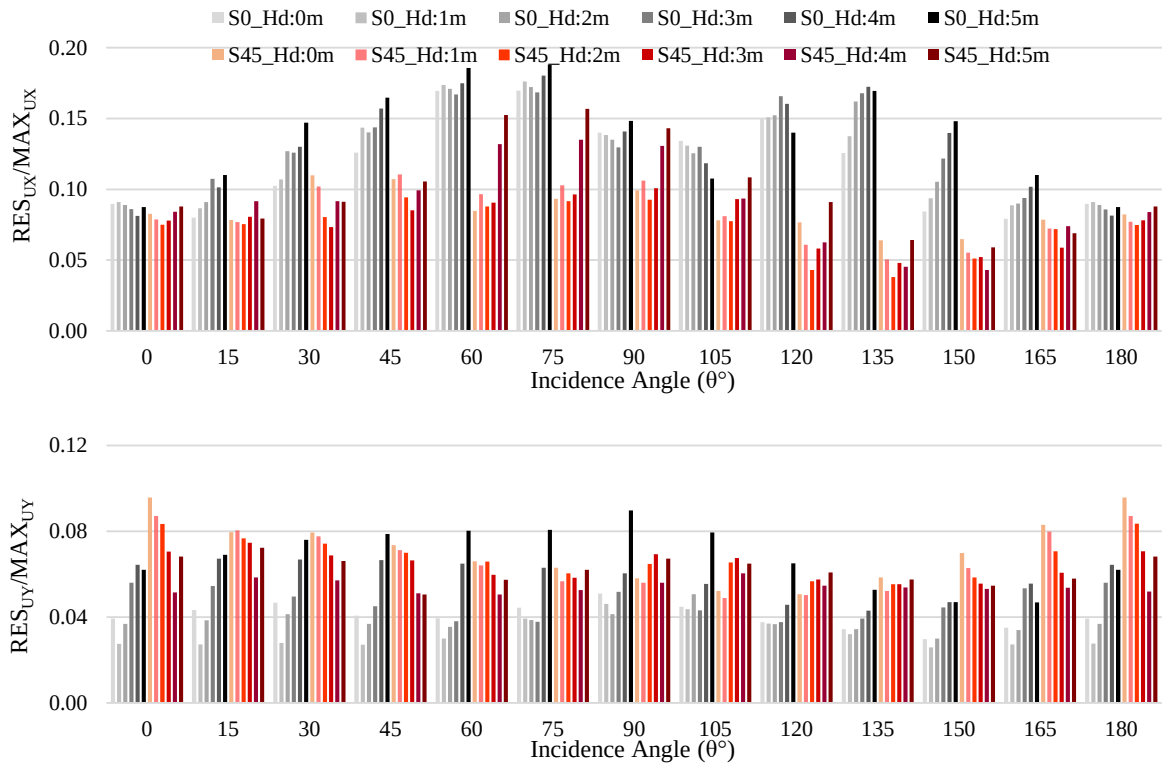


Figure 5.82. The ratio of residual displacement demand to maximum displacement of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1b)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when non-uniform scour ($\gamma=1.0$) depth is 5m at 75° incidence angle for non-skewed bridge as 28.1mm. In transverse direction it is maximum at 180° incidence angle and 1m scour depth as 8.8mm for skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 5m scour depth as 0.19 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 0m scour depth when incidence angle 0° in transverse direction of skewed bridge.

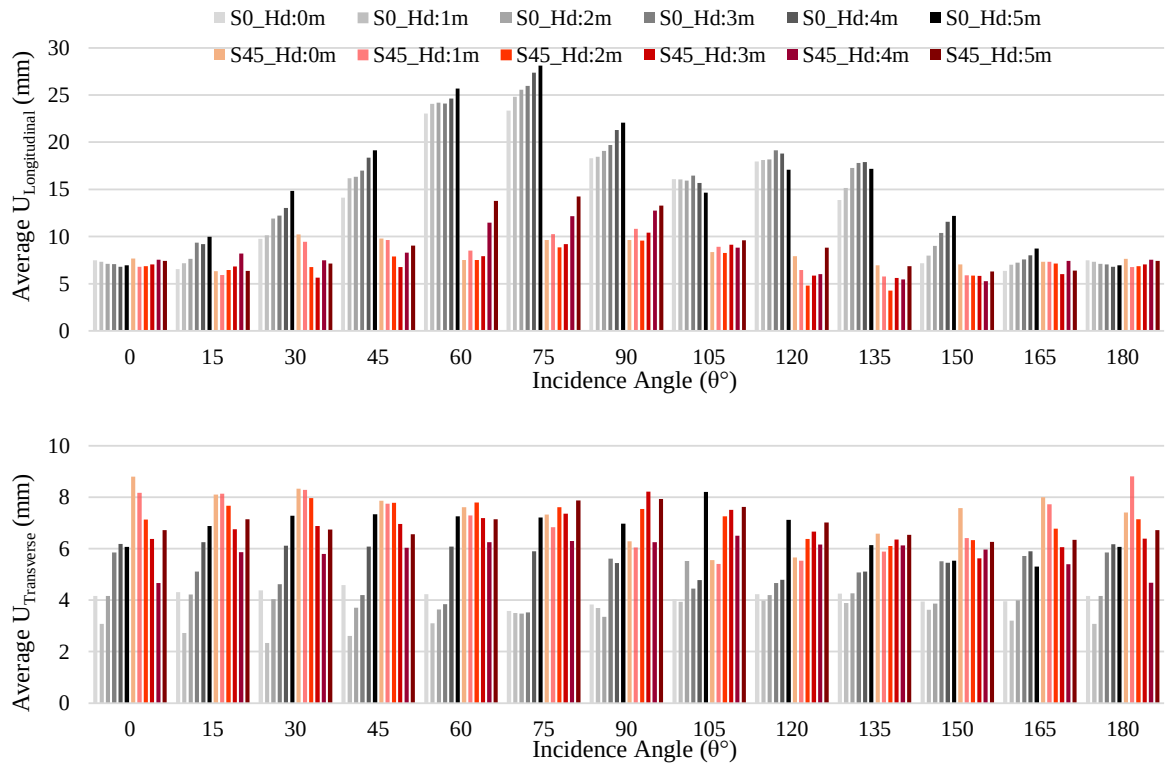


Figure 5.83. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1b)

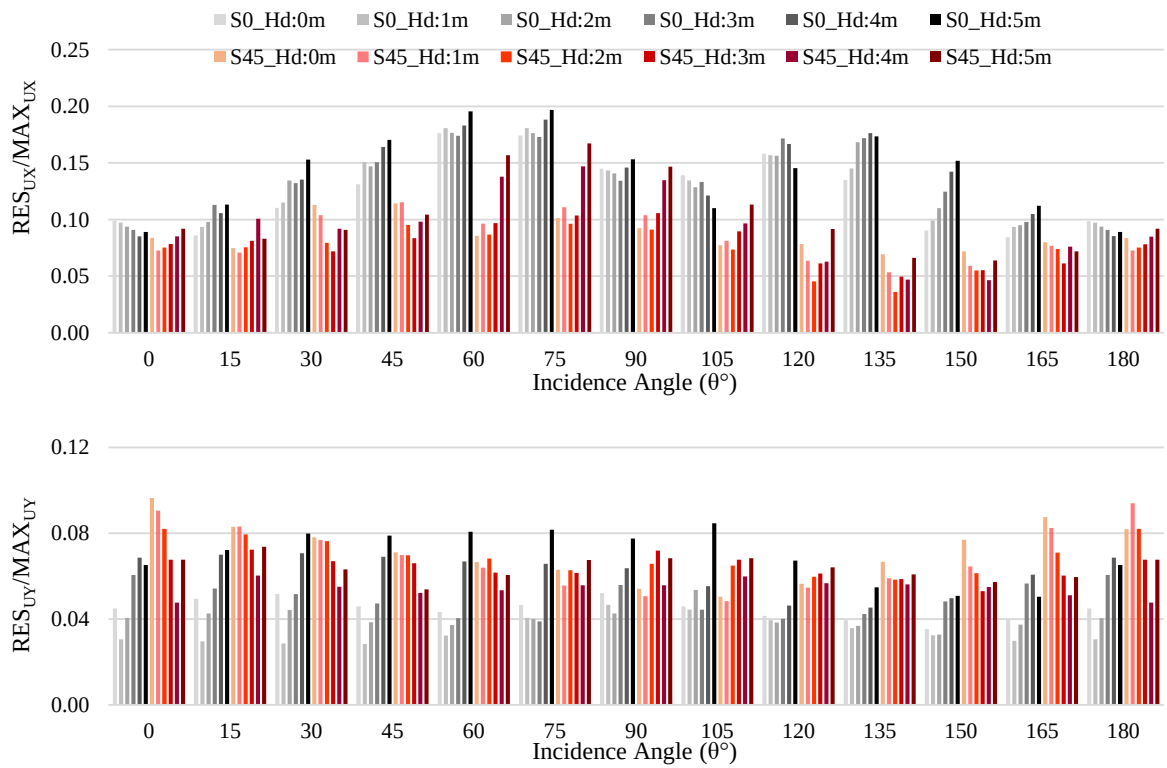


Figure 5.84. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in transverse direction (Case 2-1b)

5.3. Non-Uniform Scour in Longitudinal Direction of Bridge (Case 2-2)

As mentioned in the previous section, the scour depth around the bridge pile elements may occur in a non-uniform way depending on the direction of water flow. This non-uniformity may occur in the transverse direction of the bridge as well as in the longitudinal direction of the bridge. The fact that more scour occurs around the pile elements in the middle span, located in the longitudinal direction of the bridge, compared to the piles in the outer span, according to the direction of water flow, is examined in this section of the thesis. Accordingly, bridge models are created in which 25%, 50% and 75% more scour depth is assumed around the pile elements in the middle span, respectively, than those in the outer span as shown in Figure 3.41. The change in scour depth is chosen as 2 m, 4 m and 6 m for this case. The results obtained from nonlinear response history analyses are given in detail in the subheadings.

5.3.1. Non-uniform scour in longitudinal direction of bridge when scour is 25% more around middle piles (Case 2-2a)

In this part of thesis, non-uniform scoured bridge models in longitudinal direction are constructed by taking the scour depth 25% more around middle piles than side piles. Scour depth is changed as 2m, 4m and 6m (H_d). This means, when scour around side piles is 2m, the scour around middle piles become 25% more and calculated as 2.5m as given in Figure 3.42. Nonlinear response history analysis is done by using 7 strong ground motions for non-skewed and skewed bridge model for each scour depth. Also ground motion incidence angle is rotated starting from 0° to 180° with an increment of 15° . The engineering demand parameters (EDPs) examined within the scope of the study are superstructure displacement, bent column curvature and shear, pile shear, residual displacements of middle column and superstructure. The demands obtained from nonlinear analysis results are given below.

In Figure 5.85, the variation of 1st and 2nd vibration period of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge depending on non-uniform scour depth in longitudinal direction is given when scour is 25% more around middle piles (Case 2-2a) and the vibration period of the bridge increases when scour depth increases. For skewed bridges, first period is greater than non-skewed bridges for all scour depths. On the other hand, the second period of non-skewed bridge becomes greater than skewed one.

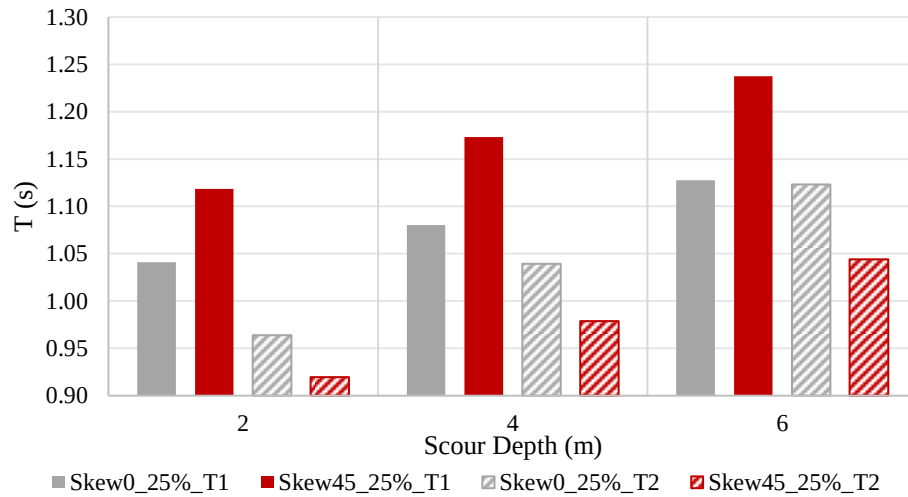


Figure 5.85. The variation of 1st and 2nd vibration period of non-skewed (0°) and skewed (45°) bridge depending on non-uniform scour depth in longitudinal direction when scour is 25% more around middle piles (Case 2-2a)

5.3.1.1. Superstructure displacement

Superstructure displacement demands obtained from nonlinear analysis results belong to midpoint of bridge deck as mentioned above. In Figure 5.86 and Figure 5.87, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.88 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which are changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results examined in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 90° although in transverse direction it is decreasing between those angles. Therefore, resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase in displacement in both directions is more obvious in some ground motion incidence angles. Considering that the stronger horizontal ground motion component is affected in transverse direction of bridge during nonlinear analyses, it is expected that the displacement demands obtained in longitudinal direction of bridge give the maximum result when earthquake components are rotated by 90° . The maximum difference of the average displacement

demands in longitudinal direction between 2 m scoured ($H_d=2\text{m}$) and 6 m scoured ($H_d=6\text{m}$) bridge is occurred at 75° incidence angle as nearly 10%. In transverse direction, it is at 15° incidence angle as 21.5%. If it is checked for resultant displacement, maximum difference becomes 16% at 0° incidence angle.

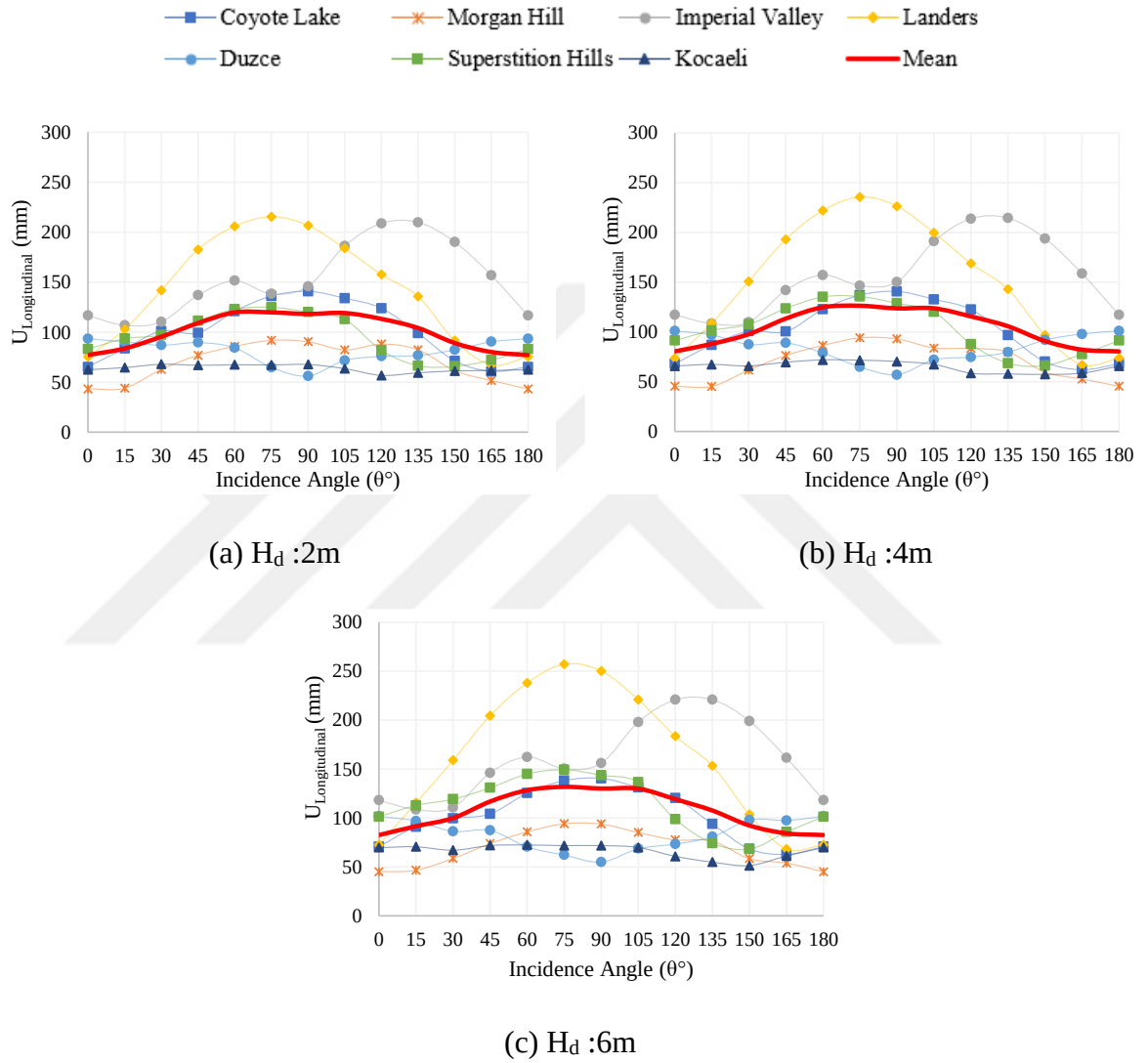


Figure 5.86. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

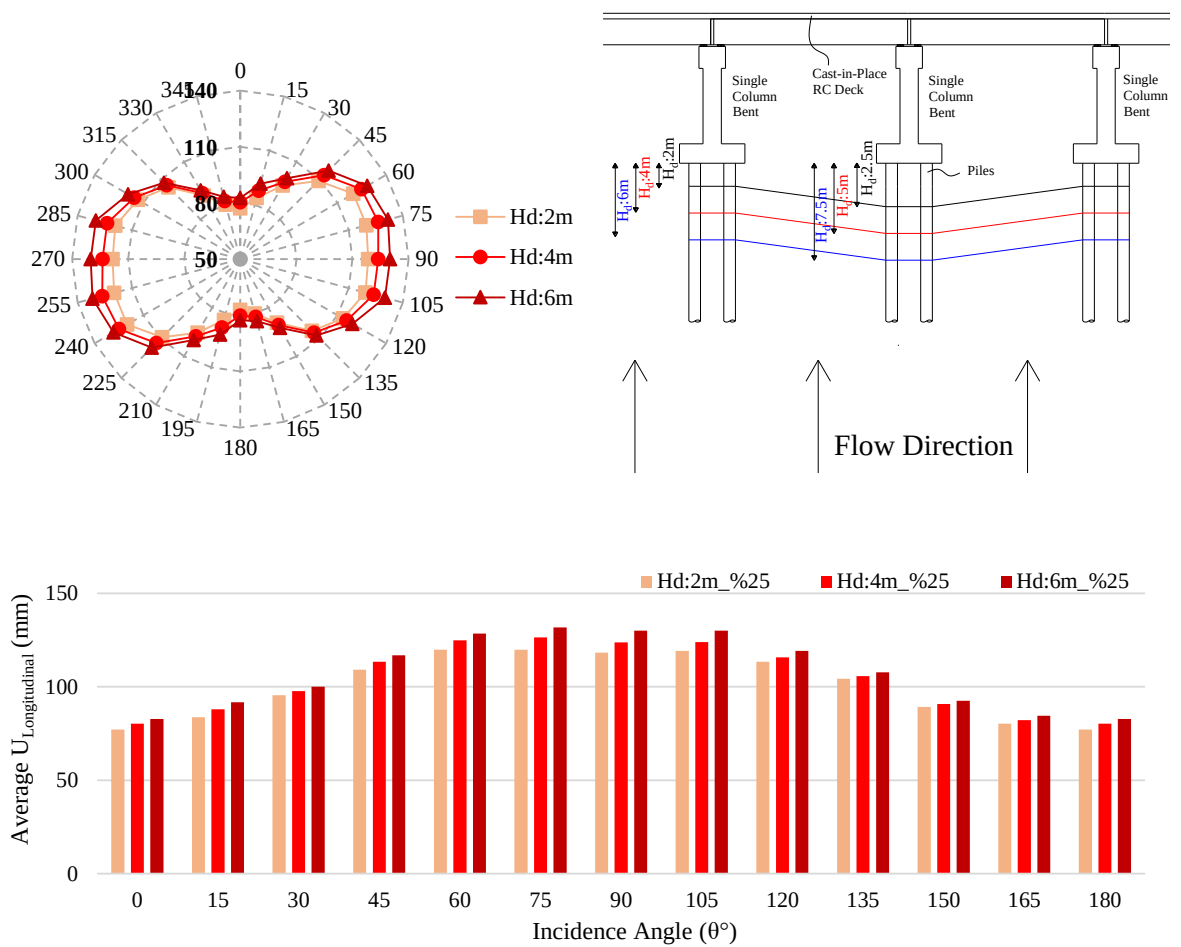


Figure 5.86. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

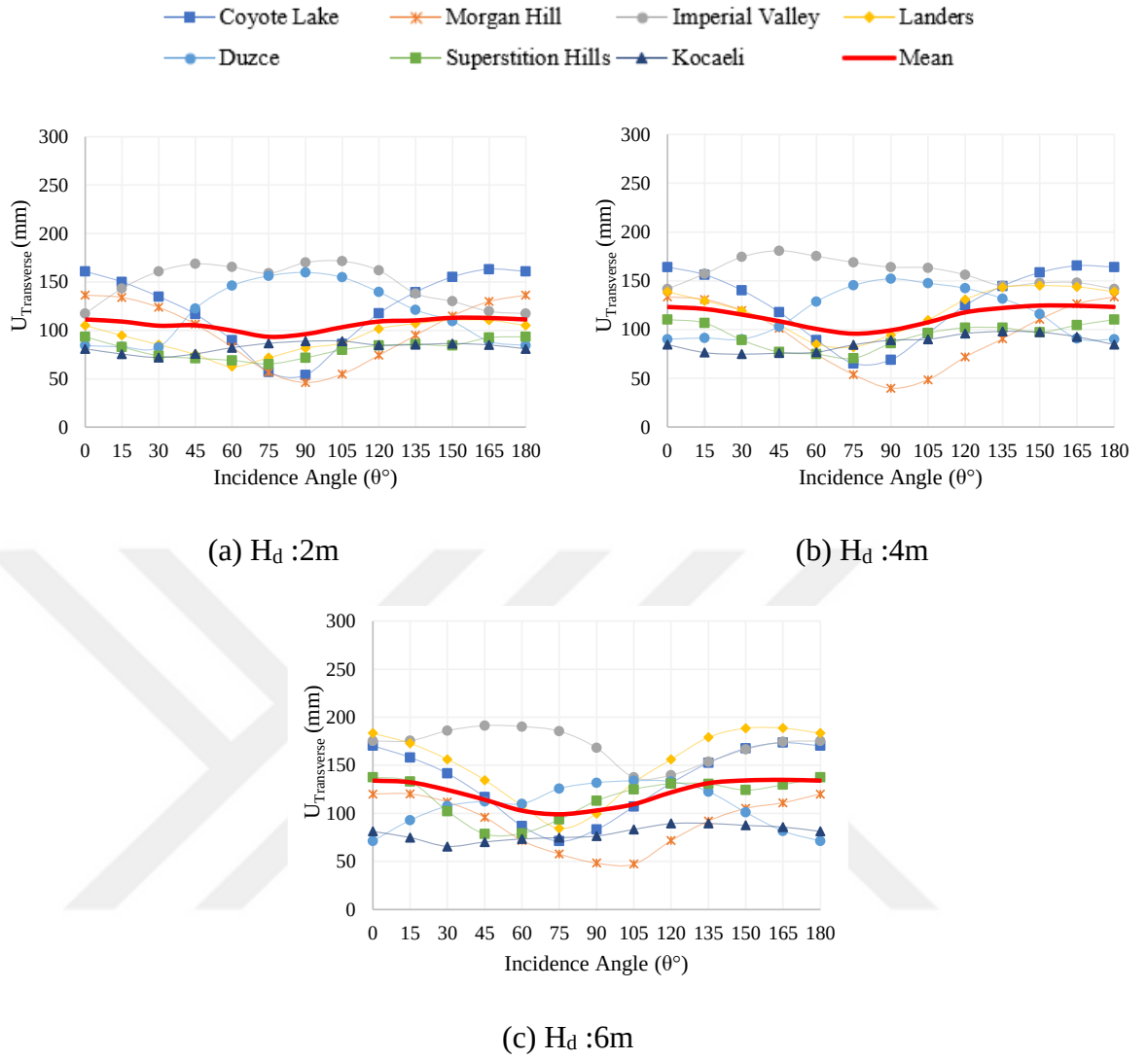


Figure 5.87. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

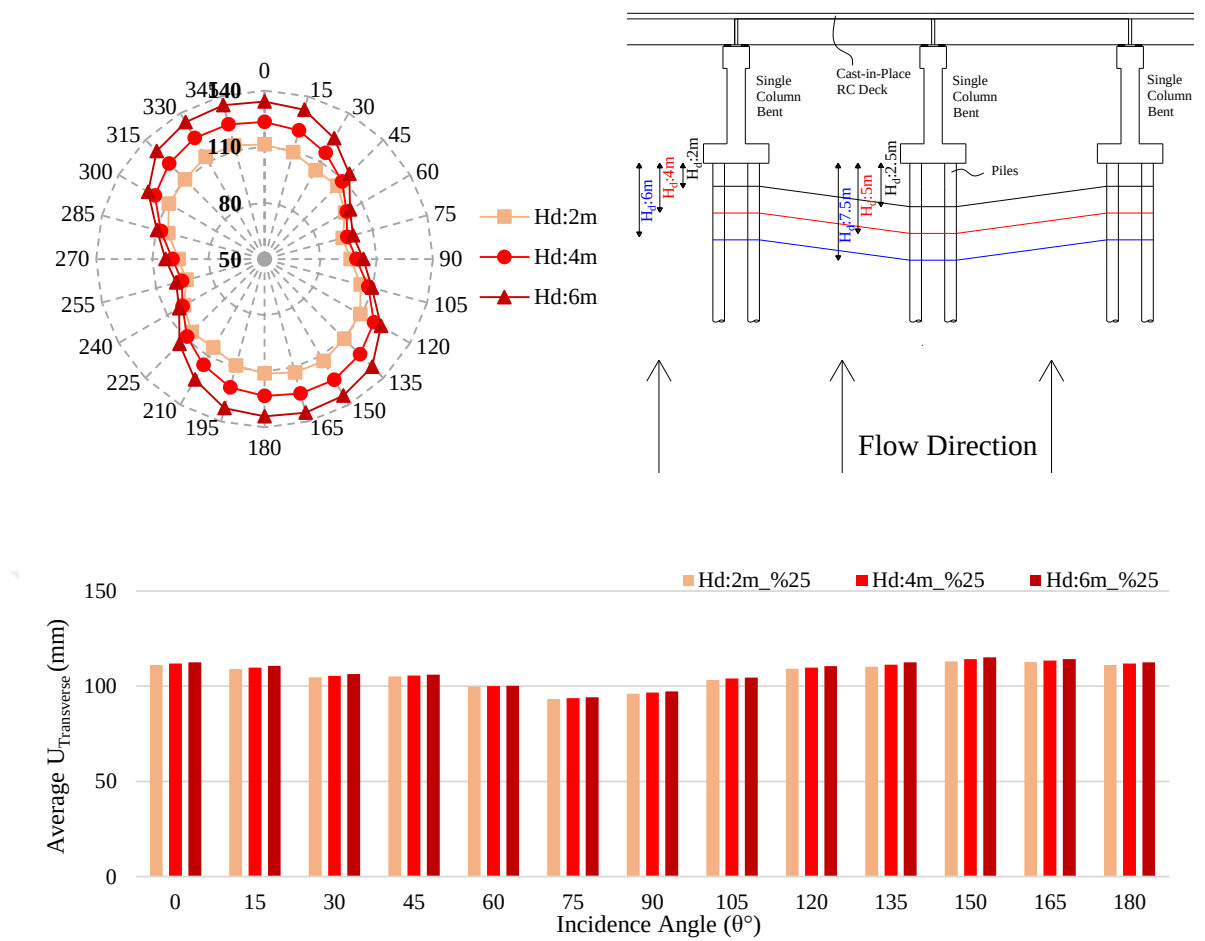


Figure 5.87. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

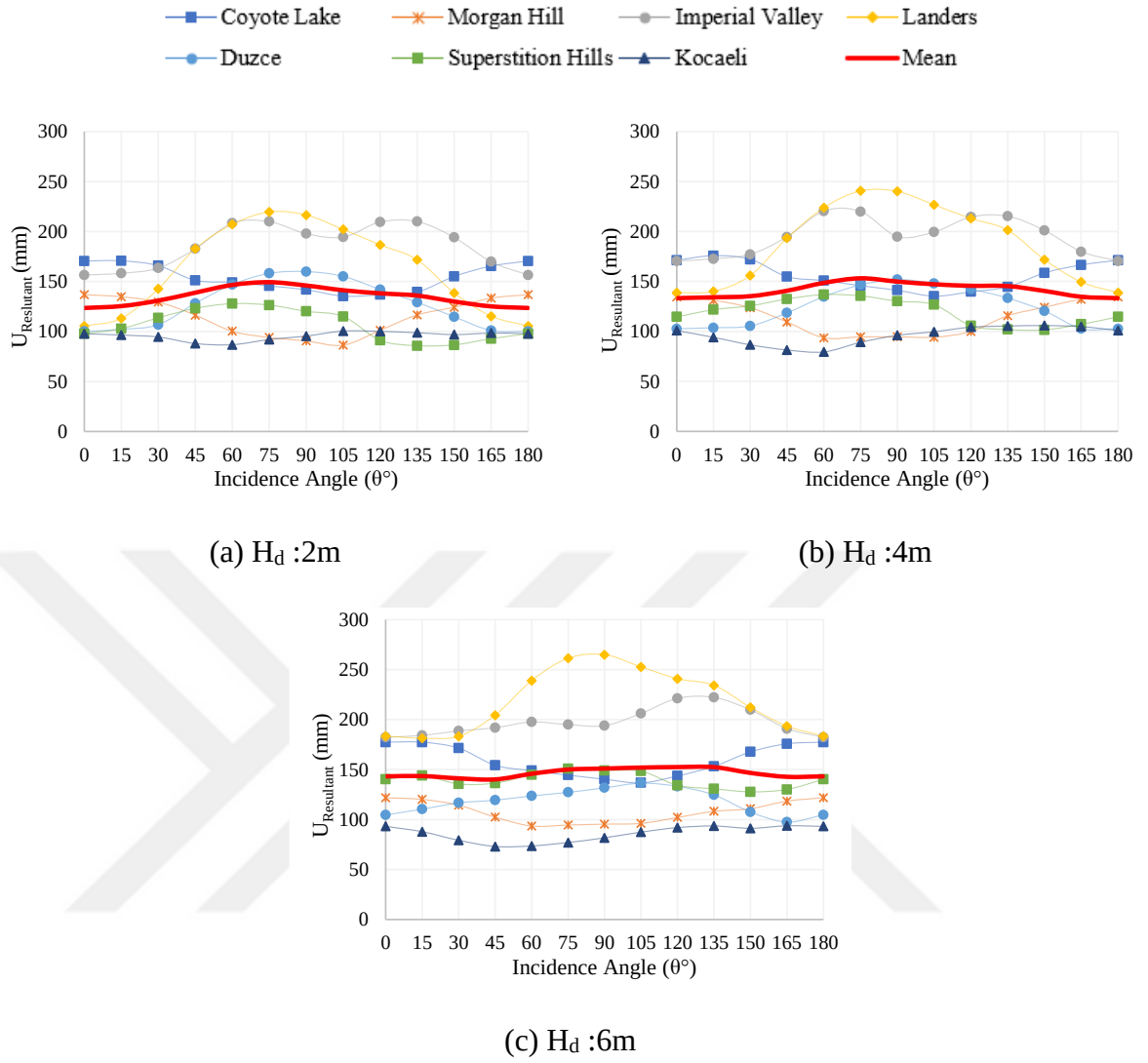


Figure 5.88. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

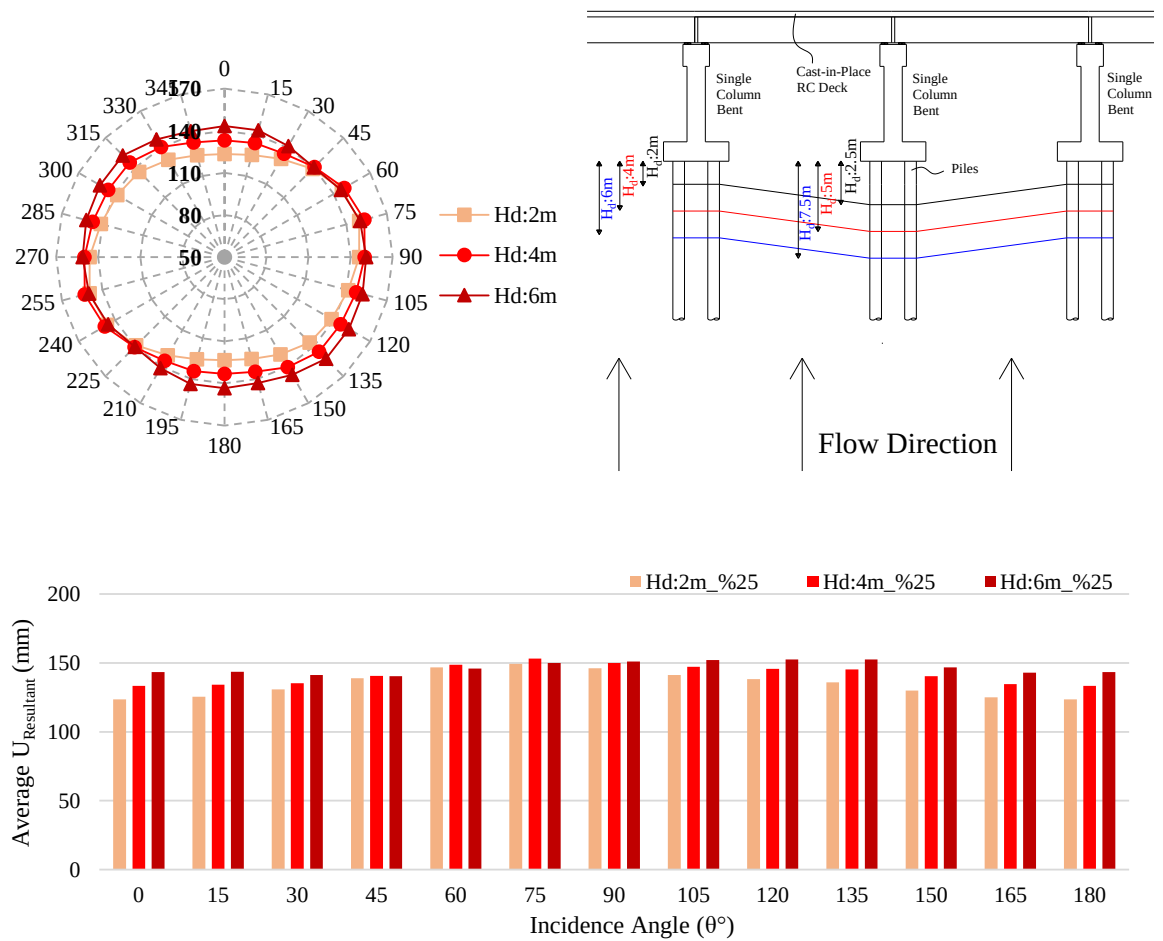


Figure 5.88. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

In Figure 5.89 and Figure 5.90, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge are given. Also, Figure 5.91 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° . When the results assessed in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° although in transverse direction it is decreasing between 0° and 75° . The resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in both

directions is more obvious in some ground motion incidence angles. The maximum difference of average displacement demands in longitudinal direction between 2 m scoured ($H_d=2\text{m}$) and 6 m scoured ($H_d=6\text{m}$) bridge is occurred at 60° incidence angle as nearly 5.8%. In transverse direction, it is at 0° as 17.5%. If it is checked for resultant displacement, maximum difference becomes 16% at 15° incidence angle.

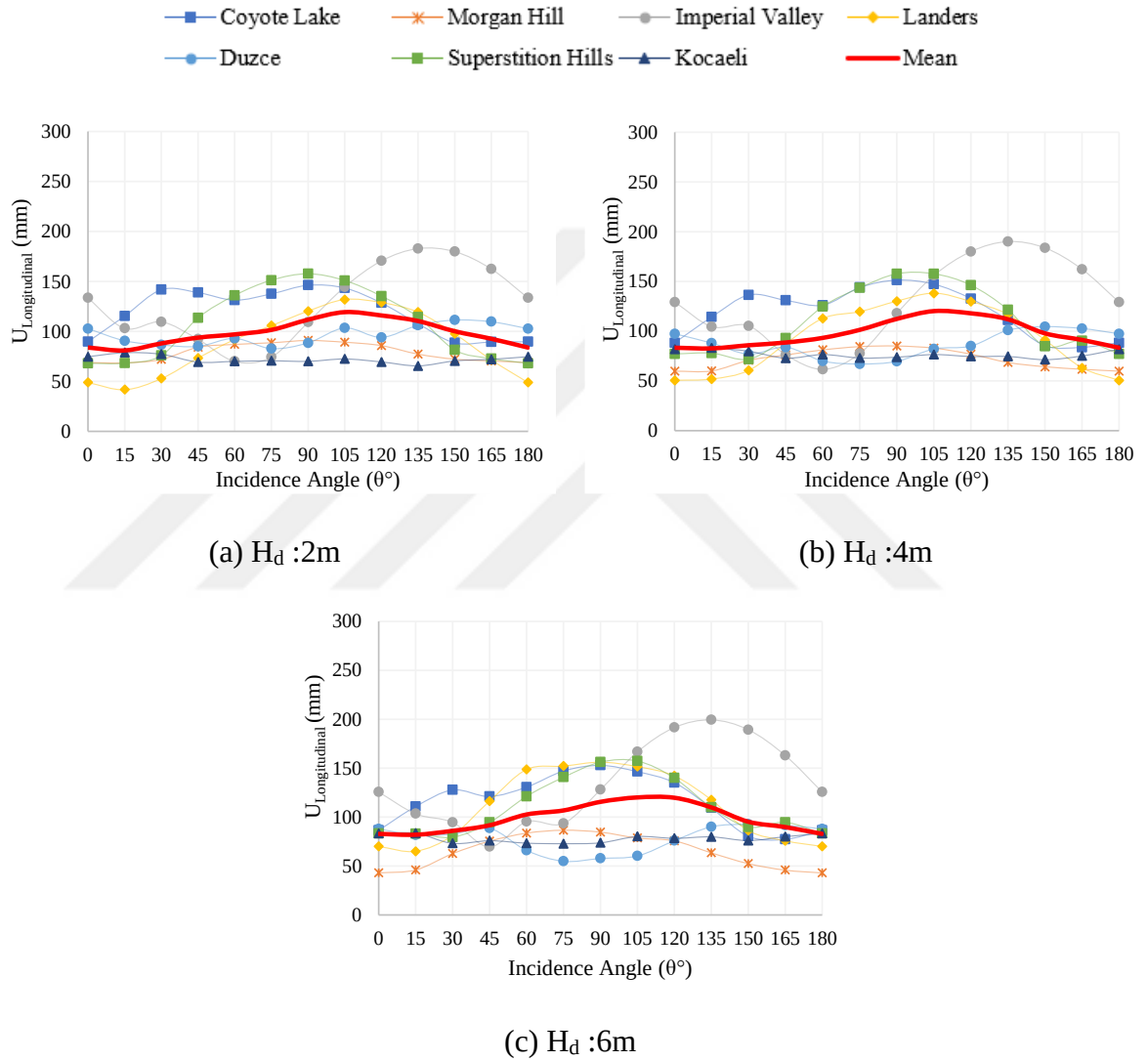


Figure 5.89. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

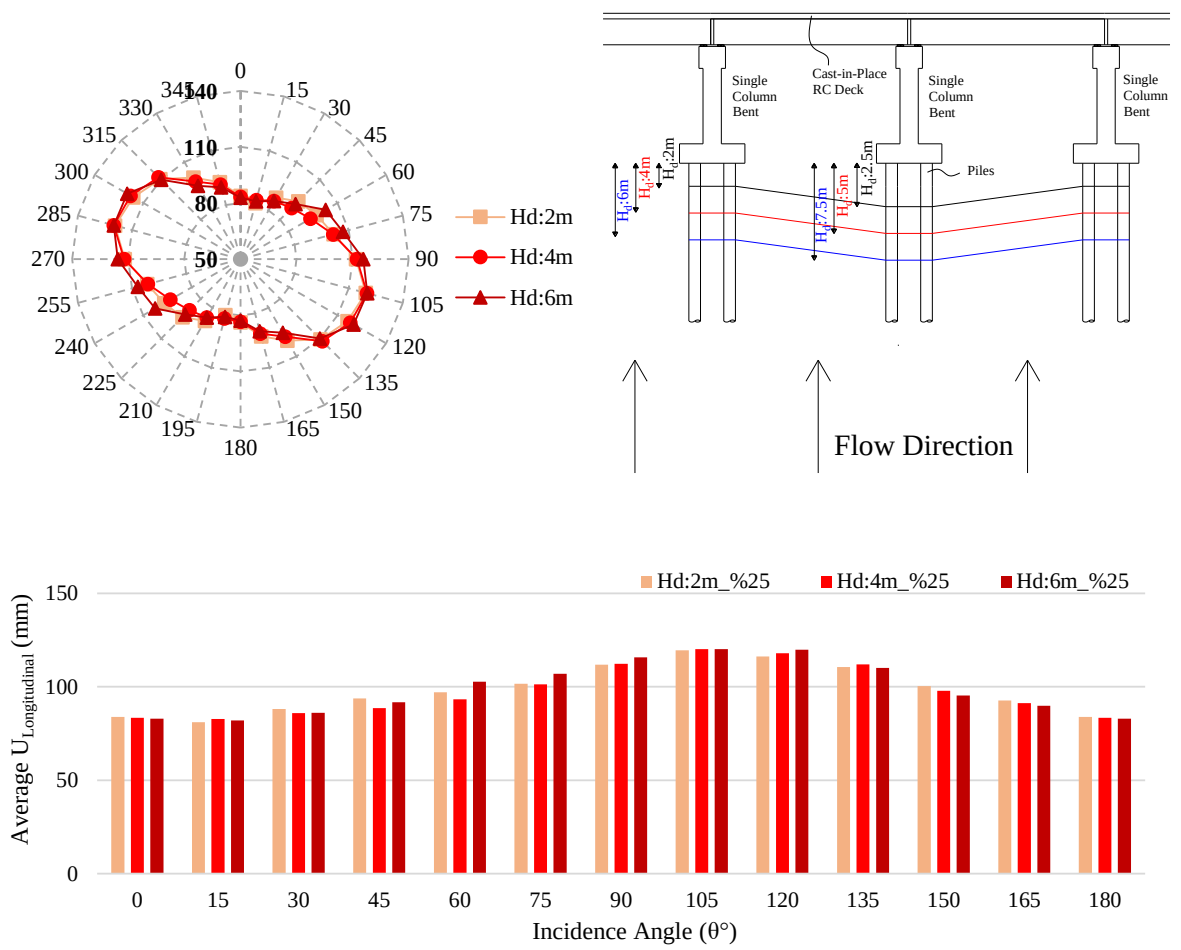


Figure 5.89. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

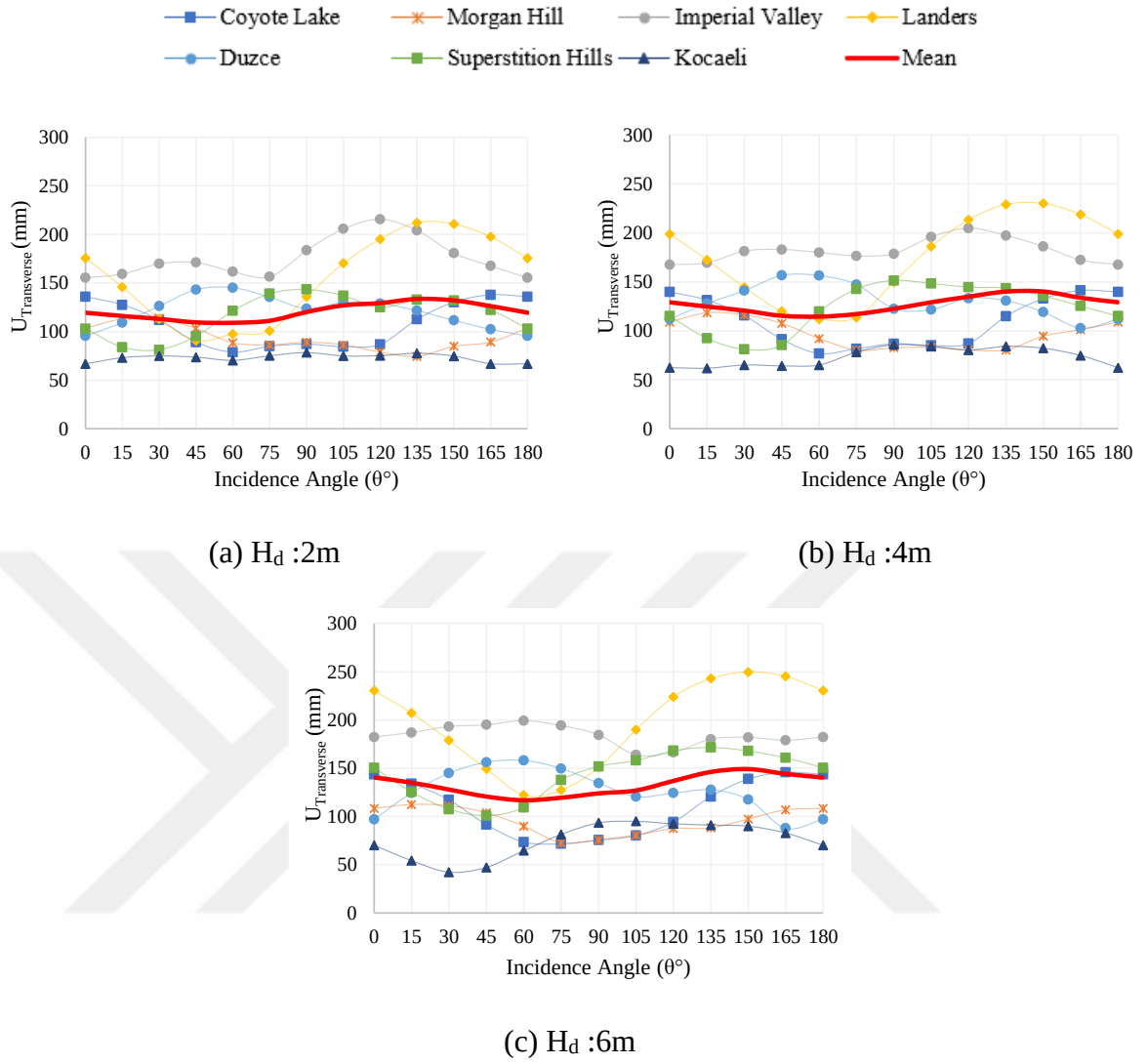


Figure 5.90. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

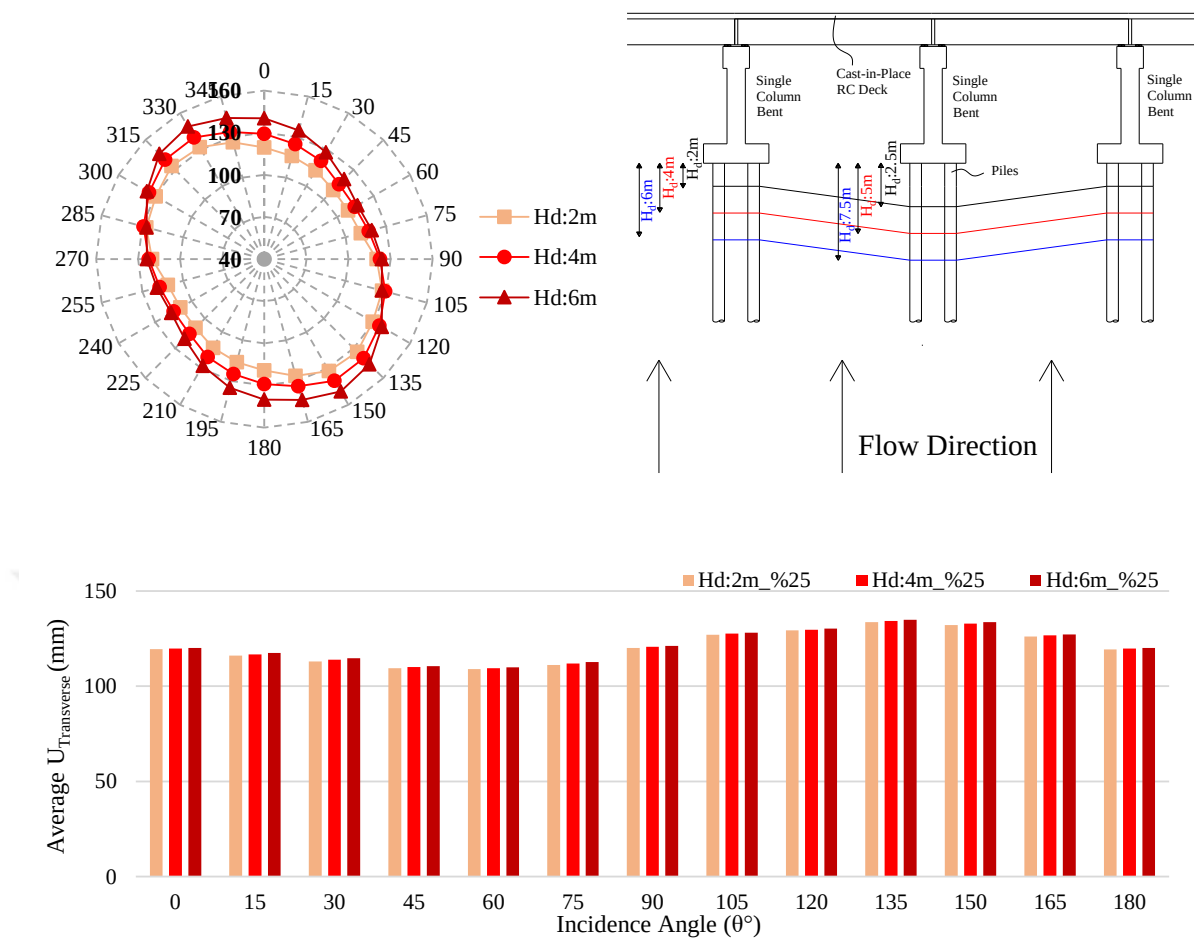


Figure 5.90. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

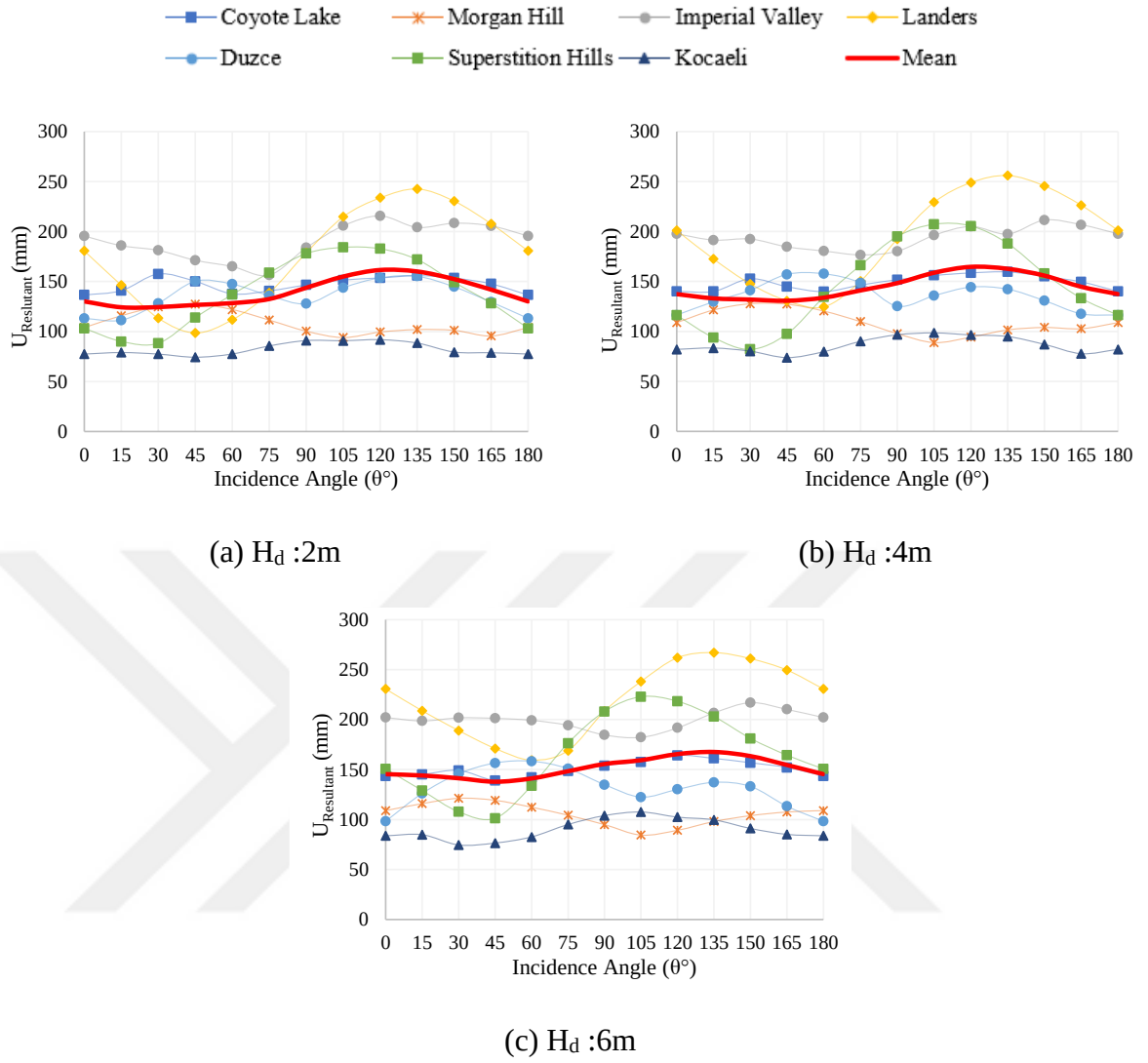


Figure 5.91. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

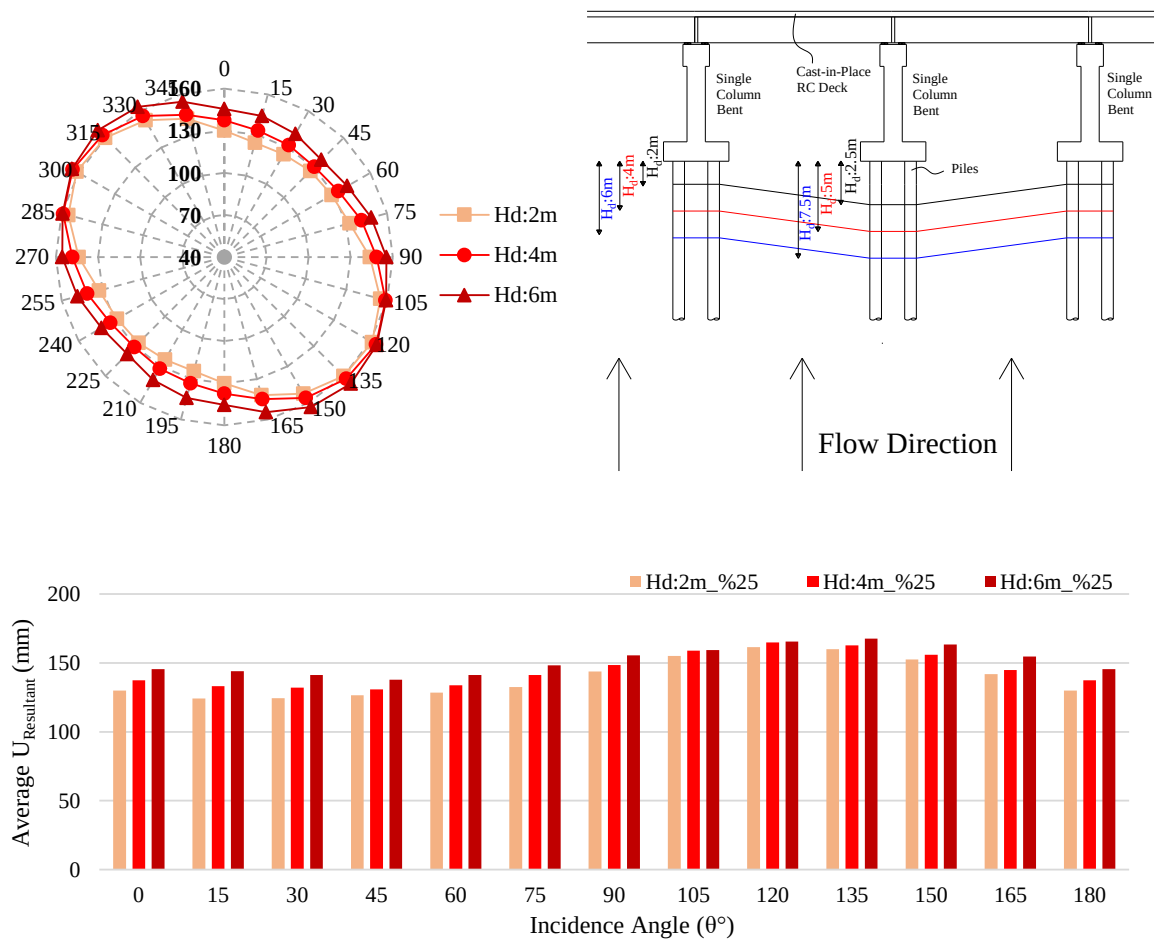


Figure 5.91. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

Moreover, in Figure 5.92, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) and 45° skewed bridges and resultant displacements are compared. The results are obtained for 7 earthquakes and average of maximum demands are calculated for each ground motion incidence angles and scour depths.

In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge especially between 15° and 105° incidence angles. On the other hand, this situation is vice versa in transverse direction. Also, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 60° incidence angle and 4m scour depth as nearly 25%. In transverse direction, it is at 90° and 2m scour depth as 25%. If it is checked for resultant

displacement, maximum difference becomes 17.7% at 135° incidence angle and 2m scour depth.

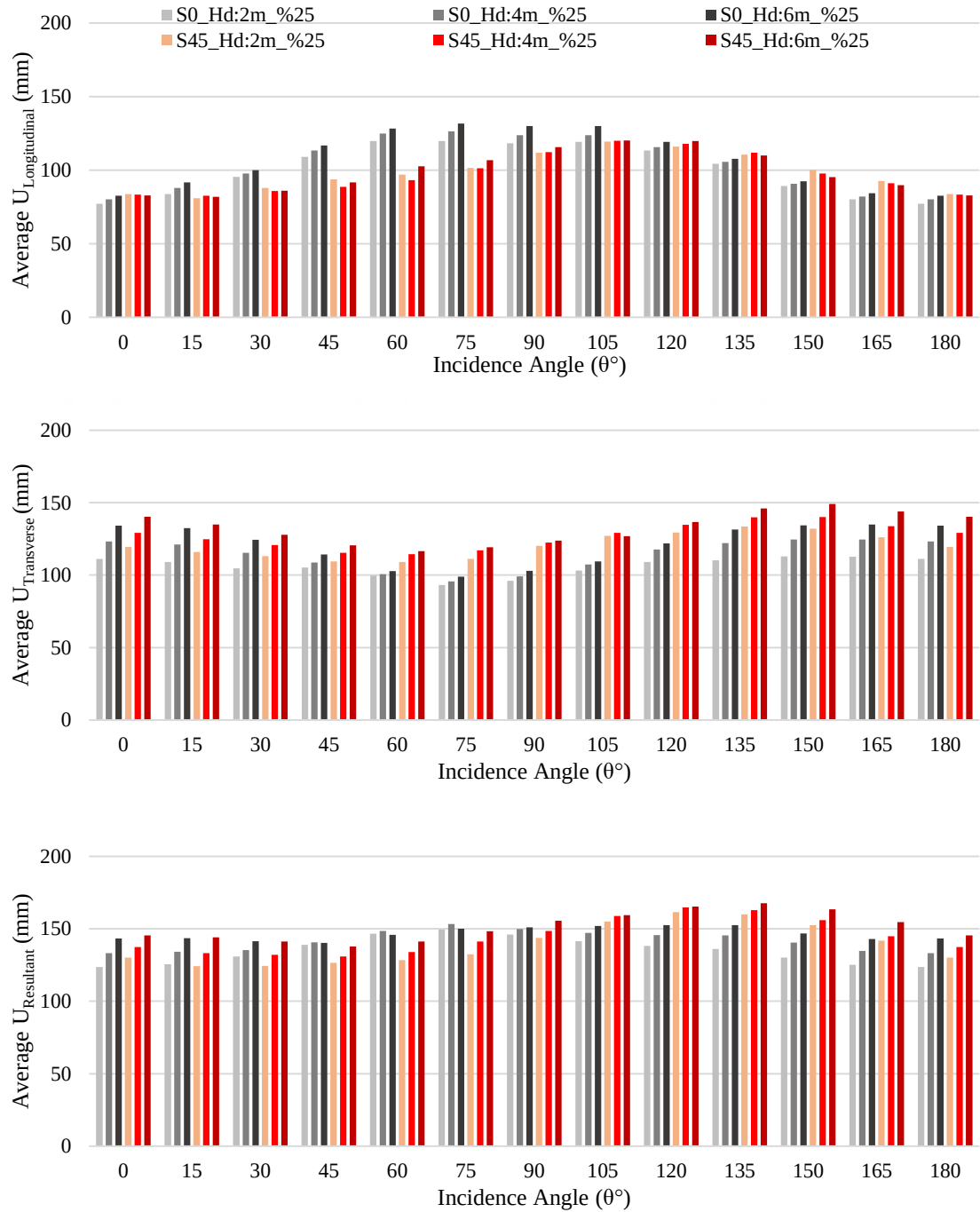


Figure 5.92. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 25% more around middle piles

5.3.1.2. Curvature demands of column pier

In Figure 5.93 and Figure 5.94, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes

and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). In strong axis (z'), it has a decreasing trend between 0° and 45° and it starts to increase between 45° and 120° incidence angles. When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. In addition, while the curvature demands on weak axis of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. This shows that earthquake incidence angle should be taken into consideration in order to obtain maximum demands in nonlinear response history analyses. In strong axis of column, the curvature demands exceed the yield curvature for various incidence angles only where scour depth is 2 m. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2\text{m}$) and 6 m scoured ($H_d=6\text{m}$) bridge is occurred at 60° incidence angle as nearly 46.8%. Also, in strong axis (z'), it becomes 70.3% at 75° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

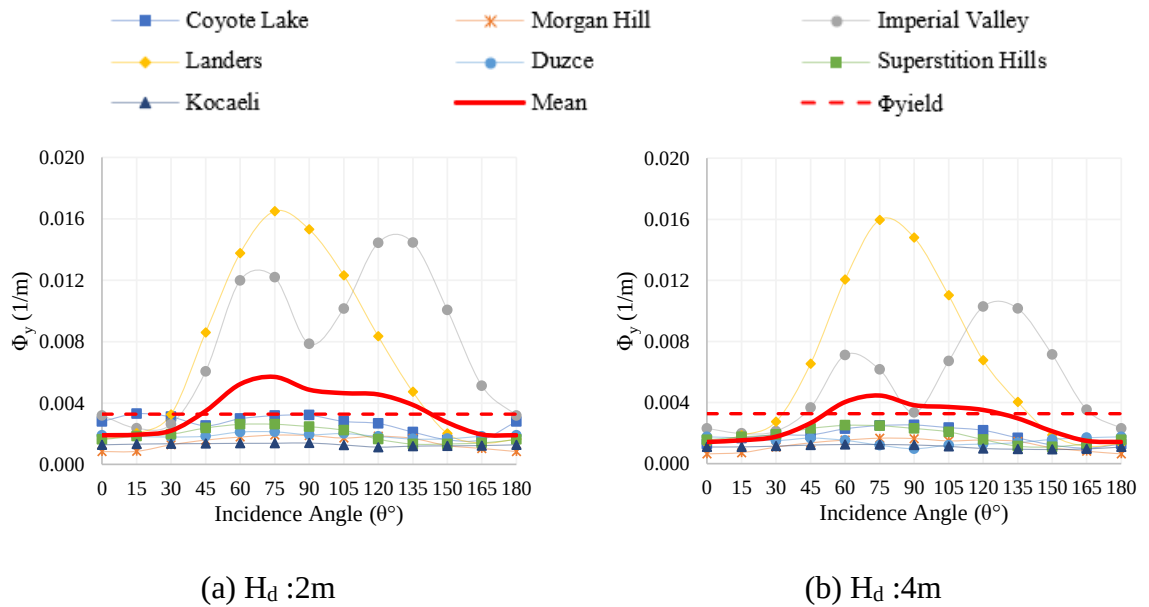


Figure 5.93. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

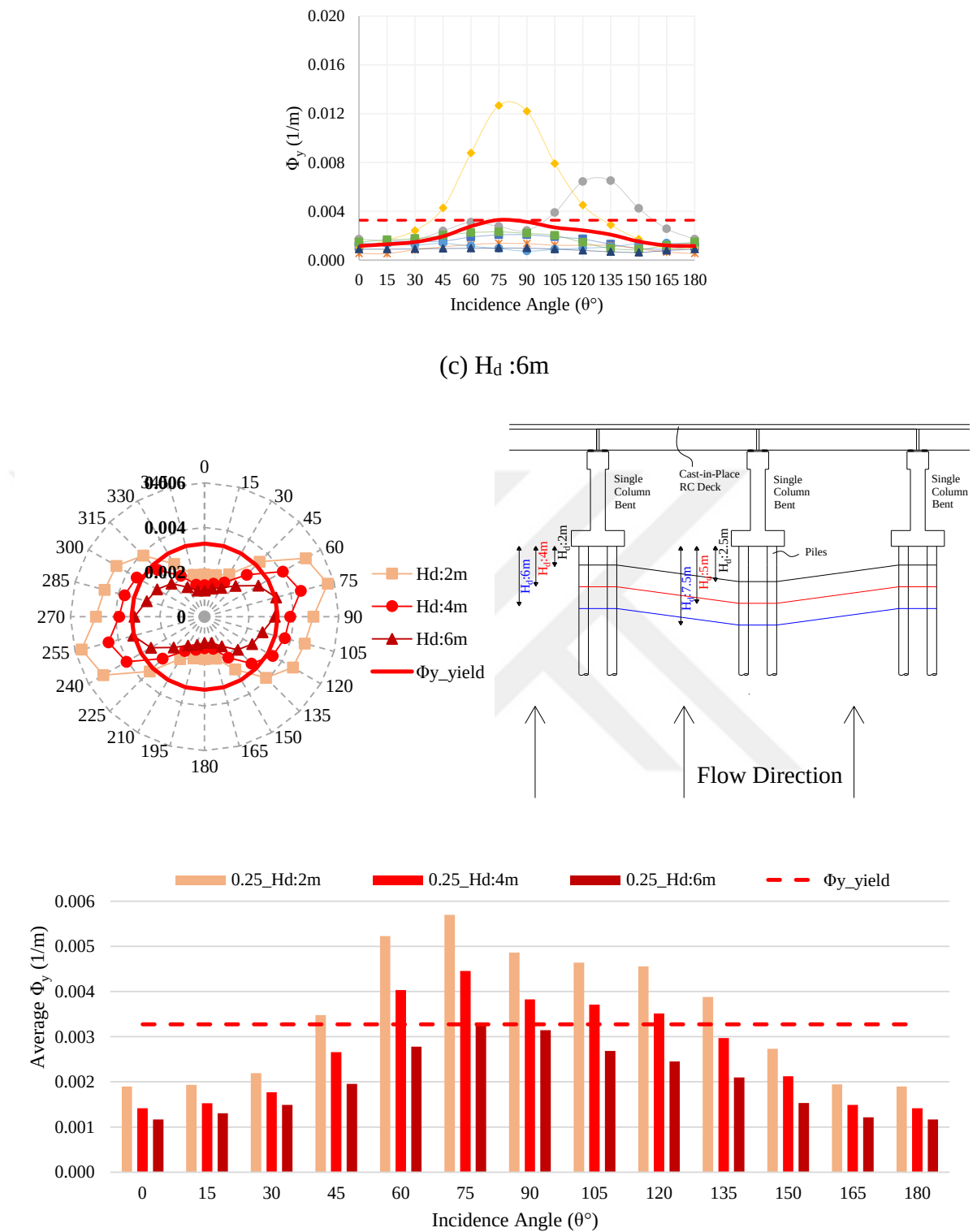
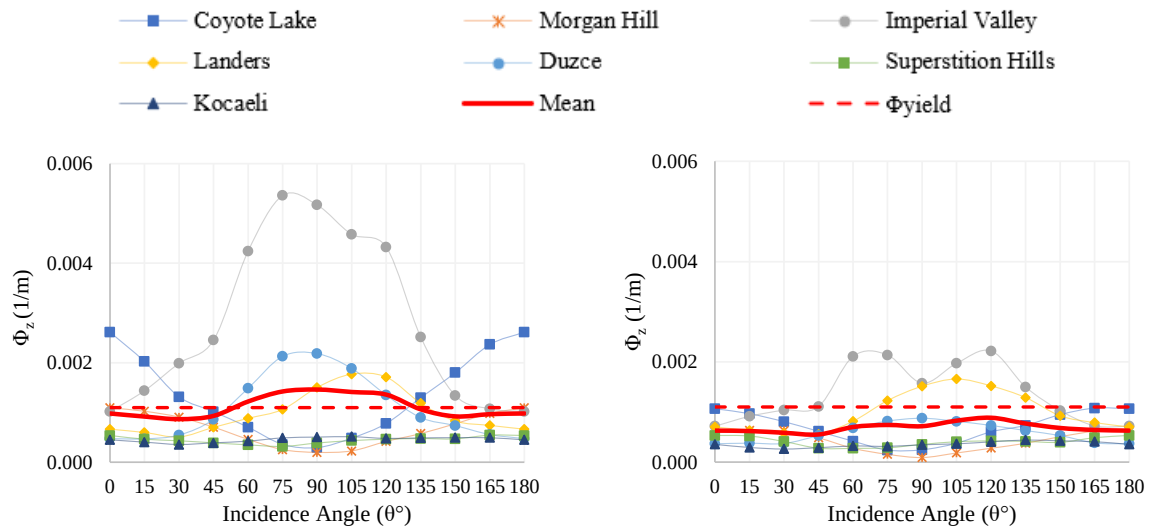
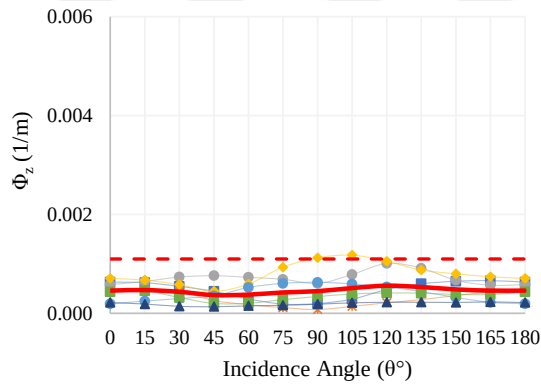


Figure 5.93. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)



(a) $H_d : 2\text{m}$

(b) $H_d : 4\text{m}$



(c) $H_d : 6\text{m}$

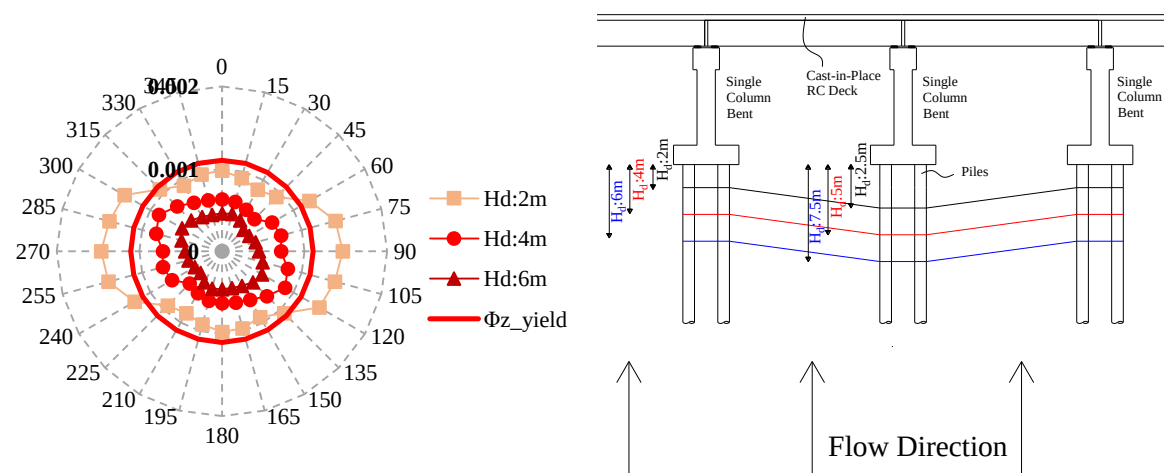


Figure 5.94. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

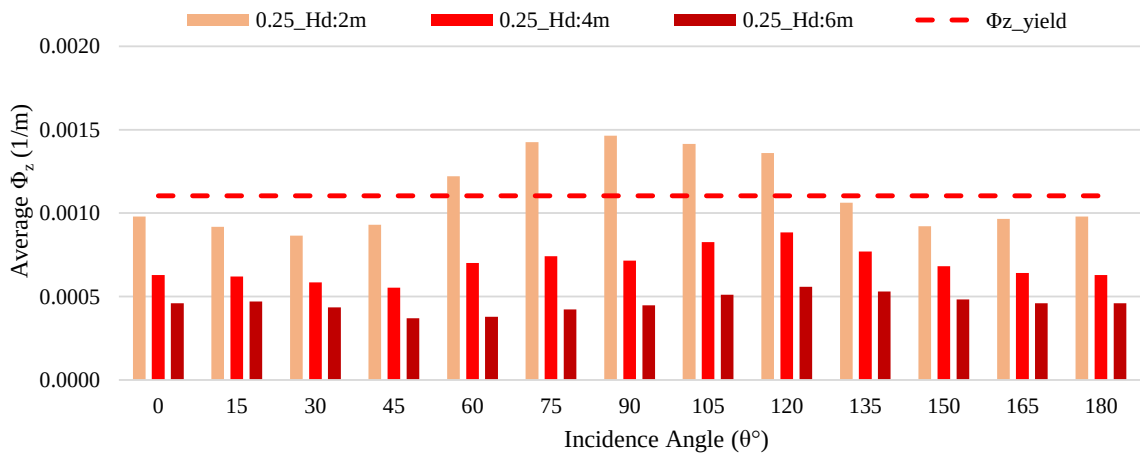


Figure 5.94. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

In Figure 5.95 and Figure 5.96, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 120° in weak axis (y') and strong axis (z'). When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. As observed in other scour cases, the reason of this outcome is the increased flexibility of the bridge column with the increasing scour depth and this causes a decreasing trend in curvature. In addition, while the curvature demands on weak axis of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. This shows that earthquake incidence angle should be taken into consideration in order to obtain maximum demands in nonlinear response history analyses. In strong axis of column, the curvature demands below the yield curvature for all incidence angles when the scour depth is 4 m and 6 m. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2\text{m}$) and 6 m scoured ($H_d=6\text{m}$) bridge is occurred at 165° incidence angle as nearly 53.6%. Also, in strong axis (z'), it becomes 64.3% at 105° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of skewed ($\alpha=45^\circ$) bridge column piers.

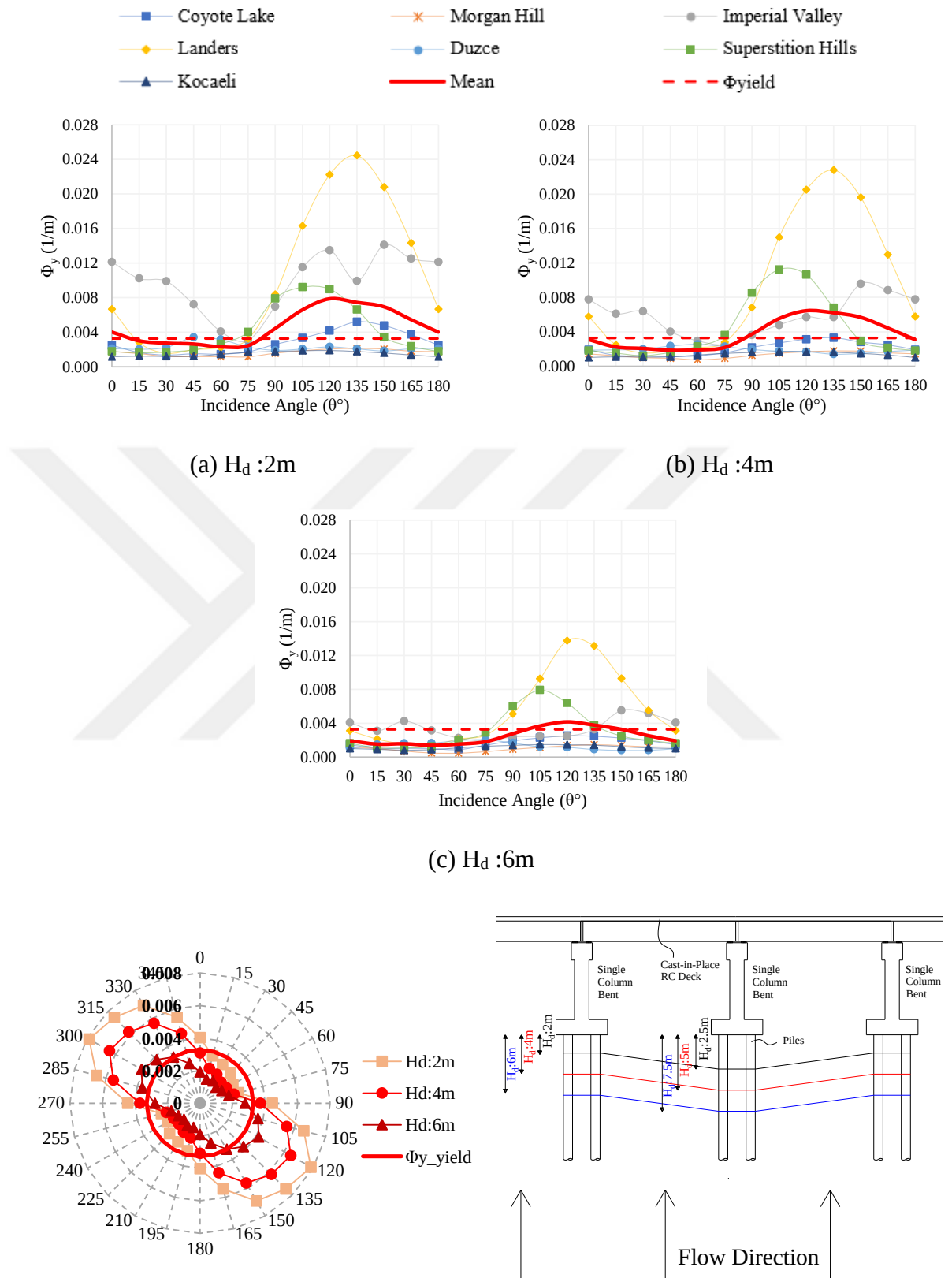


Figure 5.95. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

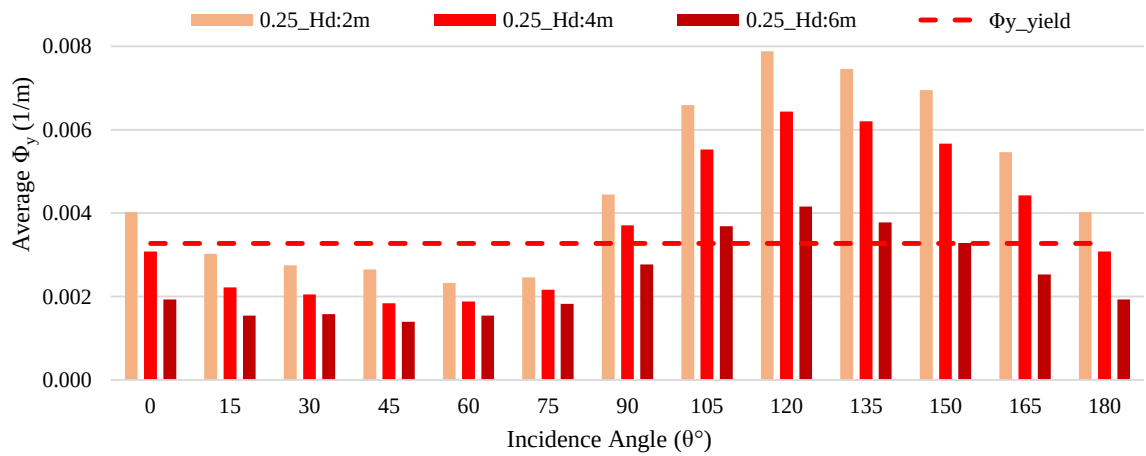


Figure 5.95. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

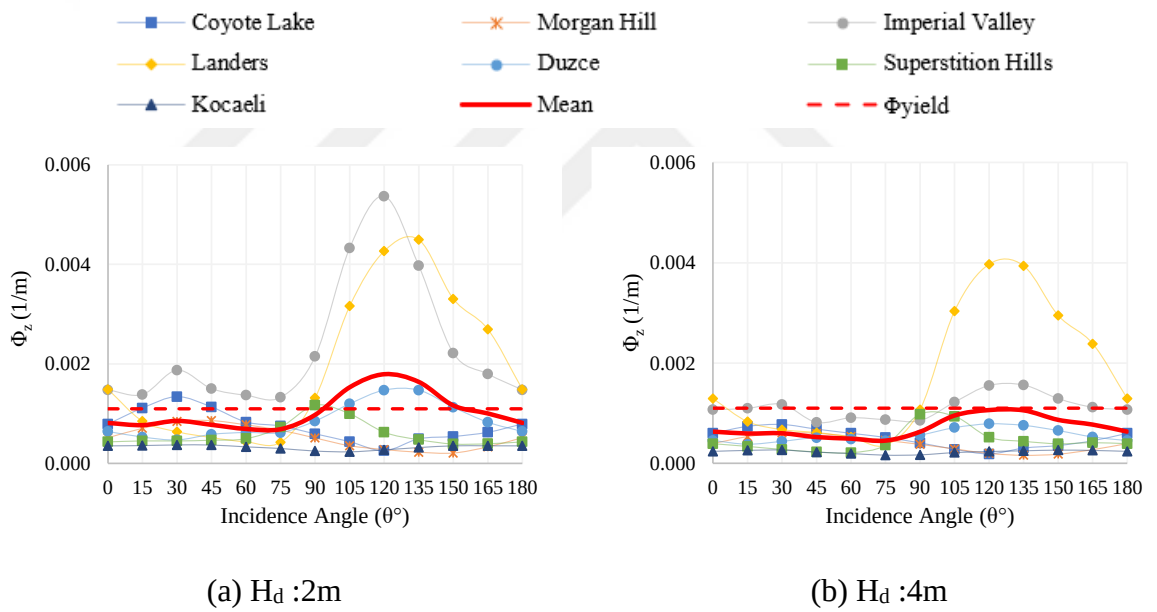


Figure 5.96. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

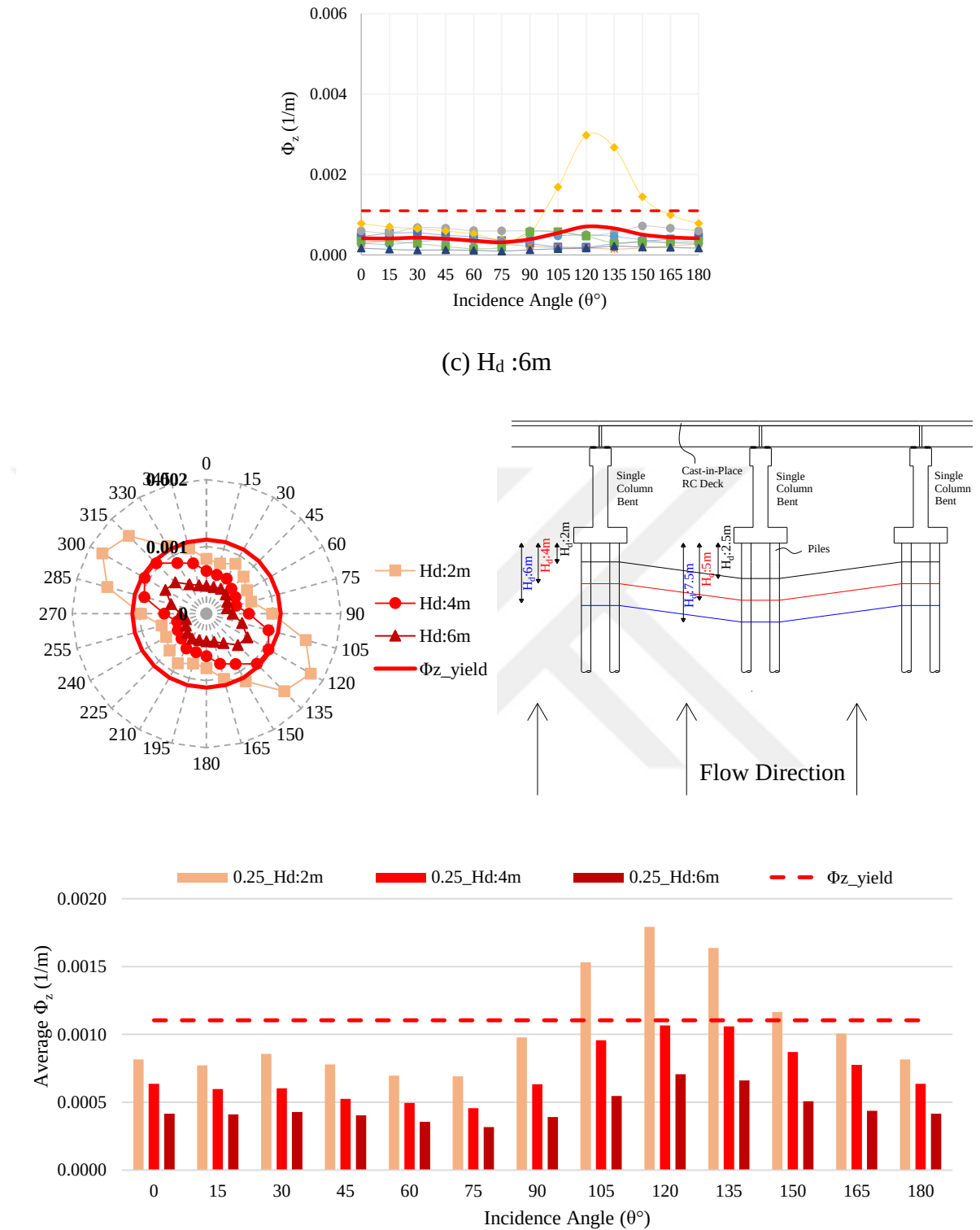


Figure. 5.96. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

In Figure 5.97, average maximum curvature demands of middle column of bridge in weak (y') and strong (z') axis are compared for 3 different scour depths and 13

incidence angles for the non-skewed and 45° skewed bridges. In column weak axis (y'), curvature demands are higher in non-skewed bridge between 45° and 90° incidence angles. However, it becomes much higher in skewed bridge between 105° and 180° incidence angles. Moreover, in strong (z') axis of column, curvature demands are higher in non-skewed bridge between 0° and 90° incidence angles and it becomes greater in skewed bridge between 105° and 165° incidence angles. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 4m scour depth as nearly 197%. In strong axis, it is at 135° and 2m scour depth as 54%.

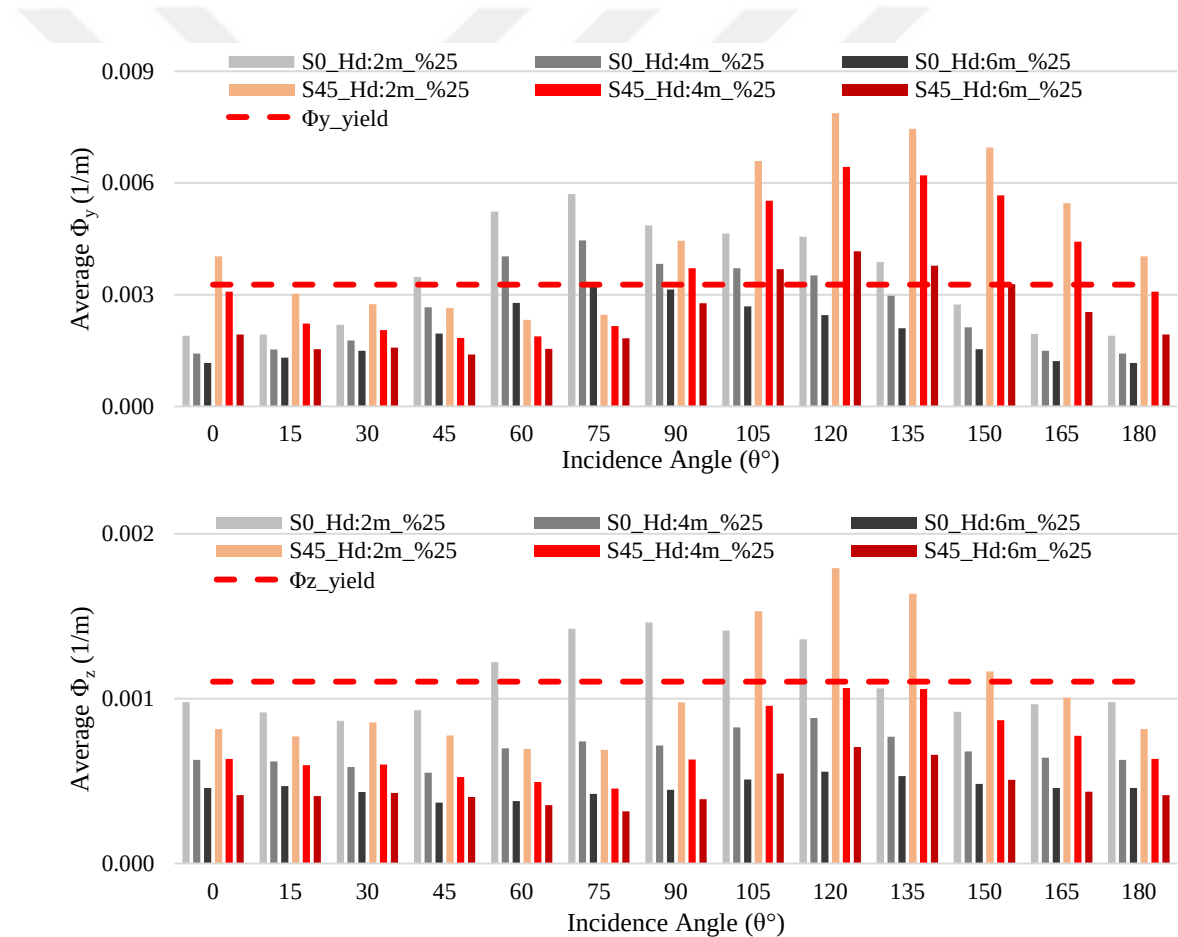


Figure 5.97. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 25% more around middle piles

5.3.1.3. Shear force demands of column pier

In Figure 5.98 and Figure 5.99, maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. However, this decrement is more obvious in local y' axis of column. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2\text{m}$) and 6m scoured ($H_d=6\text{m}$) models occurs at 60° incidence angle and nearly 33.9%. Also, it is about 17.7% at 165° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.

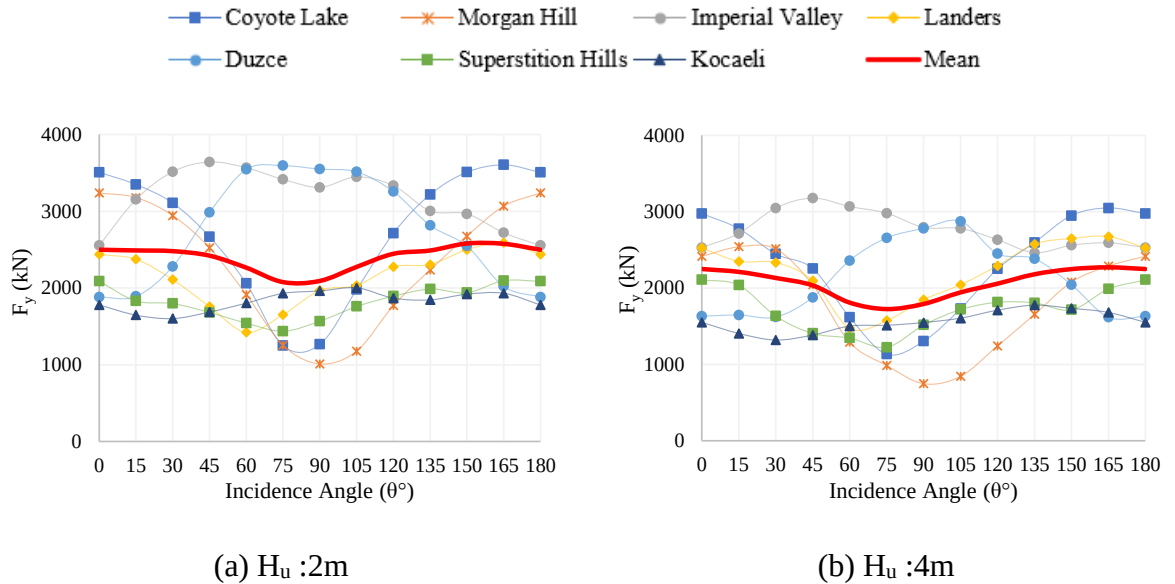
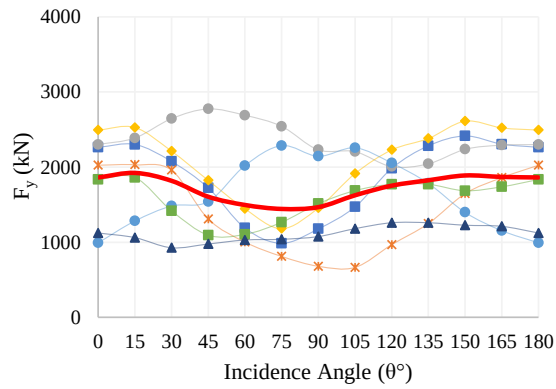


Figure 5.98. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)



(c) $H_u : 6m$

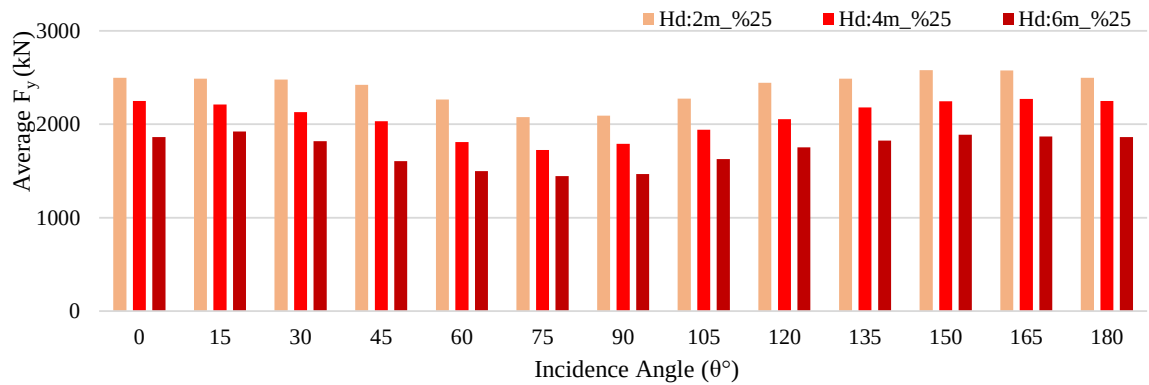
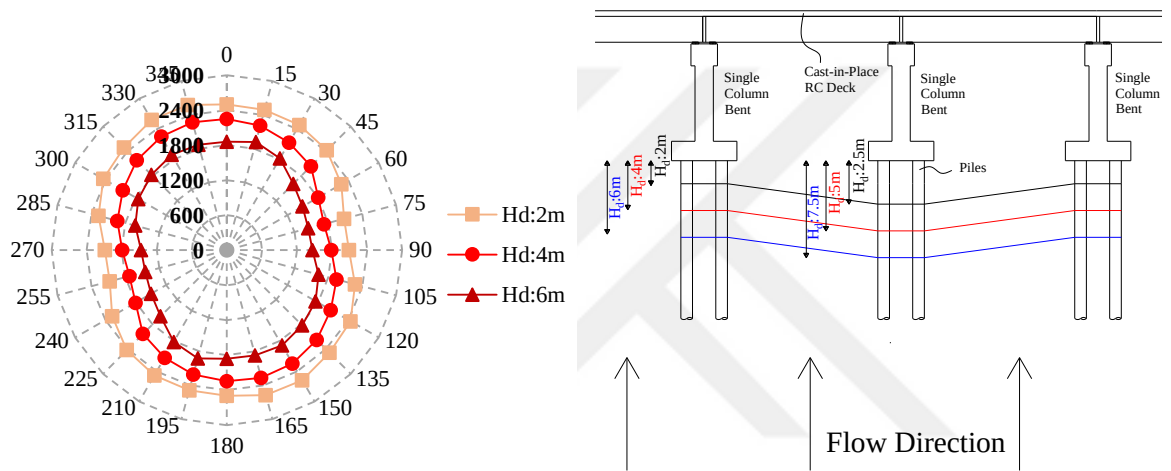


Figure 5.98. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

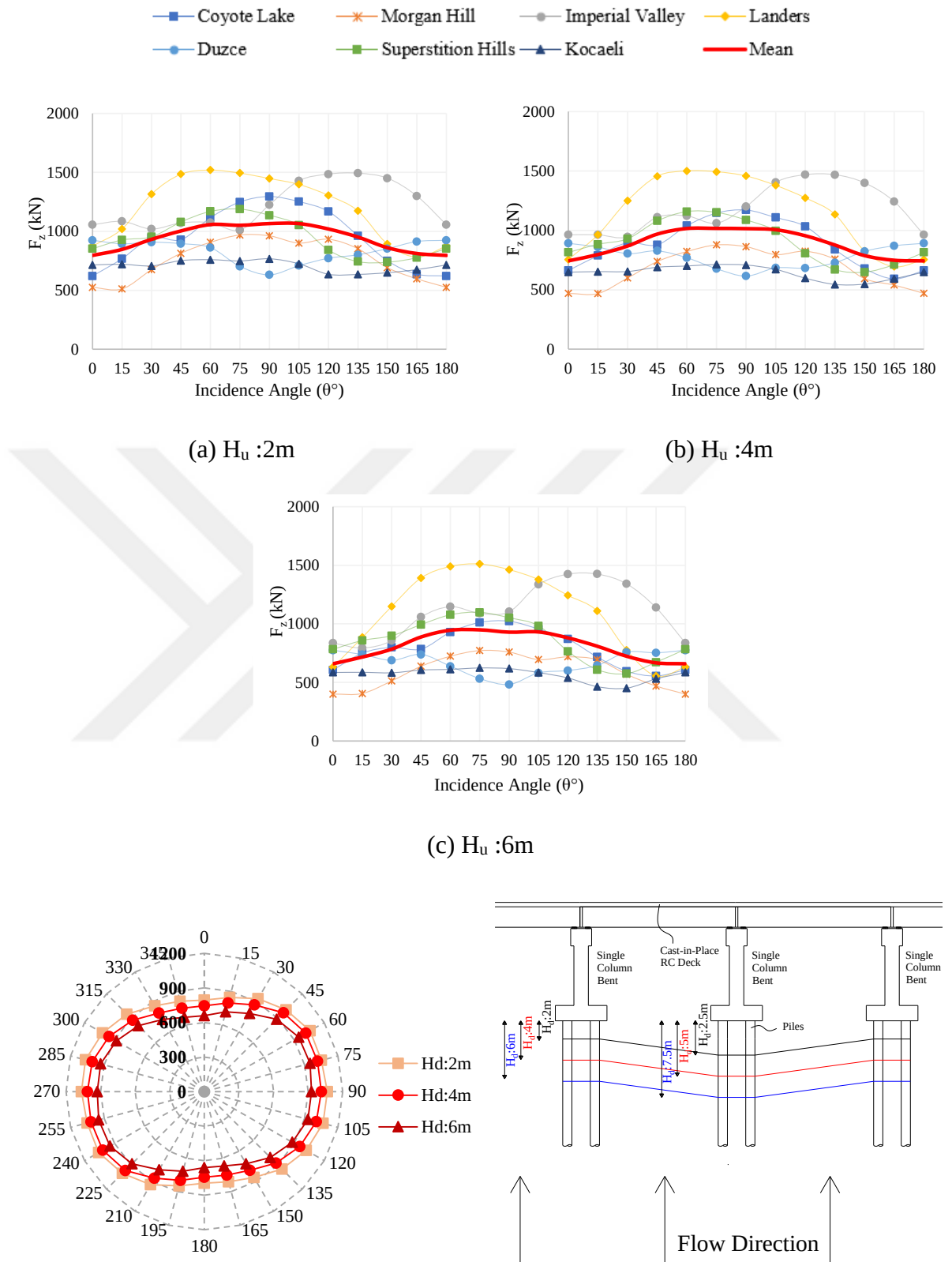


Figure 5.99. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

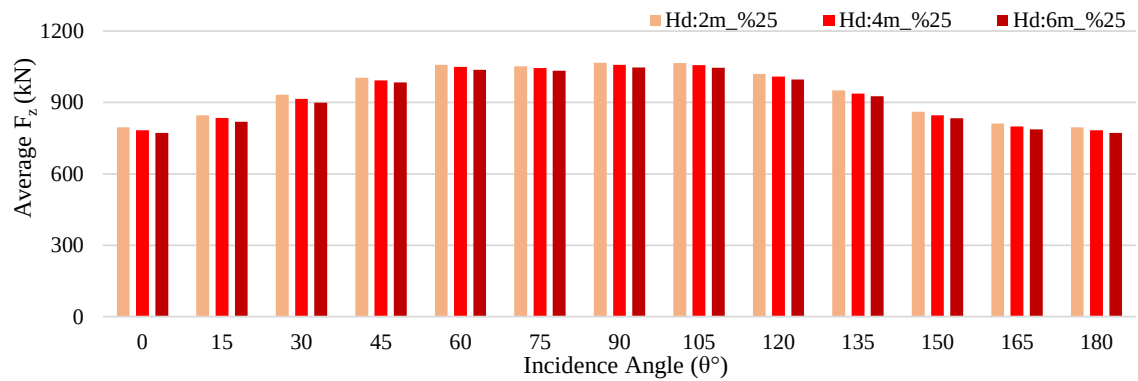


Figure 5.99. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

In Figure 5.100 and Figure 5.101, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 75° to 120° in local y' axis. Besides, it has an increasing trend between 60° and 135° incidence angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles in local y' axis of column and in local z' axis demands are nearly same for all scour depths. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2m$) and 6m scoured ($H_d=6m$) models occurs at 90° incidence angle and nearly 32.8%. Also, it is about 21.8% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in 45° skewed bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.

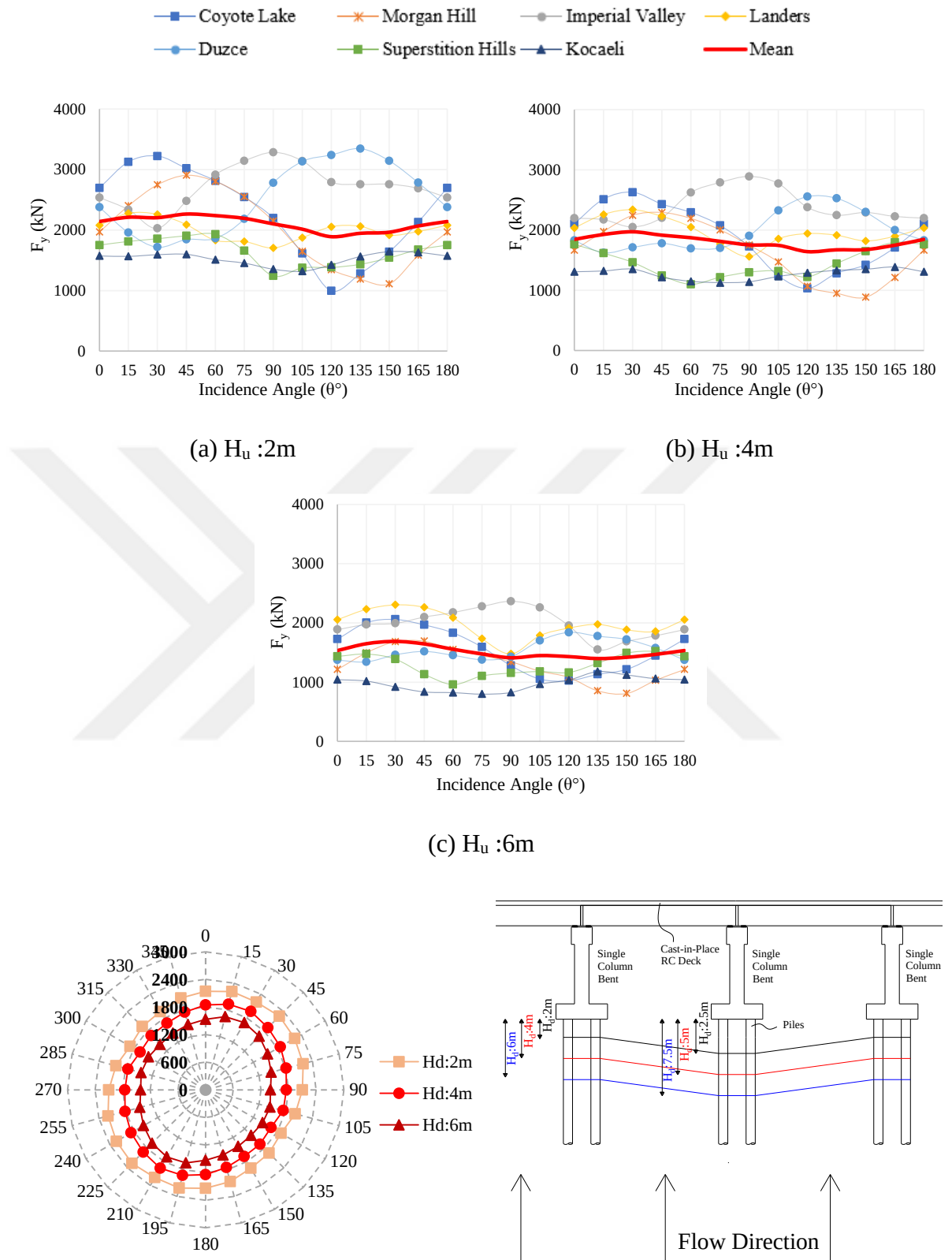


Figure 5.100. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

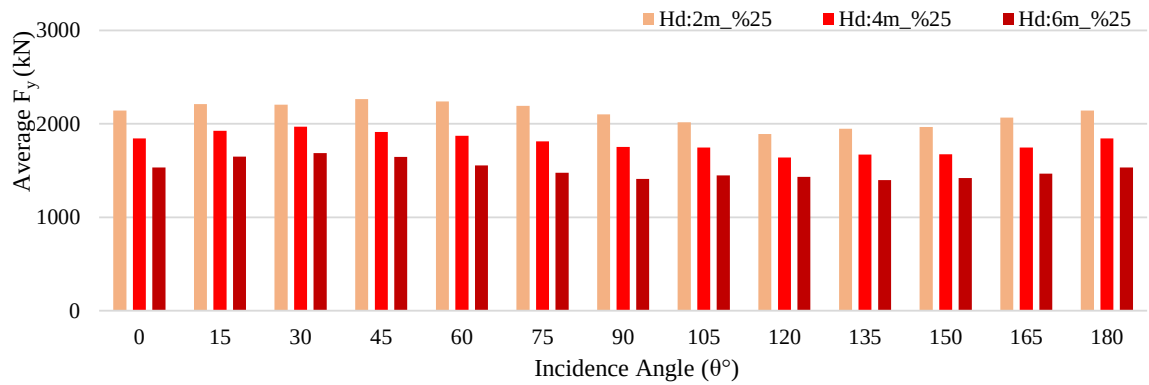


Figure 5.100. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

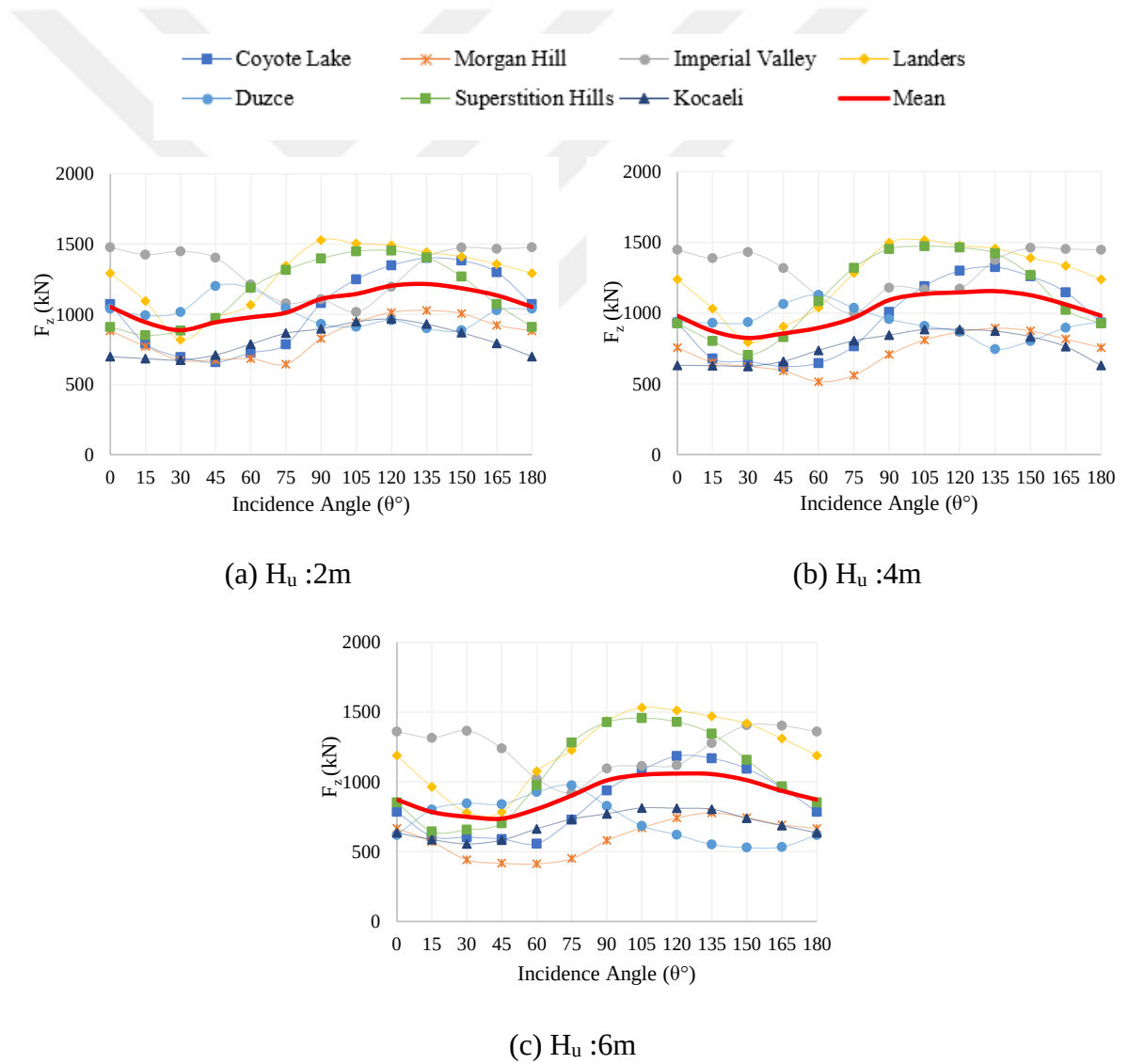


Figure 5.101. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a)

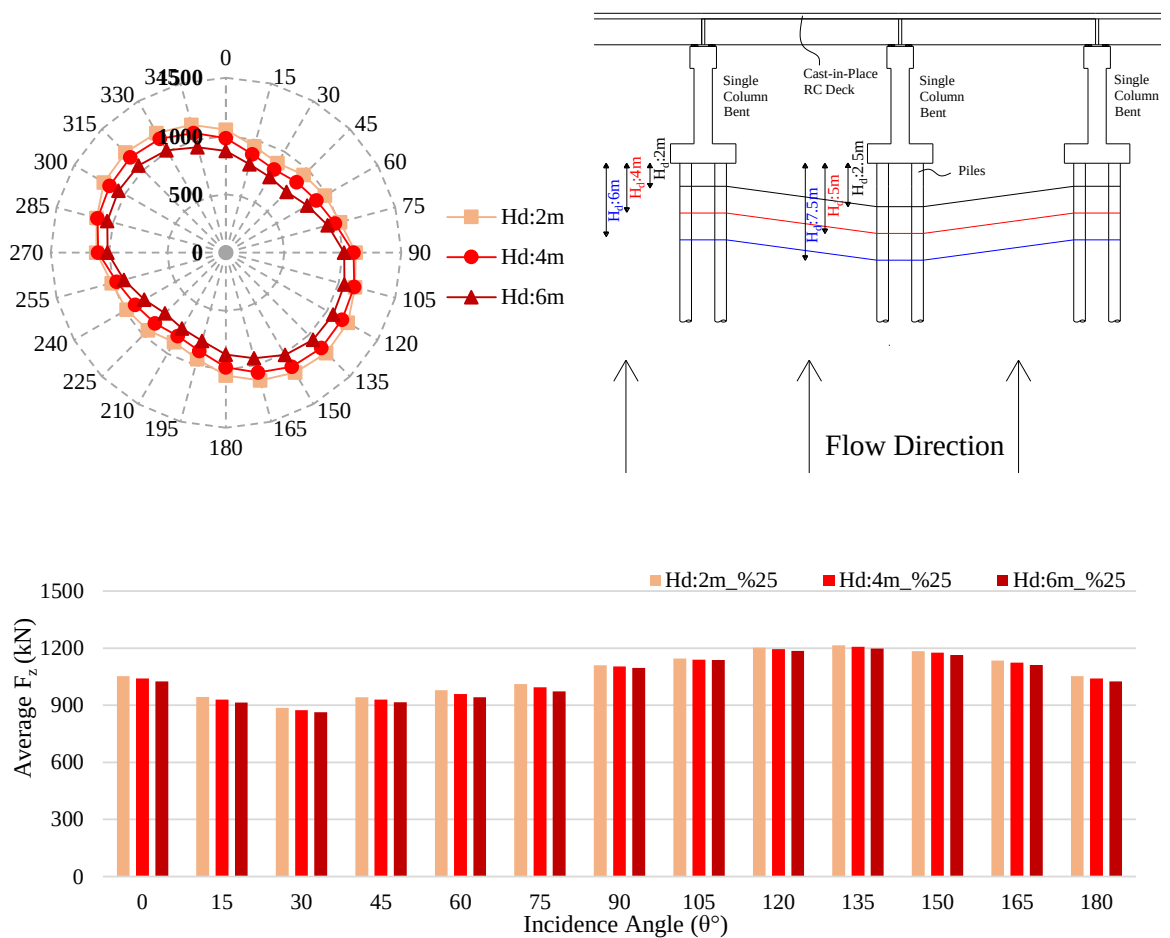


Figure 5.101. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2a) (continued)

In Figure 5.102, maximum shear force demands of column local y' and z' axes of non-skewed and 45° skewed bridges are compared for 3 different scour depths and 13 incidence angles. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 150° incidence angle and 4 m scour depth as nearly 25%. In local z' axis, it occurs again at 150° and 4m scour depth as 43%.

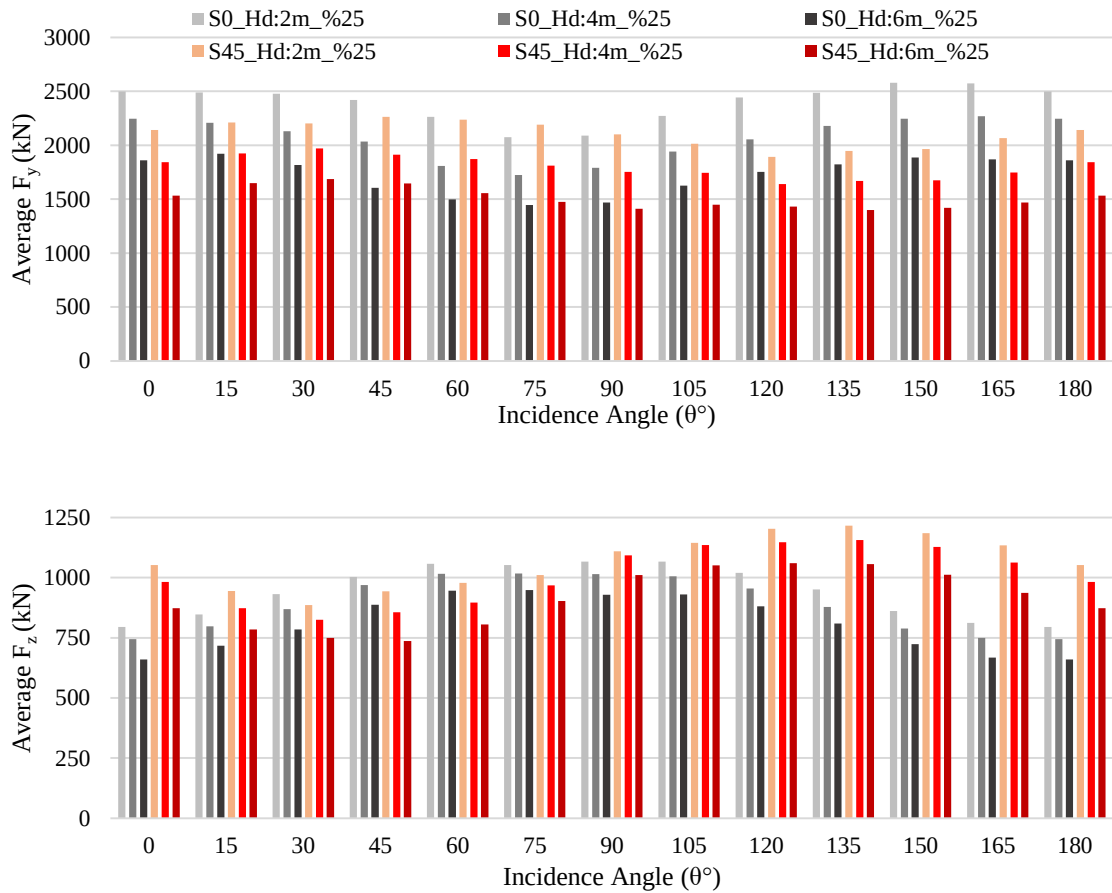


Figure 5.102. Average maximum shear force demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 25% more around middle piles

5.3.1.4. Shear force demands of piles

In Figure 5.103 and Figure 5.104, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. As it can be seen from the graphs, maximum shear force demands of local y' and z' axes of corner piles are below the pile shear capacity of 735.2 kN and demands are decreasing when scour depth increases in longitudinal direction of bridge. Also, demands are nearly same for all corner piles and they are much higher in local y' axis than z' axis. Therefore, shear force demands of local y' axis of pile number 1 (P1) is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.105. P1 pile shear demand is higher in non-skewed bridge at 2m scour depth than skewed one. For scour depths 4 m and 6 m, shear force demands of pile P1 are nearly same both bridge models.

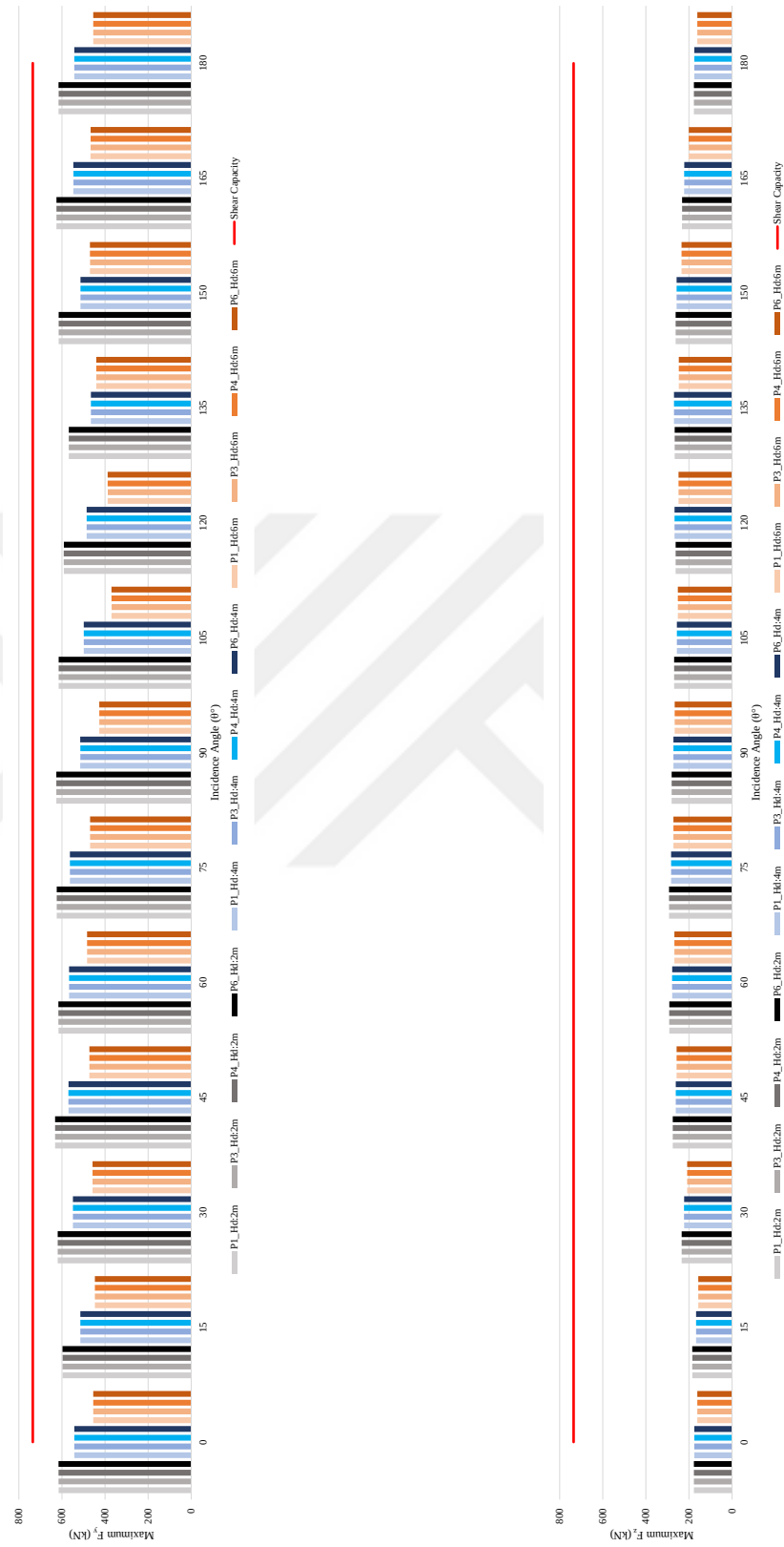


Figure 5.103. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=0^\circ$ non-skewed bridge and Case 2-2a)

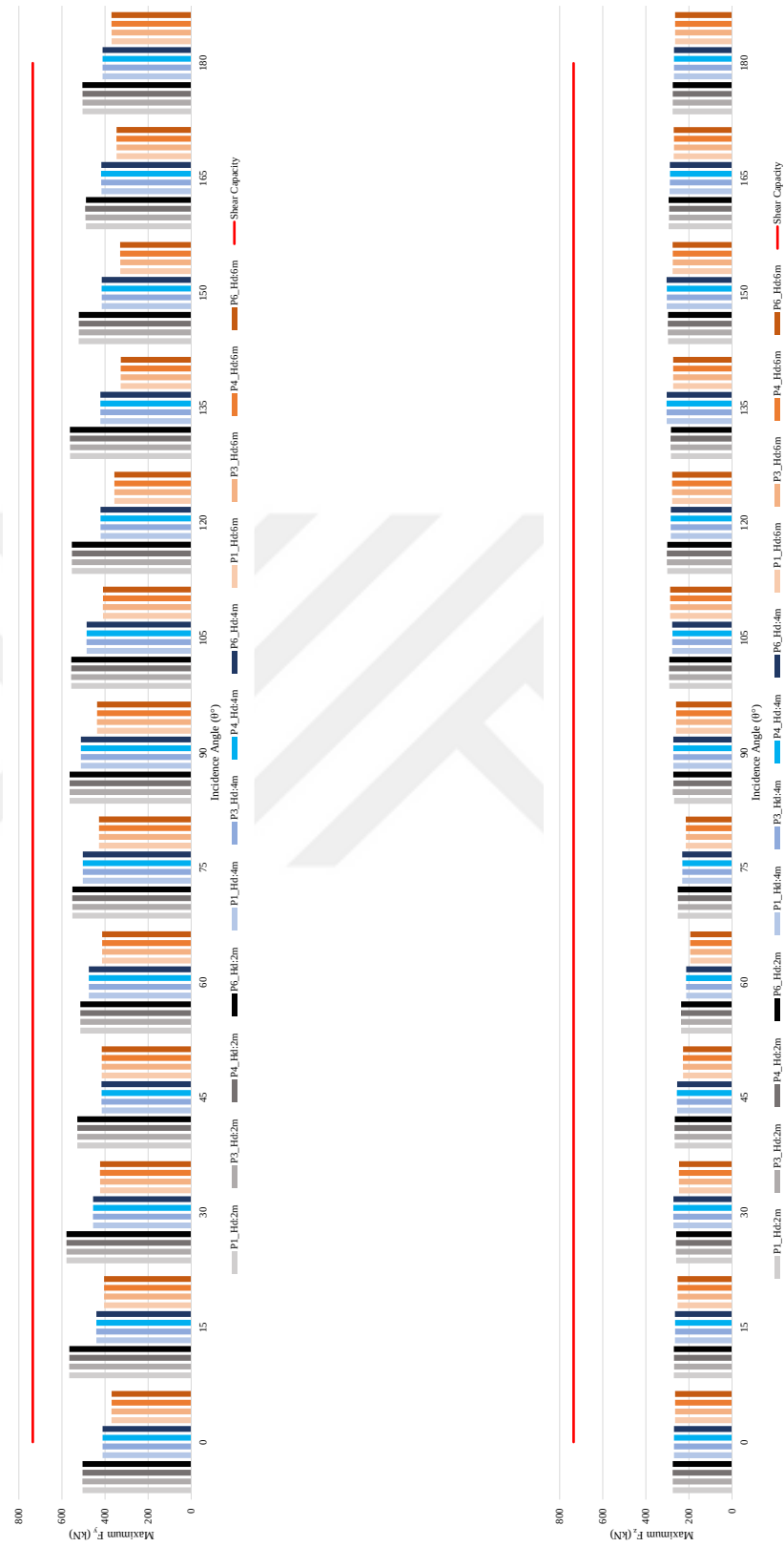


Figure 5.104. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=45^\circ$ skewed bridge and Case 2-2a)

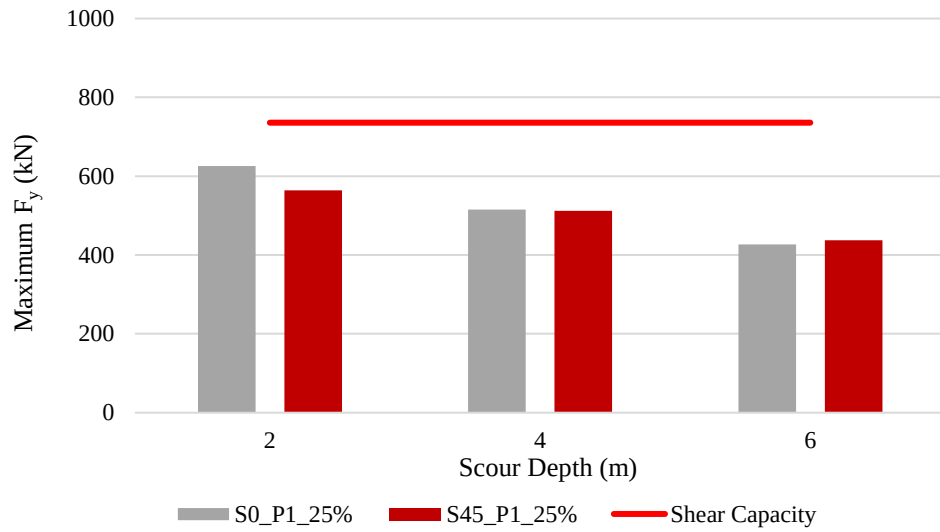


Figure 5.105. Average maximum shear force demands of local y' axis of pile (P1) for non-skewed and 45° skewed bridge when ground motion incidence angle is 90° and non-uniform scour is 25% in longitudinal direction

5.3.1.5. Residual displacements

Residual displacements were calculated for middle column and superstructure by using non-skewed and skewed bridges for non-uniformly changed scour depths in longitudinal direction (%25) and different ground motion incidence angles. In Figure 5.106, average residual displacement demands of middle column for non-skewed and 45° skewed bridge are given when scour depth change is non-uniform in longitudinal direction (Case 2-2a). Also, in Figure 5.107, the ratio of residual displacement demand to maximum displacement of middle column for non-skewed and 45° skewed bridge is shown for the same scour case. Furthermore, the same demands are evaluated for the superstructure and shown in Figure 5.108 and Figure 5.109, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal direction for middle column of bridge. Also, superstructure demands are higher in longitudinal direction for non-skewed bridge and in transverse direction the situation becomes vice versa for skewed bridge.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when non-uniform scour depth is 6m at 75° incidence angle for non-skewed bridge as 22.9mm. In transverse direction it is maximum at 90° incidence angle and 4m scour depth as 6.4mm for skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the maximum

ratio occurs at an incidence angle of 75° and 6m scour depth as 0.18 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 2m scour depth when incidence angle 180° in transverse direction of skewed bridge.

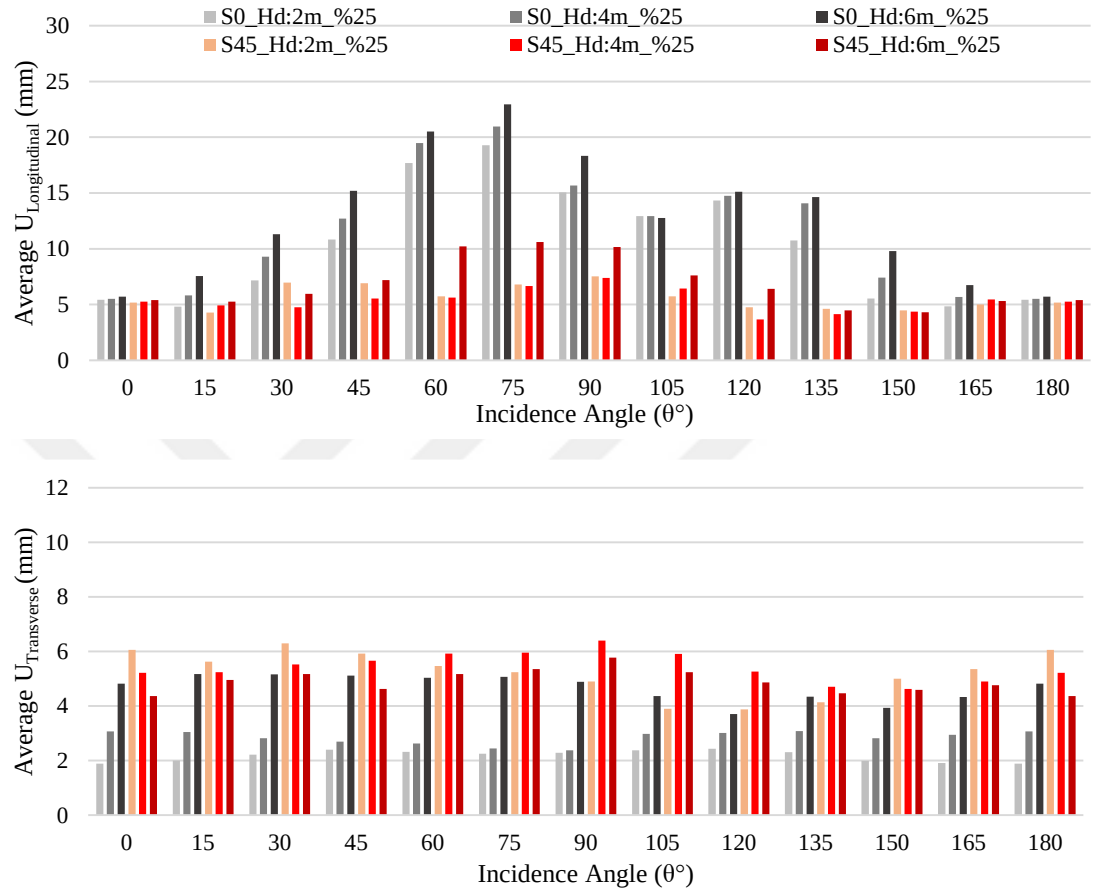


Figure 5.106. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2a)

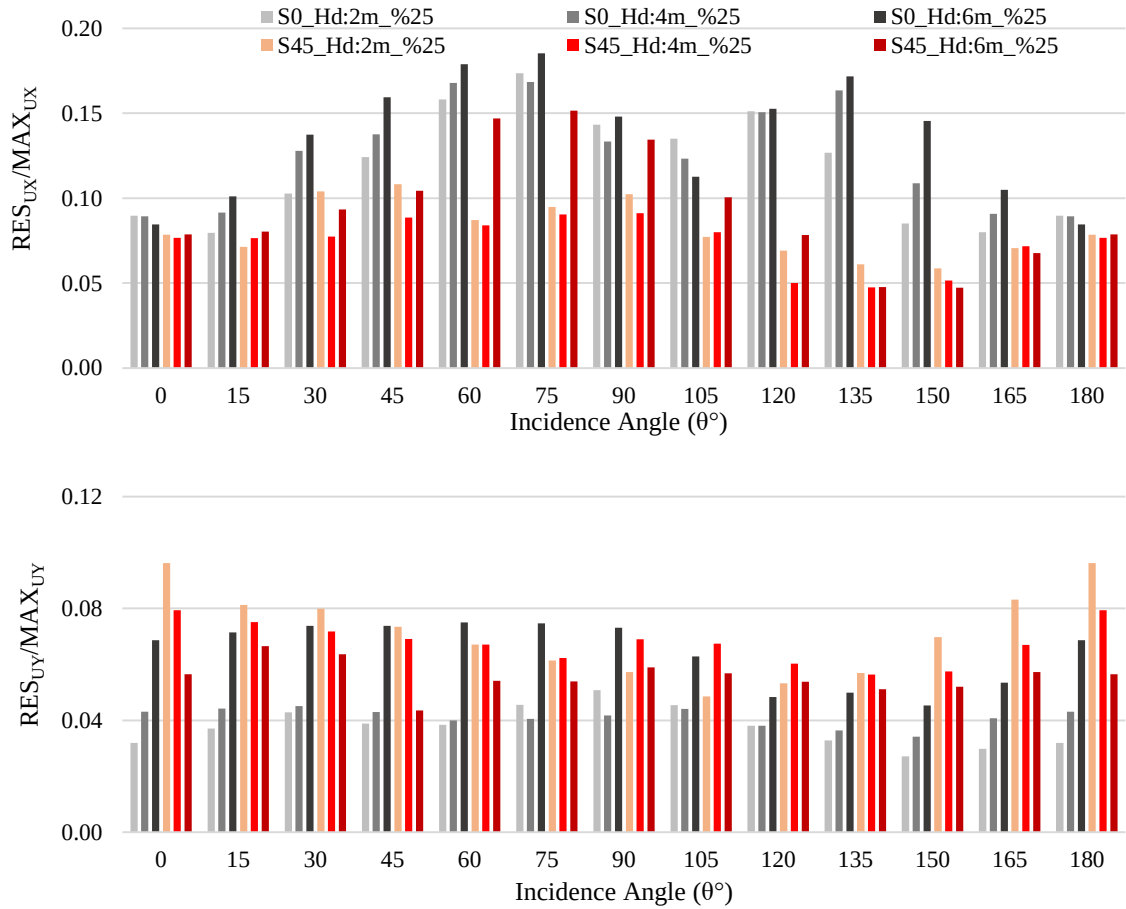


Figure 5.107. The ratio of residual displacement demand to maximum displacement of middle for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2a)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when non-uniform scour depth in longitudinal direction (%25) is 6m at 75° incidence angle for non-skewed bridge as 27.6mm. In transverse direction it is maximum at 180° incidence angle and 2m scour depth as 8.9mm for skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 6m scour depth as 0.19 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 2m scour depth when incidence angle 180° in transverse direction of skewed bridge.

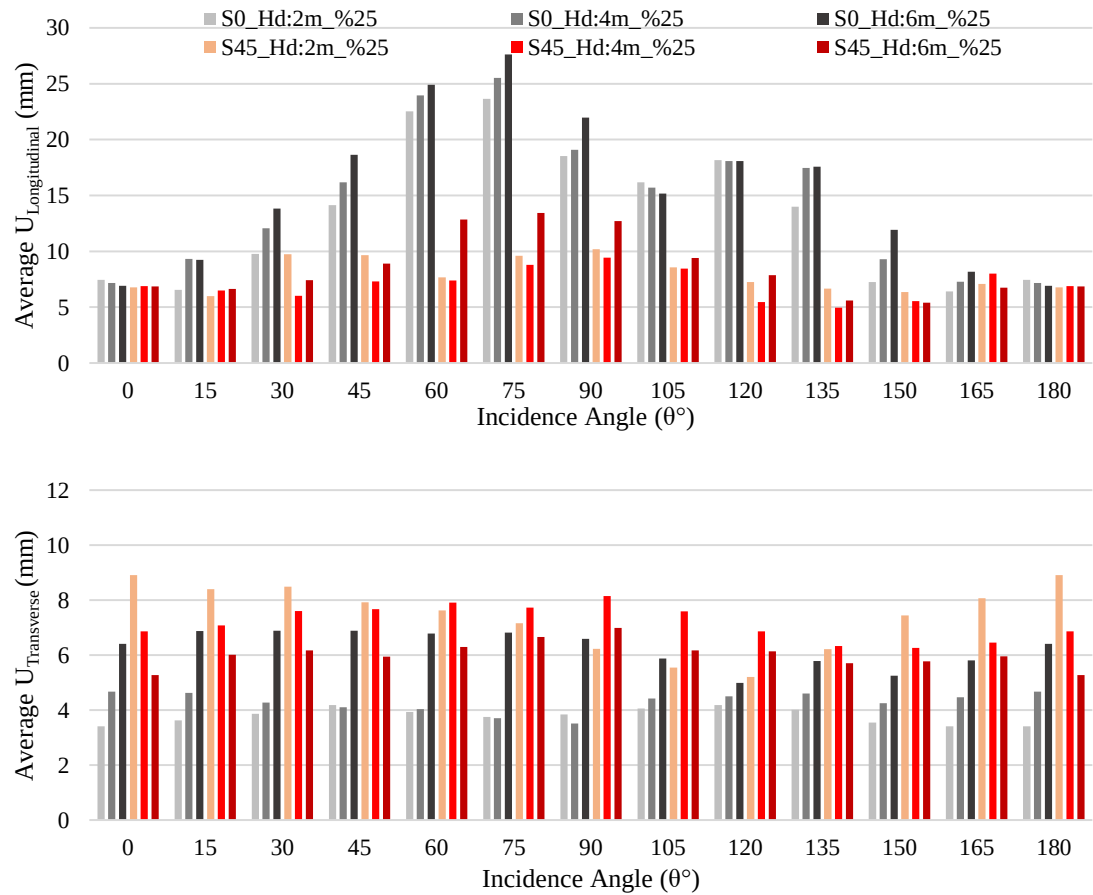


Figure 5.108. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2a)

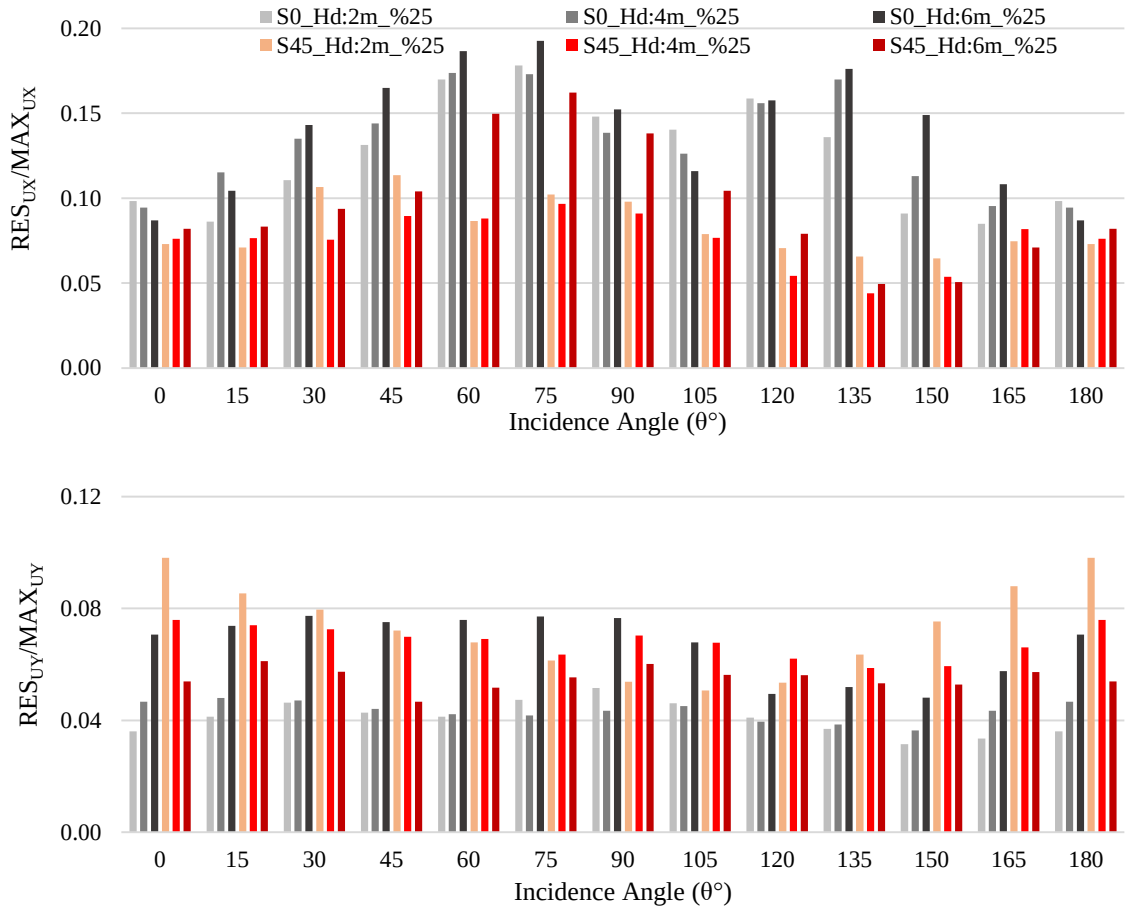


Figure 5.109. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2a)

5.3.2. Non-uniform scour in longitudinal direction of bridge when scour is 50% more around middle piles (Case 2-2b)

In this part, non-uniform scoured bridge models in longitudinal direction are constructed by taking the scour depth 50% more around middle piles than side piles. Scour depth is changed as 2m, 4m and 6m (H_d). This means, when scour around side piles is 2m, the scour around middle piles become 50% more and calculated as 3m. Nonlinear response history analysis is done by using 7 strong ground motions for non-skewed and skewed bridge model for each scour depth. Also ground motion incidence angle is rotated starting from 0° to 180° with an increment of 15° . The engineering demand parameters (EDPs) examined within the scope of the study are superstructure displacement bent column curvature and shear, pile shear, residual displacements of middle column and superstructure. The demands obtained from nonlinear analysis results are given below.

In Figure 5.110, the variation of 1st and 2nd vibration period of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge depending on non-uniform scour depth in longitudinal direction is given when scour is 50% more around middle piles (Case 2-2b) and the vibration period of the bridge increases when scour depth increases. For skewed bridges the first period is greater than the non-skewed bridges for all scour depths. On the other hand, the situation is vice versa for second period.

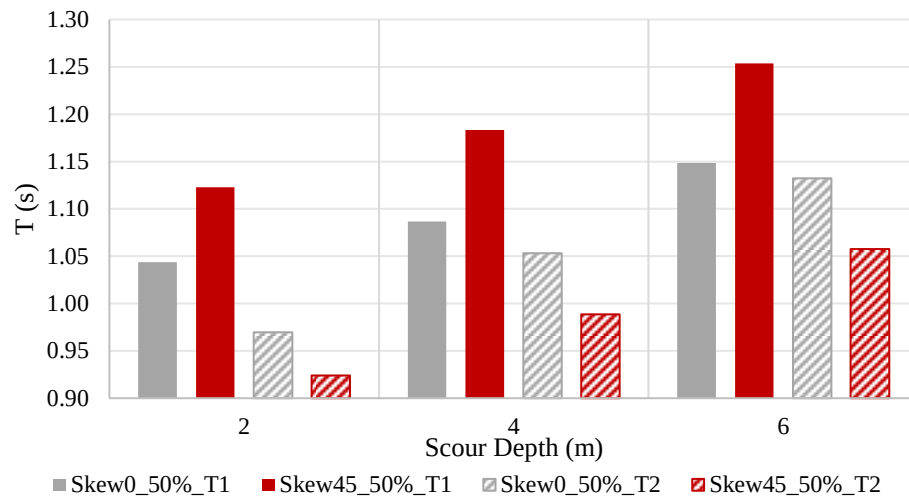


Figure 5.110. The variation of 1st and 2nd vibration period of non-skewed (0°) and skewed (45°) bridge depending on non-uniform scour depth in longitudinal direction when scour is 50% more around middle piles (Case 2-2b)

5.3.2.1. Superstructure displacement

Superstructure displacement demands obtained from nonlinear analysis results belong to midpoint of bridge deck as mentioned above. In Figure 5.111 and Figure 5.112, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.113 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results examined in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 90° although in transverse direction it is decreasing between that angles. Therefore, resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts,

average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in both directions is more obvious in some ground motion incidence angles. The maximum difference of average displacement demands in longitudinal direction between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 90° incidence angle as nearly 10.6%. In transverse direction, it is at 15° incidence angle as 24%. If it is checked for resultant displacement, maximum difference becomes 18% at 165° incidence angle.

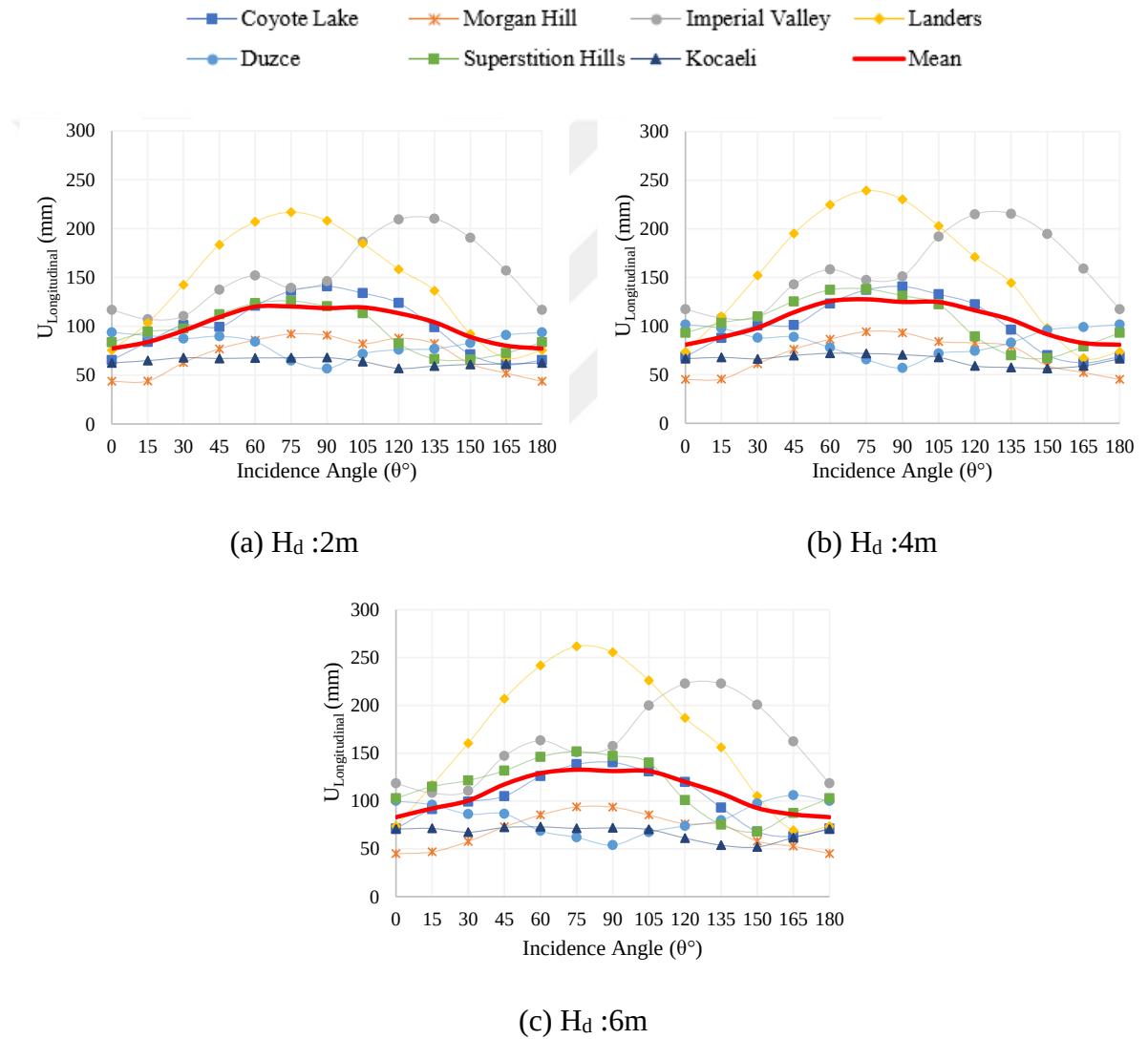


Figure 5.111. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

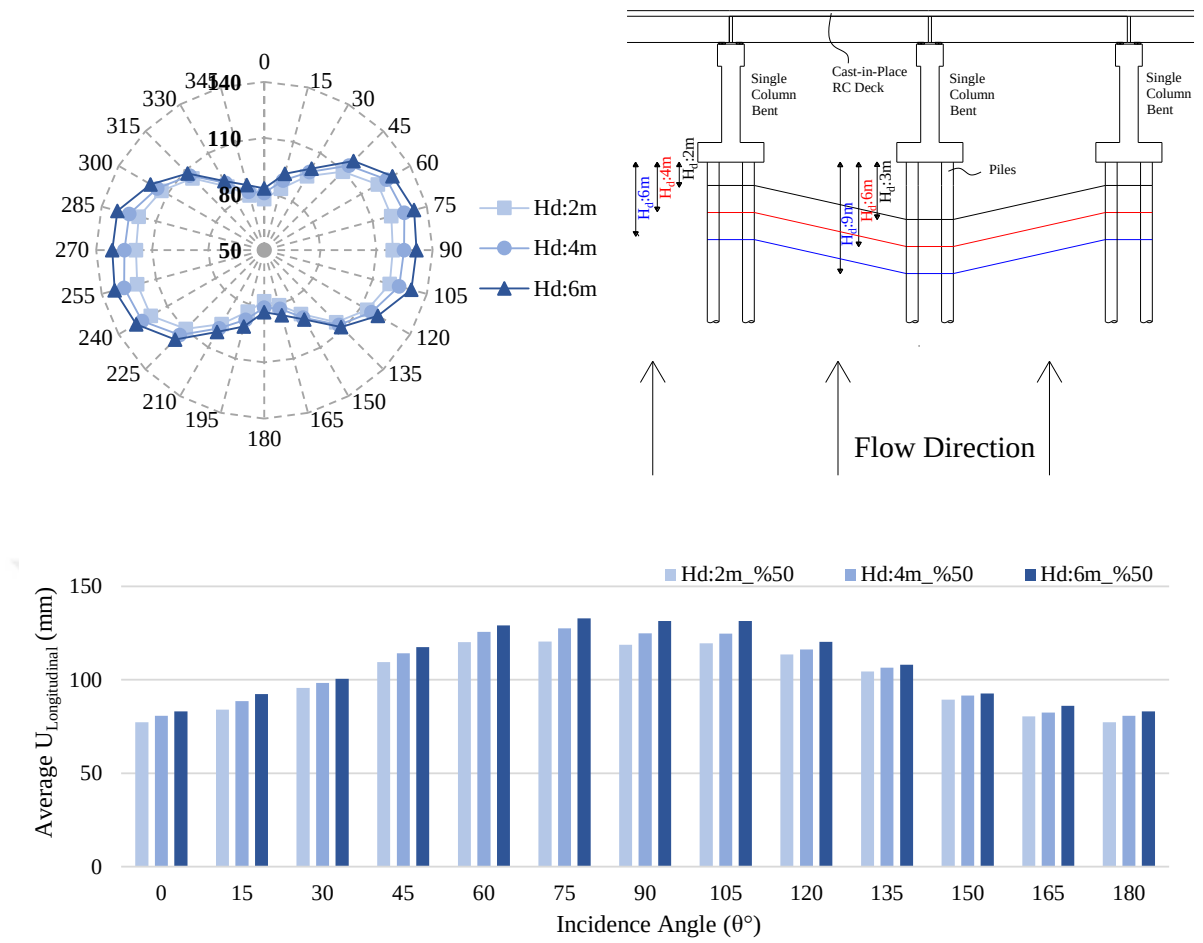


Figure 5.111. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

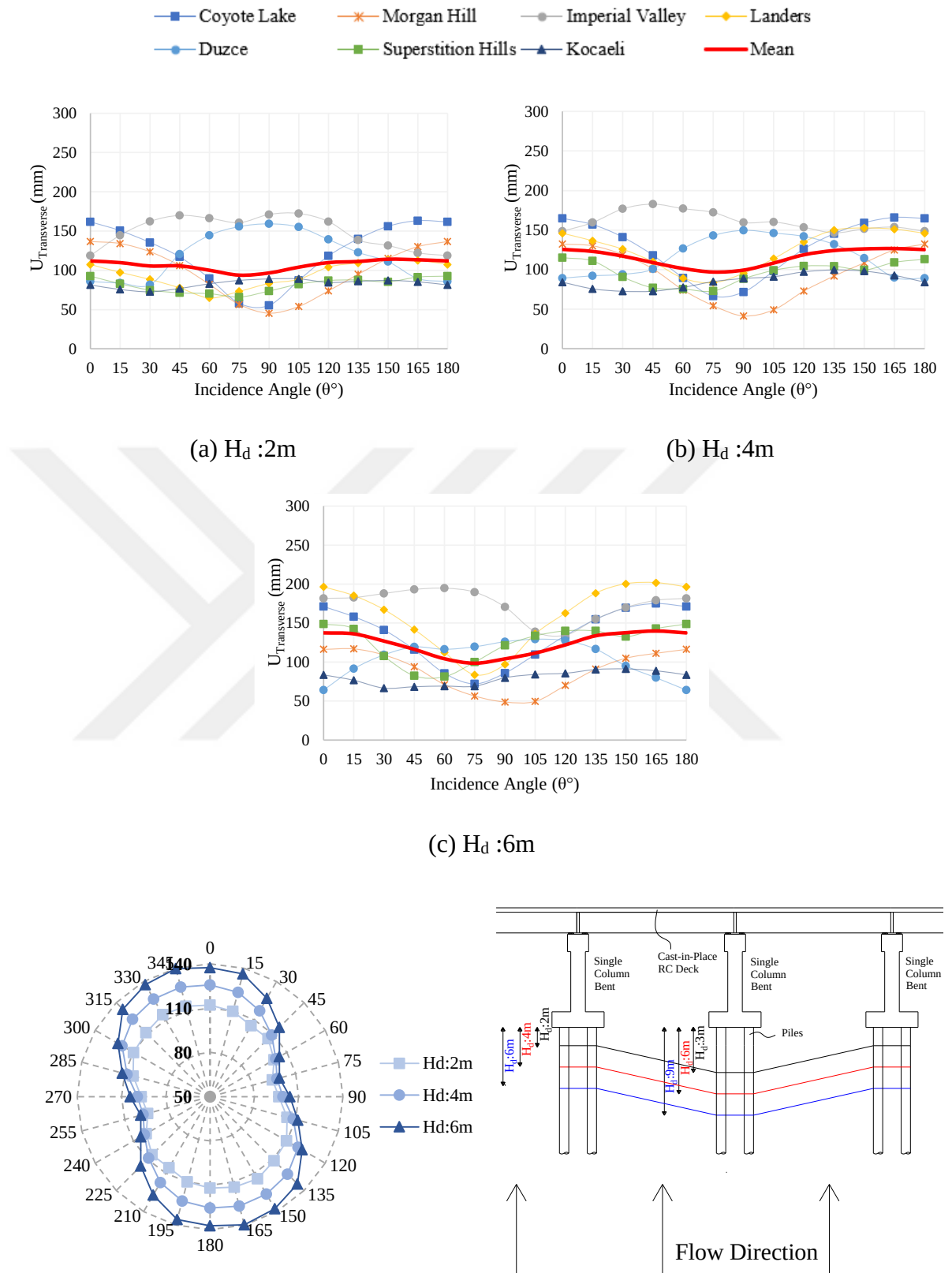


Figure 5.112. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

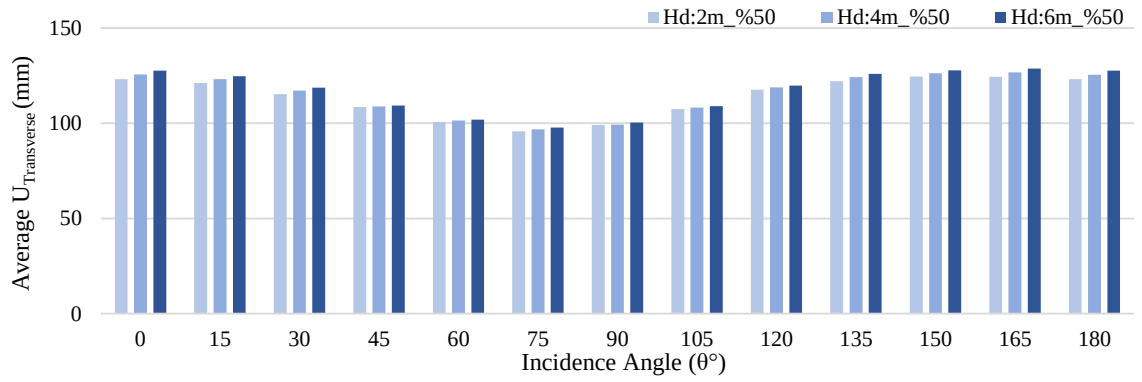


Figure 5.112. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

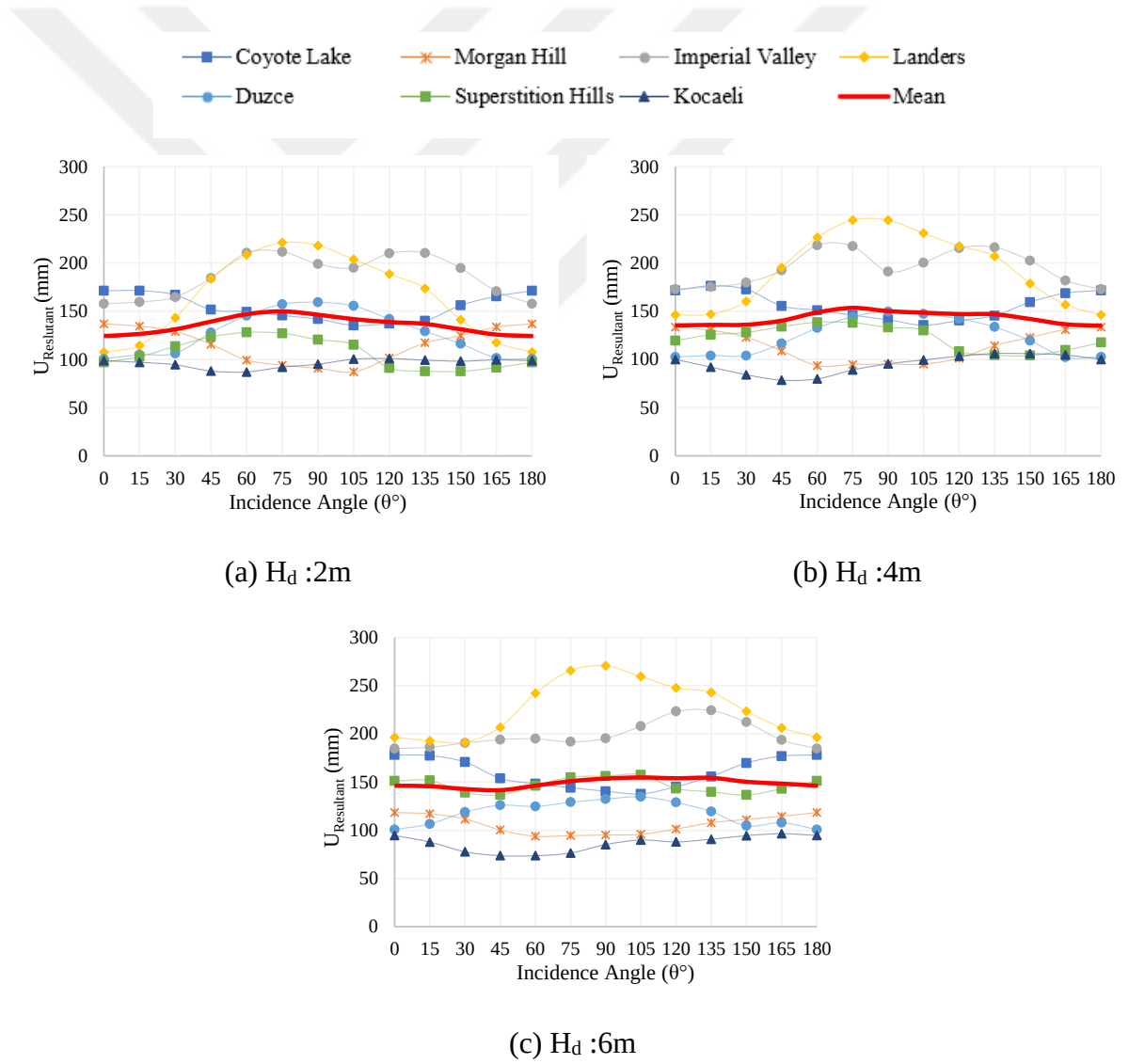


Figure 5.113. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

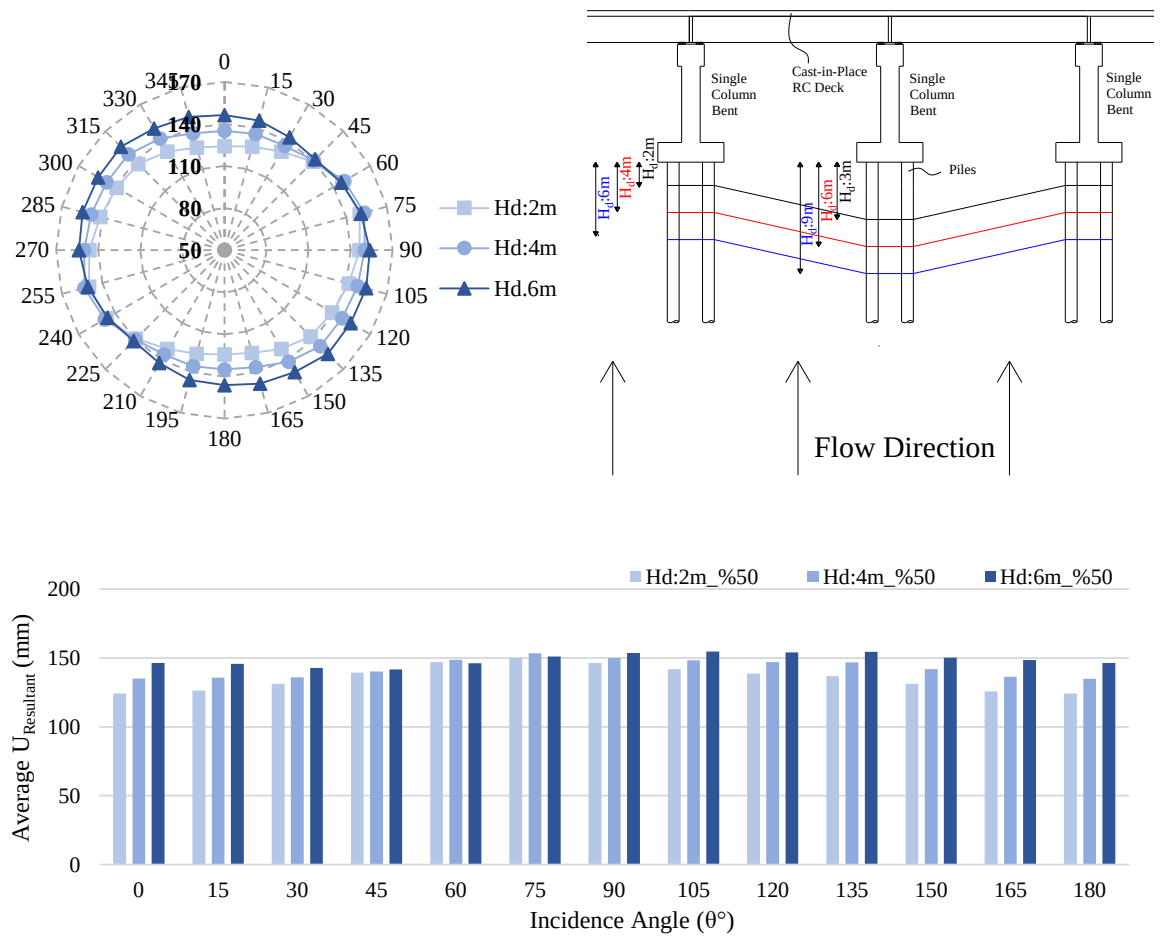


Figure 5.113. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

In Figure 5.114 and Figure 5.115, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge are given. Also, Figure 5.116 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° . When the results assessed in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° although in transverse direction it is decreasing between 0° and 75° . The resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in

transverse direction of bridge is more obvious in some ground motion incidence angles. The maximum difference of average displacement demands in longitudinal direction between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 60° incidence angle as nearly 8.5%. In transverse direction, it is at 0° as 18.4%. If it is checked for resultant displacement, maximum difference becomes 16.1% at 15° incidence angle.

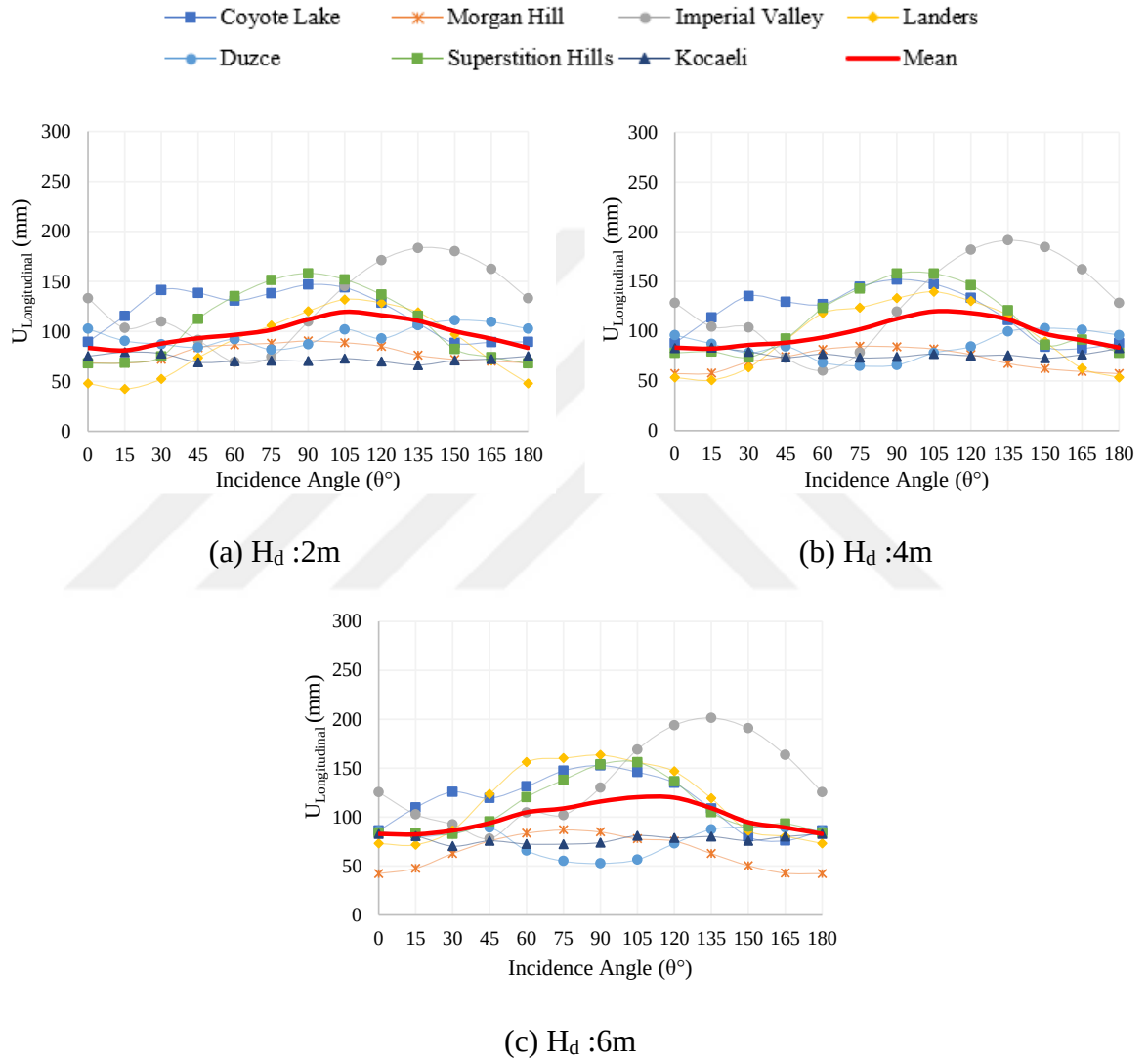


Figure 5.114. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

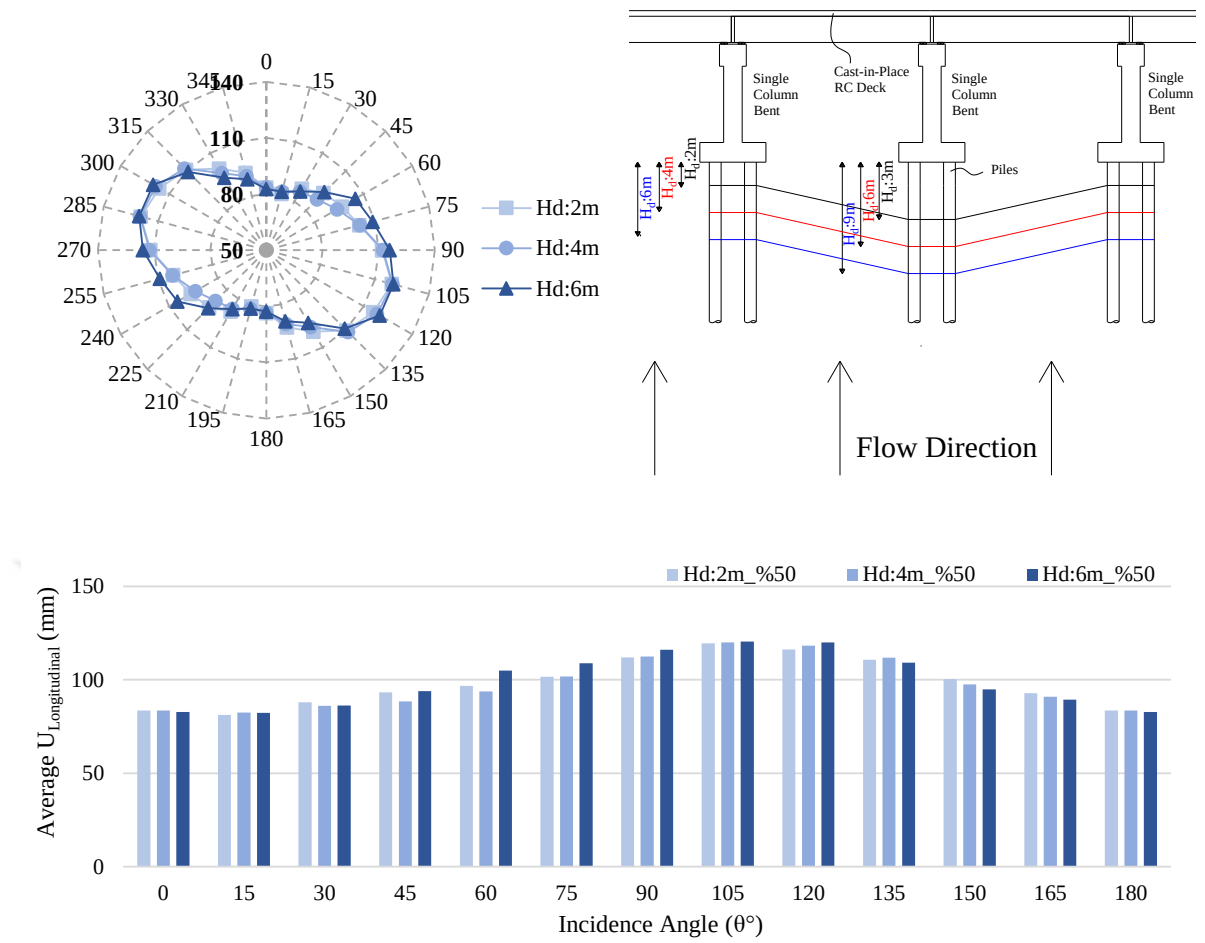


Figure 5.114. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

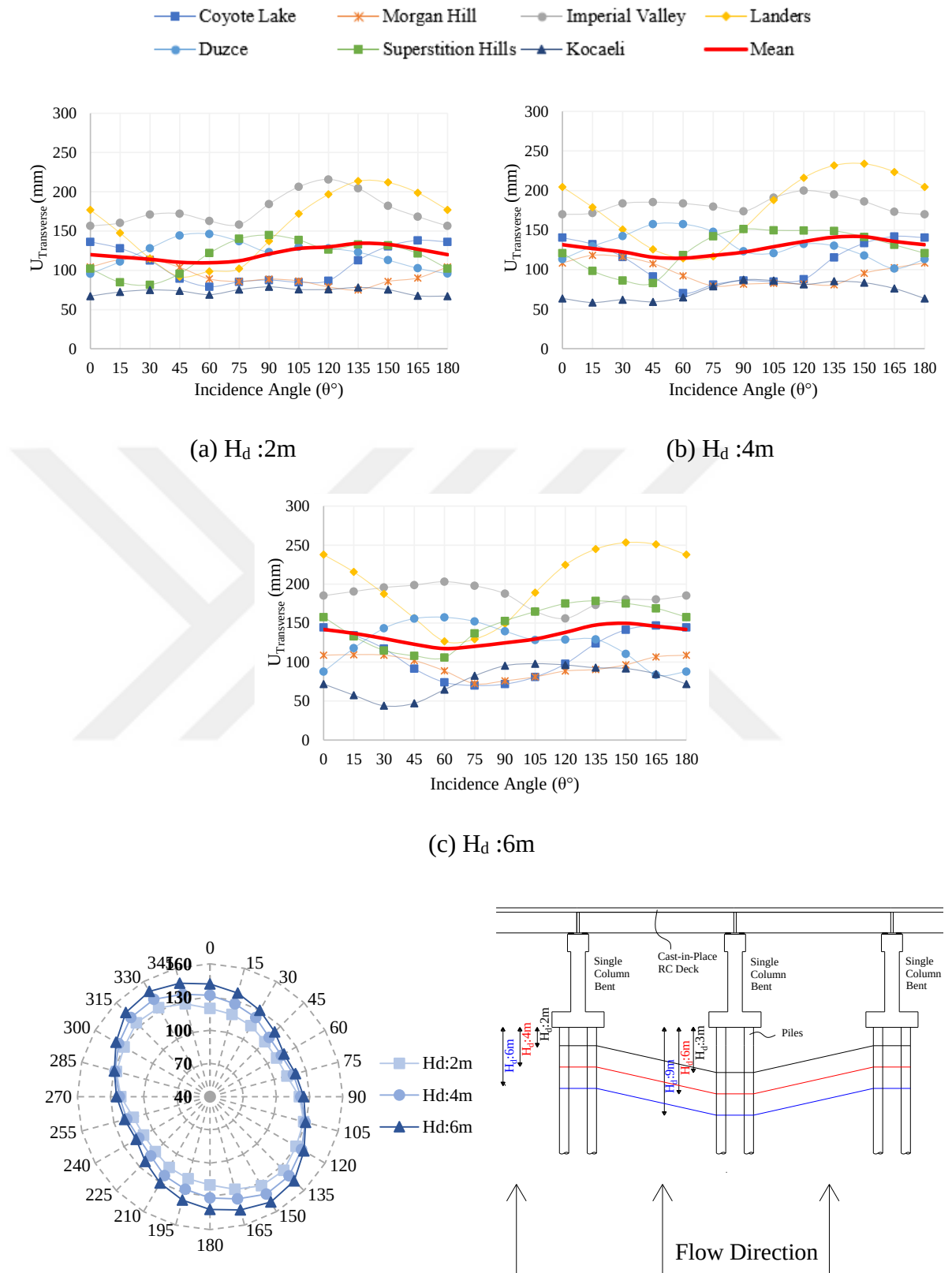


Figure 5.115. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

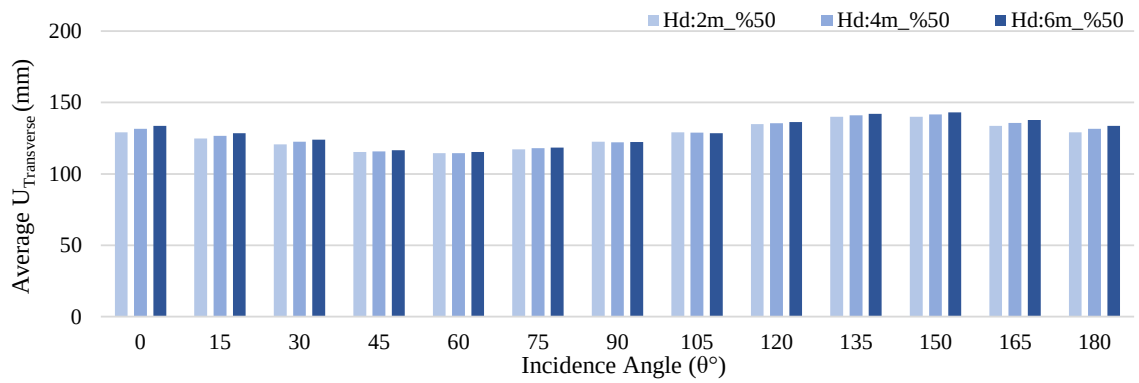


Figure 5.115. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

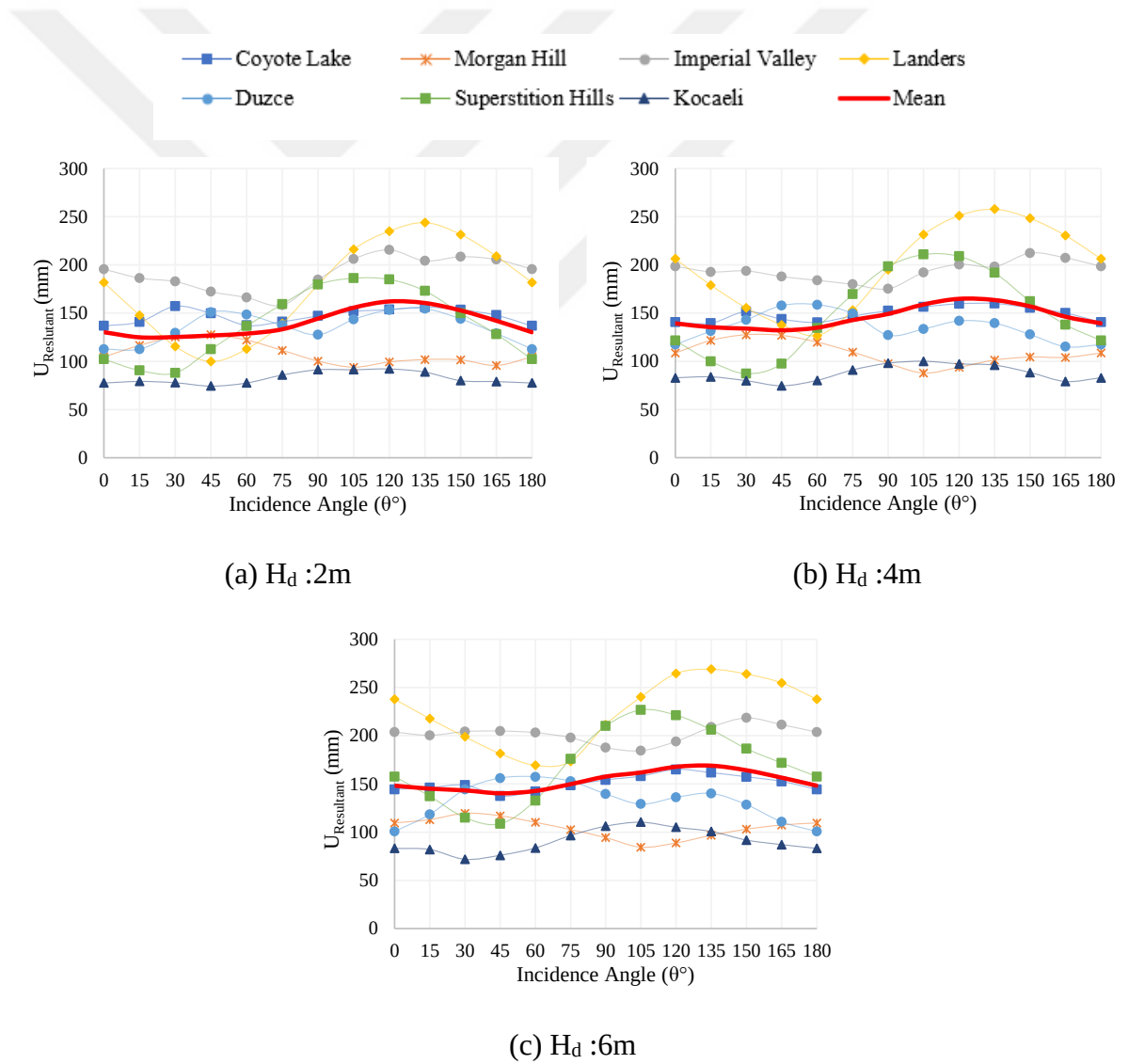


Figure 5.116. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

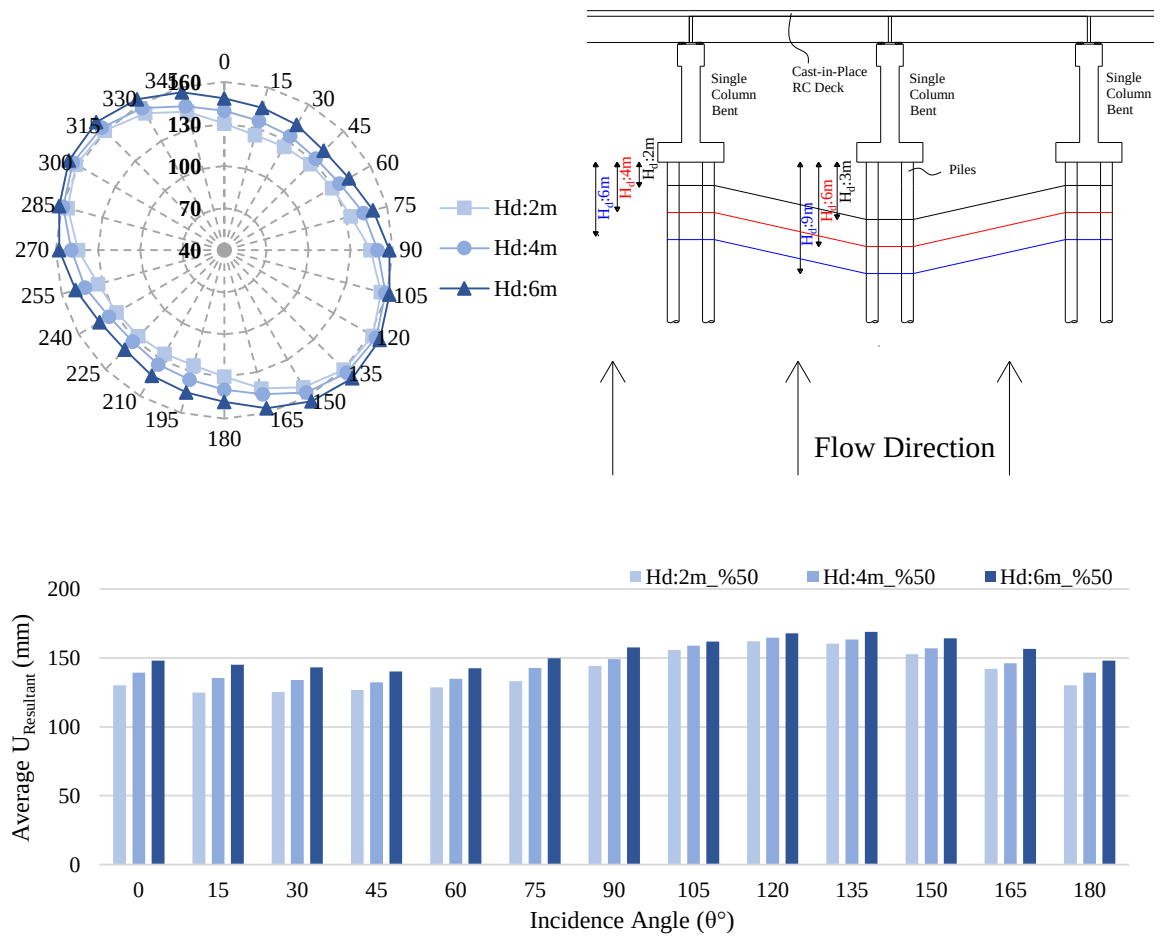


Figure 5.116. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

Also, in Figure 5.117, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) and 45° skewed bridges and resultant displacements are compared. The results are obtained for 7 earthquakes and average of maximum demands are calculated for each ground motion incidence angles and scour depths.

In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge especially between 15° and 105° incidence angles. On the other hand, this situation is vice versa in transverse direction. For both skewed and non-skewed bridges, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 60° incidence angle and 4m scour depth as nearly 25%. In transverse direction, it is at 90° and 2m scour depth as

24.8%. If it is checked for resultant displacement, maximum difference becomes 17.3% at 135° incidence angle and 2m scour depth.

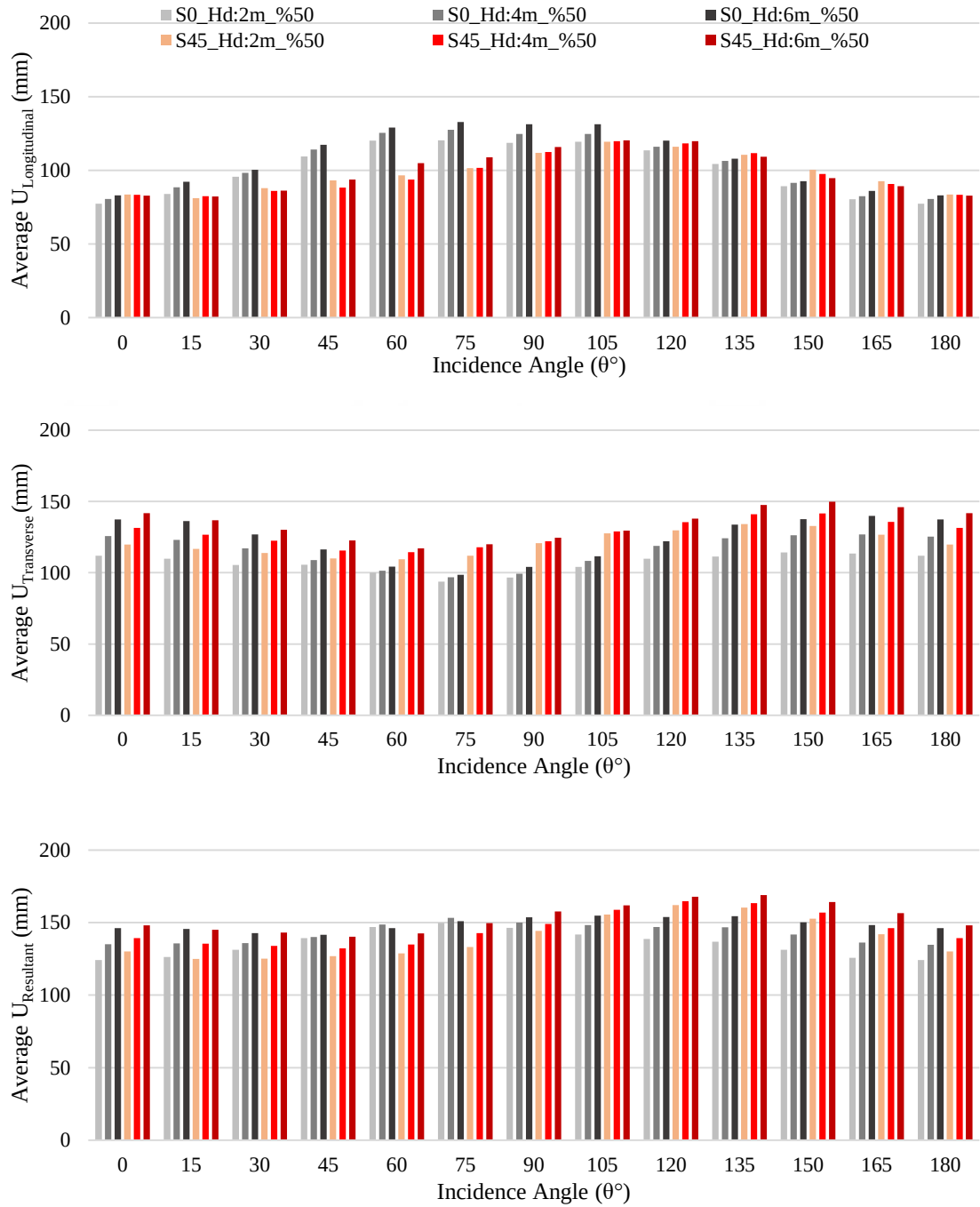


Figure 5.117. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 50% more around middle piles

5.3.2.2. Curvature demands of column pier

In Figure 5.118 and Figure 5.119, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes

and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). In strong axis (z'), it has an increasing trend between 45° and 120° incidence angles. When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. In addition, while the curvature demands on weak axis of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. This shows that earthquake incidence angle should be taken into consideration in order to obtain maximum demands in nonlinear response history analyses. In strong axis of column, the curvature demands exceed the yield curvature for various incidence angles only where scour depth is 2 m. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 120° incidence angle as nearly 58.3%. Also, in strong axis (z'), it becomes 74.5% at 75° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

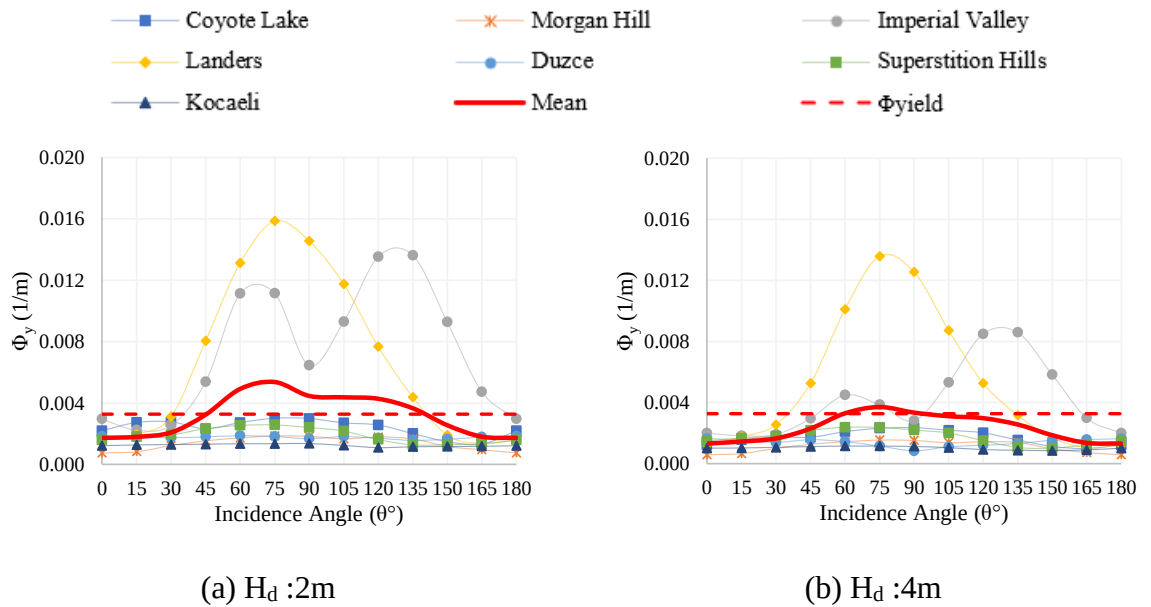


Figure 5.118. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

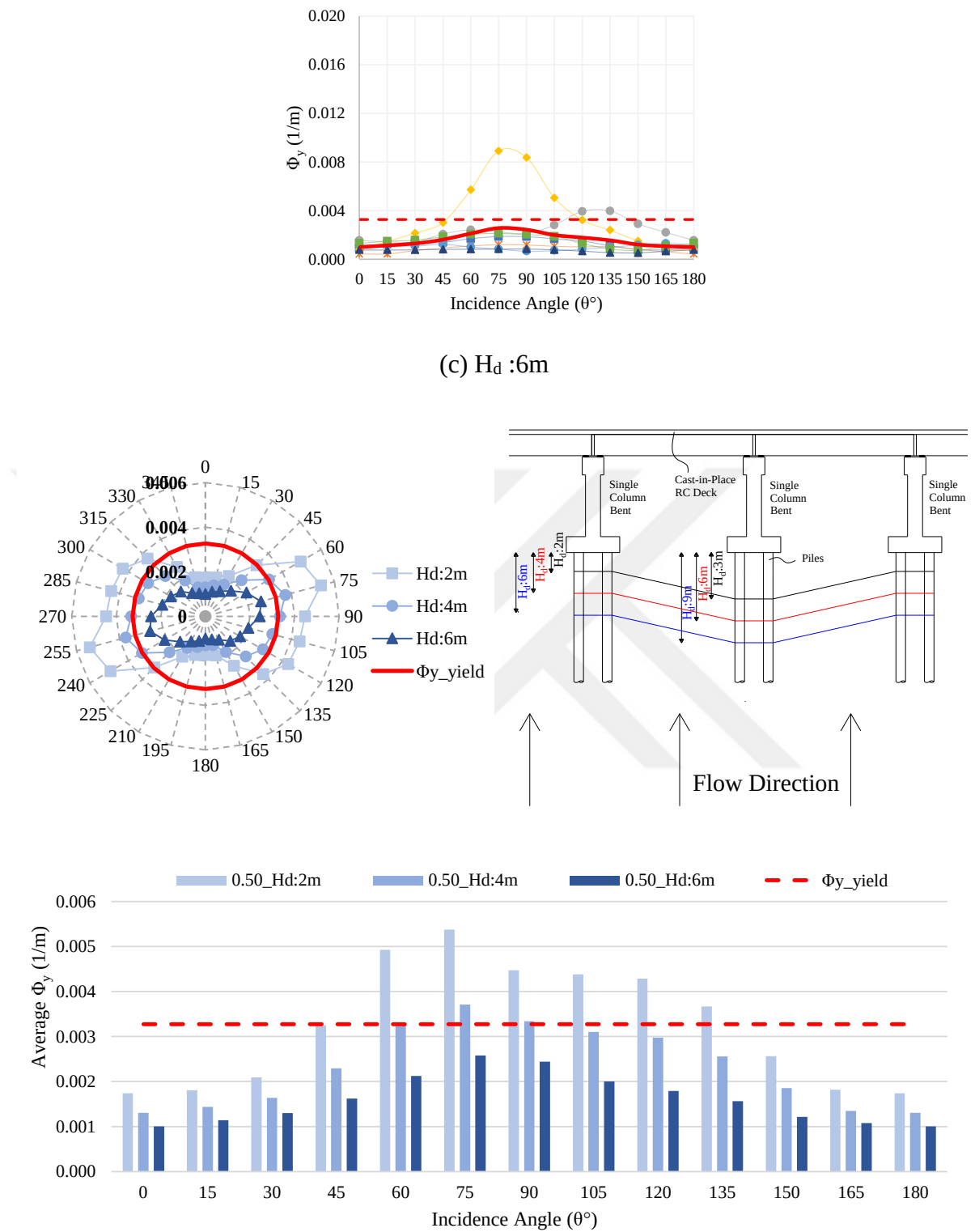


Figure 5.118. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

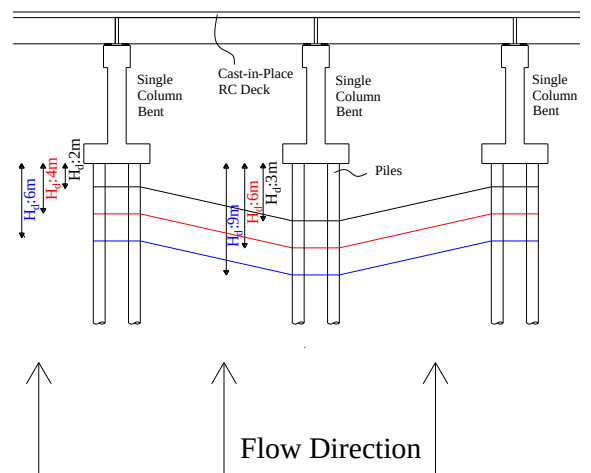
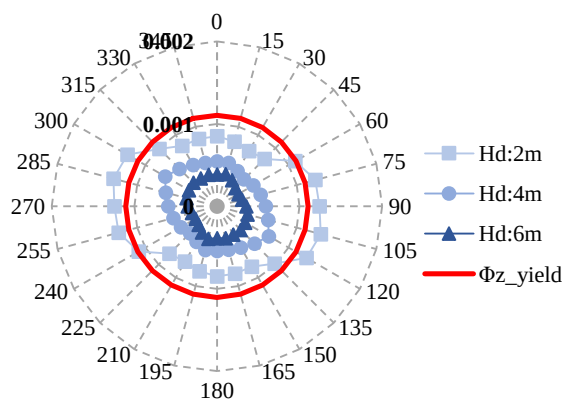
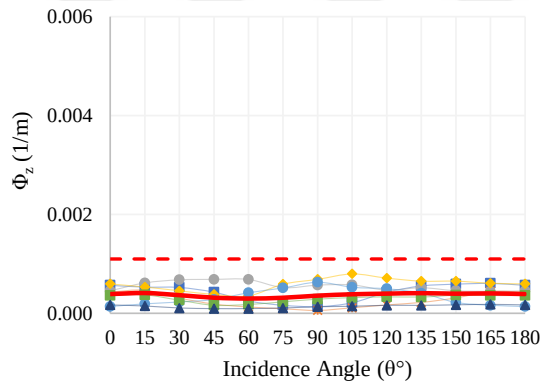
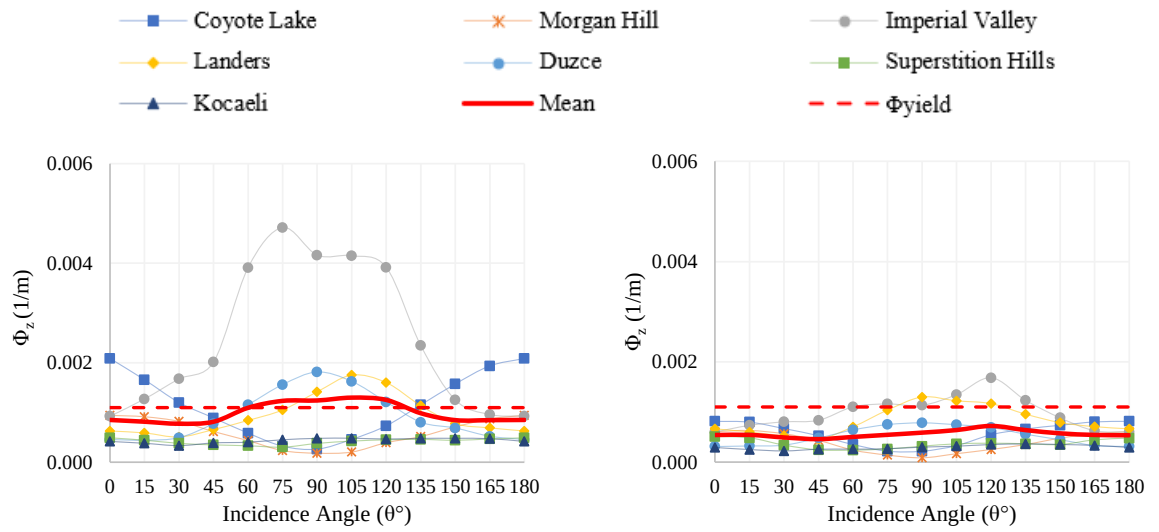


Figure 5.119. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

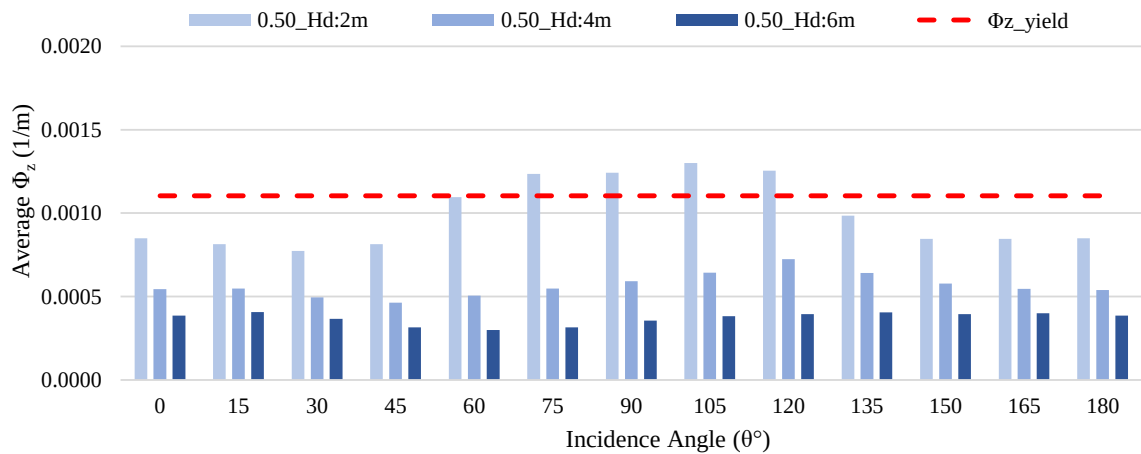
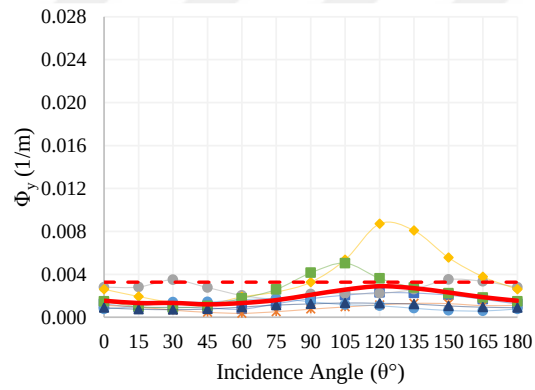
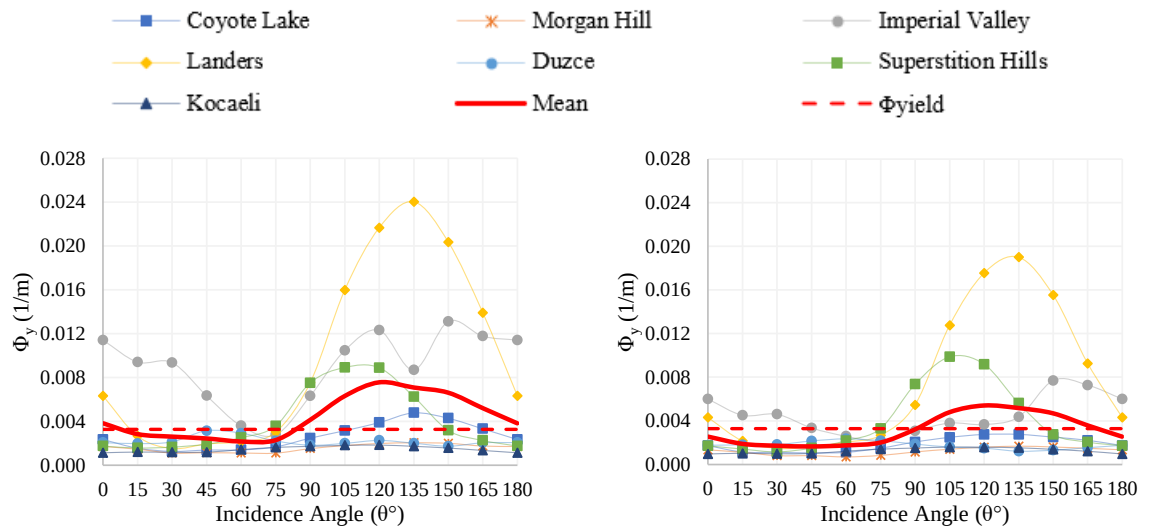


Figure 5.119. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

In Figure 5.120 and Figure 5.121, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 120° in weak axis (y') and strong axis (z'). When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is same as other scour cases as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. In addition, while the curvature demands on weak axis of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. This shows that earthquake incidence angle should be taken into consideration in order to obtain maximum demands in nonlinear response history analyses. In strong axis of column, the curvature demands below the yield curvature for all incidence angles where scour depth is 4 m and 6 m. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2\text{m}$) and 6 m scoured ($H_d=6\text{m}$) bridge is occurred at 150° incidence angle as nearly 64.8%. Also, in strong axis (z'), it becomes 75.9% at 105° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of skewed ($\alpha=45^\circ$) bridge column piers.



(c) $H_d : 6\text{m}$

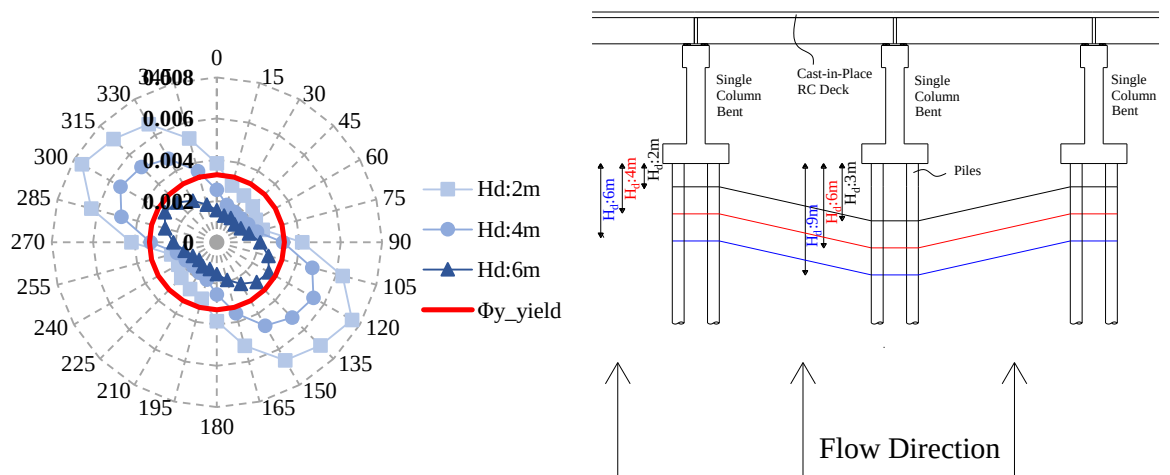


Figure 5.120. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

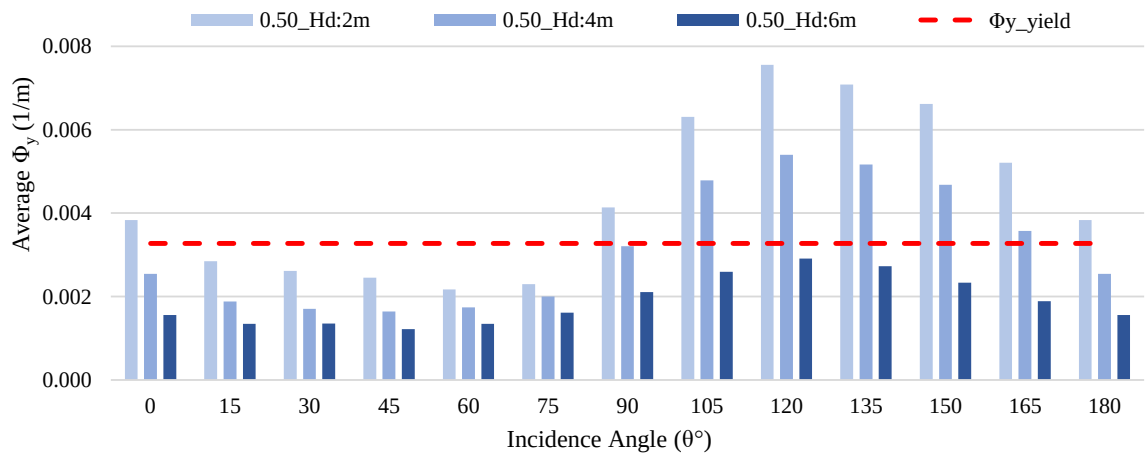


Figure 5.120. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

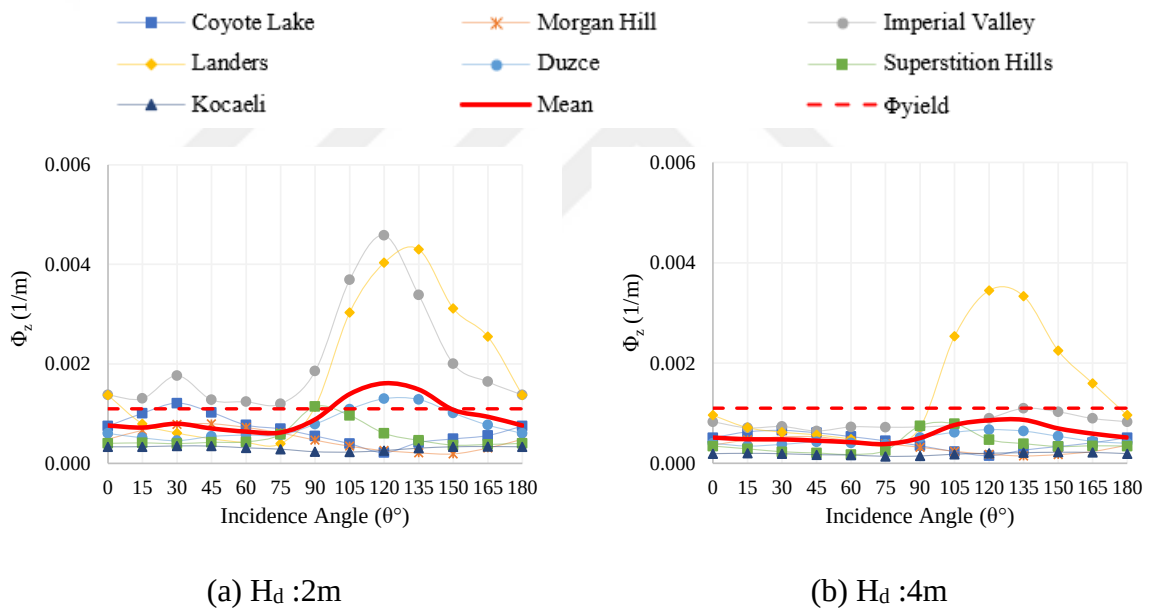


Figure 5.121. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

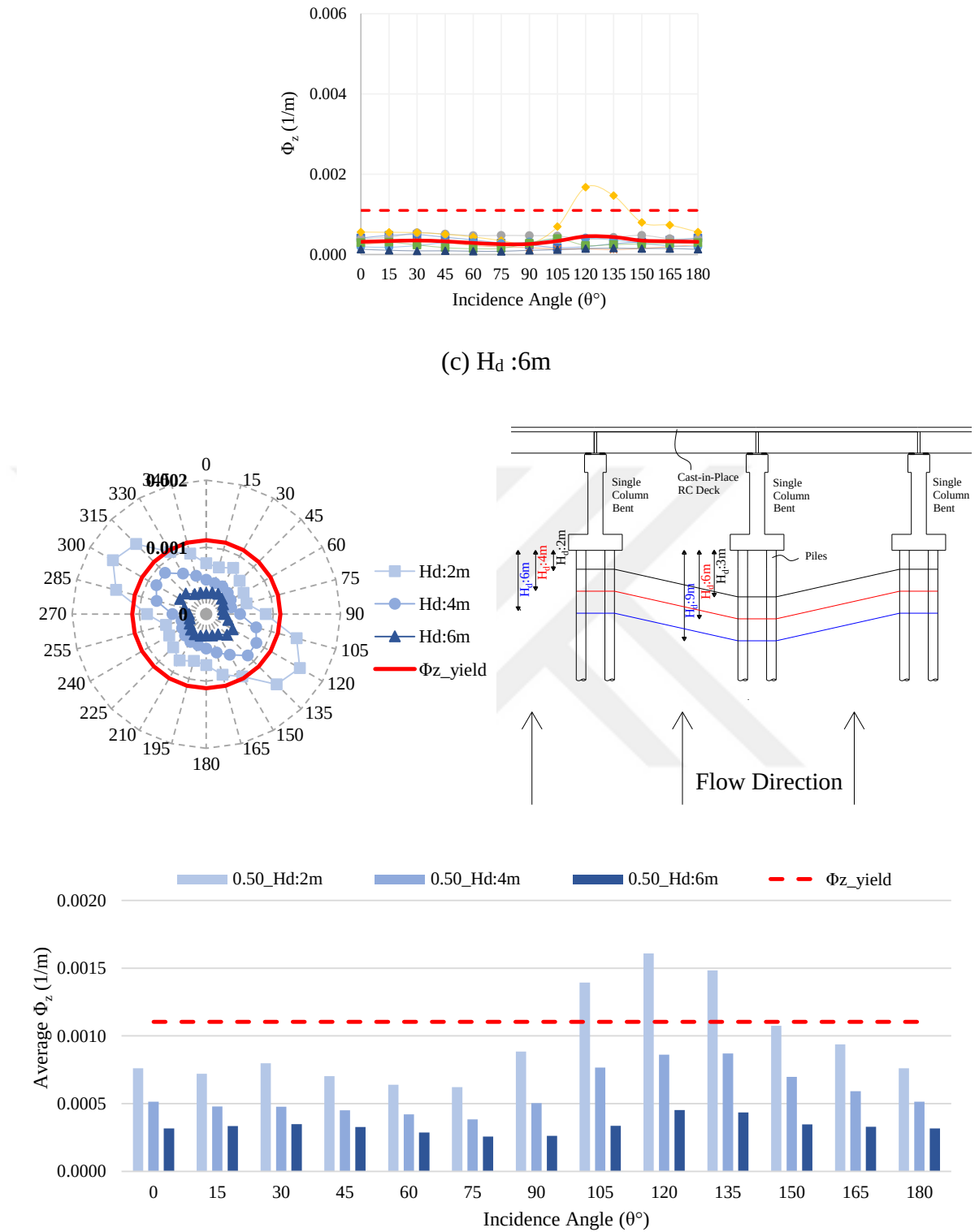


Figure 5.121. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

In Figure 5.122, average maximum curvature demands of middle column of bridge in weak (y') and strong (z') axis are compared for 3 different scour depths 13 incidence

angles for non-skewed and 45° skewed bridges. In column weak axis (y'), curvature demands are higher in non-skewed bridge between 45° and 90° incidence angles. However, it becomes much higher in skewed bridge between 105° and 180° incidence angles. Moreover, in strong (z') axis of column, curvature demands are higher in non-skewed bridge between 0° and 90° incidence angles and it becomes greater in skewed bridge between 105° and 165° incidence angles. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 2m scour depth as nearly 186%. In strong axis, it is at 135° and 2m scour depth as 50.5%.

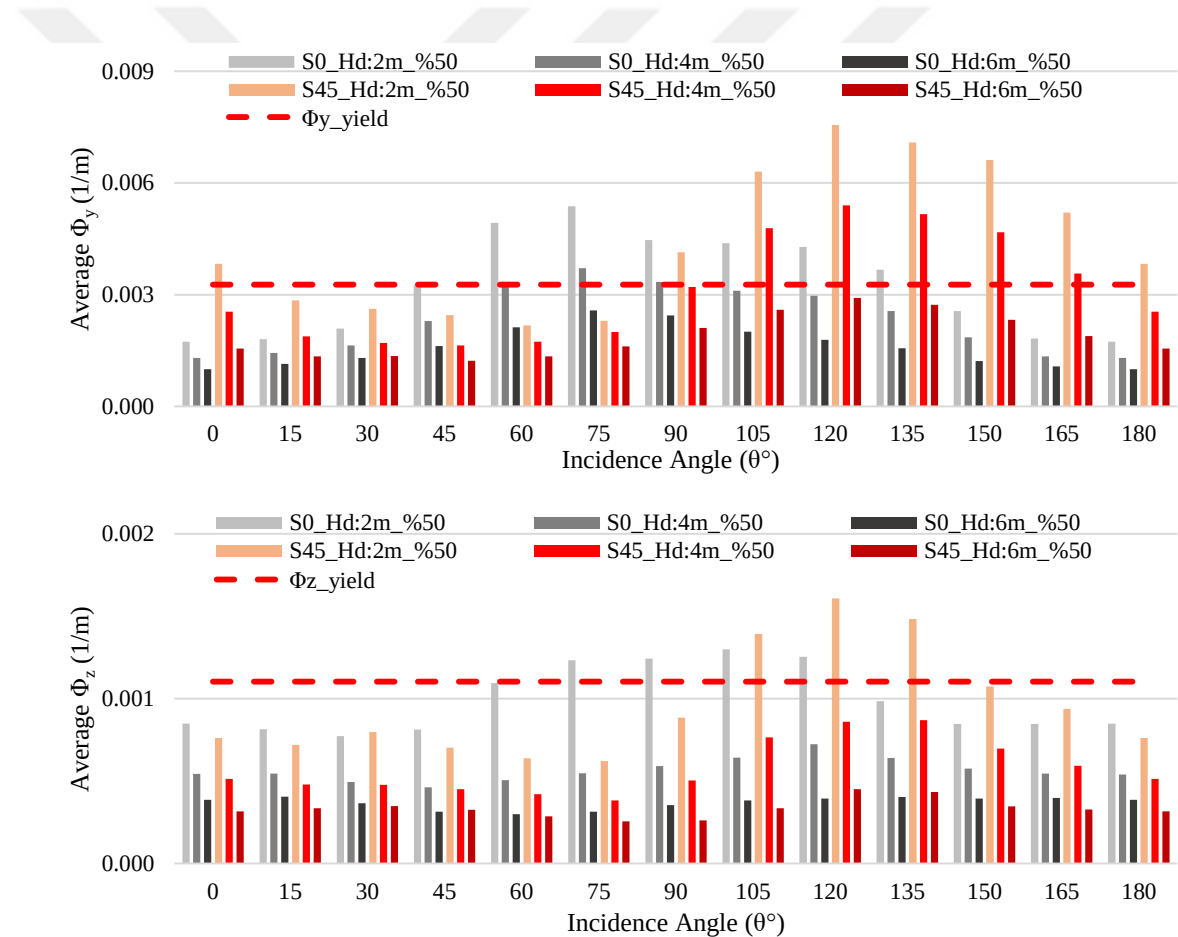


Figure 5.122. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 50% more around middle piles

5.3.2.3. Shear force demands of column pier

In Figure 5.123 and Figure 5.124, maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. However, this decrement is more obvious in local y' axis of column. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) models occurs at 60° incidence angle and nearly 39.6%. Also, it is about 23.4% at 180° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.

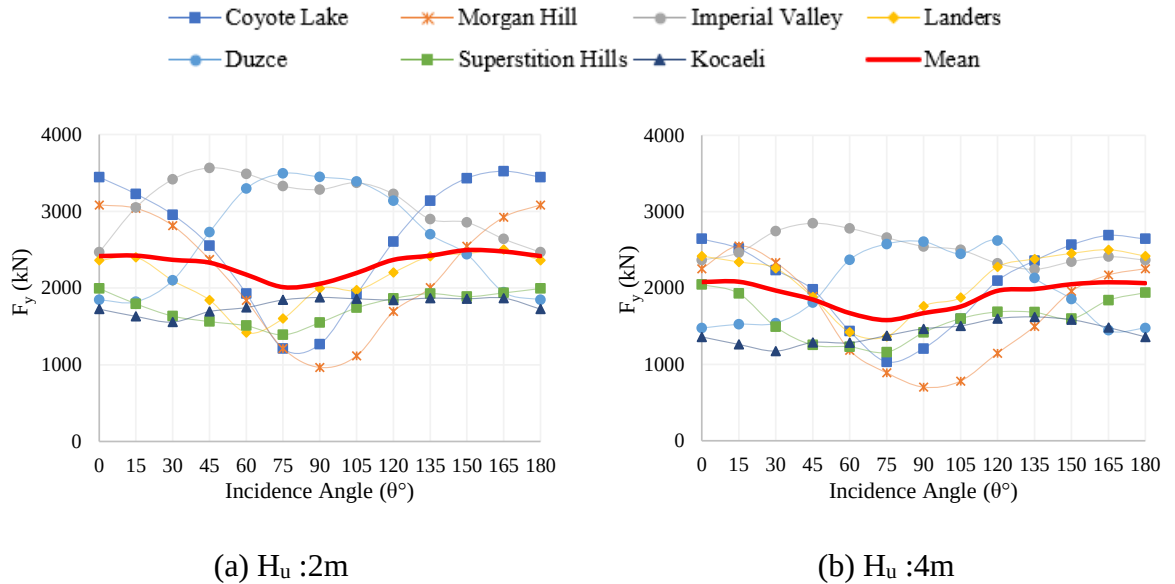
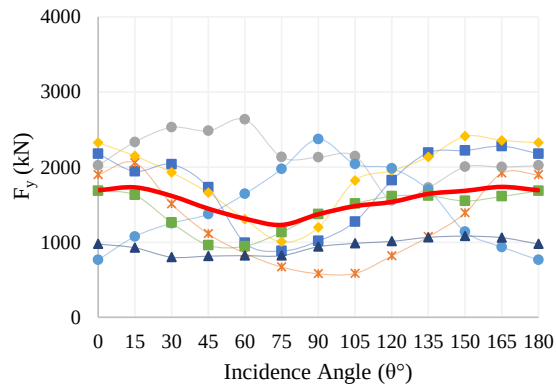


Figure 5.123. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)



(c) $H_u : 6m$

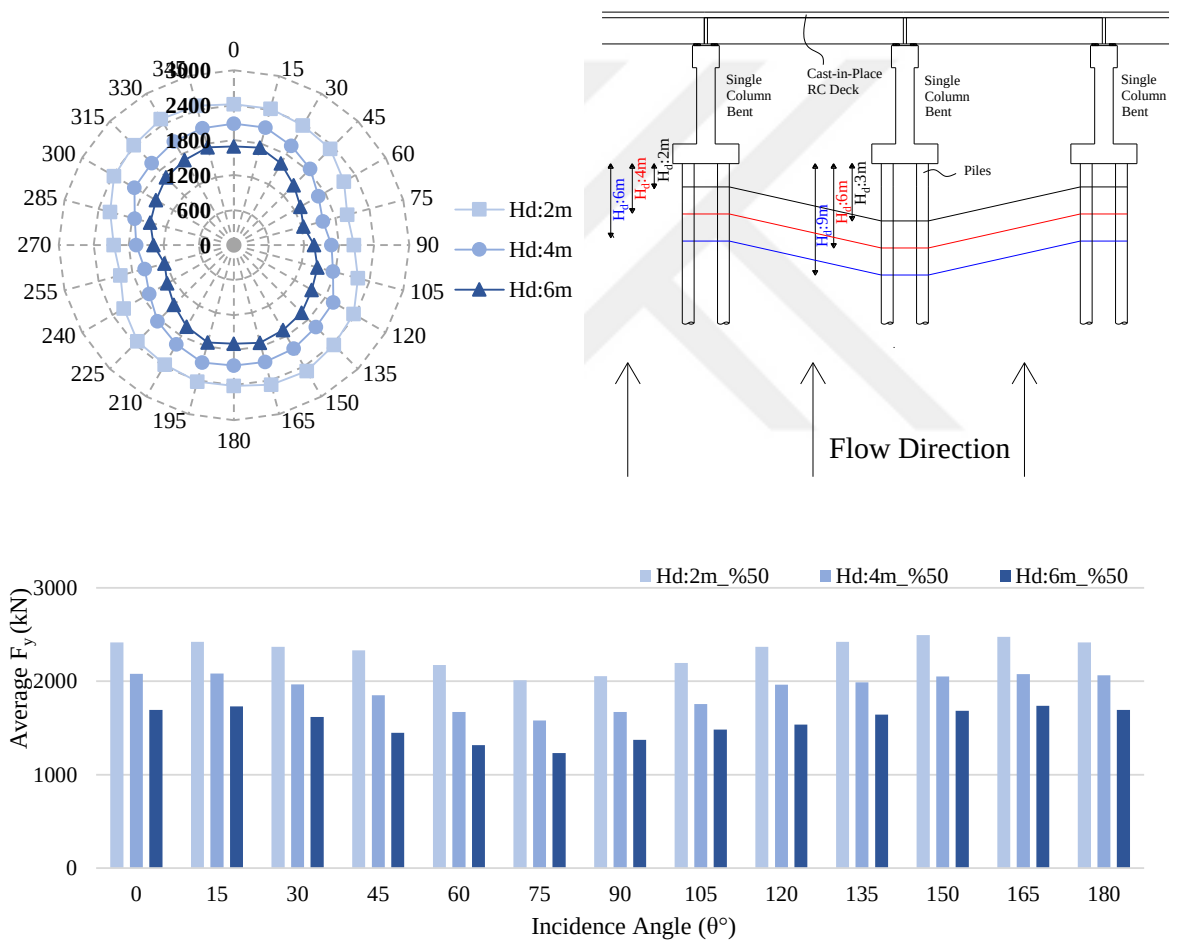


Figure 5.123. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

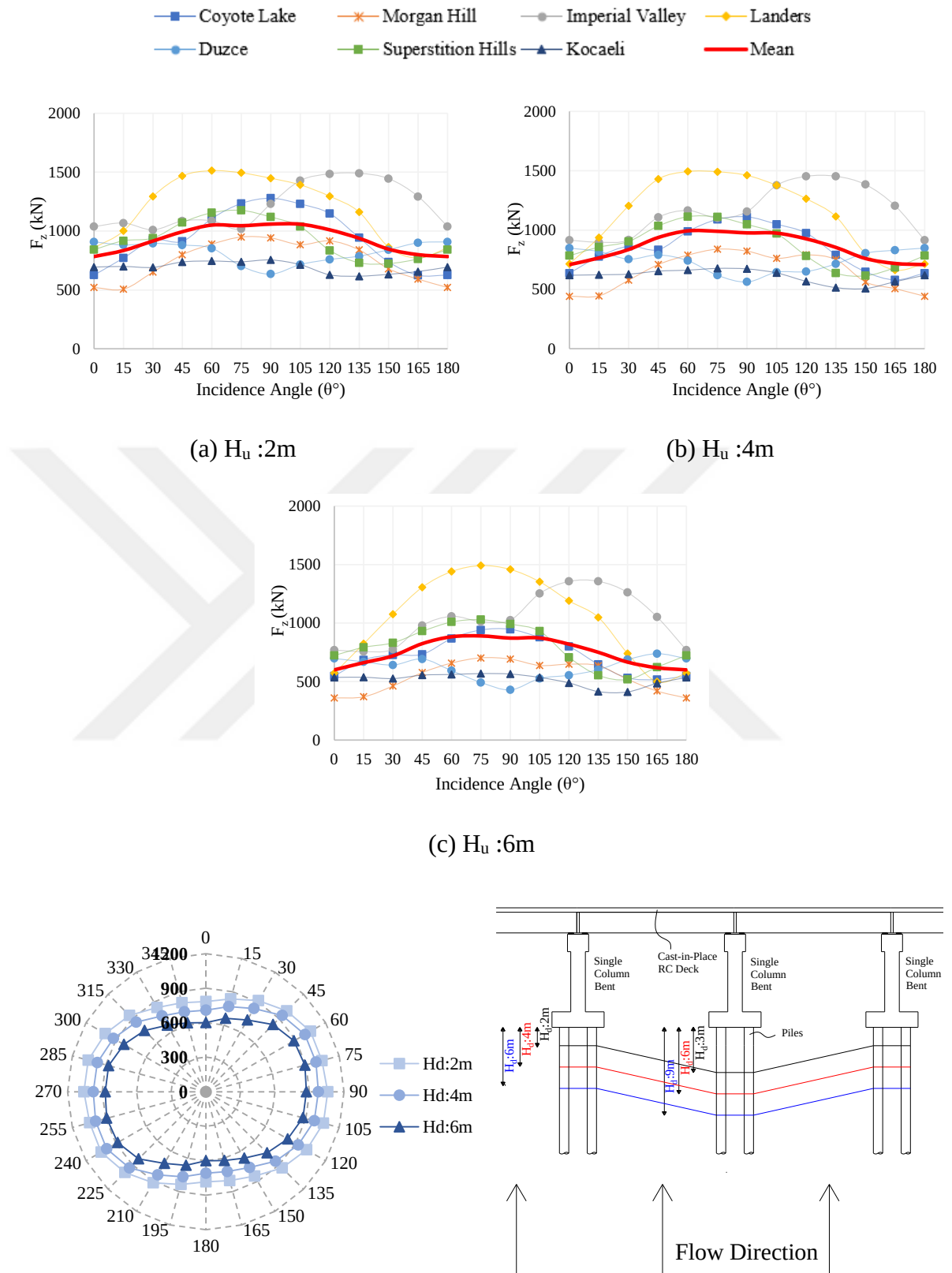


Figure 5.124. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

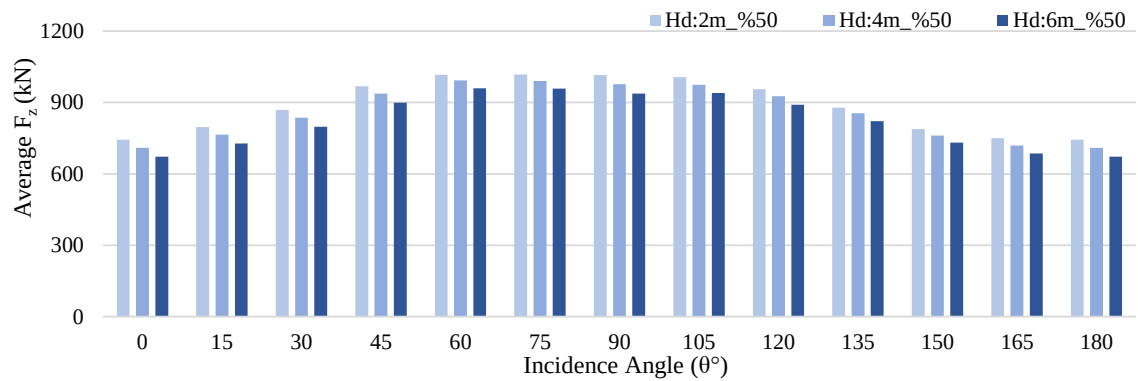


Figure 5.124. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

In Figure 5.125 and Figure 5.126, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 75° to 120° in local y' axis. Besides, it has an increasing trend between 60° and 135° incidence angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles in both local axes of column and this decrease is more obvious in local y' axis. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) models occurs at 90° incidence angle and nearly 39%. Also, it is about 26.4% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in 45° skewed bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.

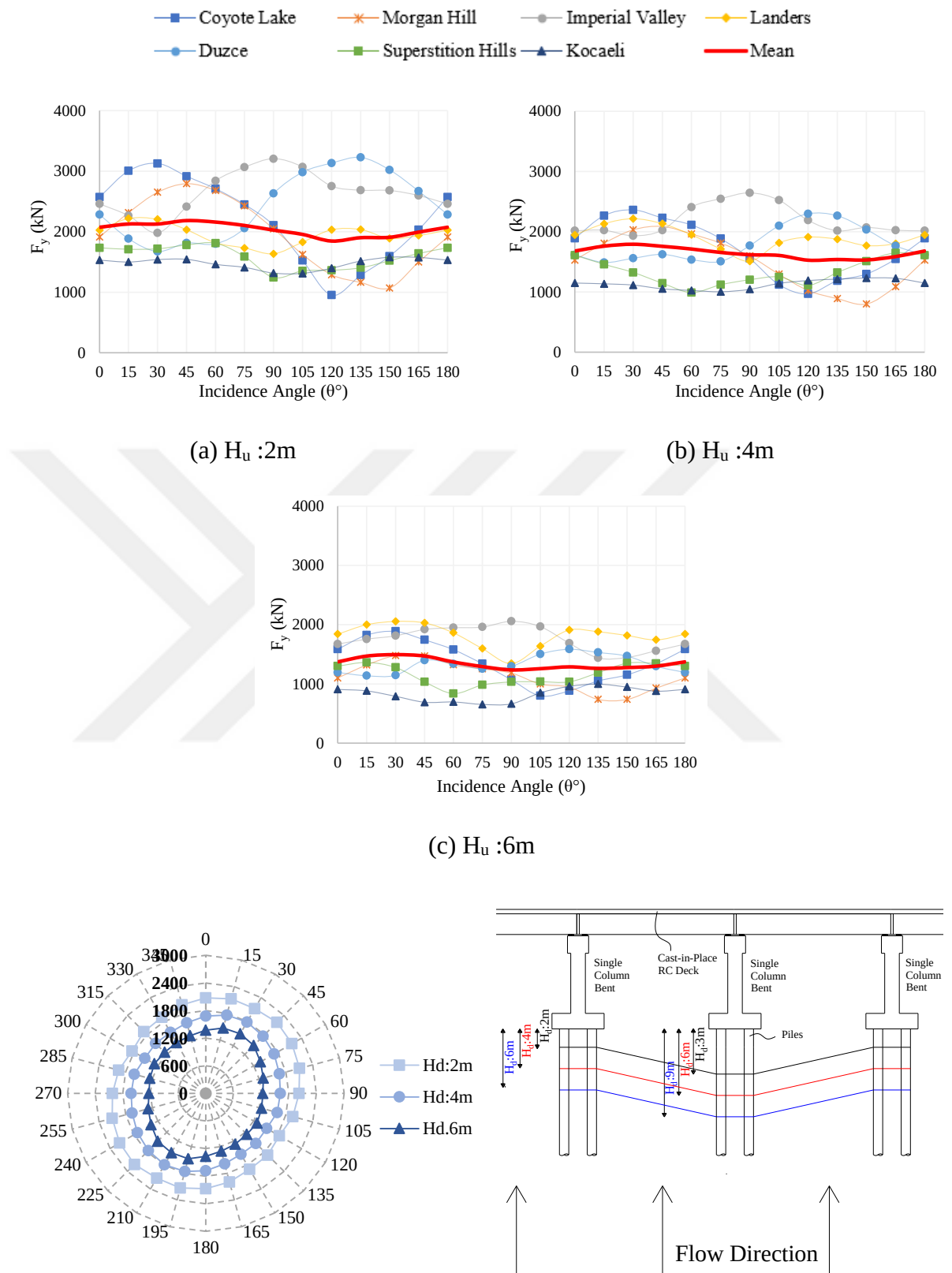


Figure 5.125. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

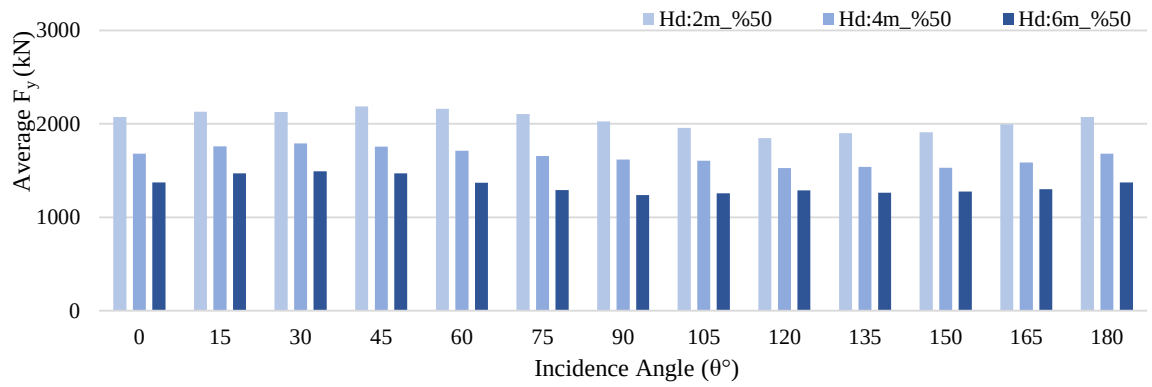


Figure 5.125. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

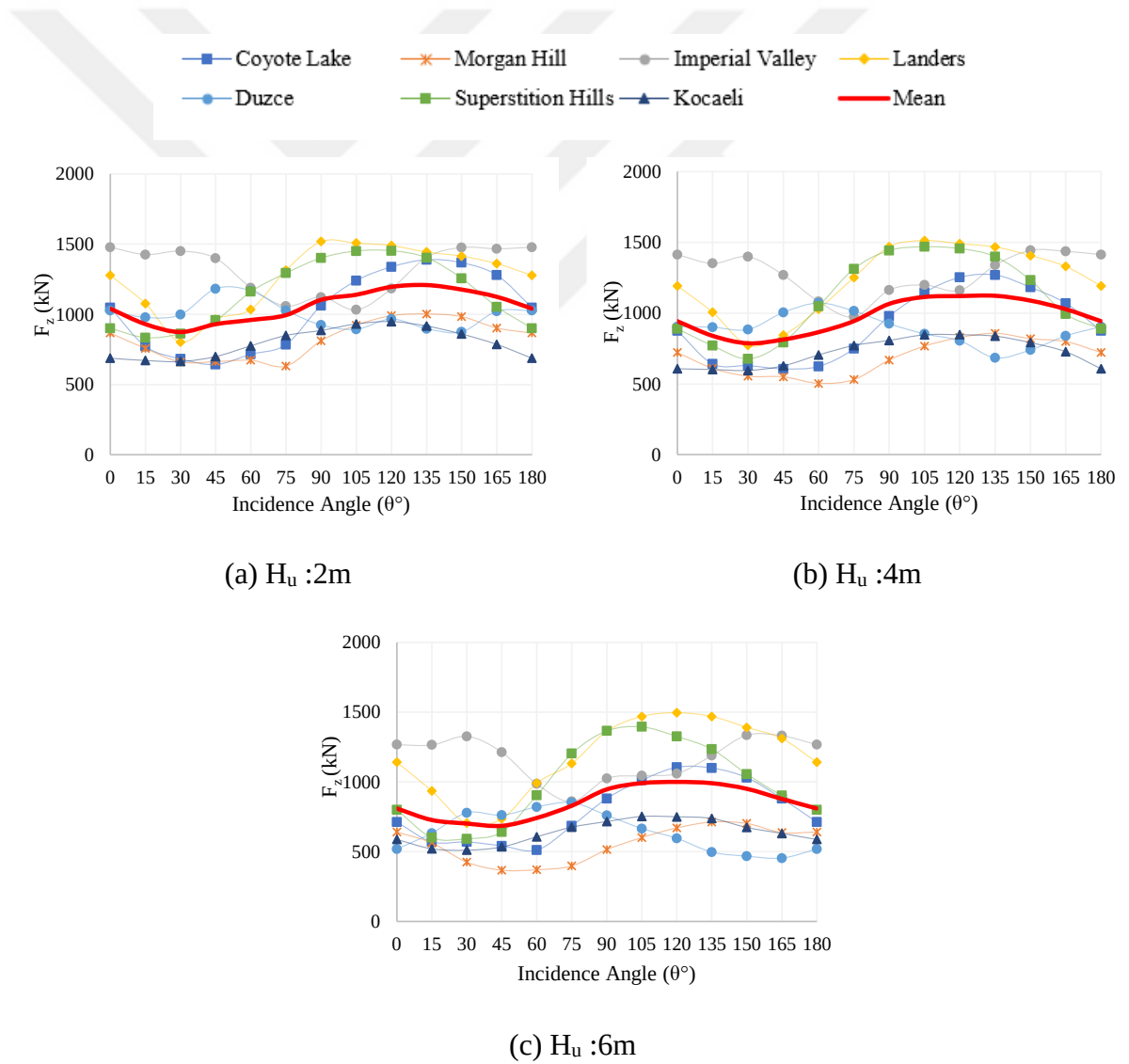


Figure 5.126. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b)

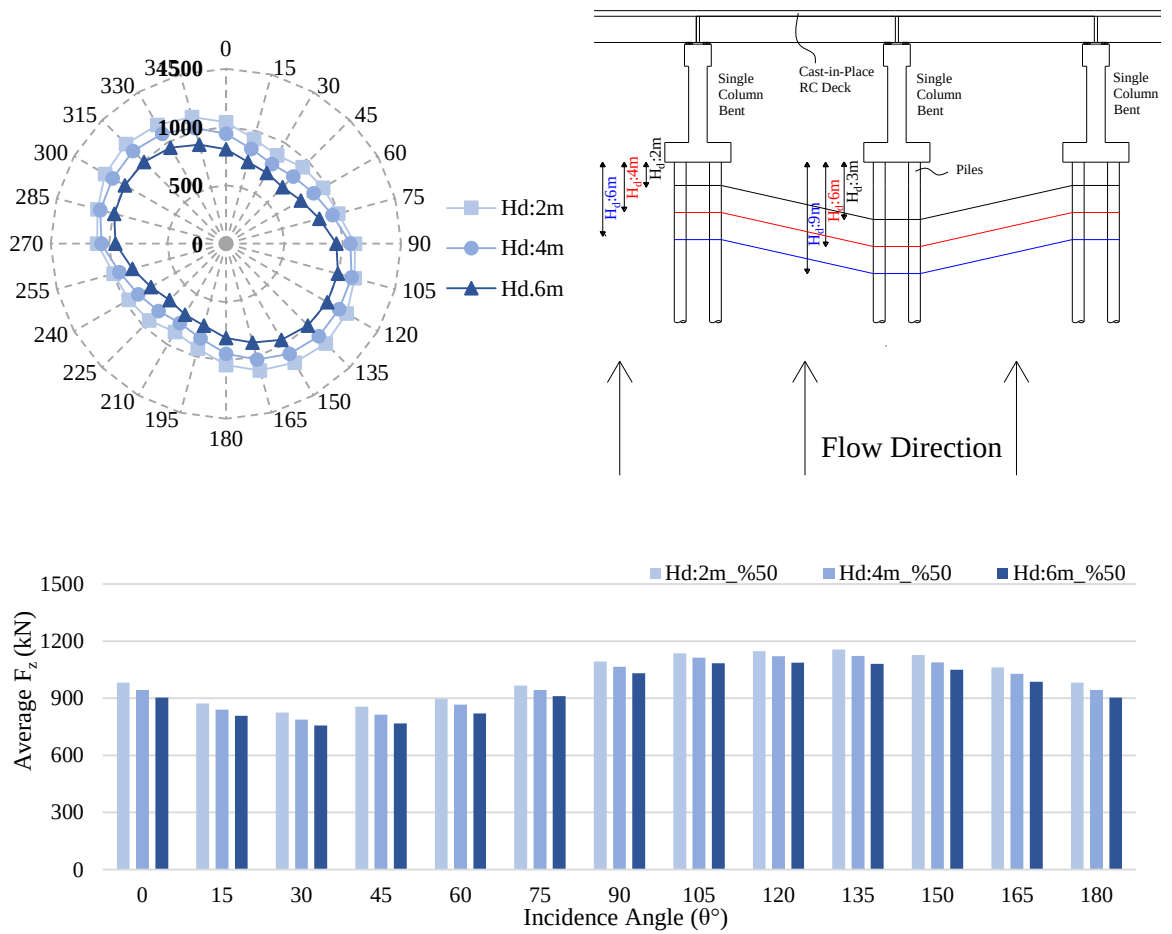


Figure 5.126. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2b) (continued)

In Figure 5.127, maximum shear force demands of column local y' and z' axes of non-skewed and 45° skewed bridges are compared for 3 different scour depths 13 incidence angles. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 150° incidence angle and 4m scour depth as nearly 25.4%. In local z' axis, it is again at 150° and 4m scour depth as 43%.

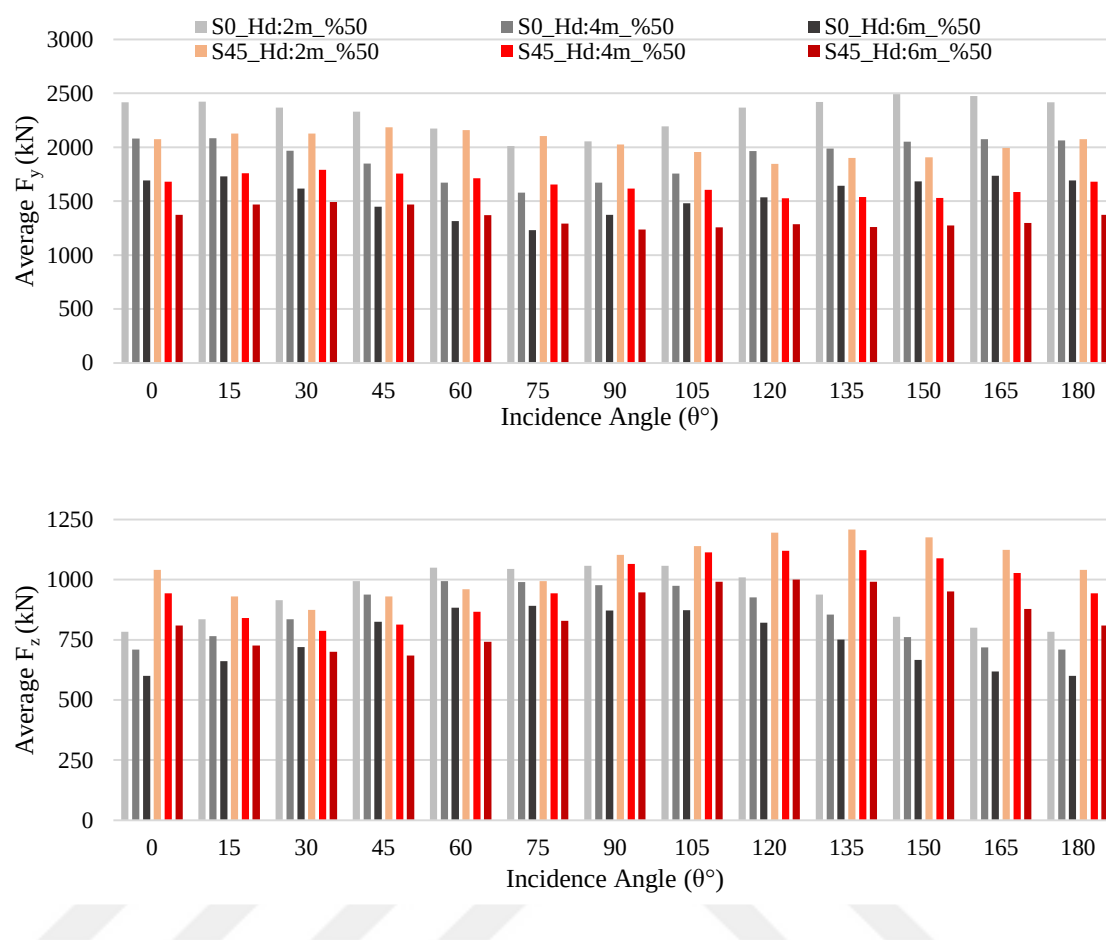


Figure 5.127. Average maximum shear force demands of the non-skewed and 45° skewed bridge when non-uniform scour in longitudinal direction is 50% more around middle piles

5.3.2.4. Shear force demands of piles

In Figure 5.128 and Figure 5.129, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. As it can be seen from the graphs, maximum shear force demands of local y' and z' axes of corner piles are below the pile shear capacity of 735.2 kN and demands are decreasing when scour depth increases in longitudinal direction of bridge. Also, demands are nearly same for all corner piles and they are much higher in local y' axis than z' axis. Therefore, shear force demands of local y' axis of pile number 1 (P1) is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.130. P1 pile shear demand is higher in non-skewed bridge at 2m scour depth than skewed one. For scour depths 4 m and 6 m, shear force demands of pile P1 are nearly same both bridge models.

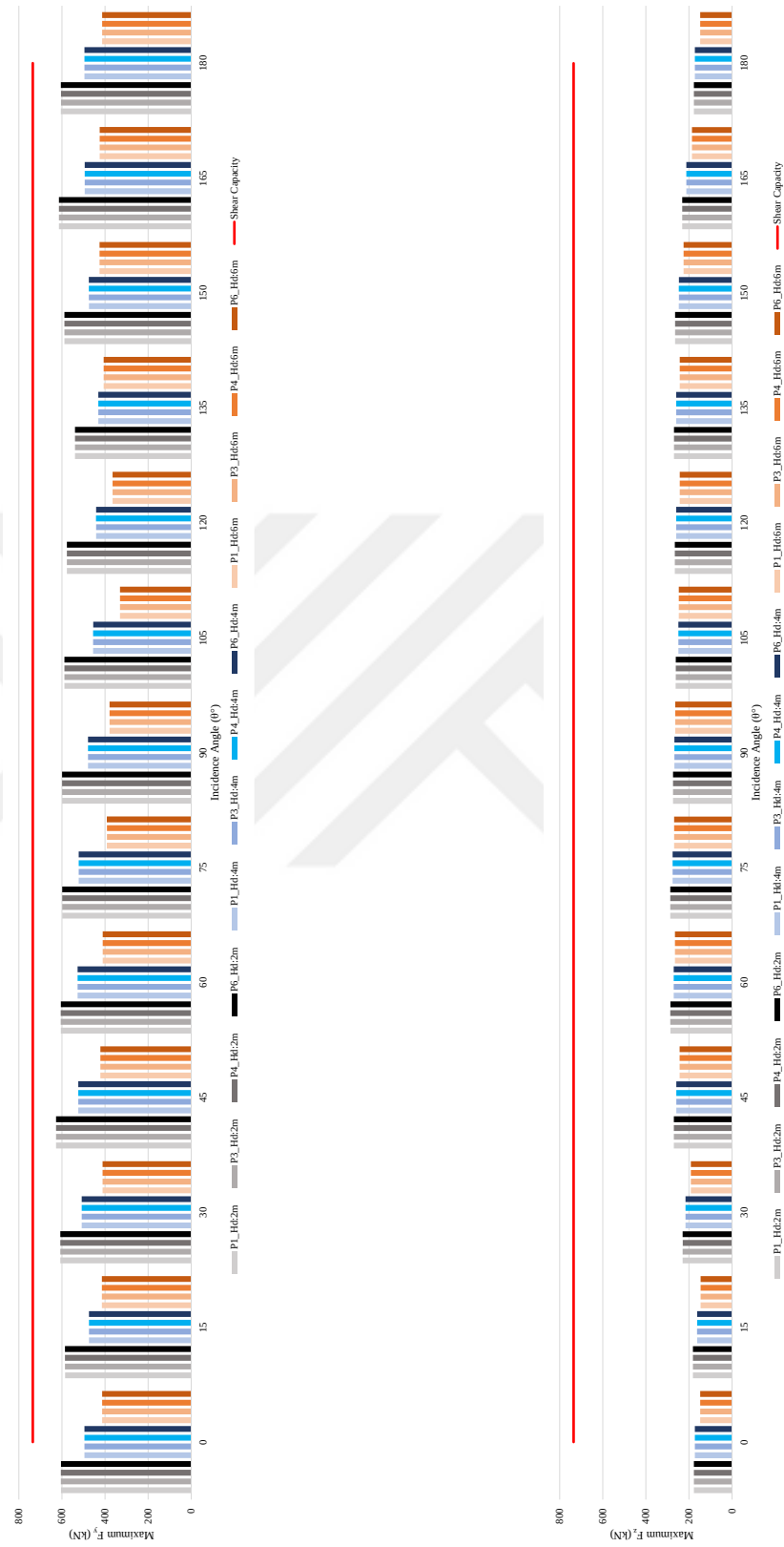


Figure 5.128. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=0^\circ$ non-skewed bridge and Case 2-2b)

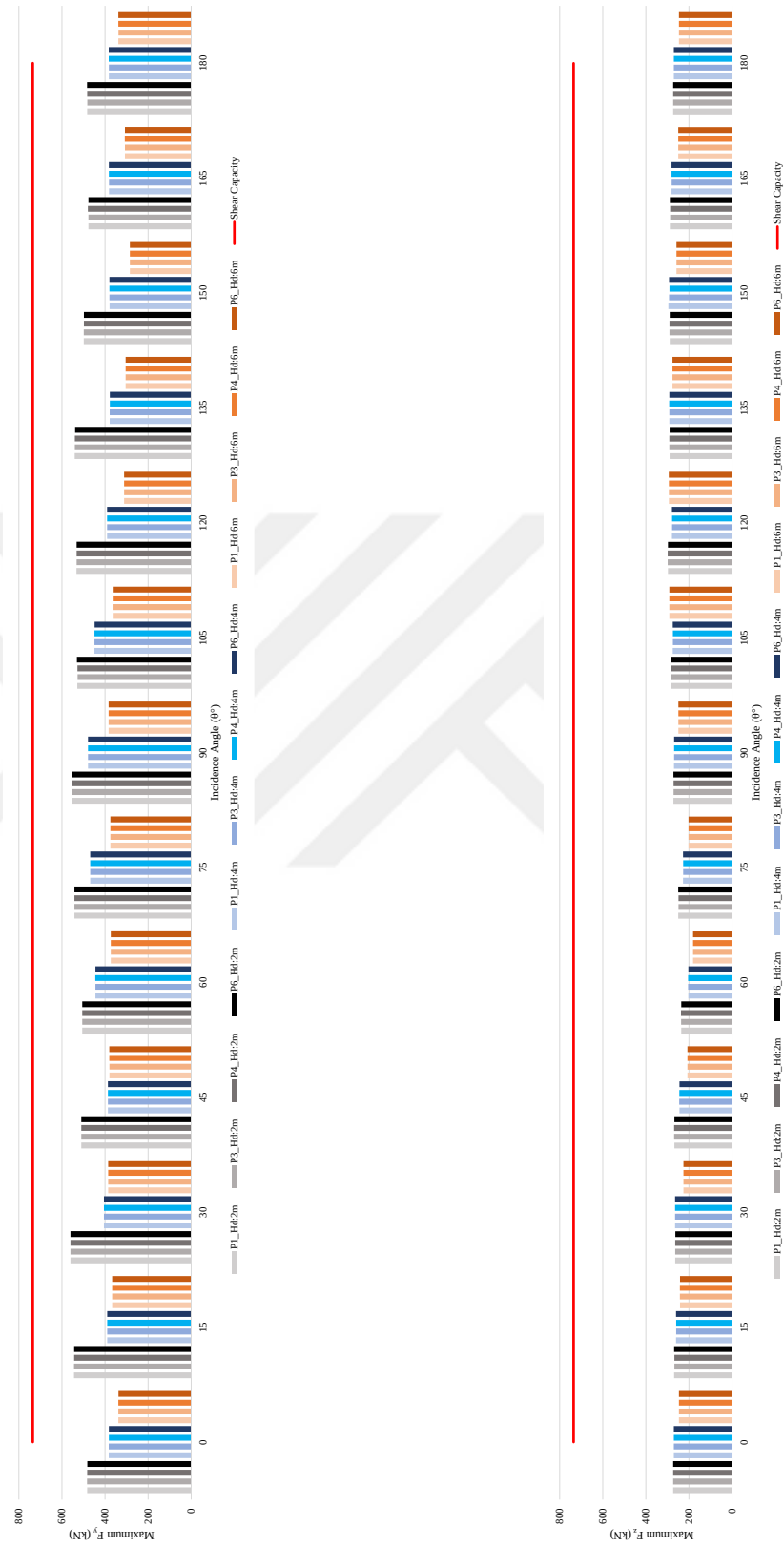


Figure 5.129. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=45^\circ$ skewed bridge and Case 2-2b)

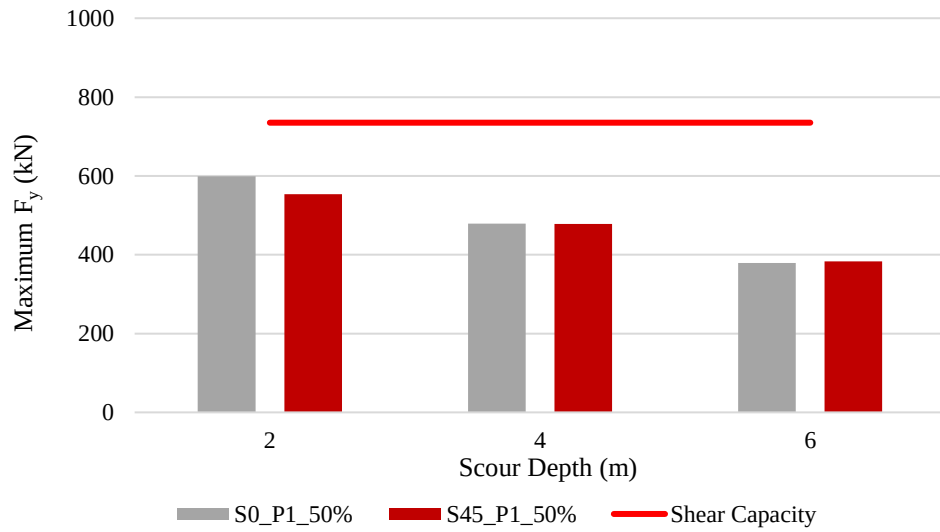


Figure 5.130. Average maximum shear force demands of local y' axis of pile (P1) for non-skewed and 45° skewed bridge when ground motion incidence angle is 90° and non-uniform scour is 50% in longitudinal direction

5.3.2.5. Residual displacements

Residual displacements were calculated for middle column and superstructure by using non-skewed and skewed bridges for non-uniformly changed scour depths in longitudinal direction (%50) and different ground motion incidence angles. In Figure 5.131, the average residual displacement demands of middle column for non-skewed and skewed bridges are given when scour depth is non-uniformly changed. Also, in Figure 5.132, the ratio of residual displacement demand to maximum displacement of middle column for non-skewed and 45° skewed bridge is shown. Furthermore, the same demands are evaluated for the superstructure and shown in Figure 5.133 and Figure 5.134, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal and transverse direction for both middle column and superstructure of bridge.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when non-uniform scour depth is 6m at 75° incidence angle for non-skewed bridge as 23.9mm. In transverse direction it is maximum at 75° incidence angle and 6m scour depth as 7.5mm for non-skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 6m scour depth as 0.19 in

longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.1 at 6m scour depth when incidence angle 60° in transverse direction of non-skewed bridge.

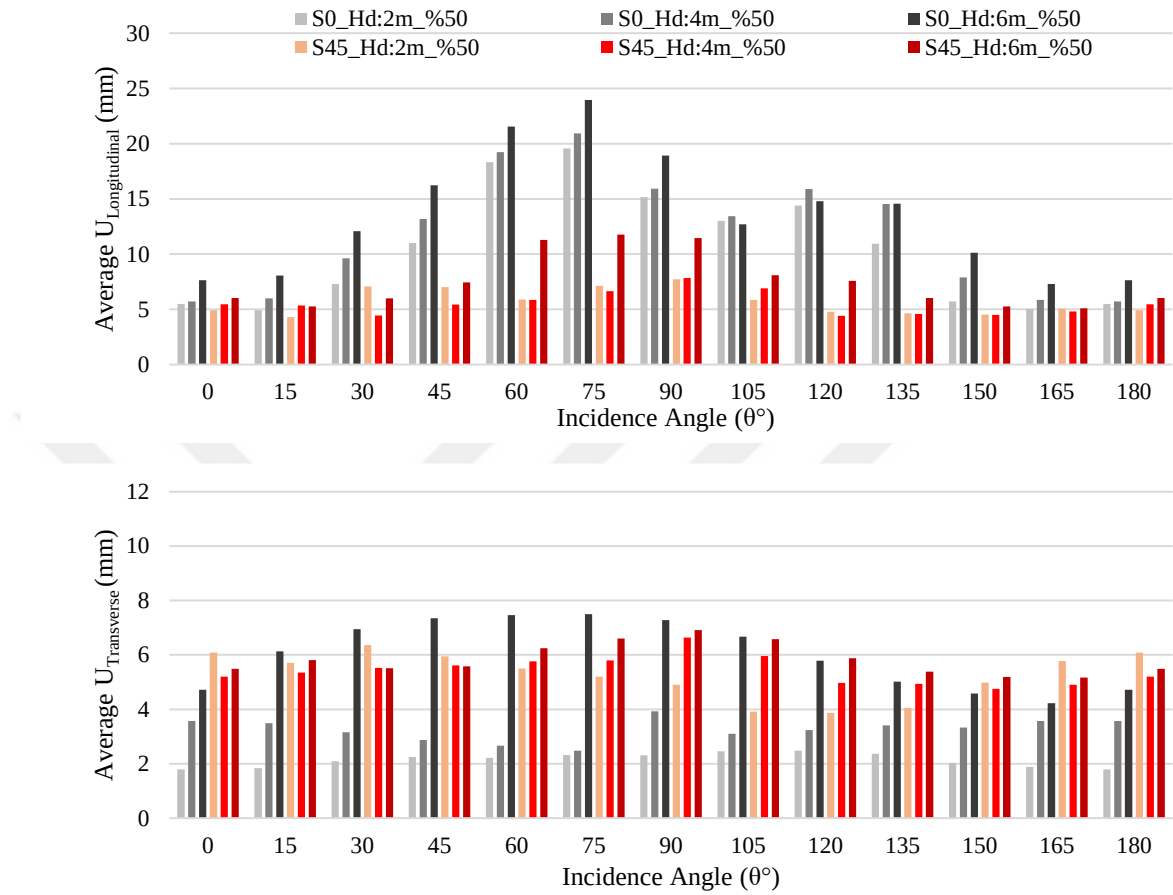


Figure 5.131. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2b)

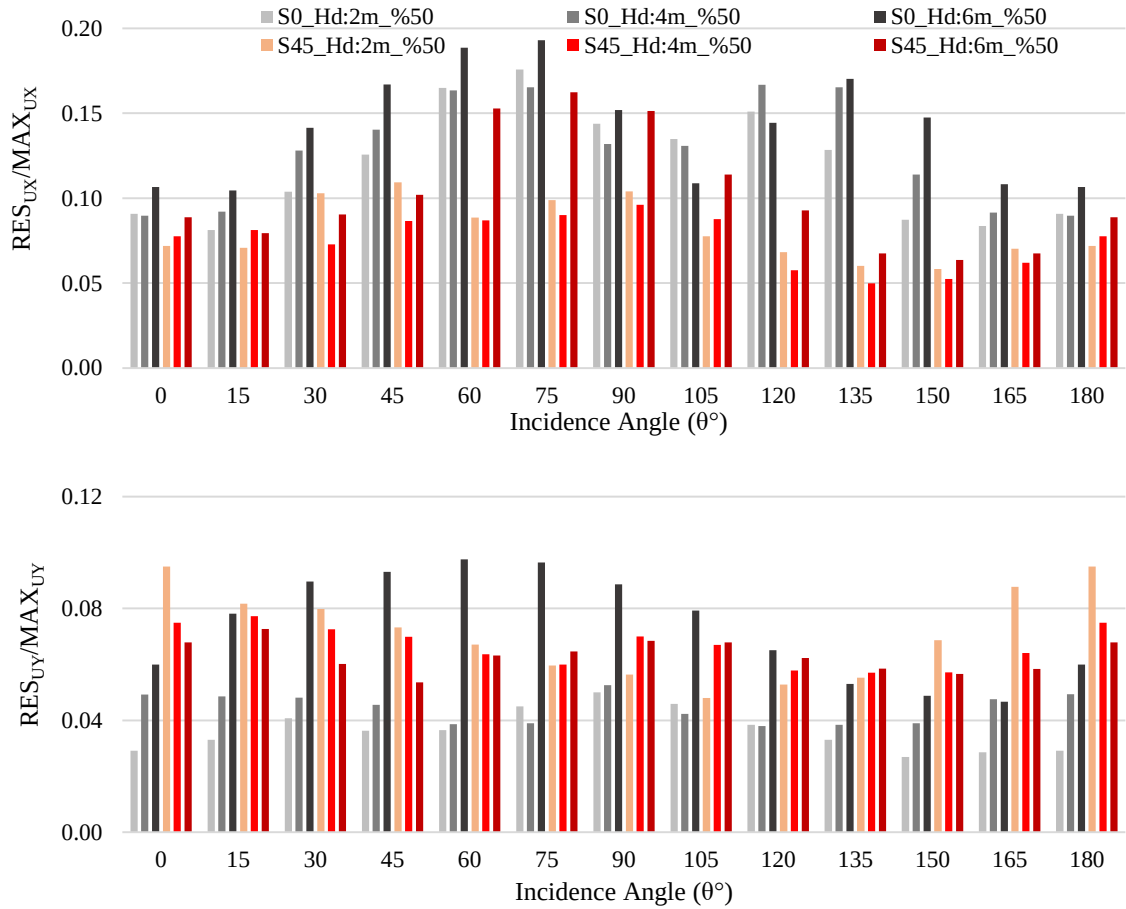


Figure 5.132. The ratio of residual displacement demand to maximum displacement of middle for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2b)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when non-uniform scour depth in longitudinal direction (%50) is 6m at 75° incidence angle for non-skewed bridge as 28.5mm. In transverse direction it is maximum at 75° incidence angle and 6m scour depth as 9.5mm for non-skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 75° and 6m scour depth as 0.19 in longitudinal direction of non-skewed bridge. Also, the maximum ratio occurs at the same scour depth and incidence angle as 0.11 in transverse direction of non-skewed bridge.

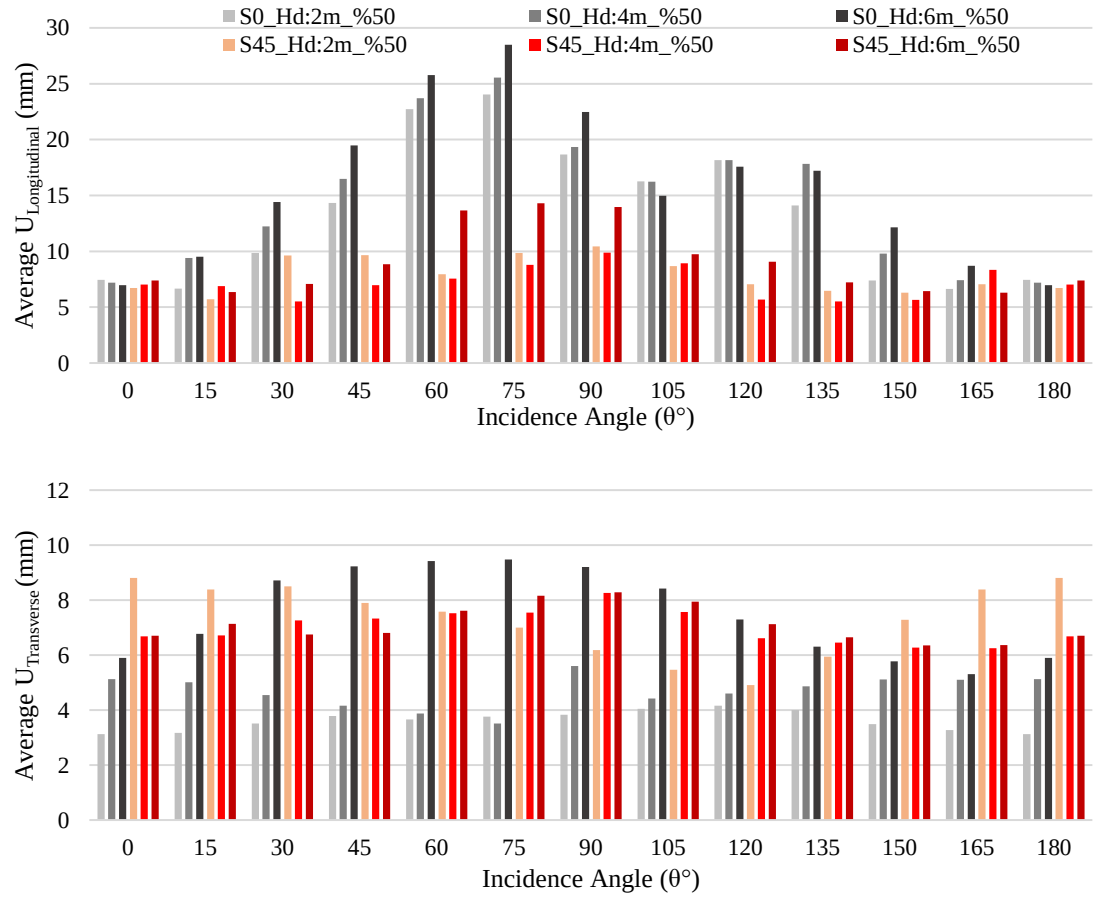


Figure 5.133. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2b)

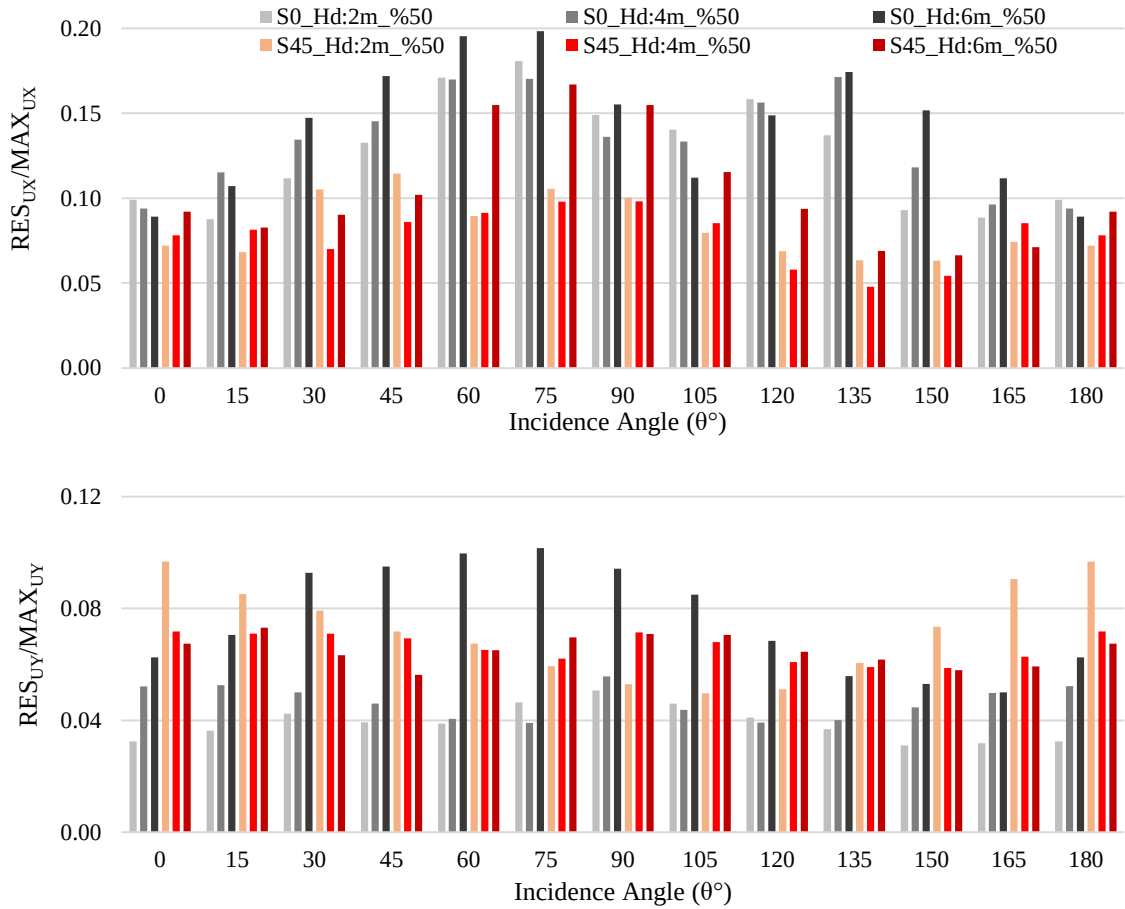


Figure 5.134. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2b)

5.3.3. Non-uniform scour in longitudinal direction of bridge when scour is 75% more around middle piles (Case 2-2c)

In this part of thesis, non-uniform scoured bridge models in longitudinal direction are constructed by taking the scour depth 75% more around middle piles than side piles. Scour depth is changed as 2m, 4m and 6m (H_d). This means, when scour around side piles is 2 m, the scour around middle piles become 75% more and calculated as 3.5 m. Nonlinear response history analysis is done by using 7 strong ground motions for non-skewed and skewed bridge model for each scour depth. Also ground motion incidence angle is rotated starting from 0° to 180° with an increment of 15° . The engineering demand parameters (EDPs) examined within the scope of the study are superstructure displacement bent column curvature and shear, pile shear, residual displacements of middle column and superstructure. The demands obtained from nonlinear analysis results are given below.

In Figure 5.135, the variation of 1st and 2nd vibration period of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge depending on non-uniform scour depth in longitudinal direction is given when scour is 75% more around middle piles (Case 2-2c) and the vibration period of the bridge increases when scour depth increases. For skewed bridges the first period is greater than the non-skewed bridges for all scour depths. On the other hand, the second period becomes higher in non-skewed bridge than skewed one.

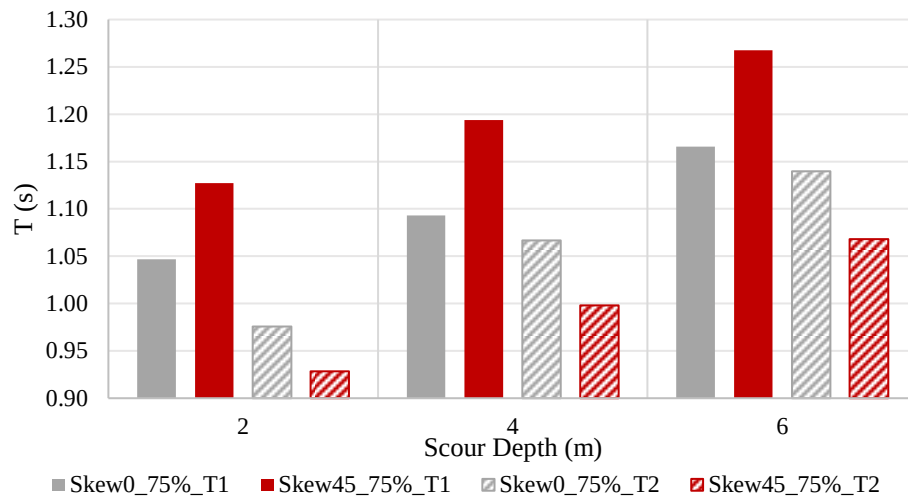


Figure 5.135. The variation of 1st and 2nd vibration period of non-skewed (0°) and skewed (45°) bridge depending on non-uniform scour depth in longitudinal direction when scour is 75% more around middle piles (Case 2-2c)

5.3.3.1. Superstructure displacement

Superstructure displacement demands obtained from nonlinear analysis results belong to midpoint of bridge deck as mentioned above. In Figure 5.136 and Figure 5.137, maximum displacement demands in longitudinal and transverse direction of non-skewed ($\alpha=0^\circ$) bridge are given. Also, Figure 5.138 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. When the results examined in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 90° although in transverse direction it is decreasing between that angles. Therefore, resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts,

average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in both directions is more obvious in some ground motion incidence angles. The maximum difference of average displacement demands in longitudinal direction between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 90° incidence angle as nearly 11.2%. In transverse direction, it is at 165° incidence angle as 25.9%. If it is checked for resultant displacement, maximum difference becomes 20.4% again at 165° incidence angle.

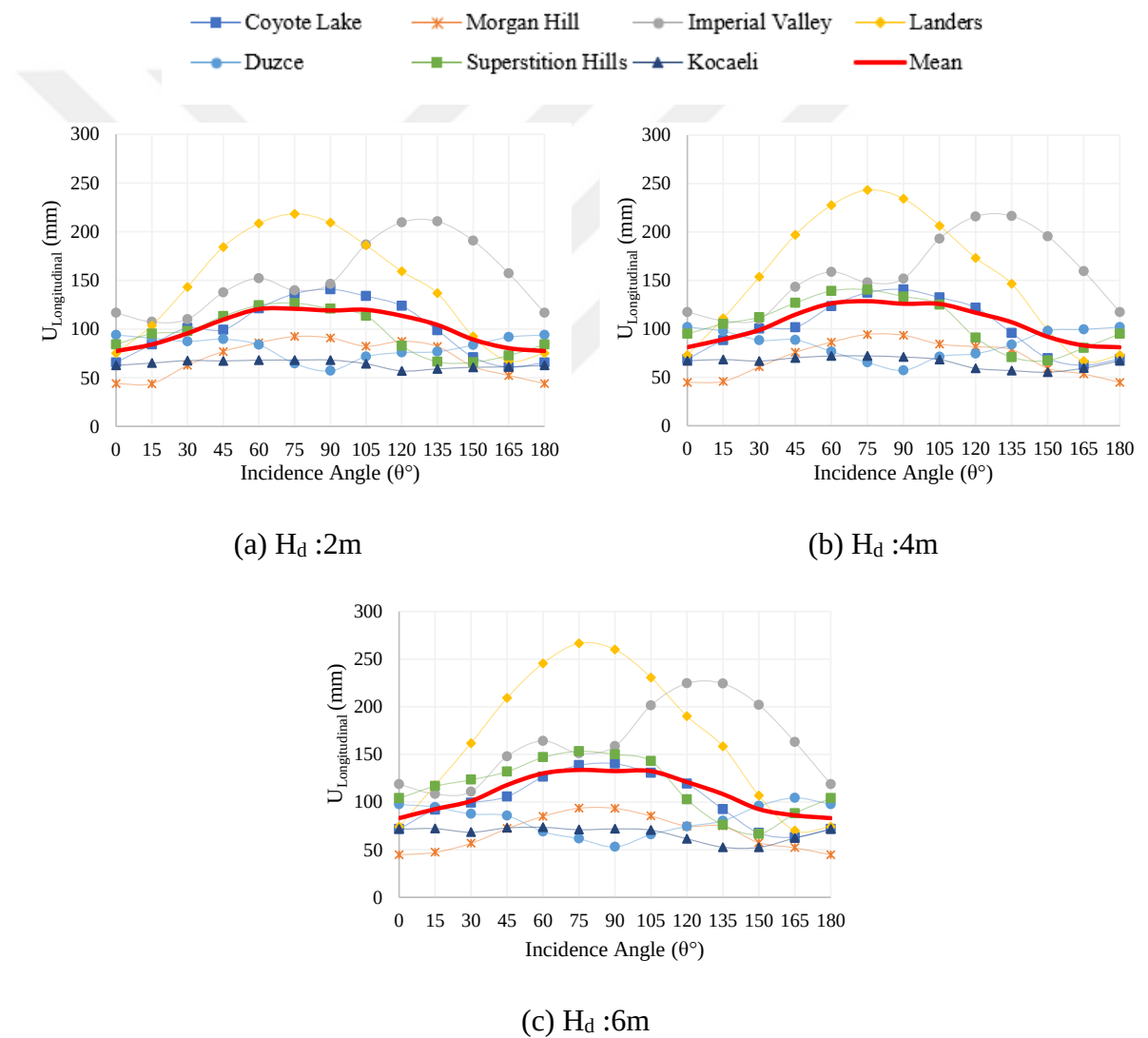


Figure 5.136. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

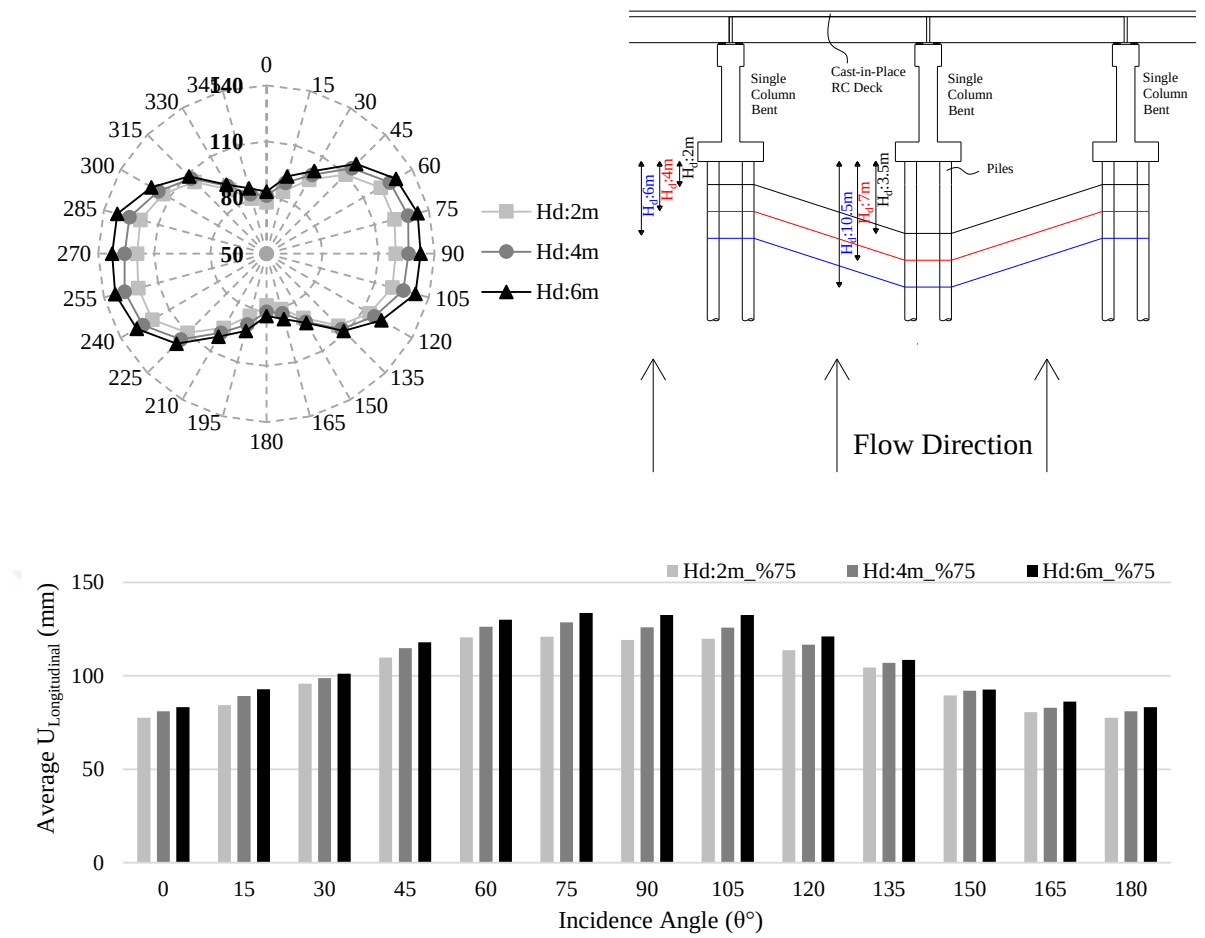


Figure 5.136. Maximum displacement demands occurred in longitudinal direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

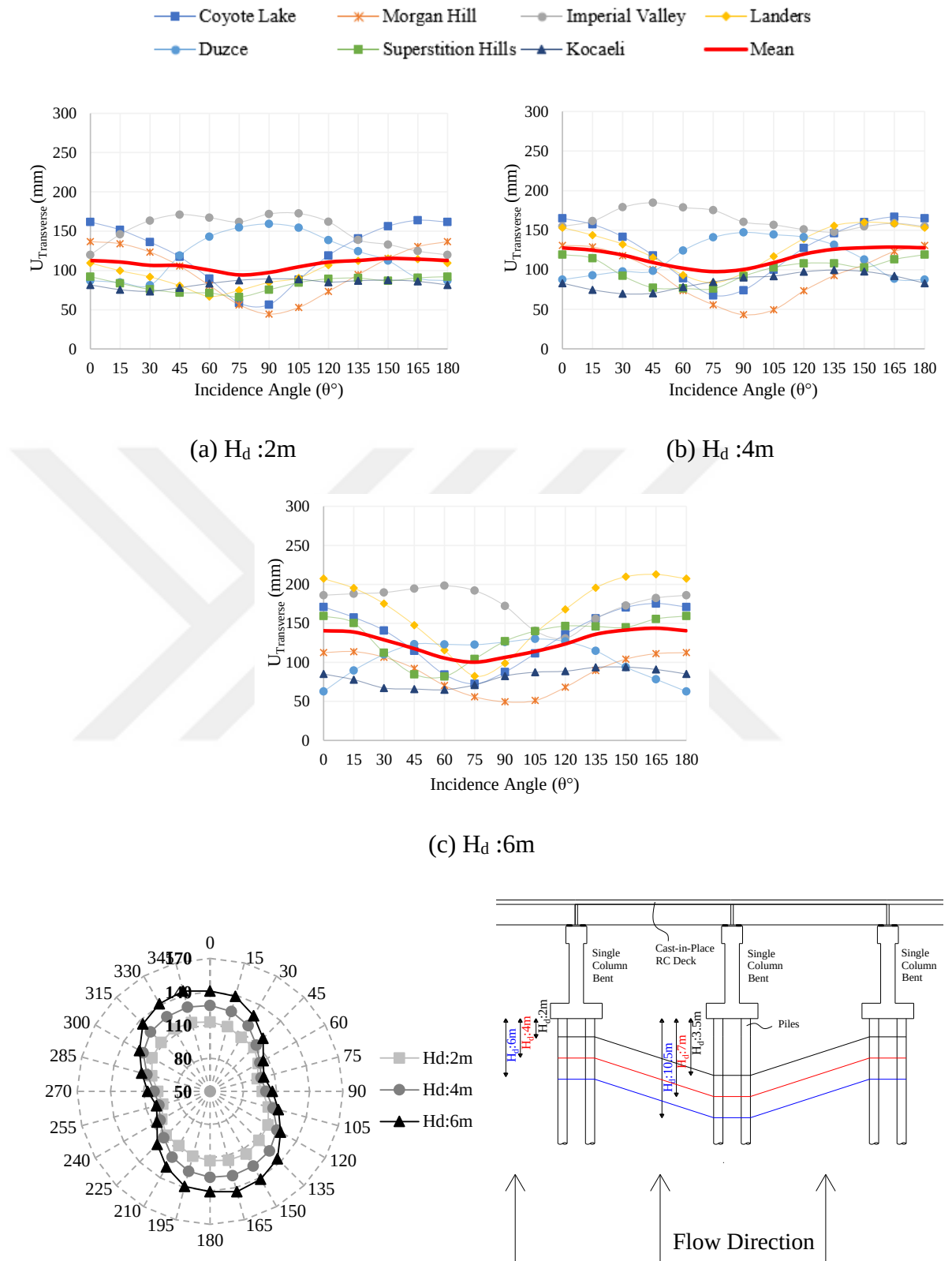


Figure 5.137. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

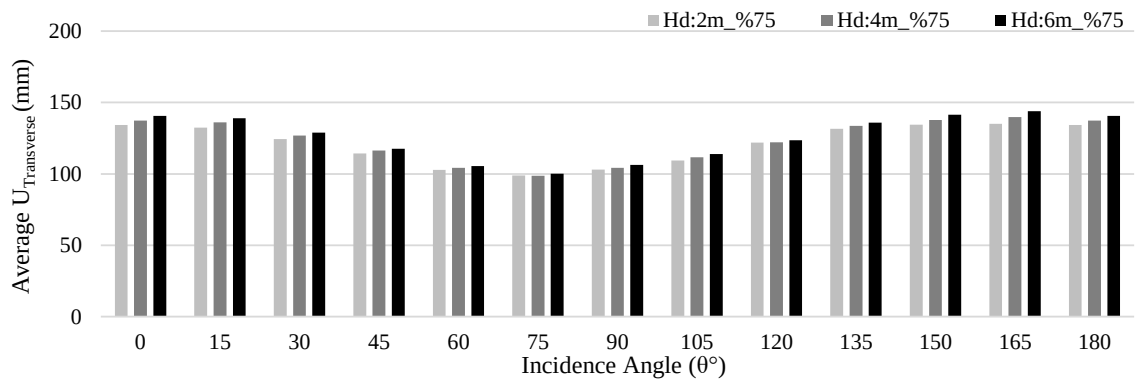


Figure 5.137. Maximum displacement demands occurred in transverse direction of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

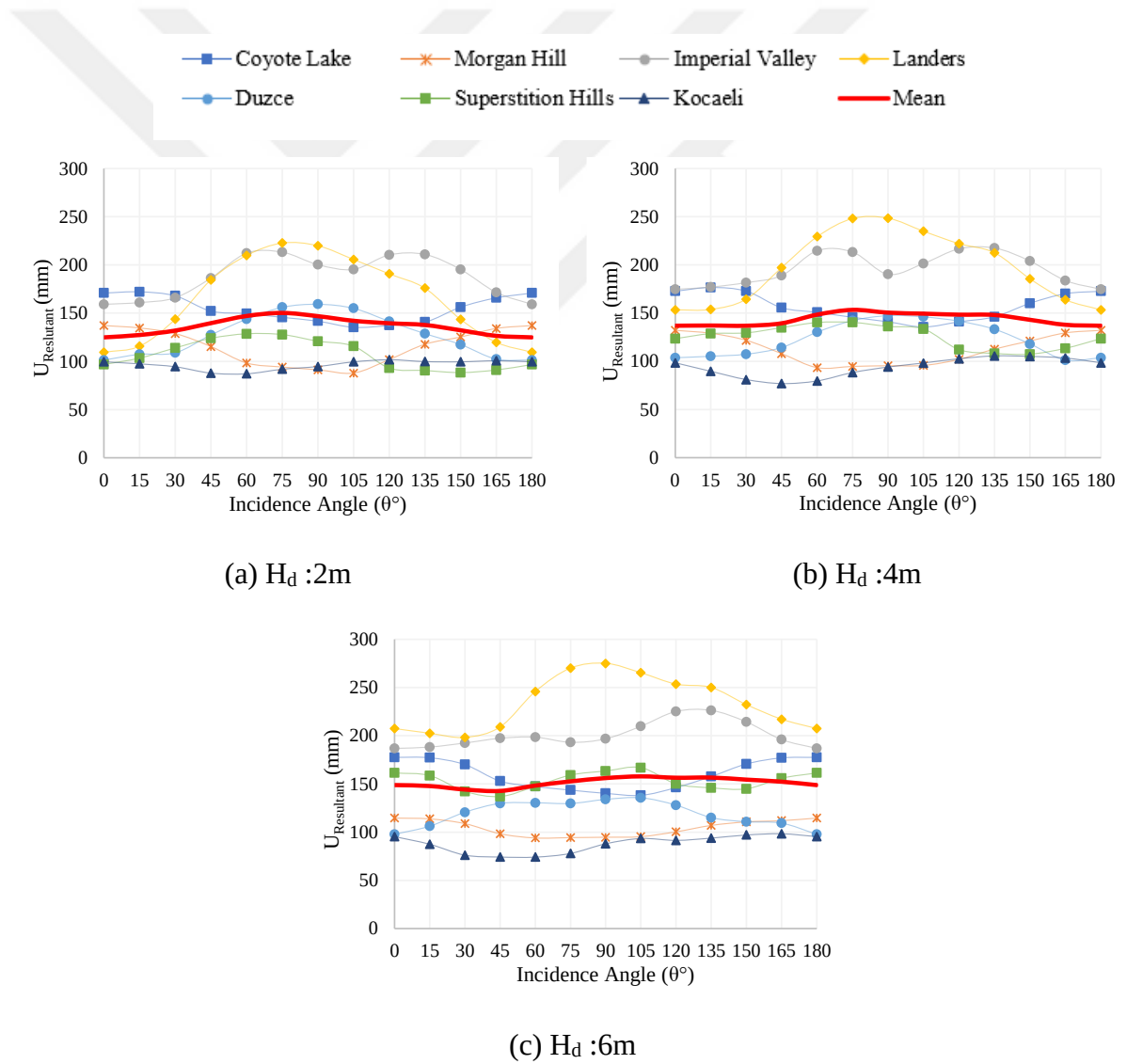


Figure 5.138. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

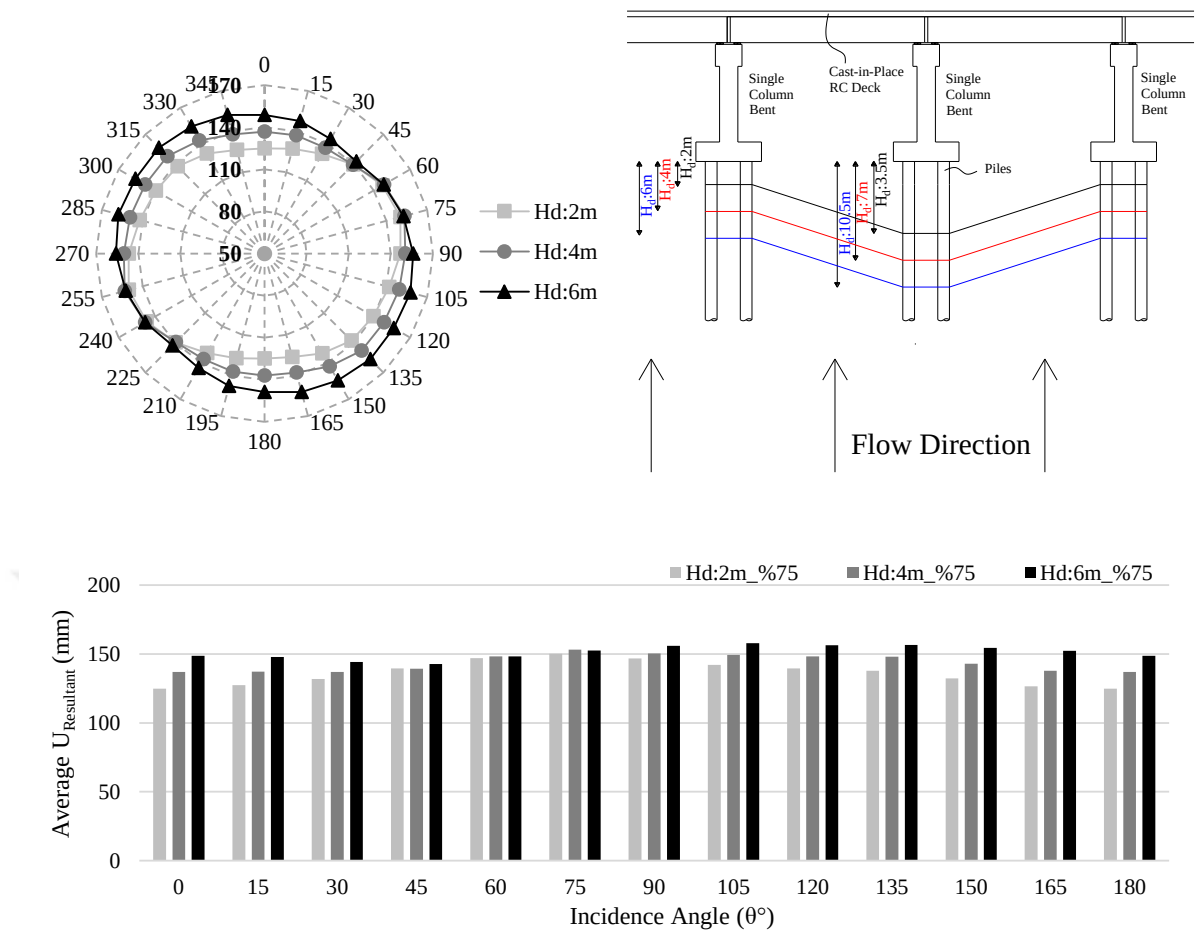


Figure 5.138. Maximum resultant displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

In Figure 5.139 and Figure 5.140, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge are given. Also, Figure 5.141 shows maximum resultant displacement that is calculated by taking the maximum of square root of sum of squares of these directions. The results are obtained for 7 earthquakes and 13 ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° . When the results assessed in terms of change of earthquake incidence angle, average maximum displacement in longitudinal direction of bridge shown with red line has an increasing trend between 0° and 105° although in transverse direction it is decreasing between 0° and 75° . The resultant displacement is not affected much from the change of ground motion incidence angle. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of displacement in transverse direction of bridge is more obvious in some ground motion incidence angles.

The maximum difference of average displacement demands in longitudinal direction between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 60° incidence angle as nearly 10.8%. In transverse direction, it is at 0° as 18.9%. If it is checked for resultant displacement, maximum difference becomes 16.1% at 15° incidence angle.

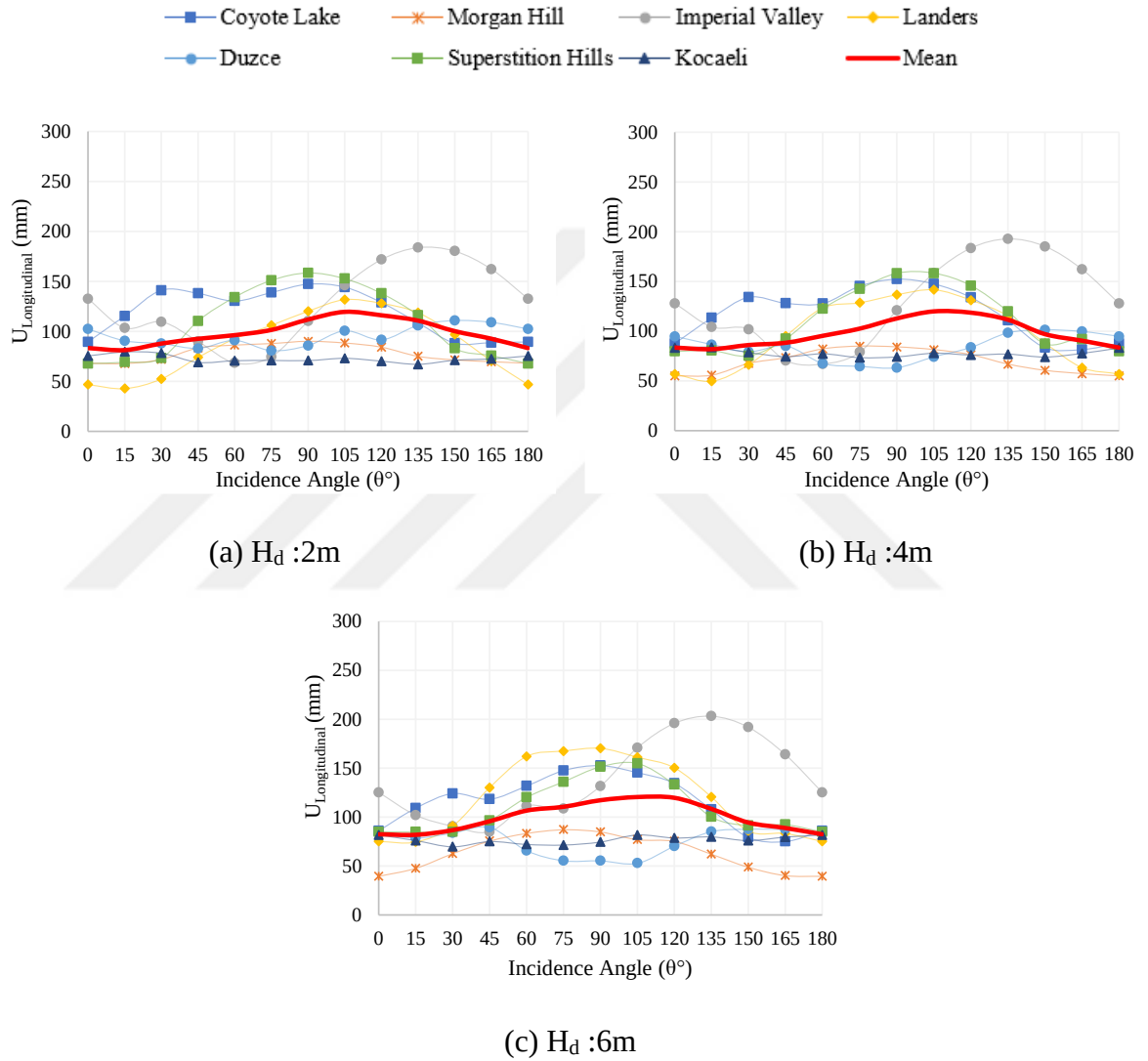


Figure 5.139. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

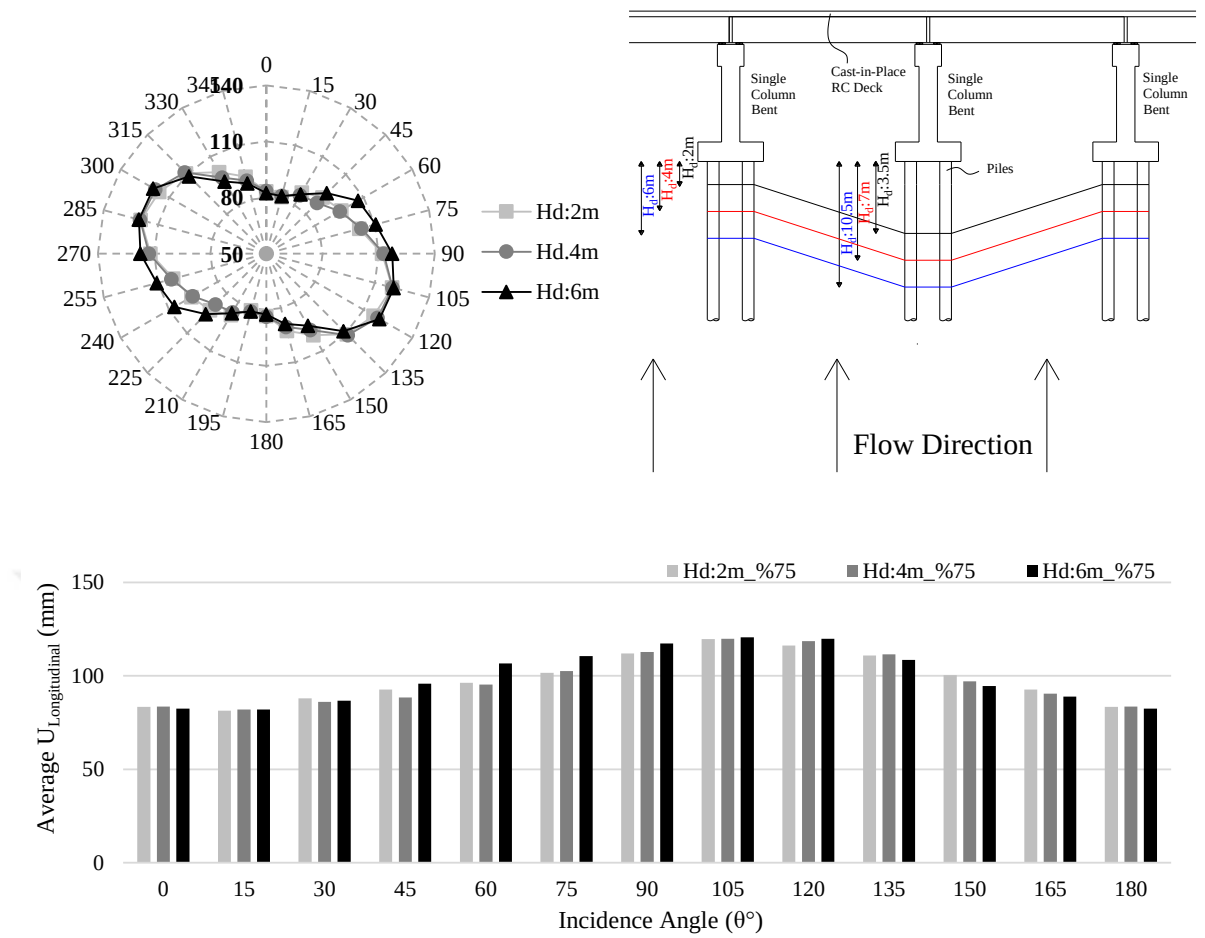


Figure 5.139. Maximum displacement demands occurred in longitudinal direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

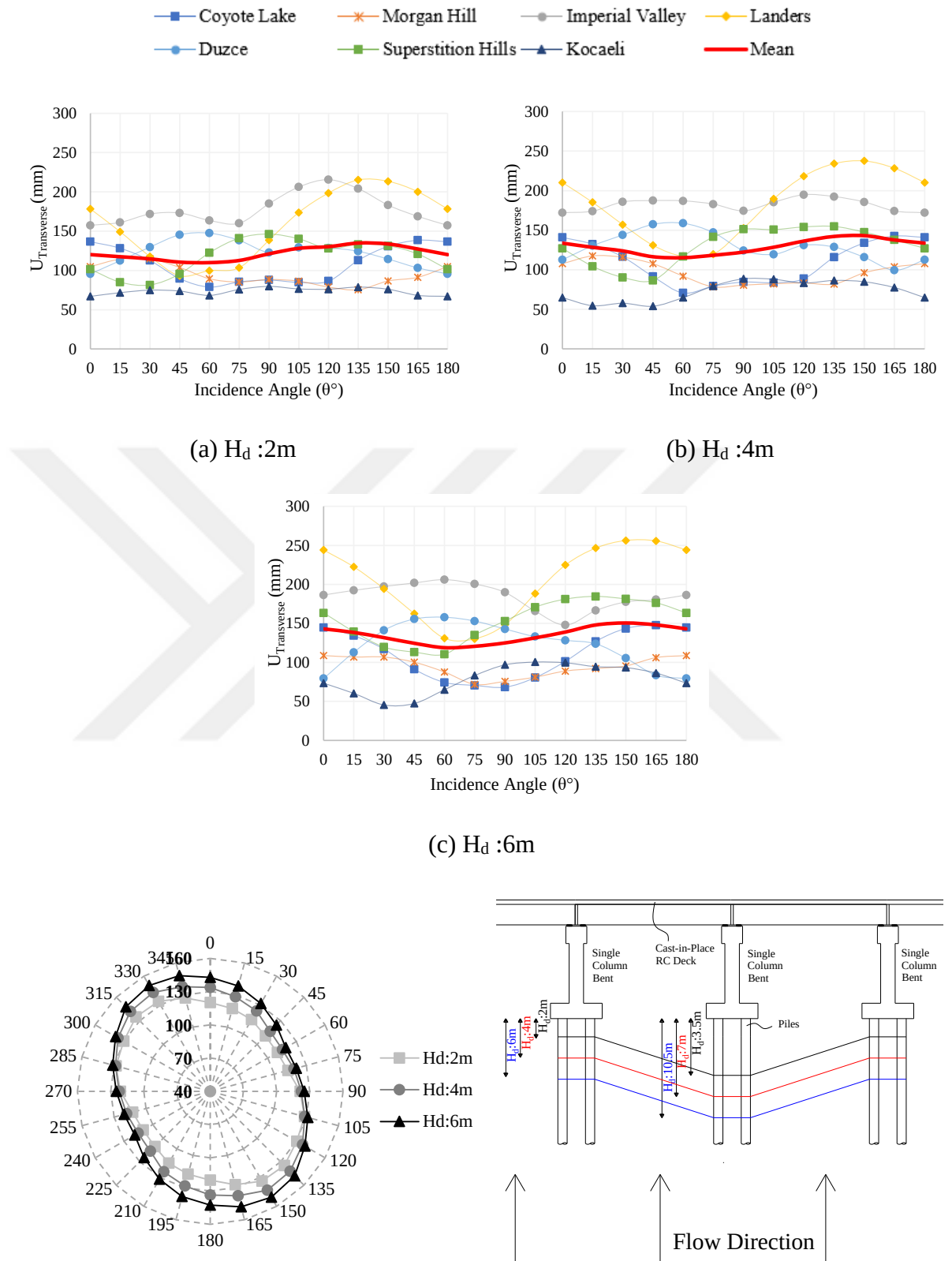


Figure 5.140. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

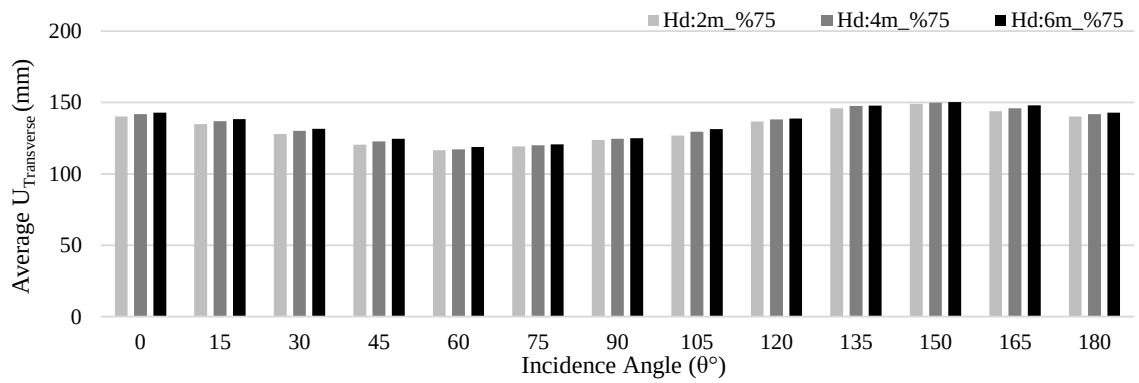


Figure 5.140. Maximum displacement demands occurred in transverse direction of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

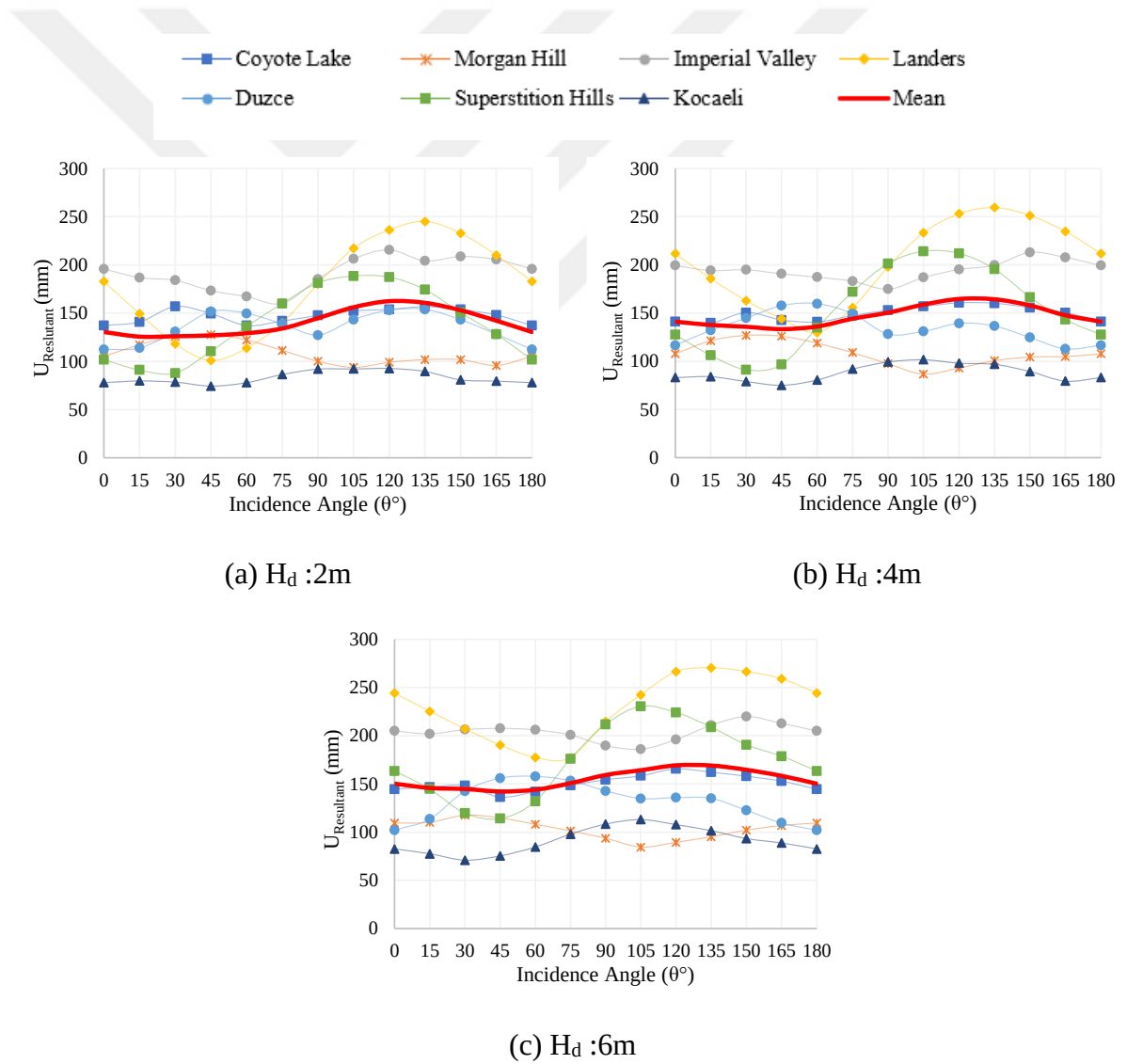


Figure 5.141. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

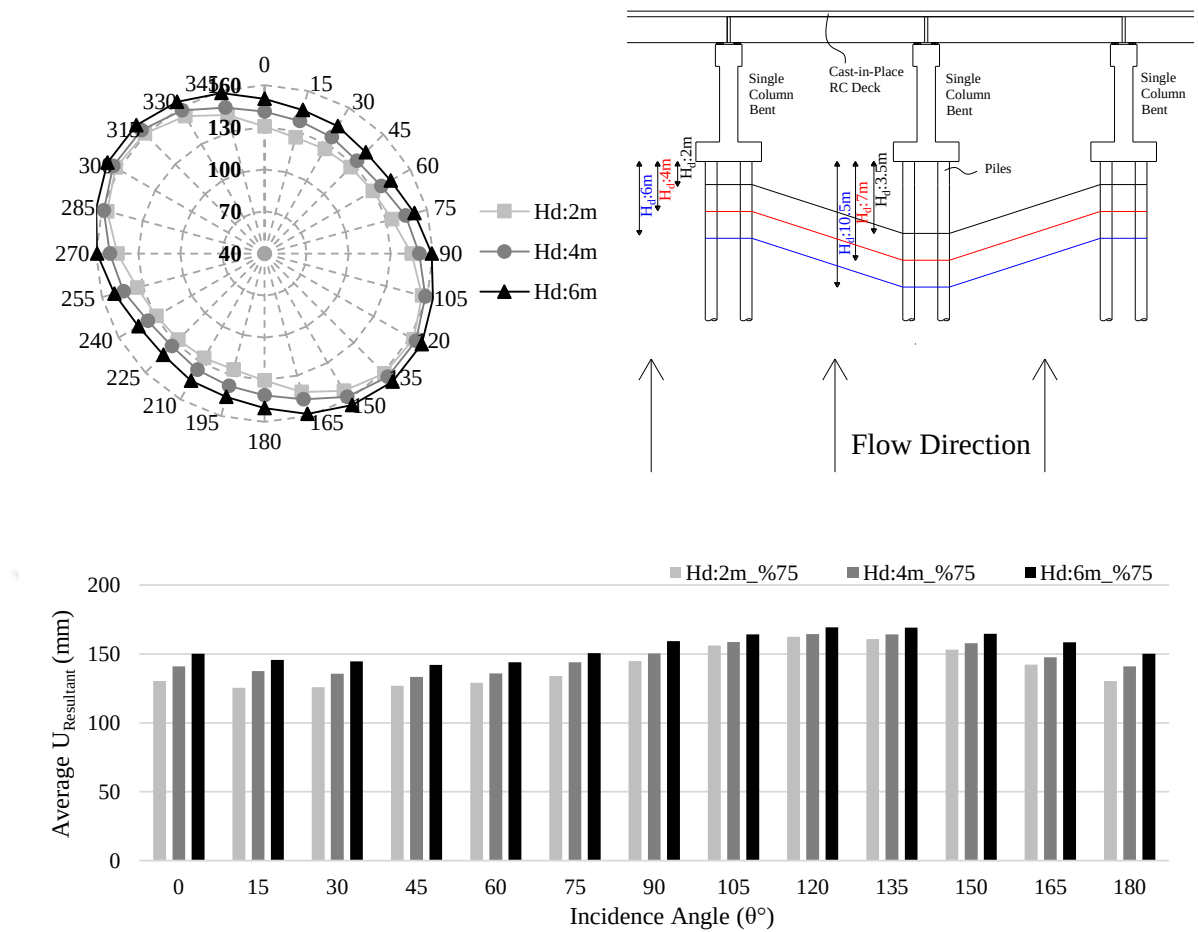


Figure 5.141. Maximum resultant displacement demands of 45° skewed bridge for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

Furthermore, in Figure 5.142, maximum displacement demands in longitudinal and transverse direction of the non-skewed ($\alpha=0^\circ$) and 45° skewed bridges and resultant displacements are compared. The results are obtained for 7 earthquakes and average of maximum demands are calculated for each ground motion incidence angles and scour depths.

In longitudinal direction, superstructure displacement demands are higher in non-skewed bridge especially between 15° and 105° incidence angles. On the other hand, this situation is vice versa in transverse direction. For both skewed and non-skewed bridges, displacement demands are increasing with an increase in scour depth. The maximum difference of average displacement demands in longitudinal direction between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 60° incidence angle and 4m scour depth as nearly 24.4%. In transverse direction, it is at 90° and 2m scour depth as

24.5%. If it is checked for resultant displacement, maximum difference becomes 16.8% at 135° incidence angle and 2m scour depth.

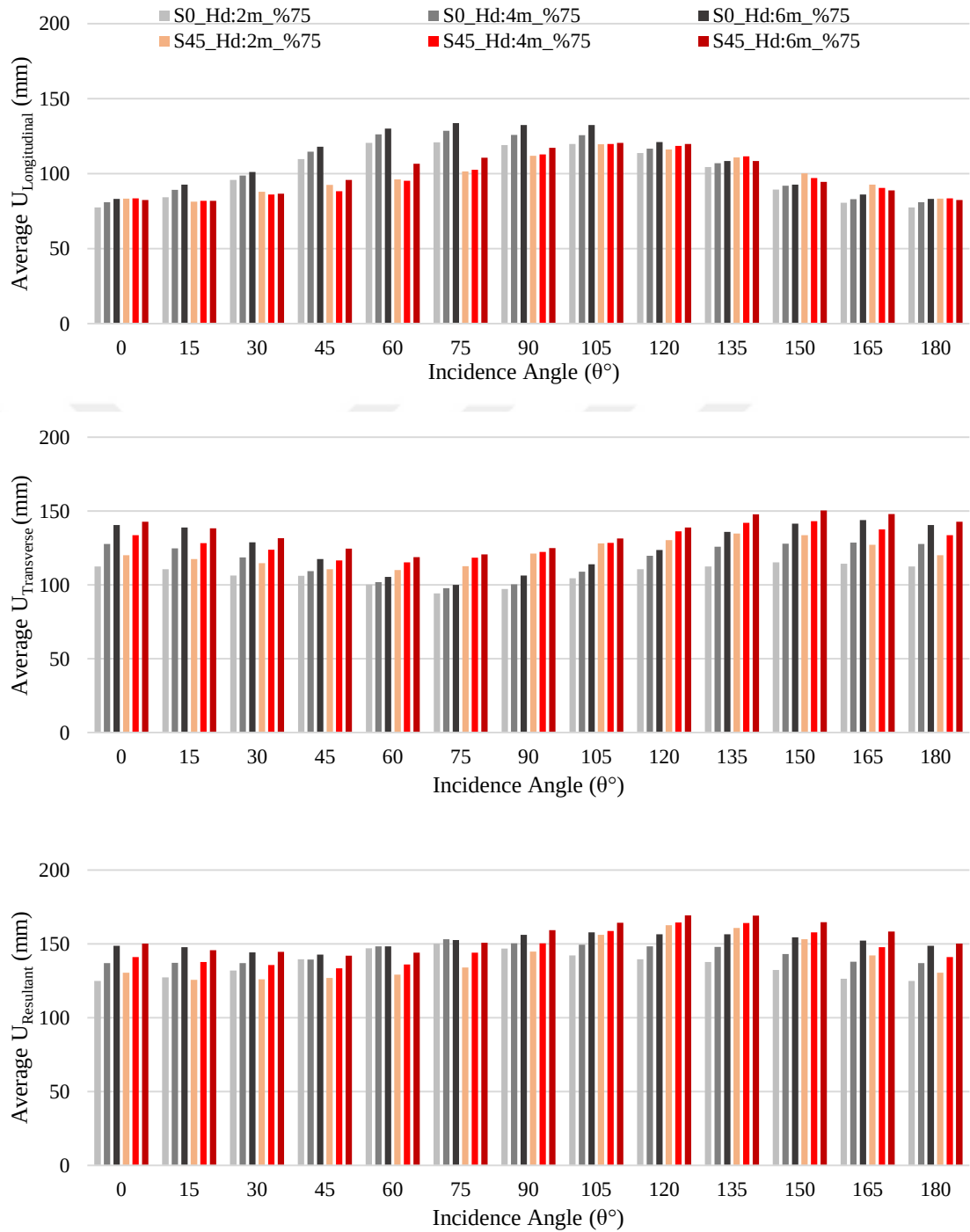


Figure 5.142. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 75% more around middle piles

5.3.3.2. Curvature demands of column pier

In Figure 5.143 and Figure 5.144, maximum curvature demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 0° to 75° in weak axis (y'). In strong axis (z'), it has an increasing trend between 45° and 120° incidence angles. When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. In addition, while the curvature demands on both axes of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. This shows that earthquake incidence angle should be taken into consideration in order to obtain maximum demands in nonlinear response history analyses. Especially when scour depth in longitudinal direction of bridge becomes 2 m, the curvature demands exceed the yield curvature for various incidence angles in both axes of column. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 120° incidence angle as nearly 65.1%. Also, in strong axis (z'), it becomes 77.6% at 60° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of non-skewed ($\alpha=0^\circ$) bridge column piers.

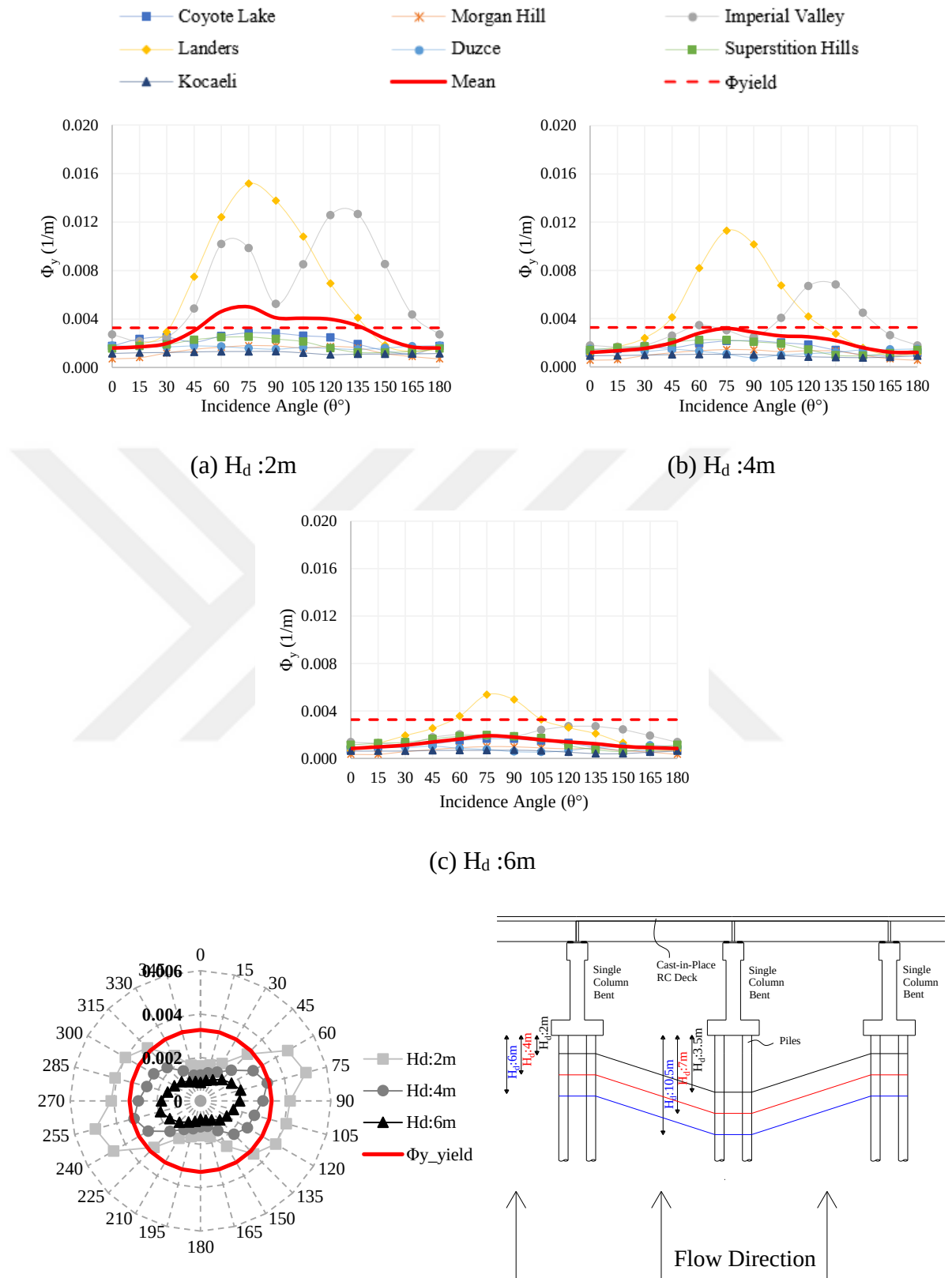


Figure 5.143. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

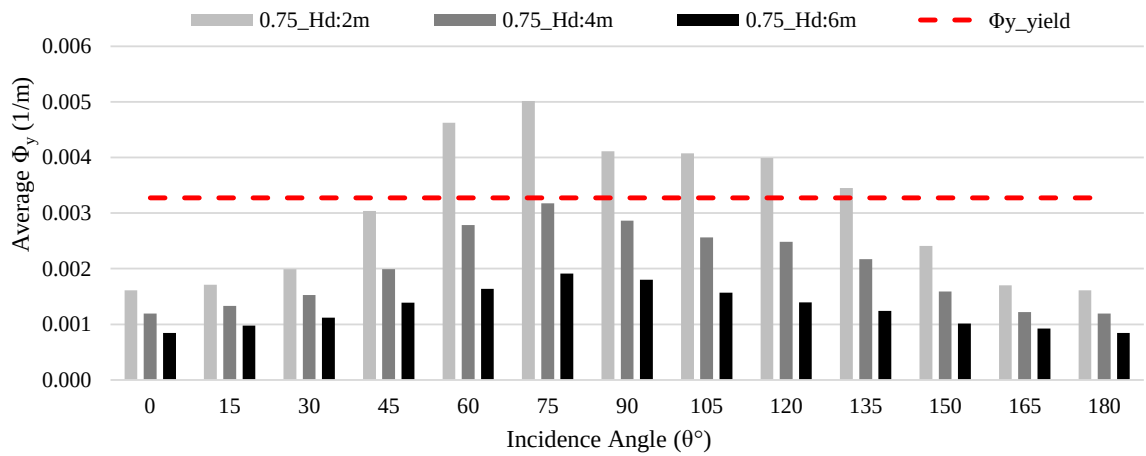


Figure 5.143. Maximum curvature demands in weak axis (y') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

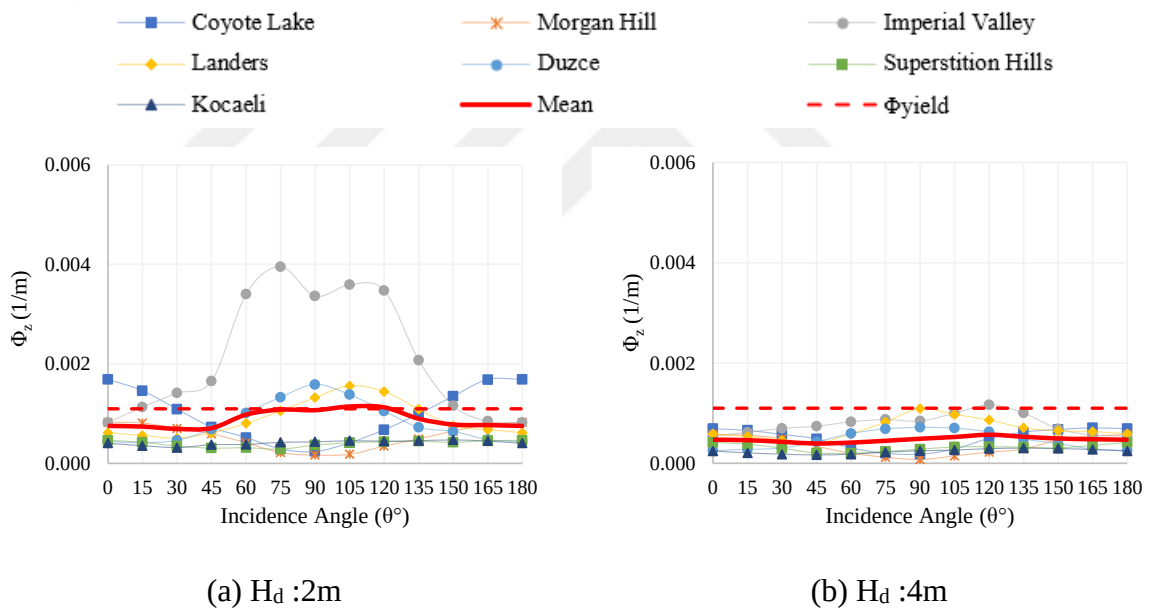


Figure 5.144. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

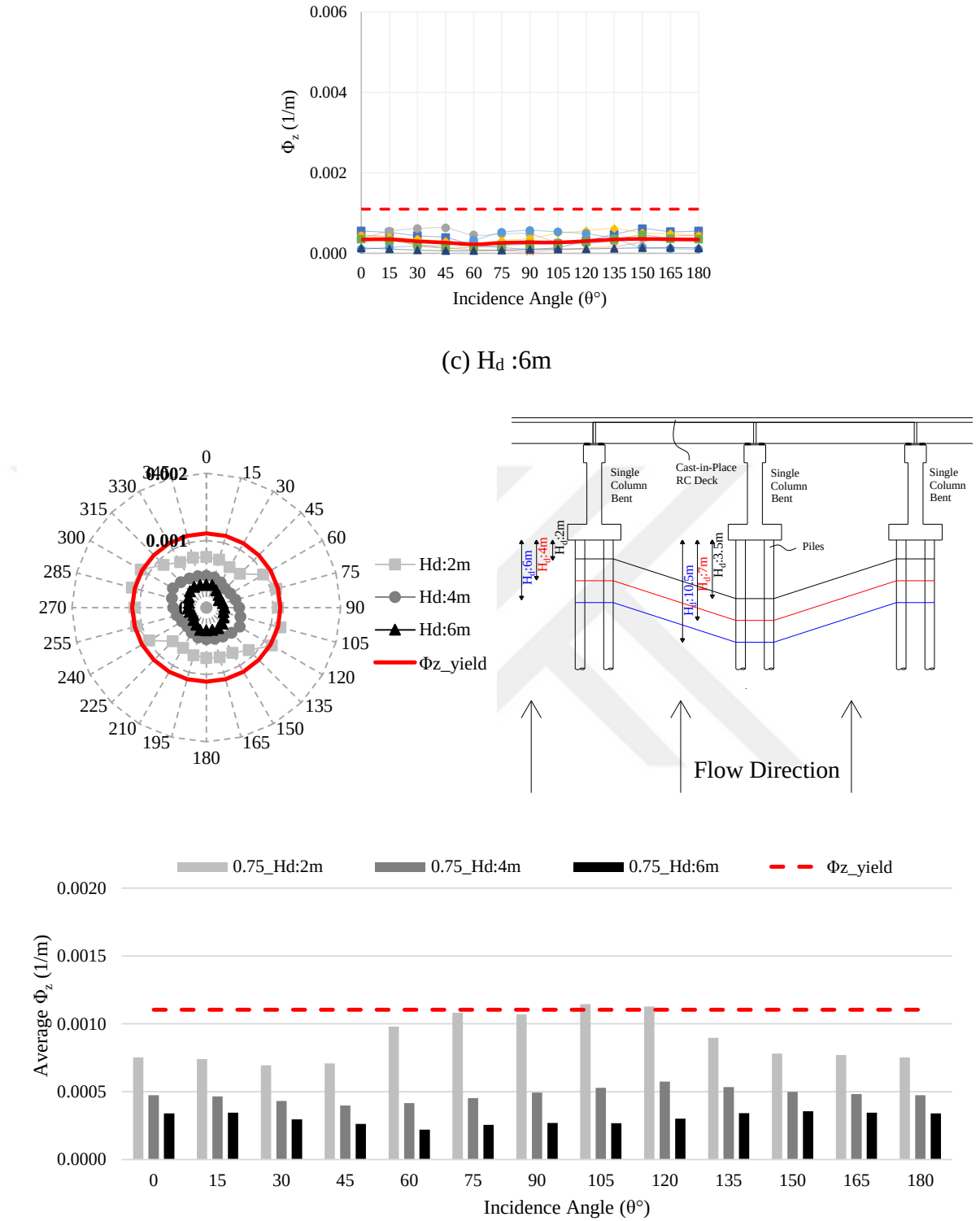


Figure 5.144. Maximum curvature demands in strong axis (z') of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

In Figure 5.145 and Figure 5.146, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13

incidence angles. Average maximum curvature demand is shown with red line for each scour depth, and it is increasing when ground motion incidence angle is changed from 75° to 120° in weak axis (y') and strong axis (z'). When the radar and bar chart is checked, average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is same as other scour cases as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. In addition, while the curvature demands on weak axis of column pier remain below the yield curvature at various earthquake incidence angles, they exceed the yield curvature at some incidence angles and causes the column pier to exhibit a nonlinear behavior during earthquake. In strong axis of column, the curvature demands below the yield curvature for all incidence angles where scour depth is 4 m and 6 m. The maximum difference of curvature demands in weak axis (y') of column between 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) bridge is occurred at 150° incidence angle as nearly 70.9%. Also, in strong axis (z'), it becomes 81.5% at 105° incidence angle. These results show that non-uniform scour around piles in longitudinal direction of bridge has a positive contribution to the curvature demands of skewed ($\alpha=45^\circ$) bridge column piers.

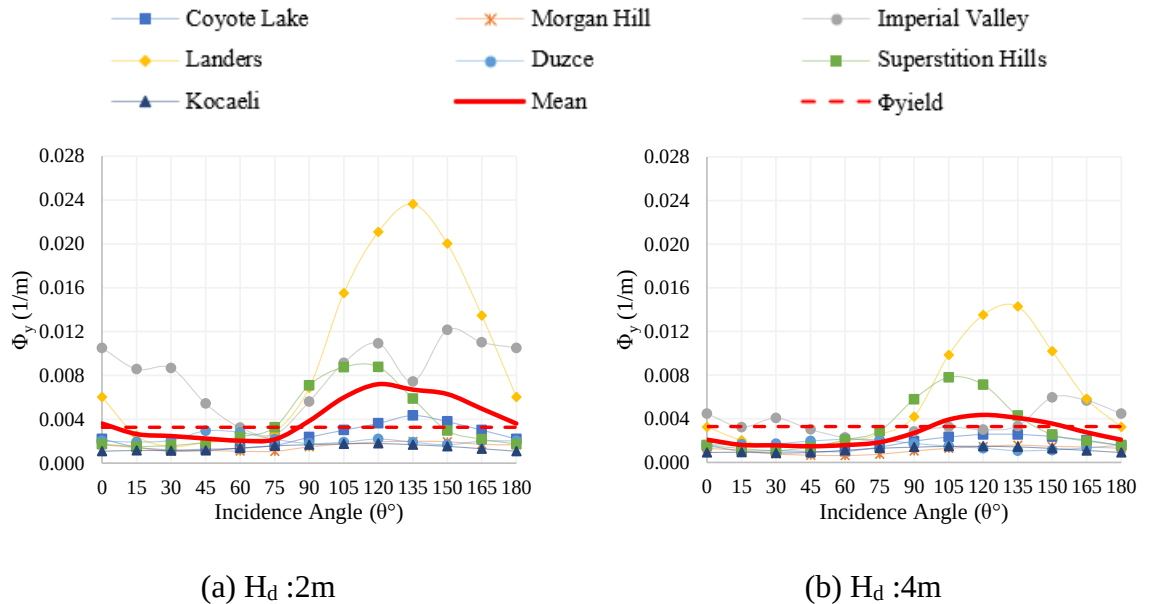


Figure 5.145. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

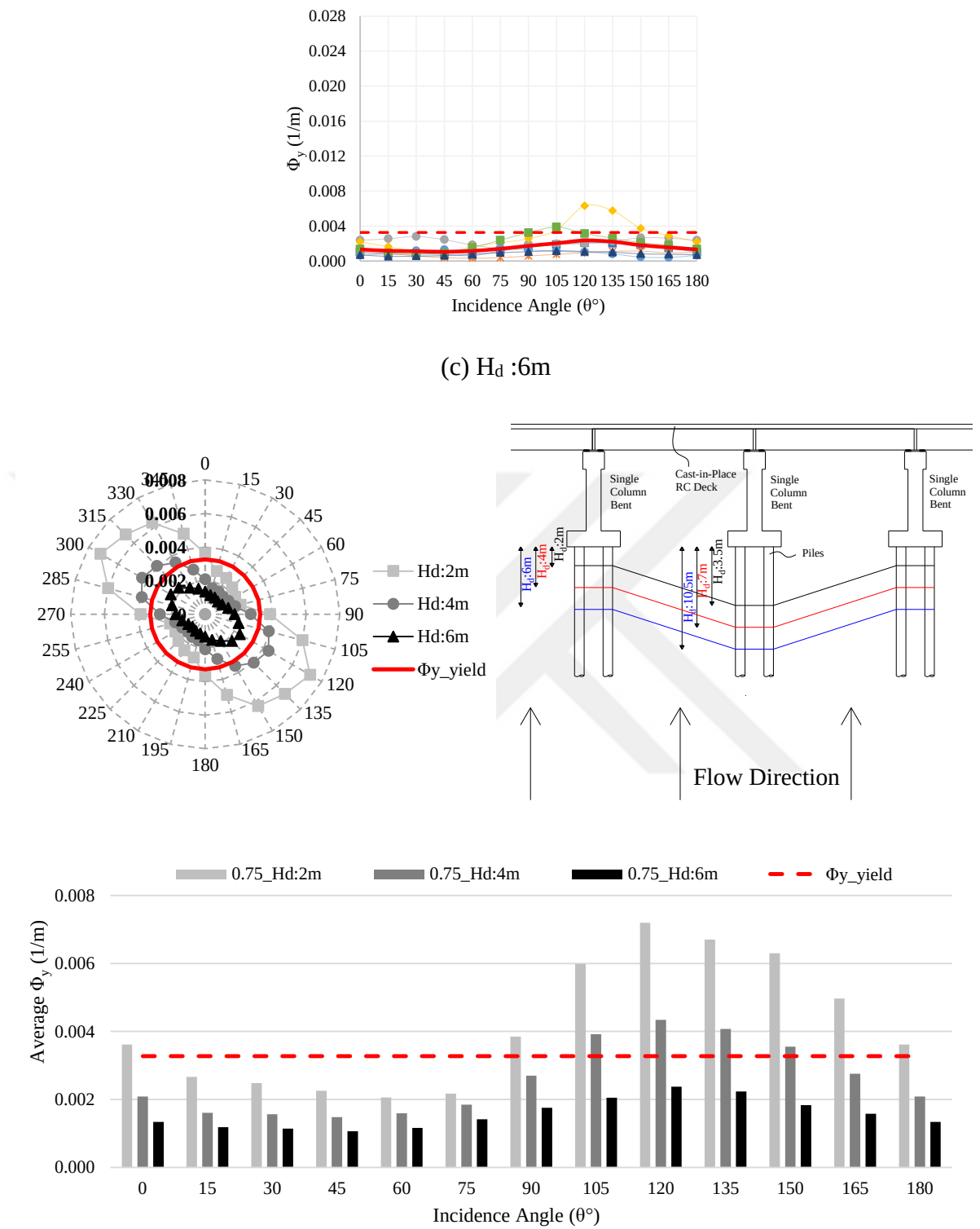


Figure 5.145. Maximum curvature demands in weak axis (y') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

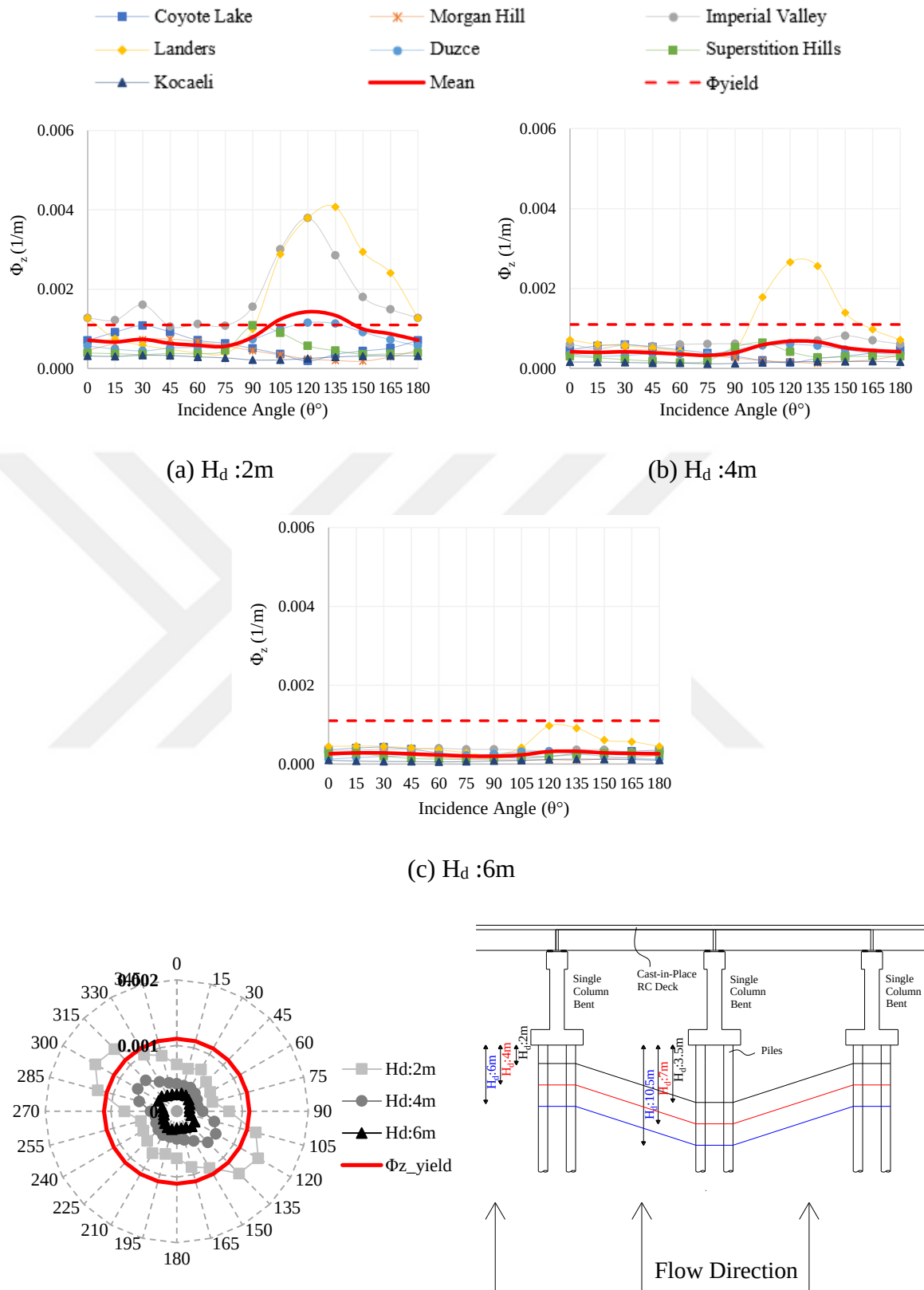


Figure 5.146. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

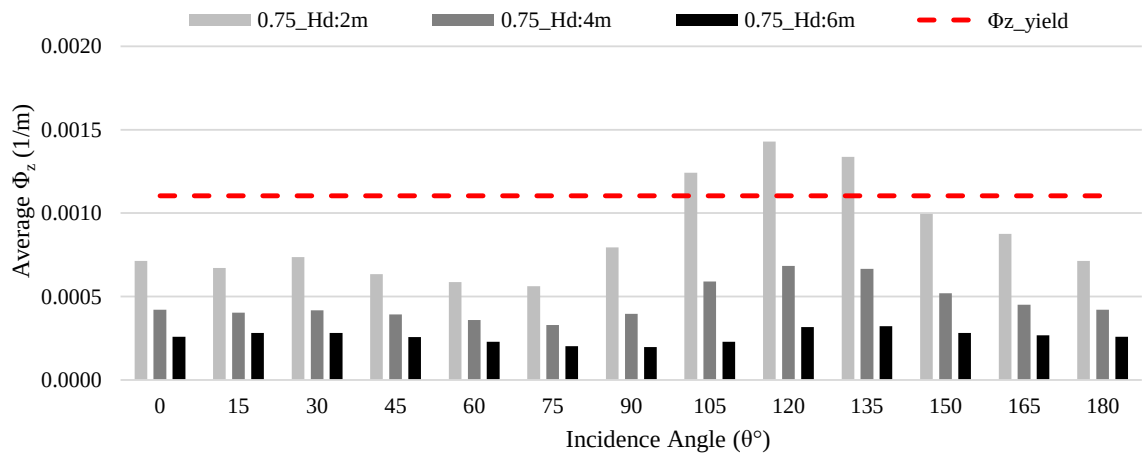


Figure 5.146. Maximum curvature demands in strong axis (z') of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

In Figure 5.147, average maximum curvature demands of the middle column of bridge in weak (y') and strong (z') axis are compared for 3 different scour depths 13 incidence angles for the non-skewed and 45° skewed bridges. In column weak axis (y'), curvature demands are higher in non-skewed bridge between 45° and 90° incidence angles. However, it becomes much higher in skewed bridge between 105° and 180° incidence angles. Moreover, in strong (z') axis of column, curvature demands are higher in non-skewed bridge between 0° and 90° incidence angles and it becomes greater in skewed bridge between 105° and 165° incidence angles. For both skewed and non-skewed bridges, curvature demands are decreasing with an increase in scour depth. The maximum difference of average curvature demands in weak axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 165° incidence angle and 2m scour depth as nearly 191%. In strong axis, it is at 135° and 2m scour depth as 49%.

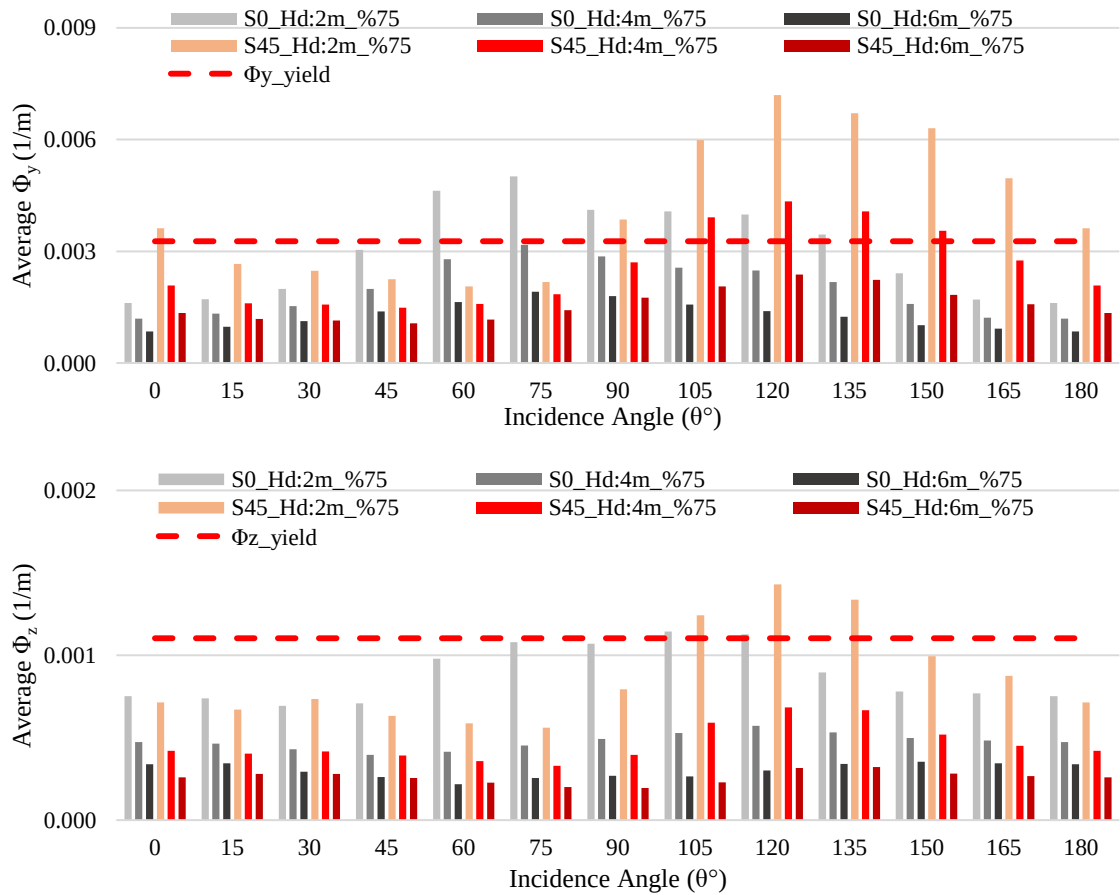


Figure 5.147. Average maximum curvature demands of non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when non-uniform scour in longitudinal direction is 75% more around middle piles

5.3.3.3. Shear force demands of column pier

In Figure 5.148 and Figure 5.149, maximum shear force demands of middle column of non-skewed ($\alpha=0^\circ$) bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 0° to 90° in local y' axis. Besides, it has an increasing trend between that angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. However, this decrement is more obvious in local y' axis of column. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2$ m) and 6m scoured ($H_d=6$ m) models occurs at 60° incidence angle and nearly 48.6%. Also, it is about 30% at 180° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are

compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the non-skewed ($\alpha=0^\circ$) bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.

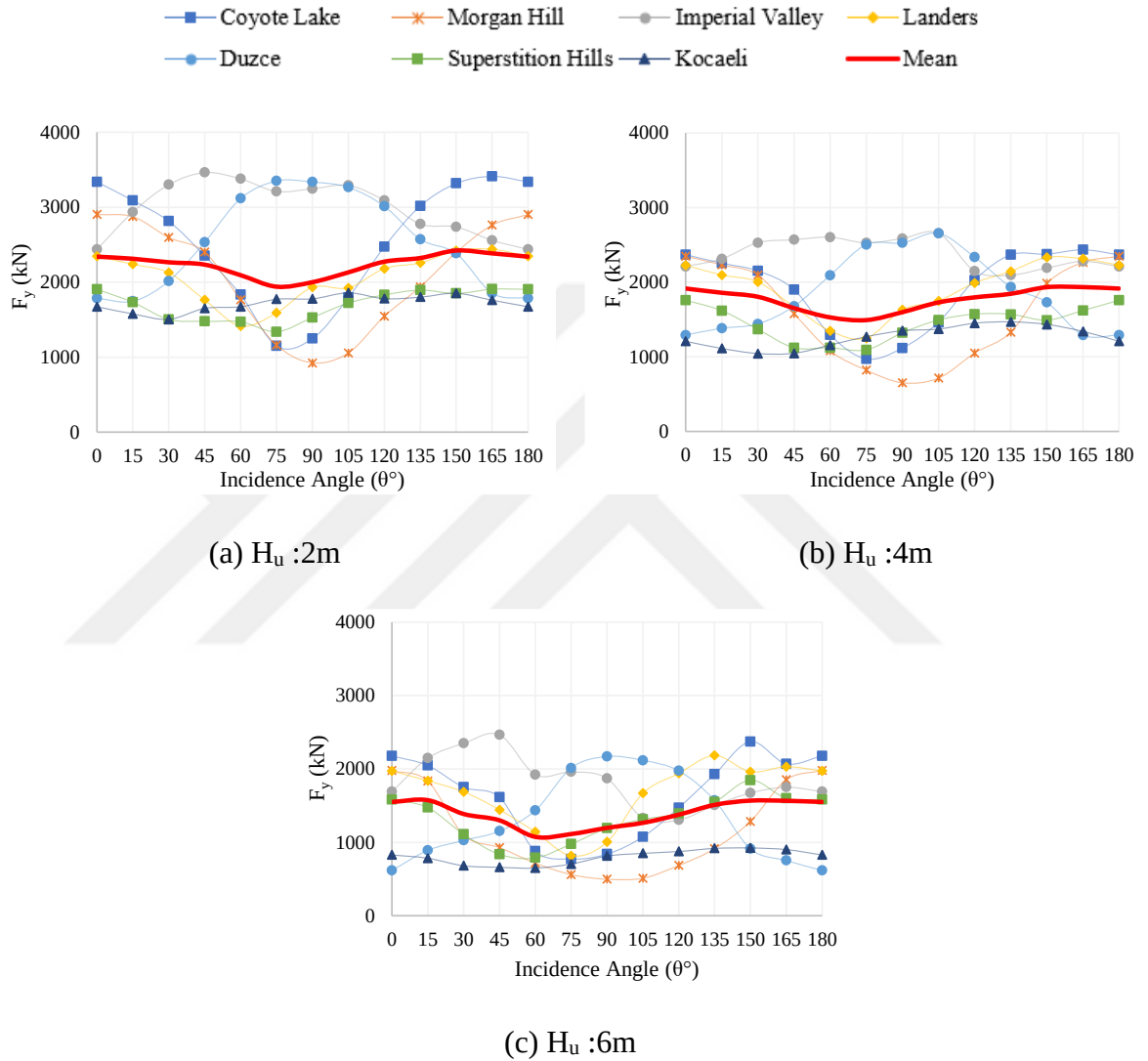


Figure 5.148. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

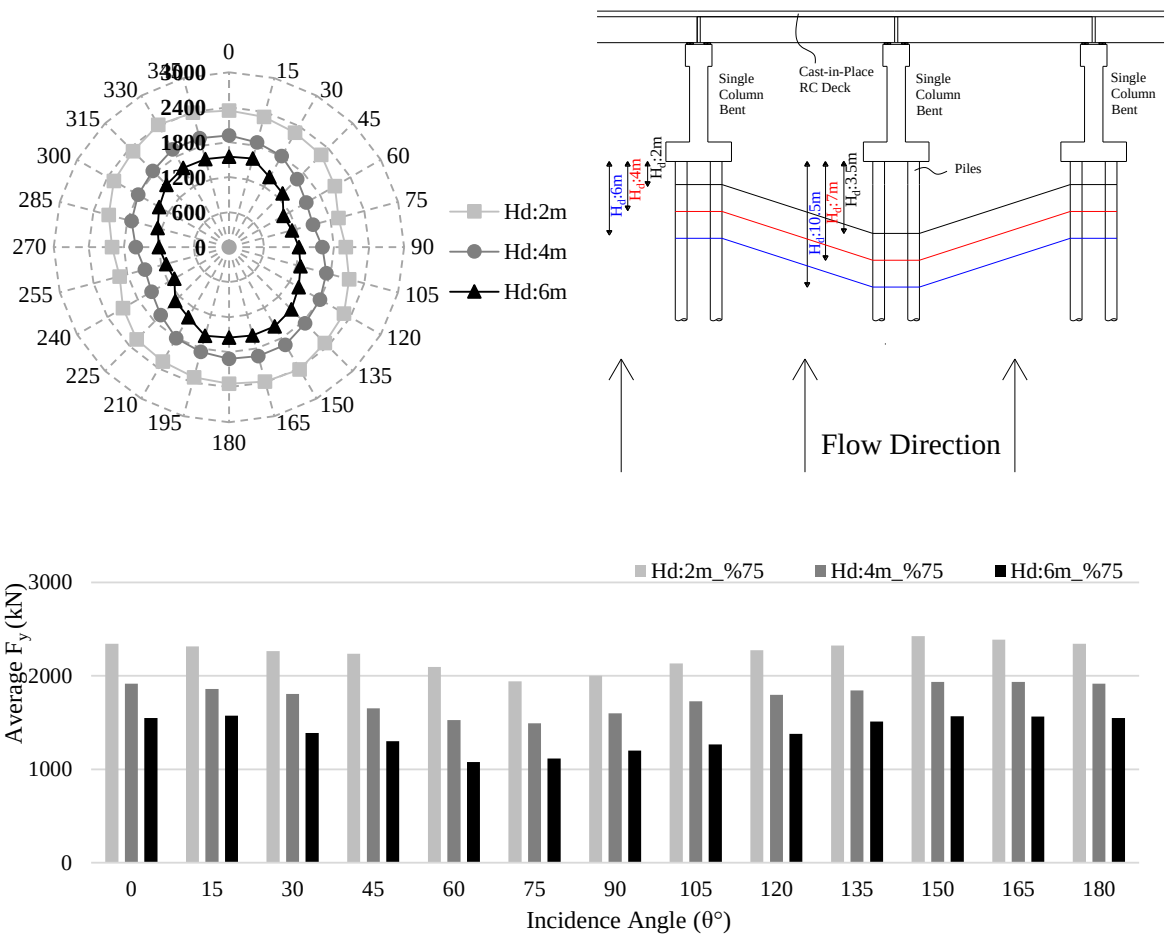


Figure 5.148. Maximum shear force demands in local y' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

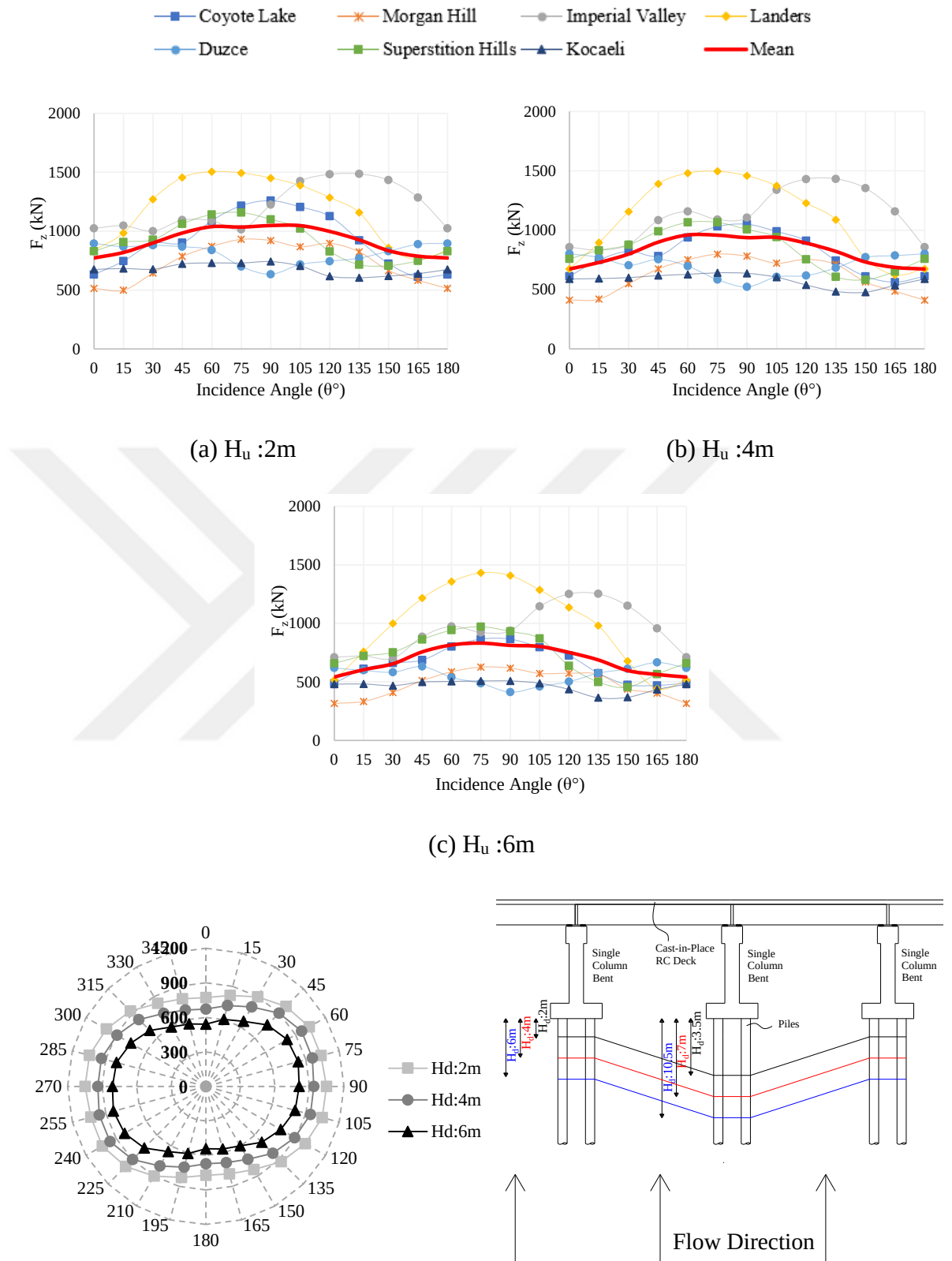


Figure 5.149. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

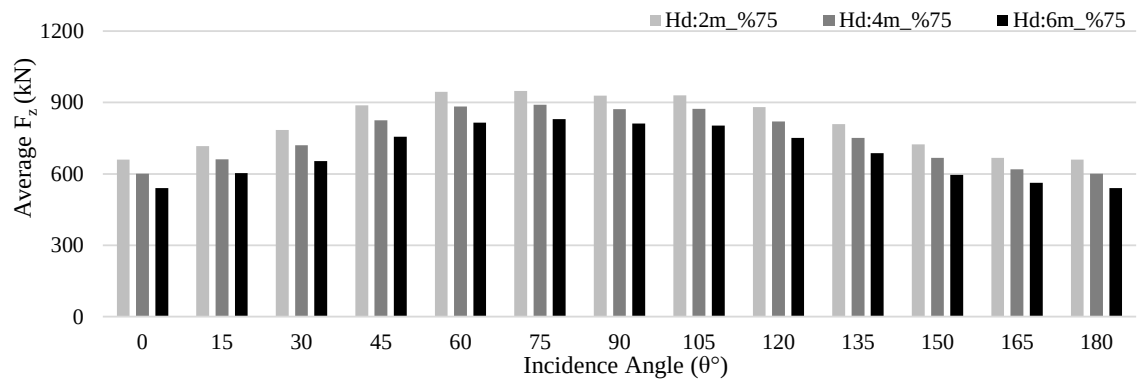
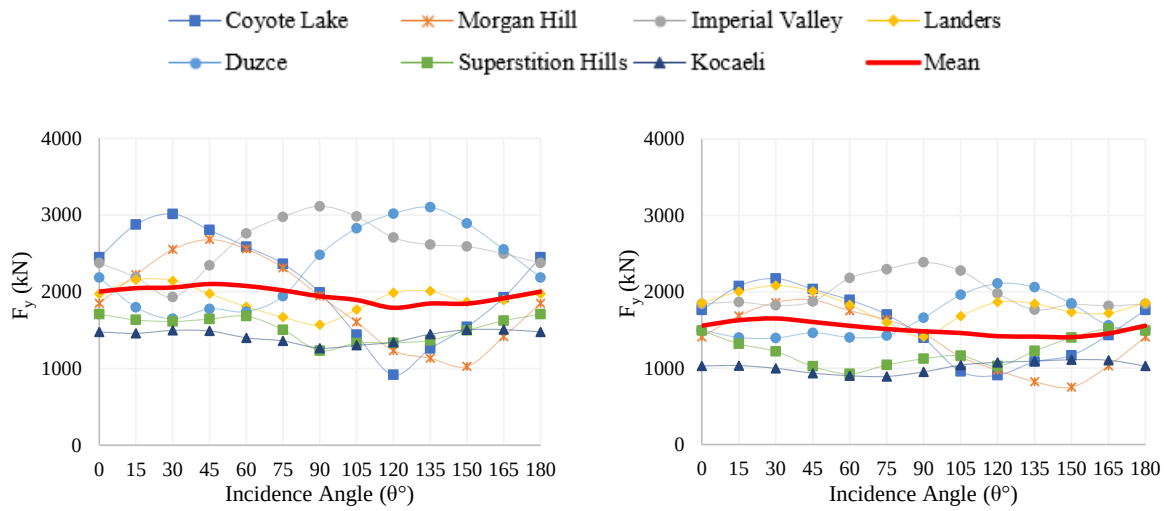


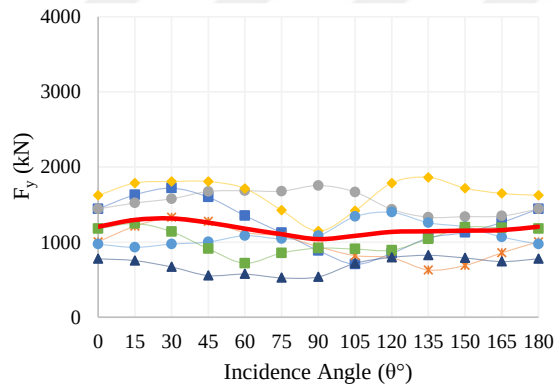
Figure 5.149. Maximum shear force demands in local z' axis of non-skewed ($\alpha=0^\circ$) bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

In Figure 5.150 and Figure 5.151, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. Average maximum shear force is shown with red line for each scour depth, and it is decreasing when ground motion incidence angle is changed from 75° to 120° in local y' axis. Besides, it has an increasing trend between 60° and 135° incidence angles in local z' axis. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles in both local axes of column and this decrease is more obvious in local y' axis. The maximum difference of average demands in local y' axis of 2 m scoured ($H_d=2$ m) and 6 m scoured ($H_d=6$ m) models occurs at 90° incidence angle and nearly 46.5%. Also, it is about 31% at 45° incidence angle in local z' axis. The shear capacity demands of column was calculated in previous sections as 5198.2 kN in local y' axis and 6519.9 kN in local z' axis. When the average maximum shear force demands are compared to these capacities, it is seen that demands are below the limits for all scour depths and incidence angles. Therefore, it can be said no shear damage occurred in 45° skewed bridge column during nonlinear analysis when scour depth change is non-uniform in longitudinal direction.



(a) $H_u : 2\text{m}$

(b) $H_u : 4\text{m}$



(c) $H_u : 6\text{m}$

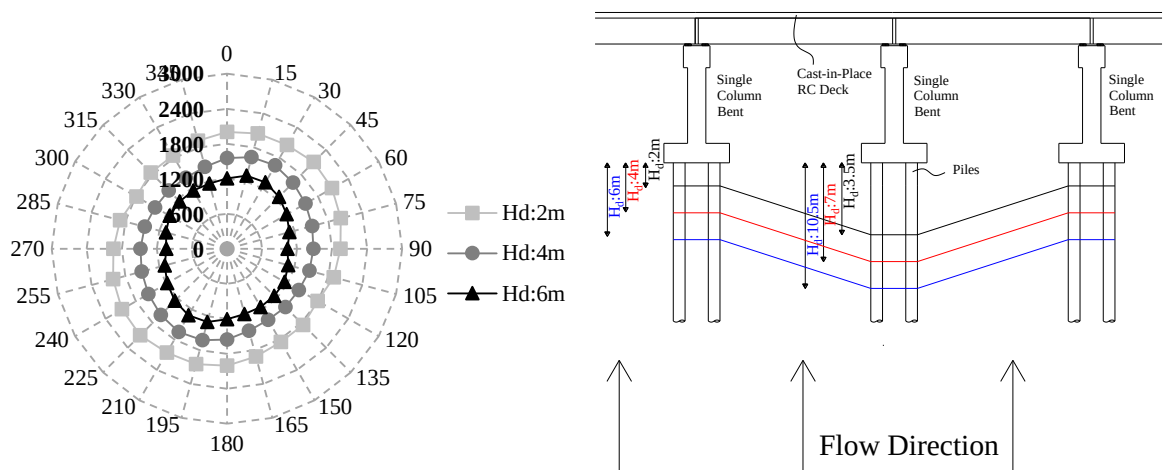


Figure 5.150. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

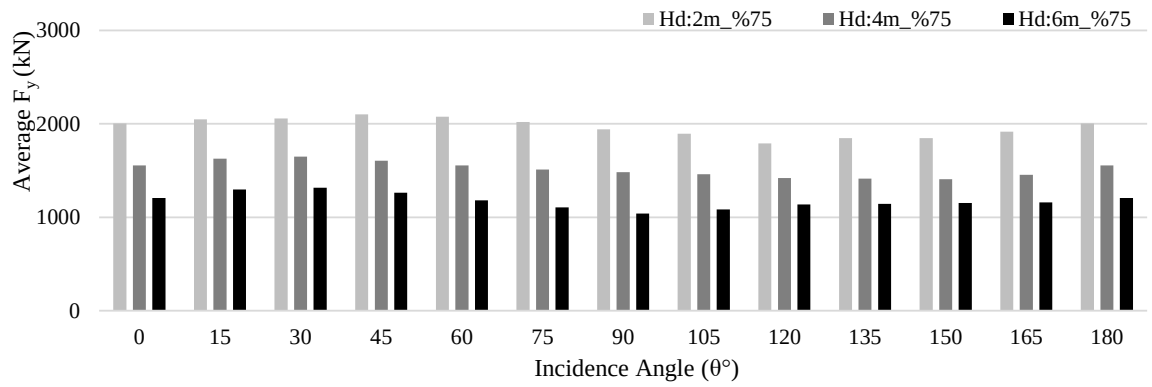


Figure 5.150. Maximum shear force demands in local y' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

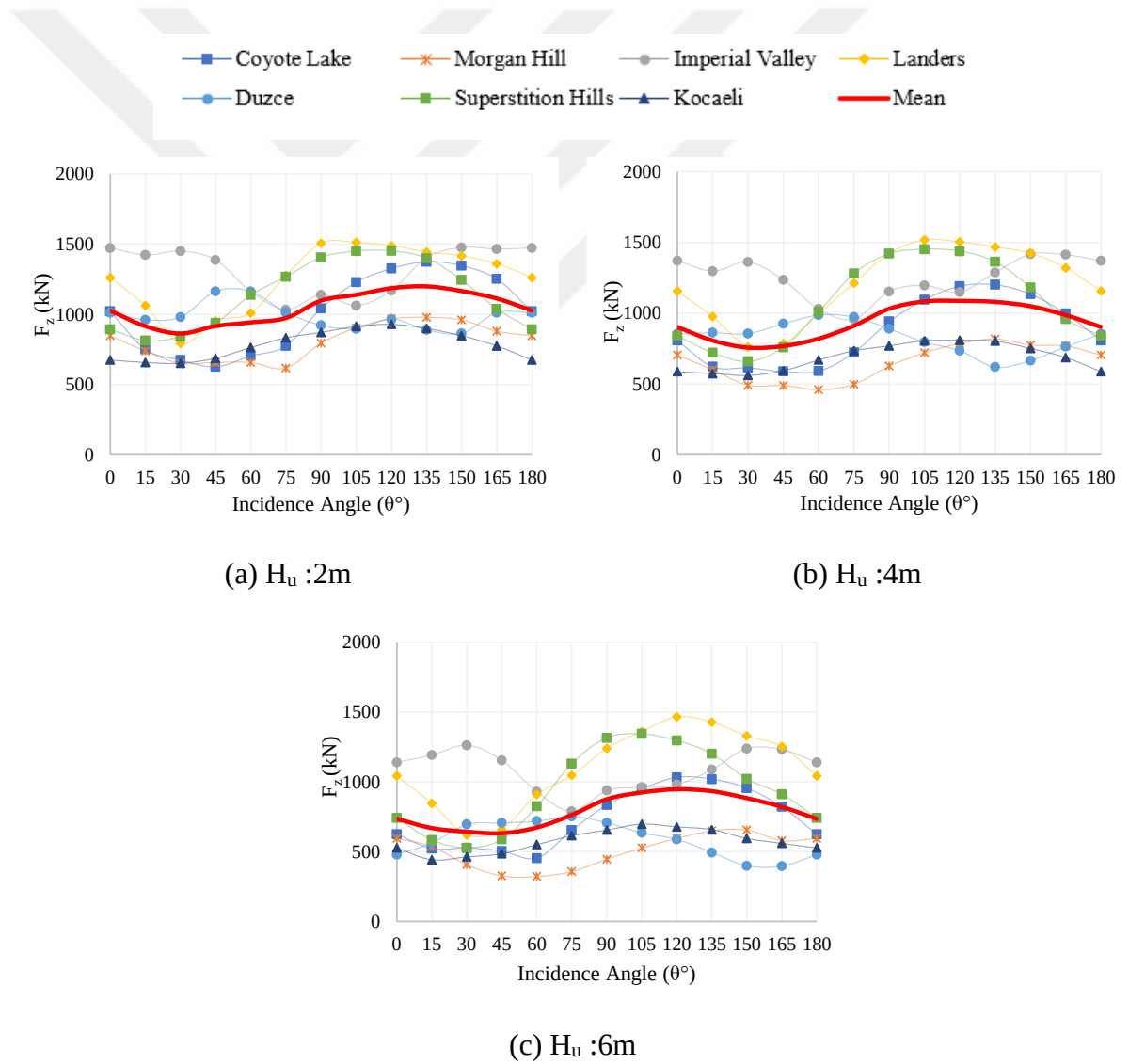


Figure 5.151. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c)

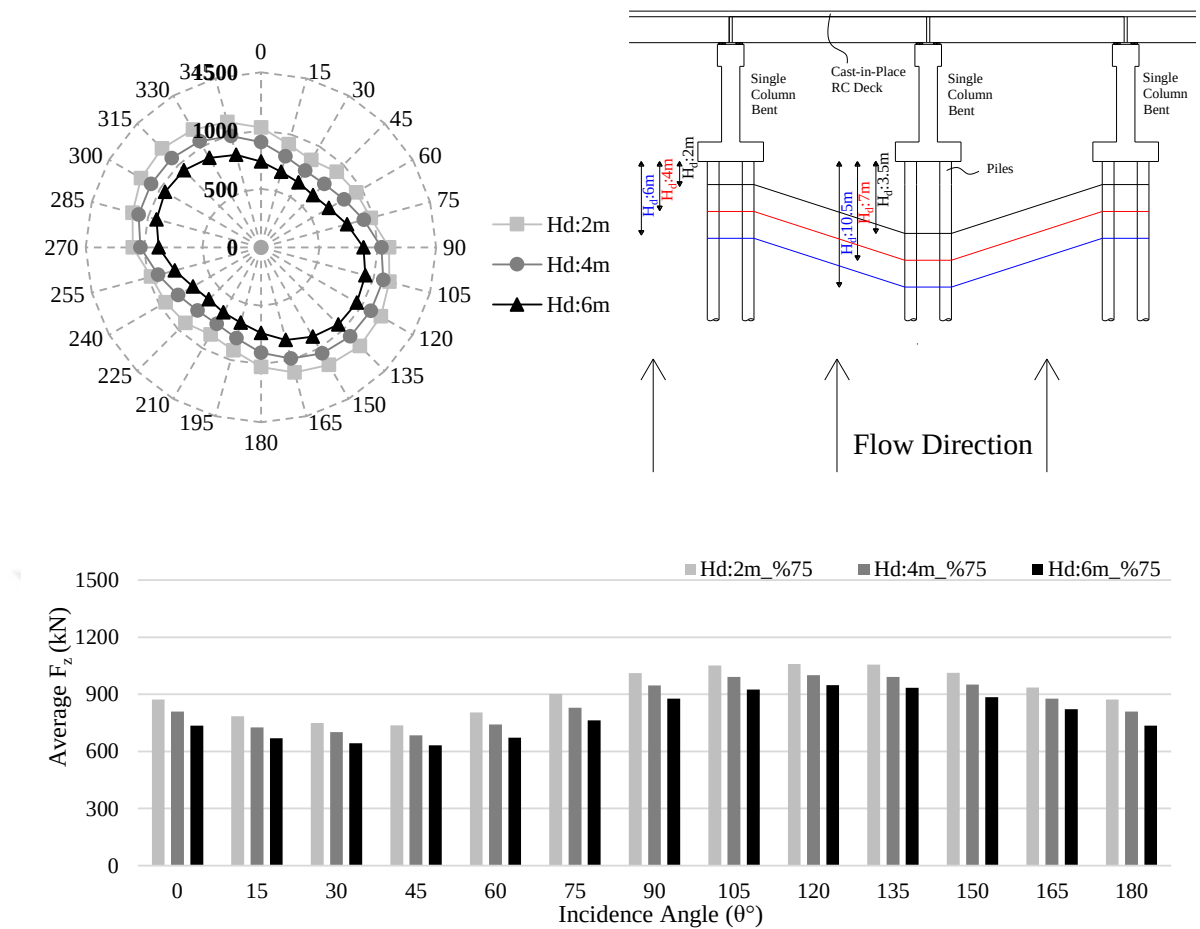


Figure 5.151. Maximum shear force demands in local z' axis of 45° skewed bridge column for different nonuniform scour depths and earthquake incidence angles (Case 2-2c) (continued)

In Figure 5.152, maximum shear force demands of column local y' and z' axes of non-skewed and 45° skewed bridges are compared for 3 different scour depths 13 incidence angles. In column local y' axis, shear force demands are higher in non-skewed bridge for all scour depths. On the other hand, this situation is vice versa in local z' axis of column. For both skewed and non-skewed bridges, shear demands are decreasing with an increase in scour depth. The maximum difference of average shear force demands in local y' axis of column between non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge is occurred at 150° incidence angle and 4m scour depth as nearly 27.3%. In local z' axis, it is again at 150° and 6m scour depth as 48.3%.

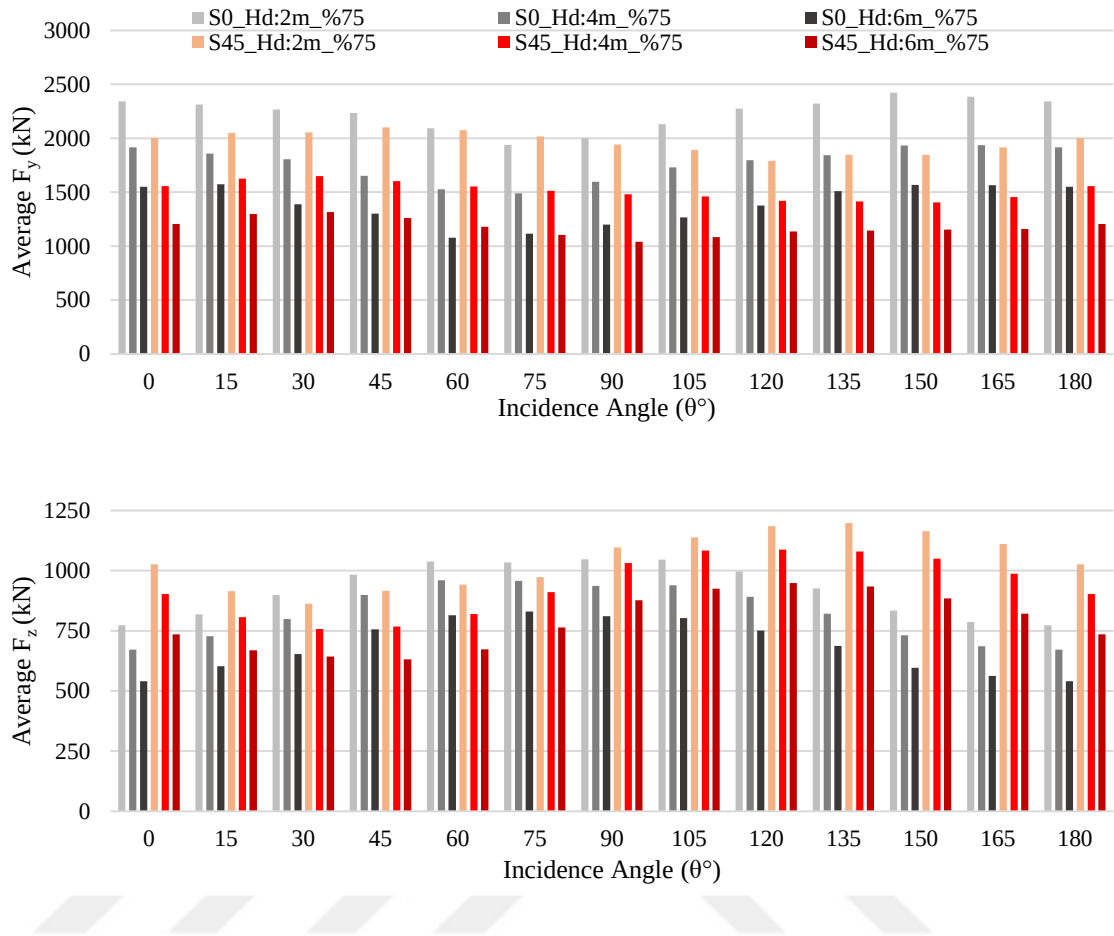


Figure 5.152. Average maximum shear force demands of the non-skewed and 45° skewed bridge when non-uniform scour in longitudinal direction is 75% more around middle piles

5.3.3.4. Shear force demands of piles

In Figure 5.153 and Figure 5.154, maximum shear force demands of local y' and z' axes of corner piles in non-skewed ($\alpha=0^\circ$) and 45° skewed bridge are given. As it can be seen from the graphs, maximum shear force demands of local y' and z' axes of corner piles are below the pile shear capacity of 735.2 kN and demands are decreasing when scour depth increases in longitudinal direction of bridge. Also, demands are nearly same for all corner piles and they are much higher in local y' axis than z' axis. Therefore, shear force demands of local y' axis of pile number 1 (P1) is given in detail for non-skewed and 45° skewed bridges at 90° earthquake incidence angle in Figure 5.155. P1 pile shear demand is higher in non-skewed bridge at 2m scour depth than skewed one. For scour depths 4 m and 6 m, shear force demands of pile P1 are nearly same both bridge models.

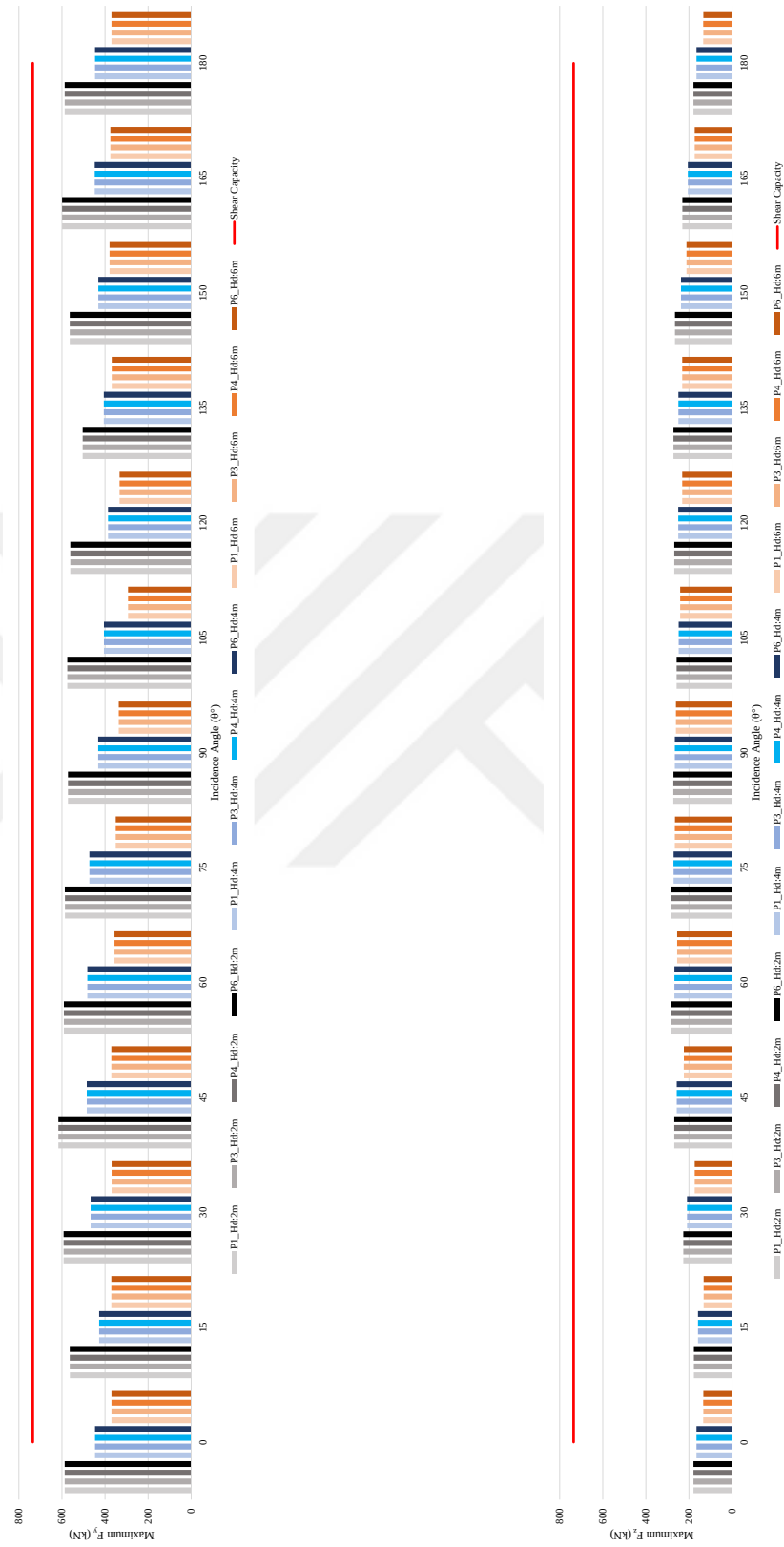


Figure 5.153. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=0^\circ$ non-skewed bridge and Case 2-2c)

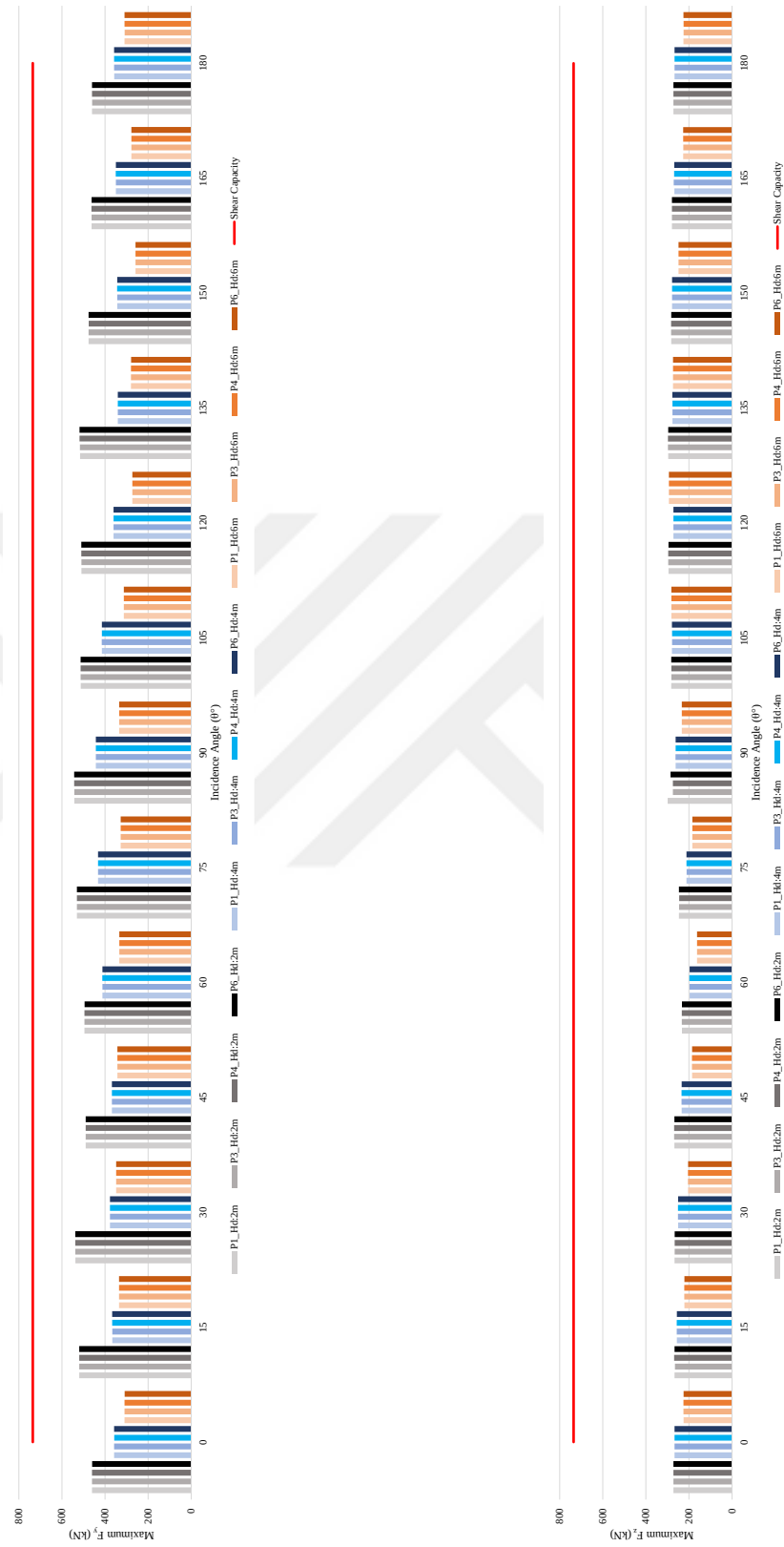


Figure 5.154. Maximum shear force demands of local y' and z' axis of corner piles for different nonuniform scour depths and earthquake incidence angles ($\alpha=45^\circ$ skewed bridge and Case 2-2c)

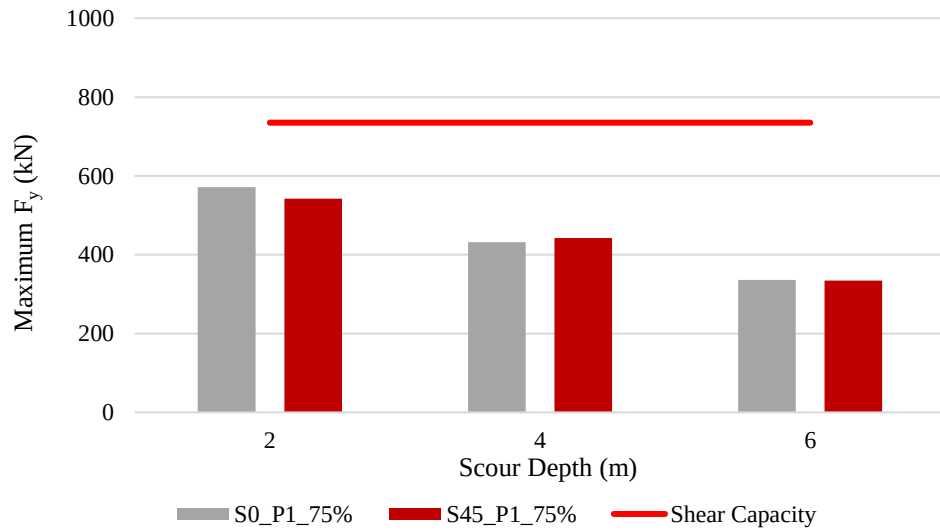


Figure 5.155. Average maximum shear force demands of local y' axis of pile (P1) for non-skewed and 45° skewed bridge when ground motion incidence angle is 90° and non-uniform scour is 75% in longitudinal direction

5.3.3.5. Residual displacements

Residual displacements were calculated for middle column and superstructure by using non-skewed and skewed bridges for non-uniformly changed scour depths in longitudinal direction (%75) and different ground motion incidence angles. In Figure 5.156, the average residual displacement demands of middle column for non-skewed and skewed bridges are given when scour depth is non-uniformly changed. Also, in Figure 5.157, the ratio of residual displacement demand to maximum displacement of middle column for the non-skewed and 45° skewed bridge is shown when scour depth change is non-uniform (Case 2-2c). Furthermore, the same demands are evaluated for the superstructure and shown in Figure 5.158 and Figure 5.159, respectively. The demands calculated by taking the average of 7 ground motion records and they are higher in non-skewed bridge model in longitudinal and transverse direction for both middle column and superstructure of bridge.

Maximum residual displacement in longitudinal direction for middle column of bridge occurs when non-uniform scour depth is 6m at 75° incidence angle for non-skewed bridge as 24.9mm. In transverse direction it is maximum at 75° incidence angle and 6m scour depth as 8.6mm for non-skewed bridge. When the residual displacement demands of middle column are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 60° and 6m scour depth as 0.19 in

longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.11 at 6m scour depth when incidence angle 60° in transverse direction of non-skewed bridge.

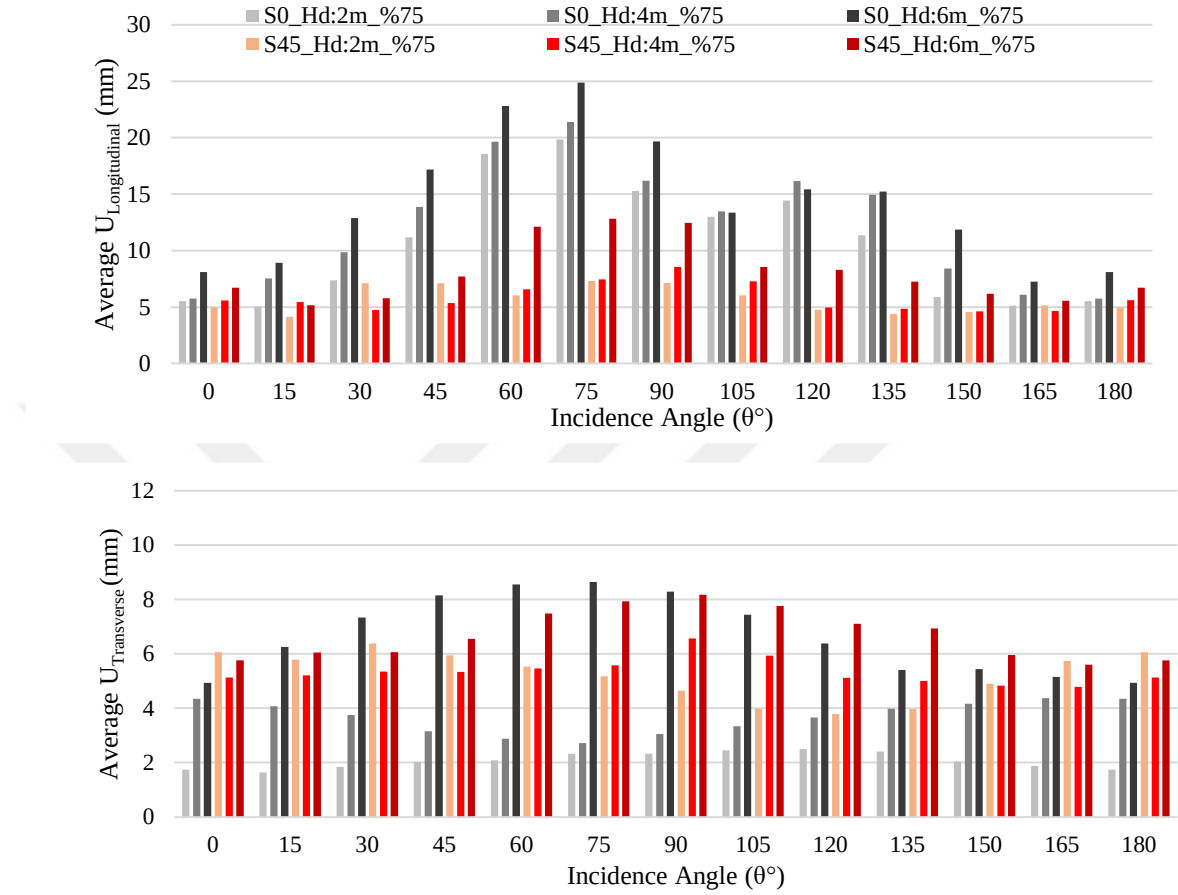


Figure 5.156. Average residual displacement demands of middle column for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2c)

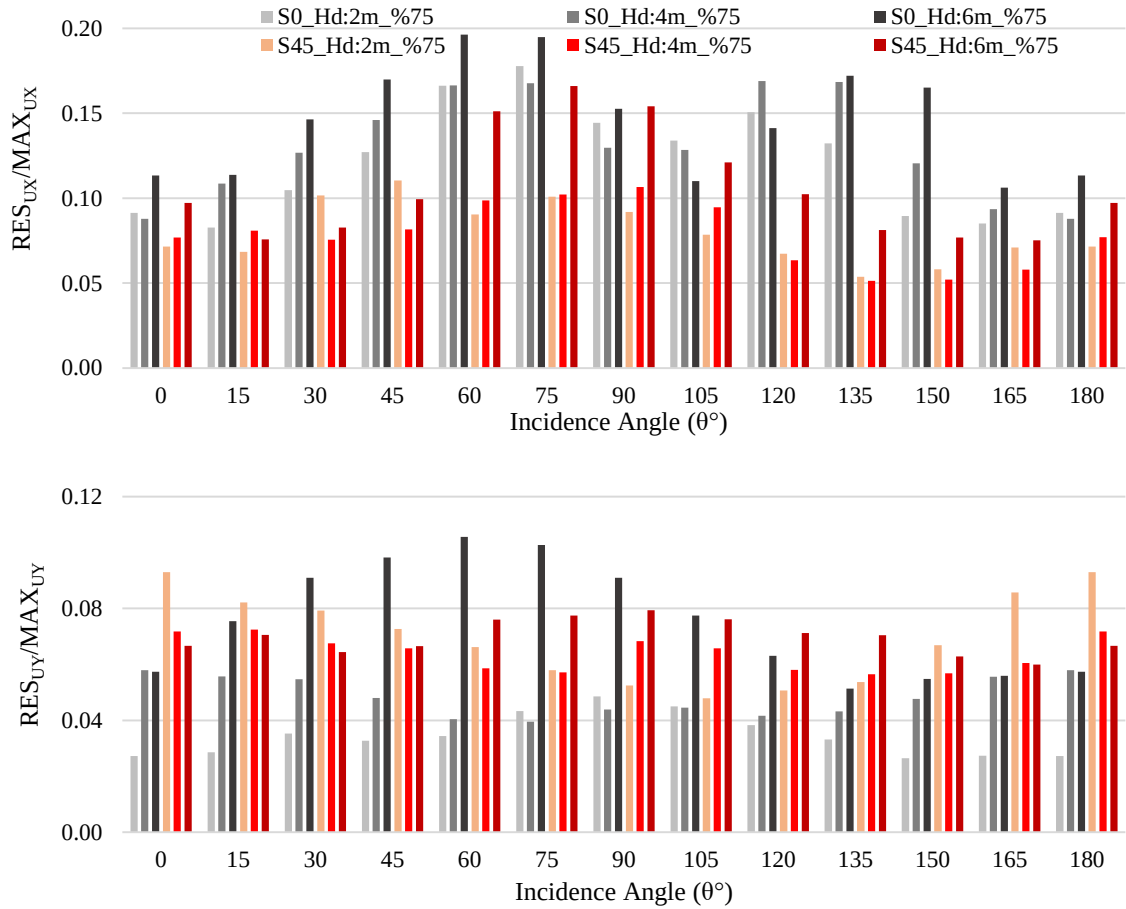


Figure 5.157. The ratio of residual displacement demand to maximum displacement of middle for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2c)

Maximum residual displacement in longitudinal direction of bridge superstructure occurs when non-uniform scour depth in longitudinal direction (%75) is 6m at 75° incidence angle for non-skewed bridge as 29.1mm. In transverse direction it is maximum at 75° incidence angle and 6m scour depth as 10.4mm for non-skewed bridge. When the residual displacement demands of superstructure are compared to the maximum displacement demands of it, the maximum ratio occurs at an incidence angle of 60° and 6m scour depth as 0.20 in longitudinal direction of non-skewed bridge. Also, the maximum ratio becomes 0.11 at 6m scour depth when incidence angle 75° in transverse direction of non-skewed bridge.

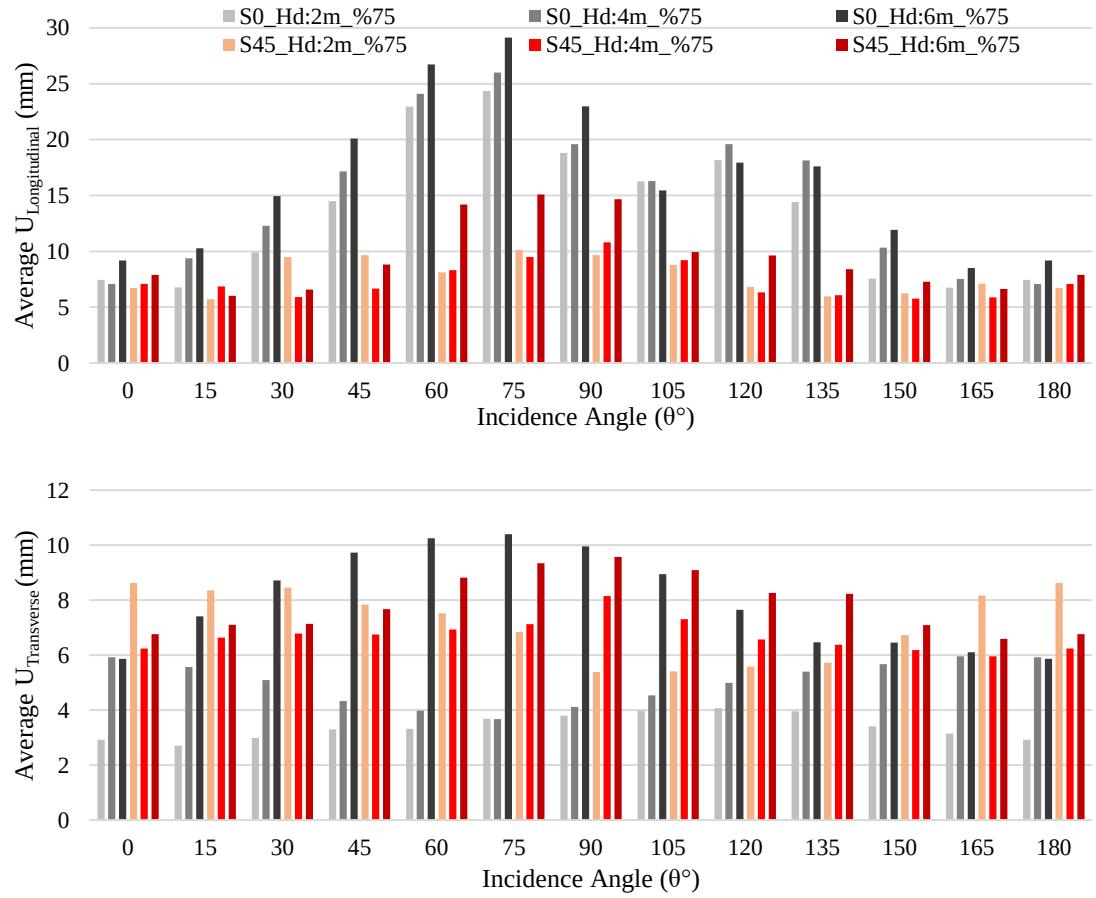


Figure 5.158. Average residual displacement demands of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2c)

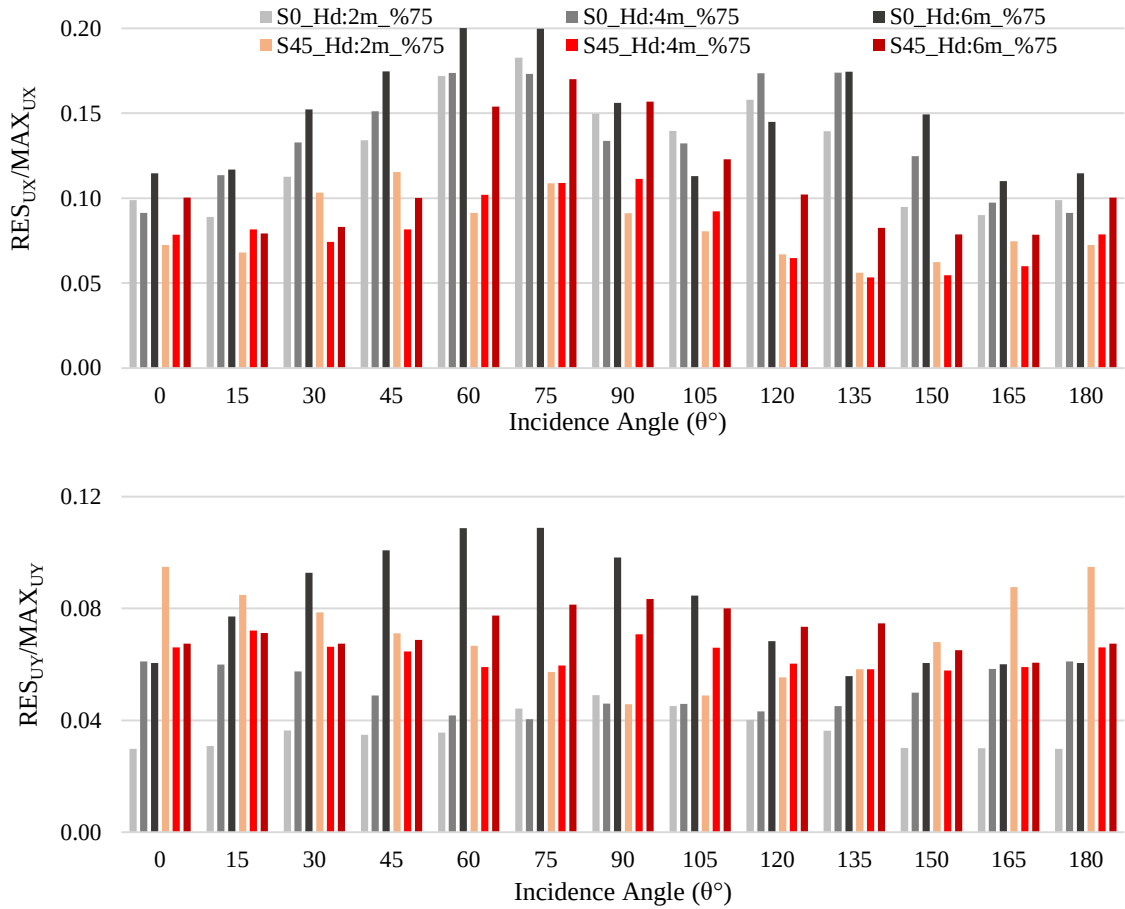


Figure 5.159. The ratio of residual displacement demand to maximum displacement of superstructure for non-skewed ($\alpha=0^\circ$) and skewed ($\alpha=45^\circ$) bridge when scour depth change is non-uniform in longitudinal direction (Case 2-2c)

5.3.4. Comparison of non-uniform scour cases in longitudinal direction

In this part of thesis, non-uniform scour occurred in longitudinal direction of bridge are constructed by taking the scour depth as 25%, 50% and 75% more around middle column piles than side column piles. Scour depth is taken as 2 m, 4 m and 6 m (H_d) at side piles and the depth around middle piles are calculated by considering the percentage difference (25%, 50% and 75%) considered for each case. The demands obtained from nonlinear analysis results are given below.

In Figure 5.160 and Figure 5.161, the 1st and 2nd vibration period of non-skewed and 45° skewed bridge are given for each non-uniform scour cases occurred in longitudinal direction of bridge. As seen from the graphs, the periods have an increasing trend when scour depth and the change of non-uniformity in longitudinal direction increases. For skewed bridges the first period is greater than the non-skewed bridges for

all scour depths. On the other hand, the second period becomes higher in non-skewed bridge than skewed one.

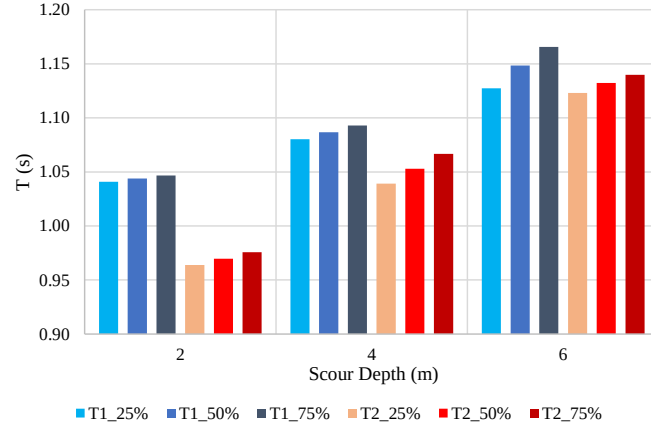


Figure 5.160. The variation of 1st and 2nd vibration period of non- skewed bridge depending on non-uniform scour depth in longitudinal direction

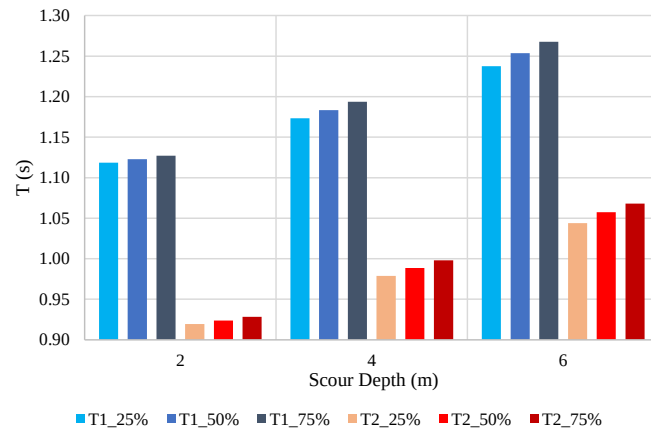


Figure 5.161. The variation of 1st and 2nd vibration period of 45° skewed bridge depending on non-uniform scour depth in longitudinal direction

Superstructure displacement demands obtained from nonlinear analysis results belong to the midpoint of the bridge deck as mentioned above. In Figure 5.162 and Figure 5.163, maximum displacement demands in longitudinal and transverse direction of non-skewed bridge and resultant displacement are given. The results are obtained for 7 earthquakes and ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. The increase of

displacement in longitudinal direction is more obvious than the transverse direction of bridge in some incidence angles. Also, displacement demands of 45° skewed bridge in both longitudinal and transverse direction tend to increase when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 75° incidence angle as nearly 9.9% when nonuniform scour change is 25% in longitudinal direction. In transverse direction, it is at 15° incidence angle as 21.5%. If it is checked for resultant displacement, maximum difference becomes 16% at 0° incidence angle.

Moreover, the maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 90° incidence angle as nearly 10.6% when nonuniform scour change is 50% in longitudinal direction. In transverse direction, it is at 15° incidence angle as 24%. If it is checked for resultant displacement, maximum difference becomes 18% at 165° incidence angle.

Finally, the maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 90° incidence angle as nearly 11.2% when nonuniform scour change is 75% in longitudinal direction. In transverse direction, it is at 165° incidence angle as 25.9%. If it is checked for resultant displacement, maximum difference becomes 20.4% at also 165° incidence angle.

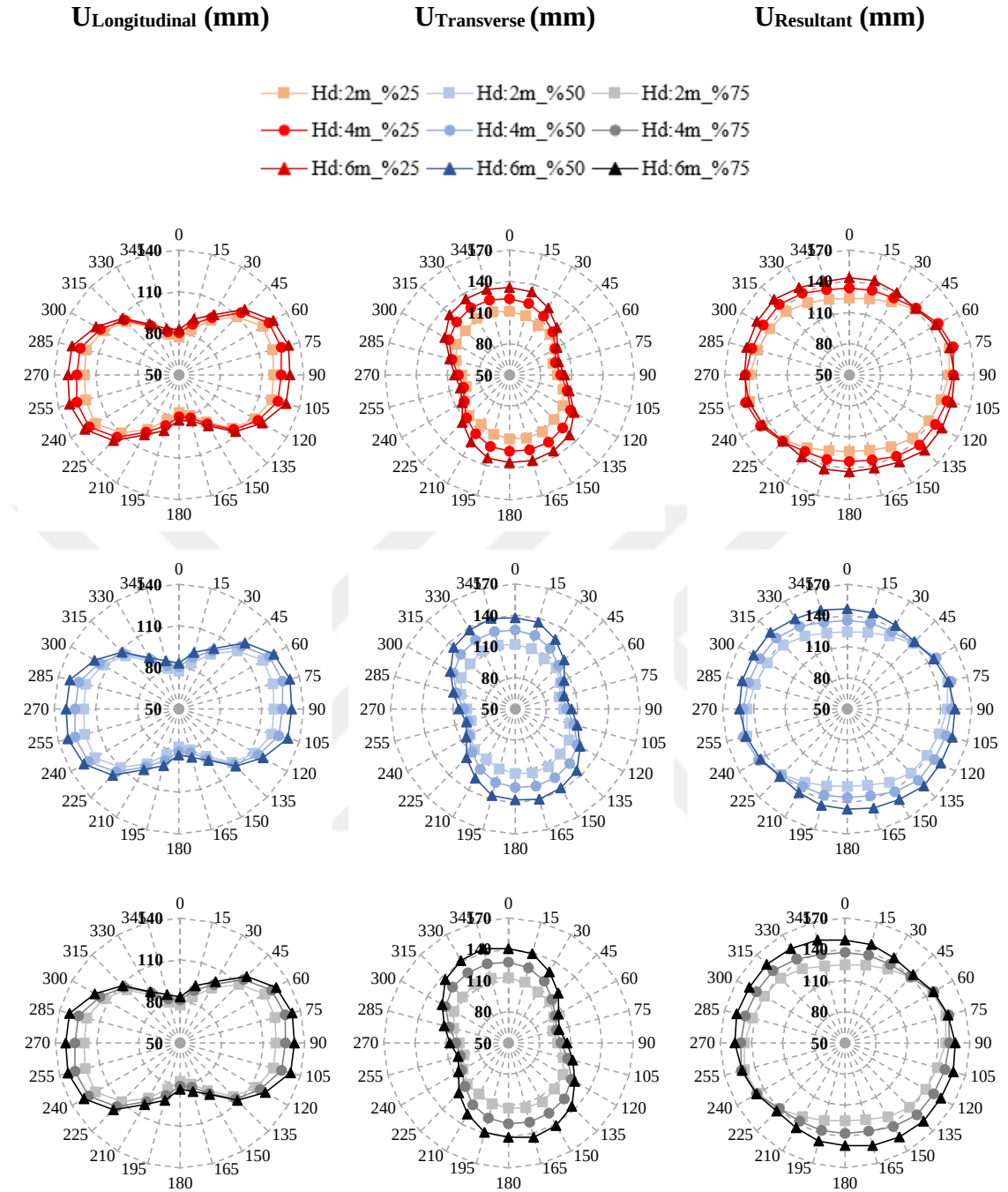


Figure 5.162. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

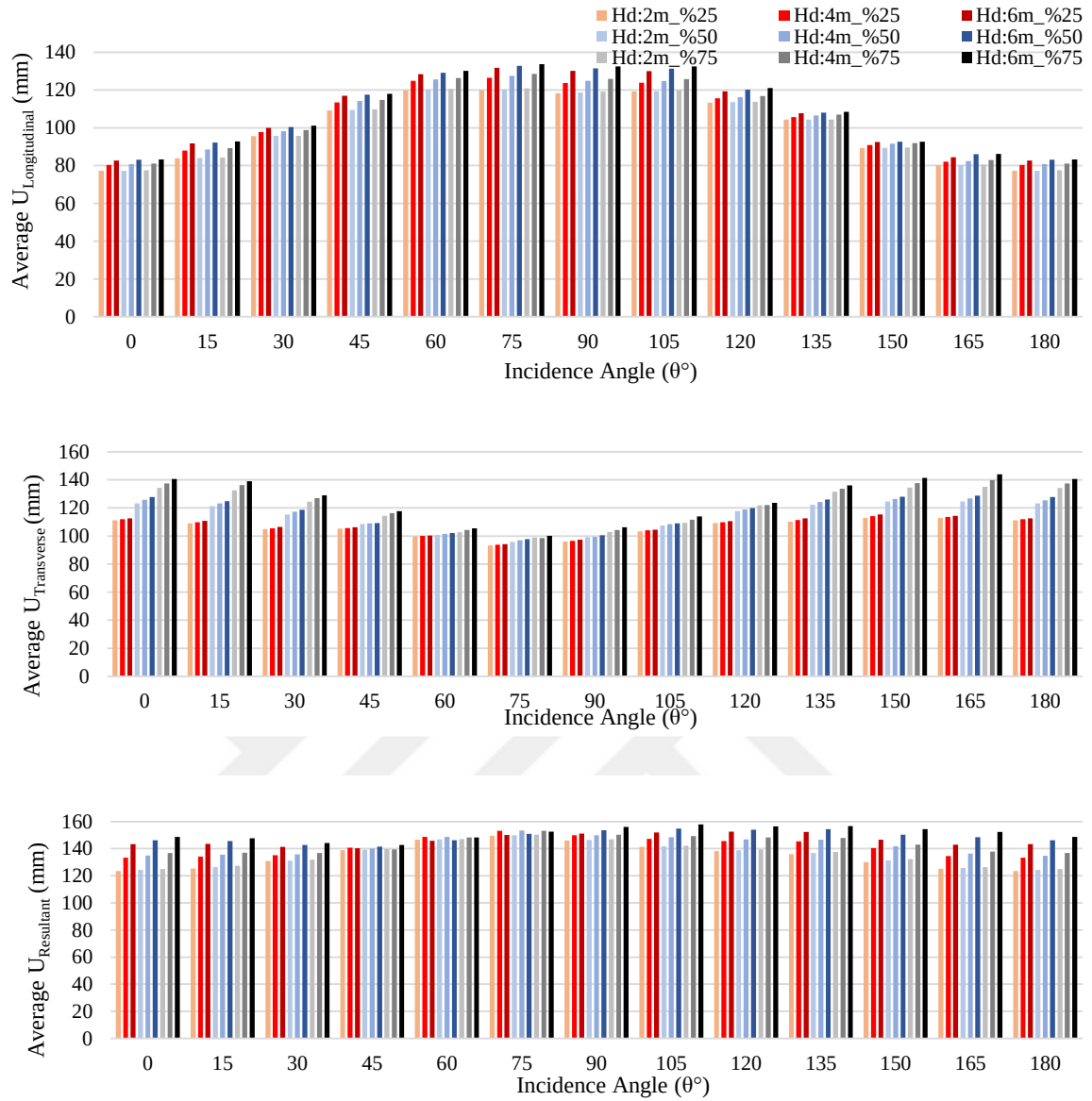


Figure 5.163. Average maximum displacement demands of non-skewed ($\alpha=0^\circ$) bridge for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

In Figure 5.164 and Figure 5.165, maximum displacement demands in longitudinal and transverse direction of 45° skewed bridge and resultant displacement are given. The results are obtained for 7 earthquakes and ground motion incidence angles which is changed starting from 0° to 180° with an increment of 15° as explained previous sections. According to the radar and bar charts, average maximum superstructure displacement increases in both directions of bridge when scour depth (H_d) increase non-uniformly around piles. Also, displacement demands in longitudinal direction of 45° skewed bridge are not affected too much to the change of non-uniform scour depth percentage. On the

contrary, demands in transverse direction tend to increase when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 60° incidence angle as nearly 5.8% when nonuniform scour change is 25% in longitudinal direction. In transverse direction, it is at 0° incidence angle as 17.5%. If it is checked for resultant displacement, maximum difference becomes 16% at 15° incidence angle.

Moreover, the maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 60° incidence angle as nearly 8.5% when nonuniform scour change is 50% in longitudinal direction. In transverse direction, it is at 0° incidence angle as 18.4%. If it is checked for resultant displacement, maximum difference becomes 16.1% at 15° incidence angle.

Finally, the maximum difference of average displacement demands in longitudinal direction between $H_d=2$ m scoured and $H_d=6$ m scoured bridge is occurred at 60° incidence angle as nearly 10.8% when nonuniform scour change is 75% in longitudinal direction. In transverse direction, it is at 0° incidence angle as 18.9%. If it is checked for resultant displacement, maximum difference becomes 16.1% at also 15° incidence angle.

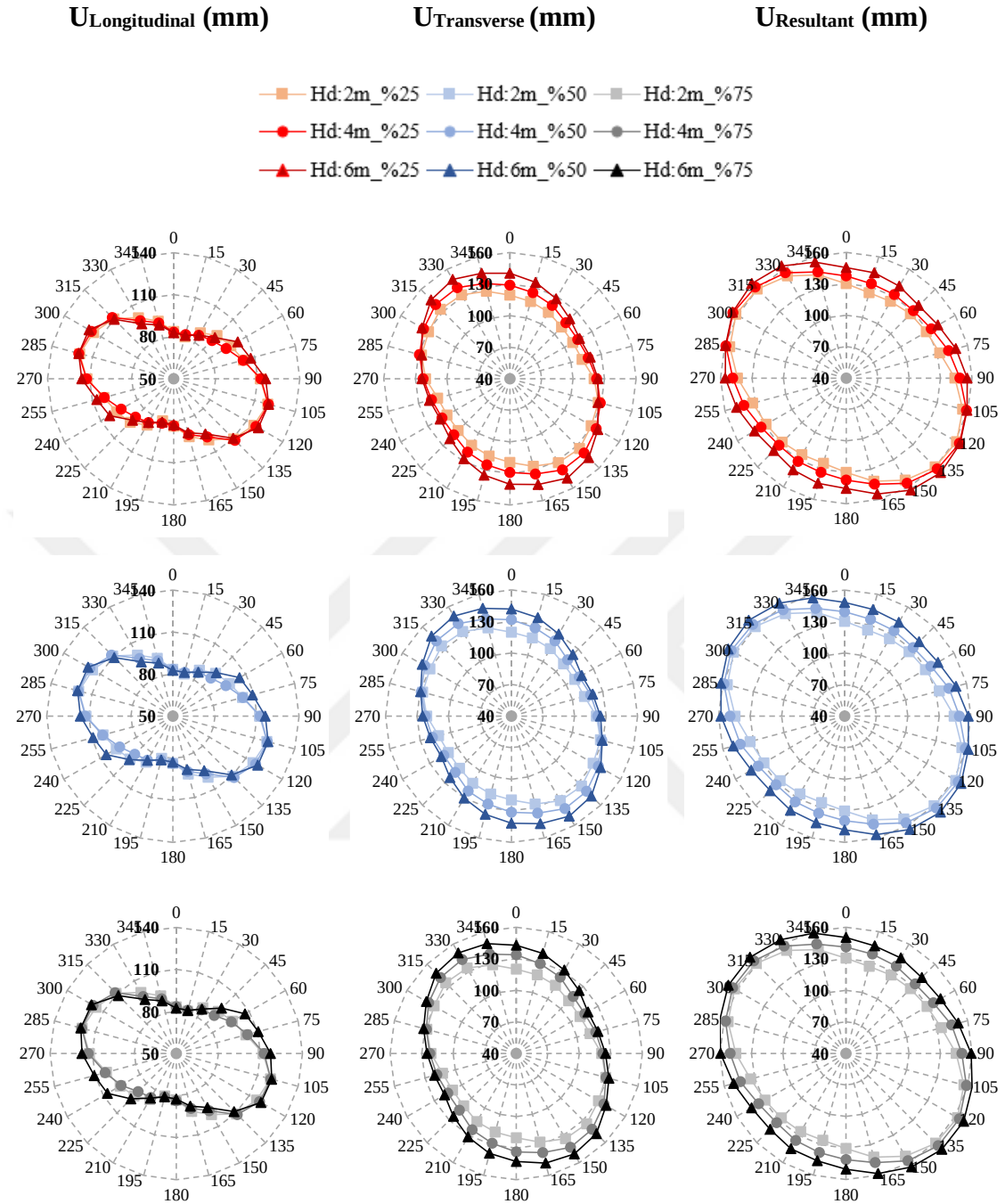


Figure 5.164. Average maximum displacement demands of 45° skewed bridge for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

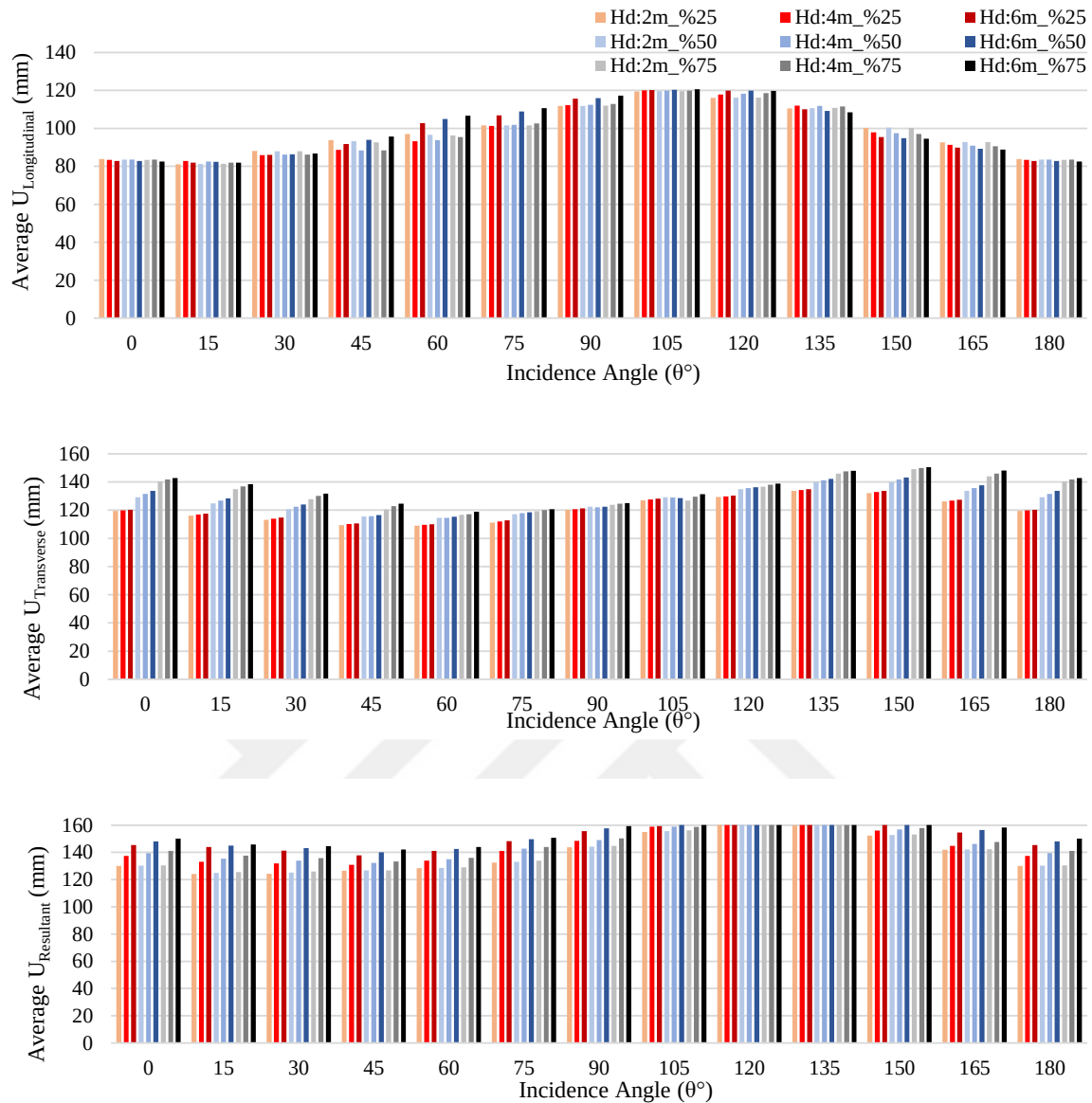


Figure 5.165. Average maximum displacement demands of 45° skewed bridge for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

In Figure 5.166 and Figure 5.167, maximum curvature demands of middle column of non-skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. When the radar and bar chart is checked, they show that average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. The reason of this is the same as uniform scour case as bridge column becomes more flexible as scour depth increases and this causes to decrease in curvature. Also, demands tend to decrease when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average curvature demands in weak axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 60° incidence angle as nearly 46.8% when nonuniform scour change is 25% in longitudinal direction. In strong axis of column, it is at 75° incidence angle as 70.3%.

Moreover, the maximum difference of average curvature demands in weak axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scoure is occurred at 120° incidence angle as nearly 58.3% when nonuniform scour change is 50% in longitudinal direction. In strong axis, it is 74.5% at 75° ground motion incidence angle.

Finally, the maximum difference of average curvature demands in weak axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scoure is occurred at 120° incidence angle as nearly 65.1% when nonuniform scour change is 75% in longitudinal direction. In strong axis of column, it is at 60° incidence angle as 77.6%.

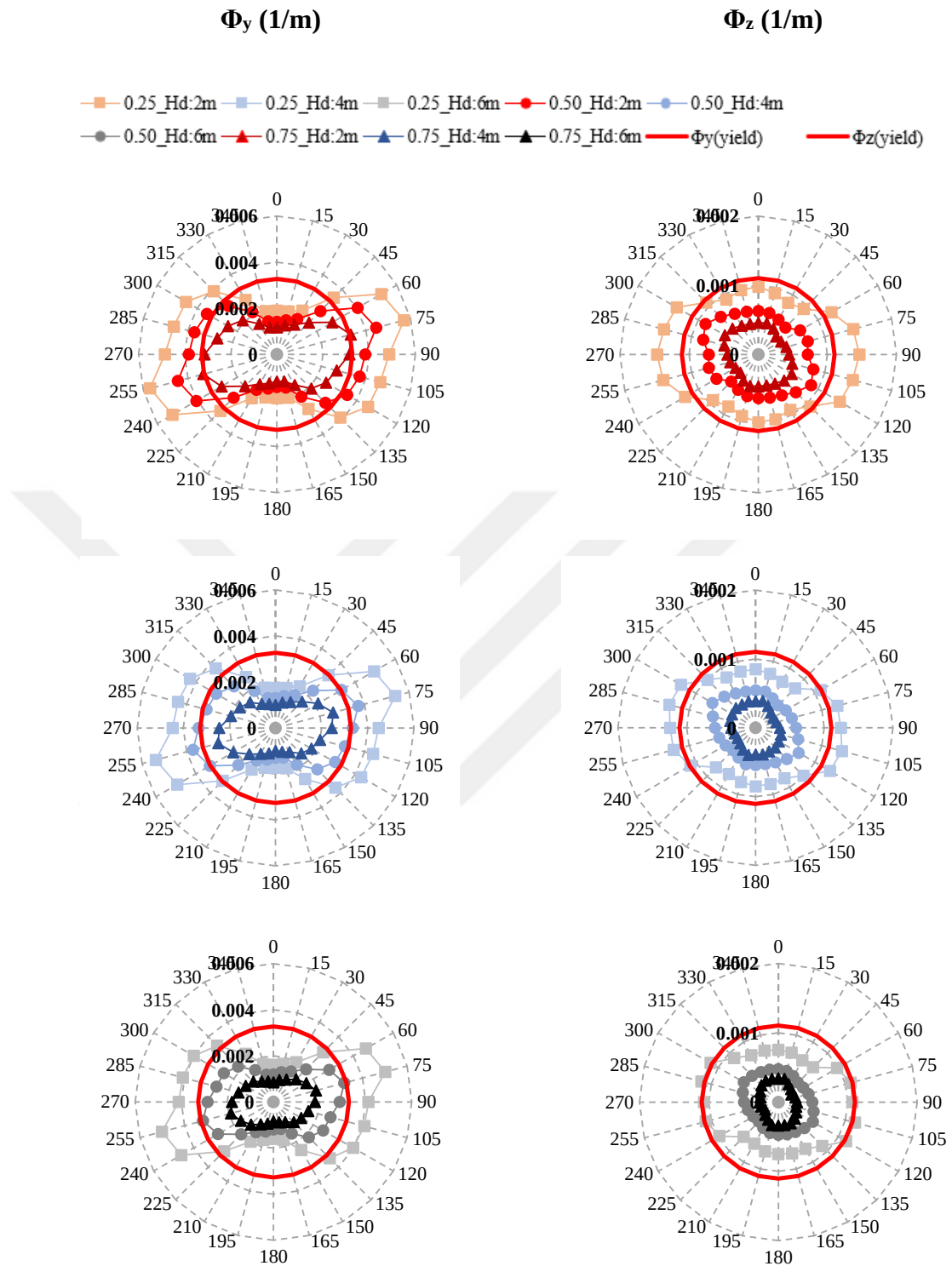


Figure 5.166. Average maximum curvature demands of non-skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

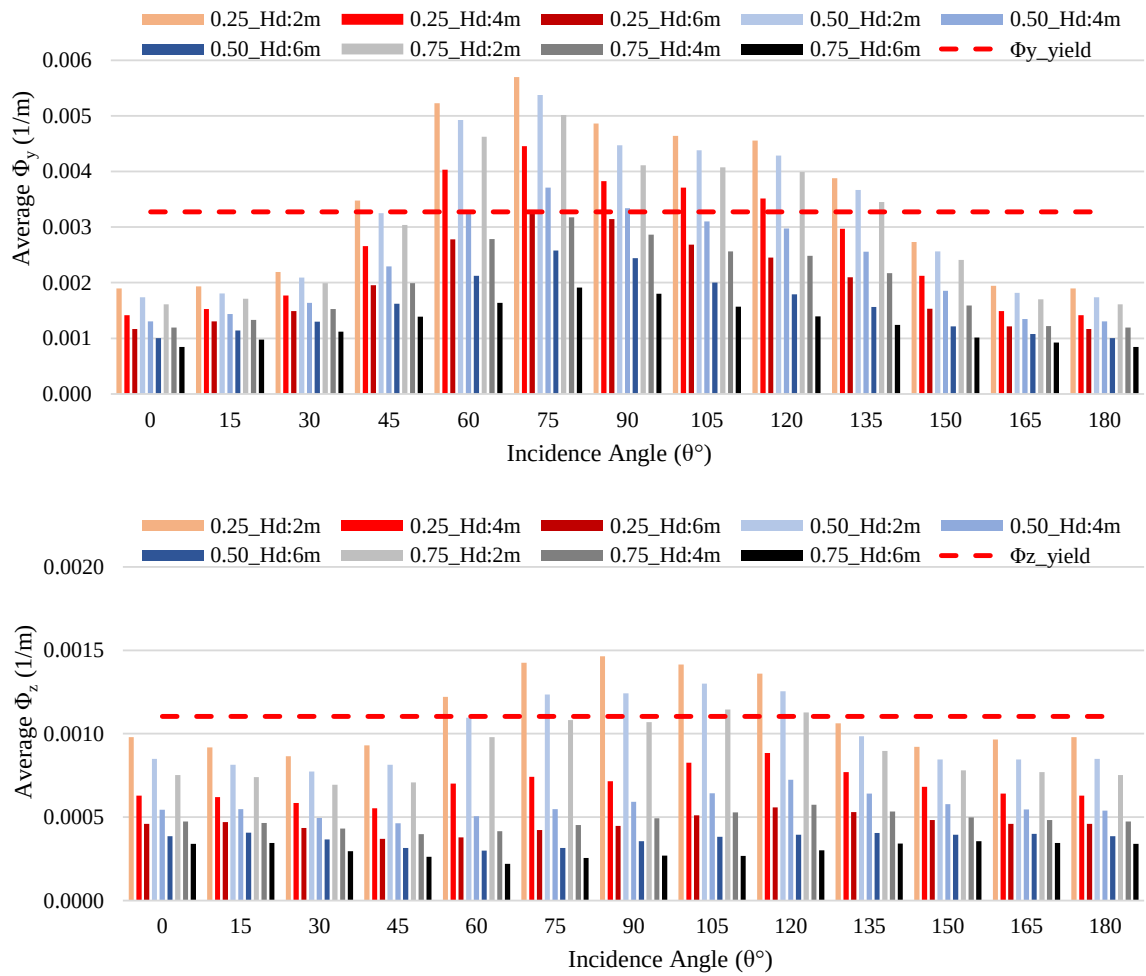


Figure 5.167. Average maximum curvature demands of non-skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

In Figure 5.168 and Figure 5.169, maximum curvature demands of middle column of 45° skewed bridge in weak (y') and strong (z') axis is given for 7 earthquakes and 13 incidence angles. When the radar and bar chart is checked, they show that average maximum column curvature demand has a decreasing trend when scour depth (H_d) increases in both axes and for all ground motion incidence angles. Also, demands tend to decrease when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average curvature demands in weak axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 165° incidence angle as nearly 53.6% when nonuniform scour change is 25% in longitudinal direction. In strong axis of column, it is at 105° incidence angle as 64.3%.

Moreover, the maximum difference of average curvature demands in weak axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scoure is occurred at 150° incidence angle as nearly 64.8% when nonuniform scour change is 50% in longitudinal direction. In strong axis, it is 75.9% at 105° ground motion incidence angle.

Finally, the maximum difference of average curvature demands in weak axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scoure is occurred at 150° incidence angle as nearly 70.9% when nonuniform scour change is 75% in longitudinal direction. In strong axis of column, it is at 105° incidence angle as 81.5%.



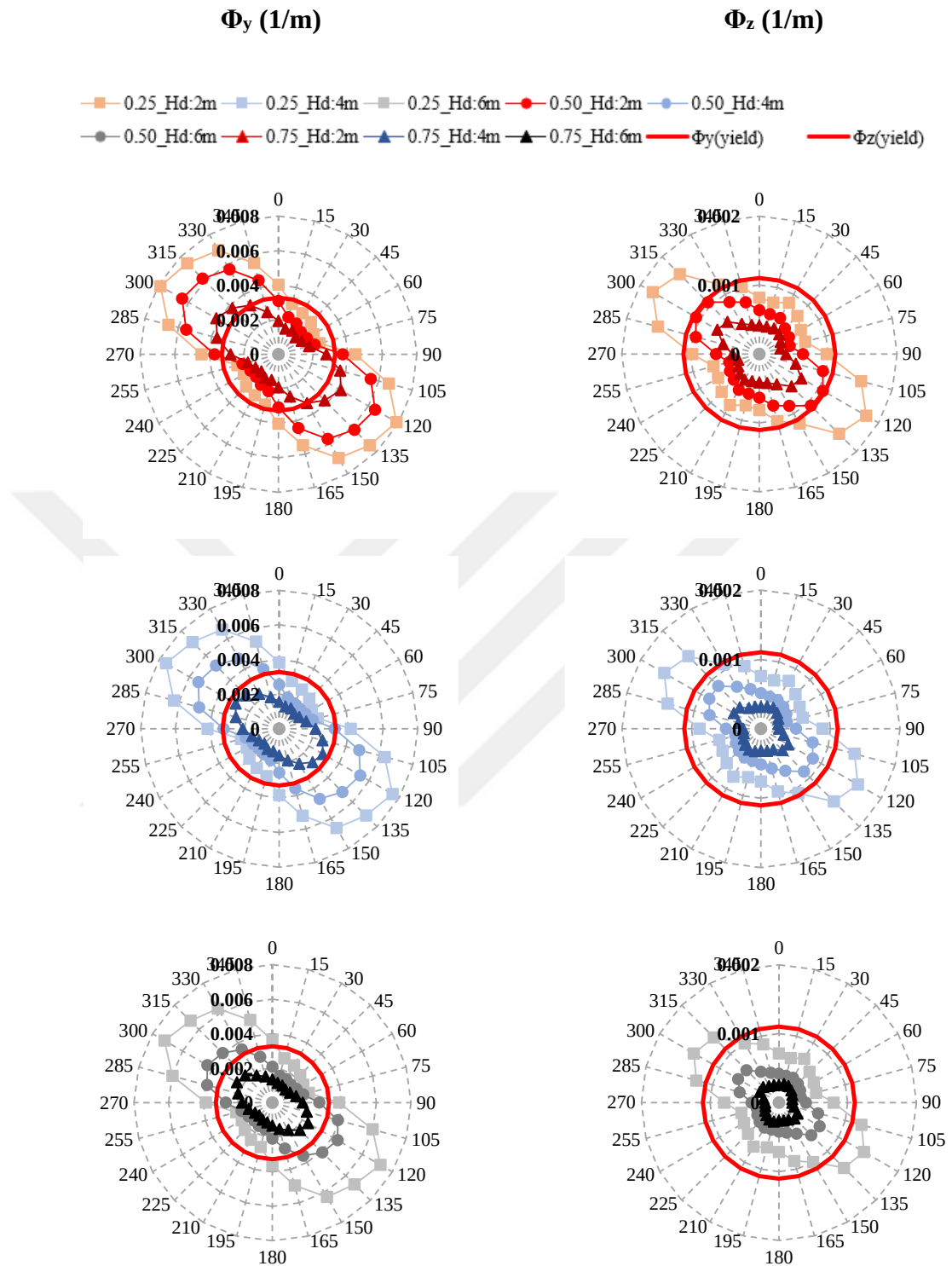


Figure 5.168. Average maximum curvature demands of 45° skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

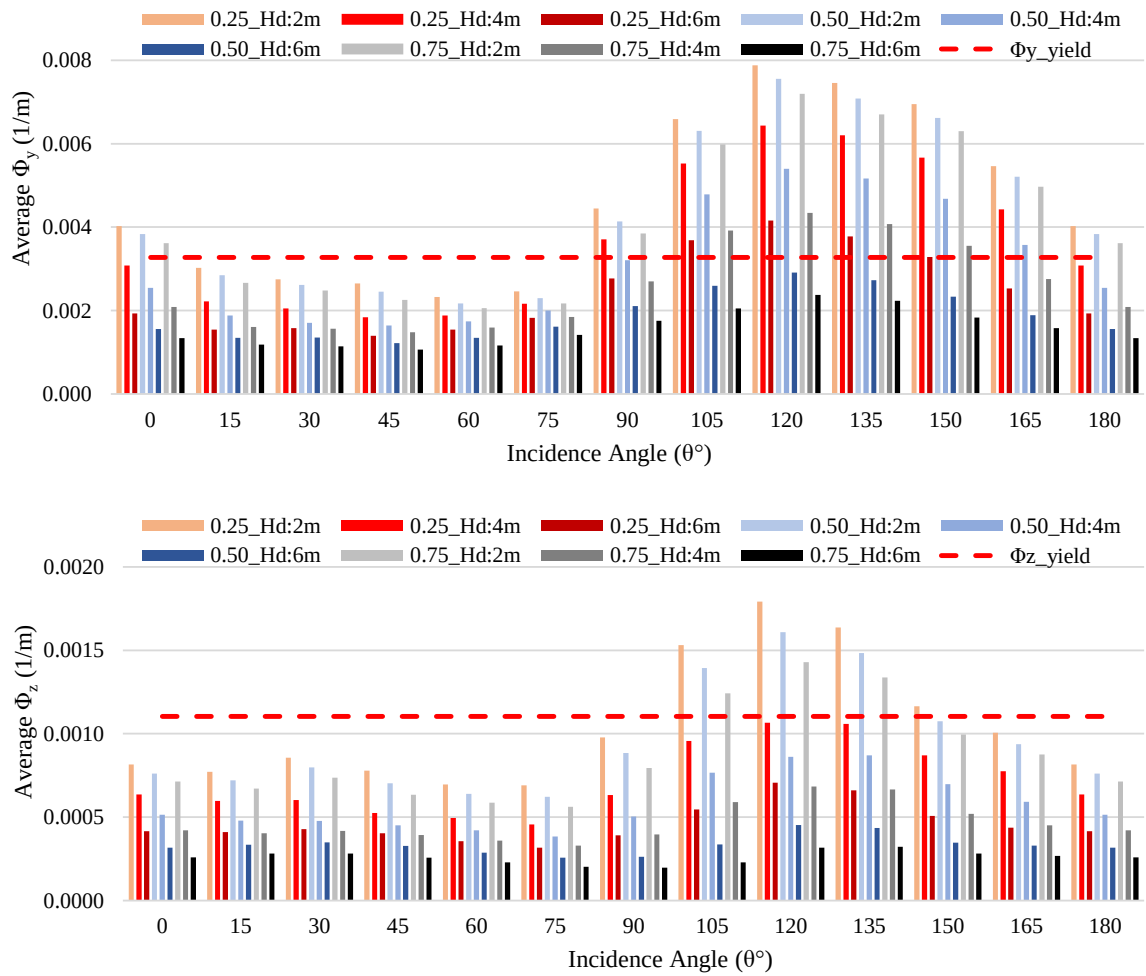


Figure 5.169. Average maximum curvature demands of 45° skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

In Figure 5.170 and Figure 5.171, maximum shear force demands of middle column of non-skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. Also, shear force demands in both local axes tend to decrease when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average shear force demands in local y' axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 60° incidence angle as nearly 33.9% when nonuniform scour change is 25% in longitudinal direction. In local z' axis of column, it is obtained at 165° incidence angle as 17.7%.

Moreover, the maximum difference of average shear force demands in local y' axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 60°

incidence angle as nearly 39.5% when nonuniform scour change is 50% in longitudinal direction. In local z' axis, it is obtained as 23.4% at 0° incidence angle.

Finally, the maximum difference of average shear force demands in local y' axis of non-skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 60° incidence angle as nearly 48.6% when nonuniform scour change is 75% in longitudinal direction. In local z' axis of column, it is obtained at 0° ground motion incidence angle as 30%.



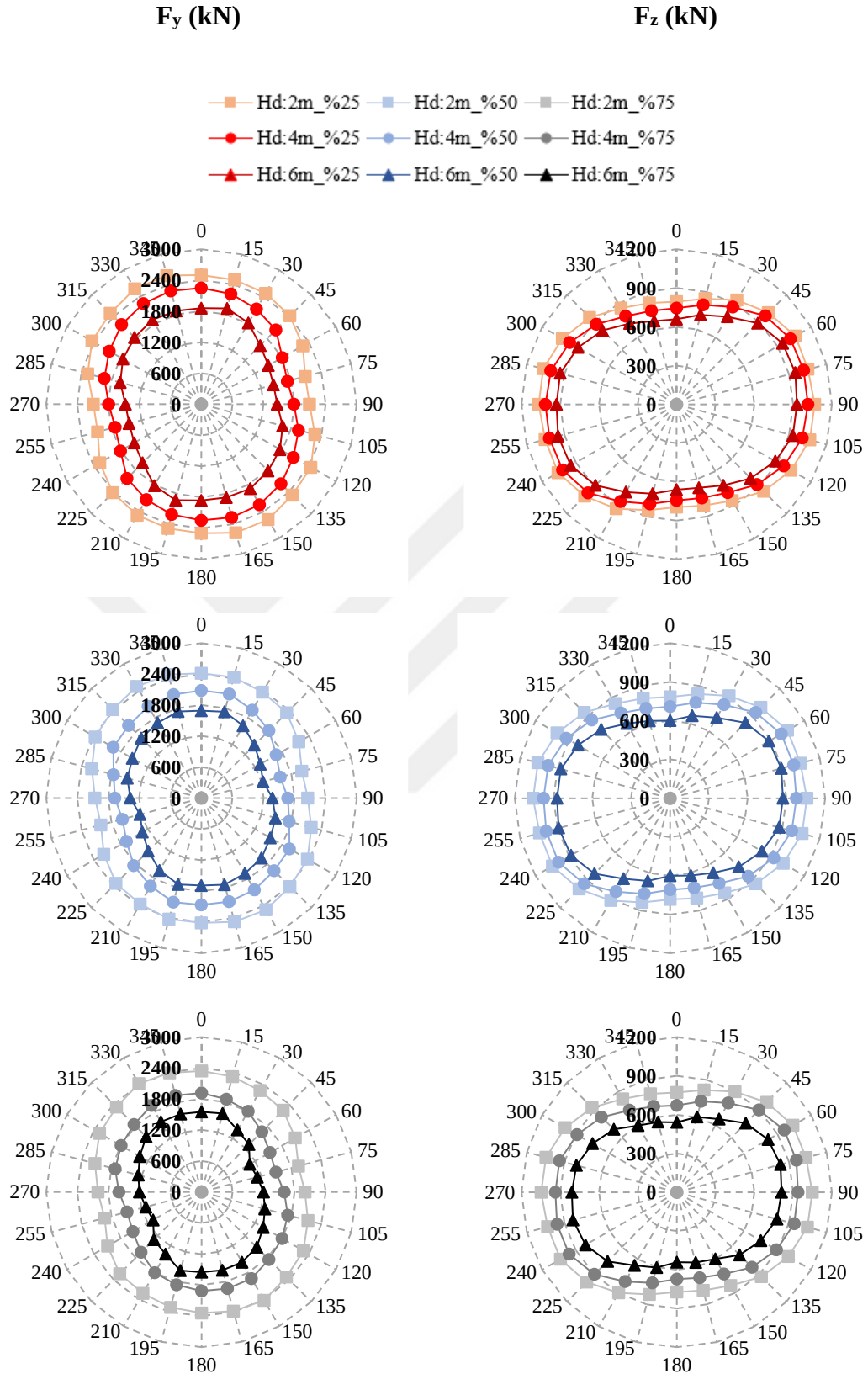


Figure 5.170. Average maximum shear force demands of non-skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

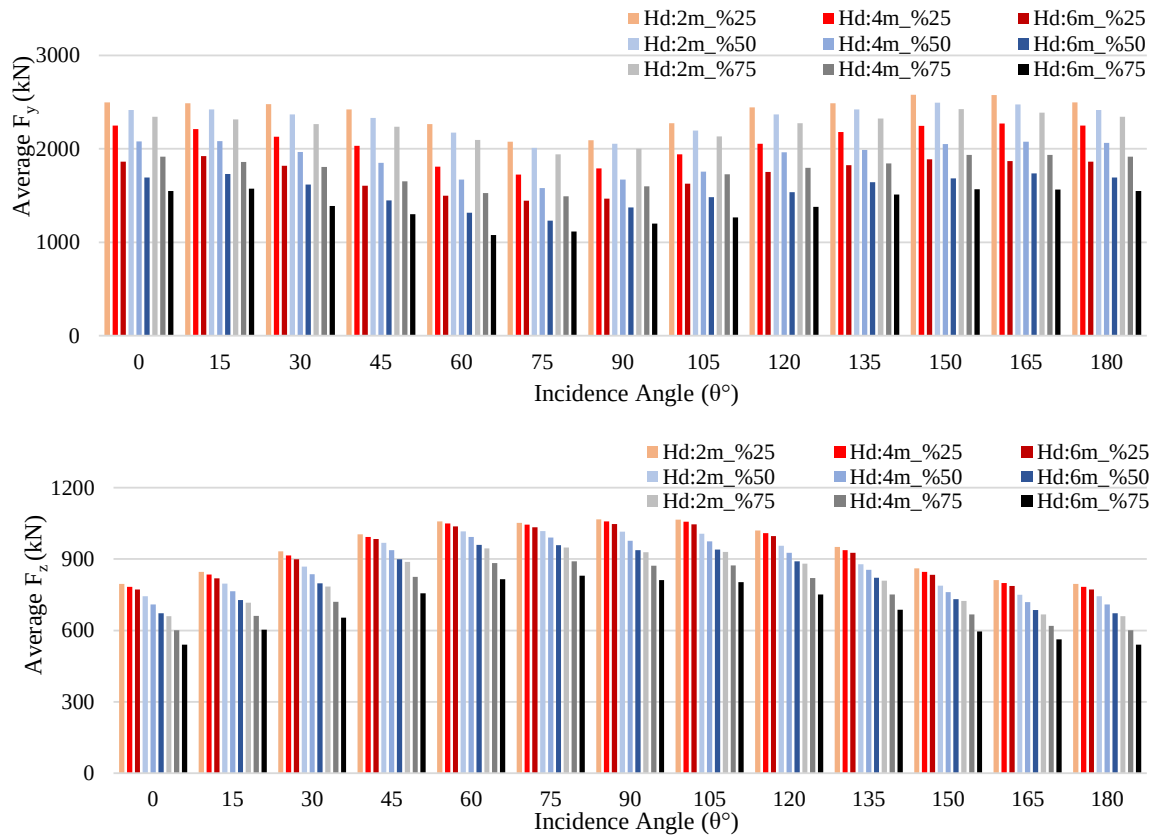


Figure 5.171. Average maximum shear force demands of non-skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

In Figure 5.172 and Figure 5.173, maximum shear force demands of middle column of 45° skewed bridge in local y' and z' axis is given for 7 earthquakes and 13 incidence angles. When the radar and bar chart is checked, shear force demands decrease as the depth of scour increases for all incidence angles. Also, shear force demands in both local axes tend to decrease when the change of non-uniform scour depth percentage in longitudinal direction increases.

The maximum difference of average shear force demands in local y' axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 90° incidence angle as nearly 32.9% when nonuniform scour change is 25% in longitudinal direction. In local z' axis of column, it is obtained at 45° incidence angle as 21.8%.

Moreover, the maximum difference of average shear force demands in local y' axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 90° incidence angle as nearly 39% when nonuniform scour change is 50% in longitudinal direction. In local z' axis, it is obtained as 26.4% at 45° incidence angle.

Finally, the maximum difference of average shear force demands in local y' axis of 45° skewed bridge column between $H_d=2$ m and $H_d=6$ m scour is occurred at 90° incidence angle as nearly 46.5% when nonuniform scour change is 75% in longitudinal direction. In local z' axis of column, it is obtained at 45° ground motion incidence angle as 31%.



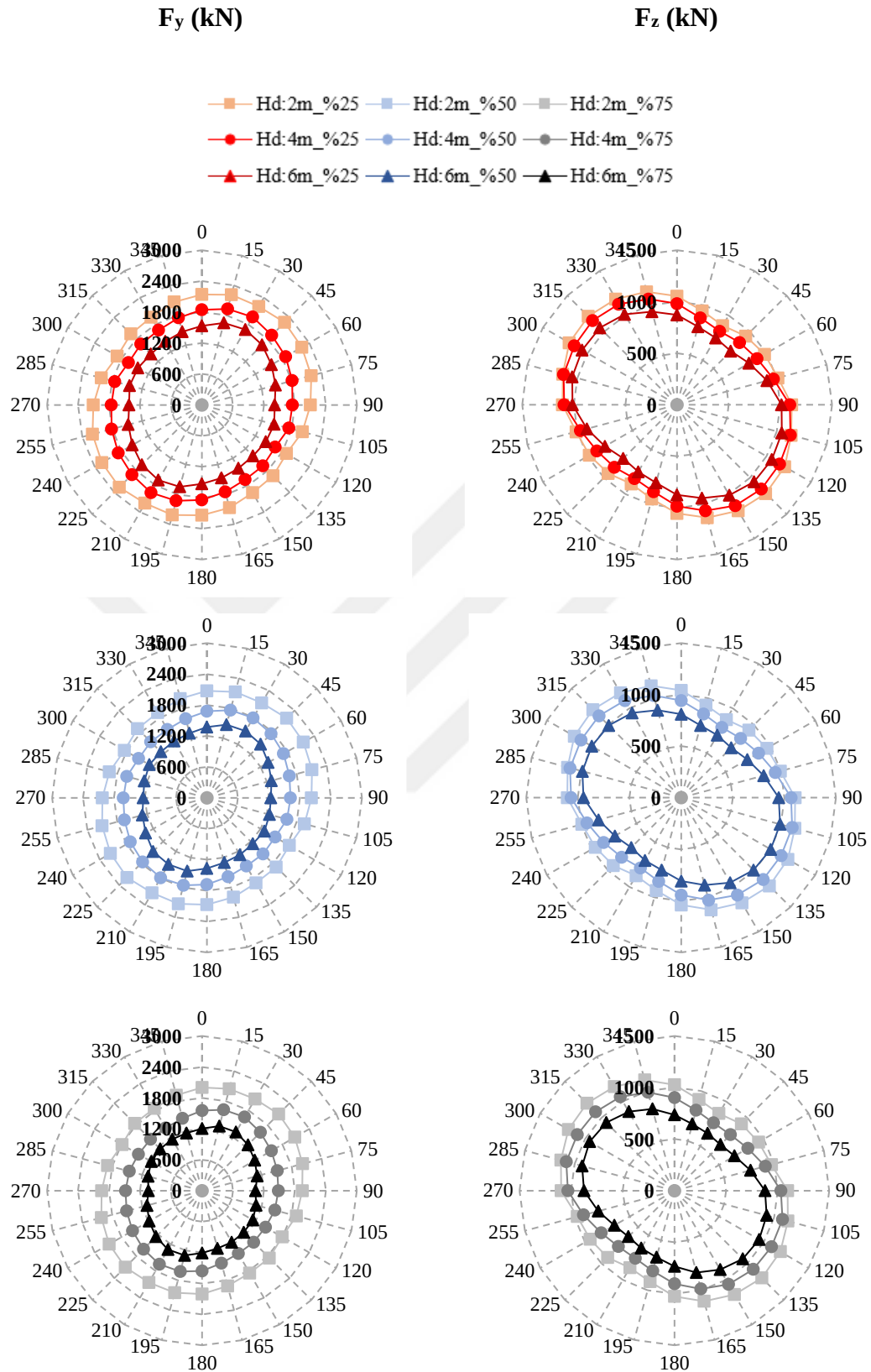


Figure 5.172. Average maximum shear force demands of 45° skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

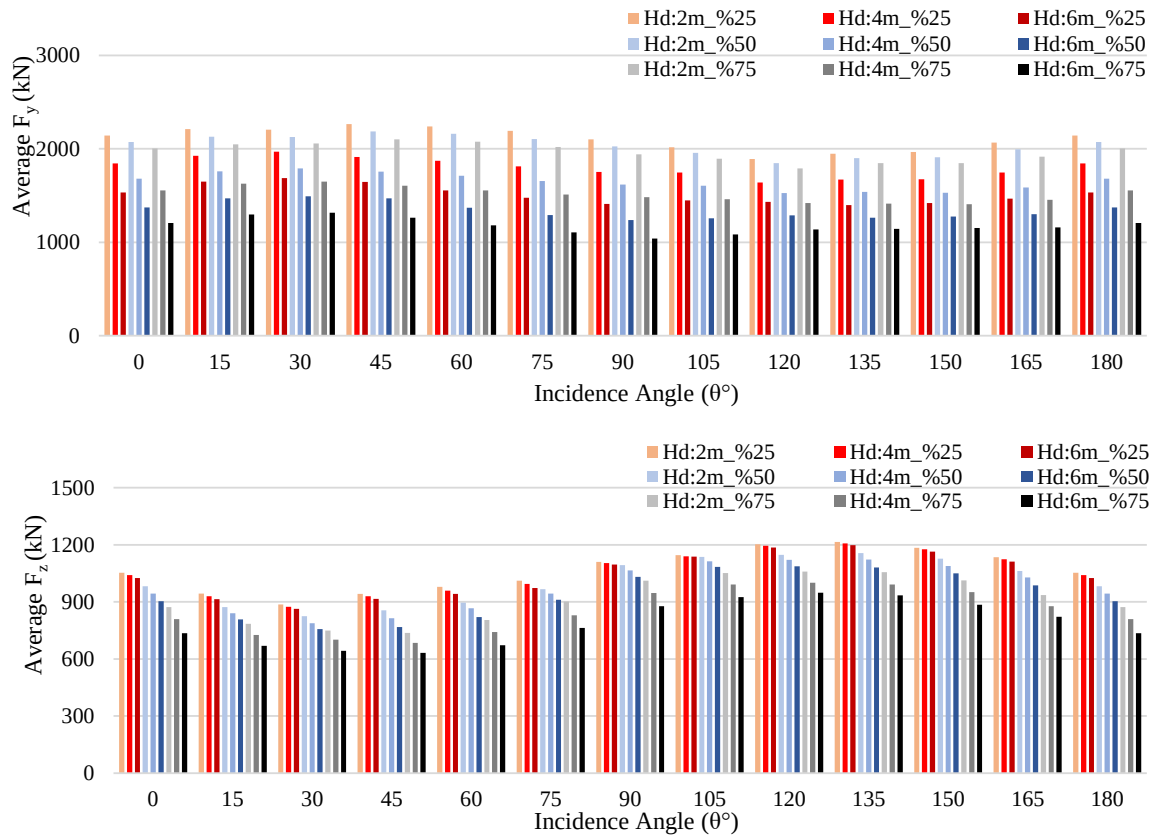


Figure 5.173. Average maximum shear force demands of 45° skewed bridge column for different nonuniform scour depths in longitudinal direction and earthquake incidence angles

Shear force demands of local y' axis of pile number 1 (P1) is given in detail for non-skewed bridge at 90° earthquake incidence angle in Figure 5.174. P1 pile shear demand is higher in 25% non-uniform scoured model when depth of scour is 2m and it is decreasing when scour depth and nonuniformity increases. Demands cannot reach the pile shear capacity for all scour depths and scour cases. In Figure 5.175, the same demands are obtained for 45° skewed bridge at 90° earthquake incidence angle and the results are same as the non-skewed bridge.

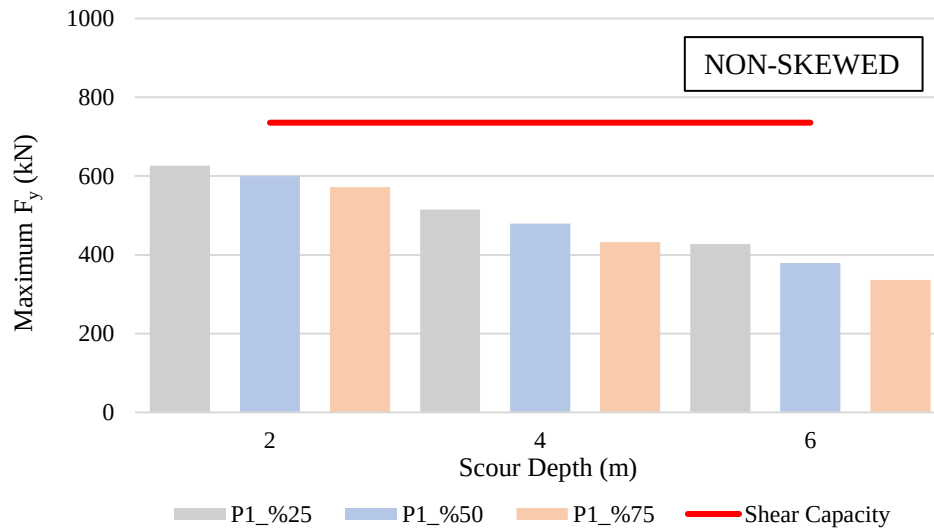


Figure 5.174. Average maximum shear force demands of local y' axis of pile (P1) for non-skewed bridge for different nonuniform scour depths in longitudinal direction and 90° earthquake incidence angle

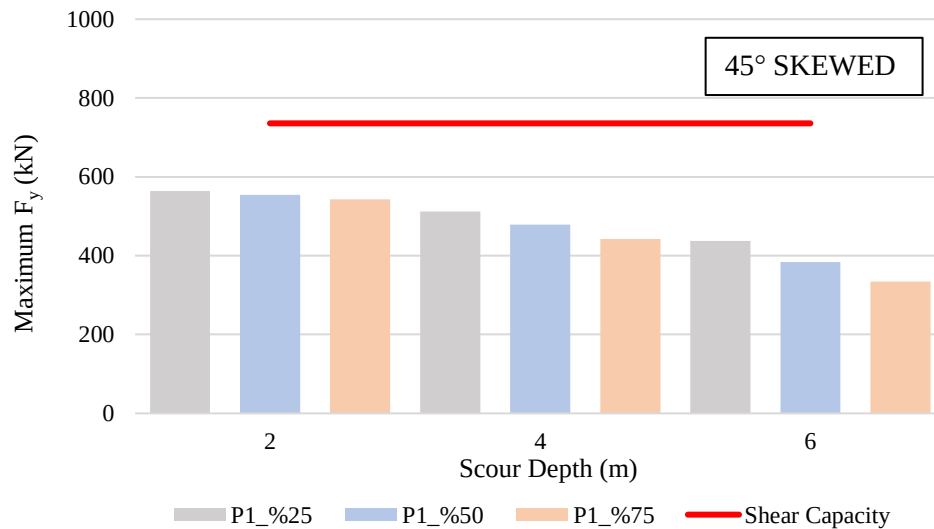


Figure 5.175. Average maximum shear force demands of local y' axis of pile (P1) for 45° skewed bridge for different nonuniform scour depths in longitudinal direction and 90° earthquake incidence angle

5.4. Comparison of Scour Cases

In the previous sections, nonlinear response history analysis results are given for each scour case separately and demands are compared according to the ground motion incidence angle, skew angle and change in scour depth. In this part of the thesis, it is aimed to compare the results obtained from bridges with uniform scour to the irregular

scoured bridges that occur in the transverse and longitudinal directions. This section consists of 2 subheadings. In the first one, the results obtained from uniform and non-uniform scour in the transverse direction are compared depending on the bridge skew angle and scour depth. In the second part, the results obtained from the bridge with uniform scour case are compared with the non-uniform scour case occurred in the longitudinal direction of the bridge. The engineering demand parameters examined are explained in detail in the subheadings.

5.4.1. Comparison of uniform (Case 1) and non-uniform scour in transverse direction (Case 2-1)

In this section, average maximum demands obtained from skewed and non-skewed bridge models under the effect of 7 ground motion records are compared in terms of scour cases which are uniform (Case-1) and non-uniform scour (Case2-1) with $\gamma=0.6$ and $\gamma=1.0$. The results are calculated for ground motion incidence angles starting from 0° to 180° with an increment of 15° and the graphs are generated for 90° incidence angle for inspected scour cases.

In Figure 5.176, 1st and 2nd vibration periods of the non-skewed and 45° skewed bridges depending on scour depth are compared for different scour cases. The maximum difference between 1st periods of Case-1 and Case 2-1a ($\gamma=0.6$) of non-skewed bridge is 2.4%, and it is 4.7% for 2nd periods of that cases when scour depth is 5 m. This difference becomes 4.4% for 1st period and 1.6% for 2nd period when Case-1 and Case 2-1b ($\gamma=1.0$) are compared to each other at same scour depth. Moreover, if skew angle becomes 45° , the difference between Case-1 and Case 2-1a ($\gamma=0.6$) becomes 3.2% for 1st period and 3.7% for 2nd period. When the periods compared for Case-1 and Case 2-1b ($\gamma=1.0$), the difference becomes 4.8% in the 1st period and 1.8% in the 2nd period. It demonstrates that when the angle between scour depth of upstream and downstream increases, the period of the structure also increases. In general, as the scour depth increases periods of both 1st and 2nd mode increase. Moreover, since the soil support around piles gets less from Case

2-1b ($\gamma=1.0$) to Case 1, both periods also increase. However, for each comparison, the increase in the periods is not significant and mostly remains in the range of 5%.

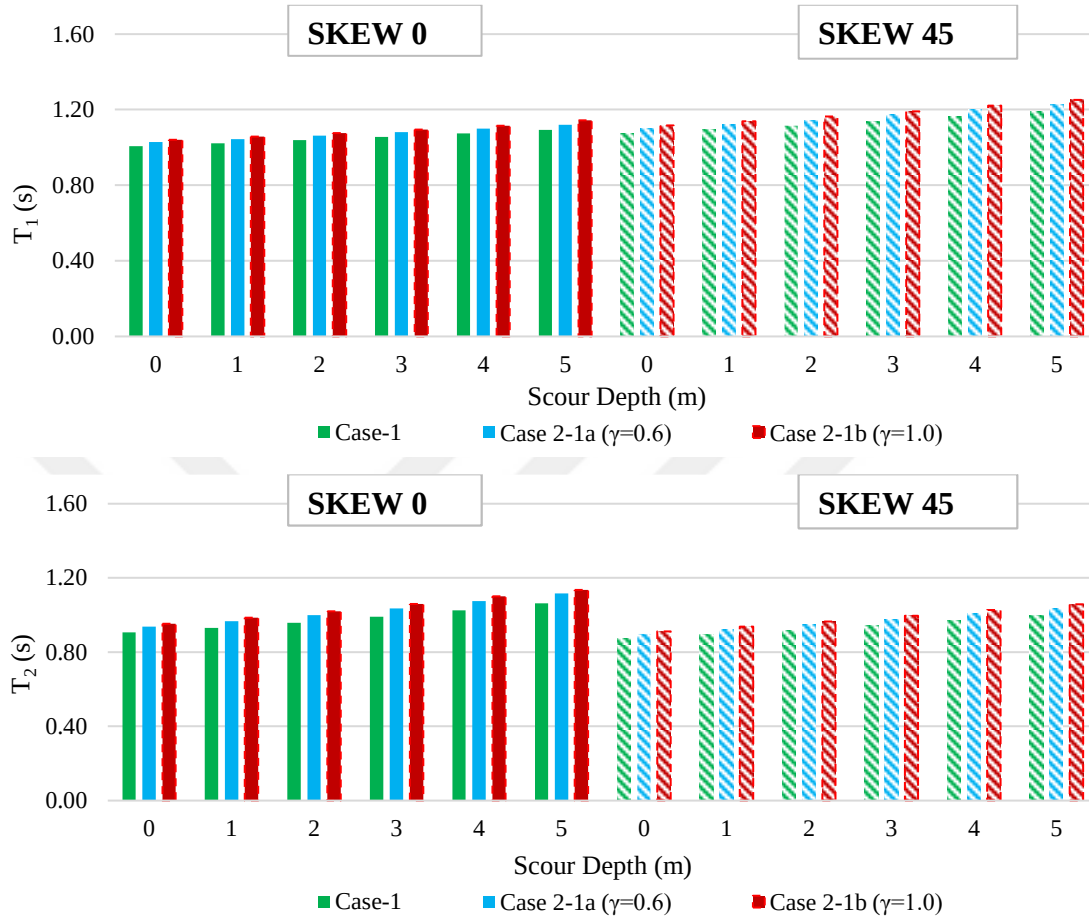


Figure 5.176. The variation of 1st and 2nd vibration period of non-skewed and 45° skewed bridge for uniform and non-uniform scour in transverse direction

Average maximum superstructure displacement demands obtained from nonlinear analysis results are given in Figure 5.177 for longitudinal and transverse directions of bridges and resultant displacement, respectively. The results are obtained for non-skewed and 45° skewed bridges at 90° ground motion incidence angle. Three different scour cases (Case-1, Case 2-1a ($\gamma=0.6$) and Case 2-1b ($\gamma=1.0$)) are compared with each other. According to the given graphs, superstructure demands are increasing with the increase in scour depth for all scour cases both in longitudinal and transverse directions of bridges, but this increase is more distinct in transverse direction. Also, the change in non-uniform scour depth affects the displacement demands more compared to the case with uniformly varying scour depth. When the results are compared according to the skew angle,

displacement demands are higher in non-skewed bridges in longitudinal direction. Besides, displacement demands are higher in 45° skewed bridge than the non-skewed bridge in transverse direction.

The maximum difference in longitudinal displacement demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 4 m scour depth as 3.3% and 4.8% for Case 2-1b. Also, the maximum difference in longitudinal displacement demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 2.2% and 3% for Case 2-1b.

In transverse direction, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 2.7% and 3.4% for Case 2-1b. Also, the maximum difference in transverse displacement demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 1 m scour depth as 5.2% and 4.2% for Case 2-1b.

If resultant displacement demands are checked, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 0 m scour as 2.8% and it reaches its maximum value as 3.8% in the same scour depth for Case 2-1b. Also, the maximum difference in resultant displacement demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 3.3% and 4.8% for Case 2-1b. Therefore, the effect of scour depth and scour case do not play a significant role on the superstructure displacement demands.

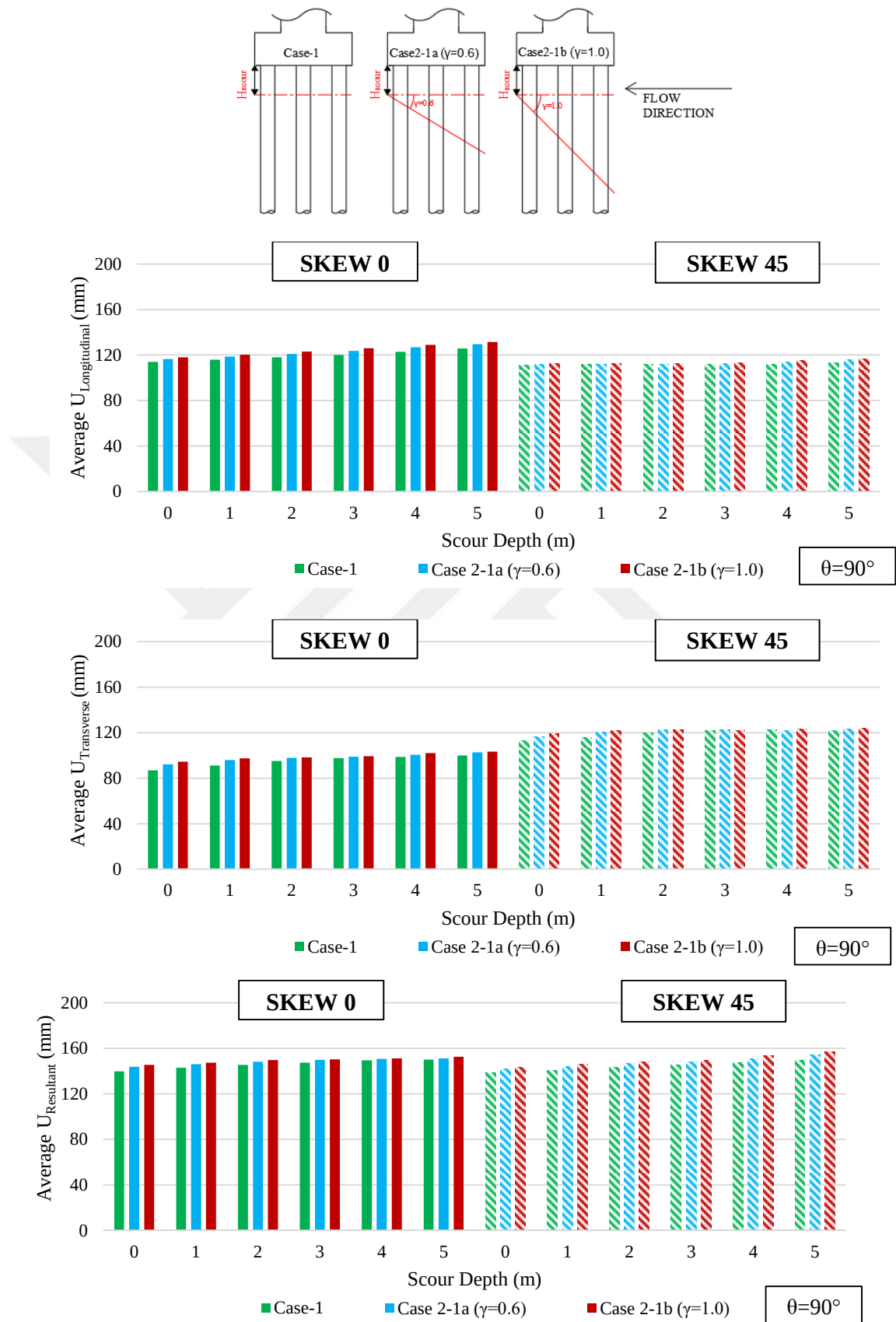


Figure 5.177. The variation of average maximum displacement demands of non-skewed and 45° skewed bridge for uniform and non-uniform scour in transverse direction for an incidence angle of 90°

Average maximum curvature demands obtained from nonlinear analysis results are given in Figure 5.178 for weak (y') and strong (z') axis of non-skewed and 45° skewed bridge middle column. The results are obtained for ground motion incidence angle of 90°. Three different scour cases (Case-1, Case 2-1a ($\gamma=0.6$) and Case 2-1b ($\gamma=1.0$)) are compared with each other. For weak axis, column curvature demands are above the yield curvature for both non-skewed and 45° skewed bridge for each scour cases and scour depths. In strong axis of the column, curvature demands are below the yield curvature in non-skewed and skewed bridge in 4 m and 5 m scour depths for all scour cases. For both bridges, column curvature demands have a decreasing trend as the scour depth increases for each axis. When the scour depth increases the unsupported clear height of the substructure, whose lateral stiffness is composed of the stiffness of the piers and piles with supporting soil, increases. This resulted in a more flexible bridge reducing the seismic demands imposed on the columns. Moreover, the contribution of pile system to the overall deformation of the bridge becomes more prevalent with the introduction of additional flexibility due to scouring, which made a relaxation on the bridge column and caused a reduction in the column curvature demands.

The maximum difference in column weak axis (y') demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 2 m scour depth as 10% and 15.8% for Case 2-1b. Also, the maximum difference in weak axis curvature demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 11.5% and similar behavior is observed in Case 2-1b.

In strong axis (z') of bridge column, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 3 m scour depth as 33% and 43% for Case 2-1b. Also, the maximum difference in strong axis curvature demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 21.5% and it is same as in Case 2-1b.

As presented in Figure 5.178, the variation in curvature demands among different scour cases is more prevalent for non-skewed bridge than 45° skewed bridge.

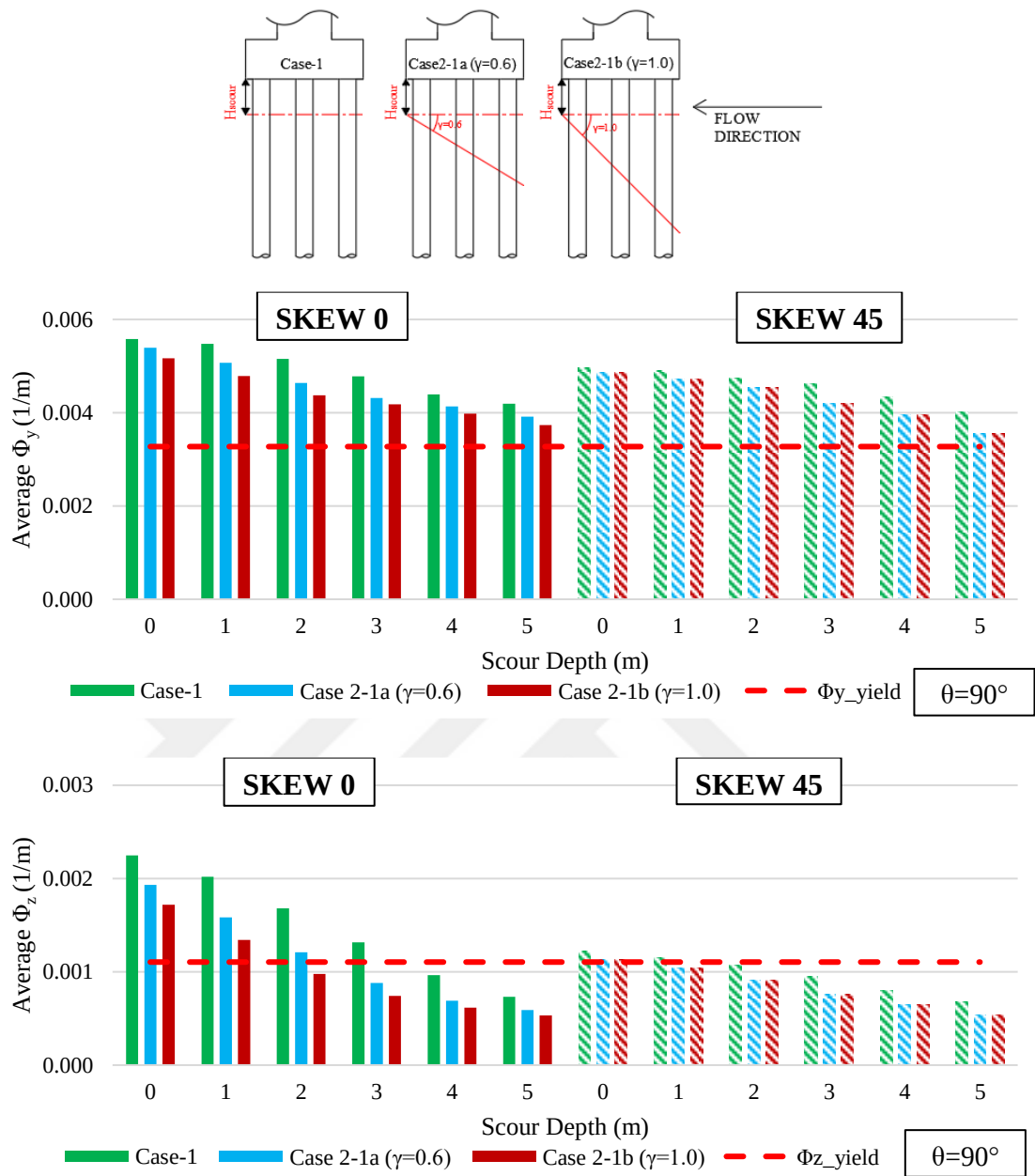


Figure 5.178. The variation of average maximum curvature demands of non-skewed and 45° skewed bridge column for uniform and non-uniform scour in transverse direction for an incidence angle of 90°

Average maximum shear force demands obtained from nonlinear analysis results are given in Figure 5.179 for local y' and z' axis of non-skewed and 45° skewed bridge middle column. The results are obtained for ground motion incidence angle of 90°. Three different scour cases (Case-1, Case 2-1a ($\gamma=0.6$) and Case 2-1b ($\gamma=1.0$)) are compared with each other. Column pier shear force demands occurred in both local y' and local z' axis are higher in the skewed bridge than in the non-skewed bridge. Additionally, as the scour depth increases, the shear force demands on the local axes tends to decrease.

Likewise, the shear force demands are less in bridge columns with non-uniform scour than in bridges with uniform scour. The reason for this is similar to curvature demands.

The maximum difference in shear force demands of column local y' axis for non-skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 11% and 15.4% for Case 2-1b. Also, the maximum difference in local y' axis shear force demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in also 5 m scour depth as 9.7% and it is 14.8% for Case 2-1b.

In local z' axis of bridge column, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 4.4% and 6.7% for Case 2-1b. Also, the maximum difference in local z' axis shear force demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 5 m scour depth as 3.8% and it is 6.1% for Case 2-1b.

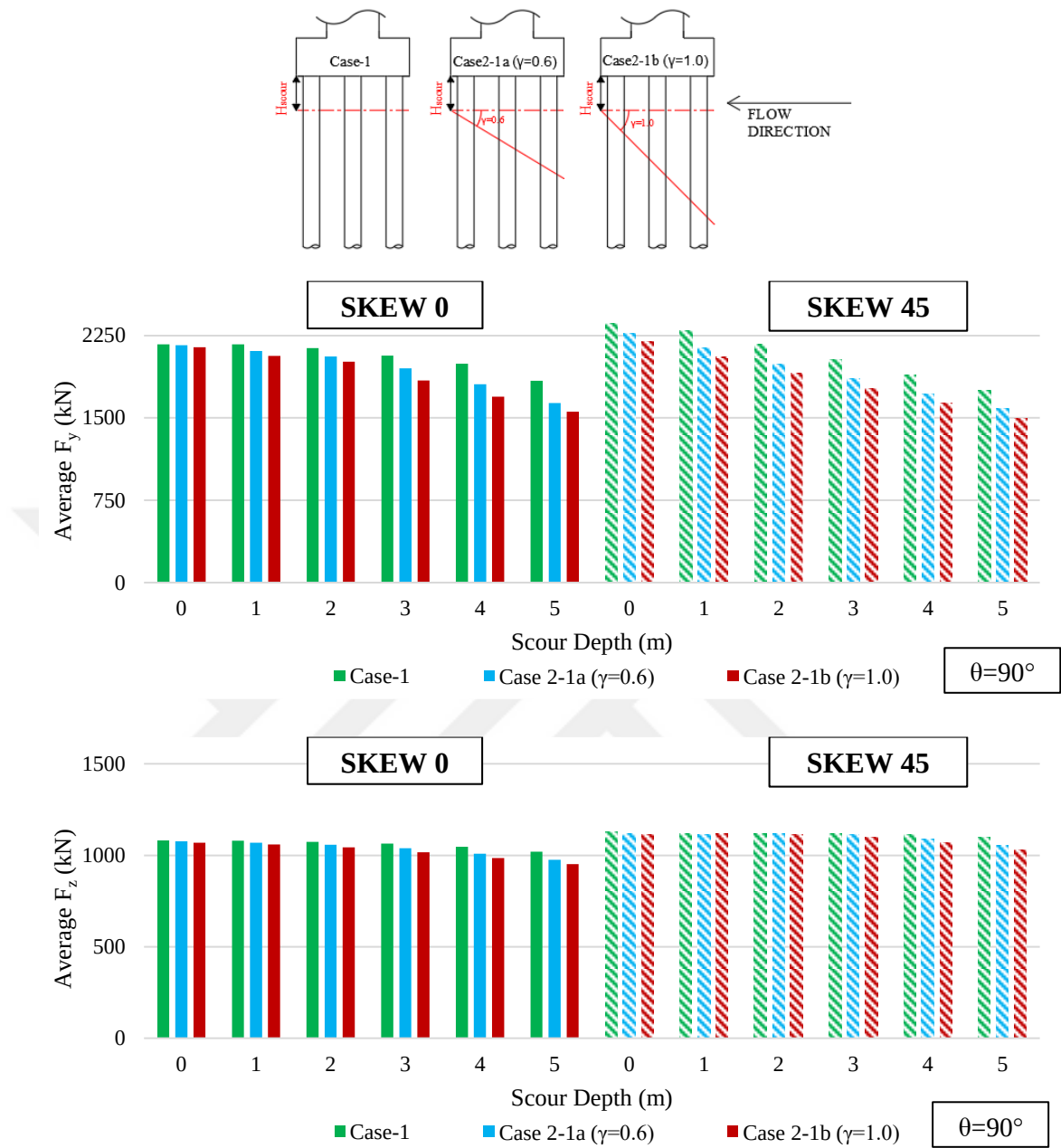


Figure 5.179. The variation of average maximum shear force demands of non-skewed and 45° skewed bridge column for uniform and non-uniform scour in transverse direction for an incidence angle of 90°

Average maximum shear force demands of P4 pile obtained from nonlinear analysis results are given in Figure 5.180 for local y' axis of non-skewed and 45° skewed bridge. The results are obtained for ground motion incidence angle of 90°. Three different scour cases (Case-1, Case 2-1a ($\gamma=0.6$) and Case 2-1b ($\gamma=1.0$)) are compared with each other. As seen from the graph, pile shear force demands tend to decrease when scour depth increases for both non-skewed and skewed bridges. When the results are compared according to the scour cases, the average of the maximum shear force of P4 pile is higher

in non-uniform scour cases than uniform scour. As the clear height of the piles and hence their stiffness varies for the non-uniform scour case, the distribution of shear force demands among the piles is not uniform. The piles having the least clear height are imposed higher shear demands than the piles having larger clear heights. Shear capacity of pile P4 was calculated as 735 kN according to the ASCE-ACI 426 (1973) as explained in previous section and it is shown with red dashed line in figure. If demands are compared with shear capacity, P4 pile do not exposed to any shear damage for the uniform scour case. On the other hand, especially in Case 2-1 where the scour depth around P4 pile is relatively less than the piles located in the upstream, shear demands of P4 are the highest. This results in shear failure of P4 pile especially for the non-skewed bridge. Such observation of shear failure is similar to the captive column shear failure observed in buildings.

The maximum difference in pile local y' axis demands for non-skewed bridge between Case-1 and Case 2-1a occurs in 0 m scour depth as 38.3% and 55.2% for Case 2-1b. Also, the maximum difference in local y' axis shear force demands for 45° skewed bridge between Case-1 and Case 2-1a occurs in 1 m scour depth as 38.5% and it is 61.6% for Case 2-1b.

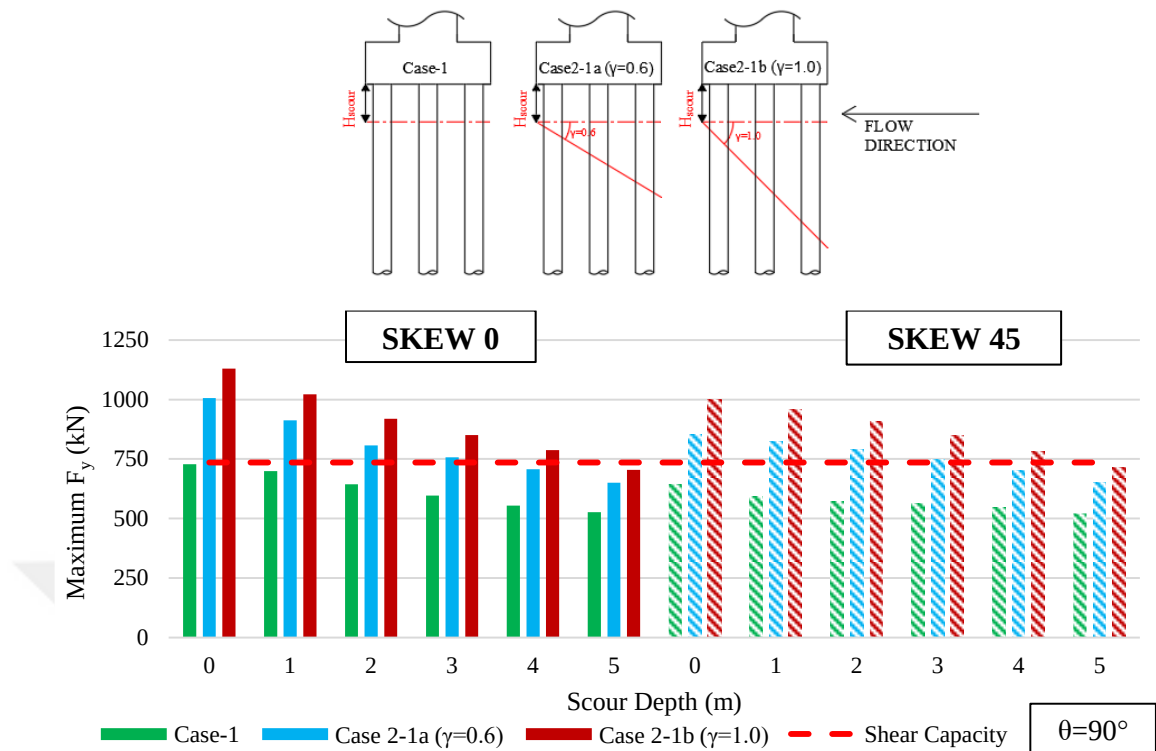


Figure 5.180. Average maximum shear force demands of local y' axis of non-skewed and 45° skewed bridge pile (P4) for different scour cases for an incidence angle of 90°

5.4.2. Comparison of uniform (Case 1) and non-uniform scour in longitudinal direction (Case 2-2)

In this section, average maximum demands obtained from skewed and non-skewed bridge models under the effect of 7 ground motion records are compared in terms of scour cases which are uniform (Case-1) and non-uniform scour in longitudinal direction (Case2-2). The results are calculated for ground motion incidence angles starting from 0° to 180° with an increment of 15° and the graphs are generated for 90° incidence angle for inspected scour cases. Since it is necessary to compare models with the same scour depth in order to compare the results obtained from bridges with uniform and non-uniform scour cases, the graphs obtained in this section are obtained only for 2 m and 4 m scour depths.

In Figure 5.181, 1st and 2nd vibration periods of the non-skewed and 45° skewed bridges depending on scour depth are given for different scour cases. As seen from the graph, in both non-skewed and skewed bridges, period increases when scour depth increases for all scour cases. On the other hand, the non-uniform change of scour depth in longitudinal direction does not cause a significant increase in periods. The maximum

difference occurs between 1st periods of Case-1 and Case 2-2c (75%) of non-skewed bridge as 1.8%, and it is 2.6% for skewed bridge of that cases when scour depth is 4 m.

Maximum difference becomes 3.9% for 2nd period of non-skewed bridge and 2.9% for 2nd period of skewed bridge for the same cases.

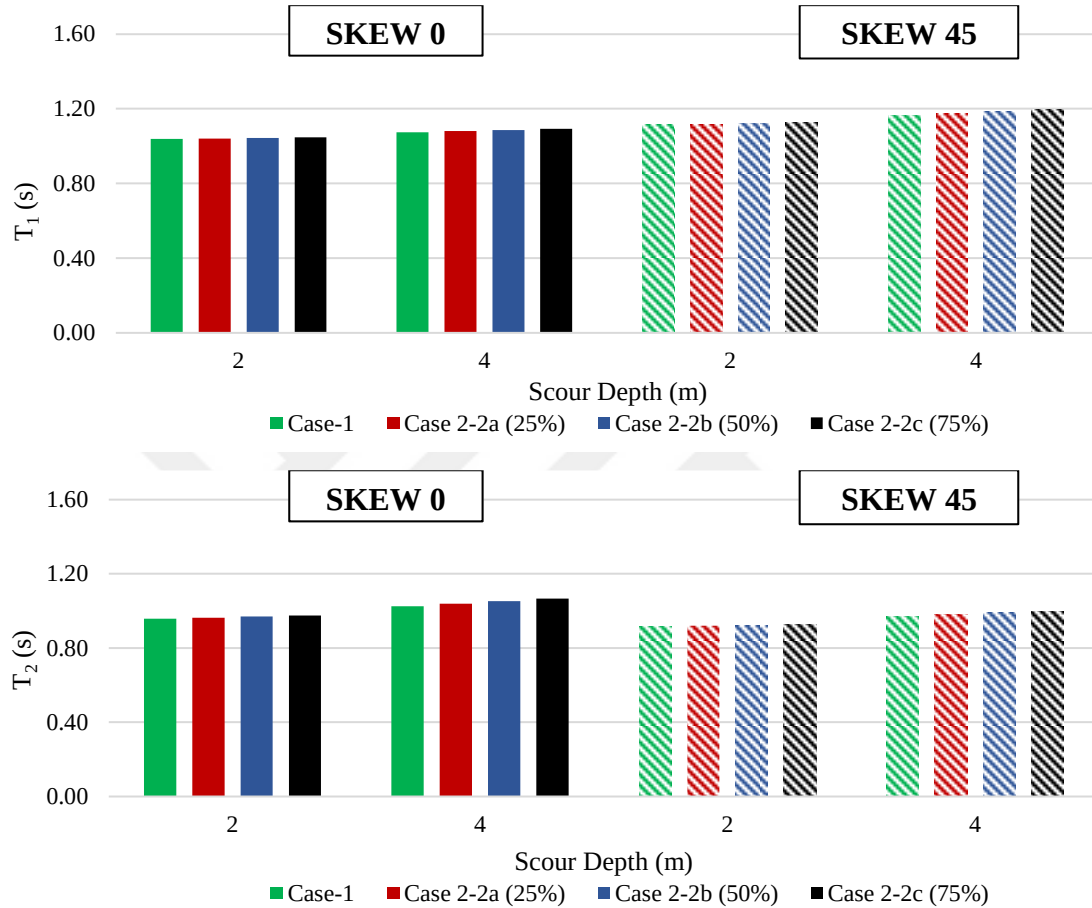


Figure 5.181. The variation of 1st and 2nd vibration period of non-skewed and 45° skewed bridge for uniform and non-uniform scour in longitudinal direction

Average maximum superstructure displacement demands obtained from nonlinear analysis results are given in Figure 5.182 for longitudinal and transverse directions of bridges and resultant displacement, respectively. The results are obtained for non-skewed and 45° skewed bridges at 90° ground motion incidence angle. Four different scour cases (Case-1, Case 2-2a (25%), Case 2-2b (50%) and Case 2-2c (75%)) are compared with each other. According to the given graphs, superstructure demands are increasing with the increase in scour depth for all scour cases both in longitudinal and transverse directions of bridges, but this increase is not distinct for different scour cases. When the

results are compared according to the skew angle, displacement demands are higher in non-skewed bridges in longitudinal direction. Besides, displacement demands are higher in 45° skewed bridge than the non-skewed bridge in transverse direction. As a result, it can be inferred that the displacement demands of the bridge superstructure are not affected much by uniform and non-uniform scour in the longitudinal direction, but the demands are affected more by the change of the skew angle, which is an important irregularity in bridges.

The maximum difference in longitudinal displacement demands for non-skewed bridge between Case-1 and Case 2-2a occurs in 4 m scour depth as 0.8%, 1.7% for Case 2-2b and it is obtained as 2.6% between Case-1 and Case 2-2c. Also, this difference becomes 0.1%, 0.2% and 0.6% for the same cases of 45° skewed bridge in 4 m scour depth, respectively.

In transverse direction, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-2a occurs in 2 m scour depth as 1.0%, 1.6% for Case 2-2b and it is obtained as 2.3% between Case-1 and Case 2-2c. Also, the maximum difference in transverse displacement demands for 45° skewed bridge between Case-1 and Case 2-2a occurs in 2 m scour depth as 0.5%, 1.0% for Case 2-1b and it is obtained as 1.4% between Case-1 and Case 2-2c.

If resultant displacement demands are checked, the maximum difference in demands for non-skewed bridge between Case-1 and Case 2-2a occurs in 2 m scour as 0.4% and it becomes 0.6% in the same scour depth for Case 2-2b and it is 1.0% between Case-1 and Case 2-2c. Also, the maximum difference in resultant displacement demands for 45° skewed bridge between Case-1 and Case 2-2a occurs in 4 m scour depth as 0.5%, it becomes 1.0% for Case 2-2b and it is 1.8% between Case-1 and Case 2-2c.

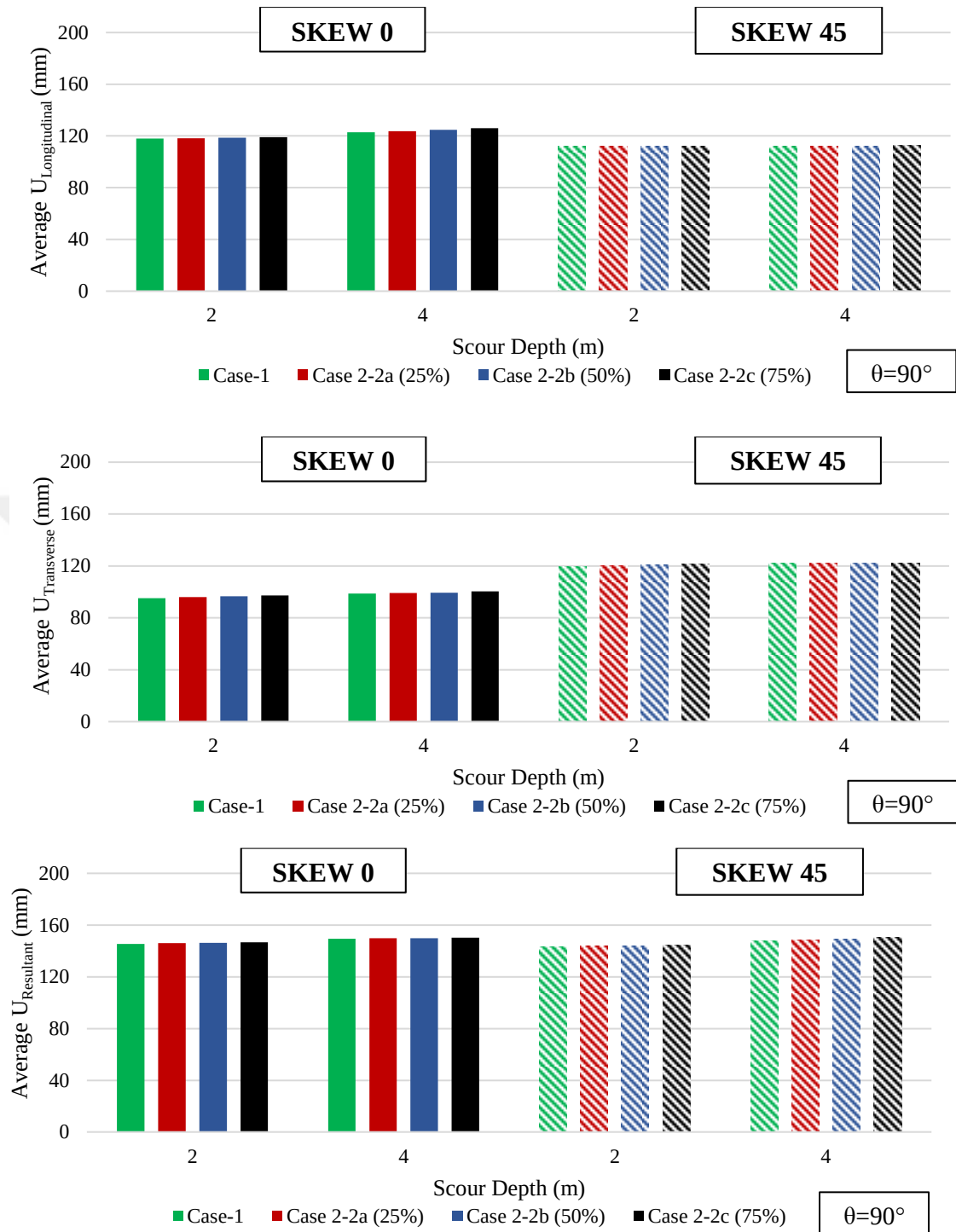


Figure 5.182. The variation of average maximum displacement demands of non-skewed and 45° skewed bridge for uniform and non-uniform scour in longitudinal direction for an incidence angle of 90°

Average maximum curvature demands obtained from nonlinear analysis results are given in Figure 5.183 for weak (y') and strong (z') axis of non-skewed and 45° skewed bridge middle column. The results are obtained for ground motion incidence angle of 90°. Four different scour cases (Case-1, Case 2-2a (25%), Case 2-2b (50%) and Case 2-2c

(75%)) are compared with each other. For weak axis, column curvature demands are above the yield curvature for both non-skewed and 45° skewed bridge for each scour cases when scour depth is 2 m. In strong axis of the column, curvature demands are below the yield curvature in 45° skewed bridge for all scour depths and scour cases. For both bridges, column curvature demands have a decreasing trend as the scour depth increases for each axis.

The maximum difference occurred in column weak axis (y') of non-skewed bridge between Case-1 and Case 2-2a achieved as 12.8%, 24% for Case 2-2b and it is obtained as 34.7% between Case-1 and Case 2-2c in 4 m scour depth. Also, the maximum difference occurred in weak axis of 45° skewed is obtained in the same scour depth as 14.6%, 26.1% and 37.8% between each cases, respectively.

In strong axis (z') of bridge column, the maximum difference of curvature demands for non-skewed bridge between Case-1 and Case 2-2a occurs in 2 m scour depth as 25.8%, 38.8% for Case 2-2b and it is obtained as 49% between Case-1 and Case 2-2c. When the maximum difference is checked for strong axis of 45° skewed bridge, it is obtained as 21.4% between Case-1 and Case 2-2a in 4m scour depth, 37.3% for Case 2-2b and it is 50.7% between Case-1 and Case 2-2c.

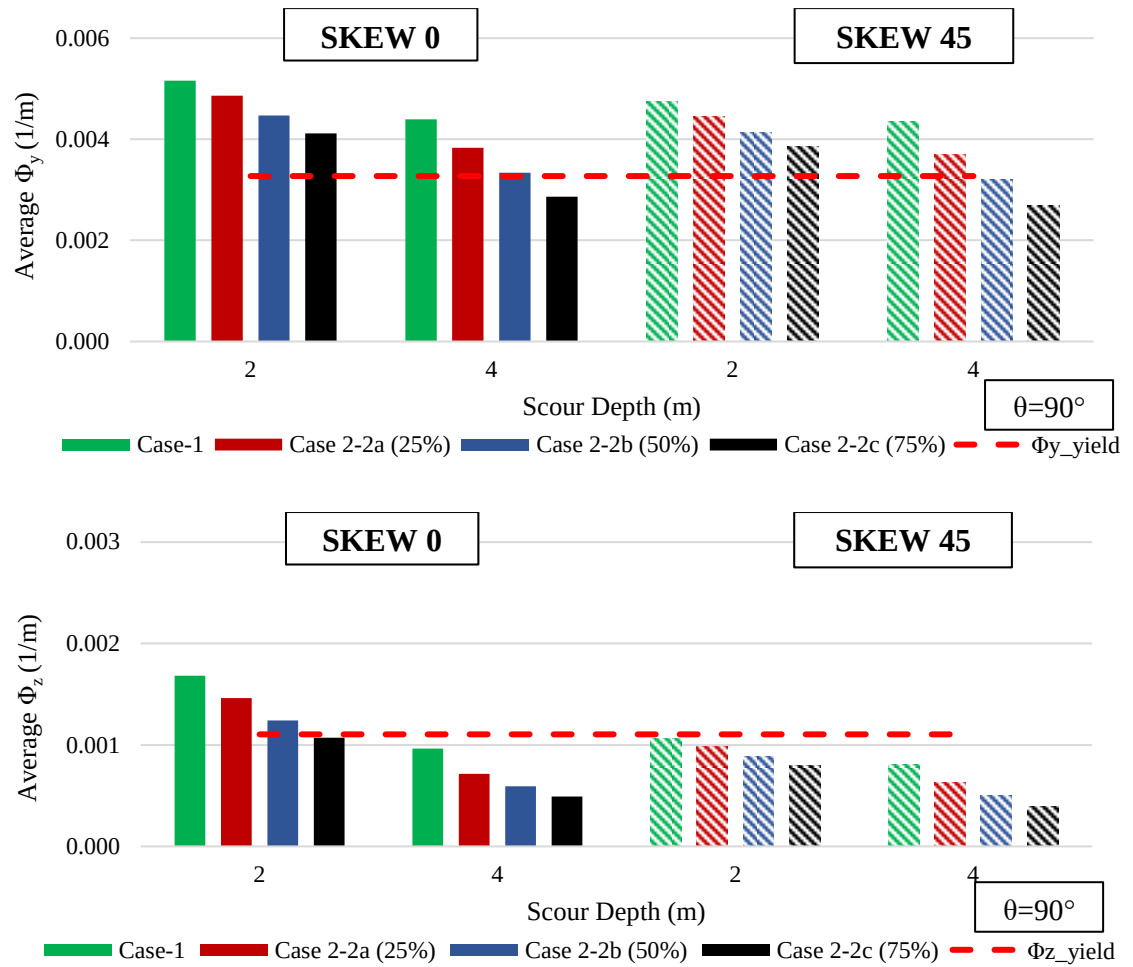


Figure 5.183. The variation of average maximum curvature demands of non-skewed and 45° skewed bridge column for uniform and non-uniform scour in longitudinal direction for an incidence angle of 90°

Average maximum shear force demands obtained from nonlinear analysis results are given in Figure 5.184 for local y' and z' axis of non-skewed and 45° skewed bridge middle column. The results are obtained for ground motion incidence angle of 90°. Four different scour cases (Case-1, Case 2-2a (25%), Case 2-2b (50%) and Case 2-2c (75%)) are compared with each other. Column pier shear force demands occurred in both the local y' and local z' axis are higher in the skewed bridge than in the non-skewed bridge. Additionally, as the scour depth increases, the shear force demands on the local axes tends to decrease. Likewise, the shear force demands are less in bridge columns with non-uniform scour than in bridges with uniform scour.

The maximum difference in shear force demands occurred in column local y' axis of non-skewed bridge between Case-1 and Case 2-2a achieved as 10.3%, 16.2% for Case 2-2b and it is obtained as 20% between Case-1 and Case 2-2c in 4 m scour depth. Also,

the maximum difference occurred in local y' axis of 45° skewed is obtained in the same scour depth as 7.5%, 14.6% and 21.7% between each cases, respectively.

In local z' axis of bridge column, the maximum difference in shear force demands for non-skewed bridge between Case-1 and Case 2-2a occurs in 4 m scour depth as 3.1%, 6.8% for Case 2-2b and it is 10.5% between Case-1 and Case 2-2c. Also, the maximum difference in shear force demands of local z' axis for 45° skewed bridge occurs in 4 m scour depth as 2%, 4.5% and 7.5% between same cases, respectively.

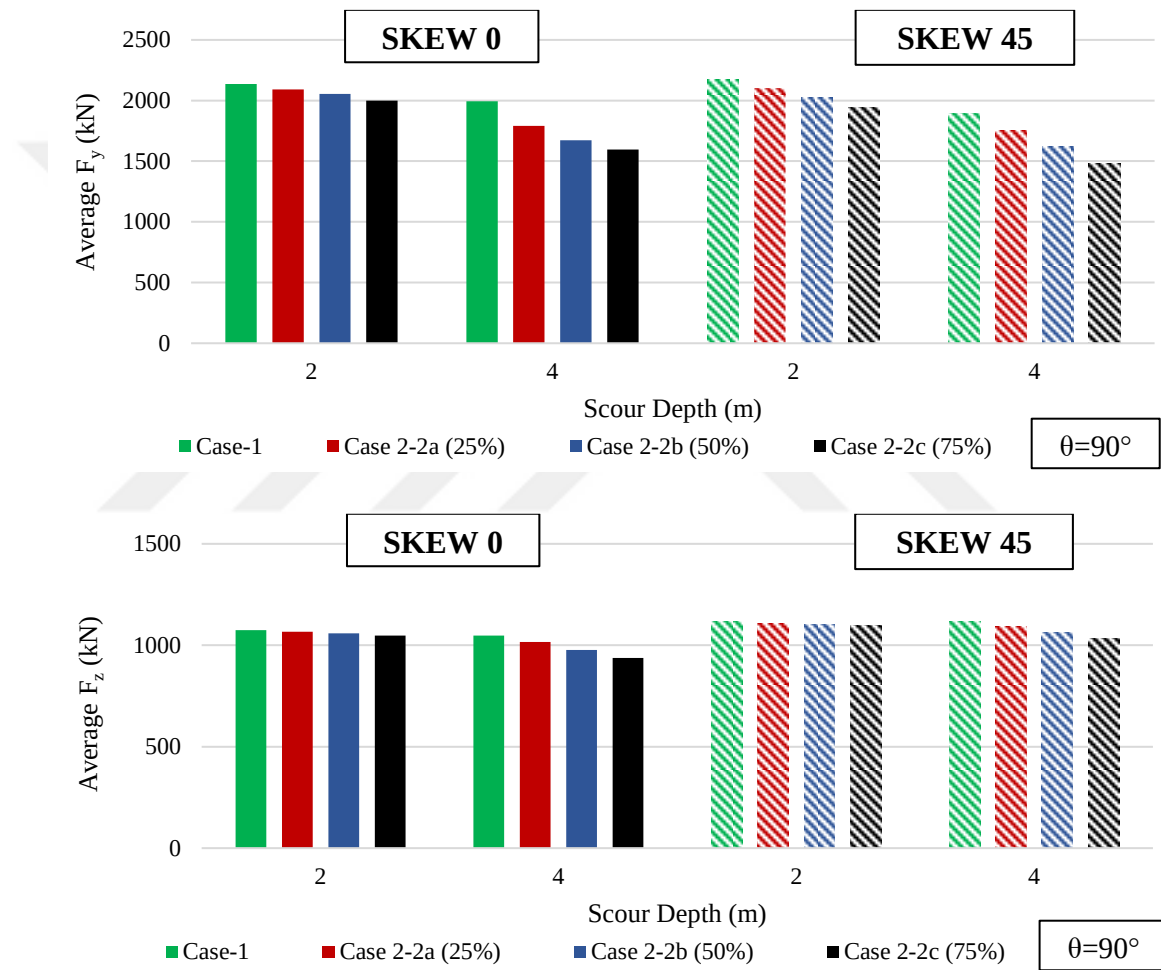


Figure 5.184. The variation of average maximum shear force demands of non-skewed and 45° skewed bridge column for uniform and non-uniform scour in longitudinal direction for an incidence angle of 90°

Average maximum shear force demands of P4 pile obtained from nonlinear analysis results are given in Figure 5.185 for local y' axis of non-skewed and 45° skewed bridge. The results are obtained for ground motion incidence angle of 90° . Four different scour cases (Case-1, Case 2-2a (25%), Case 2-2b (50%) and Case 2-2c (75%)) are compared

with each other. As seen from the graph, pile shear force demands tend to decrease when scour depth increases for both non-skewed and skewed bridges. When the results are compared according to the scour cases, the average of the maximum shear force of P4 pile is less in non-uniform scour cases than uniform scour. Shear capacity of pile P4 was calculated as 735 kN according to the ASCE-ACI 426 (1973) as explained in previous section and it is shown with red dashed line in figure. If demands are compared with shear capacity, P4 pile do not exposed to any shear damage for both uniform scour and non-uniform scour in longitudinal direction. This means, there is no brittle failure occurred on piles during earthquake for this type of scoured bridges.

The maximum difference in shear force demands occurred in P4 pile local y' axis of non-skewed bridge between Case-1 and Case 2-2a achieved as 7.1%, 13.6% for Case 2-2b and it is obtained as 22.1% between Case-1 and Case 2-2c in 4 m scour depth. Also, the maximum difference occurred in local y' axis of 45° skewed is obtained in the same scour depth as 6.1%, 12.2% and 18.9% between each cases, respectively. In Case 2-2, for the non-uniform scour case in longitudinal direction, the effective lengths of all piles are the same in the pile group. Therefore, no shear failure was observed in Case 2-2 as in the case of Case 2-1 similar to captive column shear failure.

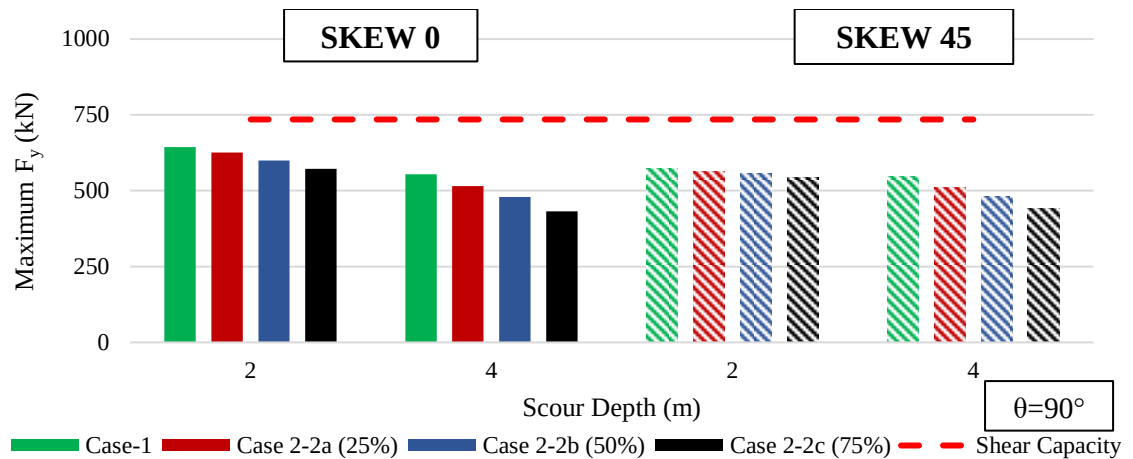


Figure 5.185. Average maximum shear force demands of local y' axis of non-skewed and 45° skewed bridge pile (P4) for uniform and non-uniform scour in longitudinal direction for an incidence angle of 90°

5.5. Comparison of Maximum Demands with Caltrans

It is obvious that the earthquake incidence angle has a significant impact on seismic demands of bridges. Within the scope of the study, the incidence angle is changed from

0° to 180° with an increment of 15°. According to Caltrans (2019), each ground motion set must be rotated at least three angular directions (i.e. 0°, 45° and 90°) to achieve maximum demands. In the content of thesis, the effect of ground motion incidence angle is researched for superstructure displacement, curvature and shear force demands of bridge column. In this part, average maximum demands are compared to the maximum demands which are obtained according to the incidence angles suggested in Caltrans (2019). In addition to the three earthquake incidence angles recommended in Caltrans (2019), the maximum demand for the 135° incidence angle is also considered for further comparison. The compared demands are given for each scour cases and scour depths in the following sections.

5.5.1. Comparison of uniform scour case (Case 1)

In Figure 5.186(a), the ratio of maximum superstructure displacement demand in longitudinal direction which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from 3 incidence angles (i.e. 0°, 45°, and 90°) according to the Caltrans is shown for uniform scour occurred around bridge piles for each scour depth (Comparison-1). On the other hand, in Figure 5.186(b) the ratio of maximum superstructure displacement in longitudinal direction obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the displacement demands in transverse direction of bridge and resultant displacement demands and results are given in Figure 5.187 and Figure 5.188, respectively. While the displacement demand ratio obtained in the longitudinal direction of the bridges is not changed when the 135° incidence angle is included, the success of the updated Caltran's recommendation is much more improved in the transverse direction of skewed bridge in obtaining the maximum demands. Although the earthquake ground motion incidence angles according to Caltrans is considered to be acceptable to obtain the maximum displacement demands for the non-skewed bridges, considering 135° incidence angle, which is perpendicular equivalent of the 45° incidence angle, is more successful in obtaining the maximum superstructure displacement demand of the skewed bridge.

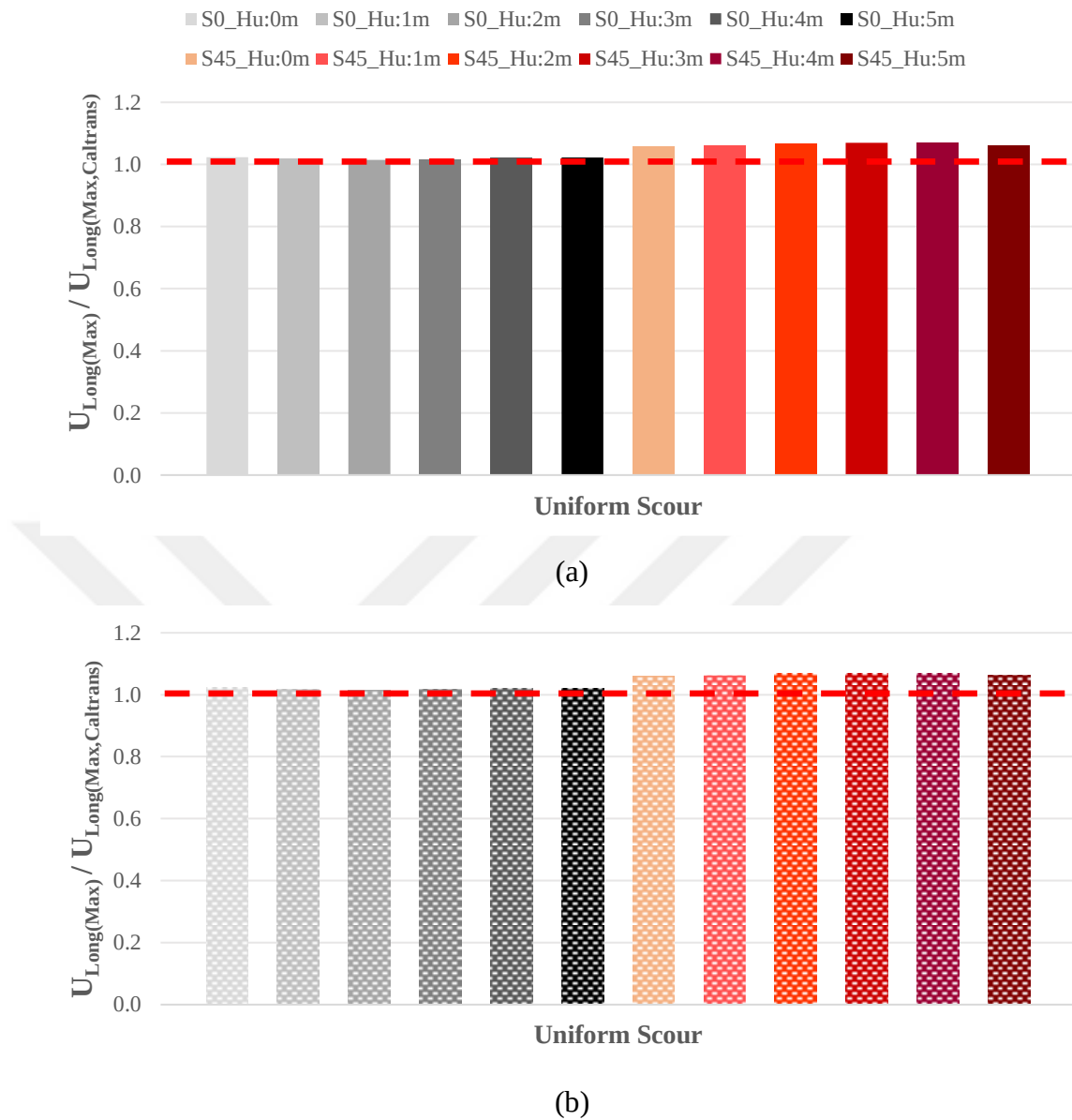


Figure 5.186. The ratio of maximum superstructure displacement in longitudinal direction to Caltrans maximum displacement when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

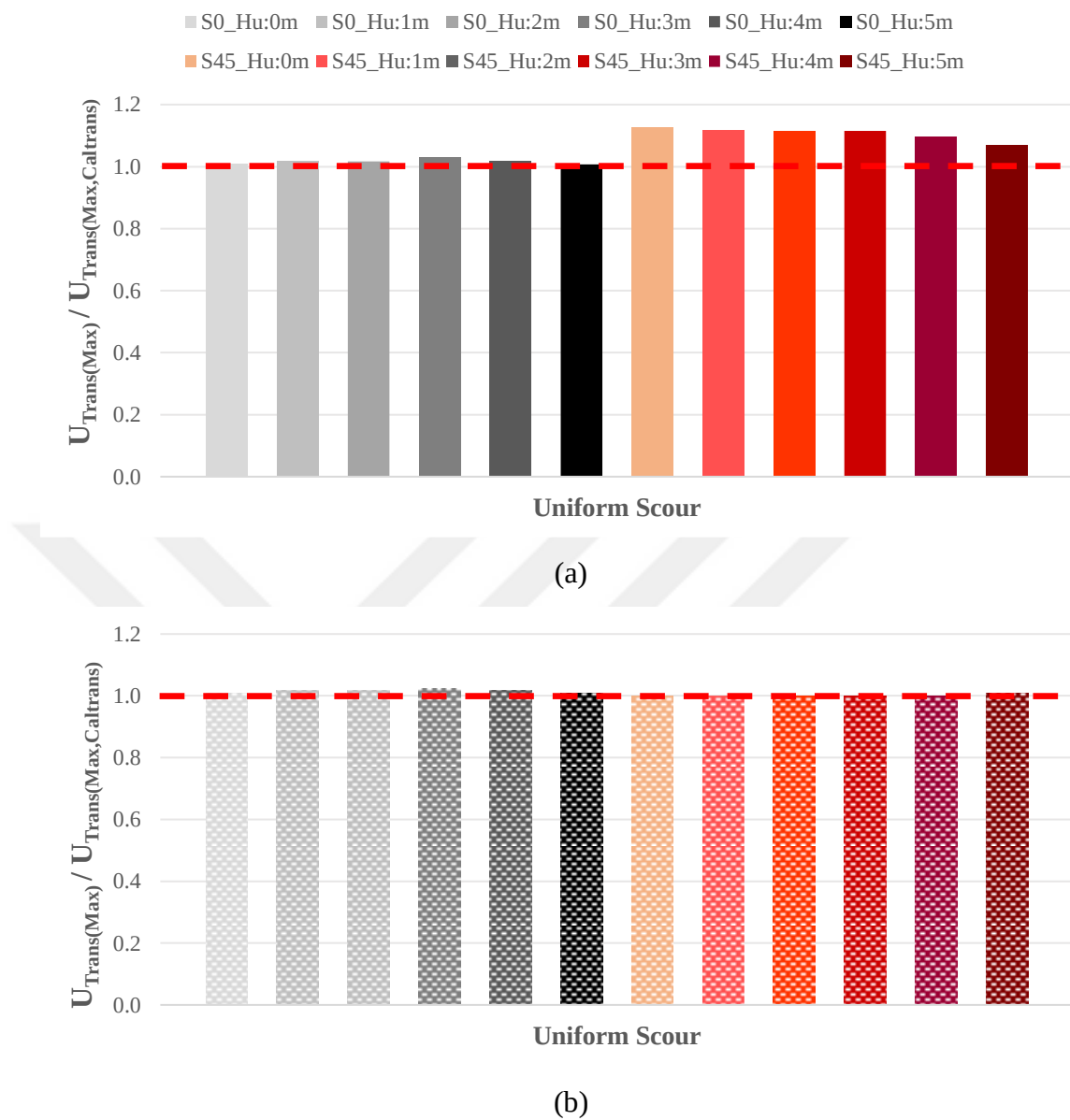


Figure 5.187. The ratio of maximum superstructure displacement in transverse direction to Caltrans maximum displacement when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

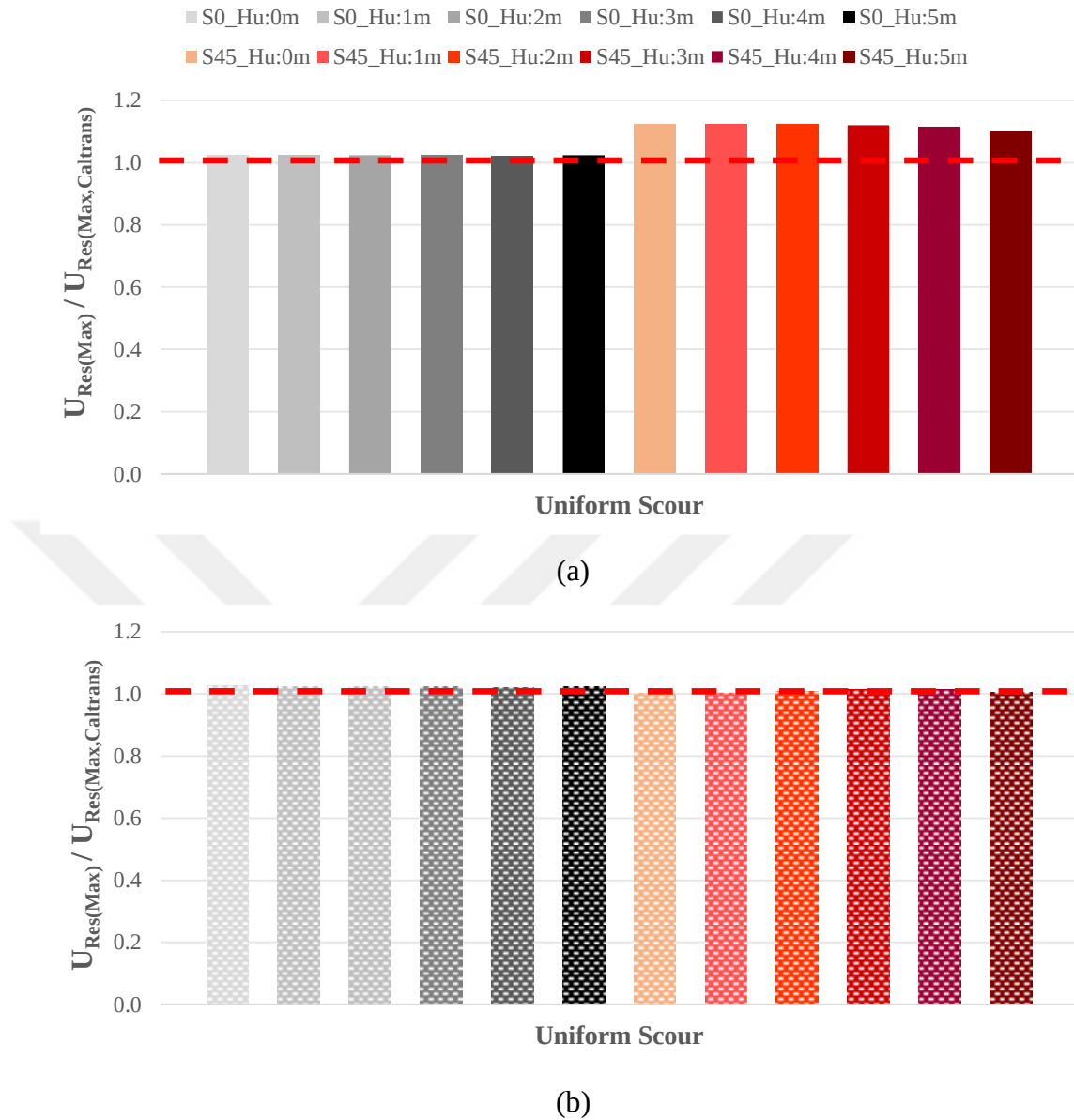


Figure 5.188. The ratio of maximum resultant superstructure displacement to Caltrans maximum displacement when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

In Figure 5.189(a), the ratio of maximum curvature demand in weak axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for uniform scour occurred around bridge piles for each scour depth (Comparison-1). On the other hand, in Figure 5.189(b) the ratio of maximum curvature demand in weak axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0° , 45° , 90° and 135°) (Comparison-2). This comparison is also done for the strong axis of bridge column as seen in Figure 5.190.

The maximum column curvature demands obtained from the nonlinear analyses considering various incidence angles are significantly higher than the demands obtained from Caltrans for both non-skewed and skewed bridges. For all the considered scour depths, skewness amplifies this ratio considerably for the selected ground motions. As seen from the results, the maximum curvature demands for both bridges are underestimated by the three earthquake ground motion incidence angles according to Caltrans. On the other hand, in addition to the 3 different incidence angles suggested in Caltrans, rotating the ground motion components by 135° is much more successful in achieving the maximum curvature demands both weak and strong axis of 45° skewed bridge column.

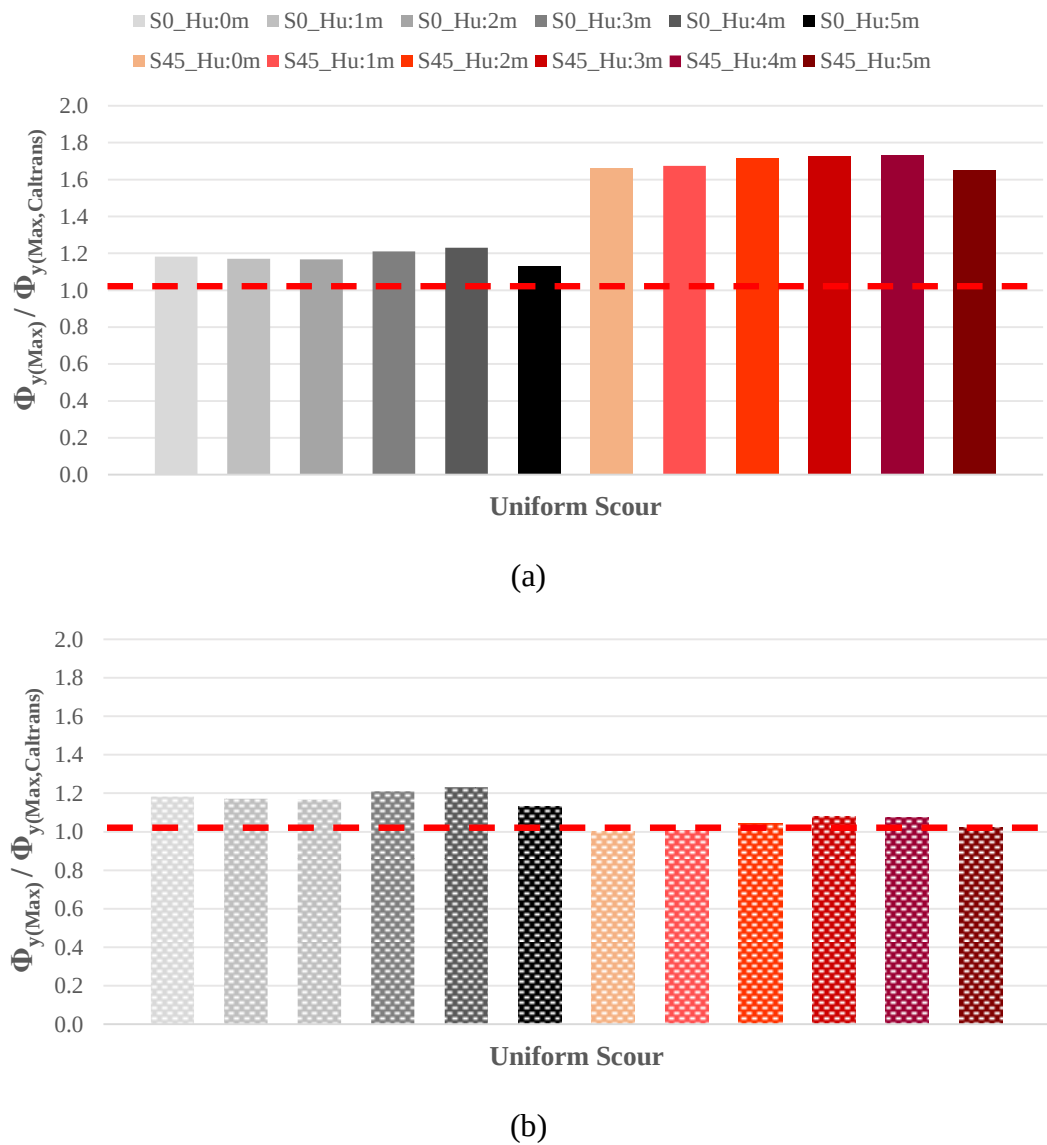


Figure 5.189. The ratio of maximum column curvature in weak axis to Caltrans maximum column curvature when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

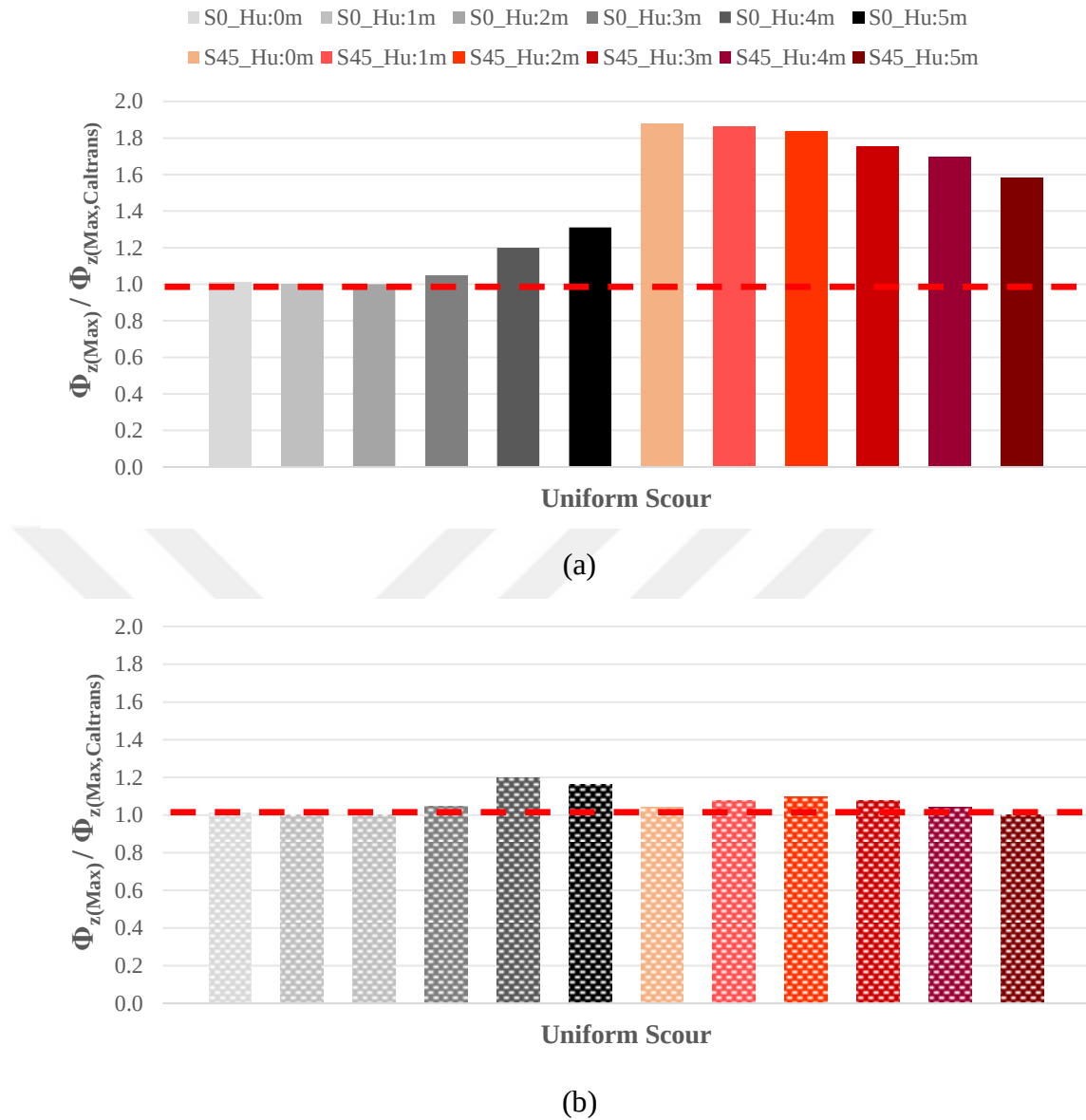


Figure 5.190. The ratio of maximum column curvature in strong axis to Caltrans maximum column curvature when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

In Figure 5.191(a), the ratio of maximum shear force demand in local y' axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for uniform scour occurred around bridge piles for each scour depth (Comparison-1). On the other hand, in Figure 5.191(b) the ratio of maximum shear force demand in local y' axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the local z' axis of bridge column as seen in Figure 5.192. According to these

comparisons, the shear demands in local y' axis obtained from the analyses are close to the demands obtained from Caltrans for both non-skewed and skewed bridges. On the contrary, maximum shear force demands are higher in skewed bridge than non-skewed one in local z' axis of column. When ground motion components are rotated 135° , maximum demands are captured also in local z' axis of skewed bridge column.

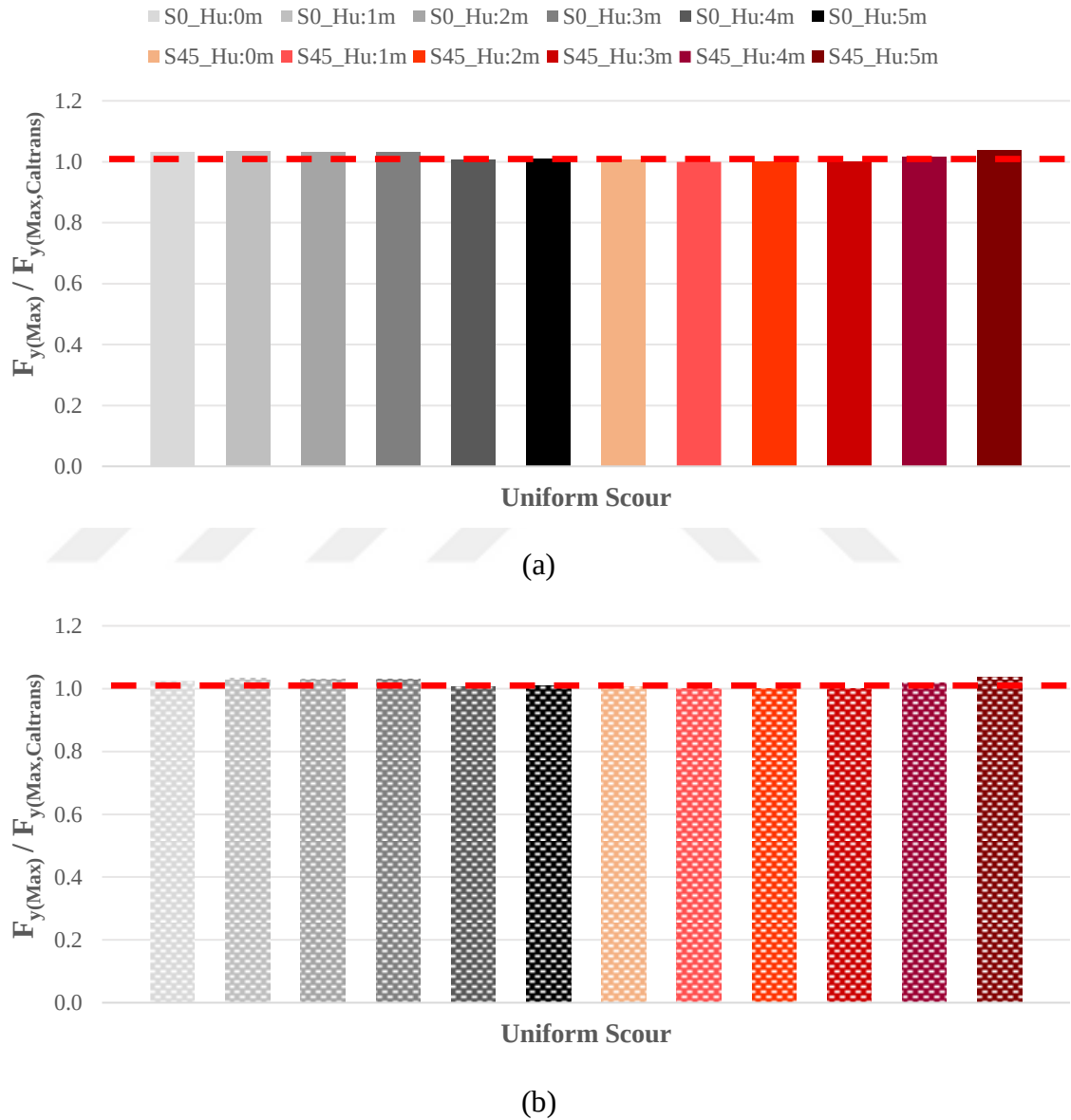


Figure 5.191. The ratio of maximum column shear force in local y' axis to Caltrans maximum column shear force when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

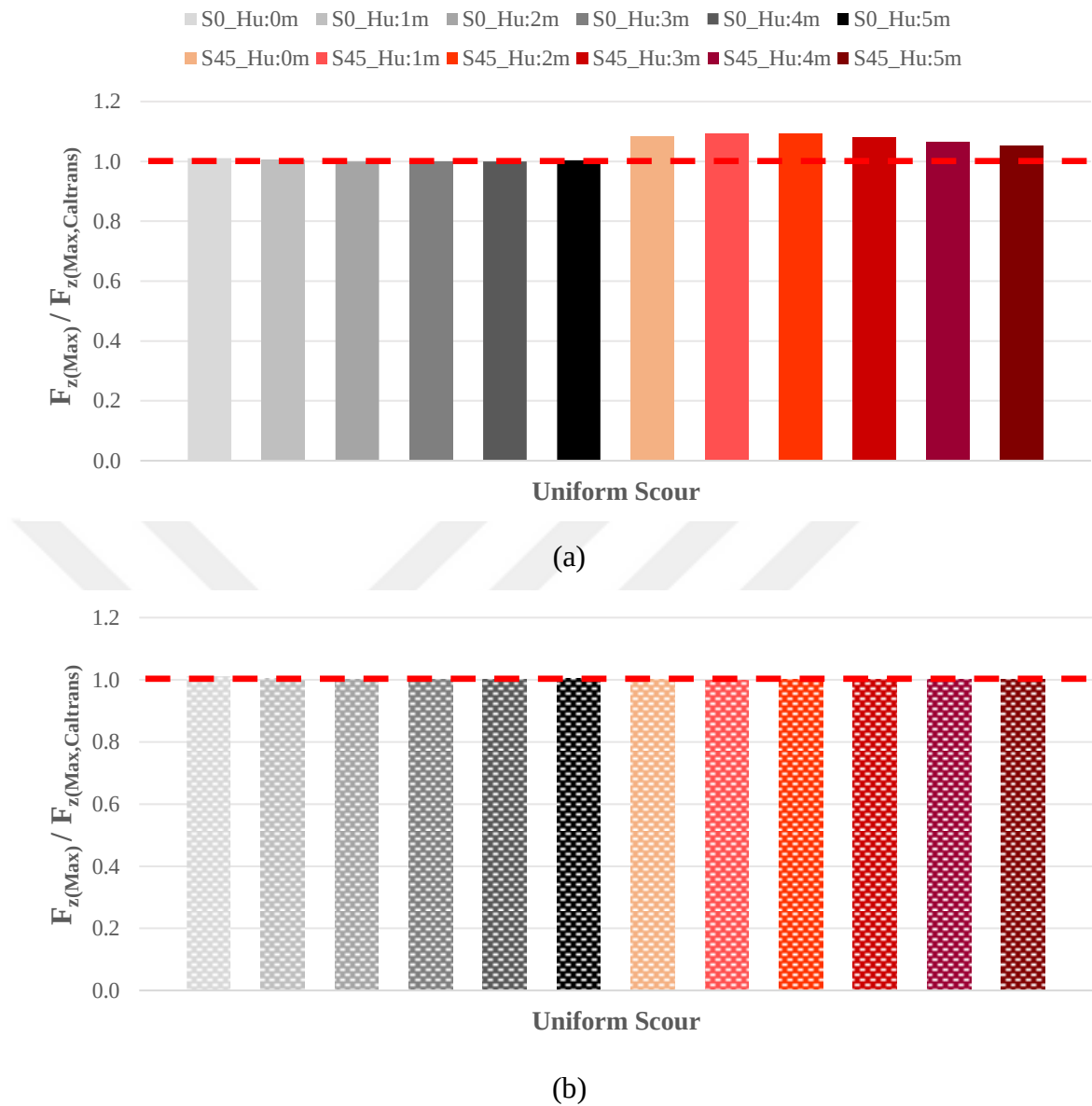
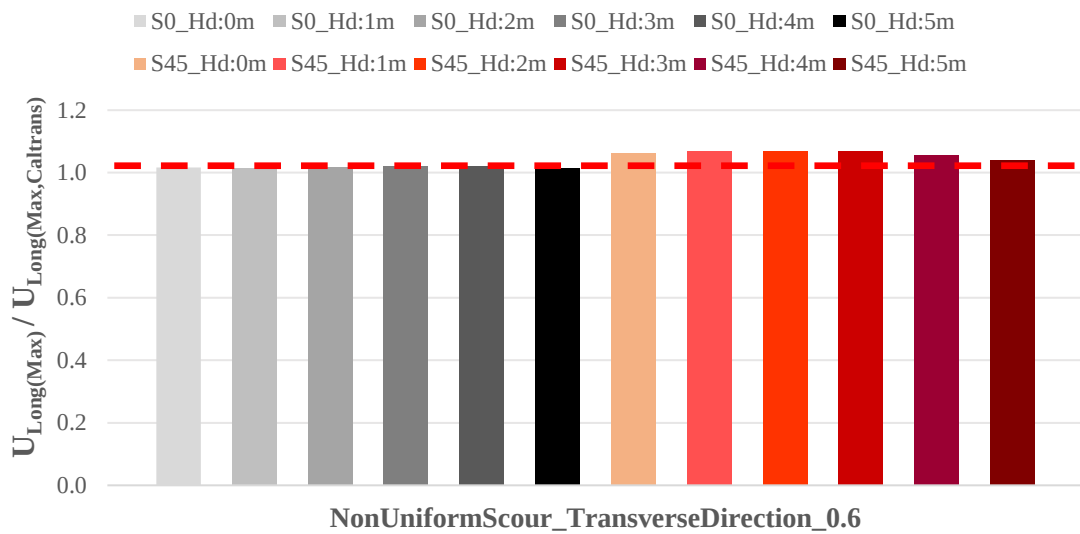


Figure 5.192. The ratio of maximum column shear force in local z' axis to Caltrans maximum column shear force when bridge scour is uniform (Case-1) (a) Comparison-1 (b) Comparison-2

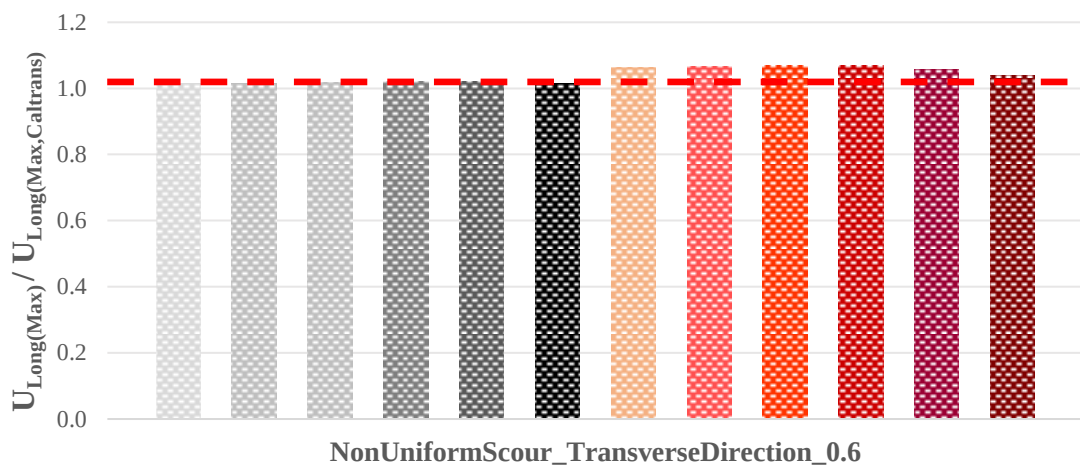
5.5.2. Comparison for non-uniform scour in transverse direction when $\gamma=0.6$ (Case 2-1a)

In Figure 5.193(a), the ratio of maximum superstructure displacement demand in longitudinal direction which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=0.6$) for each scour depth (Comparison-1). On the other hand, in Figure 5.193(b) the ratio of maximum superstructure displacement in longitudinal direction obtained from 13

different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the displacement demands in transverse direction of bridge and resultant displacement demands and results are given in Figure 5.194 and Figure 5.195, respectively. The demand ratio is nearly same for all scour depths of non-skewed and skewed bridges in both directions. While the Caltrans's recommendation is sufficient for obtaining maximum demands in both direction of non-skewed bridge, the success of the updated Caltran's recommendation is much more improved in the transverse direction of skewed bridge in obtaining the maximum demands.



(a)



(b)

Figure 5.193. The ratio of maximum superstructure displacement in longitudinal direction to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1a)
(a) Comparison-1 (b) Comparison-2

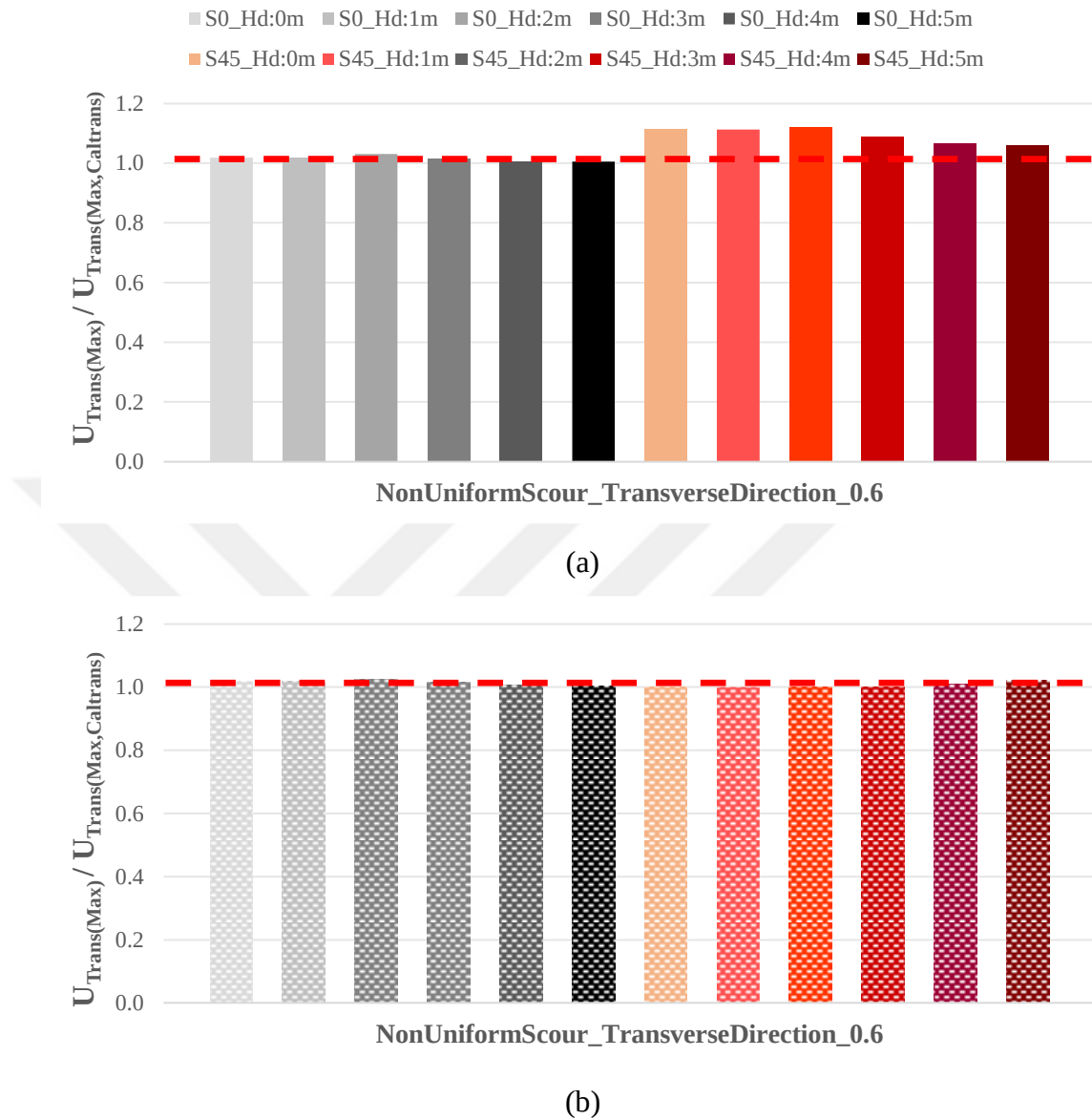


Figure 5.194. The ratio of maximum superstructure displacement in transverse direction to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

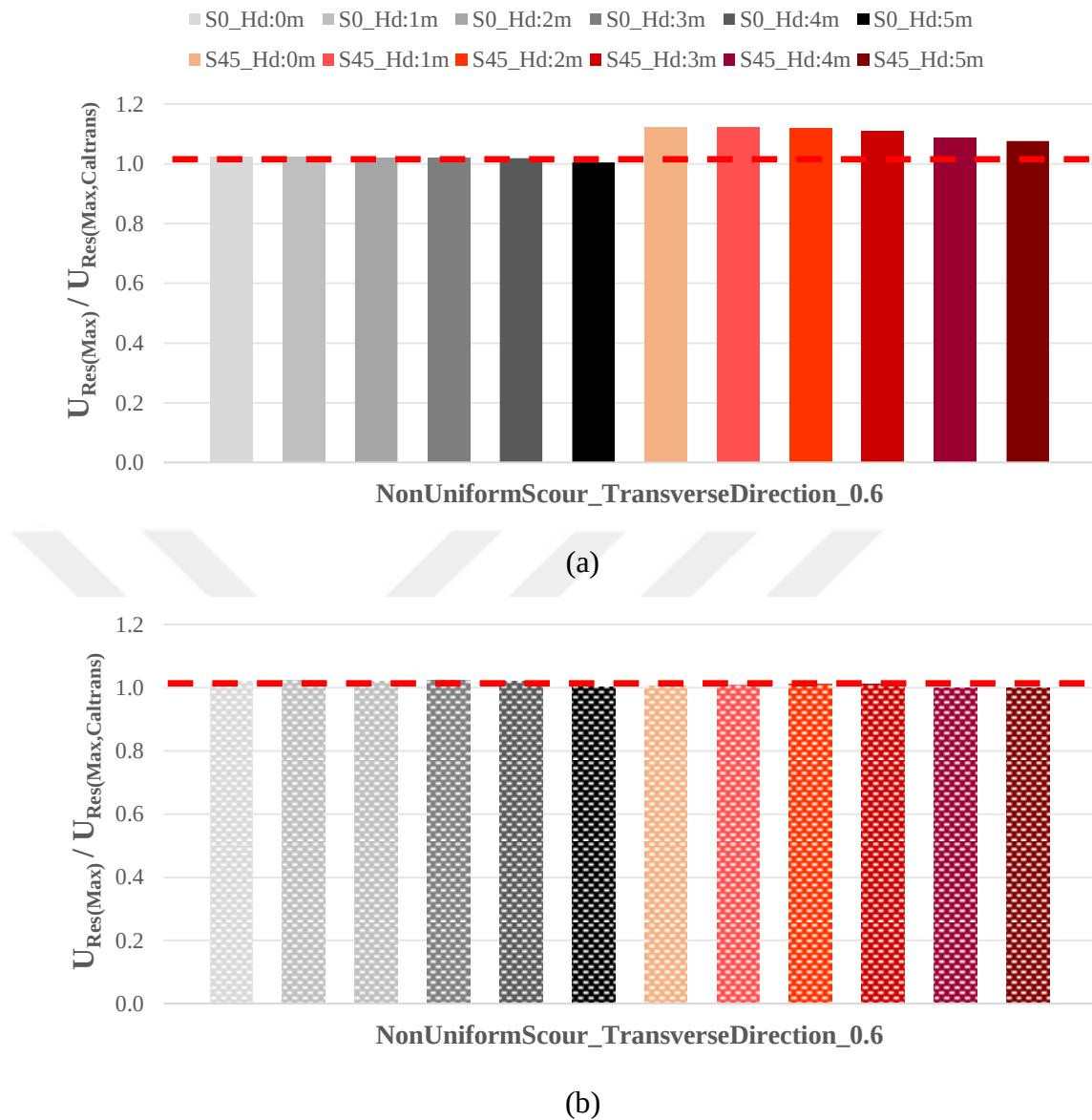


Figure 5.195. The ratio of maximum resultant superstructure displacement to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

In Figure 5.196(a), the ratio of maximum curvature demand in weak axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=0.6$) for each scour depth (Comparison-1). On the other hand, in Figure 5.196(b) the ratio of maximum curvature demand in weak axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the strong axis of bridge column as seen in Figure 5.197.

The maximum column curvature demands obtained from the nonlinear analyses considering various incidence angles are significantly higher than the demands obtained from Caltrans for 45° skewed bridge. Although the maximum curvature demands of the non-skewed bridge column are not as much as the skew bridge, they are higher than the demands obtained according to Caltrans. On the other hand, in addition to the 3 different incidence angles suggested in Caltrans, rotating the ground motion components by 135° is much more successful in achieving the maximum curvature demands both weak and strong axis of 45° skewed bridge column. However, it is still insufficient to obtain maximum curvature demands of non-skewed bridge column in some scour depths.

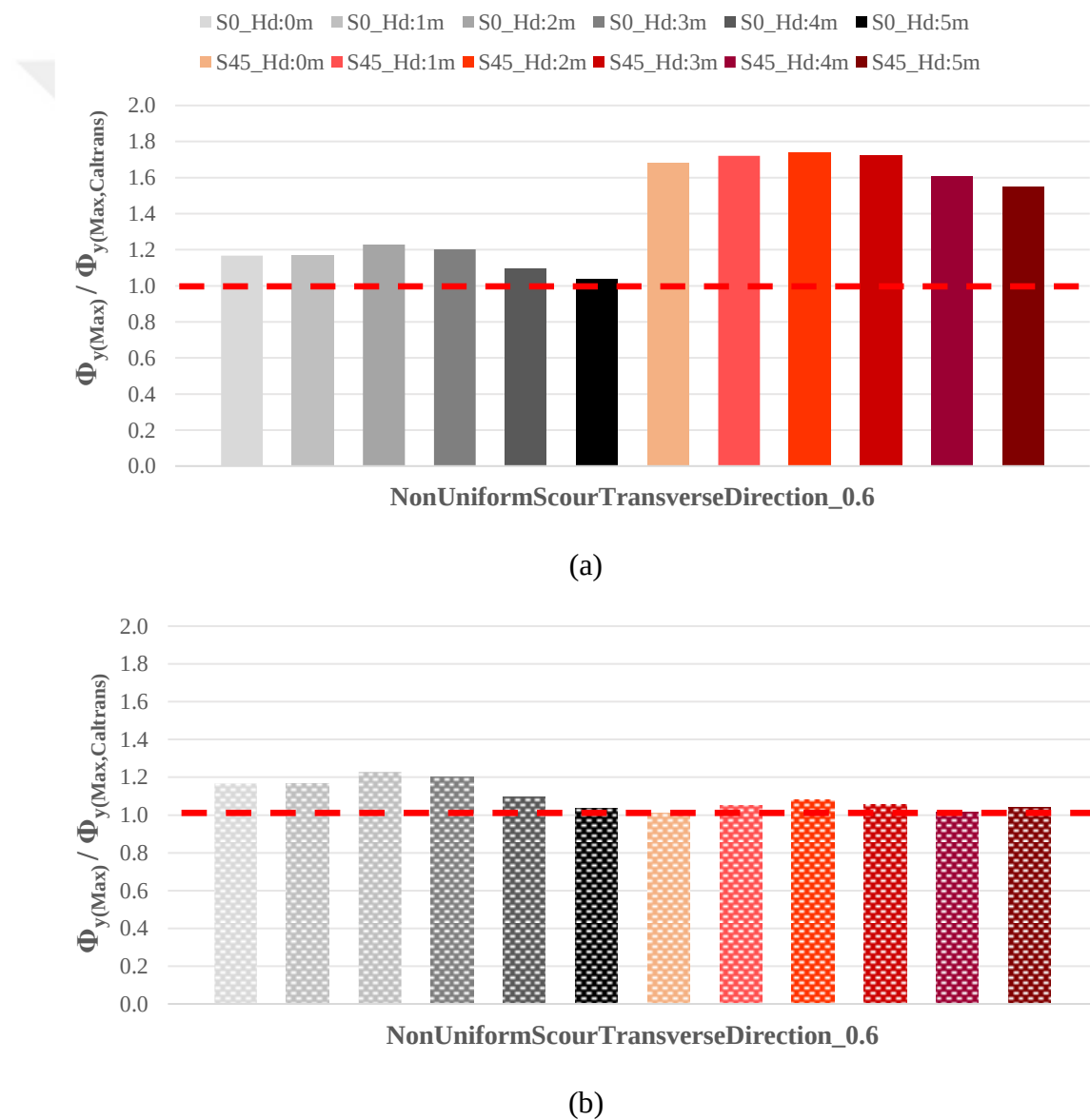


Figure 5.196. The ratio of maximum column curvature in weak axis to Caltrans maximum column curvature when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

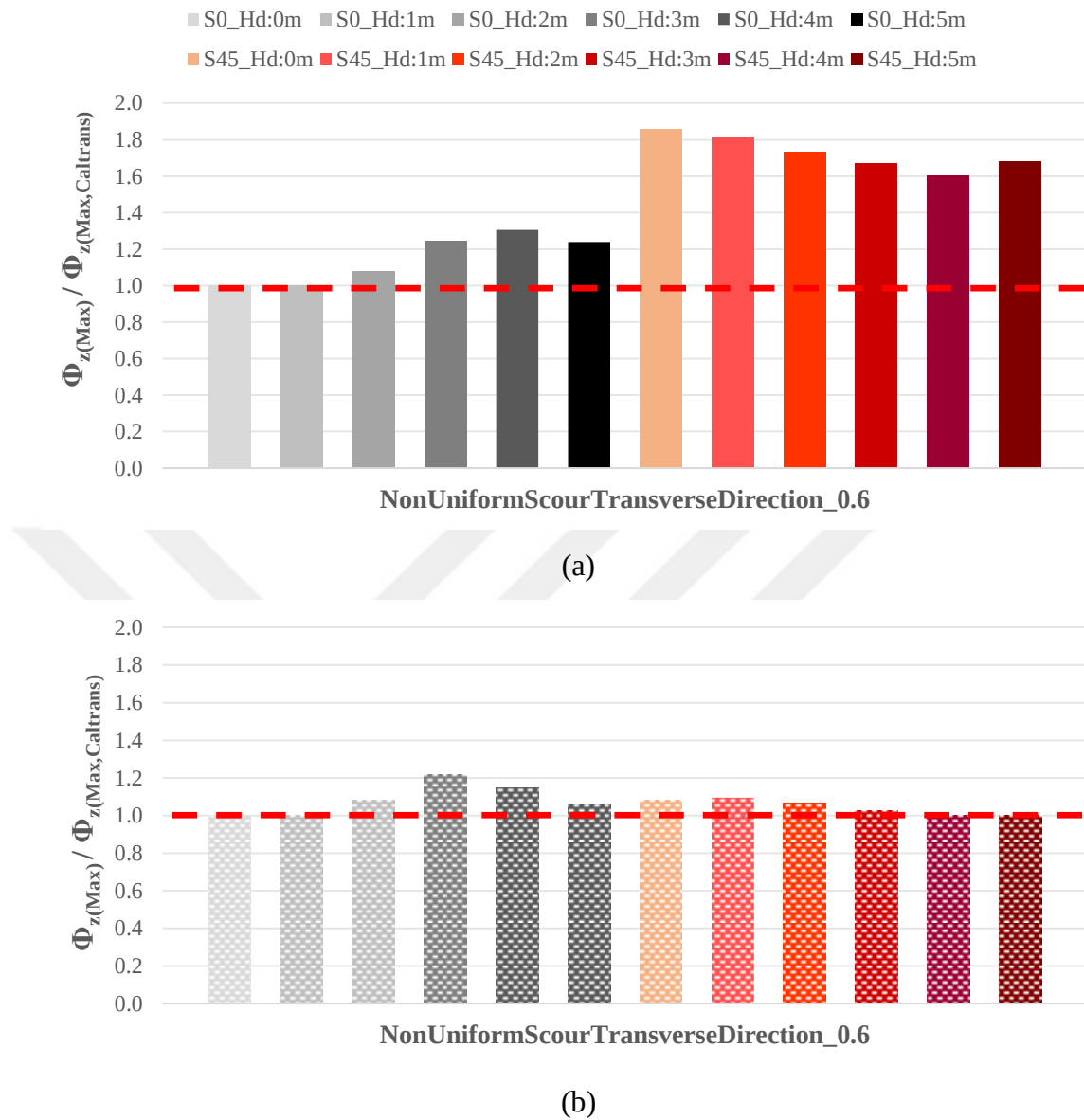
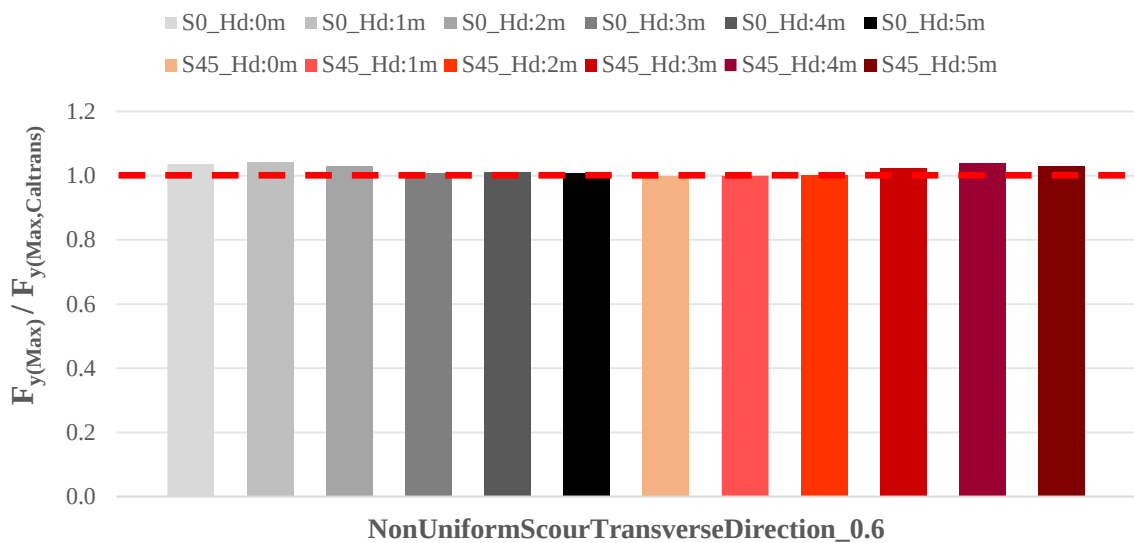


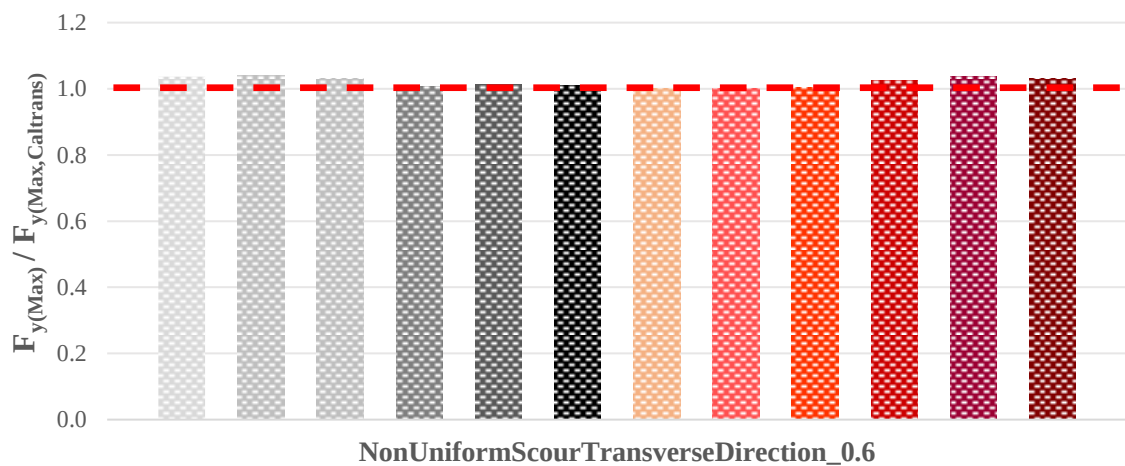
Figure 5.197. The ratio of maximum column curvature in strong axis to Caltrans maximum column curvature when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

In Figure 5.198(a), the ratio of maximum shear force demand in local y' axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=0.6$) for each scour depth (Comparison-1). On the other hand, in Figure 5.198(b) the ratio of maximum shear force demand in local y' axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the local z' axis of bridge column as seen in Figure

5.199. According to these comparisons, the shear demands in local y' axis obtained from the analyses are close to the demands obtained from Caltrans for both non-skewed and skewed bridges. On the contrary, maximum shear force demands are higher in skewed bridge in local z' axis of column when ground motion components rotated at only three angular directions. If ground motion components are rotated 135° , maximum demands are captured also in local z' axis of skewed bridge column.



(a)



(b)

Figure 5.198. The ratio of maximum column shear force in local y' axis to Caltrans maximum column shear force when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

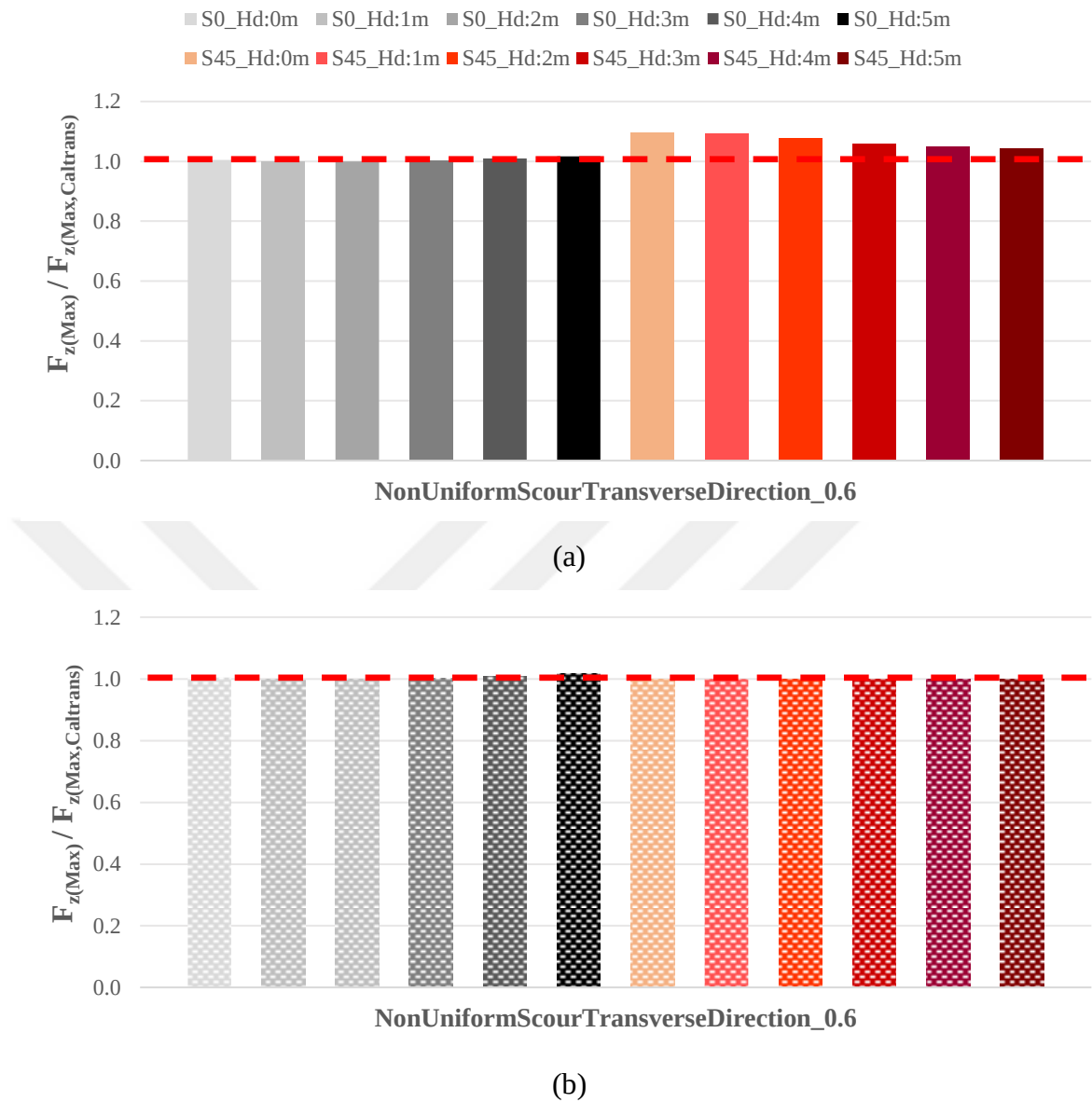
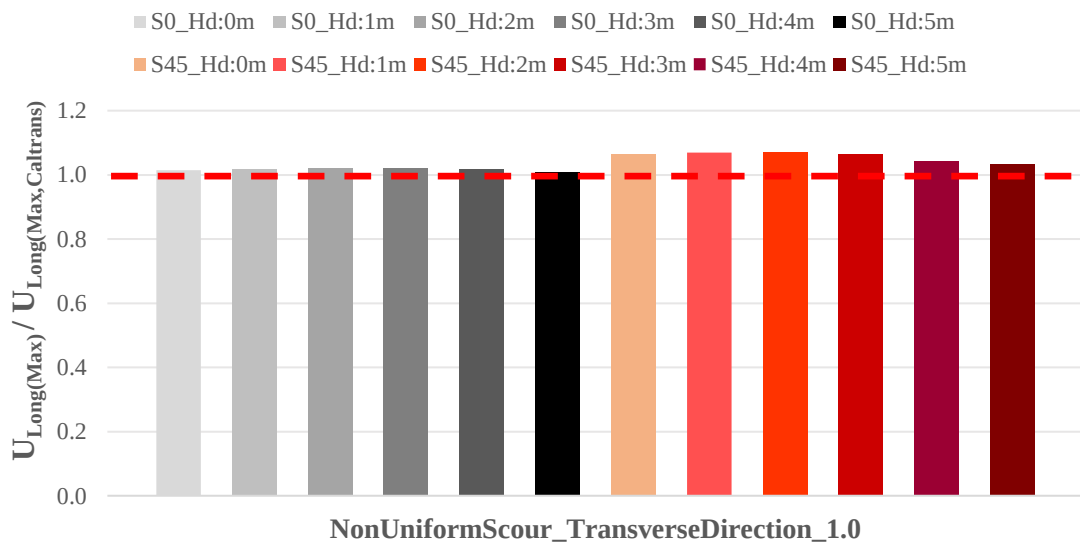


Figure 5.199. The ratio of maximum column shear force in local z' axis to Caltrans maximum column shear force when bridge scour is non-uniform in transverse direction (Case 2-1a) (a) Comparison-1 (b) Comparison-2

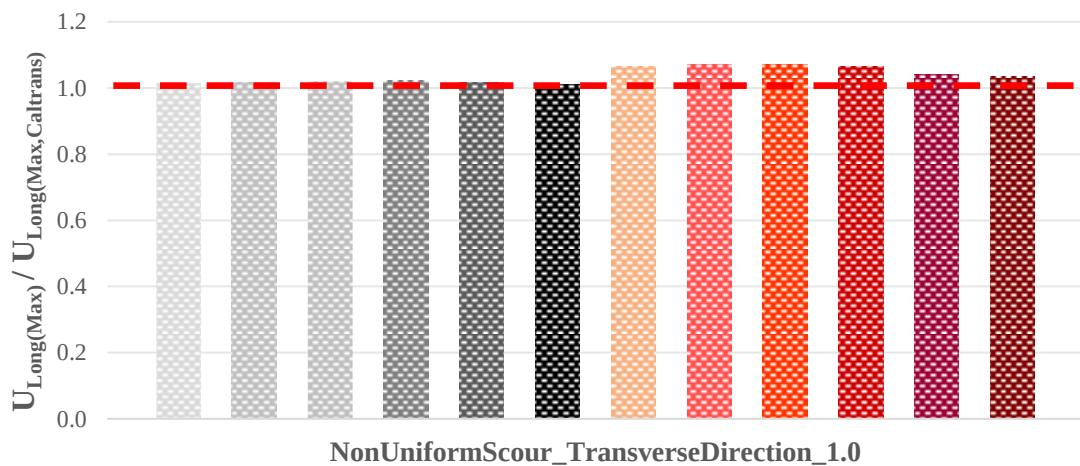
5.5.3. Comparison for non-uniform scour in transverse direction when $\gamma=1.0$ (Case 2-1b)

In Figure 5.200(a), the ratio of maximum superstructure displacement demand in longitudinal direction which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=1.0$) for each scour depth (Comparison-1). On the other hand, in Figure 5.200(b) the ratio of maximum superstructure displacement in longitudinal direction obtained from 13

different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the displacement demands in transverse direction of bridge and resultant displacement demands and results are given in Figure 5.201 and Figure 5.202, respectively. The demand ratio is nearly same for all scour depths of non-skewed and skewed bridges in both directions. Although the updated Caltrans advice is much more successful in achieving the maximum demands in the transverse direction of the skewed bridge, the original recommendation is still suitable for obtaining the maximum demands in both directions of the non-skewed bridge.



(a)



(b)

Figure 5.200. The ratio of maximum superstructure displacement in longitudinal direction to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1b)
(a) Comparison-1 (b) Comparison-2

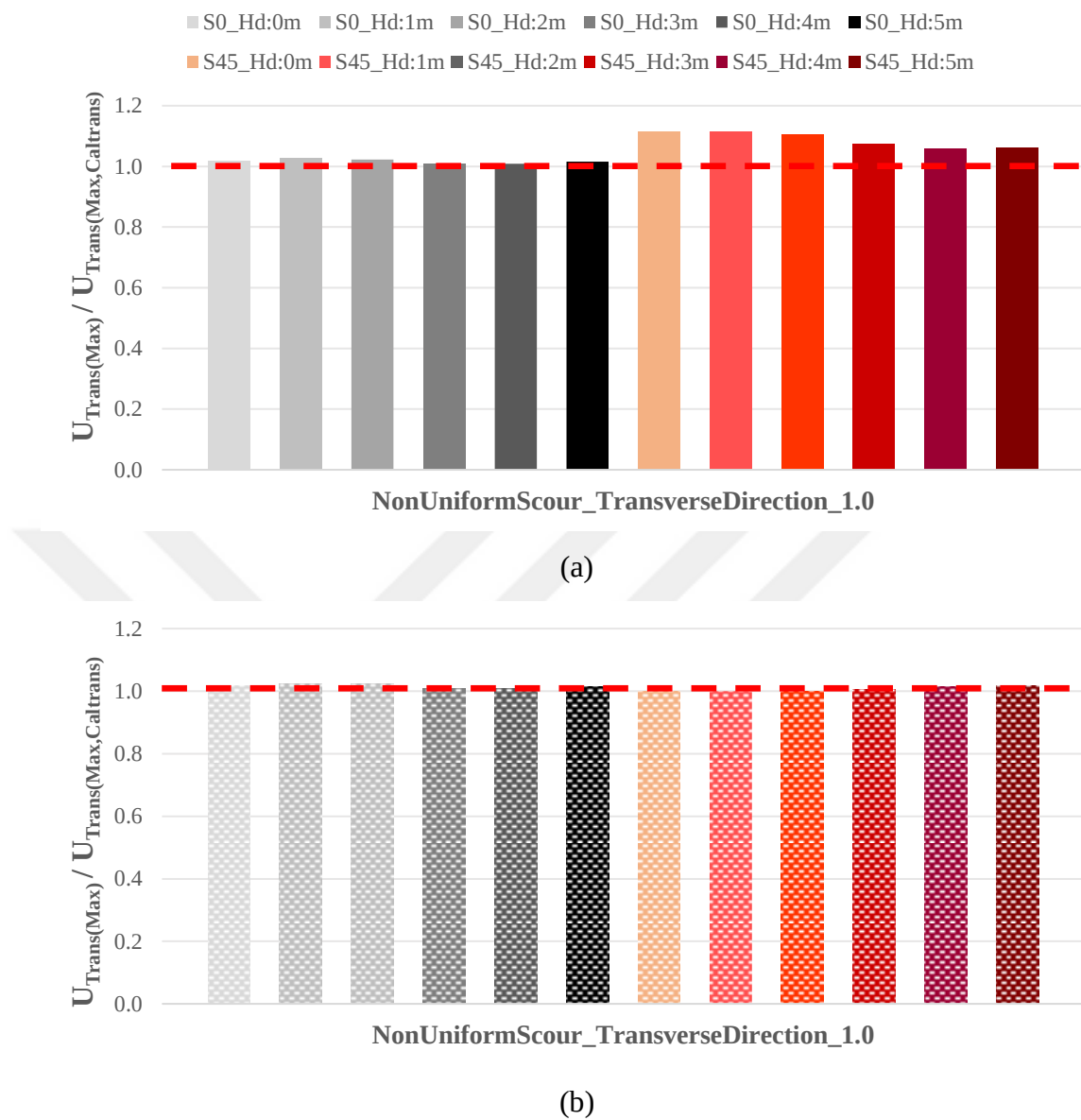


Figure 5.201. The ratio of maximum superstructure displacement in transverse direction to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

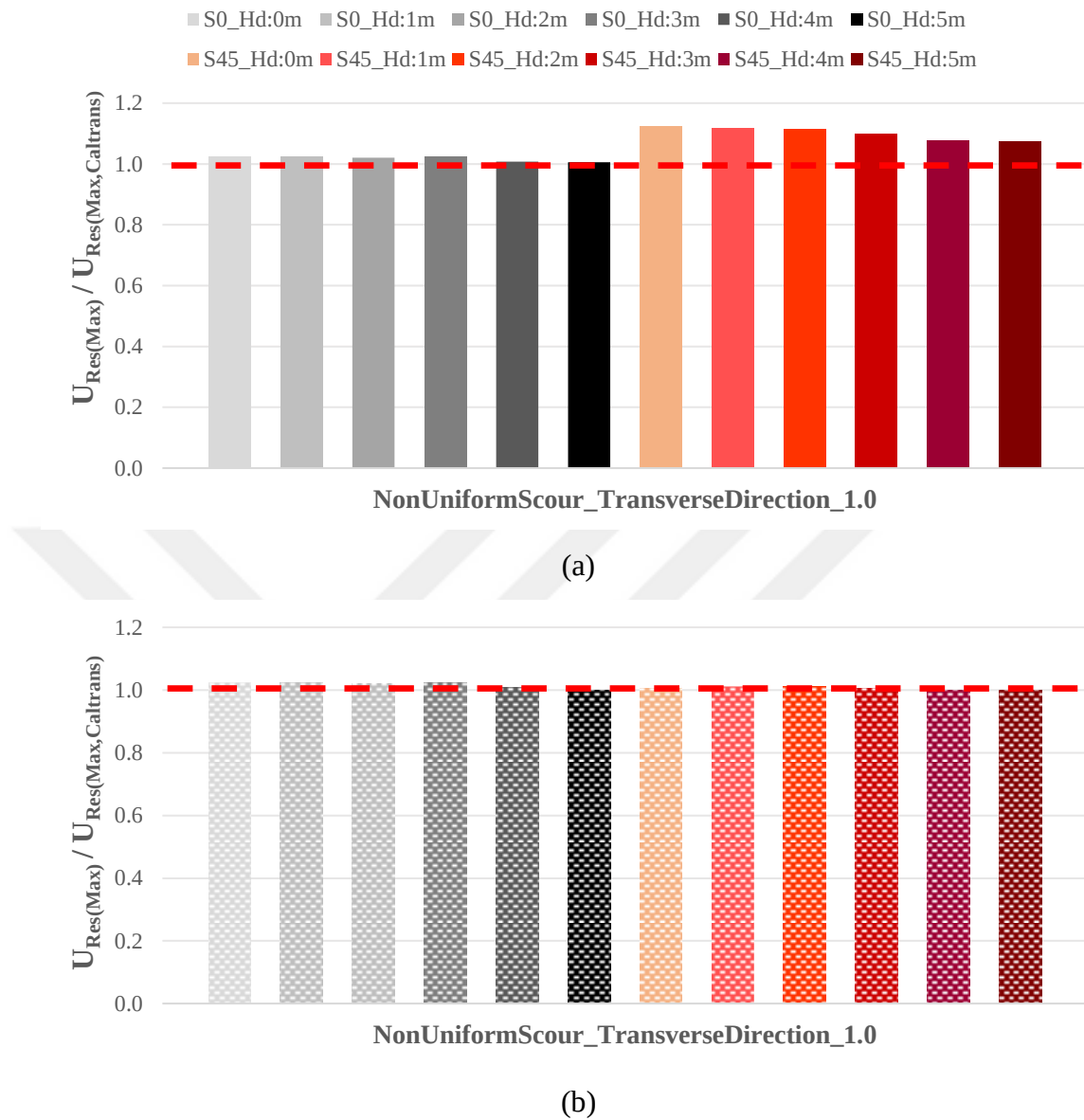
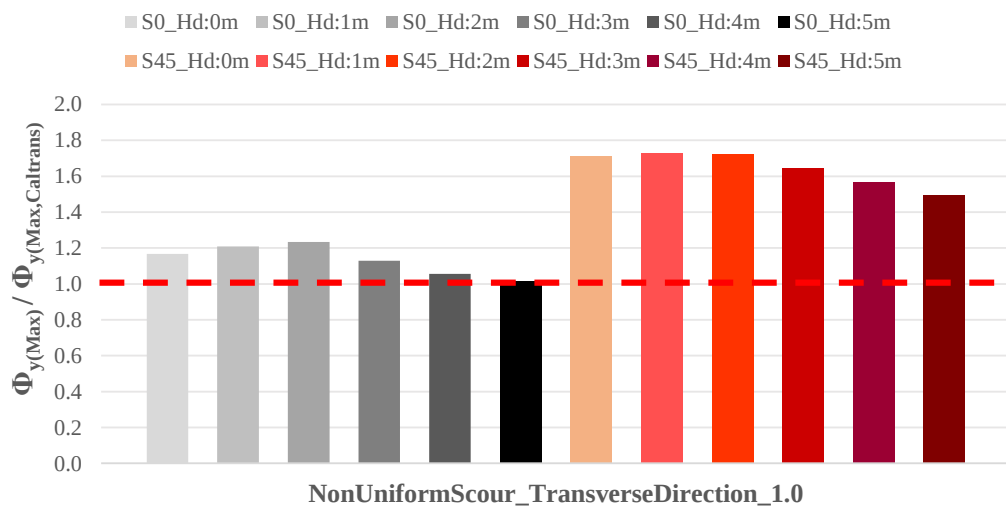


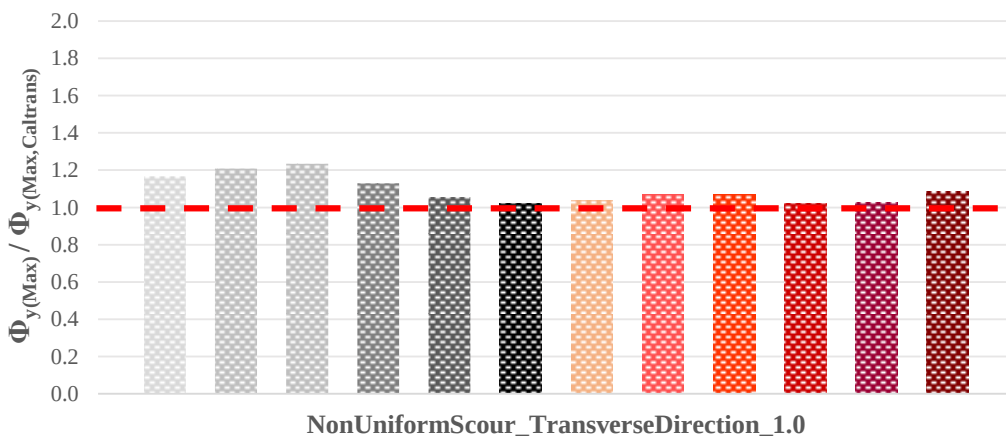
Figure 5.202. The ratio of maximum resultant superstructure displacement to Caltrans maximum displacement when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

In Figure 5.203(a), the ratio of maximum curvature demand in weak axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=1.0$) for each scour depth (Comparison-1). On the other hand, in Figure 5.203(b) the ratio of maximum curvature demand in weak axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the strong axis of bridge column as seen in Figure 5.204.

The maximum demands for column curvature gathered from nonlinear analyses that take into account different incidence angles are considerably more than those obtained from Caltrans for a 45° skewed bridge. The maximum curvature demands of the non-skewed bridge column are higher than those calculated by Caltrans, despite not being as high as those of the skew bridge. However, it is far more successful to rotate the ground motion components by 135° in addition to the three different incidence angles that Caltrans suggests in order to achieve the maximum curvature required for both the weak and strong axes of a 45° skewed bridge column. In various scour depths, it is still insufficient to meet the maximum curvature requirements of a non-skewed bridge column.



(a)



(b)

Figure 5.203. The ratio of maximum column curvature in weak axis to Caltrans maximum column curvature when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

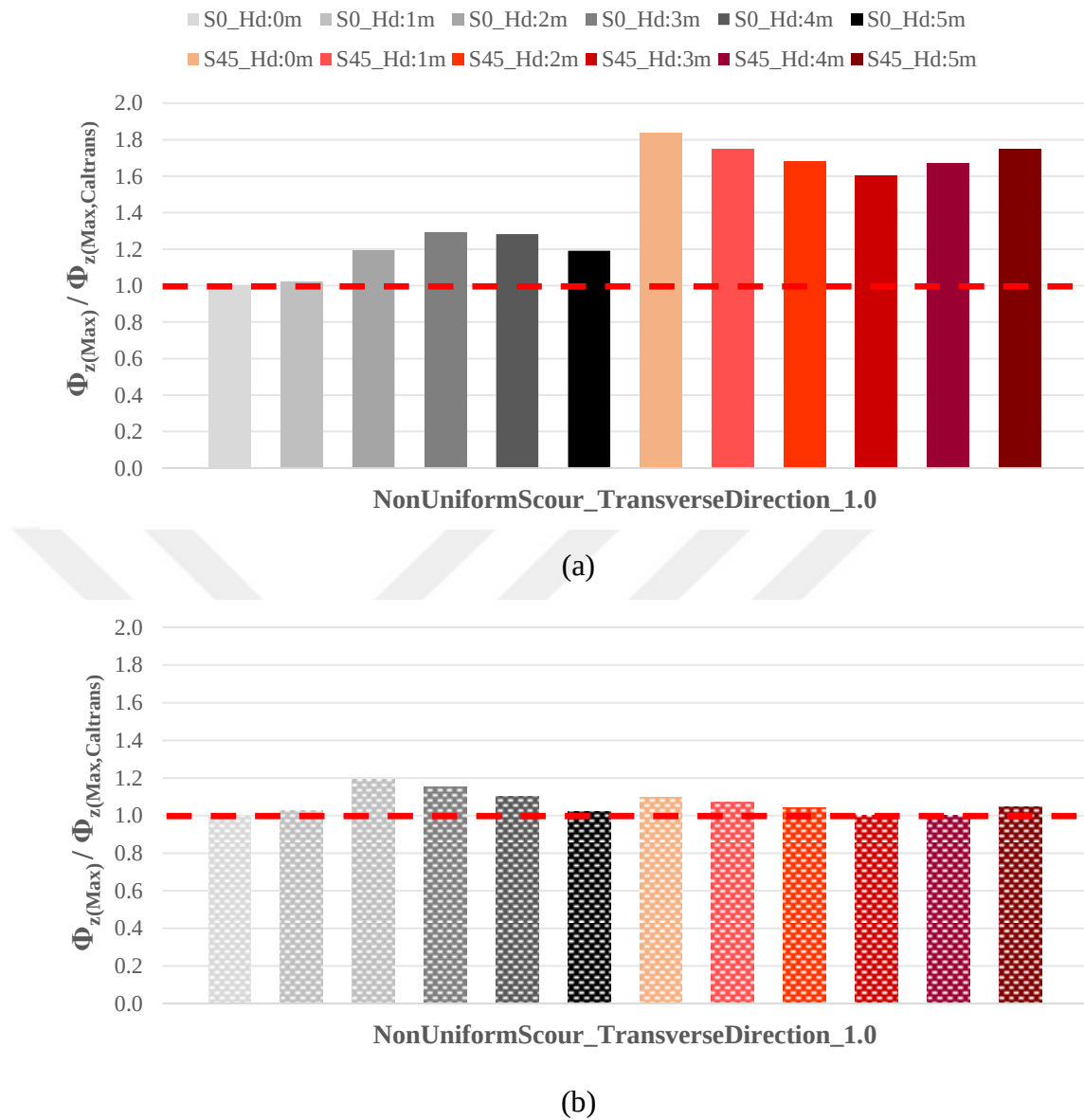
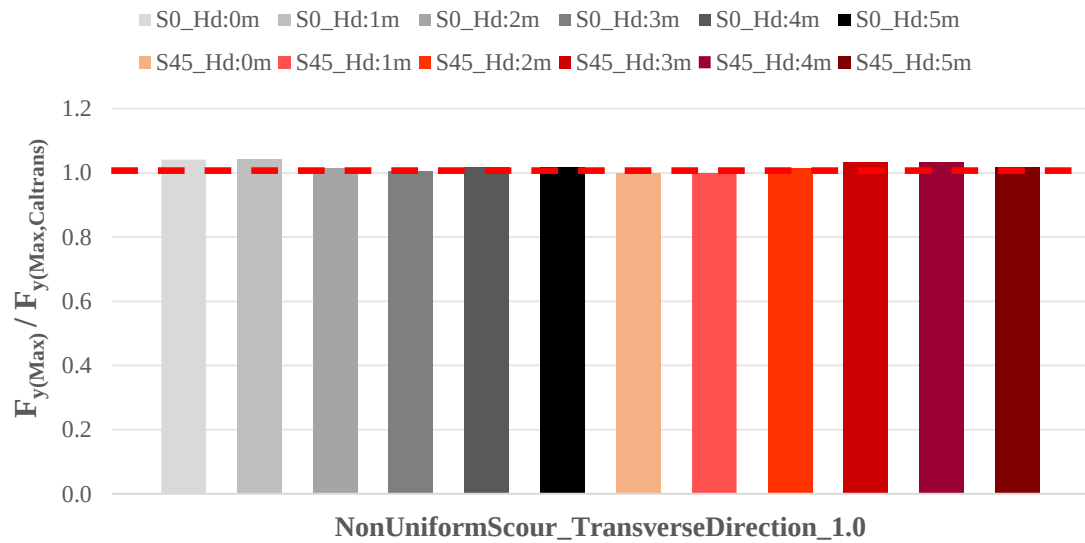


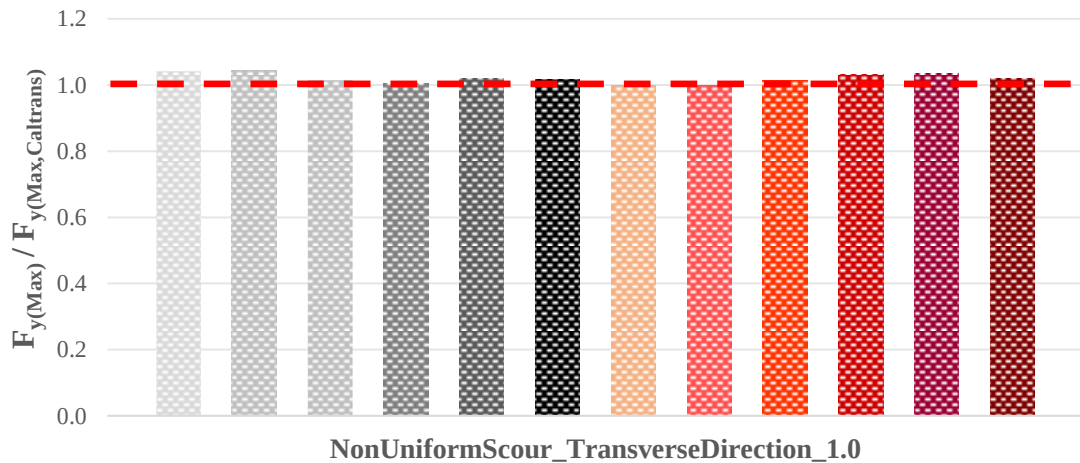
Figure 5.204. The ratio of maximum column curvature in strong axis to Caltrans maximum column curvature when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

In Figure 5.205(a), the ratio of maximum shear force demand in local y' axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in transverse direction ($\gamma=1.0$) for each scour depth (Comparison-1). On the other hand, in Figure 5.205(b) the ratio of maximum shear force demand in local y' axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the local z' axis of bridge column as seen in Figure

5.206. These comparisons show that the local y' axis shear demands derived from the analyses are relatively similar to the demands acquired from Caltrans for both skewed and non-skewed bridges. On the other hand, when ground motion components rotated in just three angular directions, the ratio of maximum shear force demands in the skewed bridge becomes larger along the local z' axis of column. The local z' axis of the skewed bridge column captures maximum demands when the ground motion components are rotated 135° .



(a)



(b)

Figure 5.205. The ratio of maximum column shear force in local y' axis to Caltrans maximum column shear force when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

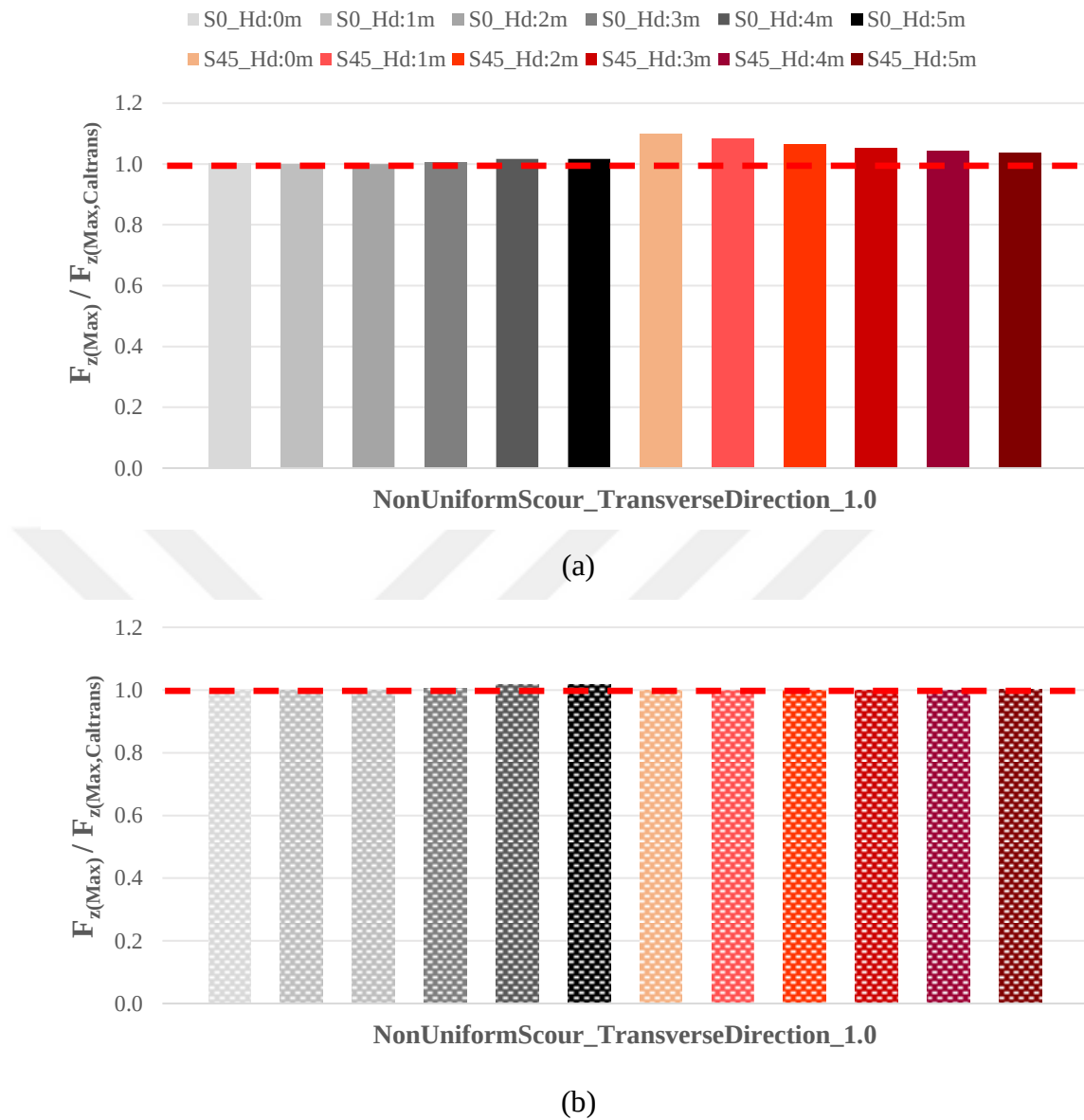
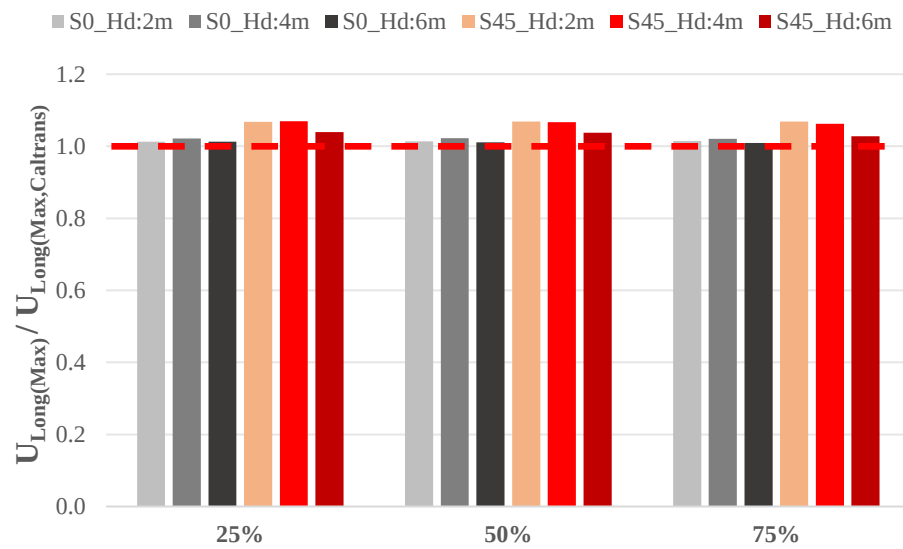


Figure 5.206. The ratio of maximum column shear force in local z' axis to Caltrans maximum column shear force when bridge scour is non-uniform in transverse direction (Case 2-1b) (a) Comparison-1 (b) Comparison-2

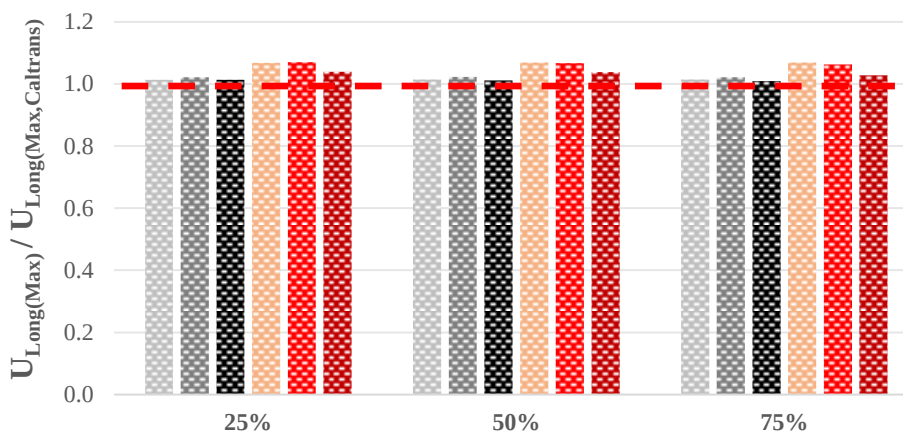
5.5.4. Comparison for non-uniform scour in longitudinal direction when scour is 25% (Case 2-2a), 50% (Case 2-2b) and 75% (Case 2-2c) more around middle piles

In Figure 5.207(a), the ratio of maximum superstructure displacement demand in longitudinal direction which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in longitudinal direction for each scour depth (Comparison-1). On the other hand, in Figure 5.207(b) the ratio of maximum superstructure displacement in longitudinal direction obtained from 13 different

incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the displacement demands in transverse direction of bridge and resultant displacement demands and results are given in Figure 5.208 and Figure 5.209, respectively. The demand ratio is decreasing with an increase in scour depth and the maximum demand ratio are much higher in skewed bridge than non-skewed one. Although the updated Caltrans advice is much more successful in achieving the maximum demands in the transverse direction of the skewed bridge, the original recommendation is still suitable for obtaining the maximum demands in both directions of the non-skewed bridge.



(a)



(b)

Figure 5.207. The ratio of maximum superstructure displacement in longitudinal direction to Caltrans maximum displacement when bridge scour is non-uniform in longitudinal direction (Case 2-2)
(a) Comparison-1 (b) Comparison-2

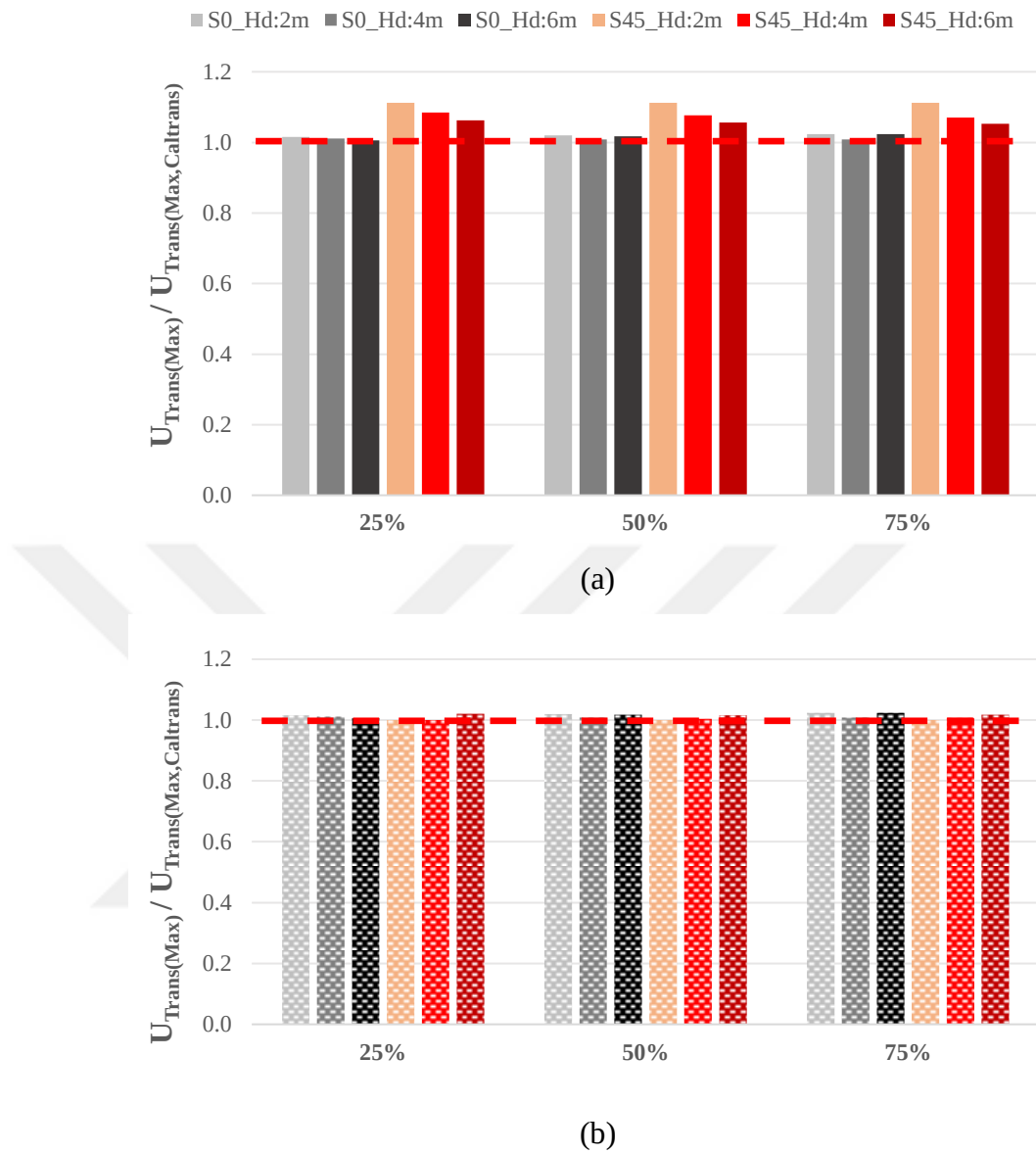


Figure 5.208. The ratio of maximum superstructure displacement in transverse direction to Caltrans maximum displacement when bridge scour is non-uniform in longitudinal direction (Case 2-2)
 (a) Comparison-1 (b) Comparison-2

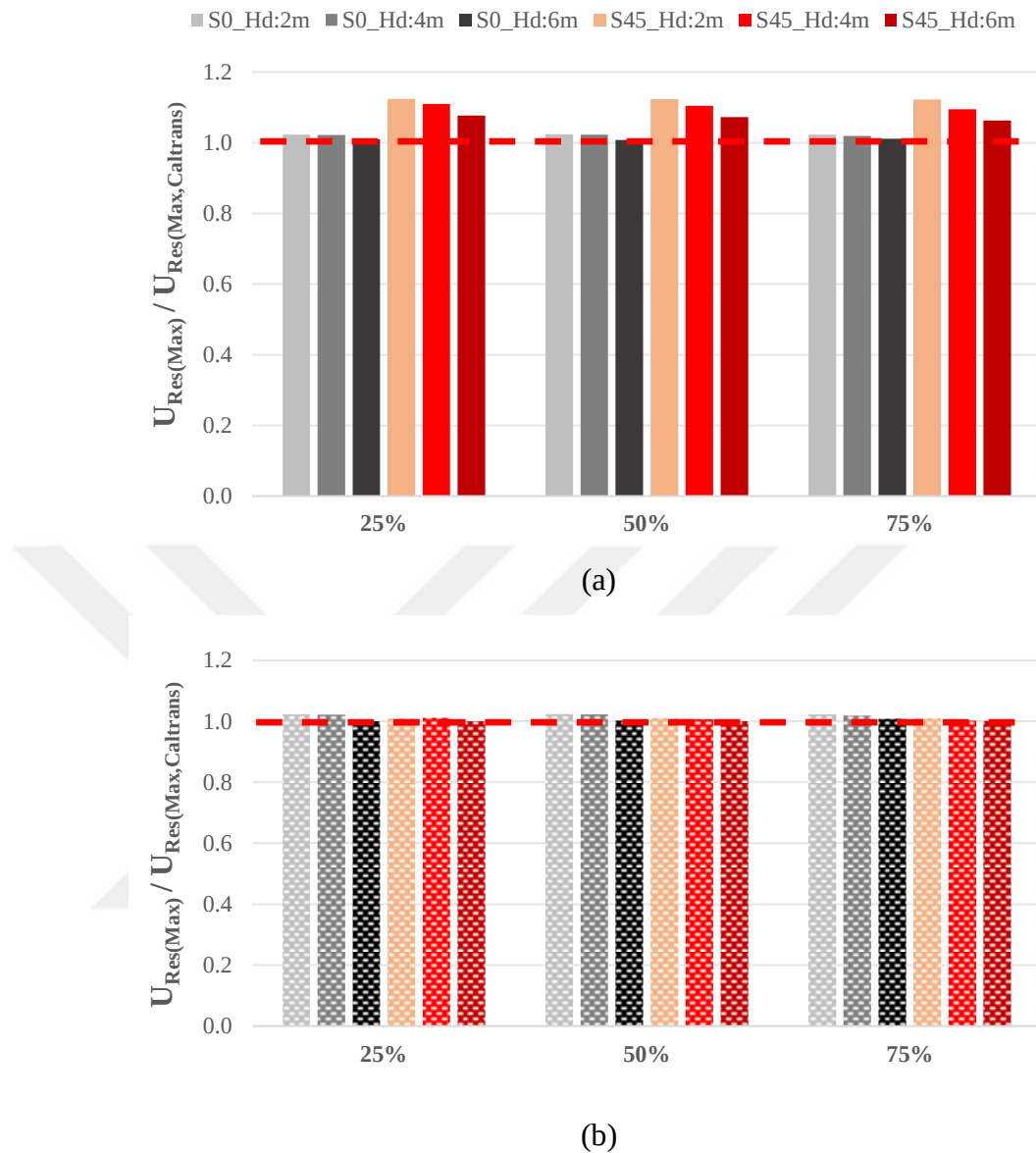
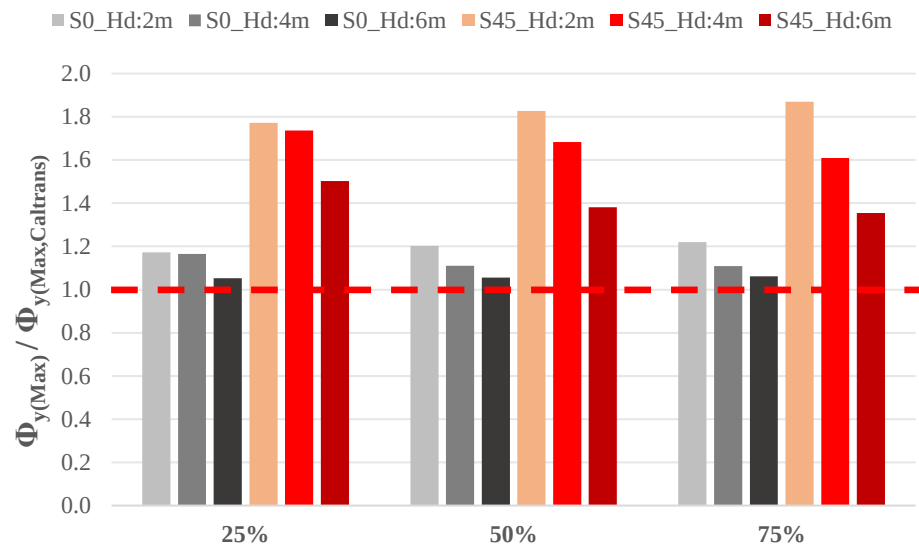


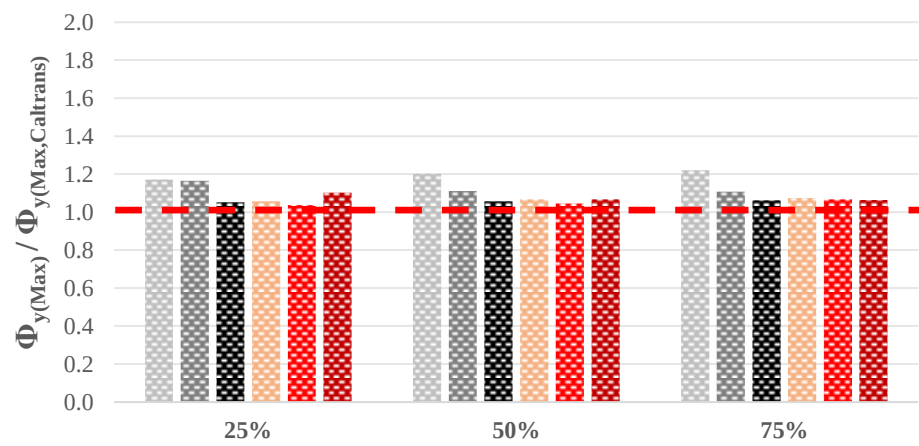
Figure 5.209. The ratio of maximum resultant superstructure displacement to Caltrans maximum displacement when bridge scour is non-uniform in longitudinal direction (Case 2-2) (a) Comparison-1 (b) Comparison-2

In Figure 5.210(a), the ratio of maximum curvature demand in weak axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in longitudinal direction for each scour depth (Comparison-1). On the other hand, in Figure 5.210(b) the ratio of maximum curvature demand in weak axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0°, 45°, 90° and 135°) (Comparison-2). This comparison is also done for the strong axis of bridge column as seen in Figure 5.211.

The maximum demands for column curvature gathered from nonlinear analyses that take into account different incidence angles are considerably more than those obtained from Caltrans for a 45° skewed bridge. The maximum curvature demands of the non-skewed bridge column are higher than those calculated by Caltrans, however not as high as those of the skew bridge. In weak axis of the column, the ratio obtained from Comparison-1 has a decreasing trend with an increase in scour depth. But there is not a distinct trend with scour depth in strong axis. It is far more successful to rotate the ground motion components by 135° in addition to the three different incidence angles that Caltrans suggests in order to achieve the maximum curvature required for both the weak and strong axes of non-skewed and 45° skewed bridge column. In various scour depths, it is still insufficient to meet the maximum curvature requirements of a non-skewed bridge column.



(a)



(b)

Figure 5.210. The ratio of maximum column curvature in weak axis to Caltrans maximum column curvature when bridge scour is non-uniform in longitudinal direction (Case 2-2) (a) Comparison-1 (b) Comparison-2

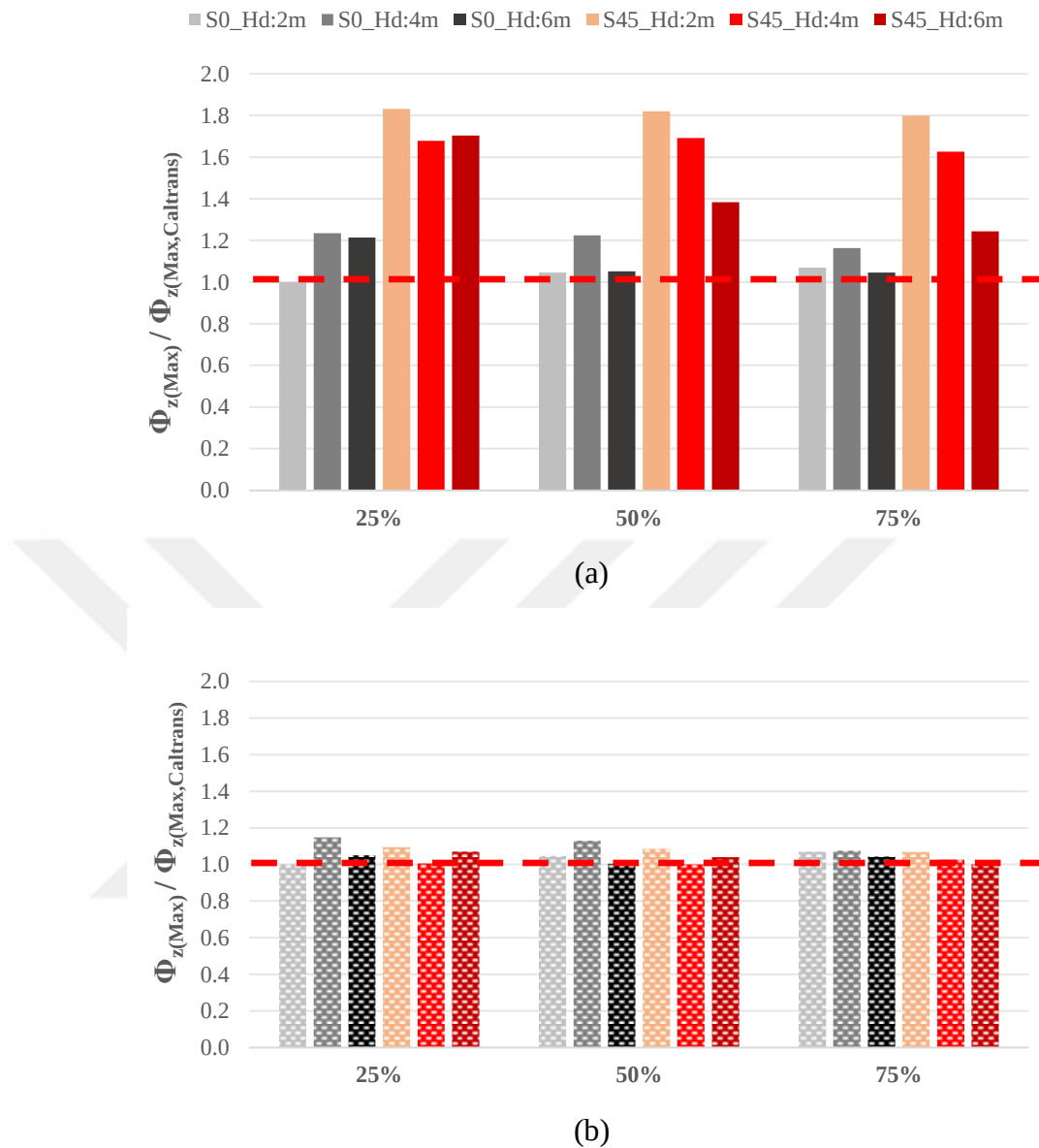


Figure 5.211. The ratio of maximum column curvature in strong axis to Caltrans maximum column curvature when bridge scour is non-uniform in longitudinal direction (Case 2-2) (a) Comparison-1 (b) Comparison-2

In Figure 5.212(a), the ratio of maximum shear force demand in local y' axis of column which is obtained from the nonlinear response history analysis with 15° increment to the maximum demand obtained from according to the Caltrans is shown for non-uniform scour occurred around bridge piles in longitudinal direction for each scour depth (Comparison-1). On the other hand, in Figure 5.212(b) the ratio of maximum shear force demand in local y' axis of column obtained from 13 different incidence angles to the demand obtained from 4 incidence angles (i.e. 0° , 45° , 90° and 135°) (Comparison-2). This comparison is also done for the local z' axis of bridge column as seen in Figure

5.213. These comparisons show that the local y' axis shear demands derived from the analyses are relatively similar to the demands acquired from Caltrans for both skewed and non-skewed bridges in all non-uniform scour cases occurred in longitudinal direction. On the other hand, when ground motion components rotated in just three angular directions, the maximum shear force demand ratio in the skewed bridge are larger along the local z' axis of column. The local z' axis of the skewed bridge column captures maximum demands when the ground motion components are rotated 135° .

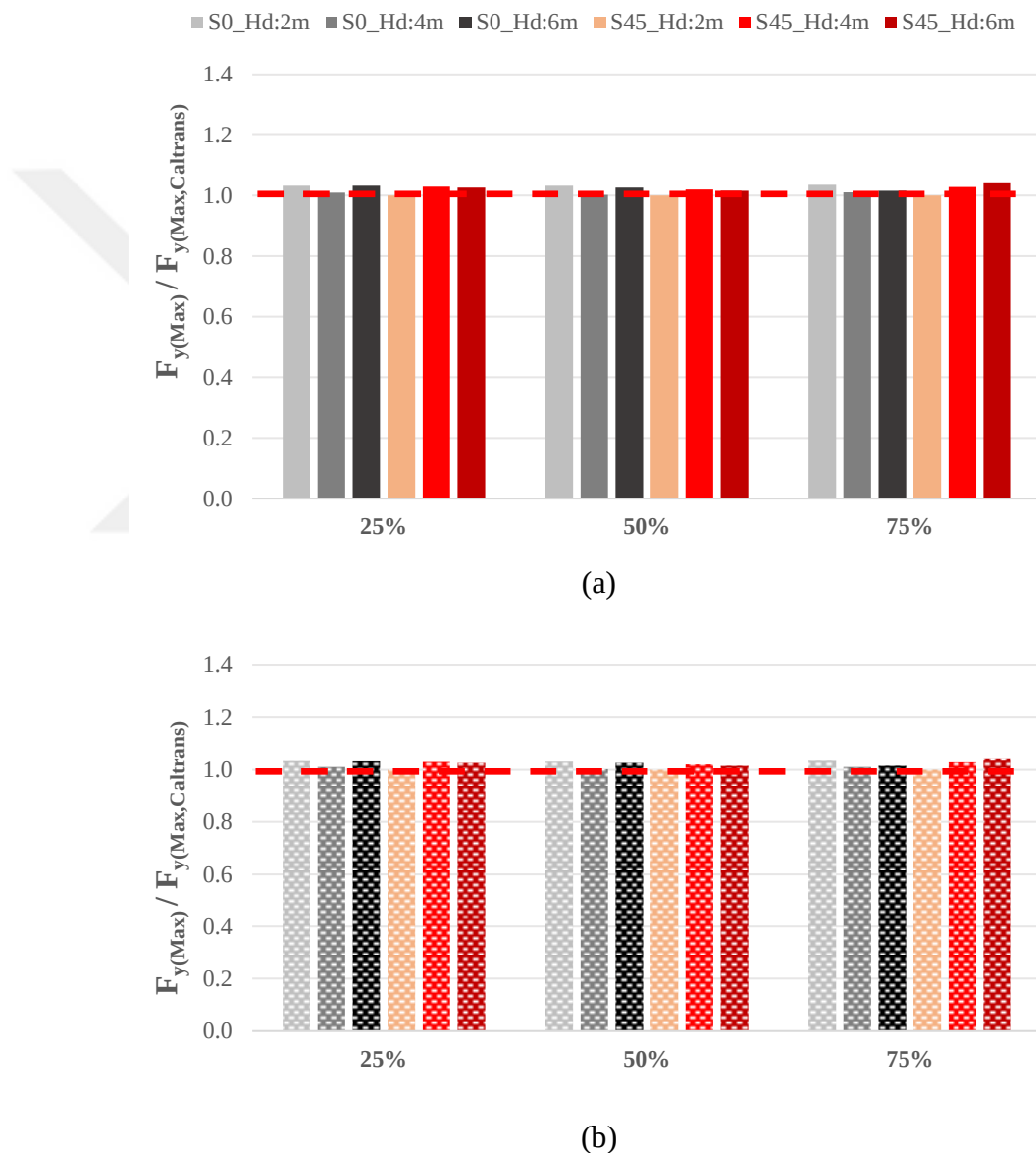


Figure 5.212. The ratio of maximum column shear force in local y' axis to Caltrans maximum column shear force when bridge scour is non-uniform in longitudinal direction (Case 2-2) (a) Comparison-1 (b) Comparison-2

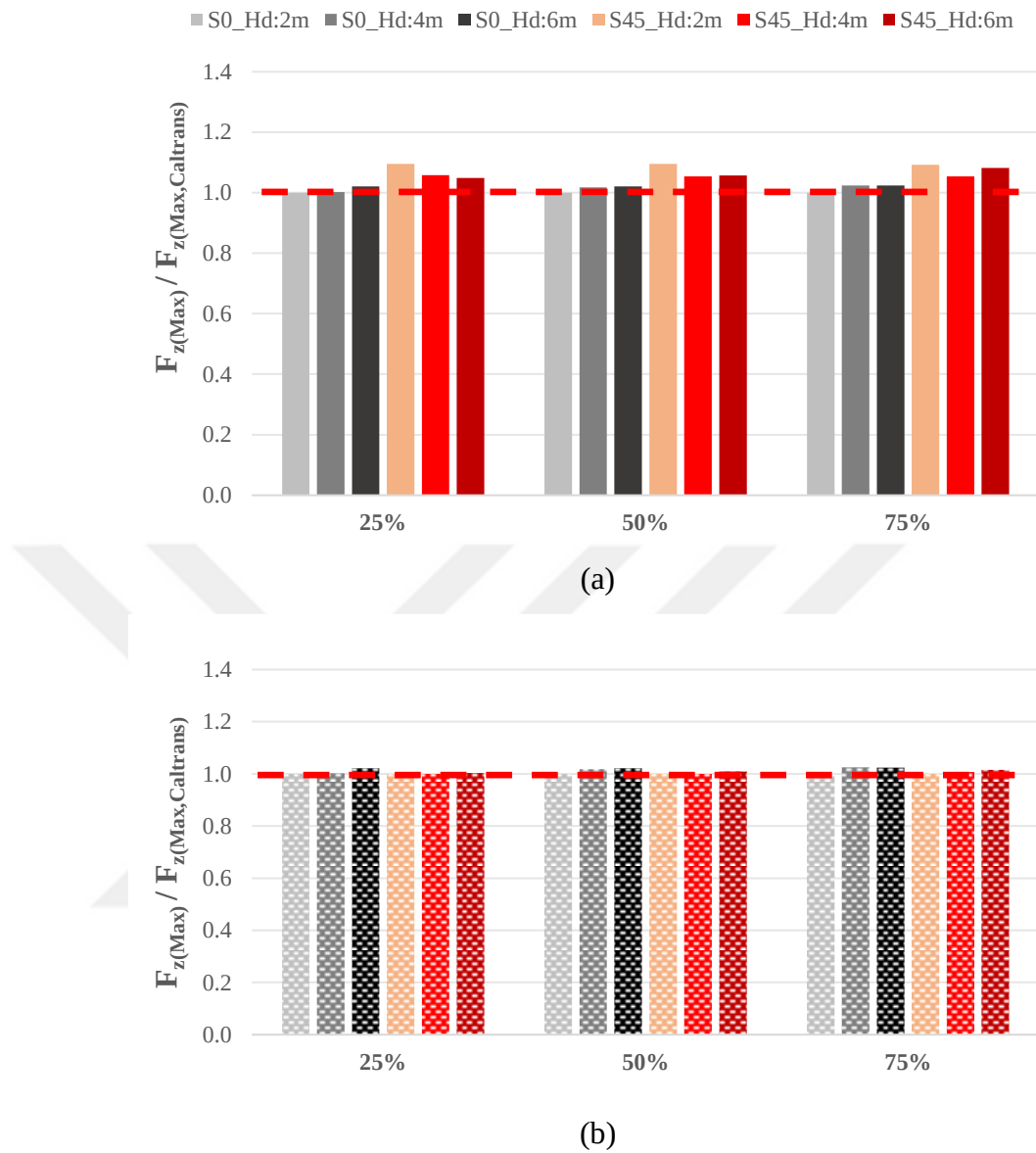


Figure 5.213. The ratio of maximum column shear force in local z' axis to Caltrans maximum column shear force when bridge scour is non-uniform in longitudinal direction (Case 2-2) (a) Comparison-1 (b) Comparison-2

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

In the first part of the doctoral dissertation, a study was conducted to investigate two distinct methodologies in reflecting the earthquake incidence angle in the nonlinear analysis of bridges. A numerical model of an ordinary reinforced concrete highway bridge with prestressed concrete beams was employed for the study. With the OpenSees program, a 3D analytical model of a 4-span bridge with a single column pier was created by taking the skewness into account as a variable parameter. Two distinct approaches were utilized to account for the impact of the earthquake incidence angle in the analysis. The linear transformation equations were used in Method 1 to rotate the ground motion components to be applied in the principal axes of the bridge model. In the second method, which is Method-2, the earthquake components remained constant while the bridge model was rotated at specific angles. Nonlinear analyses of the constructed bridge model under the effect of 7 earthquake records were conducted in the time domain utilizing both approaches. The significance of this study is demonstrated by the lack of any research comparing the two approaches in the literature. Additionally, it can help researchers in selecting the best technique for nonlinear response history analysis of bridge-type structures, taking into account variations in the incidence angle of ground motion pairs. The outcomes of the two methods were compared, and Method-1 was used to identify the most critical ground motion incidence angle for different engineering demand parameters.

In the second part of the study, the combined effect of flood induced scour and earthquakes on highway bridges was investigated by using non-skewed ($\alpha=0^\circ$) and 45° skewed bridge model with soil structure interaction. A parametric study was conducted to obtain the maximum seismic demands of bridge members by considering bridge skew angle, scour depth and scour case, which is either uniform or non-uniform. Also, ground motion incidence angle was changed 0° to 180° with an increment of 15° by using linear transformation equations. Nonlinear response history analyses were done by the selected 7 strong ground motion recordings. Superstructure displacement, curvature and shear force demands of bridge column and shear force demand of piles are the engineering demand parameters for this study. Moreover, the residual displacements that occurred at the bridge column and superstructure were investigated and compared to the maximum displacements occurred for each ground motion. In addition, within the scope of the study, the uniform scour that occurs around the bridge piles and the non-uniform scour that may

occur in the transverse and longitudinal directions of the bridge were compared with each other. After obtaining seismic demands, critical ground motion incidence angle was searched by using the same bridge models and the obtained results were compared to the demands obtained according to the regulation given in Caltrans (2019).

Following outcomes were drawn from all the investigated parameters:

- Method-1 and Method-2 for representing earthquake ground motion in dynamic analysis give similar outcomes for each bridge with different skew angle and earthquake incidence angles. Since Method-1 is simpler and easier to apply -the ground motion components are just rotated to bridge global axes using linear transformation equations. It is therefore advised that Method-1 should be taken into consideration in dynamic analysis.

- The bridge models under investigation do not have a common critical earthquake incidence angle. For every engineering demand parameter and bridge skew angle, different incidence angles are critical. Furthermore, a number of factors, including the bridge skew angle, the chosen seismic acceleration records, and the engineering demand parameters studied, have an impact on the critical earthquake incidence angle.

- The average maximum bridge superstructure displacement increases as the bridge skew angle increases and displacement demands are primarily impacted by changes in the bridge skew angle in the transverse direction.

- A change in the earthquake incidence angle has a greater impact on the average curvature demands of the pier column's weak axis. Furthermore, the curvature demands on the weak axis increases in parallel with an increase in the bridge skew angle.

- In the non-skewed bridge model, the shear force demands of the column y' local axis are mostly unaffected by the changes in the earthquake incidence angle. However, as the bridge skew angle increases the seismic demands change, which indicate a more noticeable difference in each earthquake incidence angle. On the other hand, the column shear force demands on the local y' axis tend to decrease while the demands on the local z' axis tend to increase as the bridge skew angle increases.

- The pounding between the abutment and the superstructure in the longitudinal direction of the bridge inevitably cause damage to the abutment backwall. The pounding elements defined in the longitudinal direction experienced significant deformations in the case of weak abutment wall sections. Shear keys also have a significant influence on the pounding behavior that occurs in the transverse direction of the bridge between the

superstructure and shear keys. In the case of an earthquake, the superstructure of the bridge is kept from moving out of its supports by the rigidly designed shear keys.

- Compared to the fixed base bridge model, considering soil structure interaction increases the natural vibration periods of the structural system. Because the bridge becomes more flexible in SSI model and thus, this increases the natural vibration periods compared to the bridge that has fully restraint support conditions.

- Superstructure displacements are more in SSI bridge than fixed based model for longitudinal and transverse directions of bridge. Because more flexible bridge response was achieved by taking the soil flexibility into account, which resulted in increased displacement demands.

- Column curvature demands are less in SSI bridge than fixed based for weak (y') and strong (z') axis. This is because in the fixed based bridge model, deformation demands are much more localized in the bridge column end, which is fully restraint. However, in the soil-structure interacted model, the column curvature demands were much less due to the relaxation of the column by the flexibility of the soil springs.

- Shear force demands for column local y' and z' axis also tend to decrease in the SSI bridge in a similar fashion with the column curvature demands. However, the variation in the column shear demands is not as severe as in the case of column curvature demands. The main reason behind such behavioral trend is the saturation in the column shear demands as the column attains its yield curvature capacity. This shows that soil structure interaction has a positive contribution to the shear demands of bridge columns and it eliminates the column shear failure probability.

- Scour is a significant event that has a major impact on the seismic demands of bridge members. Depending on the bridge component and engineering demand parameter, seismic demands can be substantially different in circumstances of extensive scour than in cases of no scour. Therefore, it is crucial to take the scour effects into account when designing and assessing the bridge-type structures built in flood-prone areas.

- The natural vibration period of the bridge increases with the increase in scour depth. The main cause is an increase in the effective column clear height followed by an increase in scour depth. Therefore, scour increases the vibration periods of the bridge and makes it more flexible. On the other hand, while the 1st period values of the skewed bridge model are higher than the non-skewed bridge, the 2nd period values are less. This is due

to the fact that, the first mode belongs to the longitudinal direction of bridge and the second mode belongs to the transverse direction of bridge. Therefore, the stiffness in the longitudinal direction of the bridge decreases with the increase in the skew angle, while it increases in the transverse direction of the bridge.

- Superstructure displacement has an increasing trend with the increasing scour depth for both longitudinal and transverse direction of bridges for all scour cases. Because the effective height of the bridge pier increases along with the scour depth, the superstructure elements are exposed to higher displacement demands. on the other hand, the combined effect of scour and bridge skewness can change the superstructure demands considerably. When the bridge skew angle changes, the displacement demands in the transverse direction of the superstructure show a significant increase. In the longitudinal direction, on the contrary, the superstructure displacement demands were less in the skewed bridge model.

- When scour Case-1 (uniform scour) and Case 2-1 (non-uniform scour in transverse direction) are compared to each other, non-uniform scour depth change in transverse direction affects seismic demands more than uniform change in 90° ground motion incidence angle. Also, increase in the angle of scour depth between upstream and downstream piers increases superstructure displacement demands. When the results are compared according to the skew angle, displacement demands are higher in non-skewed bridges in longitudinal direction. Besides, displacement demands are higher in 45° skewed bridge than the non-skewed bridge in transverse direction.

- When scour Case-1 (uniform scour) and Case 2-2 (non-uniform scour in longitudinal direction) are compared to each other, the non-uniform scour in the bridge longitudinal direction do not affect the superstructure displacement demands as in the case of non-uniform scour in the transverse direction (Case 2-1). It can be said that the displacement demands of the bridge superstructure are not affected much by uniform and non-uniform scour in the longitudinal direction, but the demands are more affected by the change in the skew angle, which is an important irregularity in bridges.

- Curvature demands of bridge column has a decreasing trend with the increase in scour depth. This situation can be explained by the increase in the bridge period, which results in less earthquake force on the structure. Additionally, in the fixed supported situation, the deformations are primarily concentrated in the bridge columns. However, in scour conditions, the deformations in the piles lessen the deformations in the columns.

Curvature demands occurred in the weak axis (y') of the bridge column are highly affected by the change in the skew angle especially in 120° incidence angle. In addition, curvature demands exceed yield curvature in some earthquake incidence angles and column pier shows nonlinear behavior. This proves that the earthquake incidence angle should be considered in the nonlinear analysis.

- Curvature demands are higher in Case-1 than Case 2-1 when ground motion incidence angle is 90° . It can be concluded that non-uniform scour has a positive effect to the curvature demands of bridge column. Moreover, the relieve in the column curvature demands is more in non-uniform scour case with larger scour depth angle. When results are compared according to skew angle, demands become greater in non-skewed bridge than skewed one in both axes of column.

- Column curvature demands show a significant decrease as the scour depth and the change in scour inclination in non-uniform scour in the longitudinal direction increases. For weak axis, column curvature demands are above the yield curvature for both non-skewed and 45° skewed bridge for each scour cases when scour depth is 2 m. In strong axis of the column, curvature demands are below the yield curvature in 45° skewed bridge for all scour depths and scour cases.

- While the shear force demands occurring in the local y' axis of the column are less in the skewed bridge than in the non-skewed bridge, they are higher in the local z' axis. In addition, as the depth of scour increases in both bridges, the shear demands tend to decrease. When the average maximum shear force demands are compared to shear capacities, it is seen that demands are below the limits for all scour cases, scour depths and incidence angles. Therefore, it can be said no shear damage occurred in the bridge columns during nonlinear analysis.

- Shear force demands of piles decrease with the increasing scour depth. Also, demands are higher in non-skewed bridge model than skewed one. When the results are compared for different scour cases, the average of the maximum shear force is higher in non-uniform scour cases than uniform scour. Also, one of the investigated corner piles has no shear damage when scour case becomes uniform for all depths. On the other hand, in non-uniform scour case, the shear force demands can exceed the shear capacity depending on the scour depth. The piles having the least clear height are exposed to higher shear demands than the piles having larger clear heights. Non-uniform scour in transverse direction of bridge causes a brittle damage mechanism as in the case of short column

phenomenon. Therefore, non-uniform scour case can be critical and should be considered in evaluating the seismic response of the bridges. In case of non-uniform scour in the longitudinal direction, the shear force demands of the pile elements were almost the same, but none of them reached their shear capacity.

- Residual displacements occurred in bridge column and superstructure are higher in non-skewed bridges in the longitudinal direction than transverse direction. Although the residual displacements are affected by the change in scour depth, it cannot be concluded that the residual displacement demands are proportionally related to the increase in scour depth. Residual displacements are higher in non-skewed bridge model in longitudinal direction for both column and superstructure. However, in transverse direction the situation becomes vice versa.

- The success of the Caltran's recommendation by considering three earthquake excitations angles (i.e. 0° , 45° and 90°) in achieving the most critical seismic demands is investigated by comparing the most critical seismic demands of 13 different excitation angles. Although Caltran's recommendation with three earthquake excitations angles is satisfactory for achieving the critical superstructure displacements and pile shear demands, especially for the 45° skewed bridge, the critical column curvature demands are underestimated by more than 70%. Caltran's recommendation can be improved considerably by further considering the 135° excitation angle in addition to the existing three. For the investigated bridges and scour cases, consideration of four earthquake excitations angles (i.e. 0° , 45° , 90° and 135°) can satisfactorily estimate the most critical seismic demands by less than 20% difference with the most critical achieved through 13 excitation angles.

6.2. Recommendations for Future Studies

The following suggestions for further research on the subject might be made in the light of the studies carried out in this dissertation.

- The effect of uniform and non-uniform scour on seismic demands could be investigated for different bridge types, irregularities and configurations.
- Fragility curves of bridges could be obtained by using a larger number of ground motion recordings and damage limit states for critical bridge elements should be evaluated under the effect of different scour cases.

- A definition that captures shear damage could be made in the bridge numerical model, and how seismic demands change after reaching the shear capacity of the piles, especially in cases of non-uniform scour, could be evaluated.
- Superstructure uplift phenomenon due to vertical component of ground motions or as a result of overturning due to lateral pounding could be considered for advancing the numerical model.



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APPENDIX

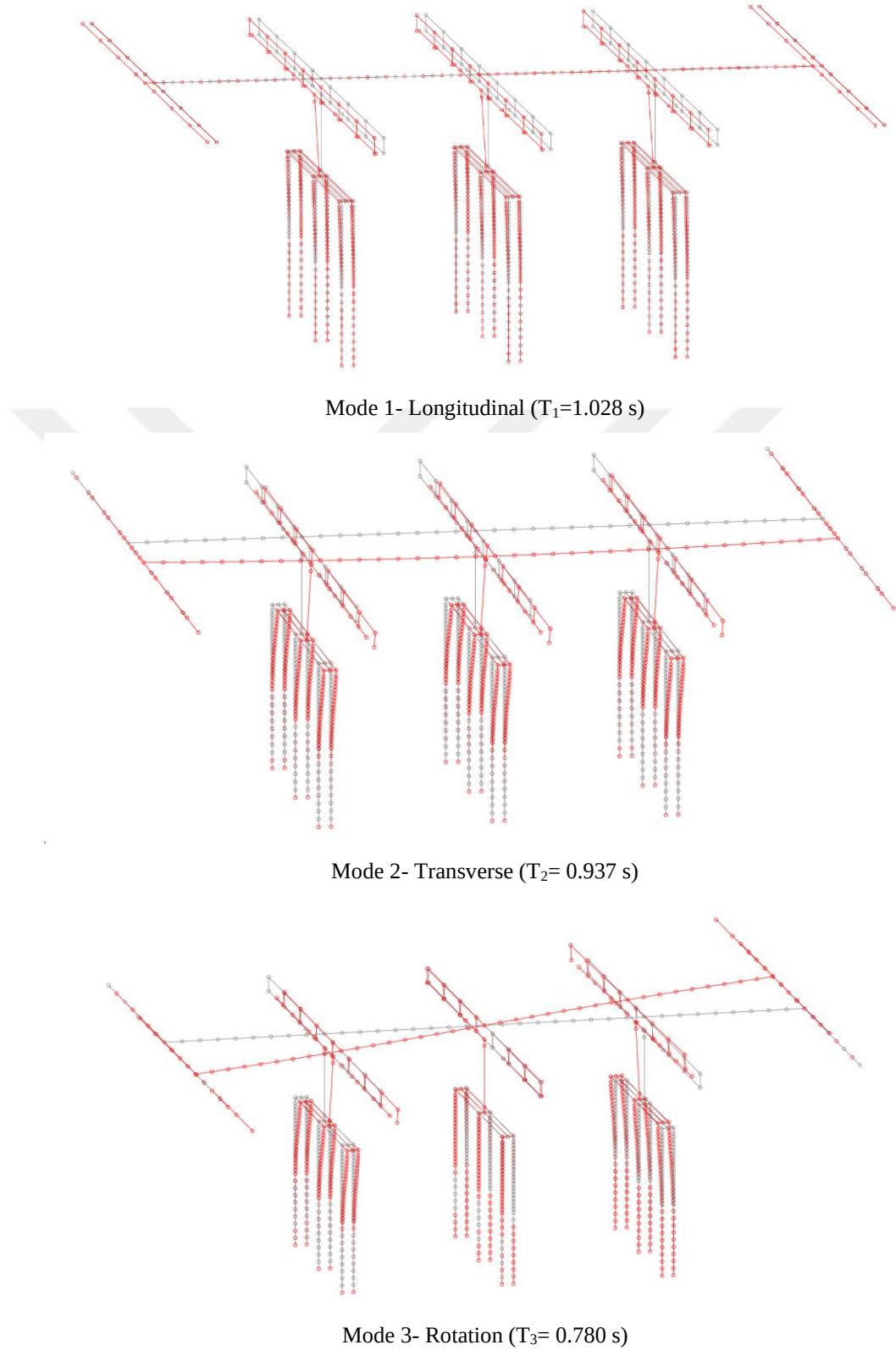
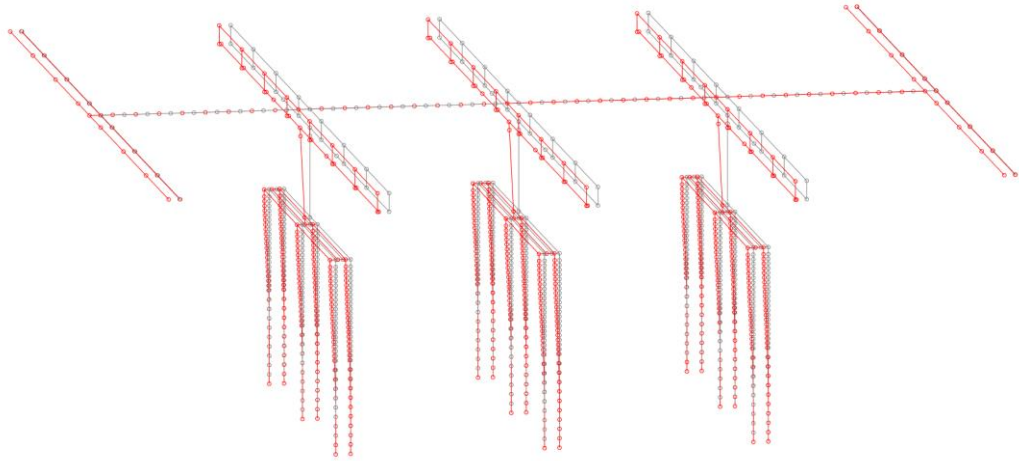
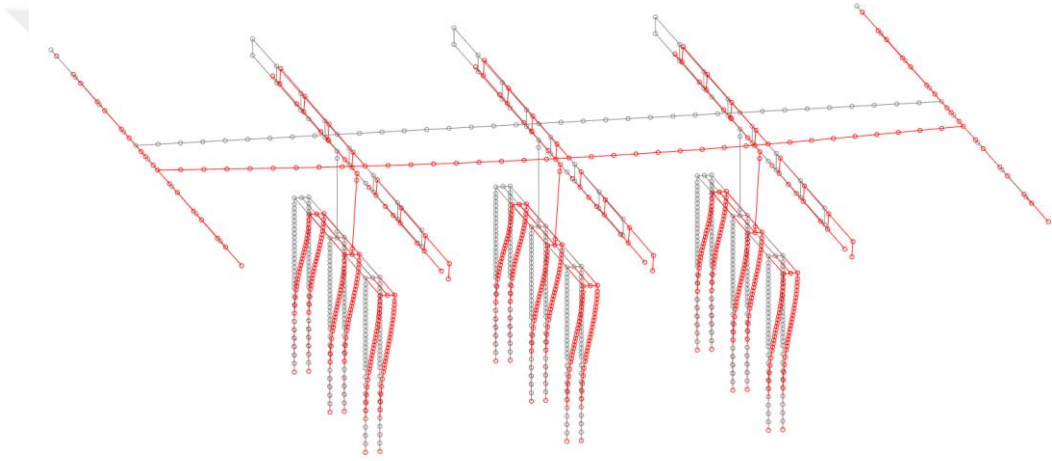


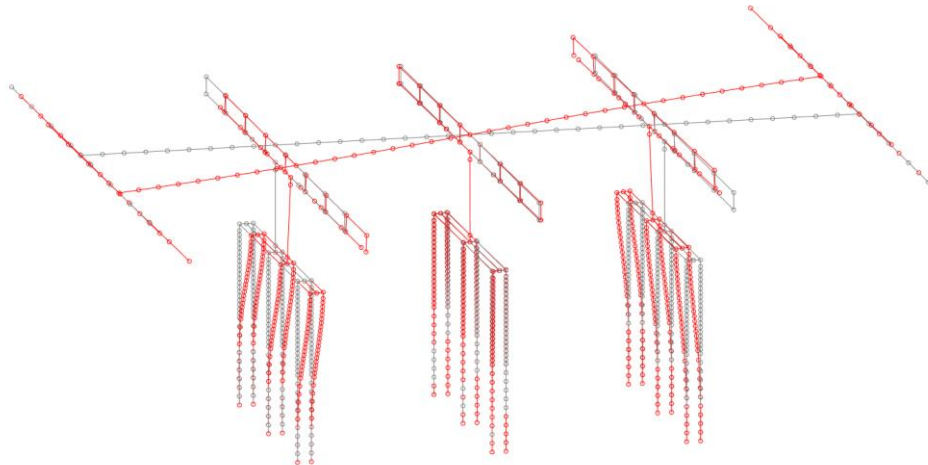
Figure A. 1. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 0 m non-uniform scour depth in transverse direction (Case 2-1a $\gamma=0.6$)



Mode 1- Longitudinal ($T_1=1.120$ s)

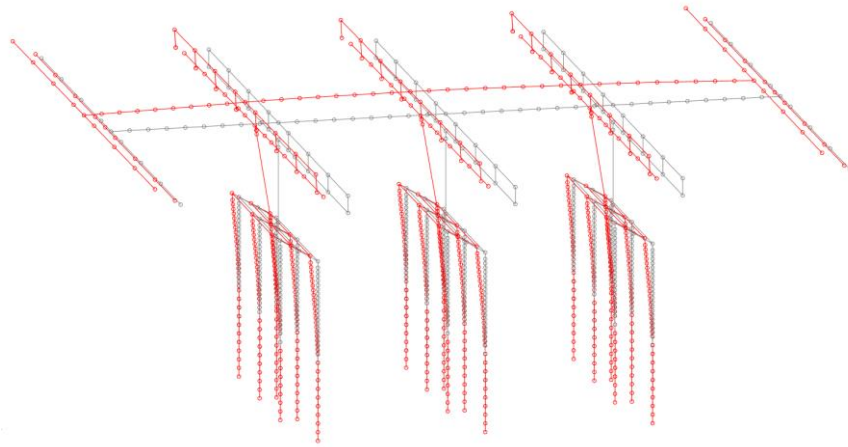


Mode 2- Transverse ($T_2= 1.116$ s)

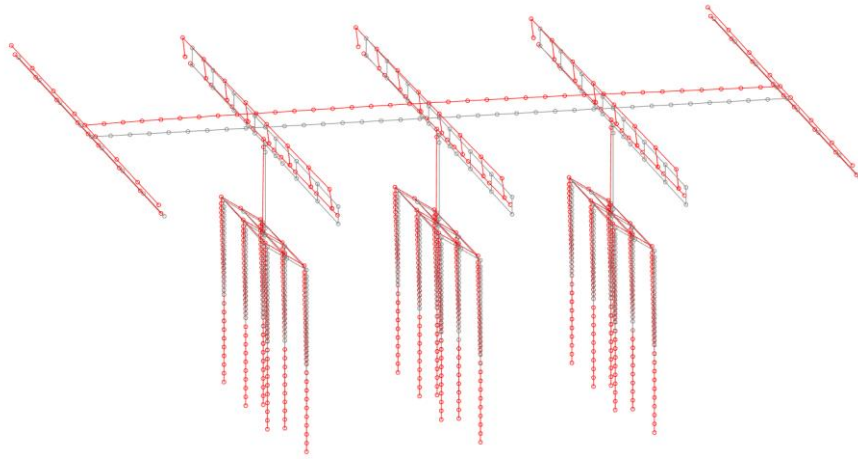


Mode 3- Rotation ($T_3= 0.830$ s)

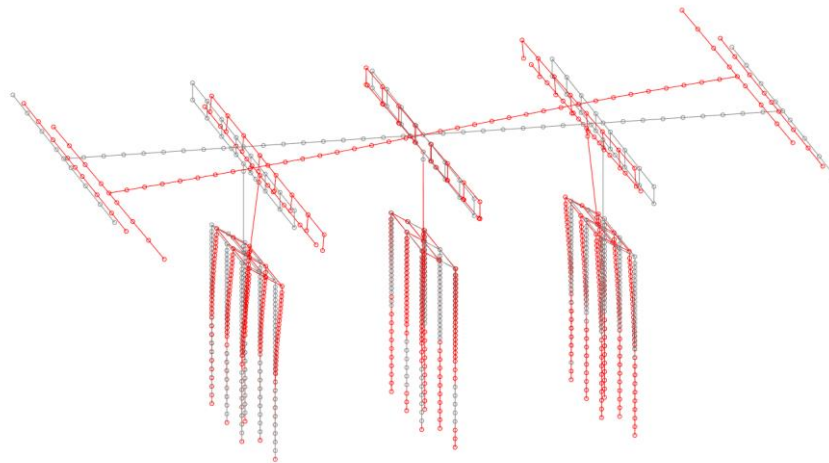
Figure A. 2. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 5 m non-uniform scour depth in transverse direction (Case 2-1a $\gamma=0.6$)



Mode 1- Longitudinal ($T_1=1.100$ s)

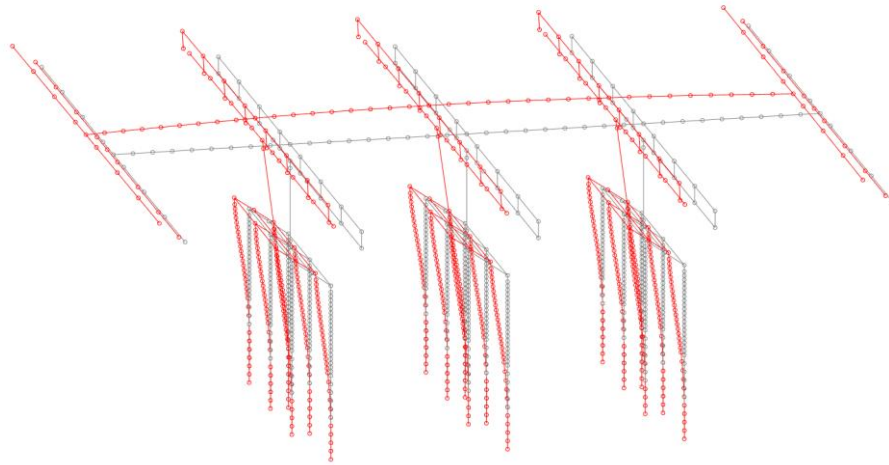


Mode 2- Transverse ($T_2= 0.897$ s)

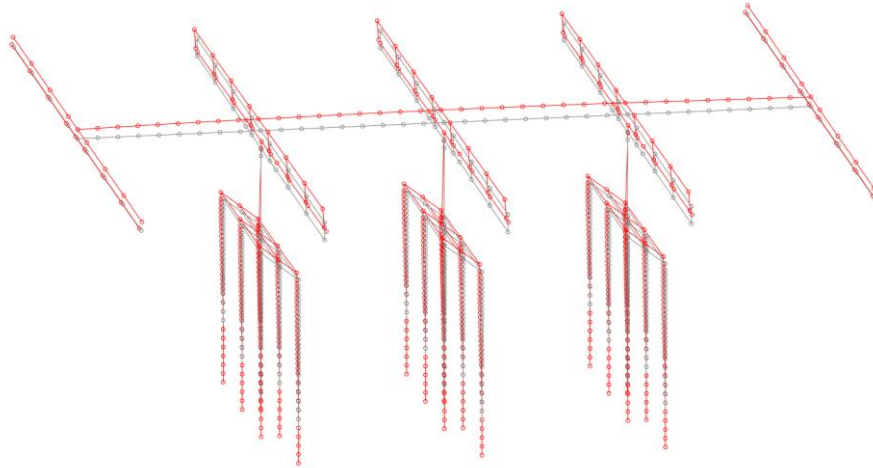


Mode 3- Rotation ($T_3= 0.807$ s)

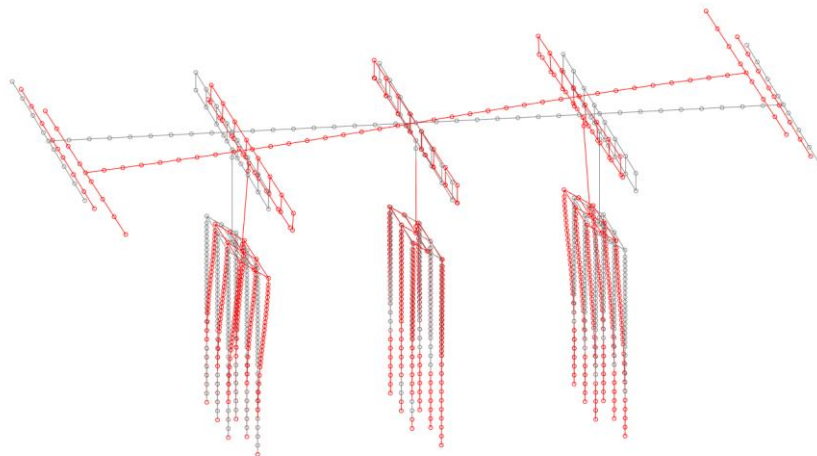
Figure A. 3. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 0 m non-uniform scour depth in transverse direction (Case 2-1a $\gamma=0.6$)



Mode 1- Longitudinal ($T_1=1.230$ s)

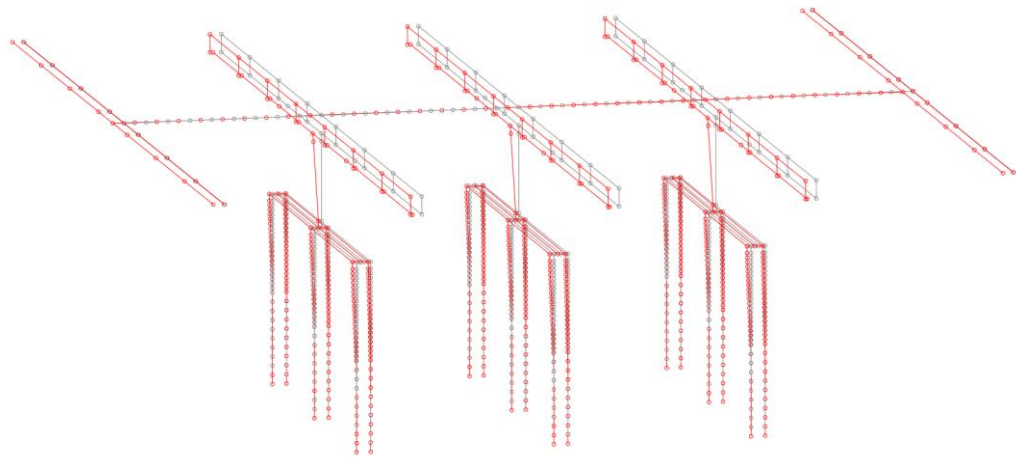


Mode 2- Transverse ($T_2= 1.037$ s)

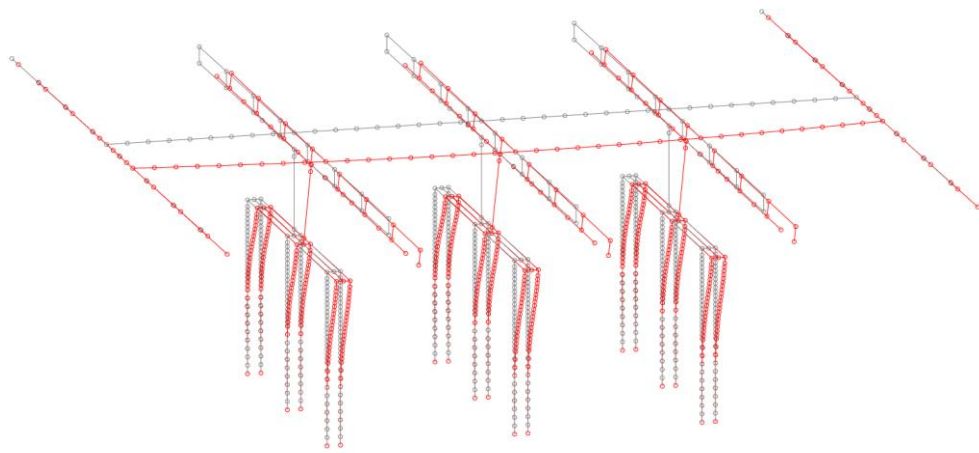


Mode 3- Rotation ($T_3= 0.845$ s)

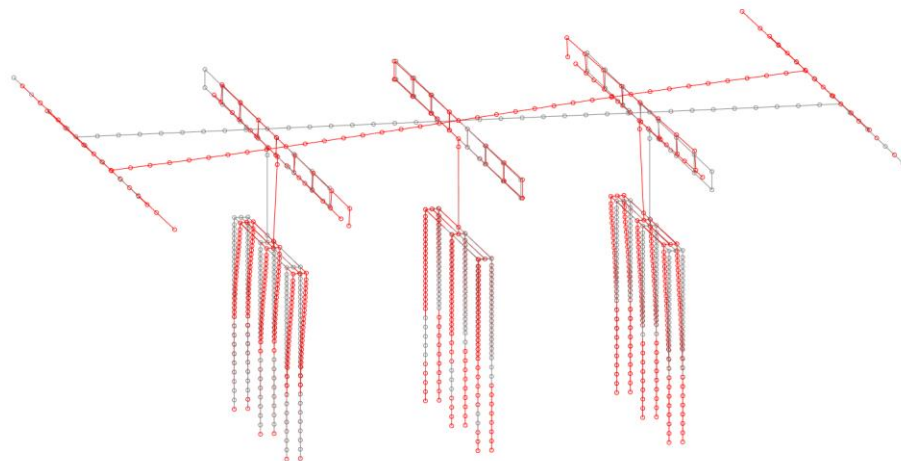
Figure A. 4. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 5 m non-uniform scour depth in transverse direction (Case 2-1a $\gamma=0.6$)



Mode 1- Longitudinal ($T_1=1.040$ s)

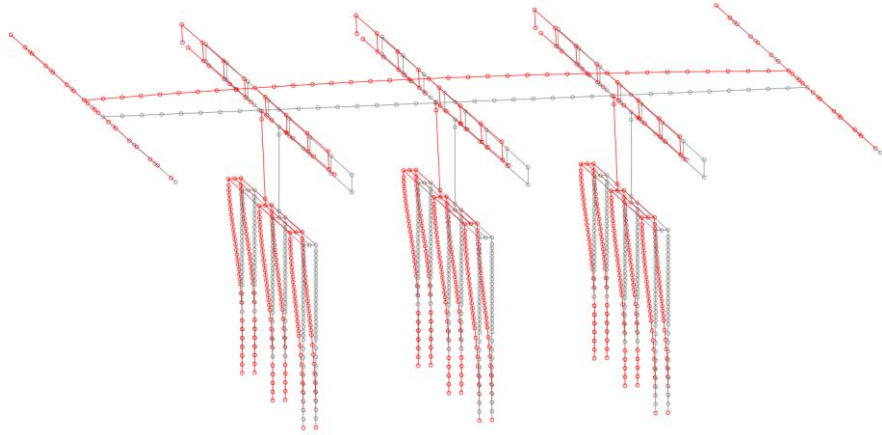


Mode 2- Transverse ($T_2= 0.953$ s)

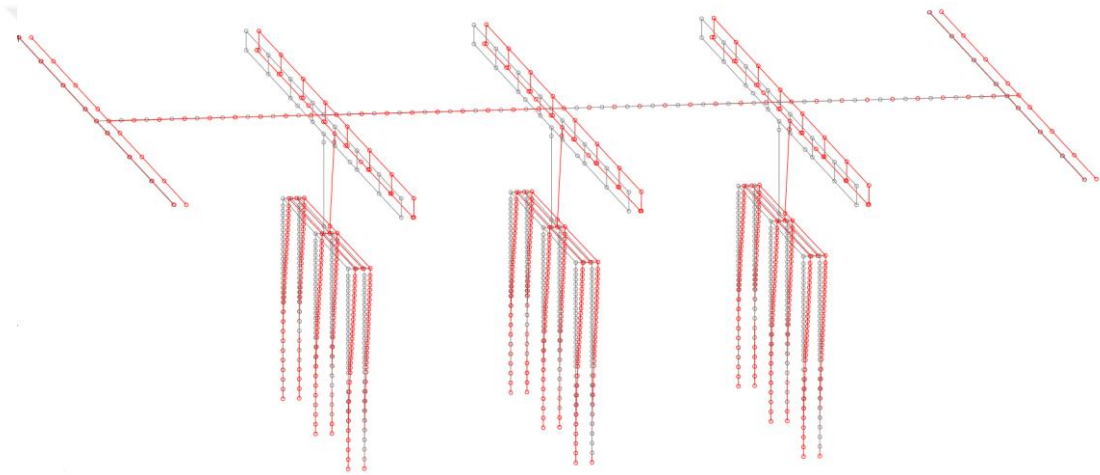


Mode 3- Rotation ($T_3= 0.785$ s)

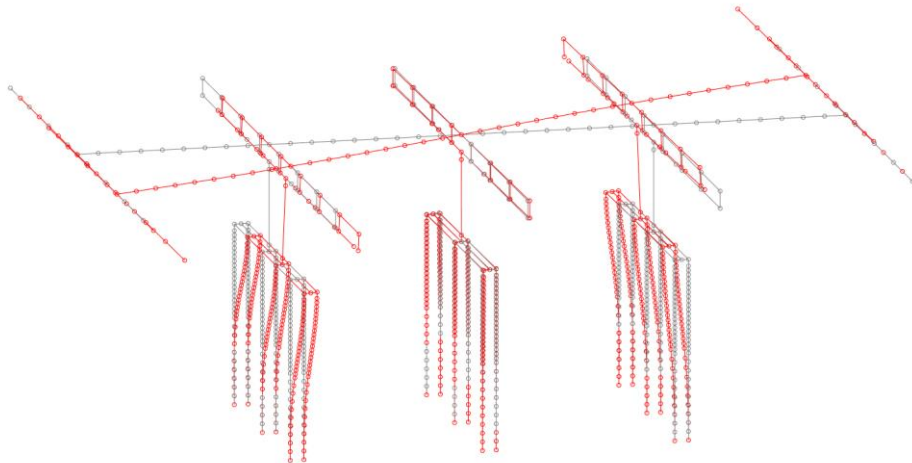
Figure A. 5. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 0 m non-uniform scour depth in transverse direction (Case 2-1b $\gamma=1.0$)



Mode 1- Transverse ($T_1=1.143$ s)

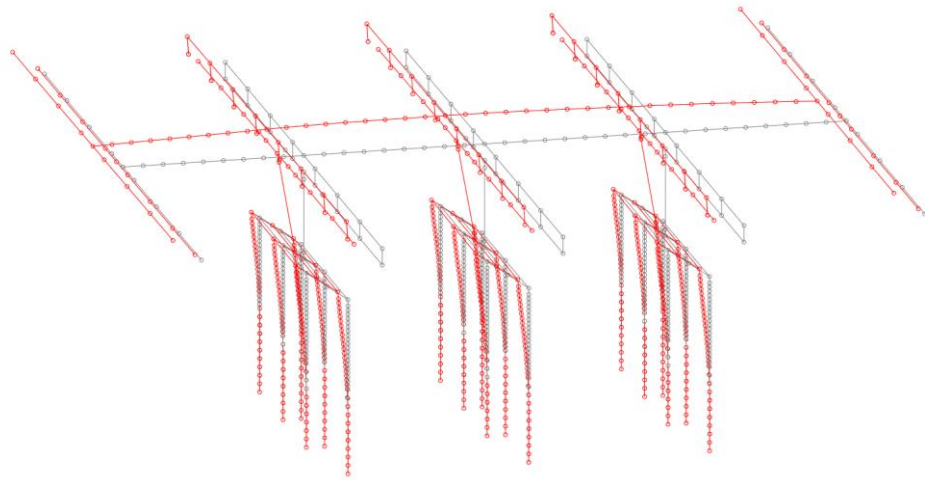


Mode 2- Longitudinal ($T_2= 1.134$ s)

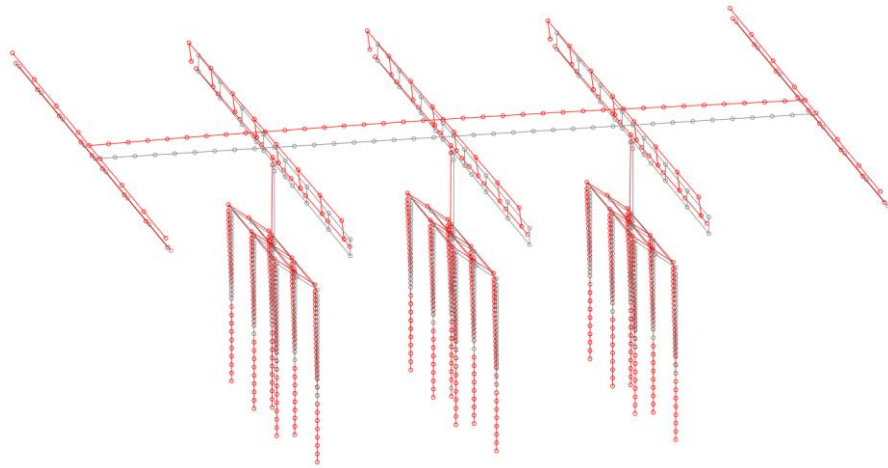


Mode 3- Rotation ($T_3= 0.836$ s)

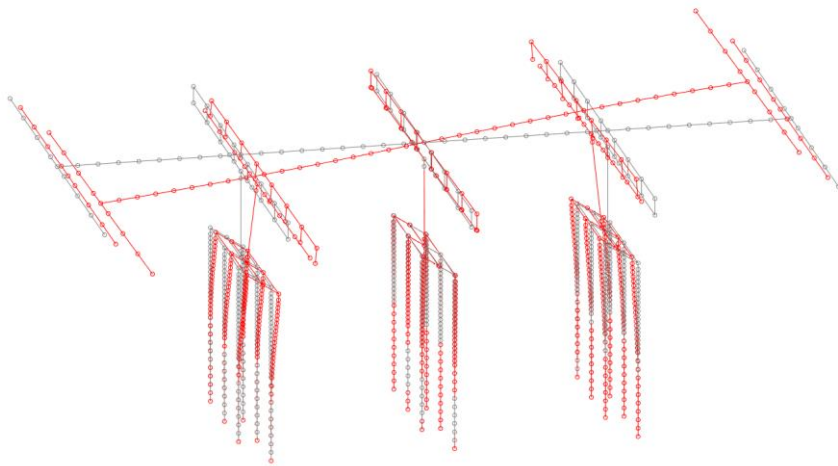
Figure A. 6. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 5 m non-uniform scour depth in transverse direction (Case 2-1b $\gamma=1.0$)



Mode 1- Longitudinal ($T_1=1.115$ s)

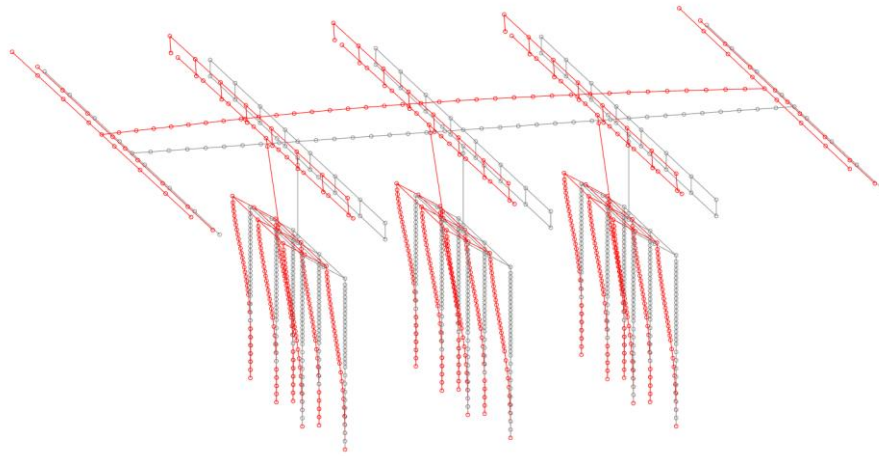


Mode 2- Transverse ($T_2= 0.911$ s)

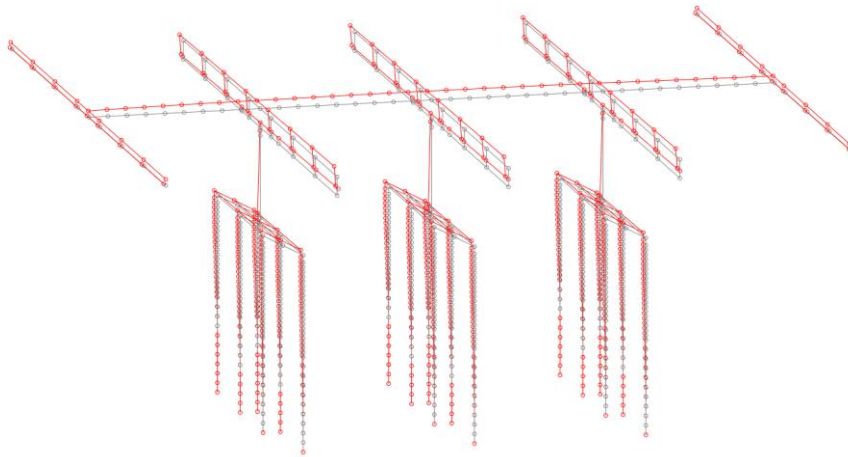


Mode 3- Rotation ($T_3= 0.811$ s)

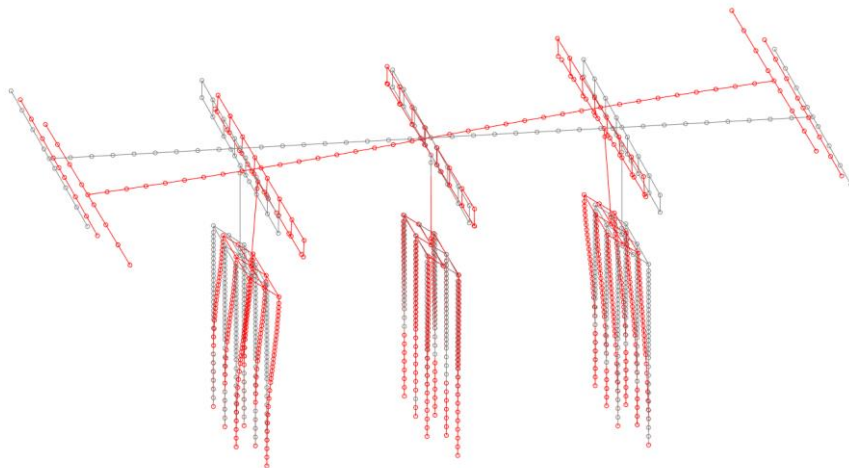
Figure A. 7. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 0 m non-uniform scour depth in transverse direction (Case 2-1b $\gamma=1.0$)



Mode 1- Longitudinal ($T_1=1.251$ s)

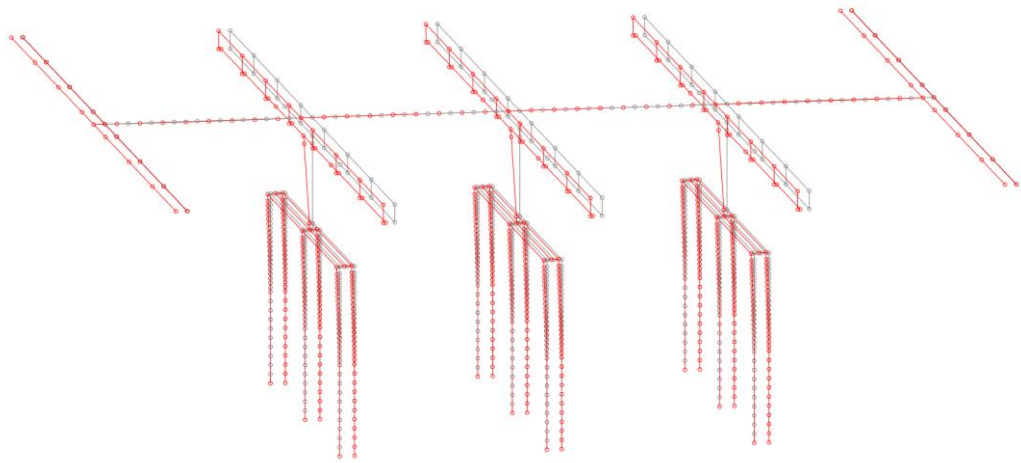


Mode 2- Transverse ($T_2= 1.057$ s)

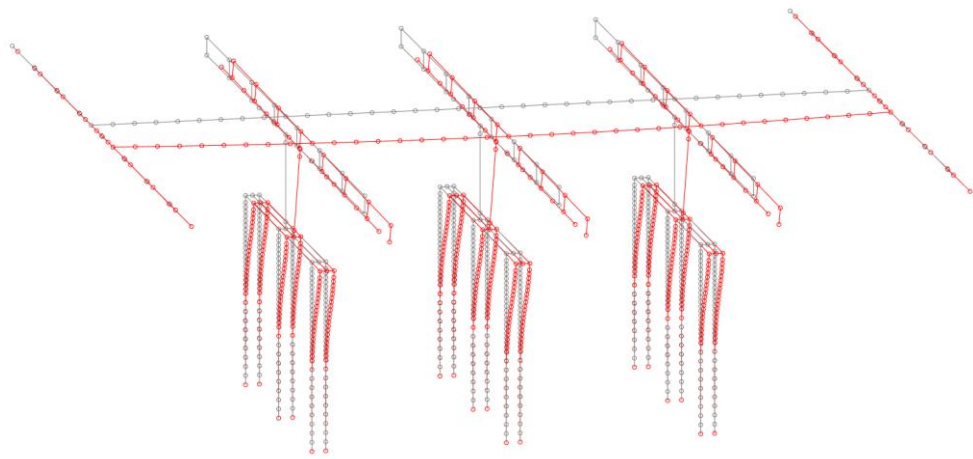


Mode 3- Rotation ($T_3= 0.850$ s)

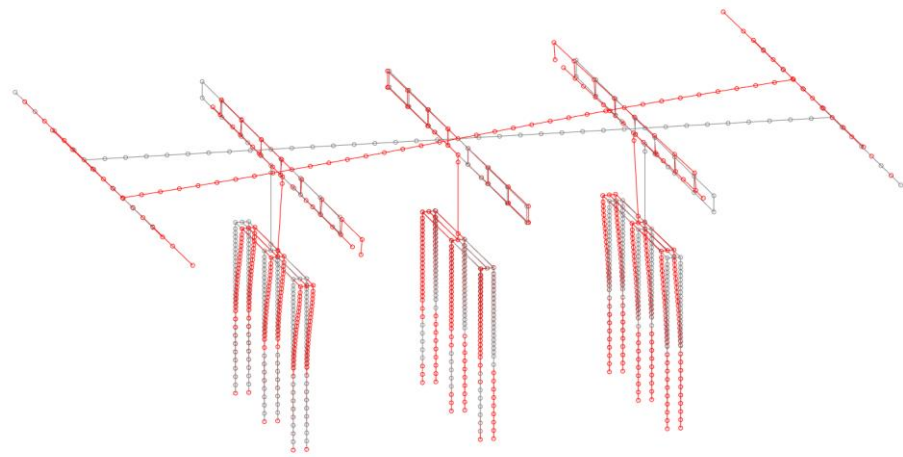
Figure A. 8. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 5 m non-uniform scour depth in transverse direction (Case 2-1b $\gamma=1.0$)



Mode 1- Longitudinal ($T_1=1.040$ s)

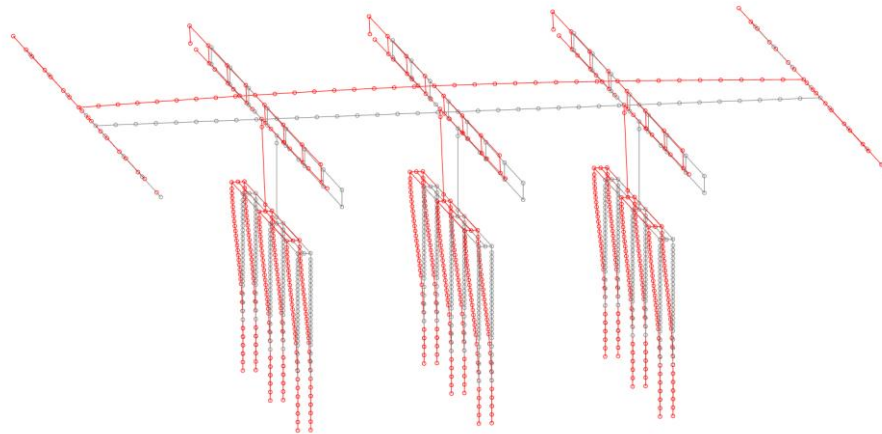


Mode 2- Transverse ($T_2= 0.963$ s)

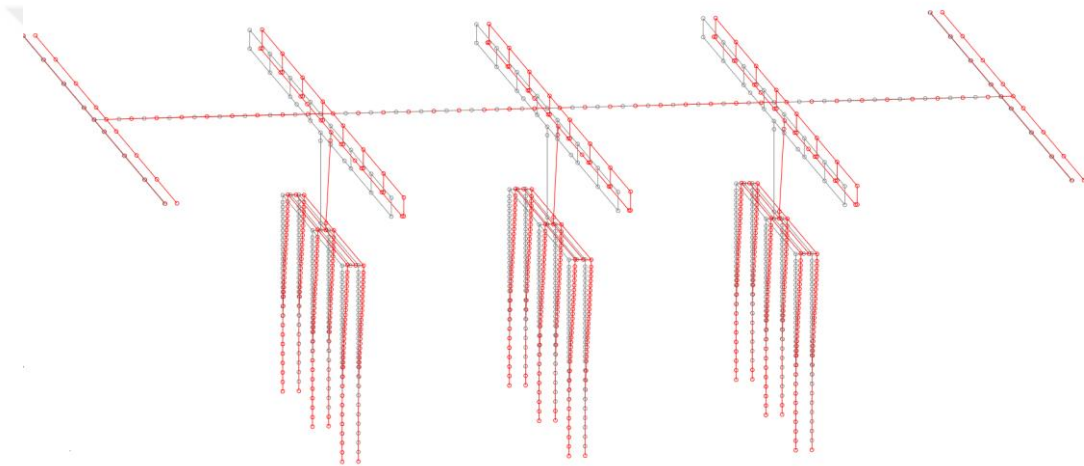


Mode 3- Rotation ($T_3= 0.787$ s)

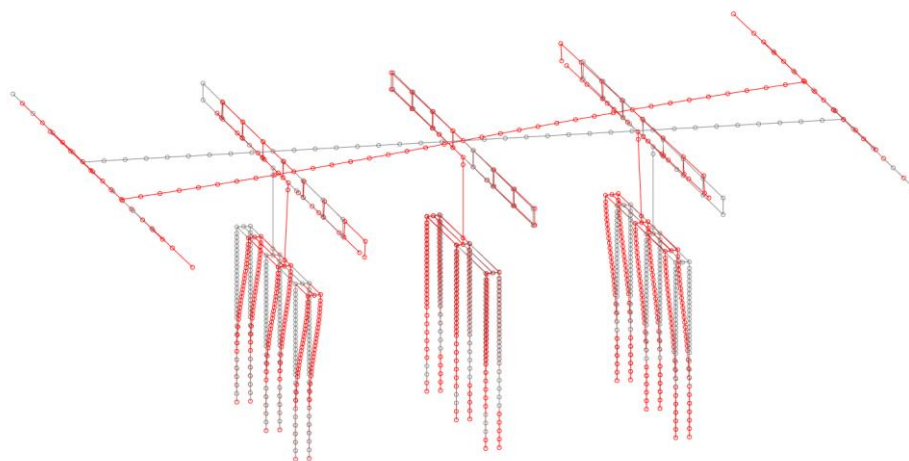
Figure A. 9. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2a %25)



Mode 1- Transverse ($T_1=1.127$ s)

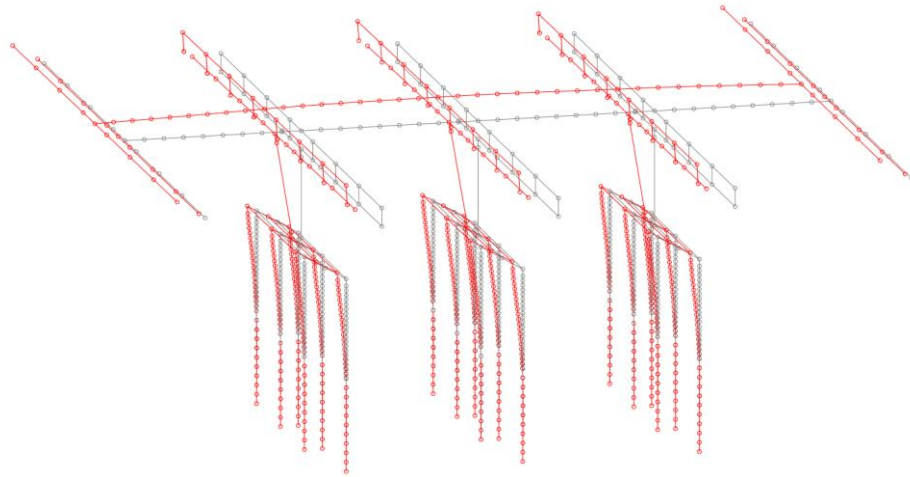


Mode 2- Longitudinal ($T_2= 1.123$ s)

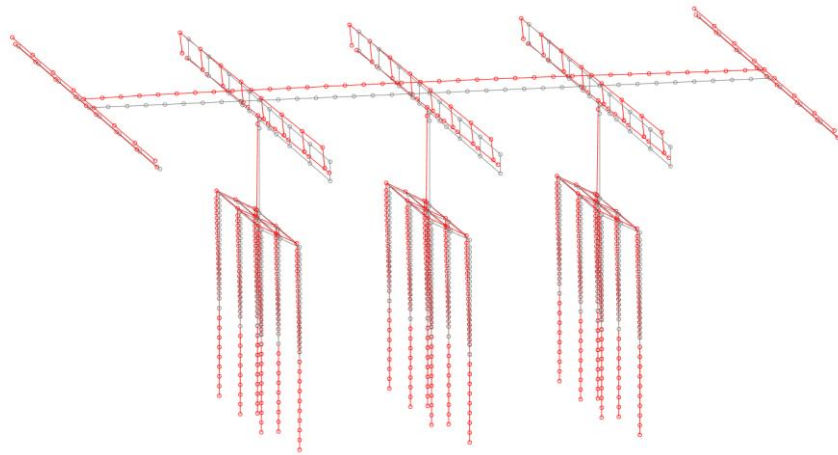


Mode 3- Rotation ($T_3= 0.827$ s)

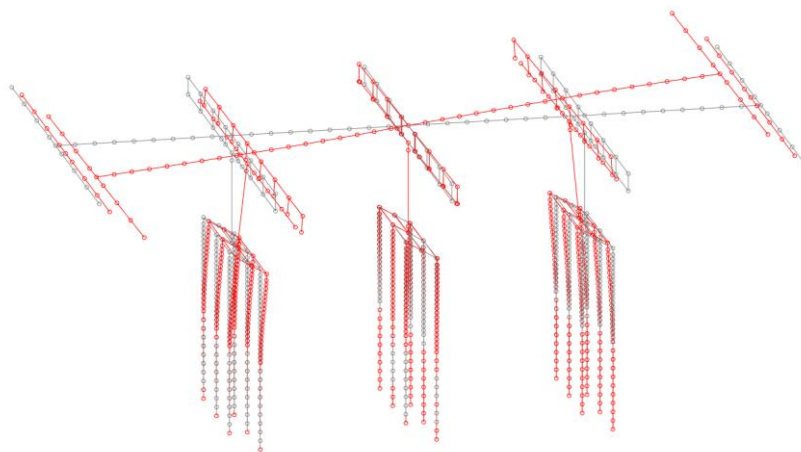
Figure A. 10. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2a %25)



Mode 1- Longitudinal ($T_1=1.118$ s)

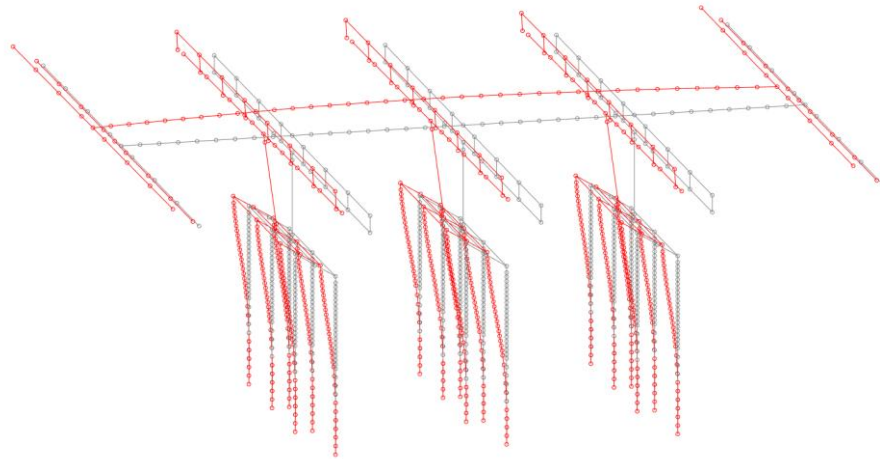


Mode 2- Transverse ($T_2= 0.919$ s)

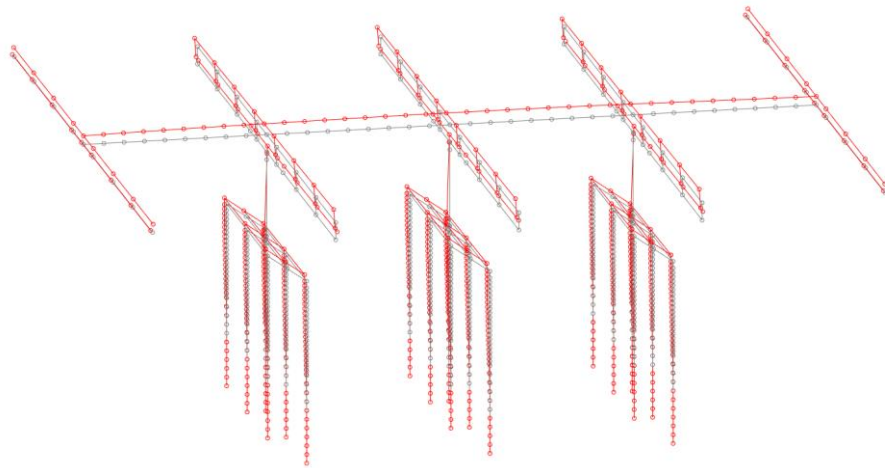


Mode 3- Rotation ($T_3= 0.812$ s)

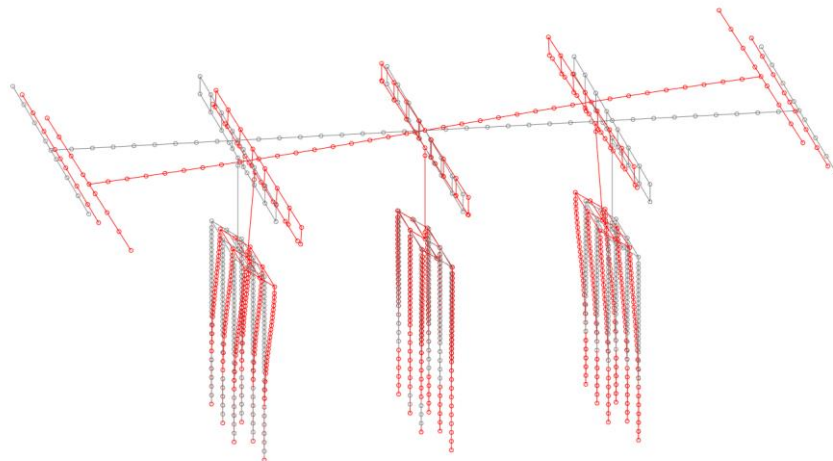
Figure A. 11. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2a %25)



Mode 1- Longitudinal ($T_1=1.237$ s)

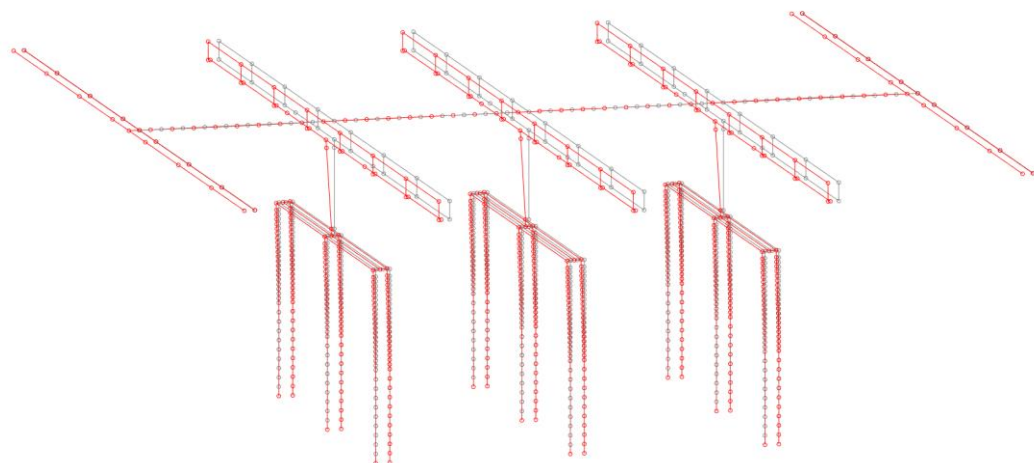


Mode 2- Transverse ($T_2= 1.043$ s)

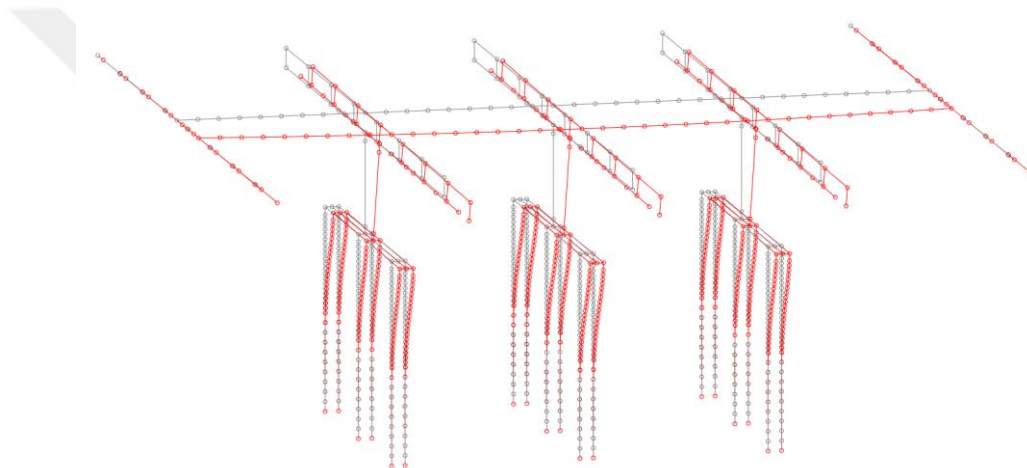


Mode 3- Rotation ($T_3= 0.843$ s)

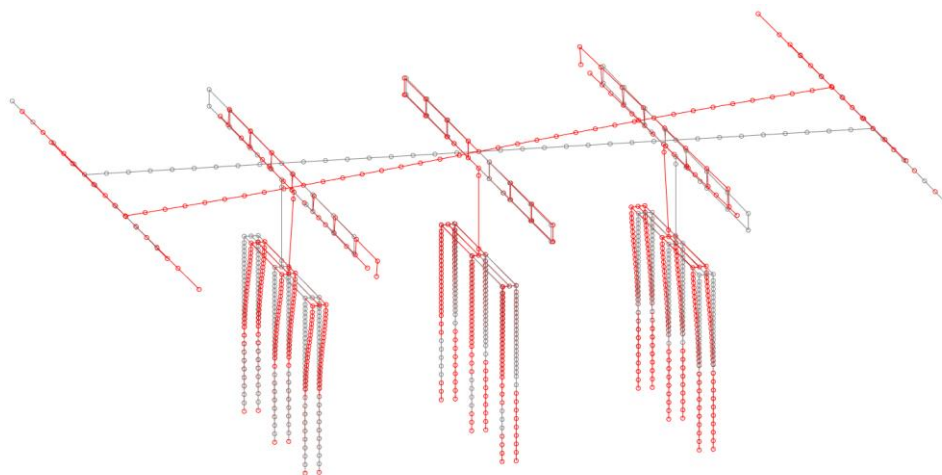
Figure A. 12. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2a %25)



Mode 1- Longitudinal ($T_1=1.043$ s)

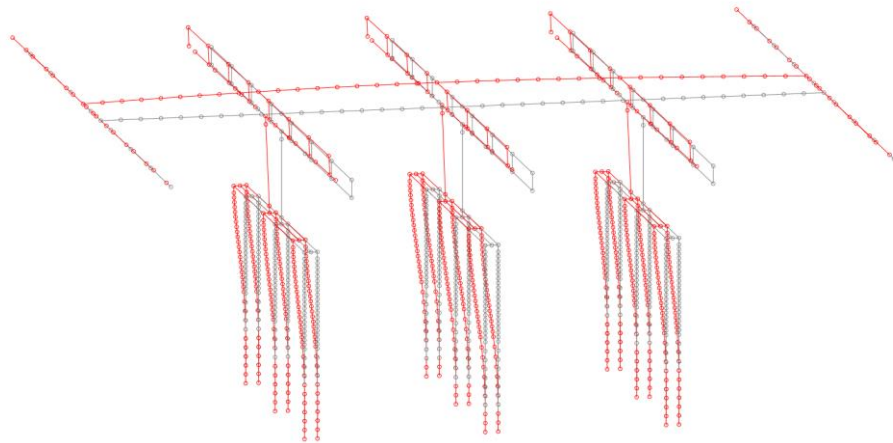


Mode 2- Transverse ($T_2= 0.969$ s)

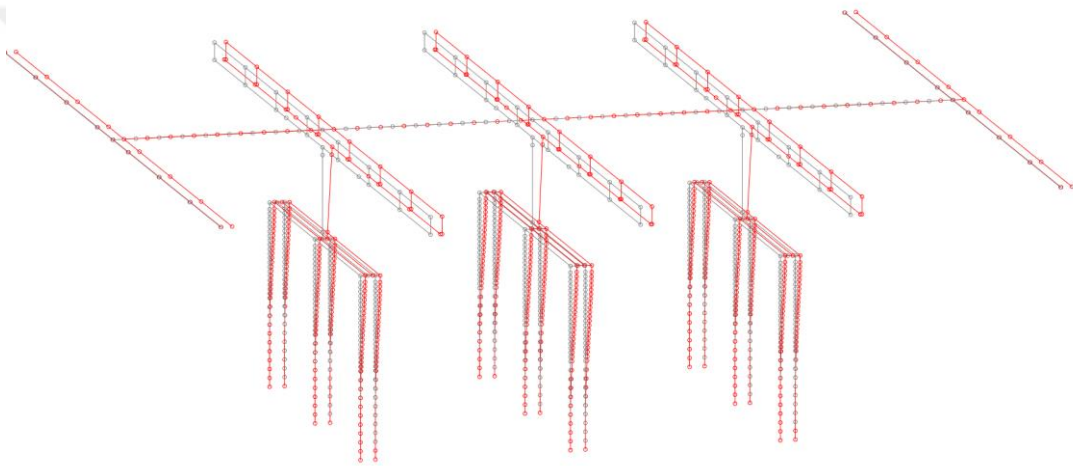


Mode 3- Rotation ($T_3= 0.787$ s)

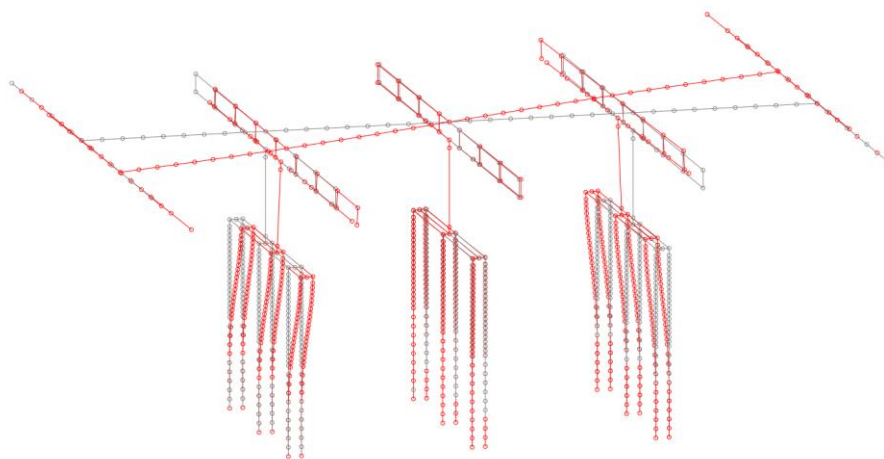
Figure A. 13. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2b %50)



Mode 1- Transverse ($T_1=1.148$ s)

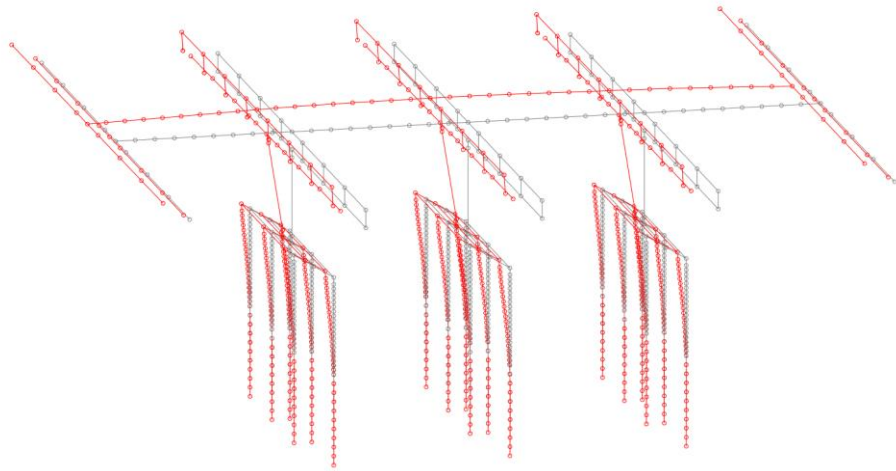


Mode 2- Longitudinal ($T_2= 1.132$ s)

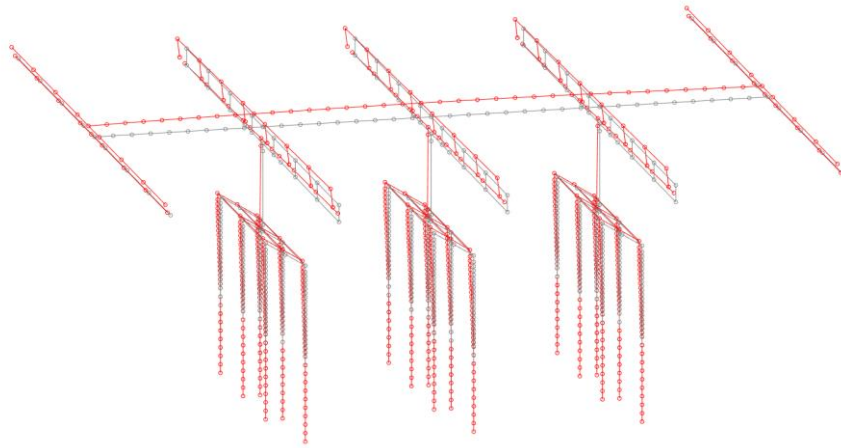


Mode 3- Rotation ($T_3= 0.827$ s)

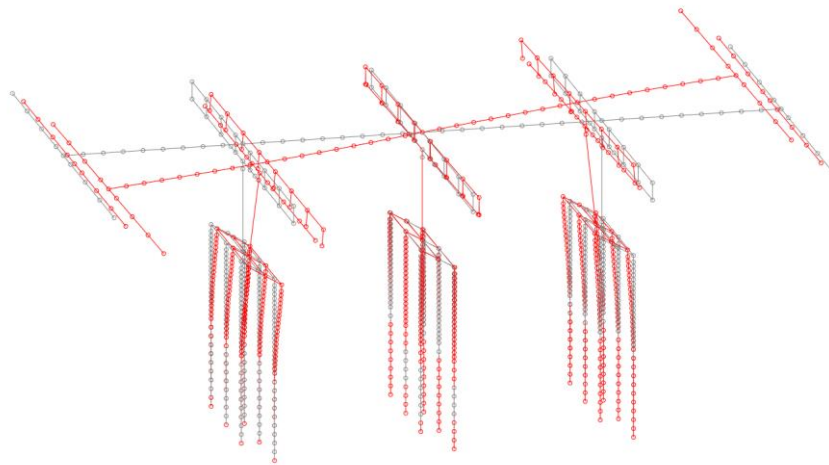
Figure A. 14. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2b %50)



Mode 1- Longitudinal ($T_1=1.122$ s)

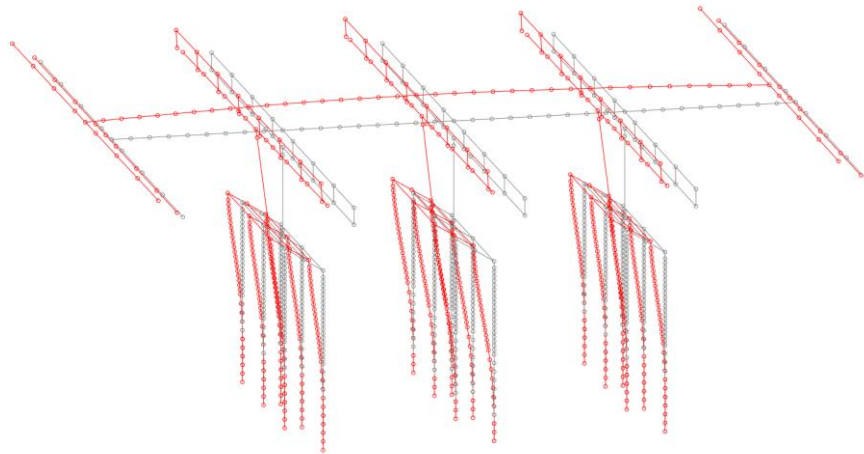


Mode 2- Transverse ($T_2= 0.923$ s)

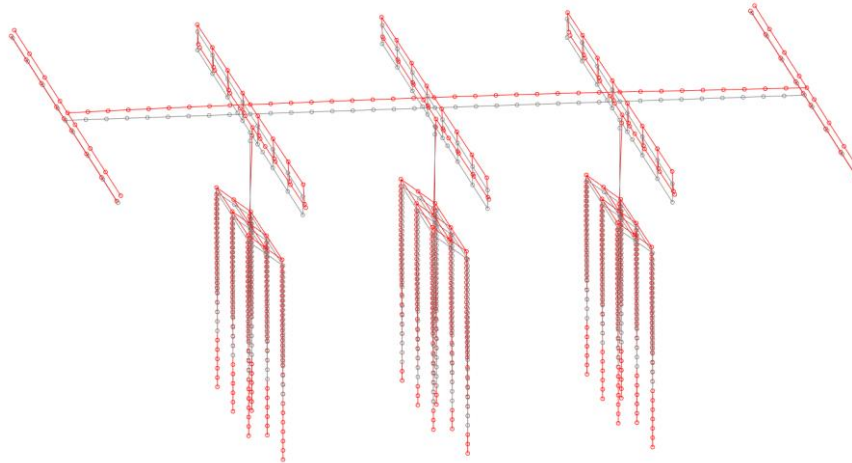


Mode 3- Rotation ($T_3= 0.812$ s)

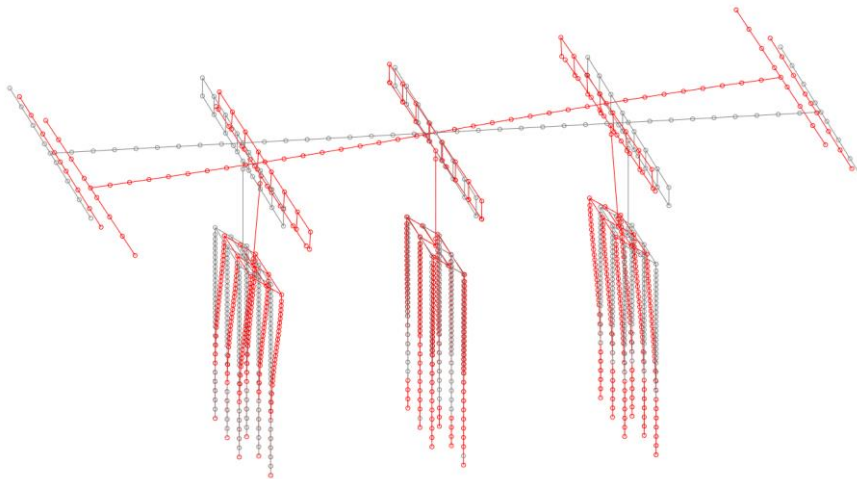
Figure A. 15. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2b %50)



Mode 1- Longitudinal ($T_1=1.253$ s)

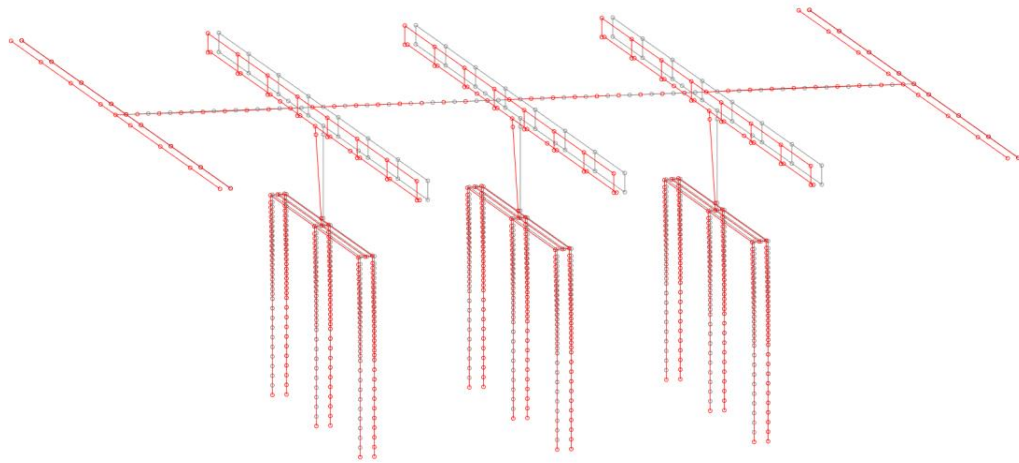


Mode 2- Transverse ($T_2= 1.057$ s)

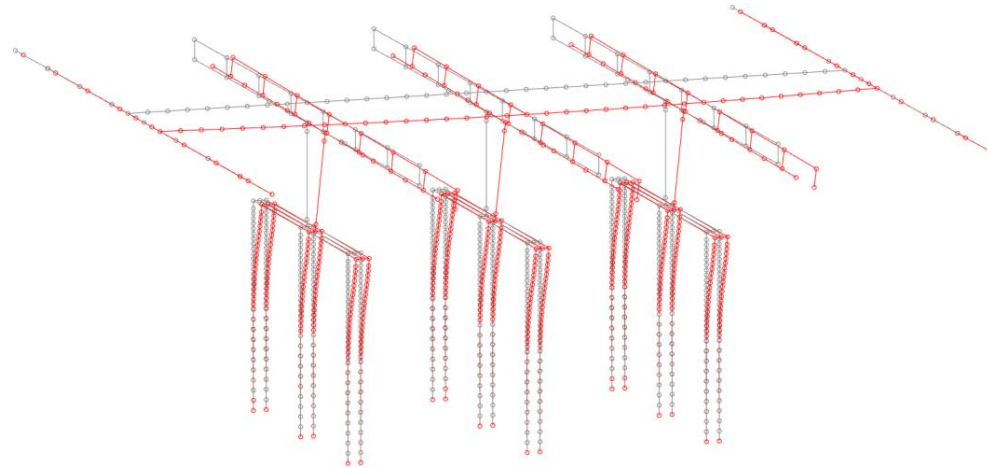


Mode 3- Rotation ($T_3= 0.843$ s)

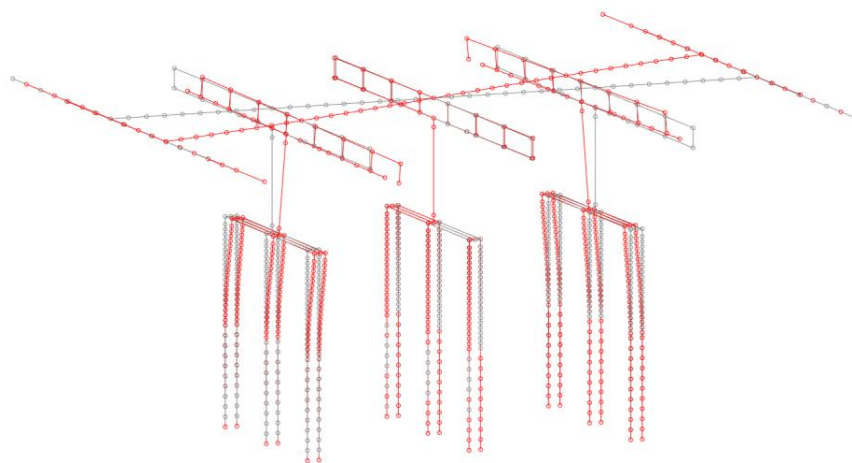
Figure A. 16. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2b %50)



Mode 1- Longitudinal ($T_1=1.046$ s)

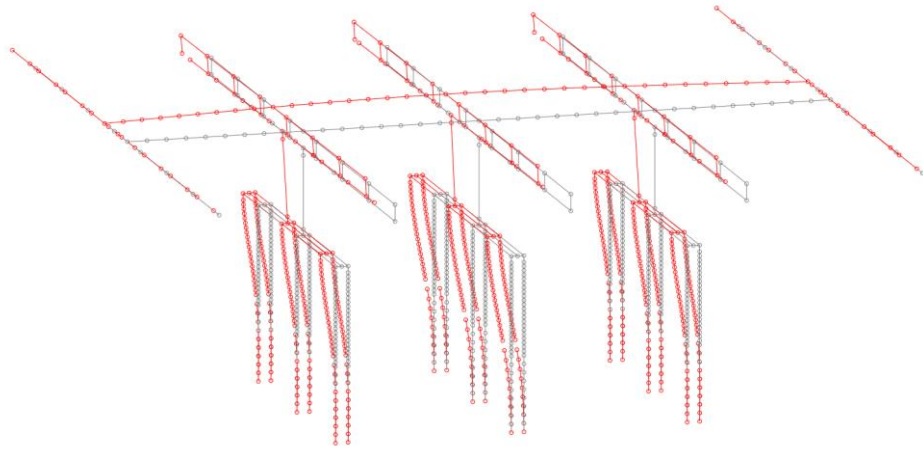


Mode 2- Transverse ($T_2= 0.975$ s)

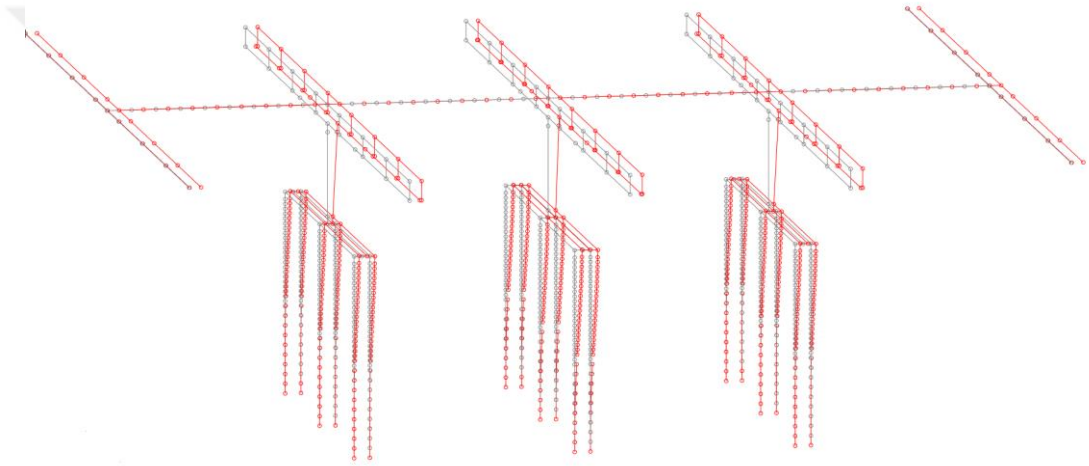


Mode 3- Rotation ($T_3= 0.787$ s)

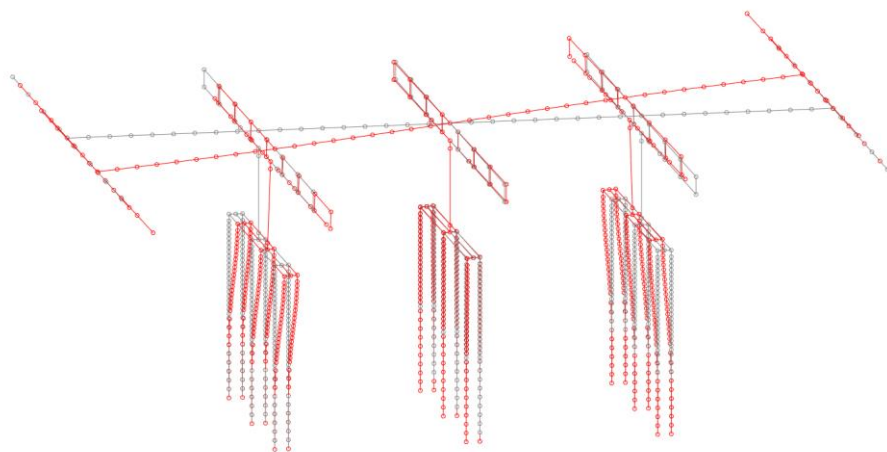
Figure A. 17. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2c %75)



Mode 1- Transverse ($T_1=1.165$ s)

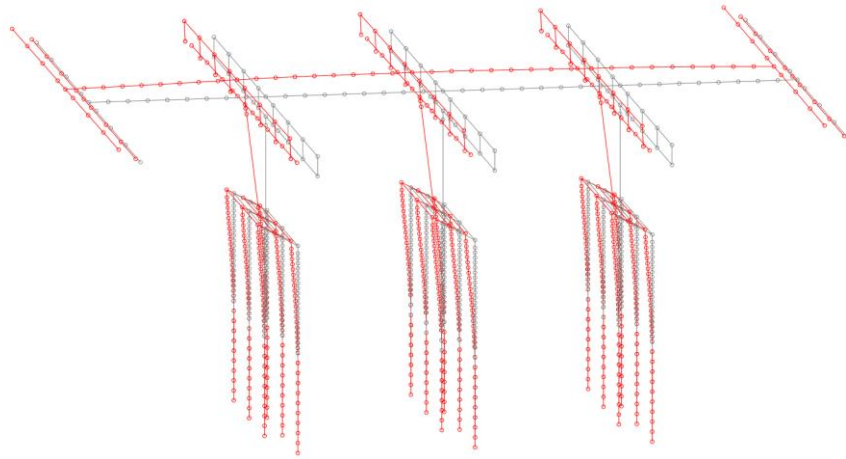


Mode 2- Longitudinal ($T_2= 1.139$ s)

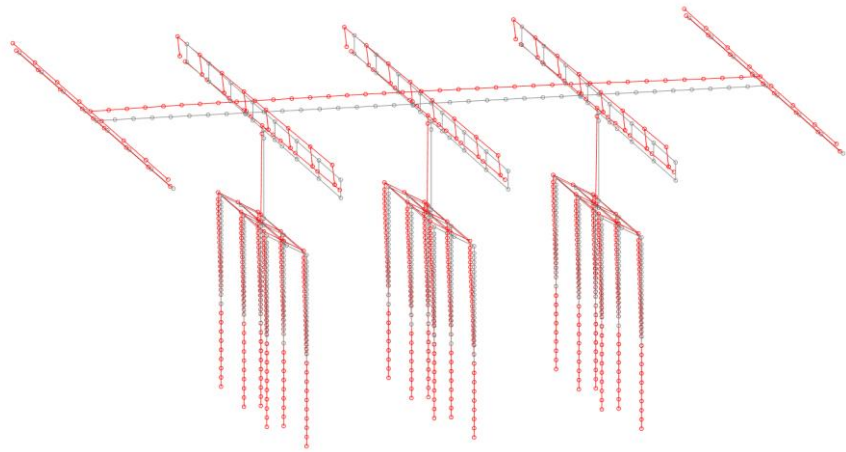


Mode 3- Rotation ($T_3= 0.826$ s)

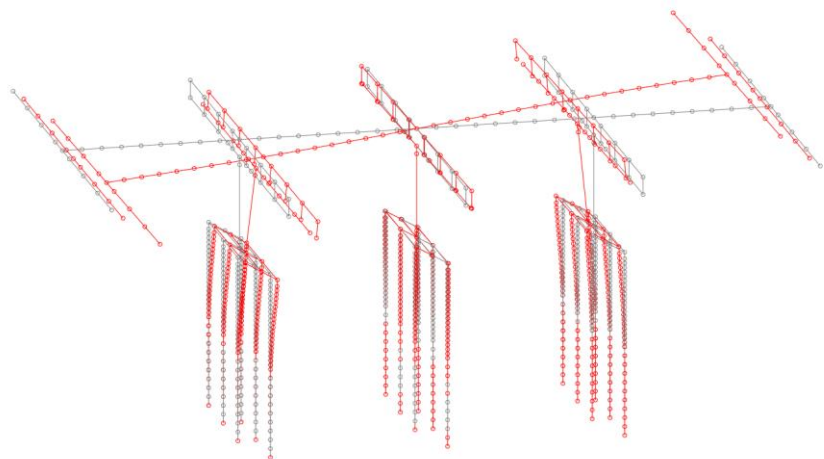
Figure A. 18. Mode shapes of non-skewed ($\alpha=0^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2c %75)



Mode 1- Longitudinal ($T_1=1.127$ s)

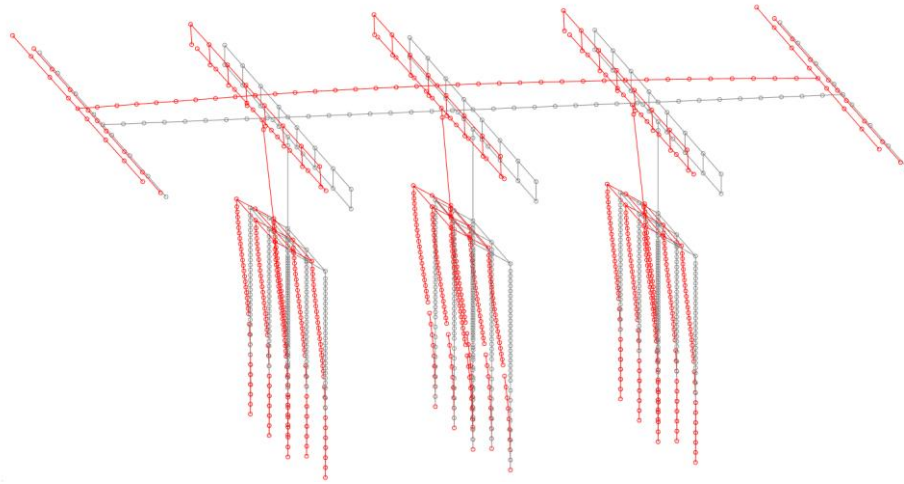


Mode 2- Transverse ($T_2= 0.928$ s)

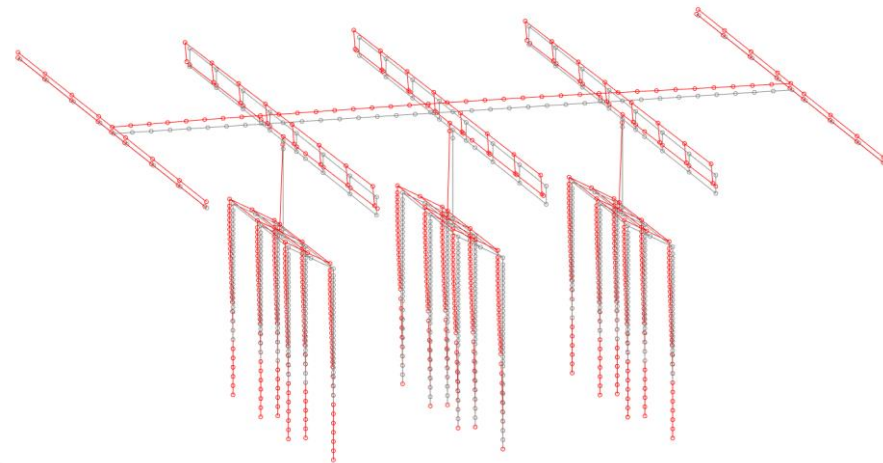


Mode 3- Rotation ($T_3= 0.812$ s)

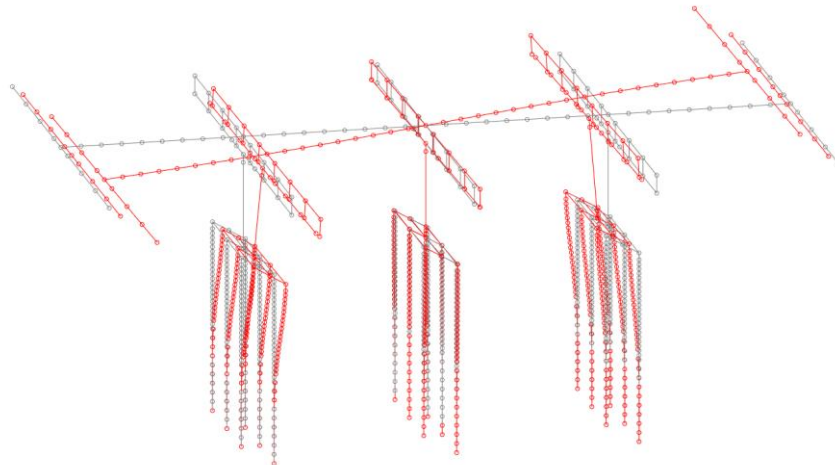
Figure A. 19. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 2 m non-uniform scour depth in longitudinal direction (Case 2-2c %75)



Mode 1- Longitudinal ($T_1=1.267$ s)



Mode 2- Transverse ($T_2= 1.068$ s)



Mode 3- Rotation ($T_3= 0.842$ s)

Figure A. 20. Mode shapes of skewed ($\alpha=45^\circ$) bridge for 6 m non-uniform scour depth in longitudinal direction (Case 2-2c %75)

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- Ateş, S., Avşar, Ö. (2023). The impact of ground motion incidence angle for skewed highway bridges under multi-hazard effects of scour and earthquake. *Proceedings of 3rd International Civil Engineering and Architecture Congress (ICEARC'23)*. DOI: 10.31462/icearc.2023.sme291
- Ateş, S., Avşar, Ö. (2023). The Effect Of Ground Motion Incidence Angle For Scoured Highway Bridges. *9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023)*
- Ateş, S., Avşar, Ö. (2021). Representation of Earthquake Ground Motion Incidence Angle in Nonlinear Dynamic Analysis of Highway Bridges. *International Congress on Advances in Civil Engineering*
- 1002- Short Term R&D Funding Program (The Scientific and Technological Research Council of Turkey), Subject: Representation of Earthquake Ground Motion Incidence Angle to Nonlinear Analysis of Skew Highway Bridges (2021-2022)
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