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NUMERICAL INVESTIGATION OF THE DYNAMIC SOIL-STRUCTURE INTERACTION OF CONCRETE BUILDINGS

Zainaldin Fadhil Abdulameer AL-TAMEEMI

Master`s Thesis

Supervisor

Assoc. Prof. Dr. Sepanta NAİMİ

Istanbul, 2023

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The thesis titled NUMERICAL INVESTIGATION OF THE DYNAMIC SOIL-STRUCTURE INTERACTION OF CONCRETE BUILDINGS prepared by ZAINALDIN FADHIL ABDULAMEER AL-TAMEEMI and submitted on 28/02/2023 has been **accepted unanimously** for the degree of Master of Science in Civil Engineering.

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I hereby declare that this thesis meets all format and submission requirements of a Master's thesis.

Submission date of the thesis to Institute of Graduate Studies: ___/___/___

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Zainaldin Fadhil Abdulameer AL-TAMEEMI

Signature

DEDICATION

In honor of my lovely father and my wonderful mother, who have continuously shown me their love, support, help, and enthusiasm as I have worked on my studies, I would like to dedicate this work to them. We also recognize and warmly thank the professors and members of the mechanical engineering faculty at Altınbaş University, as well as my supervisor and the entire mechanical engineering staff, for their assistance, guidance, and substantial expertise in this study. In addition, I received a ton of advice and assistance from my supervisor for my numerical analysis.

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I would also like to express my gratitude to the test committee members for their assistance in offering me suggestions and constructive criticism. I also wish to thank the faculty and staff of Altınbaş University's department of civil engineering for their unflagging support.

ABSTRACT

NUMERICAL INVESTIGATION OF THE DYNAMIC SOIL-STRUCTURE INTERACTION OF CONCRETE BUILDINGS

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This work is executed by identifying major soil characteristics related to the dynamic soil-structure interaction features of a reinforced concrete building. Numerical analysis and simulations were followed and adopted, relying on the ABAQUS® software package to assess the base shear, axial force, moment, and displacement, considering different types of soil. Based on the research work, the results revealed that the base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil. Also, the base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil. The base shear for a shear wall system with ten stories on medium soil is 20% less than base shear on soft soil. On hard soil, this outcome is lowered by 12%. The axial force for a five-floor building frame decreases by 2% from soft to medium soil and by 8% from medium to hard soil. Additionally, axial forces provide a 9% decrease for medium soil and a 4% reduction for hard soil in a 10-floor building frame resistance system. There is a reduction of 3% from soft to medium soil and a reduction of 12% on hard soil regarding axial force. Meantime, the axial forces are lesser for medium soil by 13% compared to soft soil and less by 6 % for hard soil. The displacement is decreased by 6% in a 5-floor building frame system on medium soil and by 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil. Displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil. Also, displacement reduces by 20% and 30% on medium and hard soil, respectively.

Keywords: ABAQUS, Dynamic Soil-Structure Interaction, Numerical Modeling, Shear Force, Building Frame Resistance System.

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ABBREVIATIONS

BF	:	Building Frame
BNWA	:	Beam on Nonlinear Winker Approach
CDP	:	Concrete Damaged Plasticity
CRT	:	Cathode-Ray Tube
DSSI	:	Dynamic Soil-Structure Interaction
FEA	:	Finite Element Analysis
GGBFS	:	Ground Granulated Blast Furnace Slag
LLRS	:	Lateral Load Resisting Systems
MDD	:	Maximum Dry Density
R&D	:	Research and Development
SEA	:	Spectral Element Approach
SW	:	Shear Wall

LIST OF SYMBOLS

E	:	Elastic Modulus (MPa)
υ	:	Poisson's ratio
ρ	:	Density (Kg/m3)
f'c	:	Compressive strength (MPa)
έc	:	Peak Compressive strain (mm/m)
ft	:	Tensile Strength (MPa)
ψ	:	Dilation angle (º)
e	:	Eccentricity
fb0/ft0	:	Bi-axial to Uni-axial strength ratio
K	:	Second stress invariant ratio
μ	:	Viscosity parameter
fy	:	Yield strength (MPa)
fu	:	Ultimate strength (MPa)

1. INTRODUCTION

1.1 RESEARCH BACKGROUND

Soil is a significant element in the construction industry on which buildings components are installed and settled [1]–[36]. Soil is utilized to make the construction materials, but it is also the major basis on which the facility settles. Throughout the building's lifespan, an interaction between the structure and the ground occurs, and it should be optimized to ensure effective facility stability. Scholars define this interaction as Dynamic Soil-Structure Interaction (DSSI), which depends on a set of variables and parameters related to the soil, such as soil density, humidity, damping, porosity, stiffness, compaction, and mass [37], [38]. A good DSSI level can distribute mutual stresses and foster the building's stabilization. One of the important activities civil engineers follow during the first phases of construction is selecting a good site containing perfect soil characteristics that enable stable structure. In addition, construction engineers create soil maps to investigate the land surface and its slope. Also, these soil maps are vital to evaluate the soil's physical, chemical, and biological characteristics. Besides, the soil maps play a critical role in determining the soil's potential to store and absorb water. All these aspects are greatly important to consider in ensuring that soil will serve the construction facility without causing future failure or damage to properties. Practical and effective soil that provides the perfect construction environment to build on should include the following substantial aspects [2]:

i. Neutral pH value and balanced chemistry,
ii. Stabilization during several drying and wetting stages,
iii. Perfect strength under diverse loading and high pressure,
iv. Capability to capture rainfall without damaging the facilities.

1.2 PROBLEM STATEMENT

Research and development (R&D) in civil engineering have been widely growing over the last decades to improve construction performance, structural facilities stability on the ground, and building workability. However, soil stability has been a challenging area that scholars and engineers greatly investigated. Due to different structural conditions, the soil has a wide range of parameters and variables that need to be explored in every construction project. One of the critical soil areas is the dynamic soil-structure interaction (DSSI) [39], [40]. DSSI analysis is greatly vital to ensure that the facility can have higher performance, workability, and stability on the ground without failure in the future. Some of the remarkable soil variables comprise soil mass, compaction, stiffness, structure, porosity, and damping. For instance, when constructing dams, bridges, reservoirs, and other high-loading facilities, engineers take into account the rate of soil porosity that influences the dynamic characteristics of soil, as higher porosity like sand would cause massive failure to these structures when it is not adjusted or modified [41], [42]. In addition, soil stiffness is considered another critical factor that influences a building's stability. Thus, the ensuing optimum rate of soil stiffness can enable higher building workability, performance, and stability. In this work, DSSI analysis is performed using numerical investigation via simulation software of a case study. The solution to the problem can identify the most critical parameters and factors of soil for optimum building stability. Figure 1.1 represents the soil stabilization major principles in the construction industry.

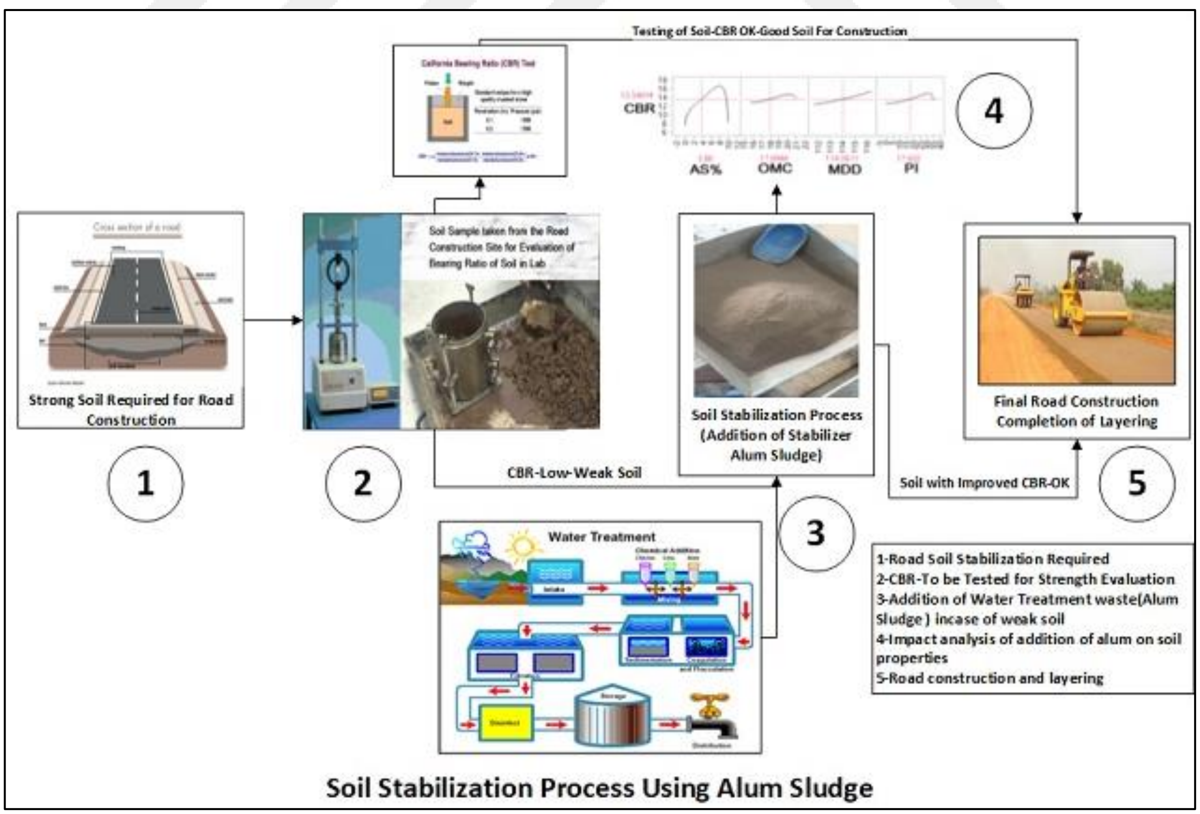


Figure 1.1: Soil stabilization major principles in the construction industry [5].

Also, Figure 1.2 indicates various critical soil stabilization approaches used in construction.

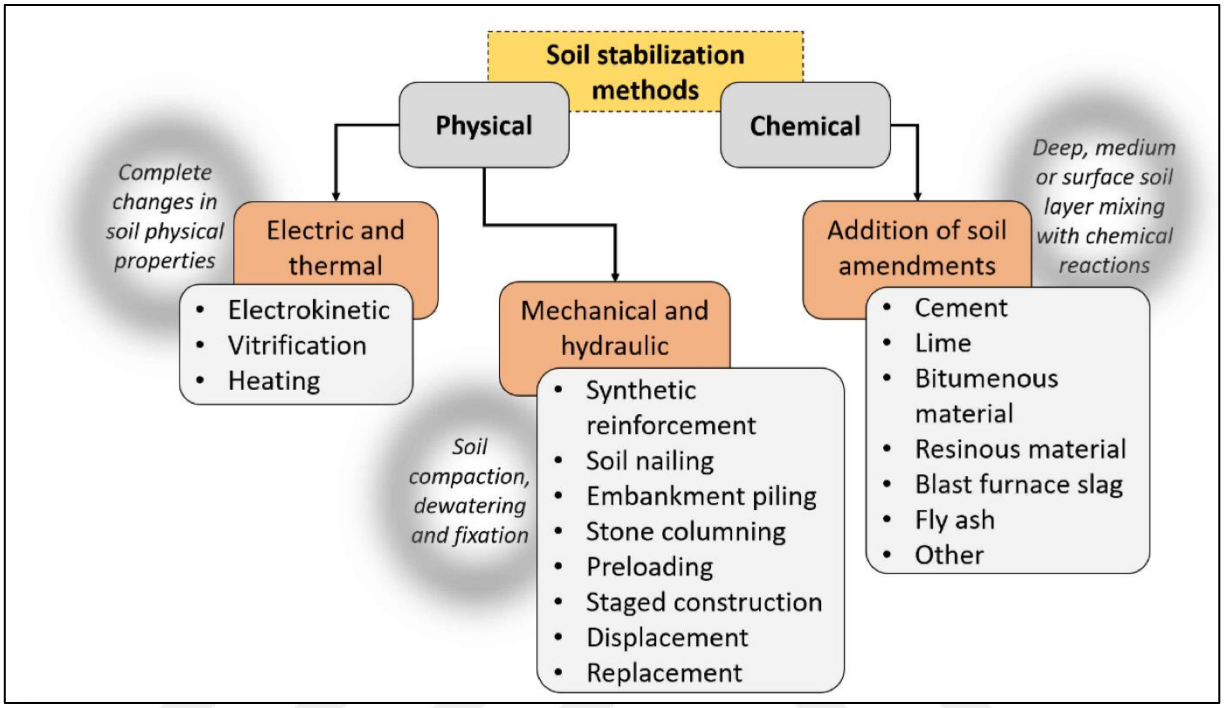


Figure 1.2: Critical soil stabilization approaches in construction [43].

1.3 RESEARCH SIGNIFICANCE

This research comes with a set of significant relevances. This work will investigate the major characteristics and key features of soil that influence the facility's stability and interaction with the ground through the first relevance. In addition, this study will highlight major soil problems and critical issues that could cause the failure of the building's stability. These data can be collected from secondary data collection using publications from Ph.D. and master dissertations and web research engines, such as ScienceDirect, ResearchGate, Google Scholar, and Academia. Additionally, the database on soil characteristics will be gathered from several conference proceedings. The second relevance of this research is to investigate a case study of a building by which the DSSI can be optimized and enhanced to enable valid building stability. This relevance is achieved through a numerical analysis by which simulations will be carried out using a software package. Moreover, this work will identify some soil features through the third relevance, including soil mass, compaction, stiffness, structure, porosity, and damping, and assess their impact on the DSSI. Finally, the research outputs of the numerical analysis will be validated, justified, and modified according to civil engineering experts' and professionals' points of view.

1.4 RESEARCH OBJECTIVES

The major thesis goal is to investigate the critical role of soil properties on the buildings' stability for several construction projects. This work follows some objectives to achieve the major goal of this research, which are presented and listed in the following paragraphs:

i. To shed light on major characteristics and key features of soil that influence the facility's stability and interaction with the ground.
ii. To identify major soil problems and key issues that could cause the failure of the building's stability.
iii. To investigate a case study of a building through which the DSSI can be optimized and improved to ensure good building stability.
iv. To model the case study using numerical analysis and simulation software.
v. To predict the impact of soil mass, compaction, stiffness, structure, porosity, and damping on DSSI.
vi. To validate, justify, and modify the results based on civil engineering experts' and professionals' points of view.

1.5 RESEARCH QUESTIONS

This study is conducted to provide some answers to the research questions regarding the effectiveness and key contribution of the DSSI in providing practical stability to the building. These study questions are described in the following paragraphs:

i. What are the major characteristics and key features of soil that can greatly influence the buildings' stability and workability?
ii. What are the critical issues and soil problems that can cause fracture and stability failure of the facility on the ground?
iii. Could the impact of the DSSI be optimized and improved to ensure good stability of structural buildings on the ground?

iv. Could the soil mass, compaction, stiffness, structure, porosity, and damping play a critical role in optimizing and enhancing the DSSI?

1.6 RESEARCH HYPOTHESES

This research is accomplished to evaluate the major impact of dynamic soil-structure interaction depending on a group of factors and key parameters associated with soil characteristics. Based on the numerical study findings, a set of hypotheses will be validated or invalidated, which are illustrated in the following paragraphs:

i. Null Hypothesis, H_o: "There is no impact of dynamic soil-structure interaction on the building's stability, structural performance, and workability."

ii. First Alternative Hypothesis, $H_{a,1}$"Dynamic soil-structure interaction greatly impacts the building's stability, structural performance, and workability."

iii. Second Alternative Hypothesis, $H_{a,2}$: "Soil mass has a significant effect on the dynamic soil-structure interaction between the ground and the structural facility."

iv. Third Alternative Hypothesis, $H_{a,3}$: "Soil compaction can considerably influence the dynamic soil-structure interaction between the ground and the building."

v. Fourth Alternative Hypothesis, $H_{a,4}$: "Soil stiffness can greatly affect the dynamic soil-structure interaction between the ground and the structure."

vi. Fifth Alternative Hypothesis, $H_{a,5}$: "Soil porosity has a remarkable influence on the dynamic soil-structure interaction between the ground and the facility."

vii. Sixth Alternative Hypothesis, $H_{a,6}$: "Soil damping has a considerable effect on the dynamic soil-structure interaction between the ground and the building."

1.7 THESIS STATEMENT

The statement of this thesis is: *"Numerical Investigation of the Dynamic Soil-Structure Interaction of Concrete Buildings."* The thesis aims to investigate the critical impact of dynamic soil-structure interaction depending on a group of factors and key parameters associated with soil properties. A case study and numerical analysis using simulation software are executed to achieve the major research goal.

1.8 THESIS STRUCTURE

Chapter one offered a description of the problem statement, research questions, research background, research significance, study critical goal and minor objectives, research hypotheses, and the thesis's title. Following the first chapter, this work will present more information regarding the critical effect of dynamic soil-structure interaction, relying on a set of variables and significant parameters related to the soil characteristics. The sequence of this thesis is shown in the following Table.

Table 1.1: A layout of the thesis structure in this work.

CHAPTER TWO	This chapter illustrates the major characteristics and key features of soil and sheds light on its major variables and parameters, such as its mass, compaction, stiffness, structure, porosity, and damping, which play a critical role in optimizing and enhancing the DSSI. In addition, this chapter will identify some soil issues which correspond to the failure of structures and facilities above the soil. The data will be collected in the second chapter depending on publications from Ph.D. and master dissertations and web research engines, such as ScienceDirect, ResearchGate, Google Scholar, and Academia. Additionally, the database on soil characteristics will be gathered from several conference proceedings.

Table 1.1: A layout of the thesis structure in this work. “tables continued”

CHAPTER THREE	Chapter three explains the research methodology of this work. It shows the major steps, research stages, and the major procedure followed in carrying out the study’s numerical analysis of the DSSI. Also, the third chapter identifies important parameters and variables associated with the soil characteristics for the numerical study. It also illustrates the boundary conditions for the case study of the DSSI impact.
CHAPTER FOUR	The fourth chapter presents key results and major research outputs obtained from the numerical analysis of the DSSI impact using the simulation software. It relates the research findings to other scholars’ research work. In addition, chapter four illustrates the main thesis’s discussions.
CHAPTER FIVE	The fifth chapter indicates the study recommendations and major conclusions associated with the numerical analysis of the DSSI impact. Additionally, chapter five presents the research limitations.

2. LITERATURE REVIEW

2.1 GENERAL

This chapter illustrates the major characteristics and key features of the soil. It sheds light on its major variables and parameters, such as its mass, compaction, stiffness, structure, porosity, and damping, which play a critical role in optimizing and enhancing the DSSI. In addition, this chapter will identify some soil issues which correspond to the failure of structures and facilities above the soil. The data are collected in chapter two depending on publications from Ph.D. and master dissertations and web research engines, such as ScienceDirect, ResearchGate, Google Scholar, and Academia. Additionally, the database on soil characteristics is gathered from several conference proceedings.

2.2 MAJOR CHARACTERISTICS AND KEY FEATURES OF SOIL IN CONSTRUCTION

[44] guided a study that aimed to investigate and assess some critical soil characteristics and significant soil properties that play a vital role in improving the stability of the foundation. They carried out an experimental test through which data related to resonant columns were collected and analyzed to explore major soil characteristics that influence the structure stability, including the energy dissipation properties and the dynamic shear modulus. In addition, they developed empirical formulas to examine the dynamic small-strain features of soil, which is characterized by the employment of a compacted sand-clay mixture. They reported that compacted sand/clay aggregate composite materials are broadly employed in variant construction applications, namely geotechnical projects, embankment dams, piles' foundations related to offshore facilities, and impervious structures and water-resistant blankets that are used in waste disposal landfill projects. Their research analysis revealed that clay plasticity index, aggregate content, void ratio, confining pressure, damping ratio, resonant frequency, shear modulus, and Maximum Dry Density (MDD) are some of the critical soil characteristics that play a significant role in affecting the soil stability and performance in different construction engineering projects. Furthermore, their research results indicated that those properties could influence the soil

functionality in some special construction applications, namely geo-facilities in which seismic stability is considered considerably remarkable for geo-structures. Figure 2.1 represents major methods of soil management to increase its stability, performance, and effectiveness in construction.

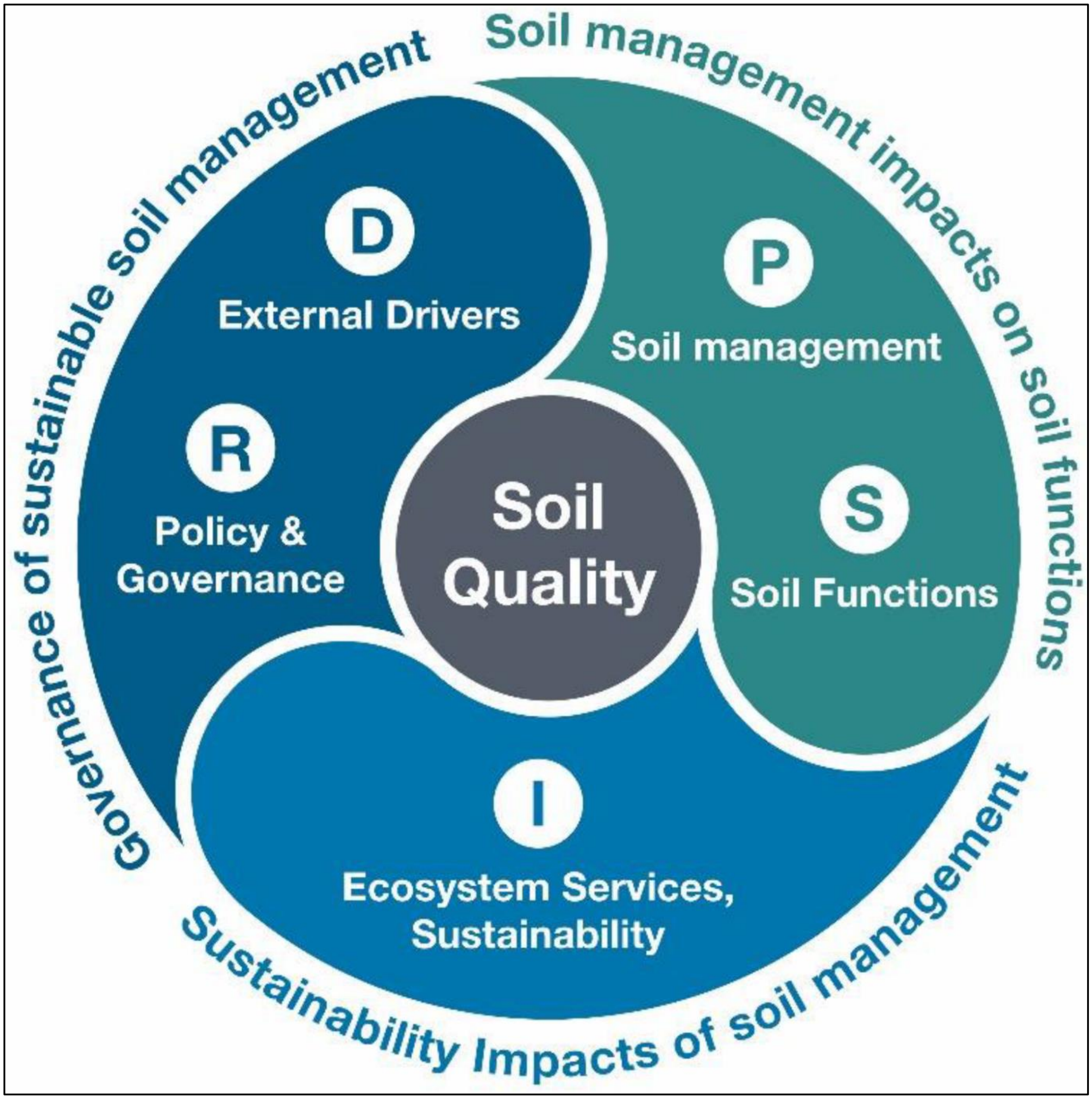


Figure 2.1: Major methods of soil management to increase its stability, performance, and effectiveness in construction [45].

[46] led an analysis through which some vital soil properties were assessed and examined. They conducted an experimental analysis in which cyclic triaxial testing was executed to validate the critical characteristics associated with soil when it is mixed with tire waste to improve its damping features. Their experimental analysis revealed that using tire waste in the soil can modify its physical properties and adjust its mechanical and dynamic characteristics, enabling the improvement of its seismic features due to the energy absorption and damping characteristics of tire waste. Thus, integrating tire waste into the soil with a percentage of 50% could make them practical for several construction engineering projects and applications by minimizing the shear modulus and increasing their damping ratio more than rubber-sand soil in which rubber and sand are uniformly distributed.

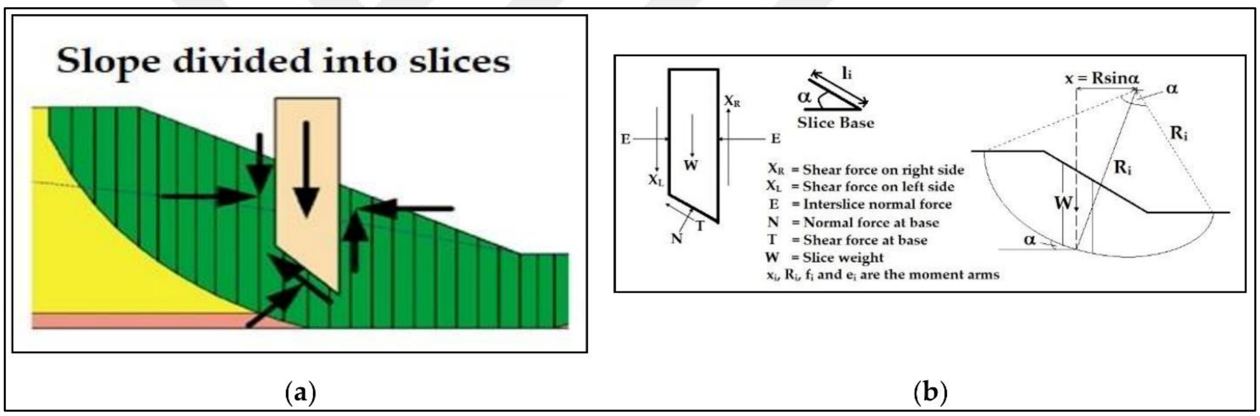


Figure 2.2: Major forces and mechanical loads encountering the structure in soil [29].

[47] published a manuscript exploring intelligent methods and practical approaches to modify and enhance some common soil properties to improve its stability and performance in different construction applications. They employed two criteria to test and verify the soil properties. They depended on a discrete element approach. They also applied dynamic compaction of dry sand to investigate its impact on the foundation depth. They make simulations and numerical analyses to validate the performance of the dynamic compaction approach. Their simulations and numerical analysis revealed that employing dynamic compaction could enhance soil strength and minimize porosity. Also, their research analysis confirmed that under a vertical strain value of 5% and a relative density ratio of 25%, the soil strength and mechanical properties were significantly improved using dynamic compaction. At the same time, the porosity is remarkably

minimized, helping make the soil reliable and stable for different construction applications. [48] carried out research investigating some critical soil properties that are vital to guarantee high-performance construction and soil stability, especially for high dams. They conducted field tests and numerical analysis to identify and locate major factors and pivotal features that have a considerable impact on the coarse-grained large-size soil. Their research analysis revealed that rockfill filling properties, compaction quality, and porosity are some vital soil characteristics that should be taken into account and carefully controlled to ensure significant stability of soil for large structures like high dams. Additionally, their numerical and field results confirmed that the ratio between the maximum particle size and the compaction layer thickness is greatly influenced by the compaction process in which the porosity can be optimized and minimized for high dams. [49] performed a study examining major soil properties that play a crucial role in influencing the facilities' stability under different loading conditions. They implemented simulations and three-dimensional (3D) continuum modeling. They also employed the transfer matrix approach and Laplace transform. They considered the analysis of a pile exposed to time-consistent vertical and horizontal loads. They evaluated the stresses and displacements of sub-zones encompassing the pile. They also utilized the Timoshenko beam principles to analyze the governing equations related to the pile. Their major research results indicated that the compaction effect of the soil played an essential role in reducing the porosity of the soil. Further, their study outputs affirmed that major factors that affect the compaction effect included the width of the boundary region of soil surrounding the pile, shear modulus, and the relaxation effect. [50] executed a study analyzing major factors and substantial properties that have a considerable contribution to enhancing the soil characteristics and stability to serve several construction projects. They followed a comprehensive review through which critical soil properties and crucial elements that influence soil stability and performance were classified and highlighted. Their research results related to the comprehensive review indicated that one of the major problems facing soil stability is soil expansion. They reported that soil expansion could be caused because of moisture fluctuations that are usually severe, resulting in dangerous disasters, distortions, and damage to different construction facilities and structures. They also articulated that employing innovative methods, including chemical stabilization approaches, such as fly ash, cement, and lime, could mitigate this issue. In addition, they stated that utilizing stabilizations techniques containing pozzolanic reactions, flocculation, cation exchange, and hydration can resolve this issue. Moreover, they mentioned that there are some factors that influence the level of soil stabilization, including sulfate compounds, organic matter, nano-silica employment, the content of molding water, the pH number related to the soil matrix, compaction delay, curing temperature, curing interval, soil mineralogy, soil type, additive contents, and additive types. [3] led a study exploring the major mechanical properties of soil and critical factors and characteristics that affect soil stability for high-performance construction. The author carried out nondestructive tests and laboratory analyses to assess and locate major factors and characteristics that influence soil stability. Their research results confirmed that there are some important elements and vital features that affect soil stability and mechanical properties (like soil strength), such as compaction rate, environmental and surrounding factors, such as shear modulus, water content, damping ratio, porosity, and natural frequency of the environment surrounding the structural soil.

2.3 MAJOR ISSUES AND PROBLEMS OF SOIL IN CONSTRUCTION

[51] conducted a study analyzing significant issues and critical issues that affect soil stability. They investigated a case study representing a real problem of soil failure due to some issues in the soil's mechanical properties. They analyzed the causes of poor soil stability that led to a building collapse in Nigeria depending on geotechnical tests. They collected soil samples from the site and considered the analysis of shear strength, Atterberg limit, specific gravity, moisture content, and sieve analysis. Their research analysis confirmed that the soil nature of silty characteristics mirrored by lower bearing capacity (which reached 36.37 kN/m^2) was considered the main reason for the building collapse. Additionally, the analysis confirmed that no geotechnical tests were implemented before the building was constructed. Thus, soil characteristics, stability, and performance were not examined and verified. [52] guided research examining significant issues and technical problems in soil that influence its stability and performance in the construction industry. The authors carried out a comprehensive review addressing several failure and collapse cases that occurred between 1994 and 2018 in China. They analyzed the reasons for these collapses and investigated the causes of soil instability that led to overall construction facilities failure. Their research overview revealed that the major

reasons for failure related to different Chinese facilities between 1994 and 2018 were associated with the heavy rain rate that negatively affected the robustness of the buildings and projects' infrastructure, leading to a significant increase in the soil's water content, which dramatically affected its strength and thus its potential to carry the buildings' loads. In addition, soil faces some problems mirrored by its contamination that may cause significant degradation in its stability for different construction projects, as illustrated in Figure 2.3

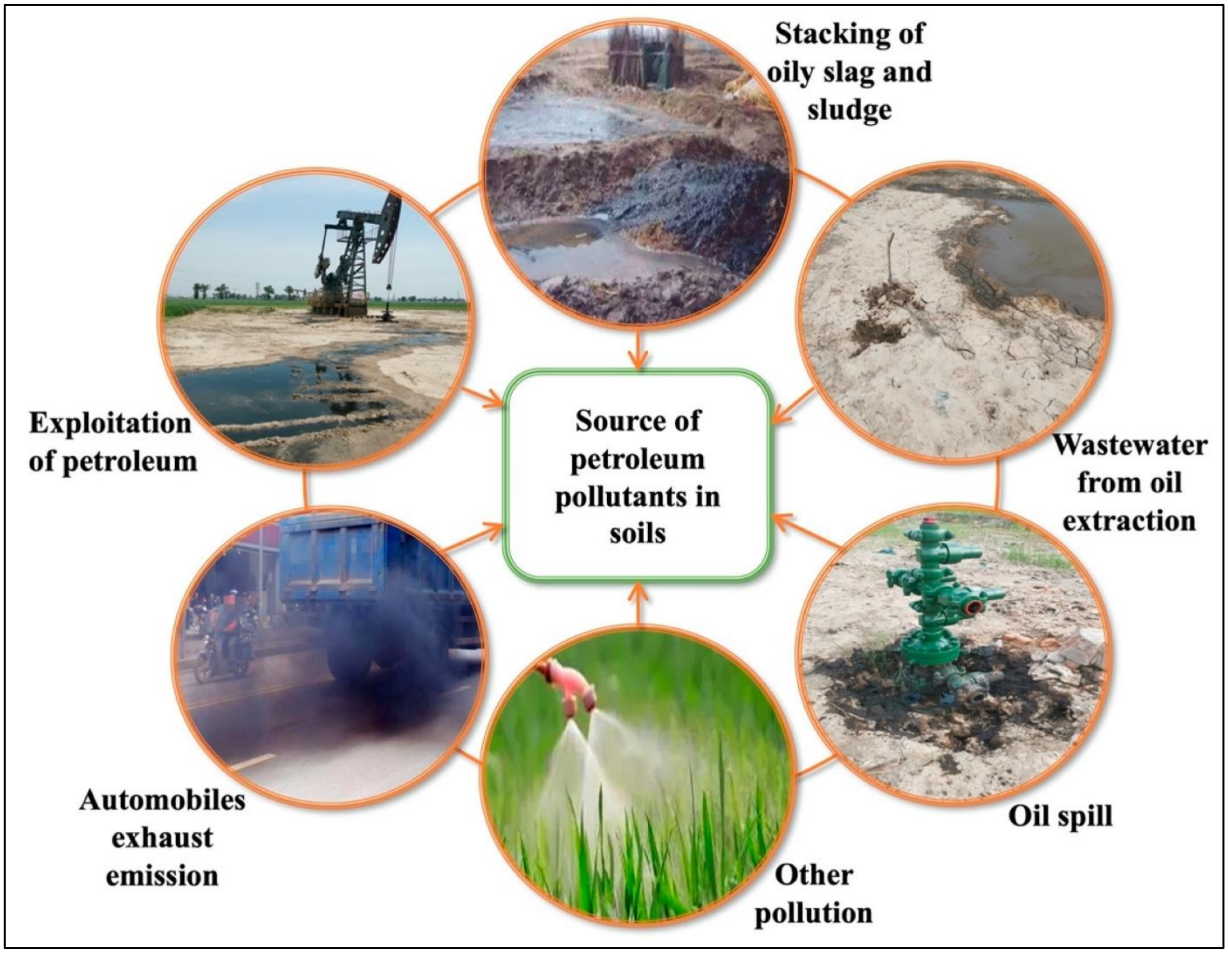


Figure 2.3: Major soil contamination problems that affect the soil stability and structure stabilization in soil [28].

[53] executed a study in which they explored a challenging issue that faced the construction of roads, pavement, and buildings of Sohag city in Egypt. They reported that roughly two-thirds of Egyptian lands are deserts, putting various pressures and making some challenges on soil stability when it comes to constructing and building roads and facilities on sandy soil. To solve

this issue, they analyzed the employment of innovative dust shields (polymer additives) to the soil to improve the soil's strength and stability. They investigated the addition of this material by 1%, 2%, 3%, and 4% to the soil's dry weight. Their analysis revealed that adding these ratios of polymer additives to the soil could increase maximum dry density, adjust the California bearing ratio, reduce swelling pressure and plasticity index, and improve unconfined compressive strength. [8] guided a study examining some critical problems and challenging issues related to the soil that affect its performance and stability in different construction projects. They analyzed the problem of expansive soil, which is characterized by a significant number of voids. These voids can influence the effectiveness and stabilization of structures' foundations during the unloading and loading circumstances. In addition, the authors reported that adding chemicals and lime to fill these voids can result in dramatic changes in soil temperature leading to soil thawing and freezing that can remarkably impact the soil's durability and mechanical properties. To address this issue, they investigated a critical solution that can be adopted to alleviate voids in the soil, maintaining significant mechanical properties in the soil without affecting its stability and performance. This solution includes the employment of nano-silica that is modified and treated to enhance its effectiveness by exposing it to several thaw-freeze cycles. They applied this material to the soil and conducted geotechnical tests to validate the mechanical properties of the soil using this material. Their research analysis and experimental results indicated that using nano-silica in the soil contributed to enhanced mechanical properties and performance. Additionally, it was found that applying various thaw-freeze cycles promoted the nano-silica effectiveness and mechanical properties, helping boost the soil properties for high-performance construction. [9] carried out research examining soil stabilization problems that influence its performance and critical role in carrying higher building loads. They implemented a comprehensive review through which soil stability issue was addressed, and practical solutions were investigated and identified to maintain higher soil stability. Their thorough review confirmed that soil stability depends remarkably on soil strength and physical and mechanical characteristics that influence its performance and enable its adequate durability to serve different construction projects. Moreover, their extensive review revealed that using alkali-activated binders is a beneficial solution that could significantly improve clayey soil stability by elevating its strength. Also, it was found that employing ground granulated blast furnace slag fly ash and fly ash as geopolymers could enhance the level of soil stabilization. [54] performed research exploring one of the critical problems facing soil performance and effectiveness, which is internal instability. They applied a comprehensive review by which critical soil issues associated with soil stabilization were addressed. In addition, their thorough review shed light on the seepage problem due to fine-particles' migration, which can lead to significant variations in the soil matrix conductivity, which can be recognized as soil's internal instability. Their extensive review indicated that soil's seepage issues related to small particles' migration could put buildings and different construction projects in danger because of the lack of soil matrix structural integrity and activating suffusion (or suffusion phenomenon), leading to considerable degradation in the internal soil stability. Besides, their comprehensive review revealed that several scholars developed and employed diverse evaluation methods and deep investigations to address this problem. These estimation methods include tracking approaches, visualization, and sending techniques, which contributed to remarkable contributions to strengthening the knowledge and experience related to this problem.

2.4 DYNAMIC SOIL–STRUCTURE INTERACTION

[39] led a research work through which they assessed and investigated the dynamic soil-structure interaction. They conducted mathematical simulations and numerical modeling of a case study in which they analyzed the dynamic soil-structure interaction of twenty-, thirty-, and forty-floor high-rise buildings under seismic loading. They used the ABAQUS software package to conduct their simulations and verify the dynamic soil-structure interaction. They applied 4 earthquake acceleration measures and used soil class Ee depending on Australian codes. Their simulations and numerical analysis revealed that dynamic soil-structure interaction had a significant effect on the high-rise buildings' seismic behavior. Additionally, the research findings indicated that dynamic soil-structure interaction had elevated the inter-floor drifts and lateral deflections and reduced the shear forces of the floors. Also, the findings affirmed that dynamic soil-structure interaction impact could vary depending on the earthquake distance (close or far to the building). [37] implemented an analysis in which they explored the impact of dynamic soil-structure interaction on the seismic behavior and distress response due to earthquakes of different construction projects. The research results indicated that dynamic soil-

structure interaction plays a critical role in affecting the soil's seismic response to various construction projects when earthquakes occur. In addition, they found that there are some factors that influence the soil's seismic behavior, including the overlying structure, the number of soil layers, and the seismic excitation at the seismic rock-outcrop or bedrock. [38] guided a research work that aimed to investigate and examine the impacts of dynamic soil-structure interaction on the soil's behavior and characteristics under specific shear and stiffness conditions. They implemented numerical modeling, optimization, and simulations using computer software to examine and explore the effect and major factors associated with dynamic soil-structure interaction. They used the Spectral Element Approach (SEA) and the Discontinuous Galerkin method (DGM). They also applied micro-vibrations to the soil and used seismic sensors to verify and predict its behavior related to dynamic soil-structure interaction. Their research findings and numerical analysis revealed that dynamic soil-structure interaction had a significant impact on the soil's shear strength related to the buildings' walls. Thus, it is greatly significant to consider flexible foundations that can optimize the shear strength of soil and buildings' walls. Furthermore, the research findings confirmed that the dynamic soil-structure interaction relies heavily on the amount of input frequency. Also, remarkable interval lengthening referred to the structures reached roughly 47%. Moreover, the results recorded a considerable decline in the floor shear, amounting to around 220%. At the same time, they found that the ultimate lateral roof displacement minimization attained a value of 34% compared with stationary roofs. [55] led research identifying the impact of unconstrained near-fault rupture on the dynamic soil-structure interaction. They followed numerical analysis and simulation work by which Finite Element Analysis (FEA) using the ABAQUS software tool was implemented to predict the physical and mechanical properties of soil under unconstrained near-fault rupture with the presence of dynamic soil-structure interaction. The simulation outputs and numerical analysis confirmed that the accelerated motion of the unconstrained near-fault rupture had significant and several lower-frequency parts. The maximum vertical acceleration was roughly one and a half higher than the maximum horizontal acceleration. Also, the study findings indicated that under far-fault and near-fault ground movement conditions, the superstructure response distributions were the same. Moreover, the results showed that these responses were 254.5% higher in near-fault ground movement compared with far-fault ground movement, indicating that the near-fault ground movement can be considered significantly destructive to structures. [56] carried out a study exploring the effect of the initial stress field of soil heterogeneity on the dynamic soil-structure interaction. They applied the wave-passage approach and calculated the structural acceleration considering the principles of dynamic soil-structure interaction. They also made 2D numerical analysis and modeling of a building consisting of three floors and a three-bay frame structure that is made out of concrete having a higher moment-resistance. They considered relative displacement and floor acceleration to make their comparative analysis related to the dynamic soil-structure interaction. They also took some soil samples from the Eastern Canadian areas and implemented geotechnical analysis. The research results affirmed that the initial stress field of soil heterogeneity could significantly influence the soil behavior, tending to boost the soil's shear strain and shear modulus. This aspect, in turn, can create a heterogeneous stress domain in the surrounding areas resulting in the adjustment and modification of the soil's dynamic behavior related to several structure soil systems. Also, the results showed that the initial stress field of soil heterogeneity had a remarkable impact on the amounts of surface acceleration. Additionally, it was found that failure to take effective actions and practical measures against the initial stress field of soil heterogeneity might lead to some errors related to the calculation of structural acceleration. [10] executed an analysis through which assessments and modeling were implemented to determine the impacts related to dynamic soil-structure interaction on soil seismic behavior and buildings' earthquake vulnerability. They depended on a case study in which they investigated the mid-rise reinforced concrete buildings located in Lisbon, Portugal. They also adopted the soil's direct modeling and the Beam on Nonlinear Winker Approach (BNWA). They also carried out 3D FEA to generate the complicated soil constitutive nonlinear formula, helping identify the soil behavior under seismic loading. The authors reported that seismic design and considerations are usually not taken into account when constructing different facilities. Their research analysis and numerical calculations revealed that the building's deformed shape and soil modal behavior were similar with and without the presence of dynamic soil-structure interaction. In addition, the study outputs indicated that elevating soil flexibility can lead to more significant periods, resulting in larger seismic disasters. Their research findings also showed that considering the dynamic soil-structure interaction would reduce the maximum buildings' seismic capacity by 15%. [57]

conducted research exploring the impact of dynamic soil-structure interaction on the seismic behavior of soil carrying higher loads of reinforced concrete middle-rise buildings. They carried out numerical analysis, FEA, and 3D modeling of different buildings having five, eight, ten, thirteen, and fifteen floors. They considered the analysis of inelastic soil volume. They estimated the buildings' displacement profiles and lateral displacement. The numerical results and FEA findings indicated that the surrounding buildings could influence each other when seismic loading takes action. In addition, it was found that surrounding buildings and soil behavior should be taken into account for several facilities that have a maximum number of floors of eight, even if no collision would take place. At the same time, the results indicated that for buildings that exceed eight floors, dynamic soil-structure interaction should be considered if no collision occurred, excluding the impact of surrounding buildings.

2.5 SUMMARY OF THE LITERATURE REVIEW

Major contributions of the publications reviewed in this work can be summarized in Table 2.1.

Table 2.1: Major contributions of the publications reviewed in this work.

#	Author(s)	Year	Paper Title	Major Contributions
1	Shafiee, A., Hassanipour, A., Payan, M., Bahmani Tajani, S., & Jamshidi Chenari, R.	2022	Analysis of the stiffness and damping characteristics of compacted sand-in-fines granular composites: a multiscale investigation.	Their research analysis revealed that clay plasticity index, aggregate content, void ratio, confining pressure, damping ratio, resonant frequency, shear modulus, and maximum dry density (MDD) are some of the critical soil characteristics that play a significant role in affecting the soil stability and performance in different construction engineering projects. Furthermore, those properties could influence the soil functionality in some special construction applications, namely geo-facilities.

Table 2.1: Major contributions of the publications reviewed in this work. “tables continued”

2	Ghazavi, M., & Kavandi, M.	2022	Shear modulus and damping characteristics of uniform and layered sand-rubber grain mixtures	Their experimental analysis revealed that using tires’ waste in the soil can modify its physical properties and adjust its mechanical and dynamic characteristics, enabling the improvement of its seismic features due to the energy absorption and damping characteristics of tire waste. Thus, integrating tire waste into the soil with a percentage of 50% could make them practical for several construction engineering projects and applications by minimizing the shear modulus and increasing their damping ratio more than rubber-sand soil in which rubber and sand are uniformly distributed.
3	Li, Y., Fang, Y., & Yang, Z.	2022	Two criteria for effective improvement depth of sand foundation under dynamic compaction using discrete element method	Their simulations and numerical analysis revealed that employing dynamic compaction could enhance soil strength and minimize porosity. Also, their research analysis confirmed that under a vertical strain value of 5% and a relative density ratio of 25%, the soil strength and mechanical properties were significantly improved using dynamic compaction. At the same time, the porosity is remarkably minimized, helping make the soil reliable and stable for different construction applications.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

4	Ye, H., Zhu, S., Feng, S., Xu, J., Yang, Y., & Zhu, J.	2022	Research into compaction characteristics of large-size coarse-grained soil and application	Their research analysis revealed that rockfill filling properties, compaction quality, and porosity are some vital soil characteristics that should be taken into account and carefully controlled to ensure significant stability of soil for large structures like high dams. Additionally, their numerical and field results confirmed that the ratio between the maximum particle size and the compaction layer thickness is greatly influenced by the compaction process in which the porosity can be optimized and minimized for high dams.
5	Wu, W., Yang, Z., Liu, X., Zhang, Y., Liu, H., El Naggar, M. H., ... & Mei, G.	2022b	Horizontal dynamic response of pile in unsaturated soil considering its construction disturbance effect	Their major research results indicated that the compaction effect of the soil played an essential role in reducing the porosity of the soil. Further, their study outputs affirmed that major factors that affect the compaction effect included the width of the boundary region of soil surrounding the pile, shear modulus, and the relaxation effect.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

6	Barman, D., & Dash, S. K.	2022	Stabilization of expansive soils using chemical additives: A review.	Their research results related to the comprehensive review indicated that one of the major problems facing soil stability is soil expansion. They reported that soil expansion could be caused because of moisture fluctuations that are usually severe, resulting in dangerous disasters, distortions, and damage to different construction facilities and structures. They also articulated that employing innovative methods, including chemical stabilization approaches, such as fly ash, cement, and lime, could mitigate this issue. In addition, they stated that utilizing stabilizations techniques containing pozzolanic reactions, flocculation, cation exchange, and hydration can resolve this issue. Moreover, they mentioned that there are some factors that influence the level of soil stabilization, including sulfate compounds, organic matter, nano-silica employment, the content of molding water, the pH number related to the soil matrix, compaction delay, curing temperature, curing interval, soil mineralogy, soil type, additive contents, and additive types.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

7	Villacreses Cabrera, J. P.	2022	Contributions to the study of fine-grained compacted soils: Mechanical properties, nondestructive tests, and applications	Their research results confirmed that there are some important elements and vital features that affect soil stability and mechanical properties (like soil strength), such as compaction rate, environmental and surrounding factors, such as shear modulus, water content, damping ratio, porosity, and natural frequency of the environment surrounding the structural soil.
8	Maude, E. H., Adamu, A. Y., Mbishida, M. A., & Danjuma, T.	2022	The Potential of Soil Properties in the Stability of Buildings a Case Study of Collapsed Building in Kwang Jos, Nigeria	Their research analysis confirmed that the soil nature of silty characteristics mirrored by lower bearing capacity (which reached 36.37 kN/m2) was considered the main reason for the building collapse. Additionally, the analysis confirmed that no geotechnical tests were implemented before the building was constructed. Thus, soil characteristics, stability, and performance were not examined and verified.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

9	Jiang, W., & Tan, Y.	2022	Overview on failures of urban underground infrastructures in complex geological conditions due to heavy rainfall in China during 1994–2018	Their research overview revealed that the major reasons for failure related to different Chinese facilities between 1994 and 2018 were associated with the heavy rain rate that negatively affected the robustness of the buildings and projects' infrastructure, leading to a significant increase in the soil's water content, which dramatically affected its strength and thus its potential to carry the buildings' loads.
10	Abdel-Wahed, T., & Mahmoud, A. O.	2022	Enhancement of polymer on Road problematic soil stabilization	Their analysis revealed that adding these ratios of polymer additives to the soil could increase maximum dry density, adjust the California bearing ratio, reduce swelling pressure and plasticity index, and improve unconfined compressive strength. They investigated the addition of this material by 1%, 2%, 3%, and 4% to the soil's dry weight.
11	Karumanchi, M., & Nerella, R.	2022	Influence of extracted nanosilica on geotechnical properties of soft-clay soil subjected to freeze-thaw cycles	Their research analysis and experimental results indicated that using nano-silica in the soil contributed to enhanced mechanical properties and performance. Additionally, it was found that applying various thaw-freeze cycles promoted the nano-silica effectiveness and mechanical properties, helping boost the soil properties for high-performance construction.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

12	Abdila, S. R., Abdullah, M. M. A. B., Ahmad, R., Burduhos Nergis, D. D., Rahim, S. Z. A., Omar, M. F., ... & Vizureanu, P.	2022	Potential of soil stabilization using Ground Granulated Blast Furnace Slag (GGBFS) and fly ash via geopolymerization method: A Review	Their thorough review confirmed that soil stability depends remarkably on soil strength and physical and mechanical characteristics that influence its performance and enable its adequate durability to serve different construction projects. Moreover, their extensive review revealed that using alkali-activated binders is a beneficial solution that could significantly improve clayey soil stability by elevating its strength. Also, it was found that employing ground granulated blast furnace slag fly ash and fly ash as geopolymers could enhance the level of soil stabilization.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

13	Dassanayake, S. M., Mousa, A. A., Ilankoon, S., & Fowmes, G. J.	2022	Internal instability in soils: a critical review of the fundamentals and ramifications	Their extensive review indicated that soil's seepage issues related to small particles' migration could put buildings and different construction projects in danger because of the lack of soil matrix structural integrity and activating suffusion (or suffusion phenomenon), leading to considerable degradation in the internal soil stability. Besides, their comprehensive review revealed that several scholars developed and employed diverse evaluation methods and deep investigations to address this problem. These estimation methods include tracking approaches, visualization, and sending techniques, which contributed to remarkable contributions to strengthening the knowledge and experience related to this problem.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

14	Zhang, X., & Far, H.	2022	Seismic Behaviour of High-rise Frame-core Tube Structures Considering Dynamic Soil-Structure Interaction	Their simulations and numerical analysis revealed that dynamic soil-structure interaction had a significant effect on the high-rise buildings' seismic behavior. Additionally, the research findings indicated that dynamic soil-structure interaction had elevated the inter-floor drifts and lateral deflections and reduced the shear forces of the floors. Also, the findings affirmed that dynamic soil-structure interaction impact could vary depending on the earthquake distance (close or far to the building).
15	Psarropoulos, P. N., Tsompanakis, Y., & Katsirakis, M.	2022	Dynamic soil-structure interaction between retaining walls, retaining soil and retained structures	The research results indicated that dynamic soil-structure interaction plays a critical role in affecting the soil's seismic response to various construction projects when earthquakes occur. In addition, they found that there are some factors that influence the soil's seismic behavior, including the overlying structure, the number of soil layers, and the seismic excitation at the seismic rock-outcrop or bedrock.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

16	Ayala, F., Sáez, E., & Magna-Verdugo, C.	2022	Computational modelling of dynamic soil-structure interaction in shear wall buildings with basements in medium stiffness sandy soils using a subdomain spectral element approach calibrated by micro-vibrations	Their research findings and numerical analysis revealed that dynamic soil-structure interaction had a significant impact on the soil's shear strength related to the buildings' walls. Thus, it is greatly significant to consider flexible foundations that can optimize the shear strength of soil and buildings' walls. Furthermore, the research findings confirmed that the dynamic soil-structure interaction relies heavily on the amount of input frequency. Also, remarkable interval lengthening referred to the structures reached roughly 47%. Moreover, the results recorded a considerable decline in the floor shear, amounting to around 220%. At the same time, they found that the ultimate lateral roof displacement minimization attained a value of 34% compared with stationary roofs.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

17	Wu, K., Ma, J., Chuai, M., Li, C. H., Chen, Y., & Lv, F.	2022a	Numerical simulation of the near-fault spontaneous rupture and its influence on dynamic soil-structure interaction	The simulation outputs and numerical analysis confirmed that the accelerated motion of the unconstrained near-fault rupture had significant and several lower-frequency parts. The maximum vertical acceleration was roughly one and a half higher than the maximum horizontal acceleration. Also, the study findings indicated that under far-fault and near-fault ground movement conditions, the superstructure response distributions were the same. Moreover, the results showed that these responses were 254.5% higher in near-fault ground movement compared with far-fault ground movement, indicating that the near-fault ground movement can be considered significantly destructive to structures.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

18	Rioux, M. D., Nollet, M. J., & Galy, B.	2022	Impact of initial stress field heterogeneity in dynamic soil–structure interaction	The research results affirmed that the initial stress field of soil heterogeneity could significantly influence the soil behavior, tending to boost the soil's shear strain and shear modulus. This aspect, in turn, can create a heterogeneous stress domain in the surrounding areas resulting in the adjustment and modification of the soil's dynamic behavior related to several structure soil systems. Also, the results showed that the initial stress field of soil heterogeneity had a remarkable impact on the amounts of surface acceleration. Additionally, it was found that failure to take effective actions and practical measures against the initial stress field of soil heterogeneity might lead to some errors related to the calculation of structural acceleration.

Table 2.1: Major contributions of the publications reviewed in this work. "tables continued"

19	Requena-Garcia-Cruz, M. V., Bento, R., Durand-Neyra, P., & Morales-Esteban, A.	2022	Analysis of the soil structure-interaction effects on the seismic vulnerability of mid-rise RC buildings in Lisbon	Their research analysis and numerical calculations revealed that the building's deformed shape and soil modal behavior were similar with and without the presence of dynamic soil-structure interaction. In addition, the study outputs indicated that elevating soil flexibility can lead to more significant periods, resulting in larger seismic disasters. Their research findings also showed that considering the dynamic soil-structure interaction would reduce the maximum buildings' seismic capacity by 15%.
20	Kamal, M., Inel, M., & Cayci, B. T.	2022	Seismic behavior of mid-rise reinforced concrete adjacent buildings considering soil-structure interaction	The numerical results and FEA findings indicated that the surrounding buildings could influence each other when seismic loading takes action. In addition, it was found that surrounding buildings and soil behavior should be taken into account for several facilities that have a maximum number of floors of eight, even if no collision would take place. At the same time, the results indicated that for buildings that exceed eight floors, dynamic soil-structure interaction should be considered if no collision occurred, excluding the impact of surrounding buildings.

2.6 CHAPTER SUMMARY

It can be inferred from the literature review carried out in this chapter that soil characteristics consist of different indices and factors that influence its properties. These factors should be taken into account to enable active and effective soil behavior that can guarantee higher soil performance to carry higher building loads without failure. These properties include shear strength, porosity, soil mass, compaction, stiffness, structure, and damping. In addition, the literature review showed that some factors could influence the dynamic soil-structure interaction and affect buildings' stability, such as seismic loading. Therefore, seismic loading codes and standards should be considered in buildings and construction, as several authors mentioned that these standards are not largely counted. Moreover, the literature review results confirmed that soil could face several problems that might influence buildings' firmness due to variations in soil stabilization, such as soil expansion and soil porosity. In this context, several authors suggested and investigated different solutions and scenarios to mitigate these problems, like the employment of nanomaterials. This work investigates the critical impact of dynamic soil-structure interaction depending on a group of factors and key parameters associated with soil properties. A case study and numerical analysis using simulation software are executed to achieve the major research goal.

3. RESEARCH METHODOLOGY

3.1 CHAPTER GOAL

This chapter shows the analysis work done on soil-structure interaction for concrete buildings. Three soil types were considered in this study: soft soil, medium soil, and hard soil. As for building heights, three height levels were considered: 1-floor, 5-floors, and 10-floors. In addition, two Lateral Load Resisting Systems (LLRS) were considered which are Building Frame (BF) system and Shear Wall (SW) system. Several outputs are extracted like: Base shear, maximum axial force in columns, maximum bending moment in columns, and maximum lateral displacement at roof level. These outputs are important to reach the final conclusion for practicing engineers about soil-structure interaction.

3.2 ANALYSIS PROGRAM

3.2.1 Cases Description

The current work is concerned with a complete examination of the outcomes of analysis of 18 cases at different floor height Building frame systems with columns as Lateral Load Resisting Systems (LLRS), in comparison to shear wall systems subjected to gravity load, seismic load, and their combinations. In addition, different soil types (soft, medium, hard) where investigated for the two Lateral Load resisting system.

Cases C1, C2, and C3 depict a one-floor building frame system on soft, medium, and hard soil, correspondingly. The building frame system and shear wall system were evaluated at one, five, and ten floor numbers to study the influence of floor number, as shown in Table 3.1. Cases C10 through C18 also investigate the behavior of shear wall systems for one, five, and ten floors on three distinct soil types (soft, medium, and hard).

Table 3.1: Cases description investigated in this work.

Case ID	Number of floors	Soil type	LLRS type
C1	1	Soft	Building frame
C2	1	Medium	Building frame

Table 3.1: Cases description investigated in this work. "tables continued"

C3	1	hard	Building frame
C4	5	Soft	Building frame
C5	5	Medium	Building frame
C6	5	hard	Building frame
C7	10	Soft	Building frame
C8	10	Medium	Building frame
C9	10	hard	Building frame
C10	1	Soft	Shear wall
C11	1	Medium	Shear wall
C12	1	hard	Shear wall
C13	5	Soft	Shear wall
C14	5	Medium	Shear wall
C15	5	hard	Shear wall
C16	10	Soft	Shear wall
C17	10	Medium	Shear wall
C18	10	hard	Shear wall

3.3 PLAN AND HEIGHT OF THE FRAME SYSTEM

As indicated in Figure 3.1 and Figure 3.2, the design consists of two bays of 5 m span each along the X direction and two bays of 5 m span each along the Z direction. The typical Ten-Floor building has each floor height of 3.0 m along Y direction. For both systems, the columns were 30*60 cm at the borders and 60*60 cm in the center with 10 T16 mm reinforcement. The cross section of the beams and the thickness of the slab were 30*50 cm and 20 cm, respectively.

The main flexural reinforcement and secondary flexure reinforcement were placed as 3T16 mm and 3T10 mm respectively.

The slab reinforcement was 5 T12 mm per meter, shear walls are employed as LLRS.

Figure 3.1 shows external shear walls with a thickness of 30 cm and a length of 150 cm installed in the X and Z directions. The reinforcement used in the shear walls was 10T12 mm. Meanwhile all stirrups placed were considered 5 T10mm per meter. The building was placed on footings of dimensions 2.5x2.5x0.4 m each with 6T20 mm per meter as main footing reinforcement.

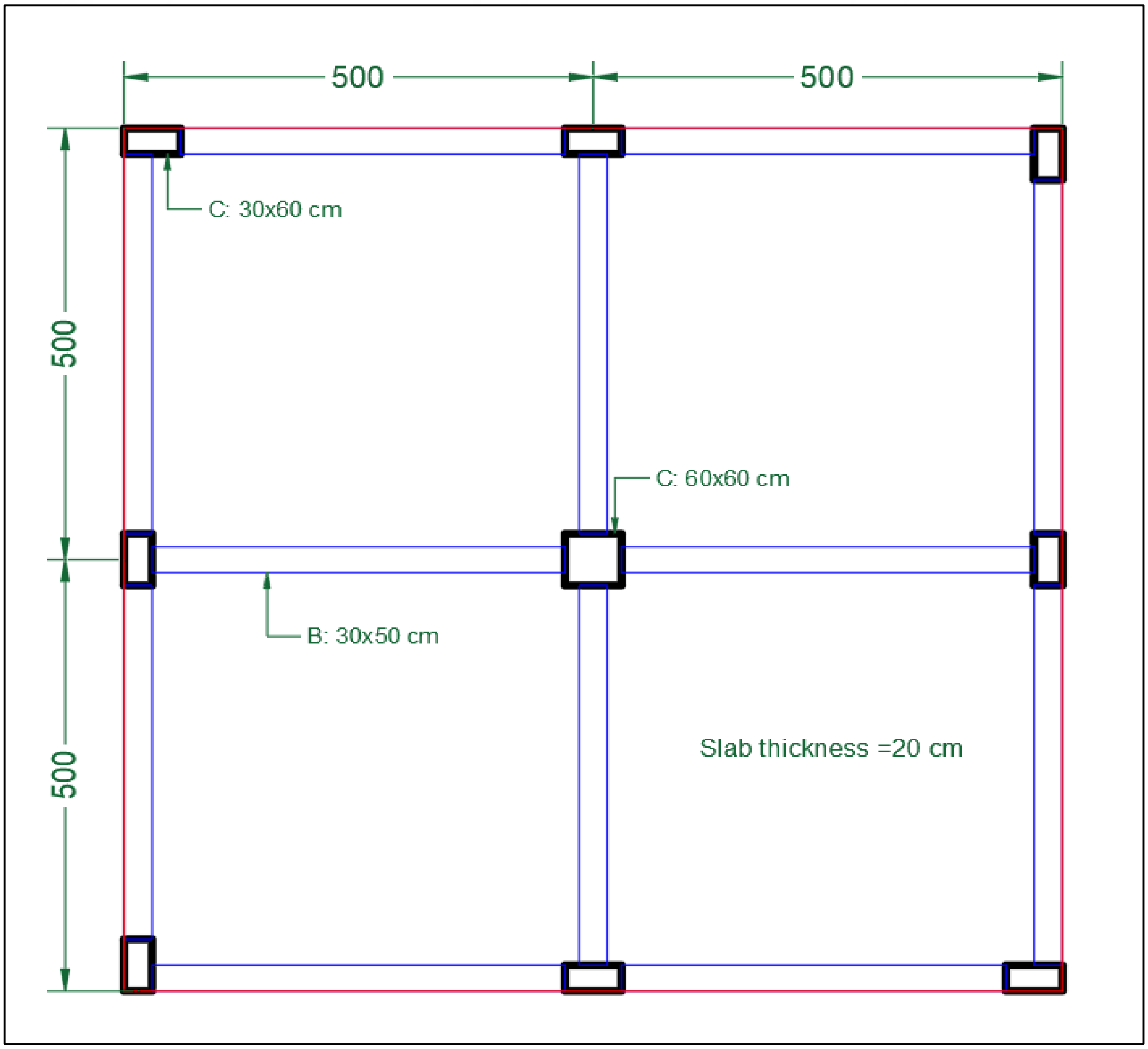


Figure 3.1: A configuration of the building frame system.

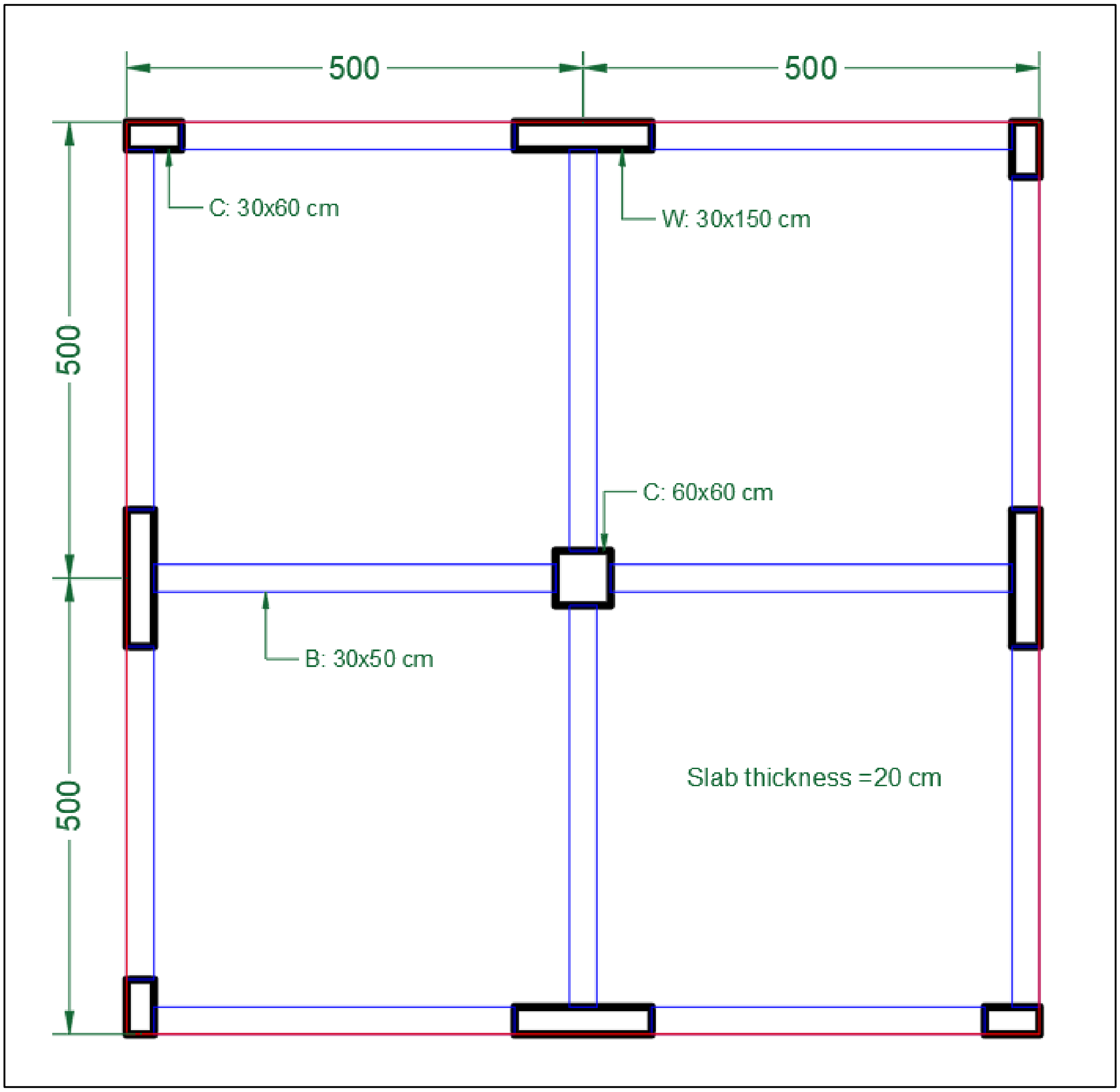


Figure 3.2: A configuration of the shear wall system.

3.4 MATERIAL PROPERTIES

"f'c=45" was chosen as the compressive strength of concrete. In terms of steel characteristics, the yield stress for flexural steel was set at 400 MPa and for shear reinforcement at 320 MPa.

Table 3.2 and Table 3.3 show the characteristics of concrete and steel, correspondingly. The cohesiveness of soft, medium, and hard soils is 10, 30, and 50.8 kPa, respectively. The angle of friction is zero in all three soil types.

Table 3.2: Concrete properties [58].

Concrete mix	Compressive strength (MPa)	Flexural strength (MPa)	Elasticity modulus (MPa)
C45	45	5.5	37900

Table 3.3: Steel properties.

Steel grade	Yield strength (MPa)	Ultimate strength (MPa)	Elasticity modulus (MPa)
T400	400	500	200000
T320	320	400	200000

Furthermore, the soil properties are represented in Table 3.4.

Table 3.4: Soil properties.

Soil Type	Unit weight (kN/m^3)	Angle of friction (Ø)	Cohesion (kPa)
Soft	20	0	10
Medium	20.1	0	30
Hard	20.8	0	50.8

3.5 LOADING BOUNDARY CONDITIONS

The structural systems are exposed to three different types of Primary Loads superimposed dead load, live load, and seismic lateral load in x direction. As indicated in Table 3.5, the superimposed dead load was 5 kN/m^2. The live load considered is adopted for residential building 3 kN/m^2 as per ASCE 7-16-table 4-1.

Table 3.5: Major loading boundary conditions.

Gravity load	kN/m2
SDL	5
Live	3

The behavior of all models is investigated for Seismic Zone 2.5. The typical El Centro earthquake waves are utilized as the input seismic waves in this study, which is the classic and widely used earthquake. In order to investigate the seismic zone 2.5, the data was fitted on a scale in the graph shown in Figure 3.3.

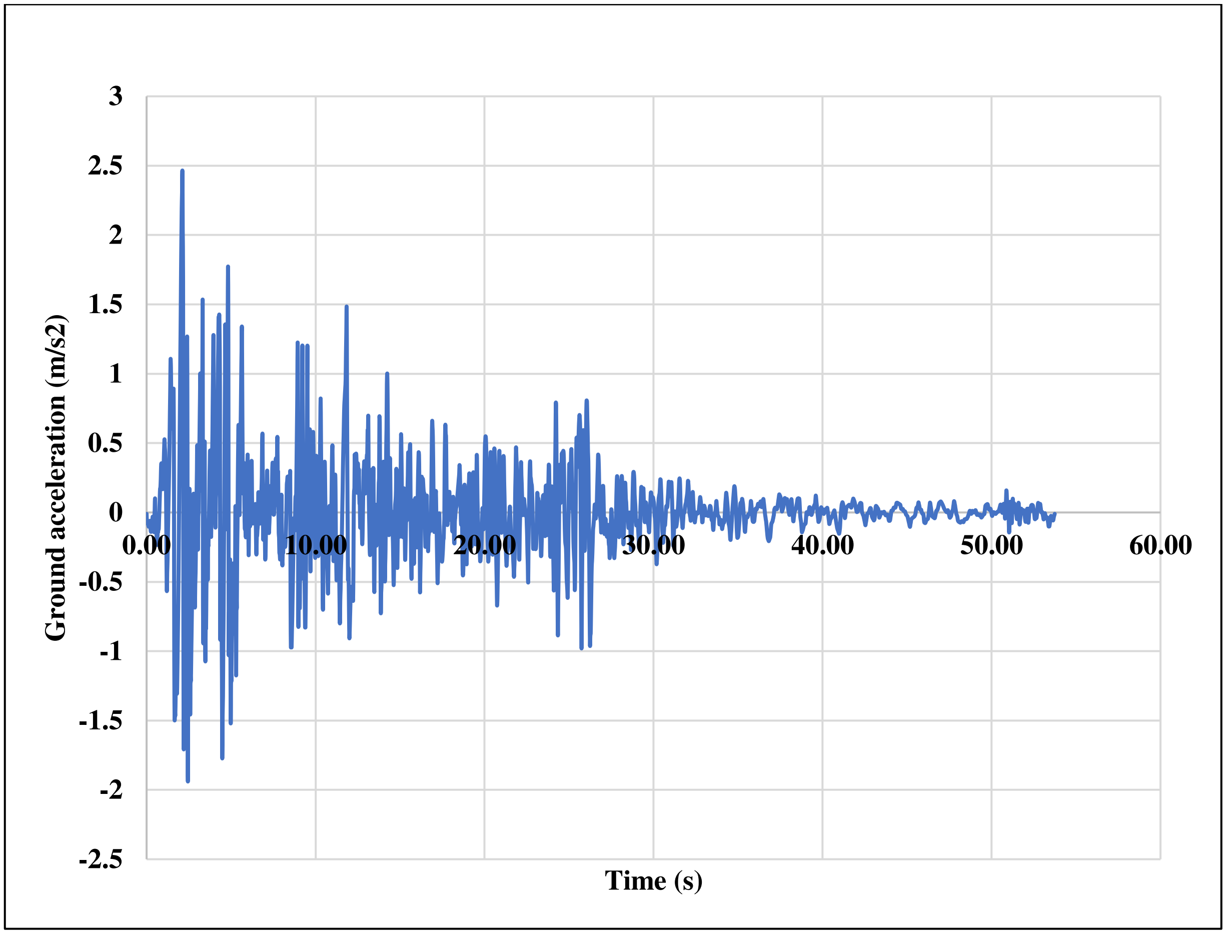


Figure 3.3: El Centro approach associated with seismic data.

3.6 NUMERICAL MODELING

ABAQUS software package finite element analysis of the seismic response in different lateral load resisting systems for the various cases listed above [59]. This program is frequently used by static and dynamic researchers (seismic and impact) [60]–[63]. ABAQUS software package is a finite element analysis tool that may be used to evaluate the behavior of structures under different loads. Columns and beams were modeled as frame members. Furthermore, the walls and slabs were considered shell components. Meanwhile, the soil and footings were investigated as volumetric elements, as described in Figure 3.4 and Figure 3.5.

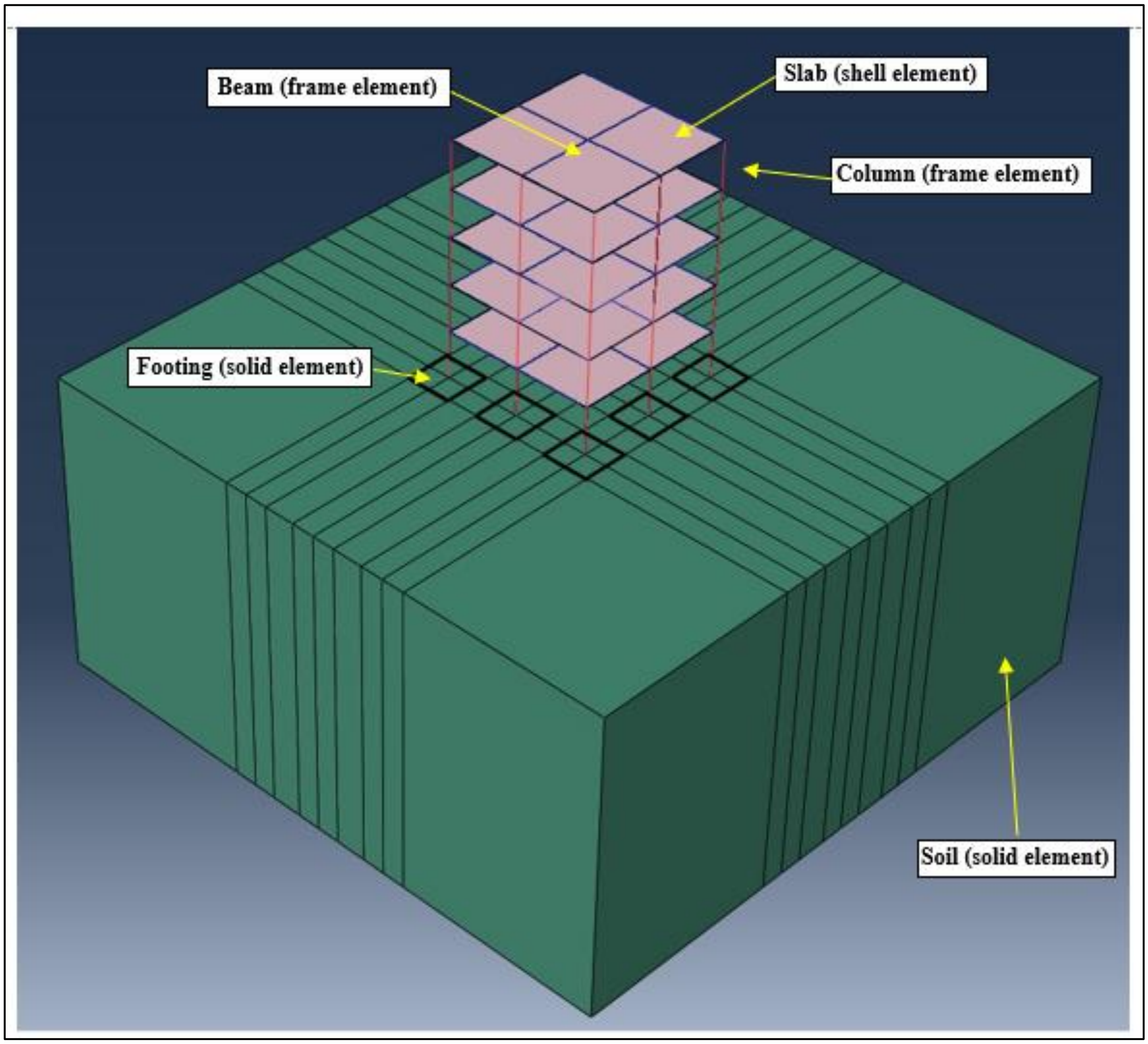


Figure 3.4: Elements modeling in ABAQUS software package for the building frame system.

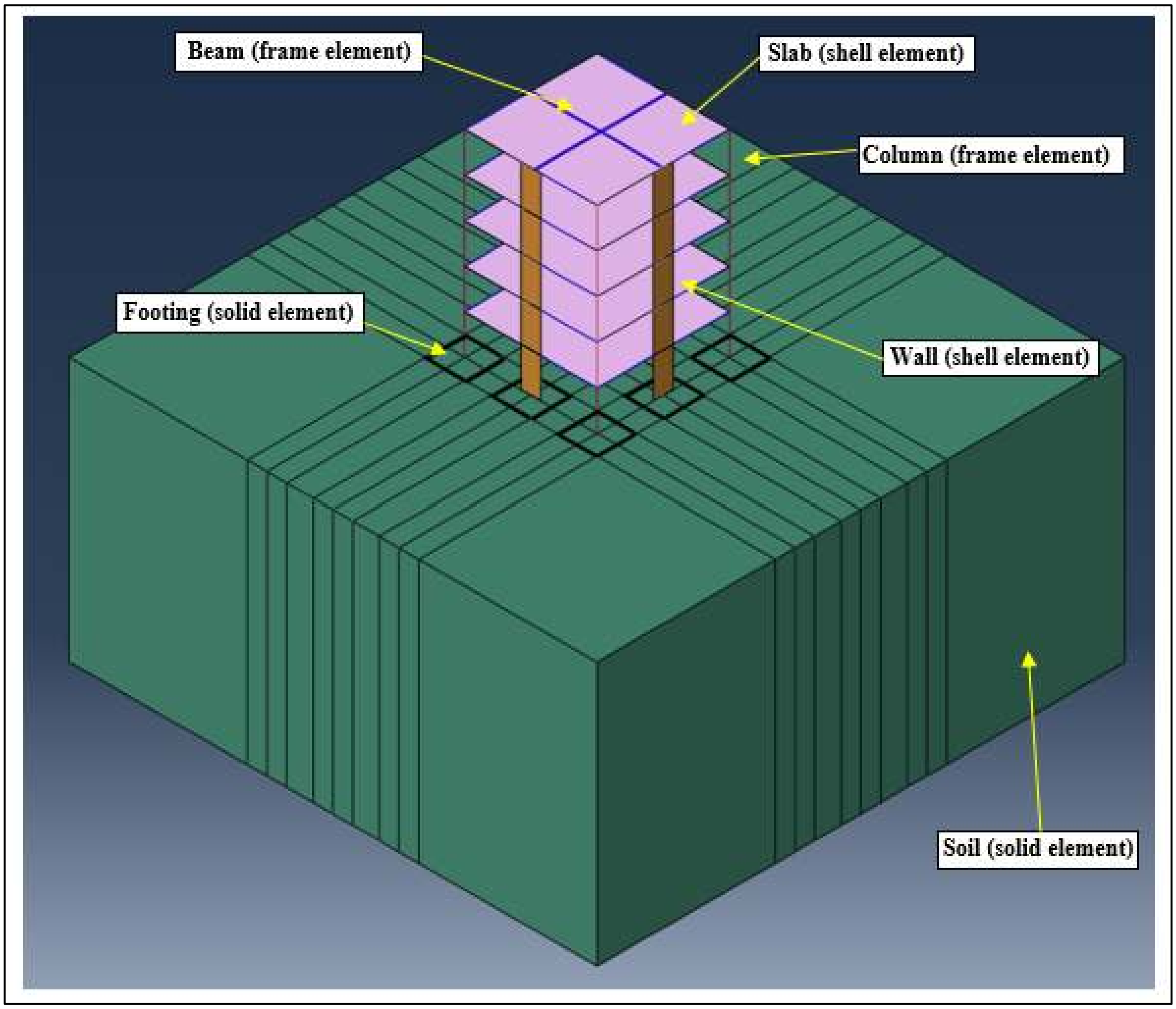


Figure 3.5: Elements modeling in ABAQUS software package for the shear wall system.

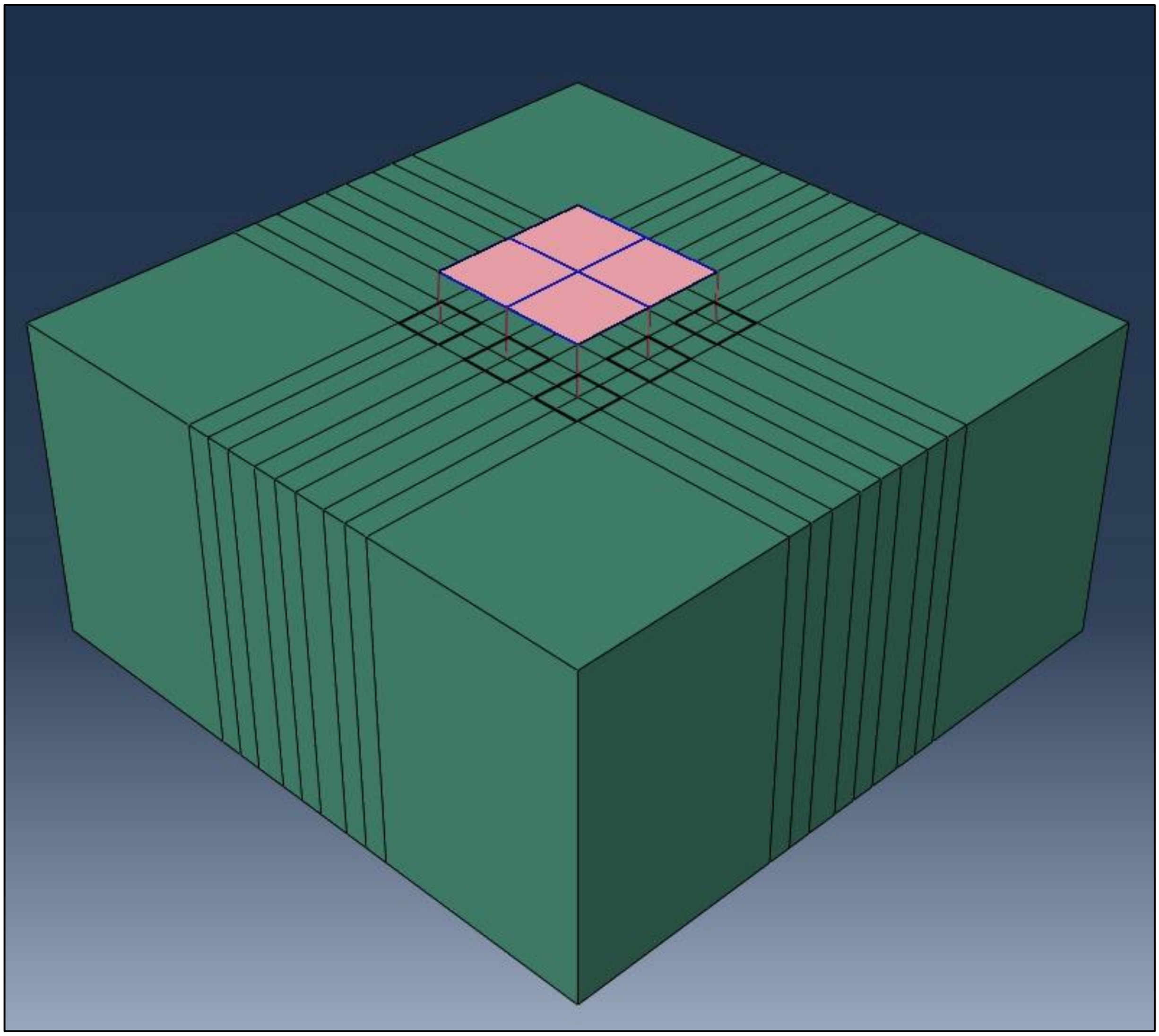


Figure 3.6: Another 3D configuration of the soil and footing investigated in this master's thesis from the ABAQUS software tool numerical analysis (with single slab).

Furthermore, Figure 3.7 indicates another 3D configuration of the soil and footing investigated in this master's thesis from the ABAQUS software tool numerical analysis (with multiple slabs).

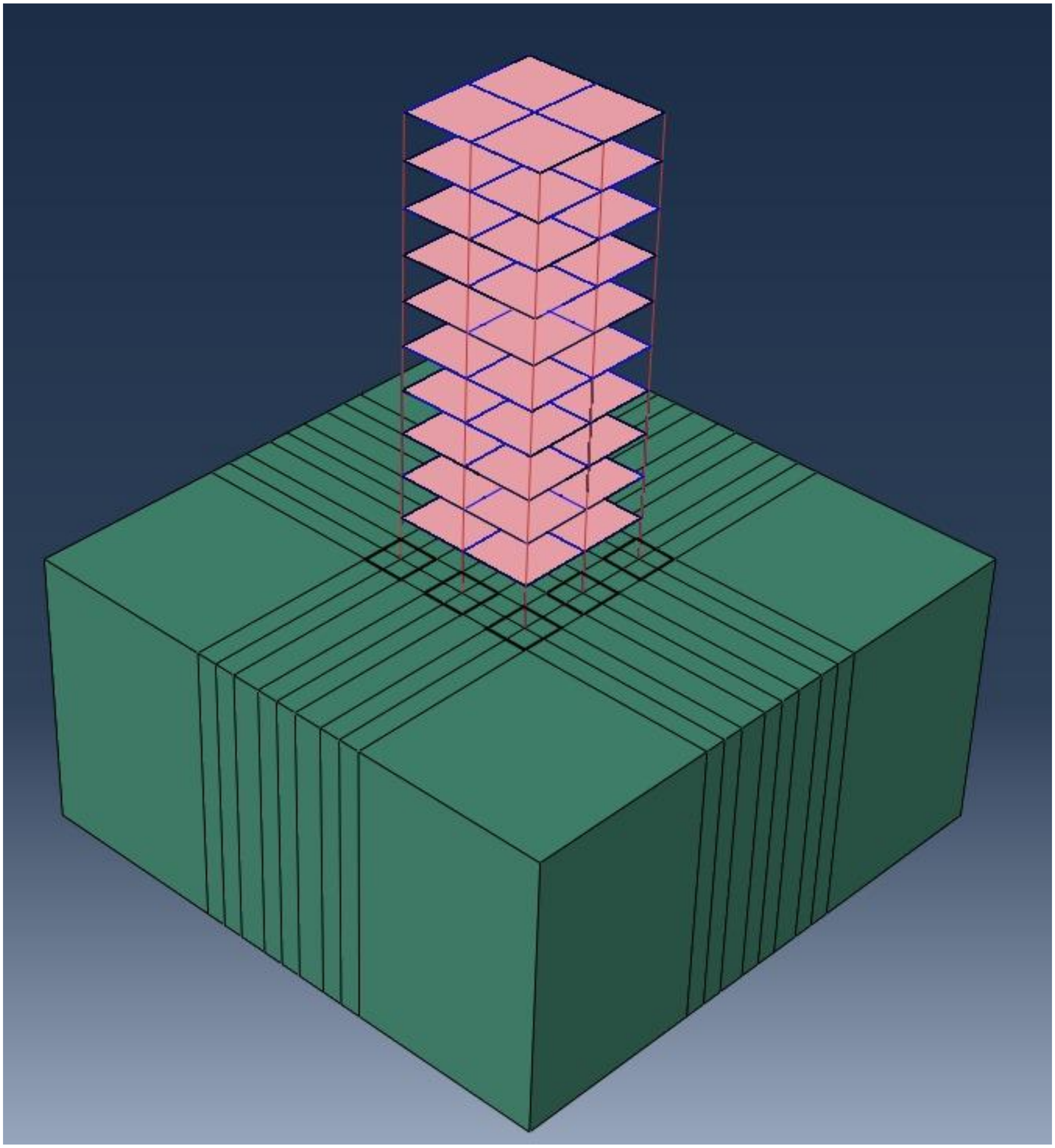


Figure 3.7: Another 3D configuration of the soil and footing investigated in this master's thesis from the ABAQUS software tool numerical analysis (with multiple slabs).

Additionally, Figures 3.8 to 3.13 show the details for the section and reinforcement definition for all structural components.

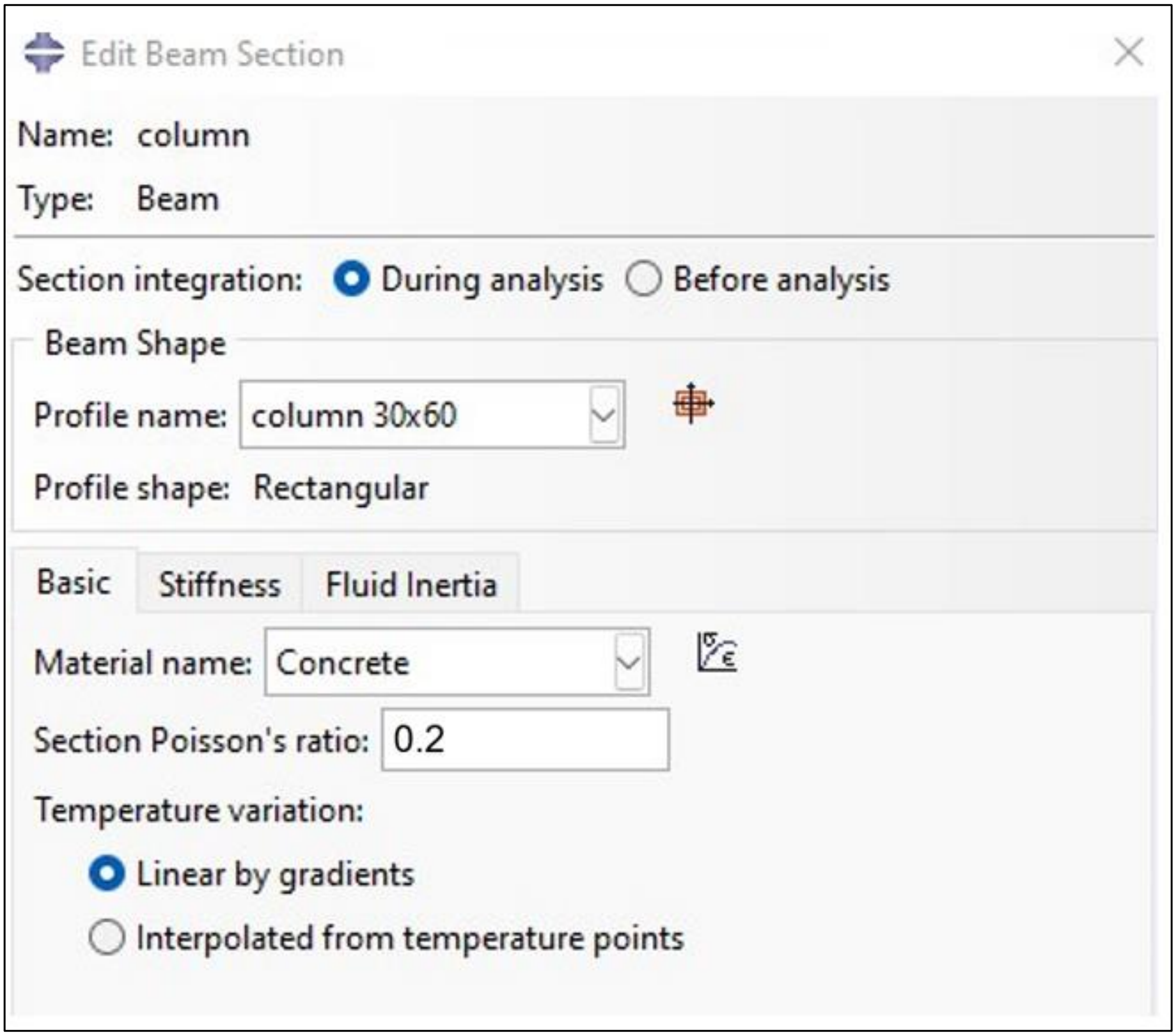


Figure 3.8: Column section properties.

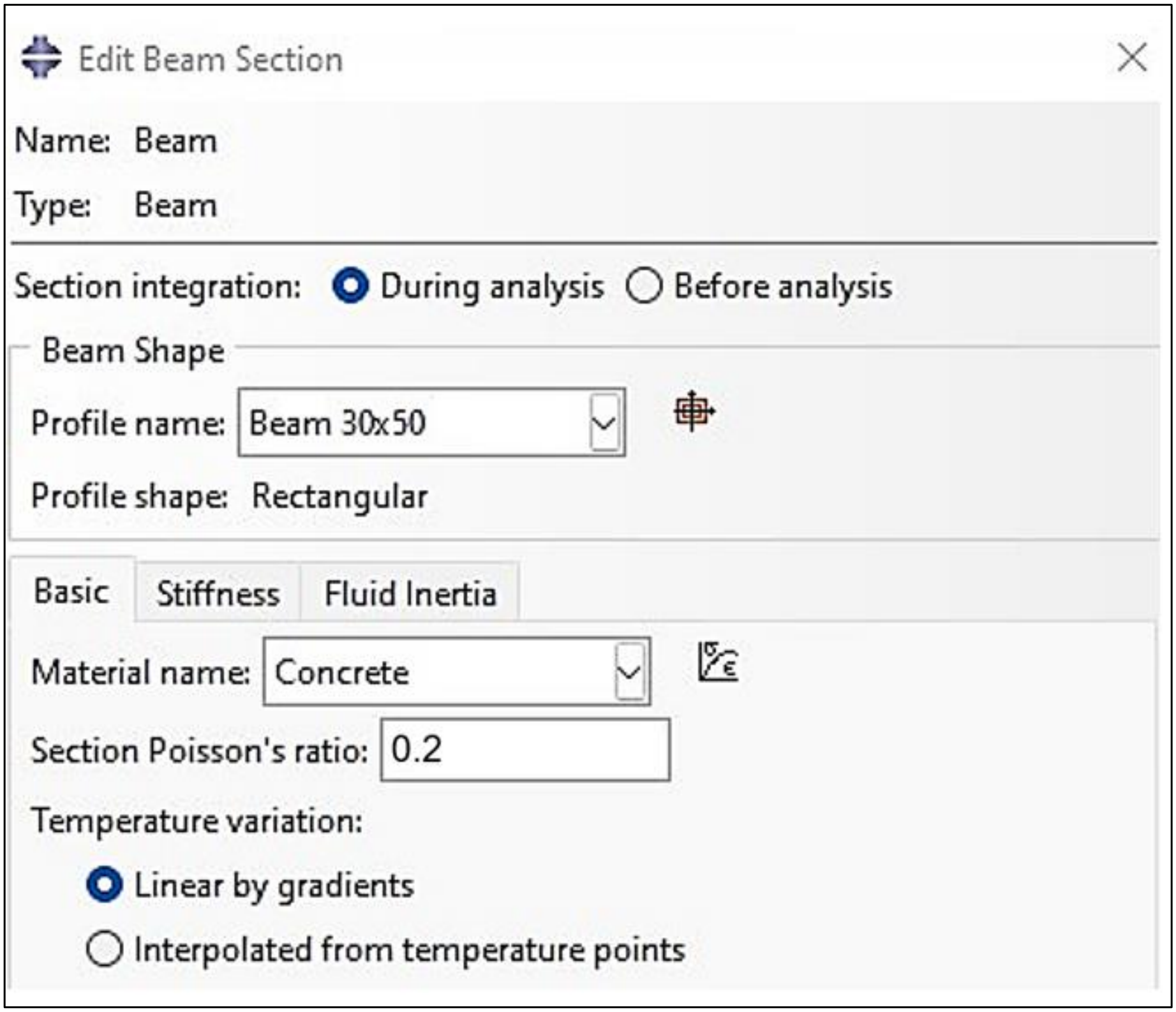


Figure 3.9: Beam section properties.

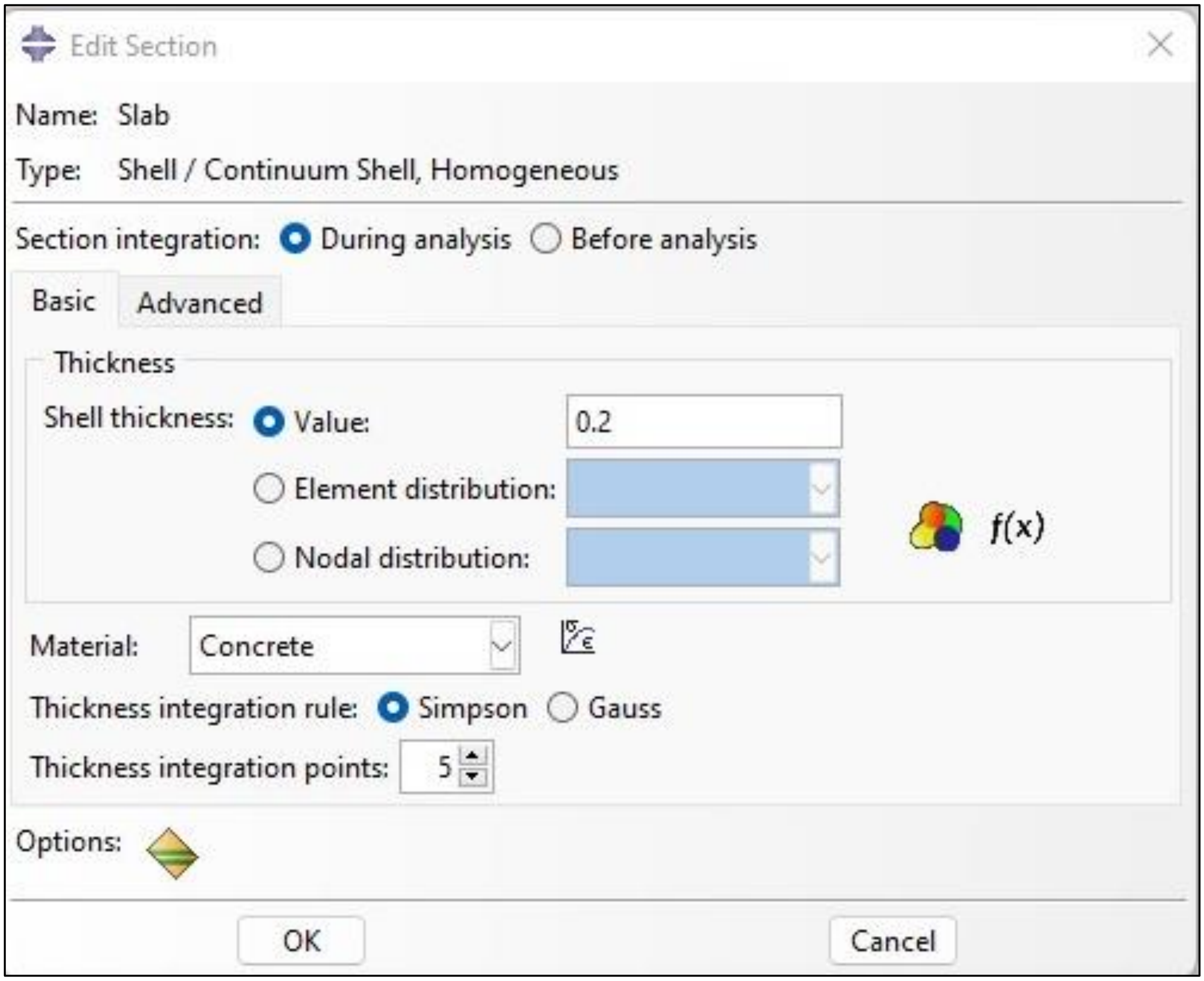


Figure 3.10: Definition of the boundary conditions related to the slab section.

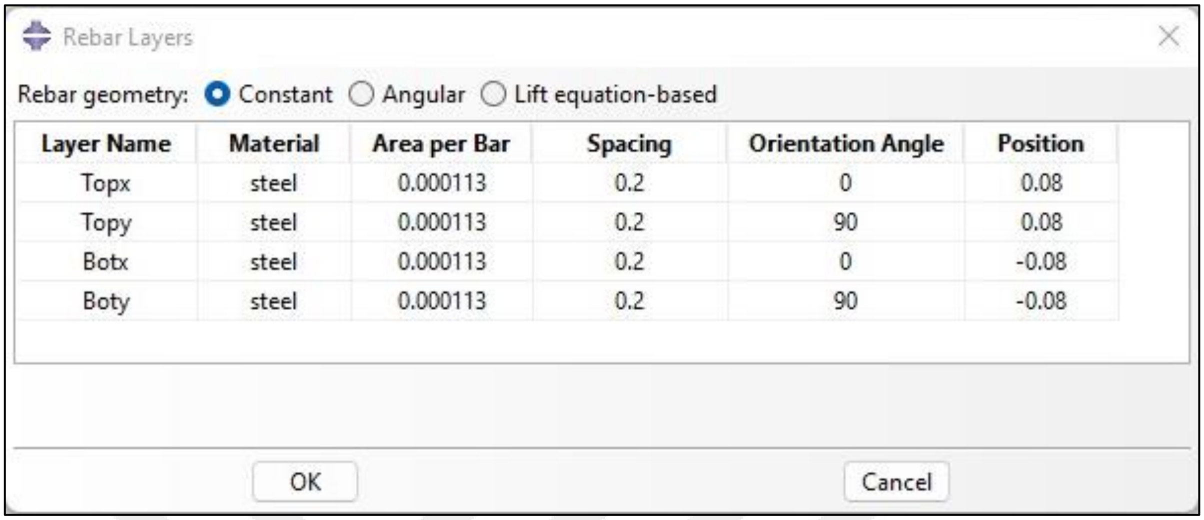


Figure 3.11: Definition of the boundary conditions related to the steel rebar layers of the slab.

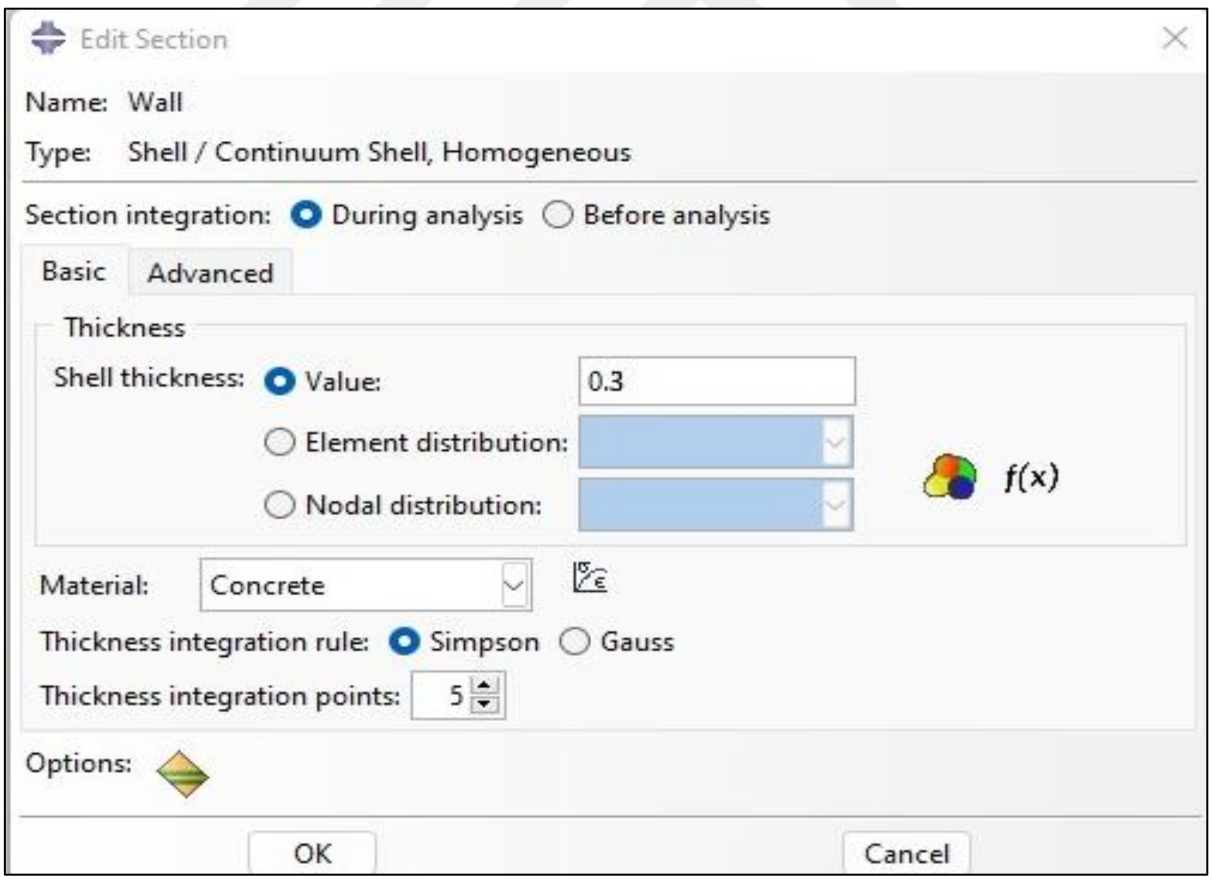
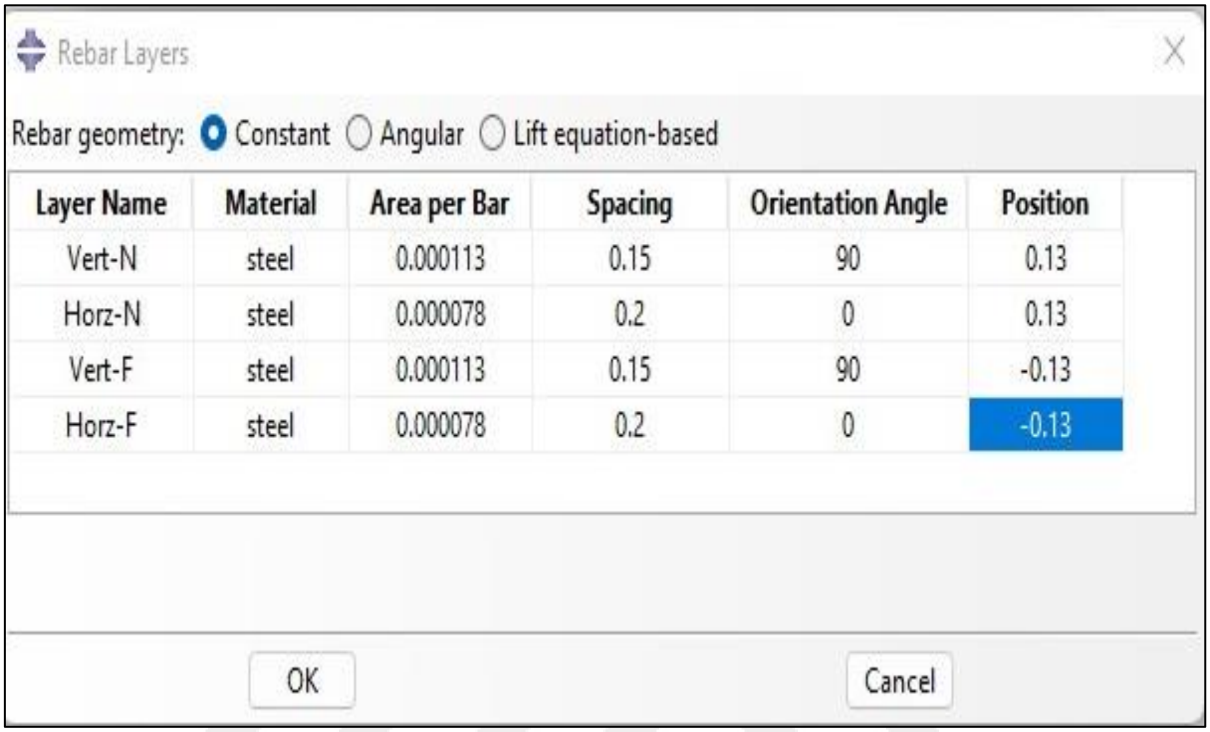


Figure 3.12: Definition of the boundary conditions related to the shear wall.



Layer Name	Material	Area per Bar	Spacing	Orientation Angle	Position
Vert-N	steel	0.000113	0.15	90	0.13
Horz-N	steel	0.000078	0.2	0	0.13
Vert-F	steel	0.000113	0.15	90	-0.13
Horz-F	steel	0.000078	0.2	0	-0.13

Figure 3.13: Definition of the boundary conditions related to the steel rebar layers of the shear wall.

Furthermore, the boundary fixations of the different elements in the model are illustrated in Figure 3.14. Slabs, columns, shear walls, and beams are all susceptible to a fixed support. Meanwhile, the footing and soil were tied together to prevent relative motion. Furthermore, the bottom surface of the soil was fixed in the y and z directions but released in the x direction to analyze the lateral displacement caused by the lateral seismic load. A mesh size of 20 cm was employed in this research for all the elements.

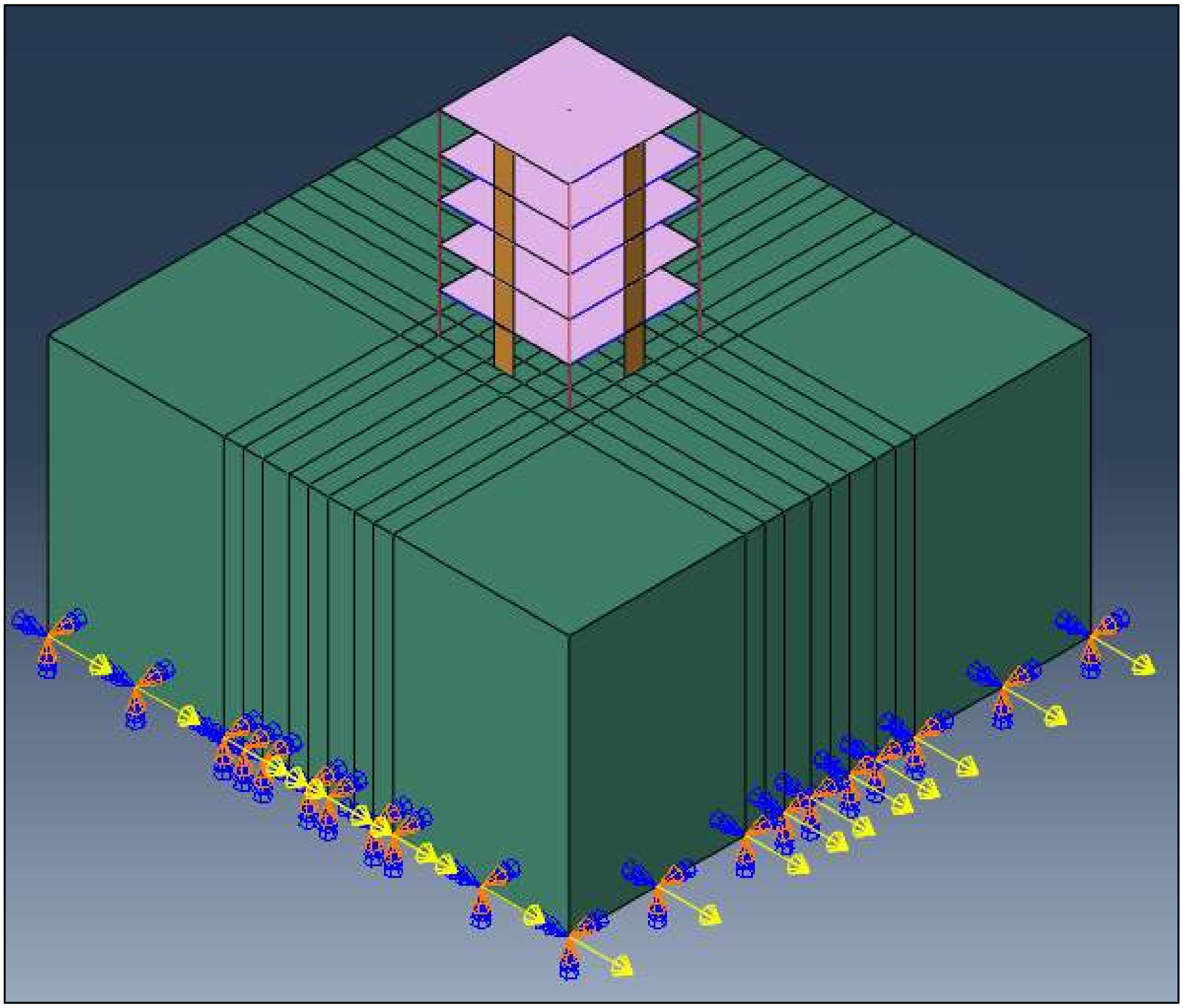


Figure 3.14: Definition of the boundary conditions linked to the model.

One of the constitutive models for modeling concrete behavior was the Concrete Damaged Plasticity model (CDP model) created in ABAQUS software package. This approach is extremely successful for examining concrete under dynamic and impulsive pressures. The CDP model accounts for nonlinear concrete behavior by describing many input variables such as inelastic strain, cracking strain, stiffness deterioration, and recovery. The various characteristics inputs of concrete are summarized in Table 3.6. In addition, the soil was modeled using Mohr-coulomb built in model in ABAQUS software package referring to soil properties represented in Table 3.6.

Table 3.6: Major input parameters related to the concrete CDP.

Parameter	Symbol	C45
Elastic Modulus (MPa)	E	37900
Poisson's ratio	υ	0.2
Density (Kg/m^3)	ρ	2400
Compressive strength (MPa)	f'_c	45
Peak Compressive strain (mm/m)	$\acute{\varepsilon}_c$	2.4
Tensile Strength (MPa)	f_t	5.5
Dilation angle (°)	ψ	36
Eccentricity	*e*	0.1
Bi-axial to Uni-axial strength ratio	f_{b0}/f_{t0}	1.16
Second stress invariant ratio	K	0.67
Viscosity parameter	μ	0

The elastoplastic behavior of steel rebar material is used in this investigation as elastic-perfectly plastic behavior. Till reaching the yield point, steel material acts elastically. After yielding, it is completely plastic. Table 3.7 shows the mechanical parameters of steel grades utilized in ABAQUS software package model.

Table 3.7: Steel inputs in the software.

Parameter	Symbol	T400	T320
Elastic Modulus (MPa)	E	200000	200000
Poisson's ratio	υ	0.3	0.3

Table 3.7: Steel inputs in the software. "tables continued"

Density (Kg/m^3)	ρ	7850	7850
Yield strength (MPa)	fy	400	320
Ultimate strength (MPa)	f_u	500	400

It is expected that the findings and discussion of the 18 cases evaluated with the ABAQUS software package will be obtained using the ABAQUS software tool. Base shear, axial force in the column, bending moment in the column, and lateral displacement at the roof level is the expected outputs. The effect of floor numbers, lateral load-resisting system type, and soil type will also be evaluated.

4. RESULTS AND DISCUSSION

4.1 CHAPTER GOAL

This chapter illustrates the numerical results obtained from the modeling, simulation and computer analysis using the ABAQUS software to identify the critical role of the dynamic soil-structure interaction in achieving a significant rate of soil stability and performance for various concrete buildings. Some findings will be obtained linked to the base shear, axial force in the column, bending moment in the column, and lateral displacement at the roof level are the expected outputs. In addition, the effect of floor numbers, lateral load-resisting system type, and soil type are also presented in this chapter.

4.2 EFFECT OF SOIL TYPE

On the three-floor heights, the effect of soil type on Abaqus results for the two frame systems was investigated. The results of the modeling indicate four major outputs: base shear, axial force, moment, and displacement. Meanwhile, at one-floor height, all the findings were almost identical.

4.2.1 Base Shear Results on Different Soil Types

Figure 4.1 depicts the base shear findings for the building frame system for 5 and 10 floors. It shows a base shear of 1500, 1425, and 1095 for soft, medium, and hard soil for a five-floor building using a building frame. The base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil. For a ten-floor building frame system, base shears of 2100, 1680, and 1512 for soft, medium, and hard soil, respectively, are shown in Figure 4.1. It provides a 20% decrease for medium soil and 10% reduction for hard soil in a 10-floor building frame resistance system.

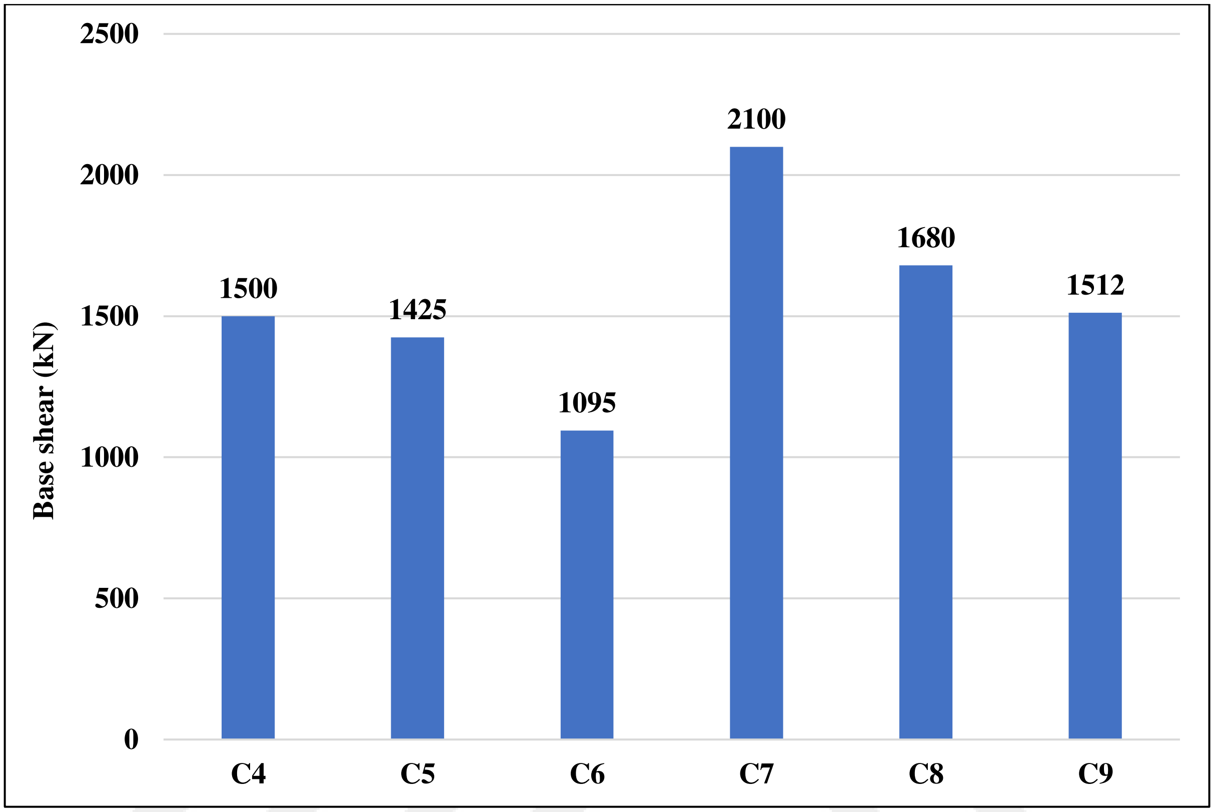


Figure 4.1: Base Shear results of Building frame on different soil types.

Figure 4.2 depicts the base shear findings for the shear wall system for 5 and 10 floors on different soil types. It displays a soft, medium, and hard soil base shear of 2088, 1984, and 1504 for a five-floor structure. This represents a 5% reduction for medium soil and a 24% reduction for hard soil in a shear wall system. Meanwhile, the base shear for a 10-floor shear wall system was 2952, 2362, and 2066 for soft, medium, and hard soil, respectively. Base shear for a shear wall system with ten floors on medium soil is 20% less than base shear on soft soil. On hard soil, this outcome is lowered by 12%.

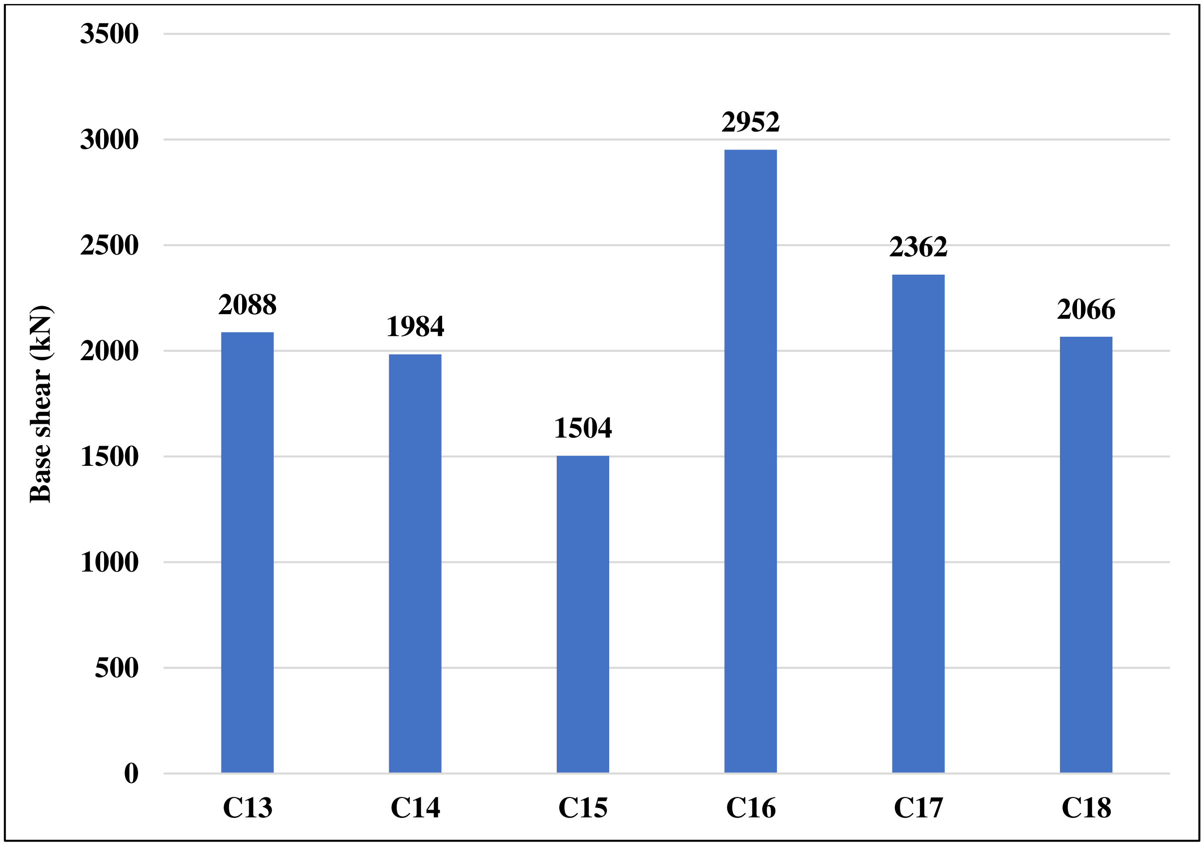


Figure 4.2: Base Shear results for Shear wall on different soil types.

4.2.2 Axial Force Results on Different Soil Types

Figure 4.3 depicts the axial force findings for the building frame system for 5 and 10 floors. It shows an axial force of 4160, 4077, and 3744 for soft, medium, and hard soil for a five-floor building using a building frame. The axial force for a five-floor building frame decreases by 2% from soft to medium soil and by 8% from medium to hard soil. For a ten-floor building frame system, axial force of 12480, 11356, and 10858 for soft, medium, and hard soil, respectively, are shown in **Error! Reference source not found.**. It provides a 9% decrease for medium soil a nd 4% reduction for hard soil in a 10-floor building frame resistance system.

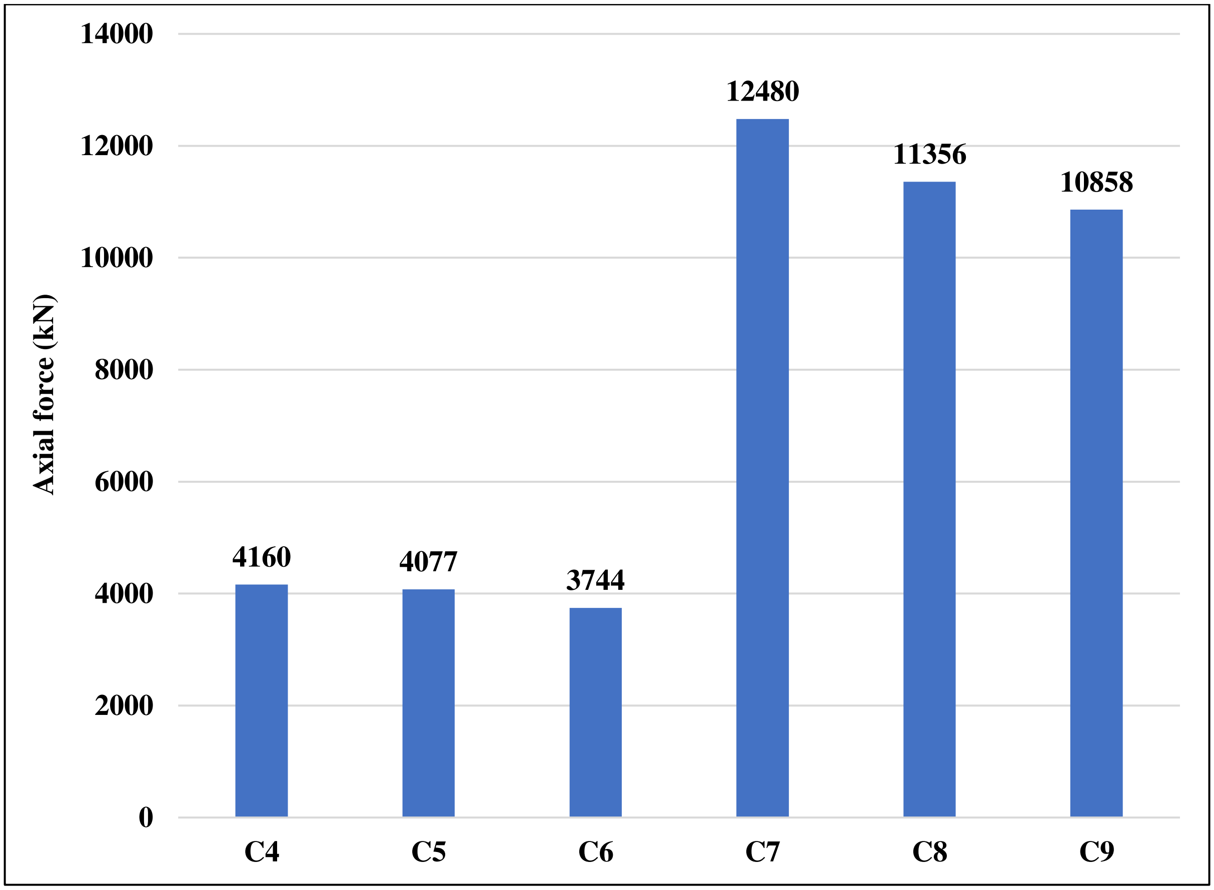


Figure 4.3: Axial force results for building frame on different soil types.

In comparison, Figure 4.4 represents the axial forces for shear wall lateral load resisting system for 5 and 10 floors. The axial force for this system on soft, medium, and hard soil for 5 floors was 1430, 1387 and 1215. There is a reduction of 3% from soft to medium soil and a reduction of 12% on hard soil regarding axial force.

Meanwhile, axial force in kN for shear wall system was 2210, 1922, 1812 kN for soft, medium, and hard soil in 10 floors building. The axial forces are lesser for medium soil by 13% compared to soft soil and less by 6% for hard soil.

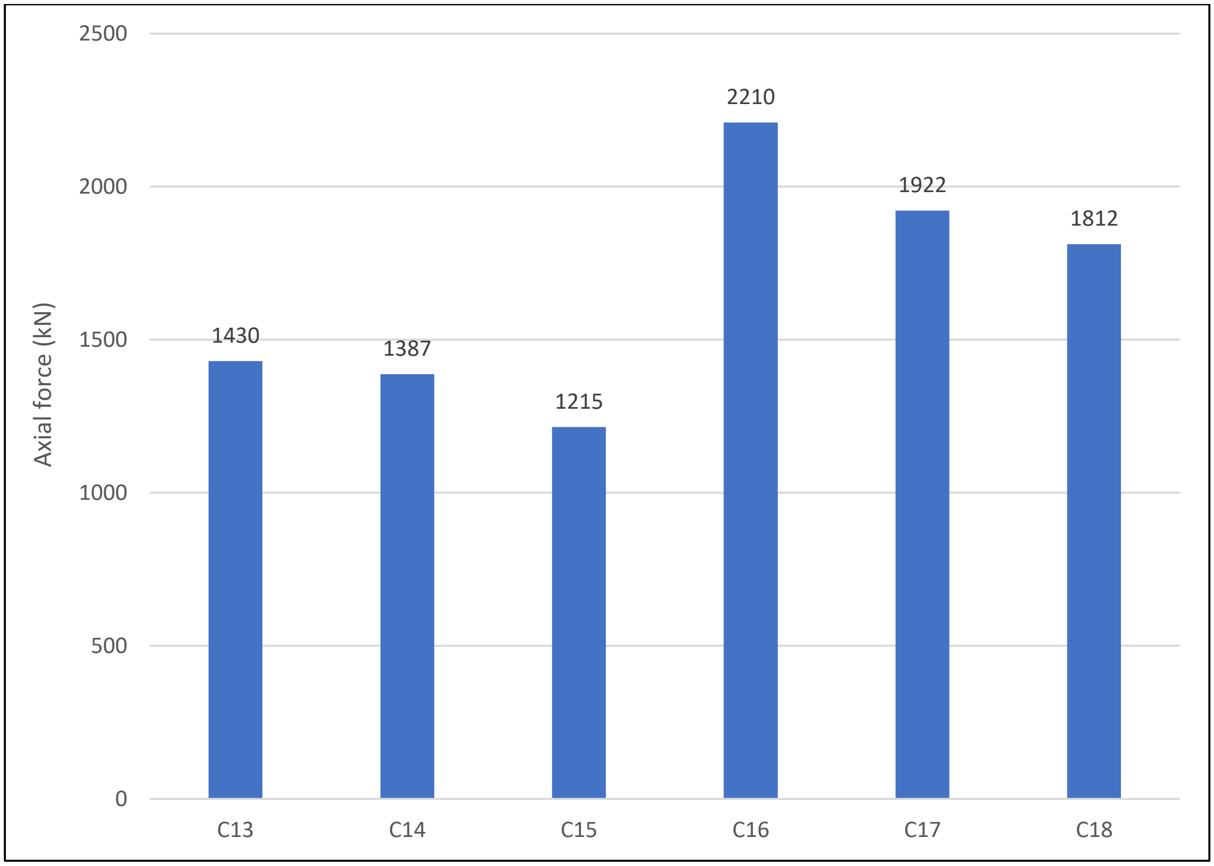


Figure 4.4: Axial force results for Shear wall building on different soil types.

4.2.3 Moment Results on Different Soil Types

Figure 4.5 illustrates the moment values on columns. The moments for a five-floor building frame system were 1600, 1520, and 1200 kN.m. This represents a 5% reduction in moment on medium soil and a 21% reduction on hard soil. The moment values on columns for a 10-floor building frame system, on the other hand, were 2240, 1792, and 1568 kN.m for the three soil types. The moment of a 10 floor building frame system on medium soil is 20% less than that of soft soil, while the moment of a building frame on hard soil is 13% less than that of medium soil. As the moment of column is taken by shear wall in shear wall system, the moment values were not significant in columns.

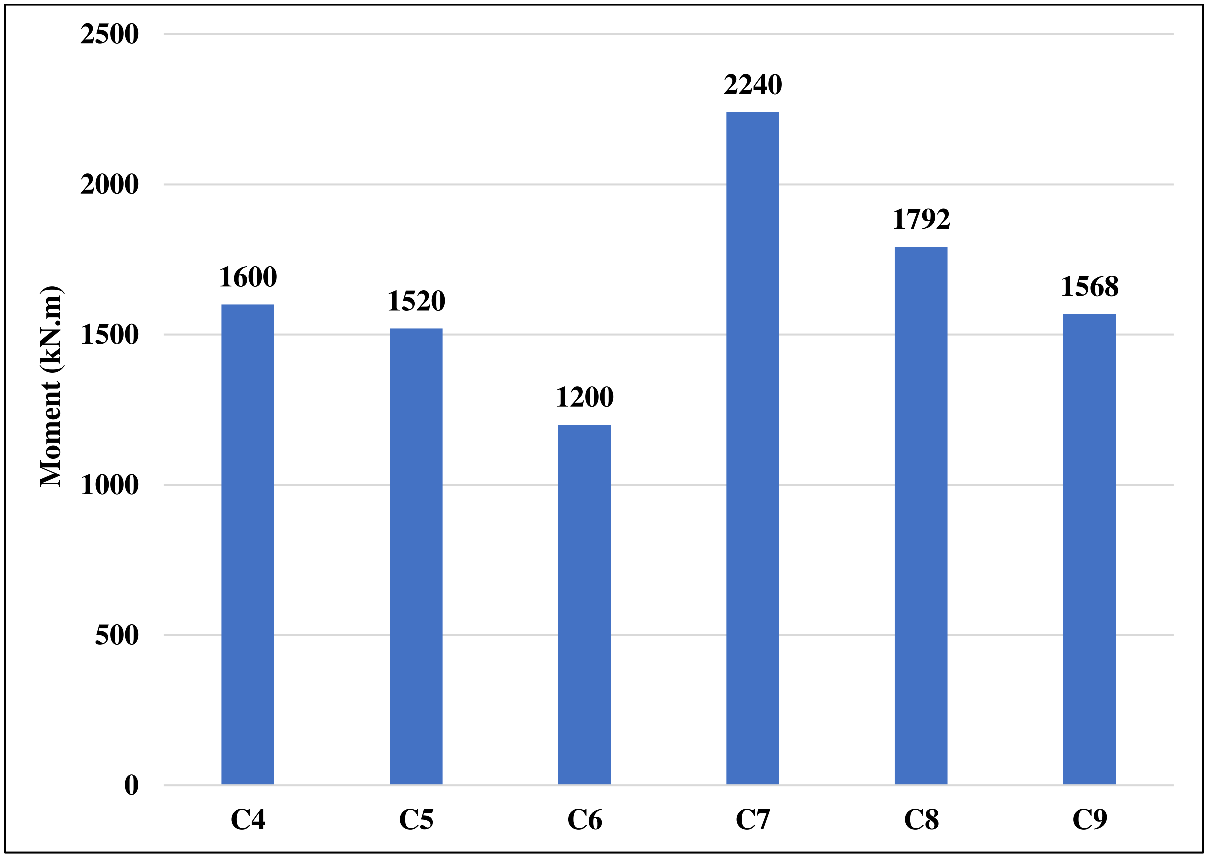


Figure 4.5: Moment results for building frame system on different soil types.

4.2.4 Displacement Results for Different Soil Type

Figure 4.6 and Figure 4.7 illustrate the displacement findings for the building frame and shear wall frame systems, respectively. The displacements for the building frame system for 5 floors were 45, 38.3, and 33.9 mm for soft, medium, and hard soil, respectively.

Meanwhile, displacements for a 10-floor building structure were 75, 67.5, and 52.5 mm for soft, medium, and hard soil, respectively. Displacements for the shear frame system were 3, 2.8, and 2.3 mm for soft, medium, and hard soil, respectively, for 5 floors.

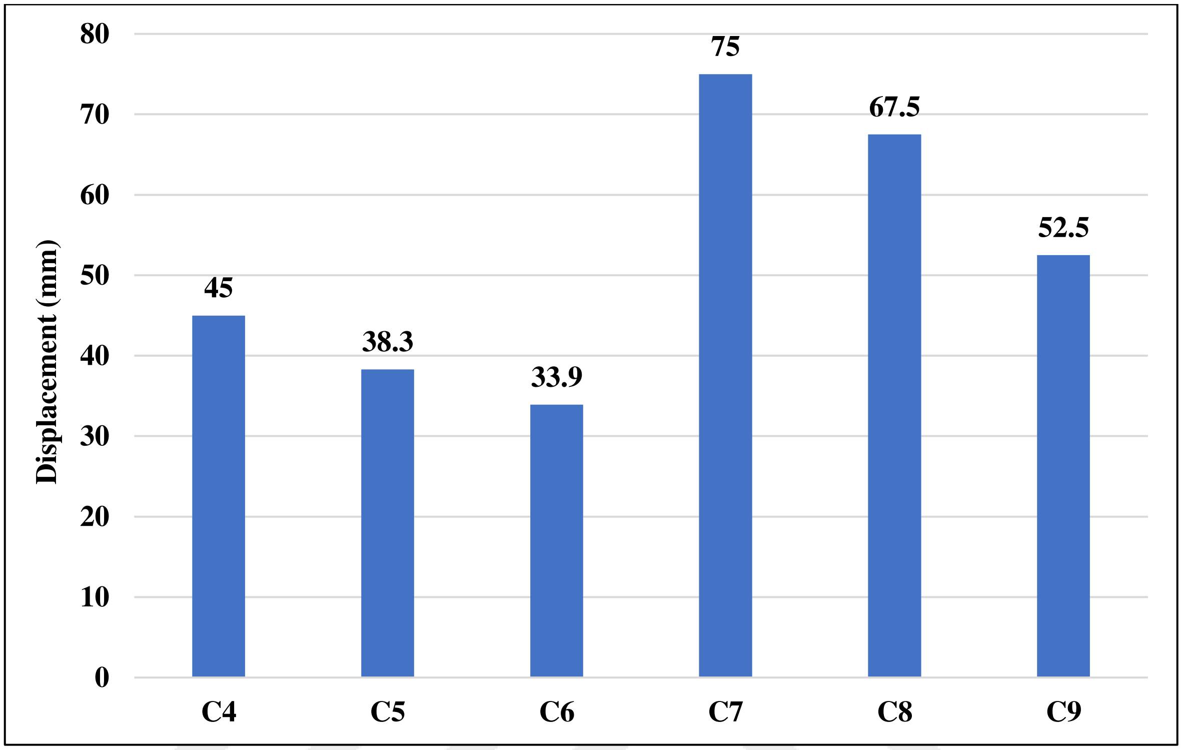


Figure 4.6: Displacement results for building frame on different type of soil.

The displacements for the 10 floors shear frame systems are 30, 24, and 21 mm for soft, medium, and hard soil, respectively.

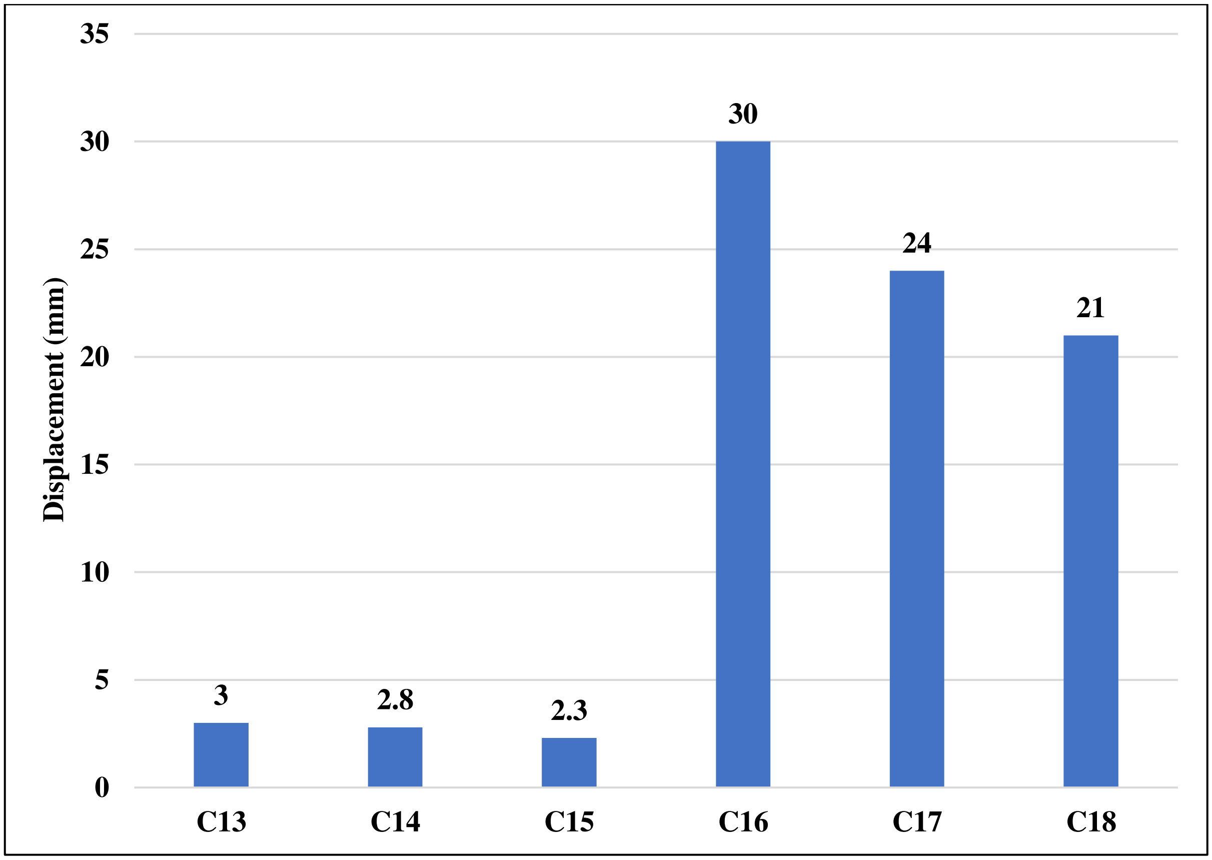


Figure 4.7: Displacement results for shear wall system on different type of soil.

The displacement is decreased by 6% in a 5 floor building frame system on medium soil and by 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil. On the other hand, displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil, correspondingly. Furthermore, the findings of a shear wall system with ten floors demonstrate that displacement reduces by 20% and 30% on medium and hard soil, respectively.

4.3 EFFECT OF BUILDING HEIGHT

The various cases of building height on soft, medium, and hard soil regarding the two lateral load resisting system were studied in order to evaluate the effects of building height.

4.3.1 Base Shear Results in Building Frame

Figure 4.8 displays the base shear results on soft soil for one, five, and ten floors. For one, five, and ten floors on soft soil in building frame, the base shear was 300, 1500, and 2100 kN. There is a 400% increase in base shear in 5 floors on soft soil compared to one floor and a 40% increase in base shear in 10 floors on soft soil compared to 5 floor building frames.

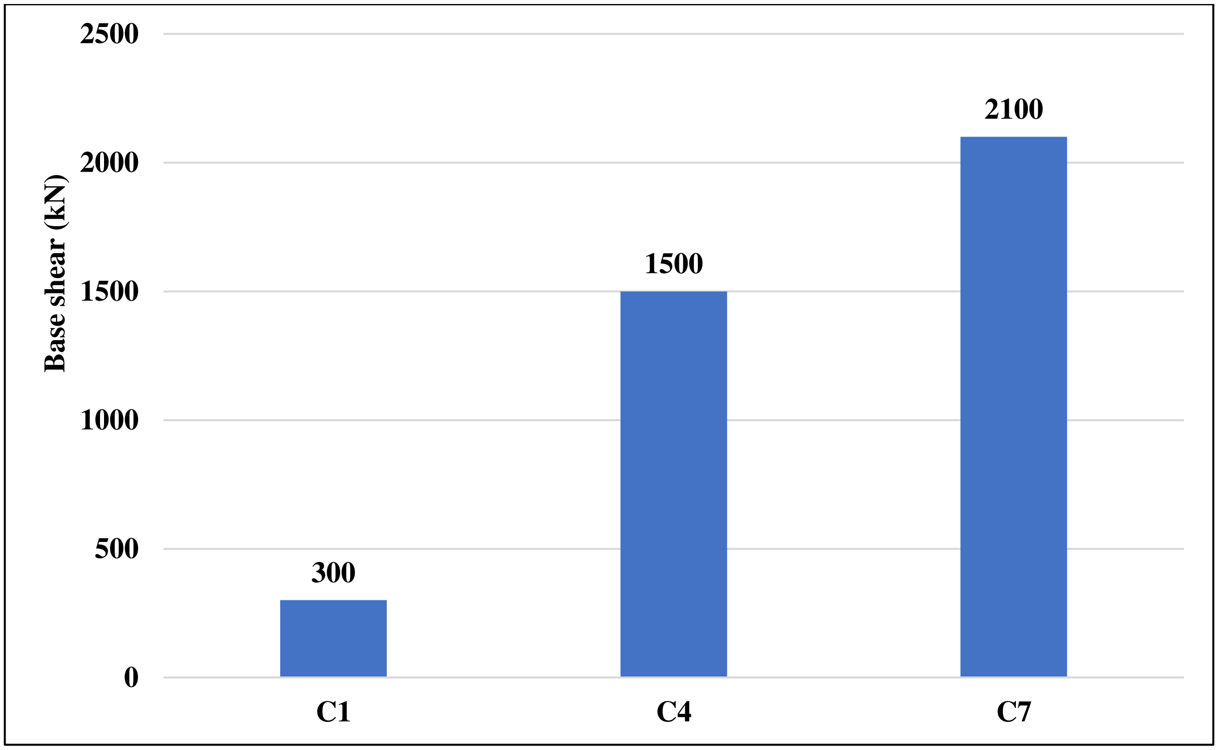


Figure 4.8: Base shear results of Building frame on soft soil at different height.

Figure 4.9 depicts the base shear findings for the medium soil for building frame system. The base shear for 5 floors on medium soil is 380 percent greater than for a one-floor structure frame, and it is 18 percent greater for 10 floors than for 5 floors.

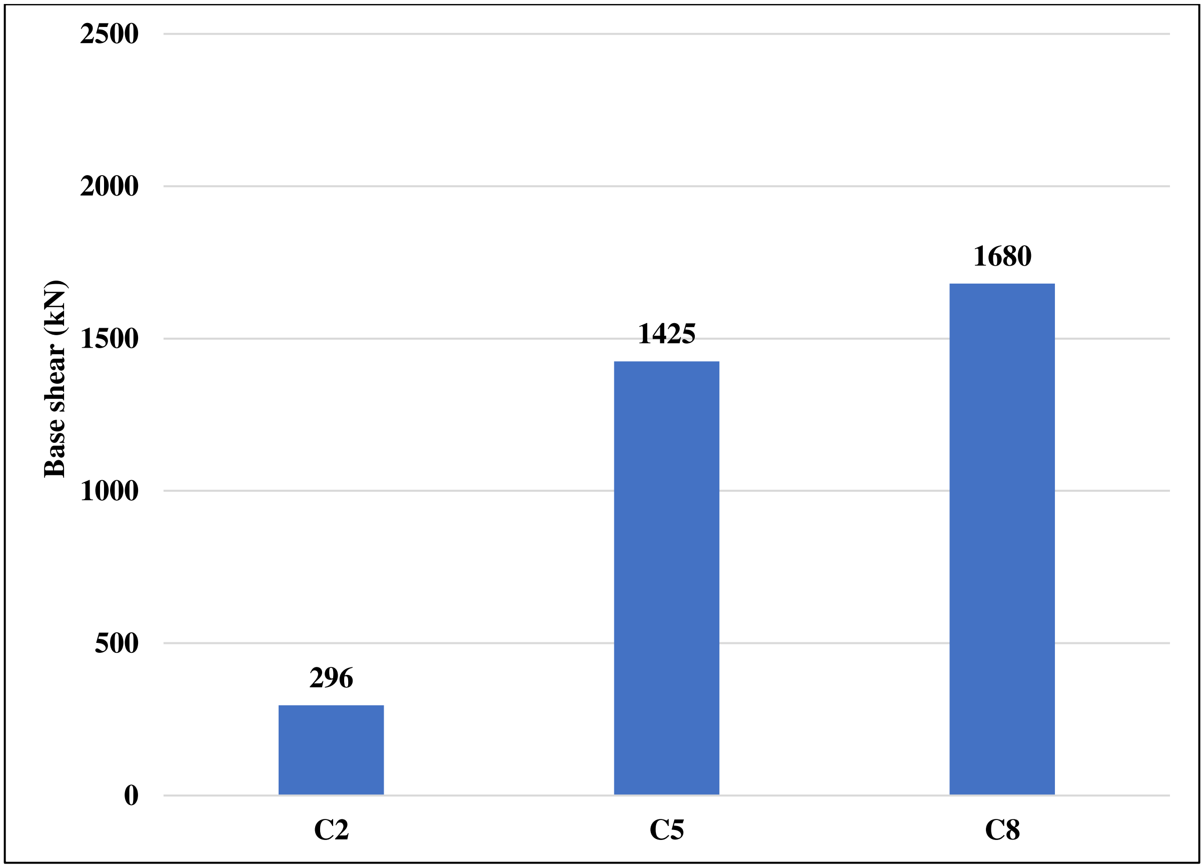


Figure 4.9: Base shear results of Building frame on medium soil at different height.

The base shear on hard soil for building frame, as shown in Figure 4.10, represents a 275 percent increase between one and five floors and a 38 percent increase between five and ten floors.

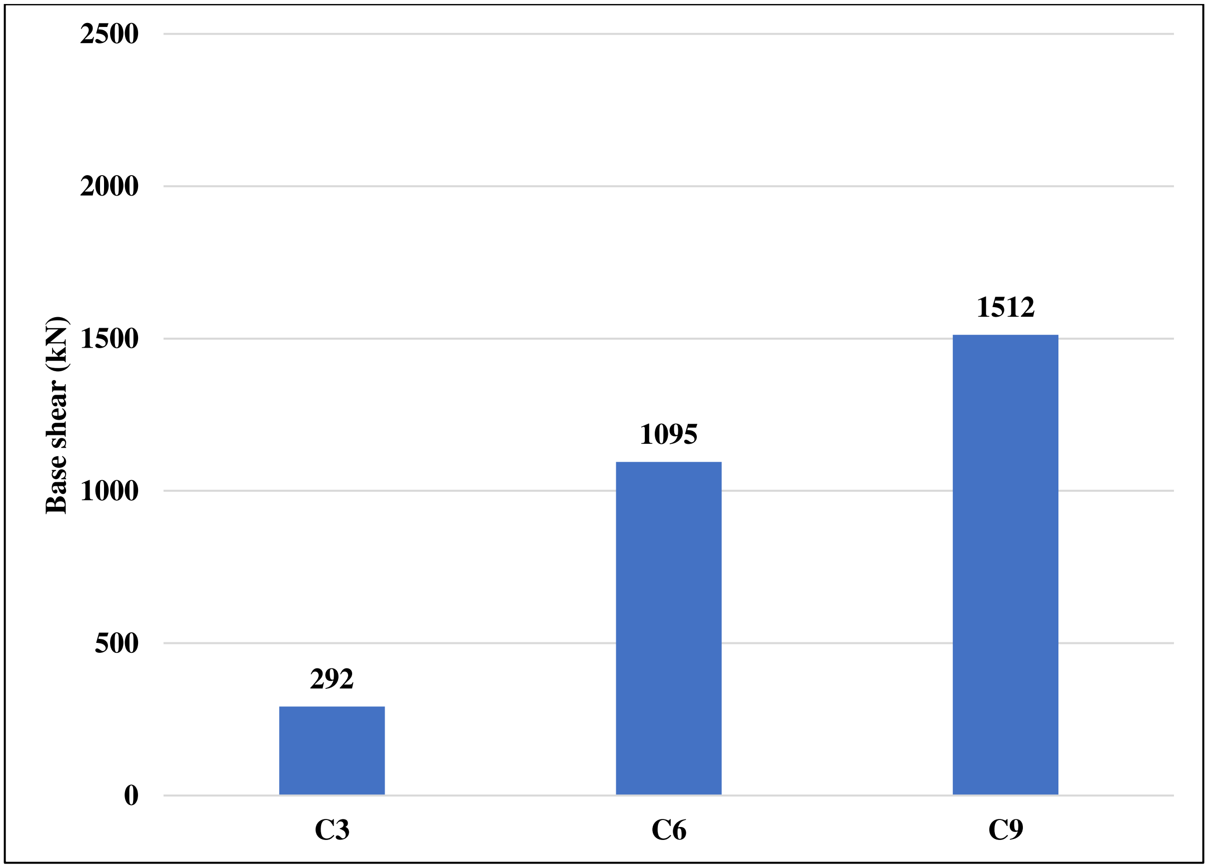


Figure 4.10: Base shear results of Building frame on hard soil at different height.

4.3.2 Axial Force in Building Frame

Figure 4.11 displays the axial force findings for the building frame system on soft soil for one, five, and ten floors. It demonstrates axial forces of 520, 4160, and 12480 kN at three different floor heights with a building frame. The axial force on soft soil in a building frame rises by 700% from one to five floors and by 200% from five to ten floors.

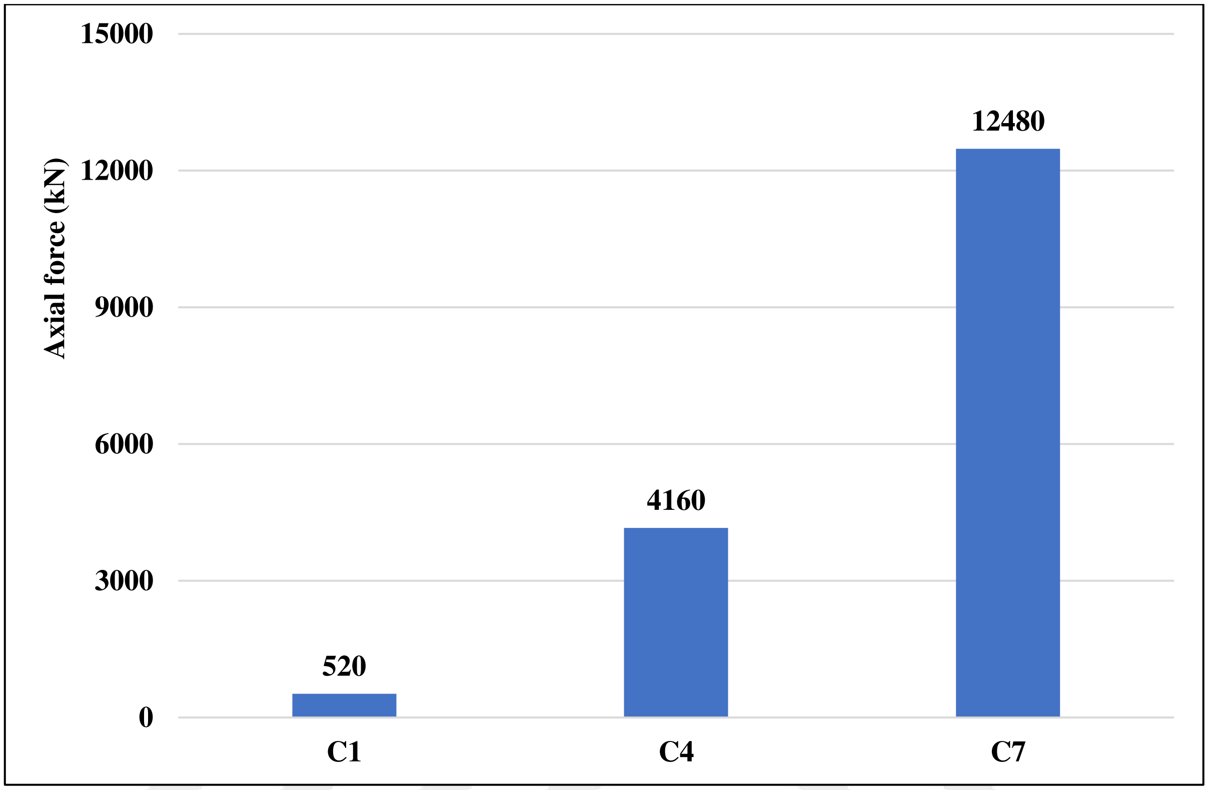


Figure 4.11: Axial force results of Building frame on soft soil at different height.

Furthermore, Figure 4.12 shows the axial force for a building frame system on medium soil of 516, 4077, and 11356 for one, five, and ten floor heights, respectively. It gives a 690 percent increase for 5 floor height vs one floor and a 179 percent increase for a 10-floor building frame resistance system versus 5 floors.

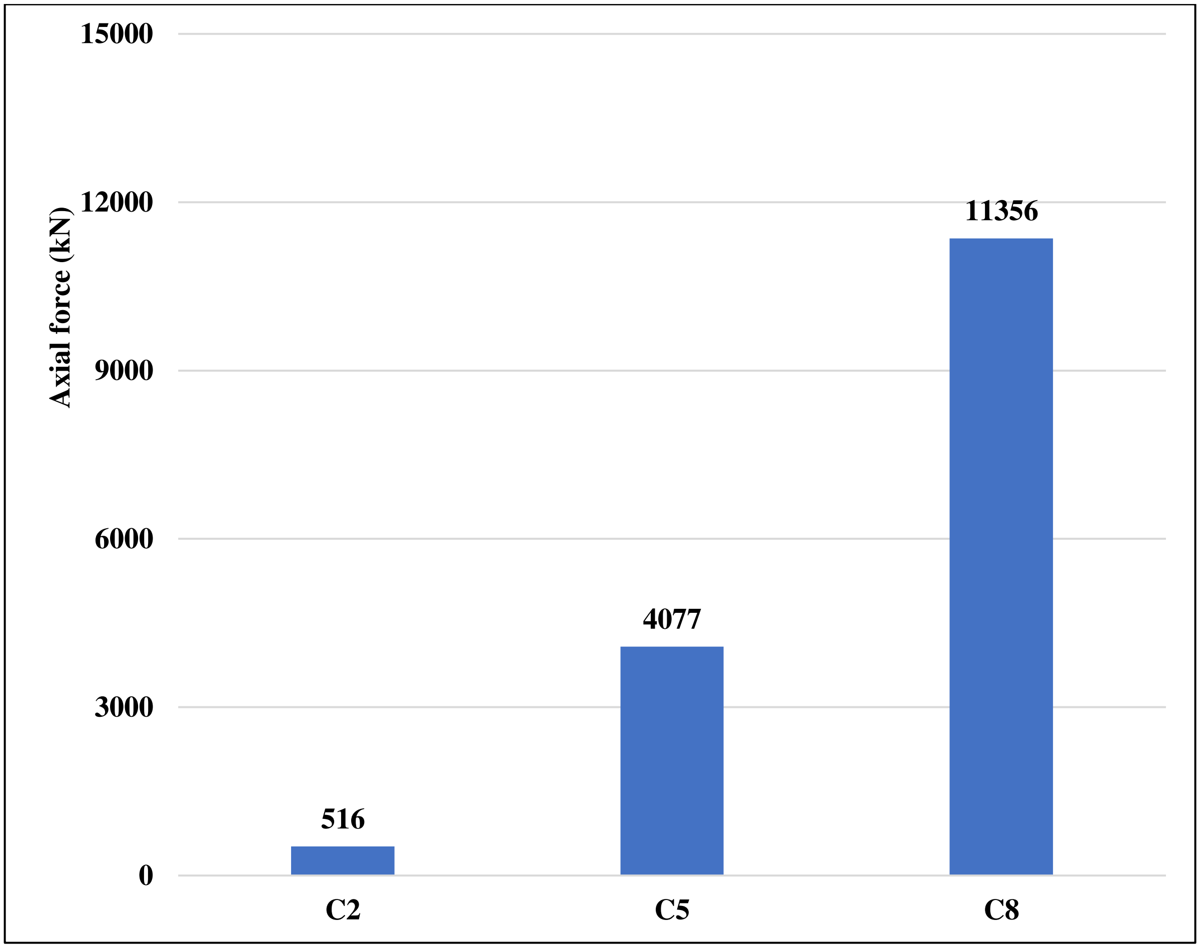


Figure 4.12: Axial force results of Building frame on medium soil at different height.

However, in Figure 4.13, the axial force shows the results of a building frame system on hard soil at three different floor heights. It indicated an improvement in axial force of 634 percent between one and five floors and 190 percent between five and ten floors building frame.

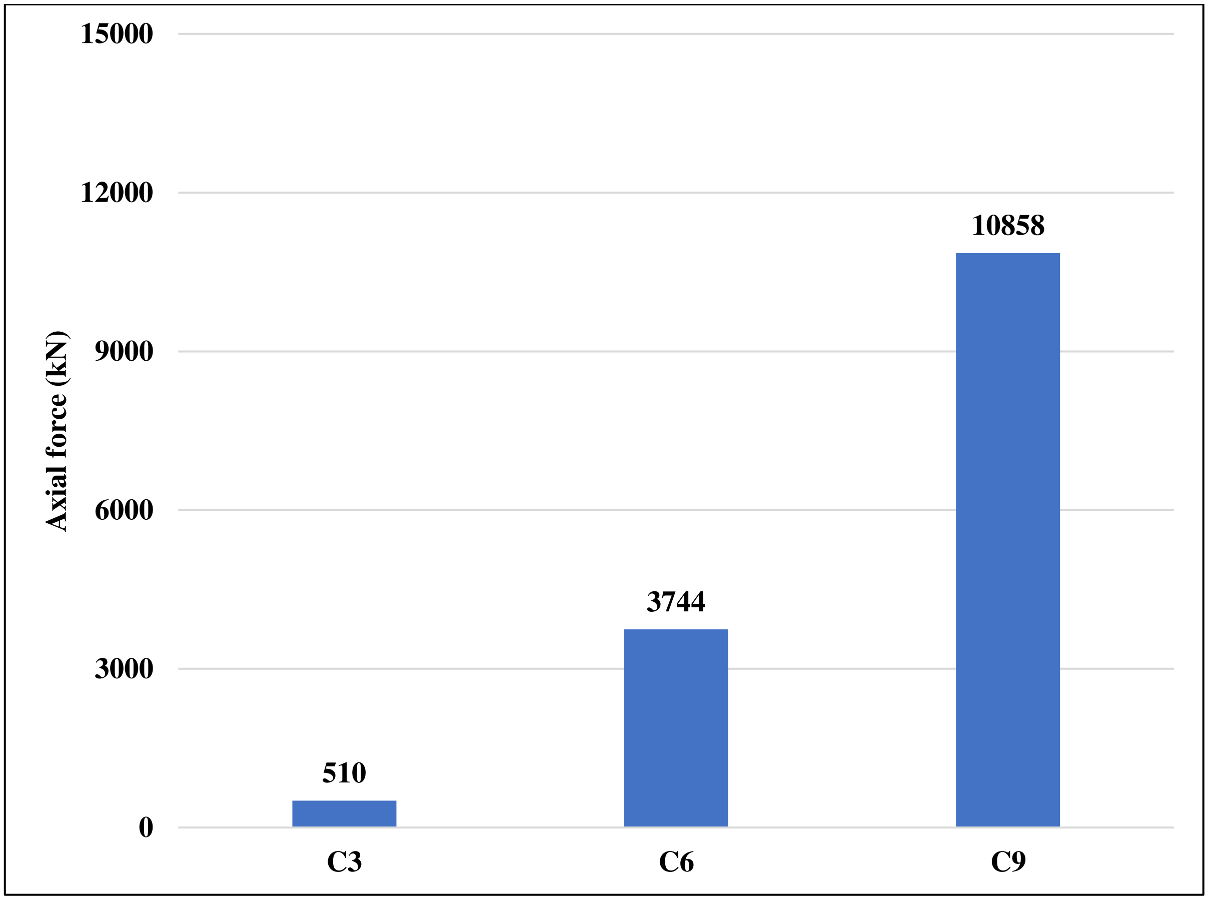


Figure 4.13: Axial force results of Building frame on hard soil at different height.

4.3.3 Moment Results for Building Frame System

Figure 4.14, Figure 4.15, and Figure 4.16 show the moment values on columns for soft, medium, and hard soil. The outcomes for each soil type were compared based on the various floor heights. For one, five, and ten floor heights, the moment for a building frame system on soft soil was 160, 1600, and 2240 kN.m. This represents a 900 percent increase in moment on soft soil for 5 floors and a 40% increase for 10 floors compared to 5 floors.

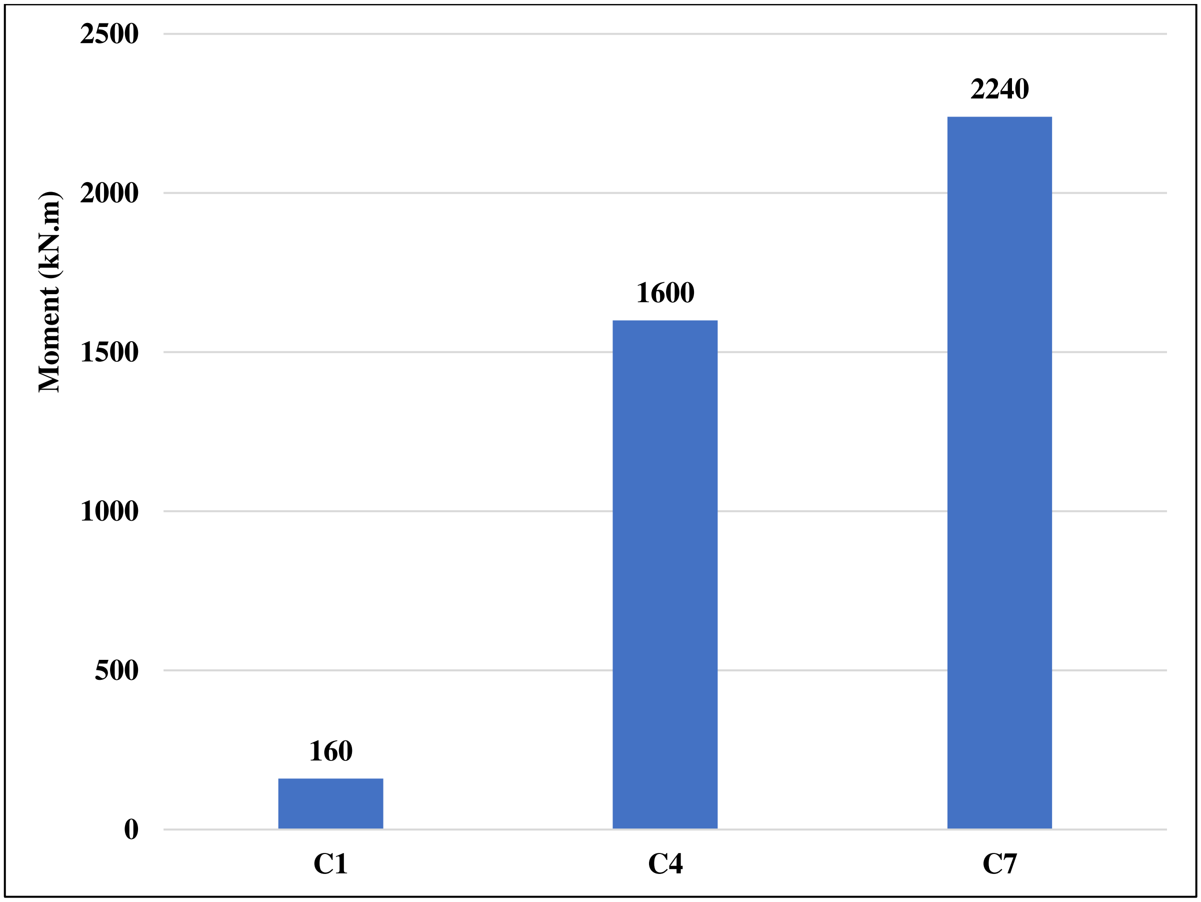


Figure 4.14: Moment results of Building frame on soft soil at different height.

The moment values on columns for the building frame system on medium soil, on the other hand, were 155, 1520, and 1792 kN.m for the three floor height, as shown in Figure 4.15.

The 5 floor building frame system on medium soil has higher moment than one floor building frame by 880% and the moment of building frame at 10 floor is higher by 18% compared to a 5 floor building frame. In addition, the moment in a 5 floor building on hard soil was higher by 684% than that of one floor building frame. The results also show an increase trend of moment by 31% between 5 floor and 10 floor building frame system on hard soil.

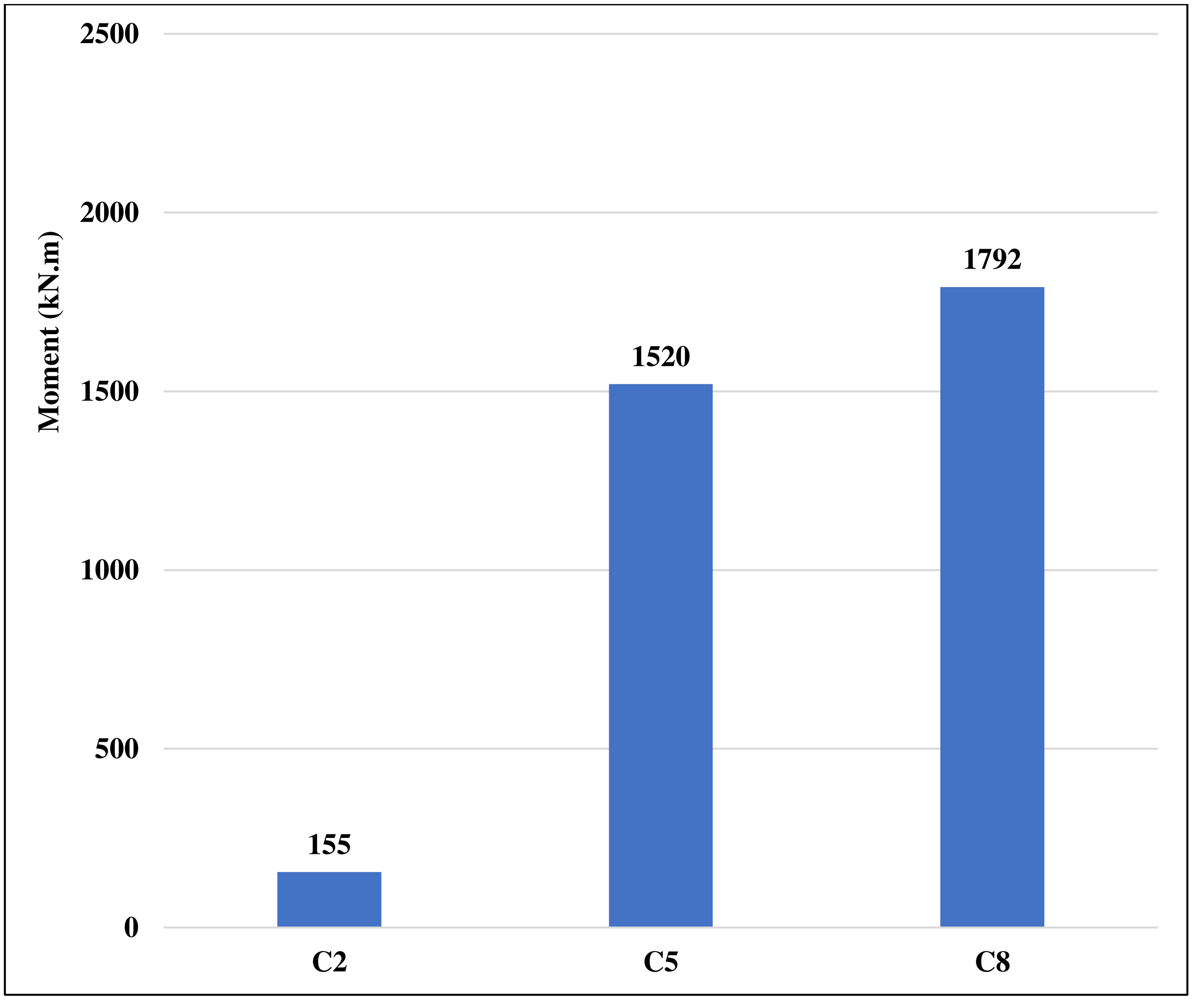


Figure 4.15: Moment results of Building frame on medium soil at different height.

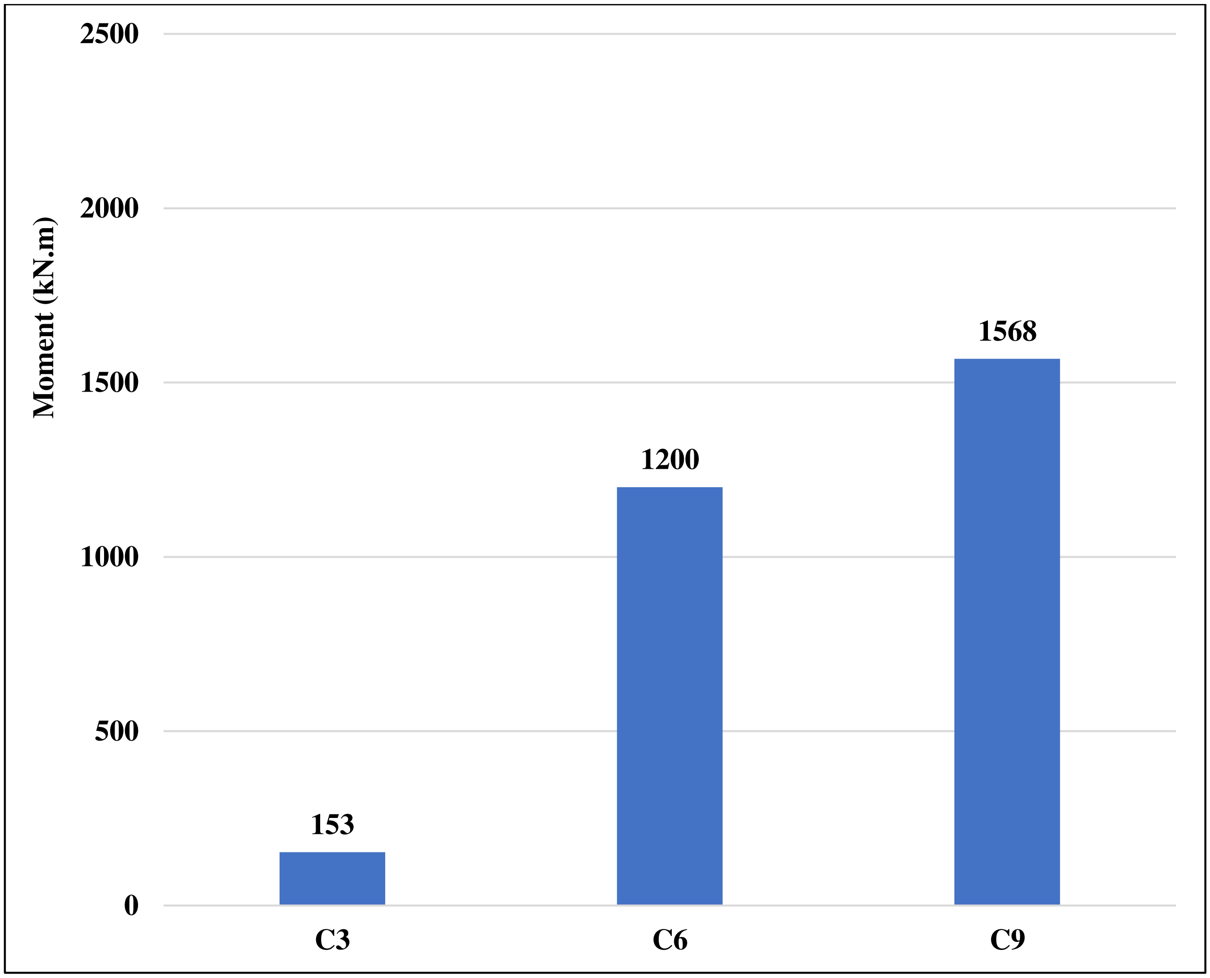


Figure 4.16: Moment results of Building frame on hard soil at different height.

4.3.4 Displacement Results for Building Frame System

Figure 4.17, Figure 4.18, and Figure 4.19 indicate the displacement results for a building frame on soft, medium, and hard soil, respectively. The displacements of the building frame system on soft soil were 3, 45, and 75 mm for one, five, and ten floors, respectively. Furthermore, displacements for building frames on medium soil were 2.8, 38.3, and 67.5 mm for one, five, and ten floors, respectively. For the different floor heights of the building frame system on hard soil, displacements were 2.7, 33.9, and 52.5 mm.

The displacement of a building frame on soft soil increases by 1400 percent for five floors compared to one, and by 67 percent for ten floors. Additionally, displacement on medium soil increases by 1220 percent between one and five floors and by 76 percent between five and ten floors. So, on hard soil, the value of displacement increases by 1115 percent on 5 floors and by 55 percent on 10 floors. The displacement increases as floor height increases.

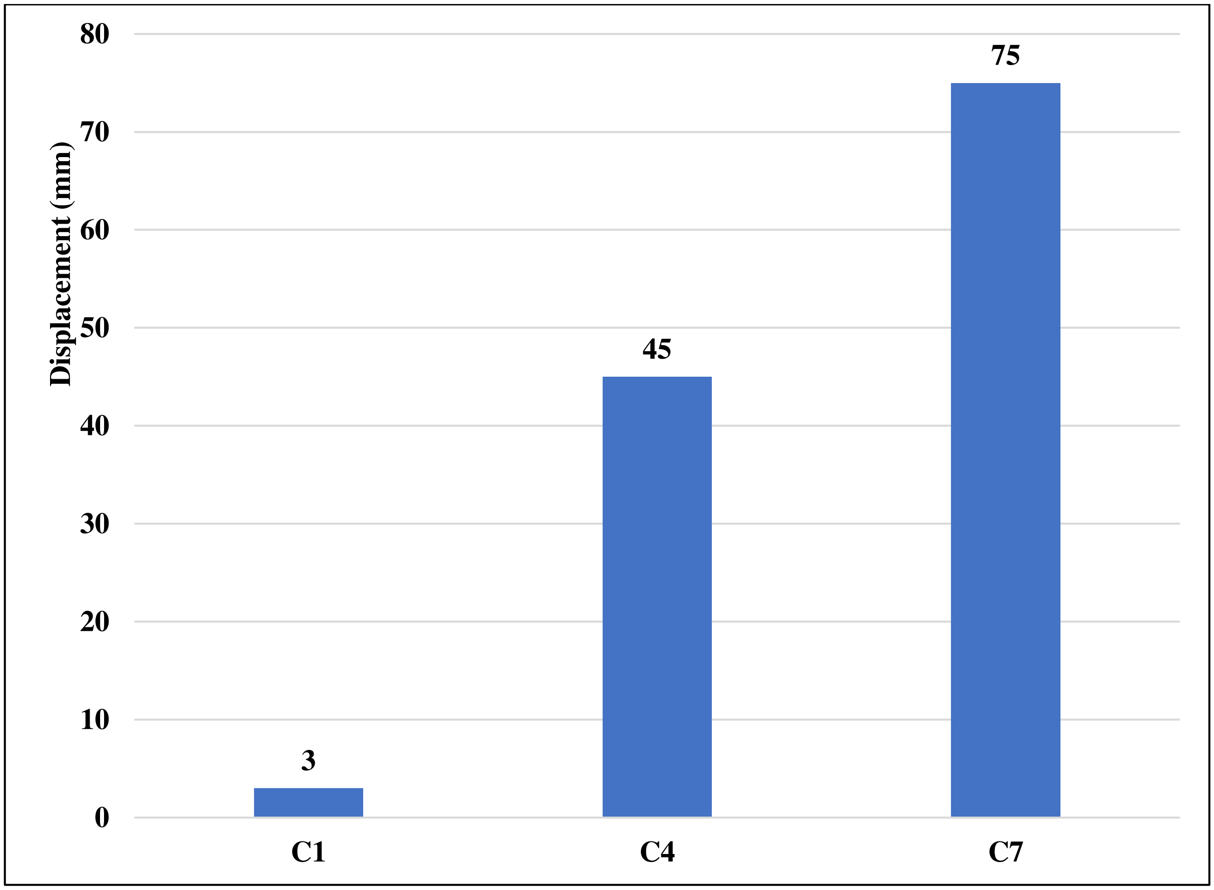


Figure 4.17: Displacement results of Building frame on soft soil at different height.

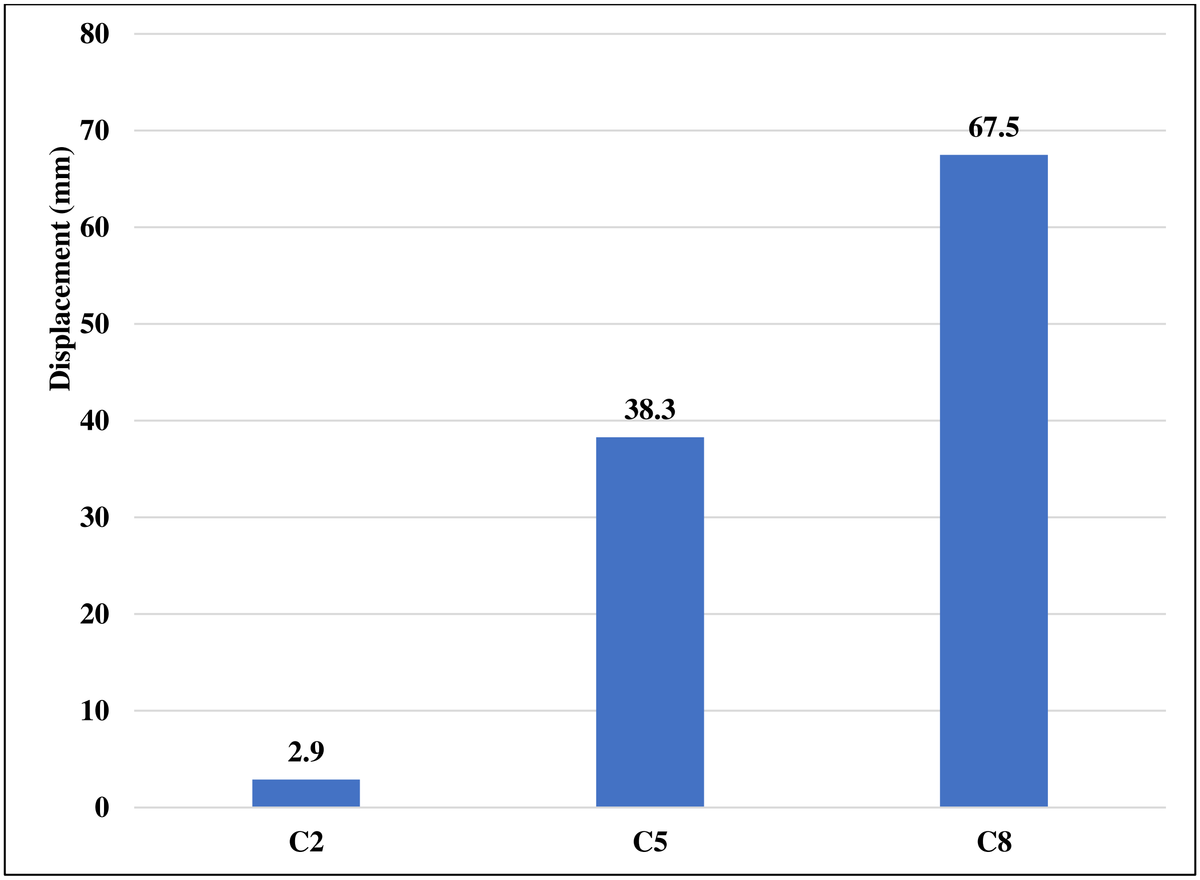


Figure 4.18: Displacement results of Building frame on medium soil at different height.

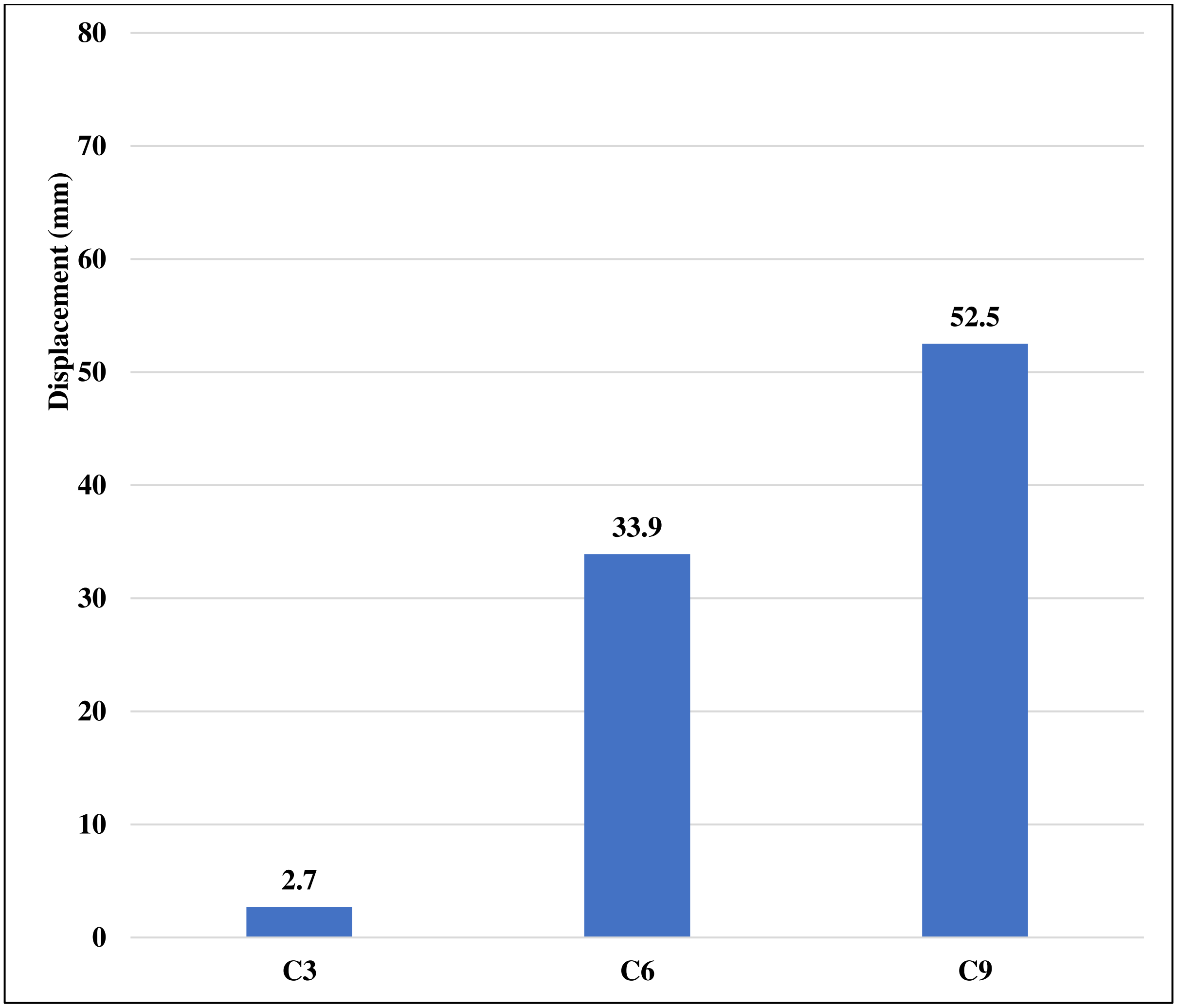


Figure 4.19: Displacement results of Building frame on hard soil at different height.

4.4 BASE SHEAR RESULTS FOR SHEAR WALL SYSTEM

Figure 4.20 represents the results of base shear on soft soil for shear wall systems of one, five, and ten floors. For one, five, and ten floors on soft soil, the base shear was 360, 2088, and 2953 kN, respectively. There is a 480 percent increase in base shear in 5 floors on soft soil compared to one floor, and a 41 percent increase in base shear in 10 floors on soft soil compared to 5 floors.

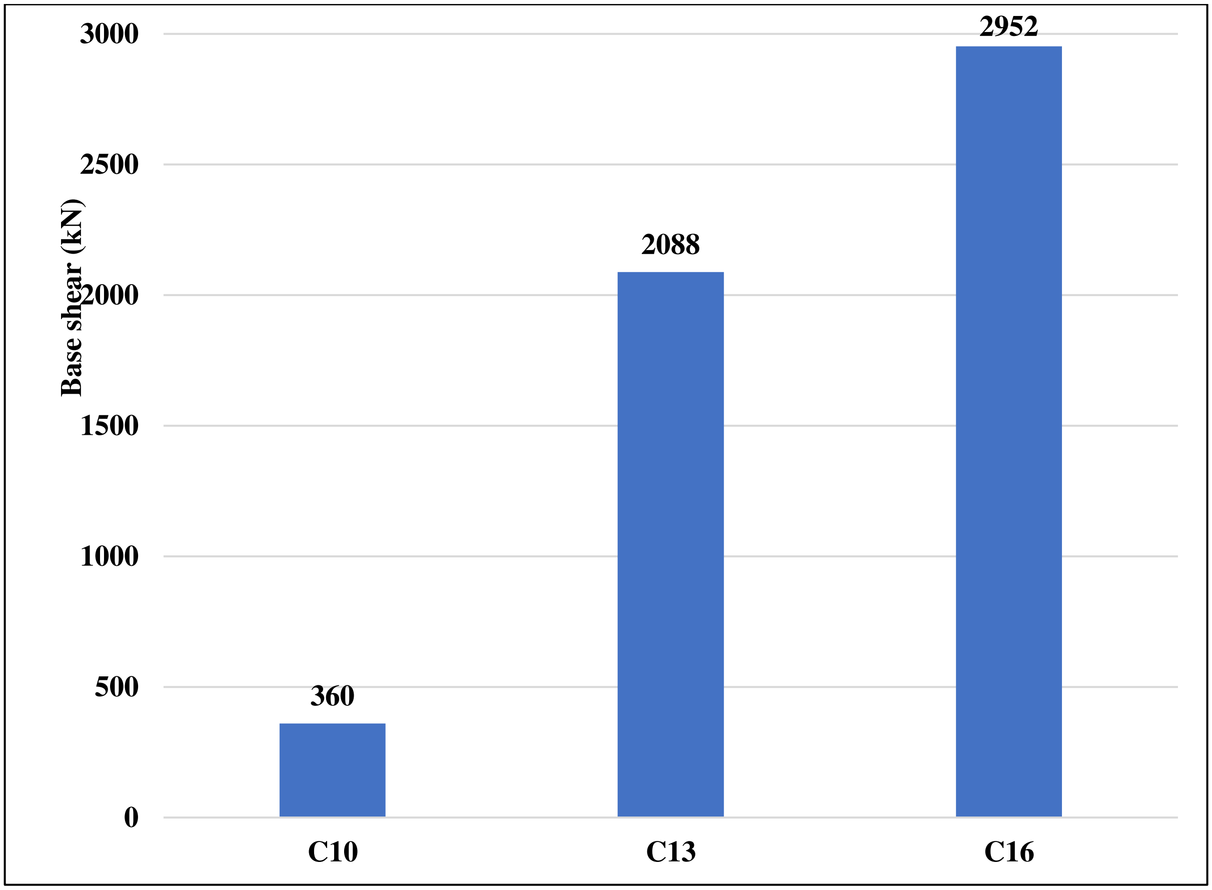


Figure 4.20: Base shear results of shear wall frame on soft soil at different height.

Figure 4.21 depicts the base shear findings for the medium soil for shear wall system. The base shear for 5 floors on medium soil is 495 percent more than for one floor, and it is 19 percent greater for 10 floors than for 5 floors.

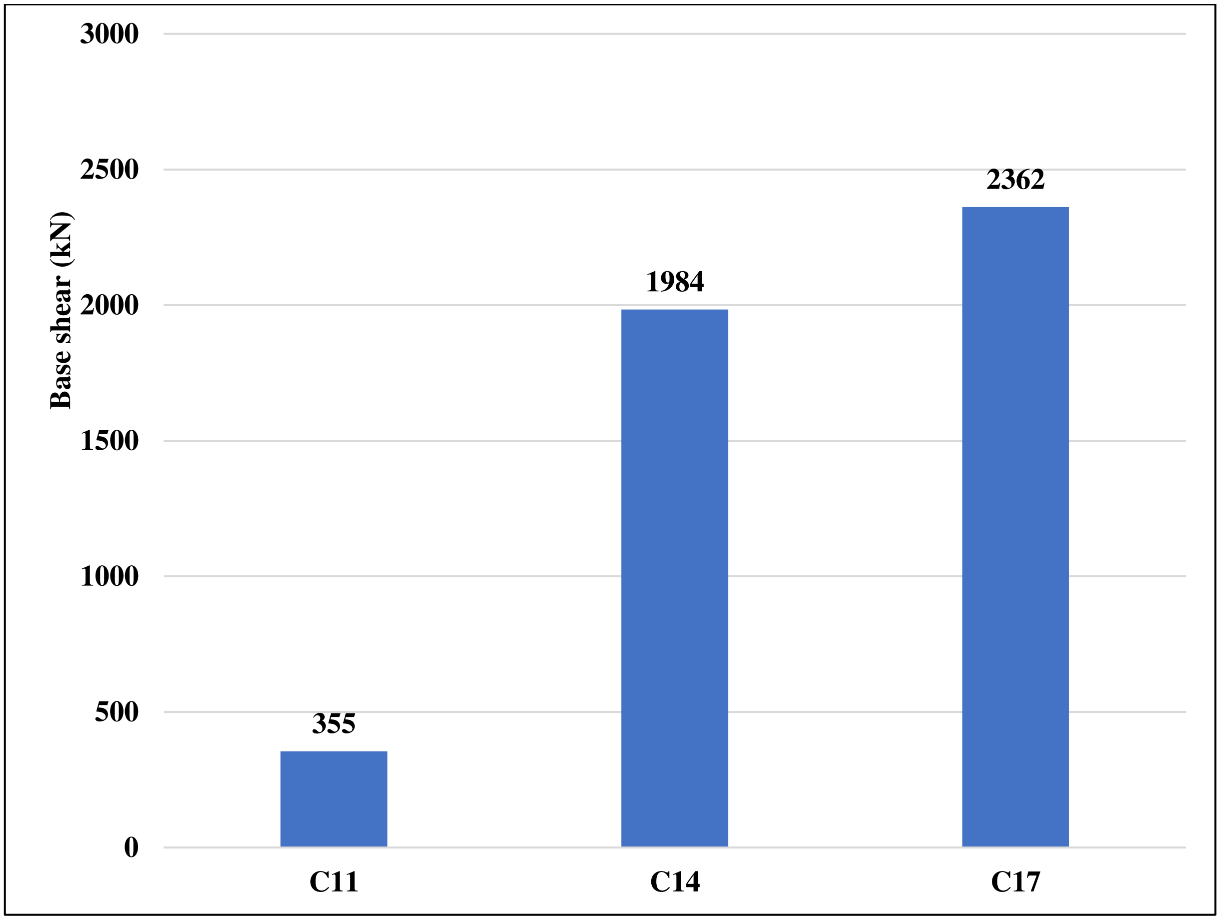


Figure 4.21: Base shear results of shear wall frame on medium soil at different height.

The base shear on hard soil, as shown in Figure 4.22, represents a 330 percent increase between one and five floors and a 37 percent rise between five and ten floors.

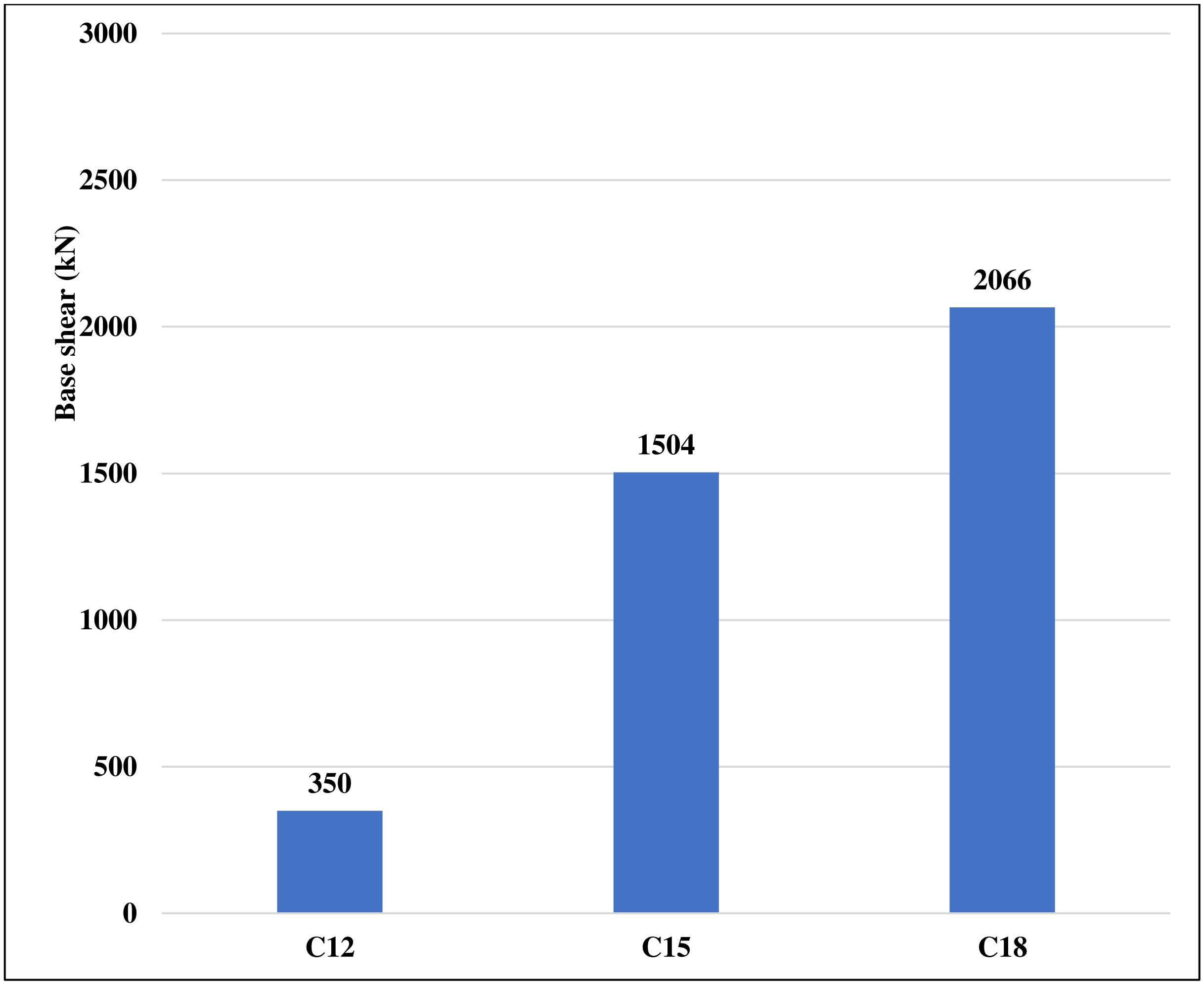


Figure 4.22: Base shear results of shear wall frame on hard soil at different height.

4.4.1 Axial Force Results for Shear Wall System at Different Heights

Figure 4.23 depicts the axial force findings for the shear wall system for one, 5 and 10 floors on soft soil. It shows an axial force of 130, 1430, and 2210 kN for the three different floor heights using shear walls. The axial force on soft soil in building frame increases by 1000% from one to 5 floors and by 55% from 5 to 10 floors.

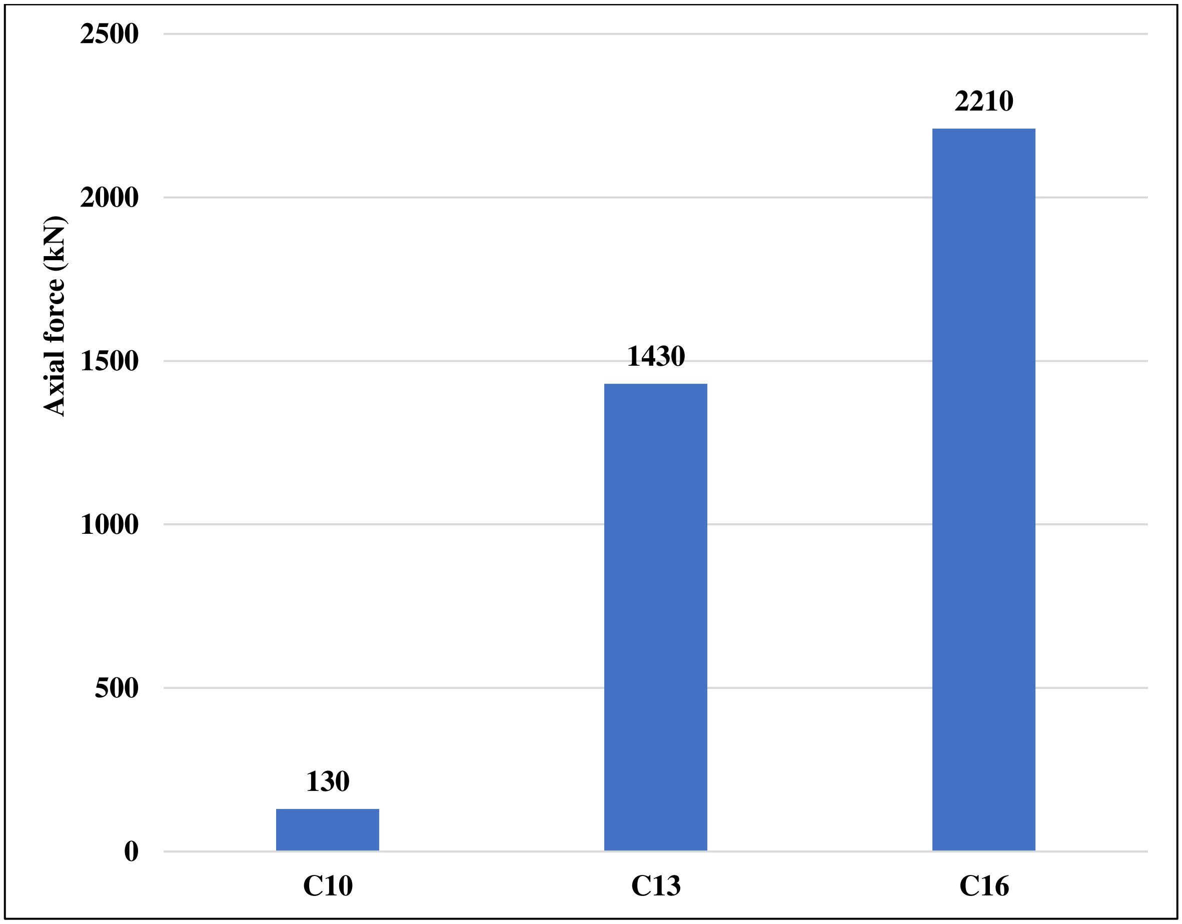


Figure 4.23: Axial force results of shear wall frame on soft soil at different heights.

For a shear wall system on medium soil, axial force of 126, 1387, and 1922 for one, five and ten floor height, respectively, as shown in Figure 4.24. It provides a 1000% increase for 5 floor height compared to one floor and 39% increase in a 10-floor shear wall resistance system compared to 5 floors.

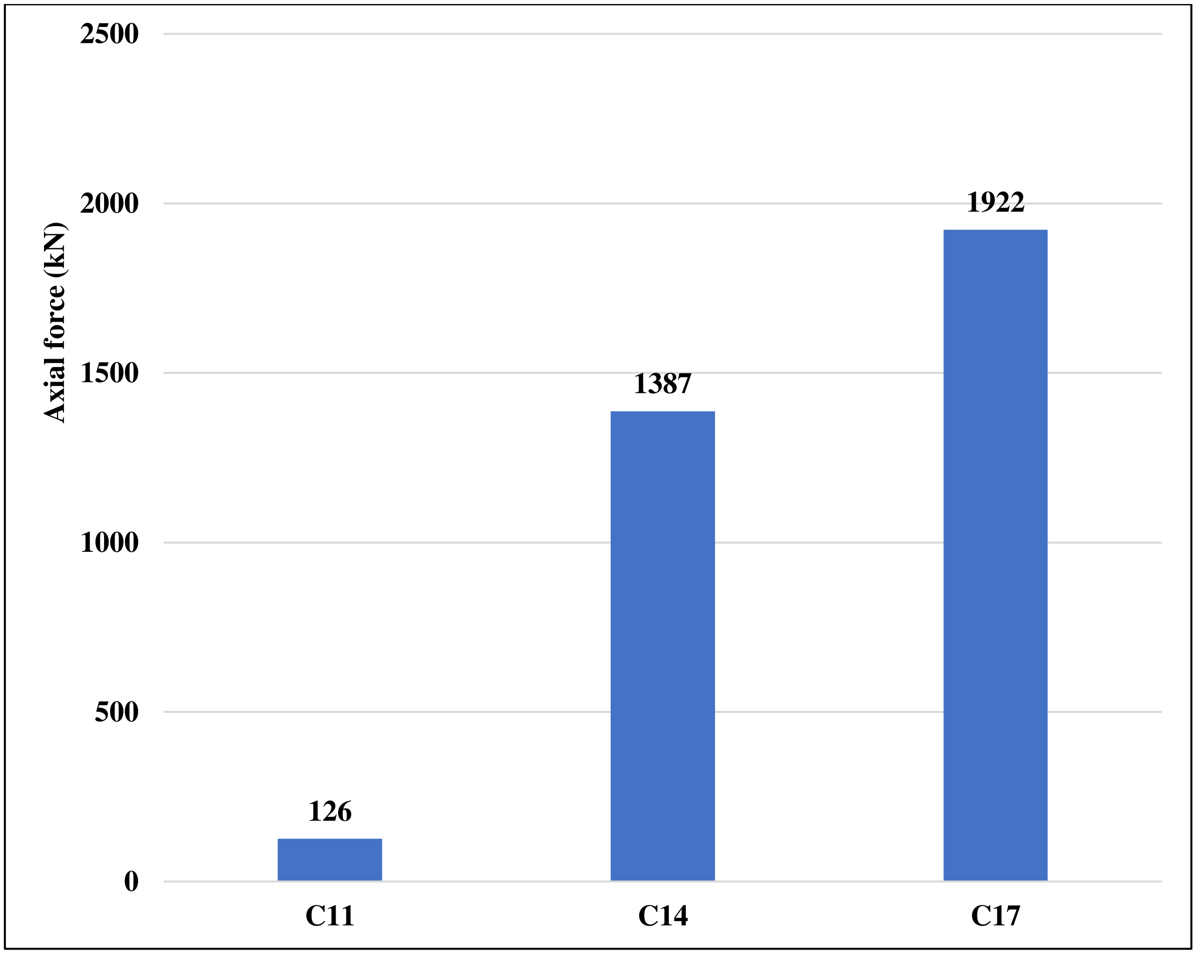


Figure 4.24: Axial force results of shear wall frame on medium soil at different heights.

Meanwhile the axial force in Figure 4.25 represents the results of shear wall system on hard soil at the three different floor heights. It displays an increase trend in axial force by 887% between one floor and five floors and by 49% between five floors and 10 floors building frame.

The moment results in columns for shear wall system are negligible.

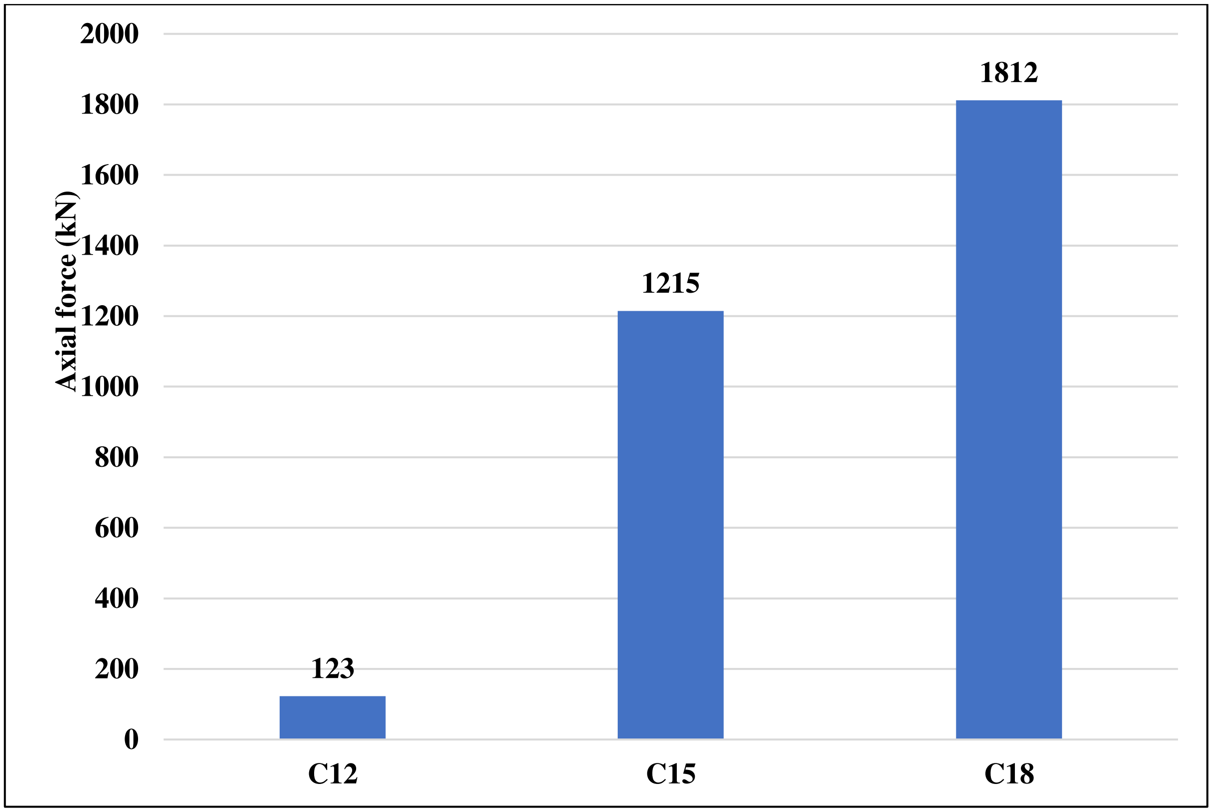


Figure 4.25: Axial force results of shear wall frame on hard soil at different heights.

4.4.2 Displacement Results for Shear Wall System at Different Heights

Figure 4.26, Figure 4.27, and Figure 4.28 indicate the displacement values for a shear wall system on soft, medium, and hard soil, respectively.

In all scenarios, the displacement outputs for one floor are zero. Displacements on soft soil for five and ten floor shear wall systems were 3 and 30 mm, respectively. Meanwhile, displacements for shear wall systems on medium soil were 2.8 and 24 mm for five and ten floors, respectively. Displacements for a shear wall system on hard soil were 2.3 and 21 mm for varied floor heights.

The displacement shear wall system on soft soil achieves 900 percent higher values for ten floors compared to five floors. Furthermore, displacement on medium soil increases by 757 percent between five and 10 floors. As a result, the value of displacement on hard soil increased by 813 percent on 10 floors. The displacement rises as floor number increases.

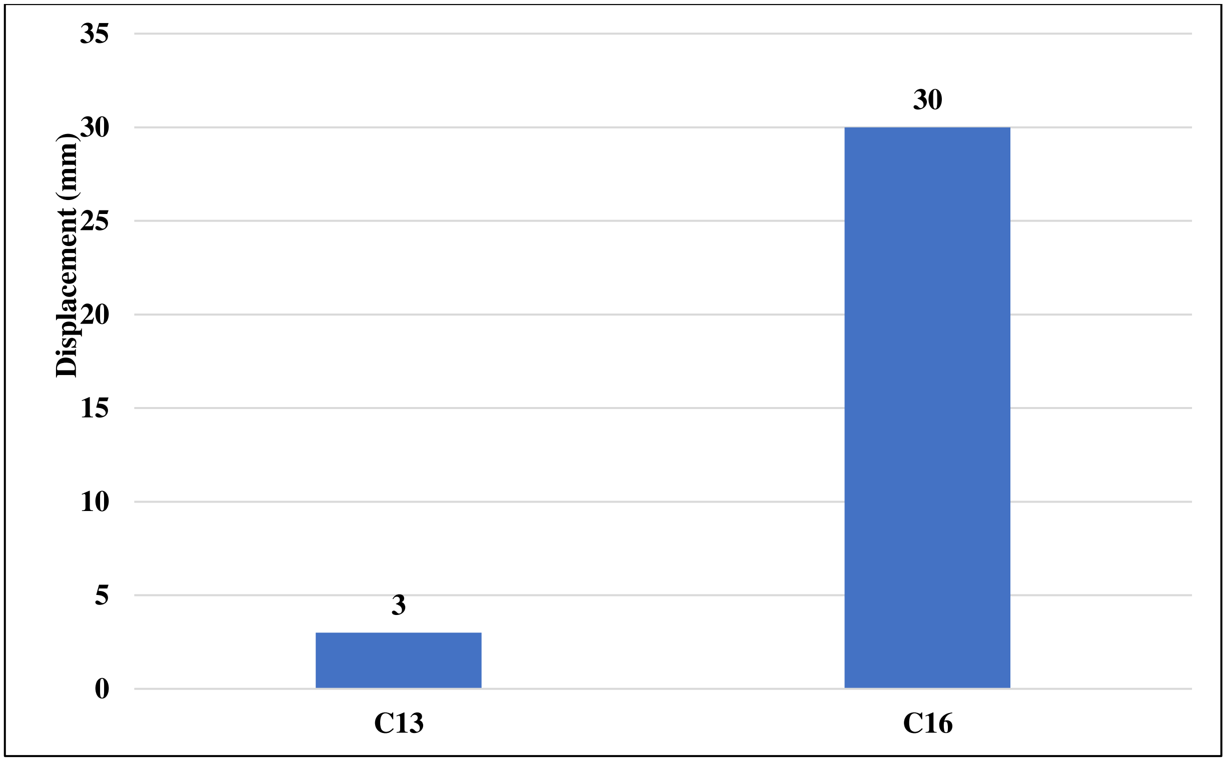


Figure 4.26: Displacement results of shear wall frame on soft soil at different heights.

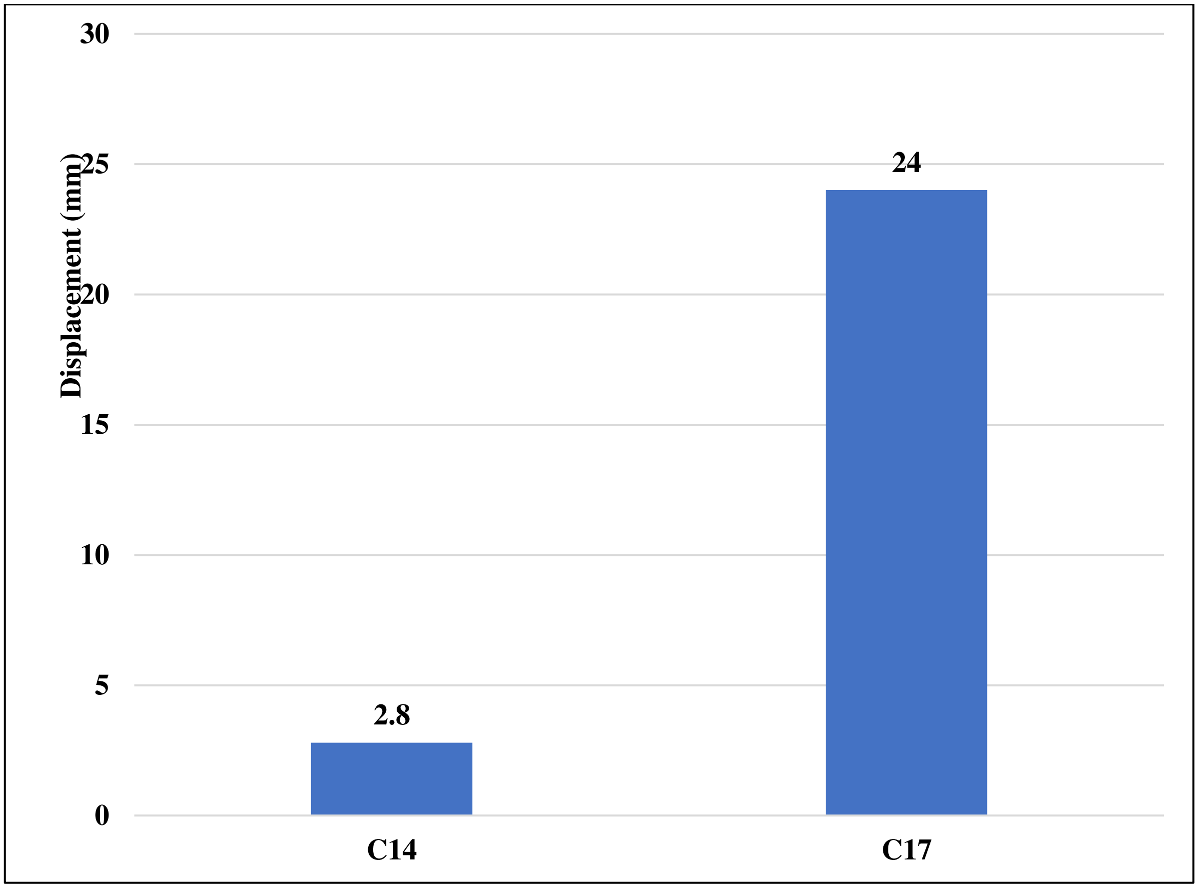


Figure 4.27: Displacement results of shear wall frame on medium soil at different heights.

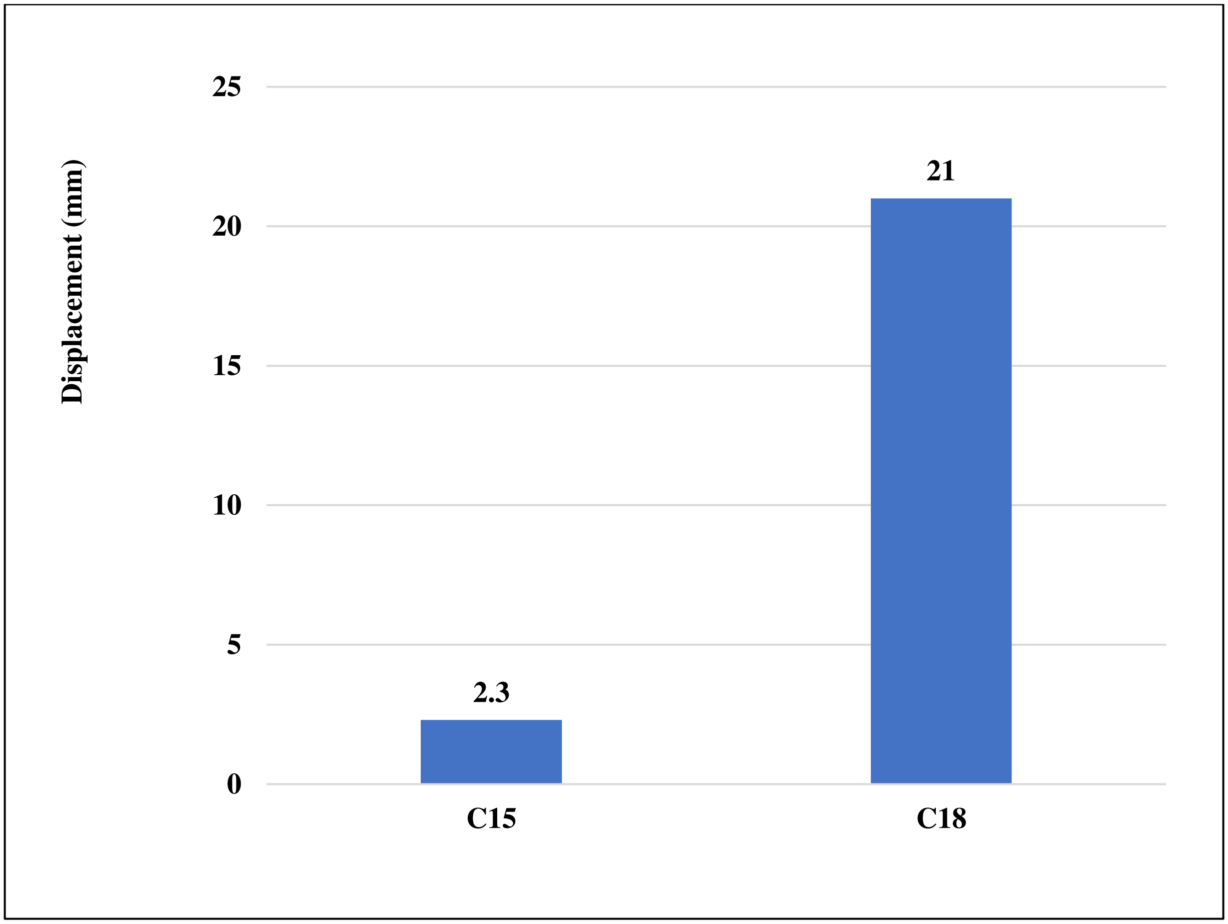


Figure 4.28: Displacement results of shear wall frame on hard soil at different heights.

4.5 EFFECT OF LATERAL LOAD RESISTING SYSTEM

4.5.1 Base Shear Results Comparison between Building Frame and Shear Wall System

Figure 4.29, Figure 4.30, and Figure 4.31 show a comparison of base shear results between a building frame and a shear wall system at various floor heights. The graph illustrates that the base shear for a shear wall system is 20% more than the base shear for a building frame at one floor. Meanwhile it is greater by 40-45% in shear wall system compared to building frame system in 5 floor building.

Furthermore, the results show a 33 to 38 percent increase in base shear in a shear wall system at 10 floors.

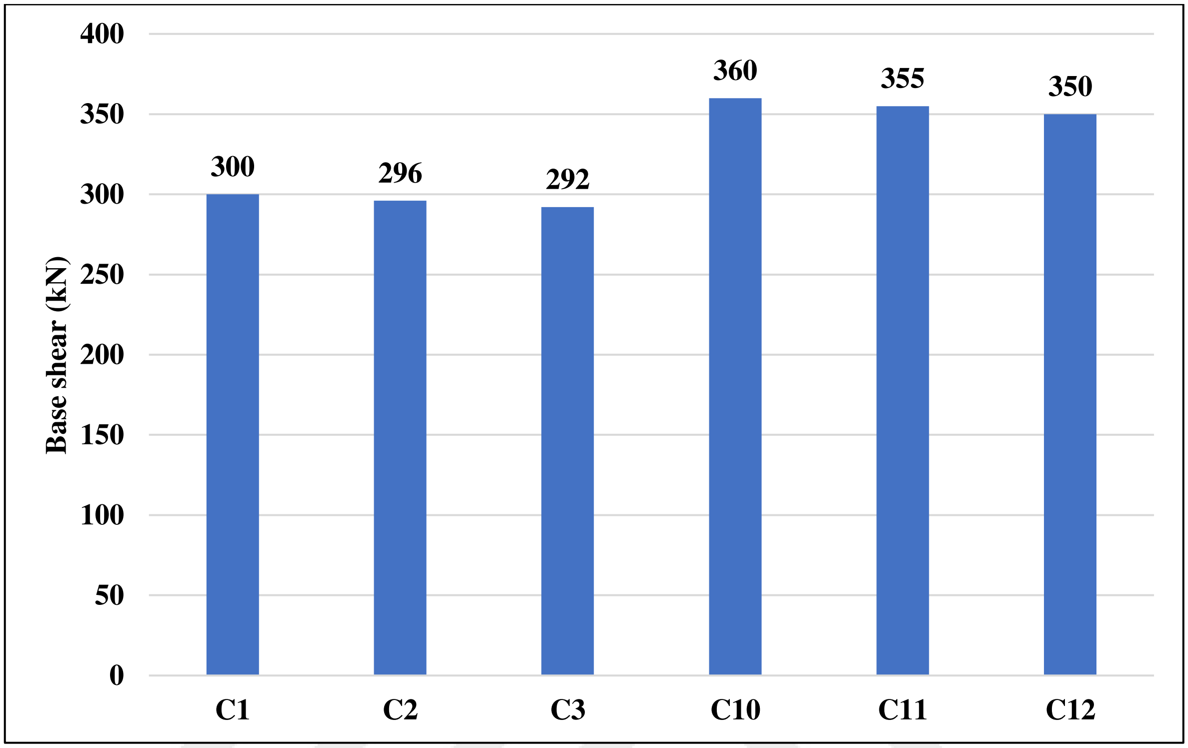


Figure 4.29: Base shear results comparison for BF and SW one floor.

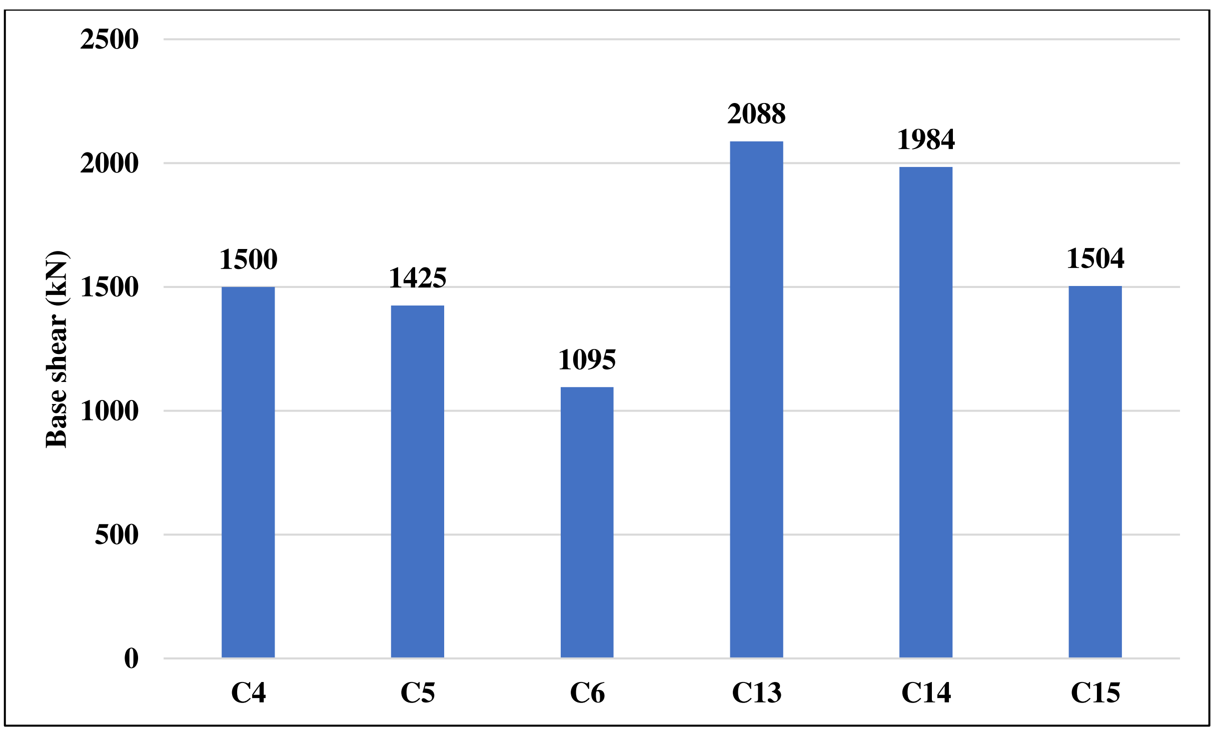


Figure 4.30: Base shear results comparison for BF and SW five floors.

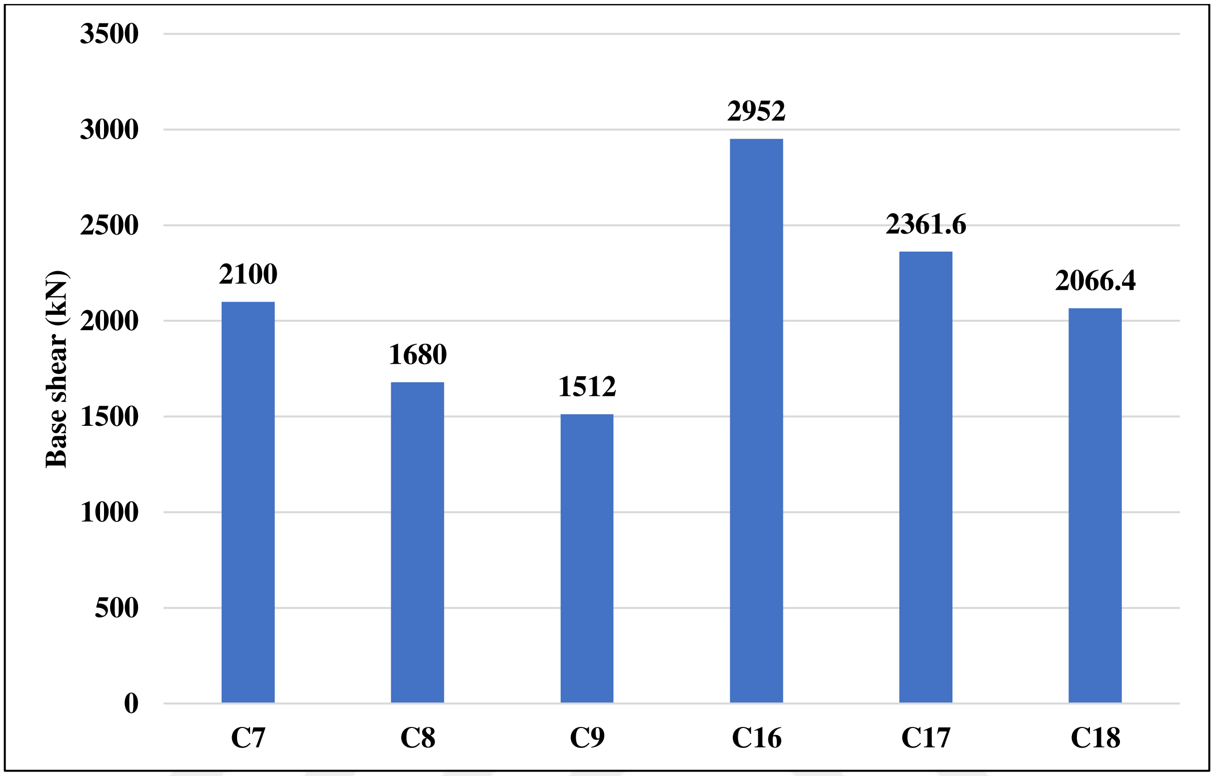


Figure 4.31: Base shear results comparison for BF and SW ten floors.

4.5.2 Axial Force Results Comparison between Building Frame and Shear Wall System

Axial force results comparison between building frame and shear wall system at different floor height are represented in Figure 4.32, Figure 4.33, and Figure 4.34.

The chart shows that axial force for building frame system is 300% greater than that of shear wall system at one floor. Meanwhile, it is greater by 190% in building frame system compared to shear wall system in 5 floor building. In addition, results present an increase in axial force by 460 to 490% in building frame system at 10 floors.

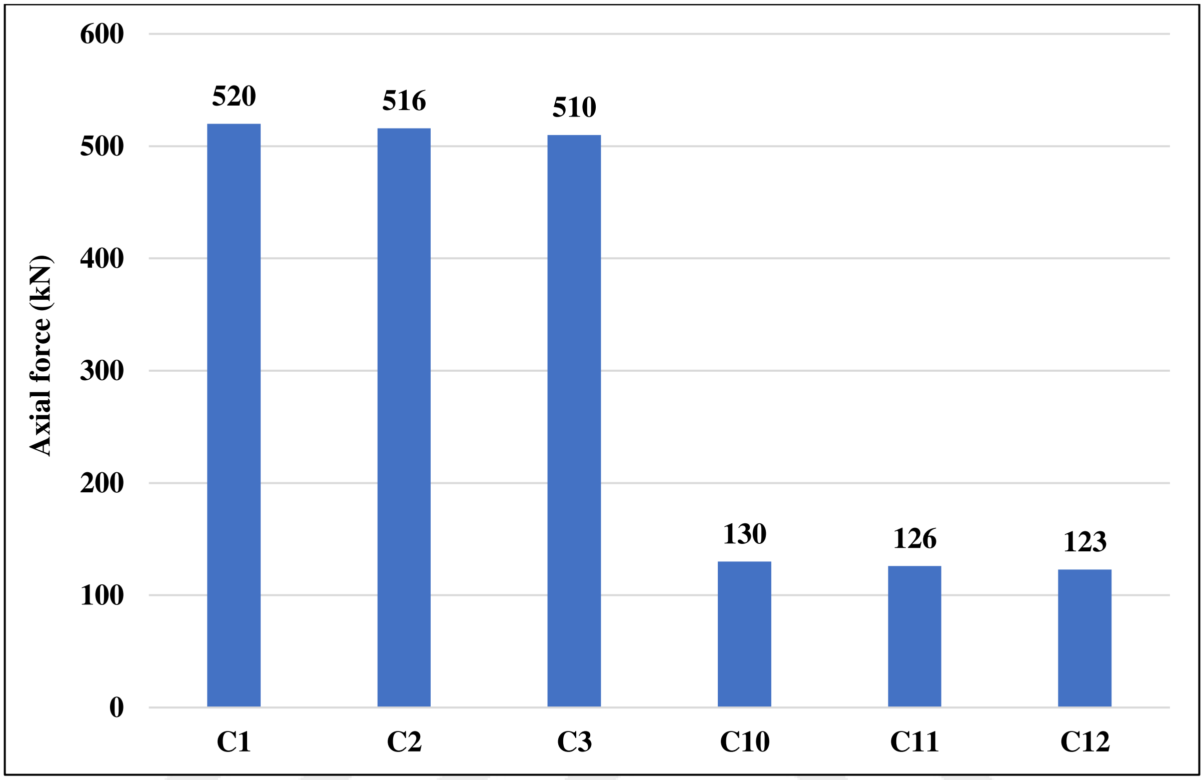


Figure 4.32: Axial force results comparison for BF and SW one floor.

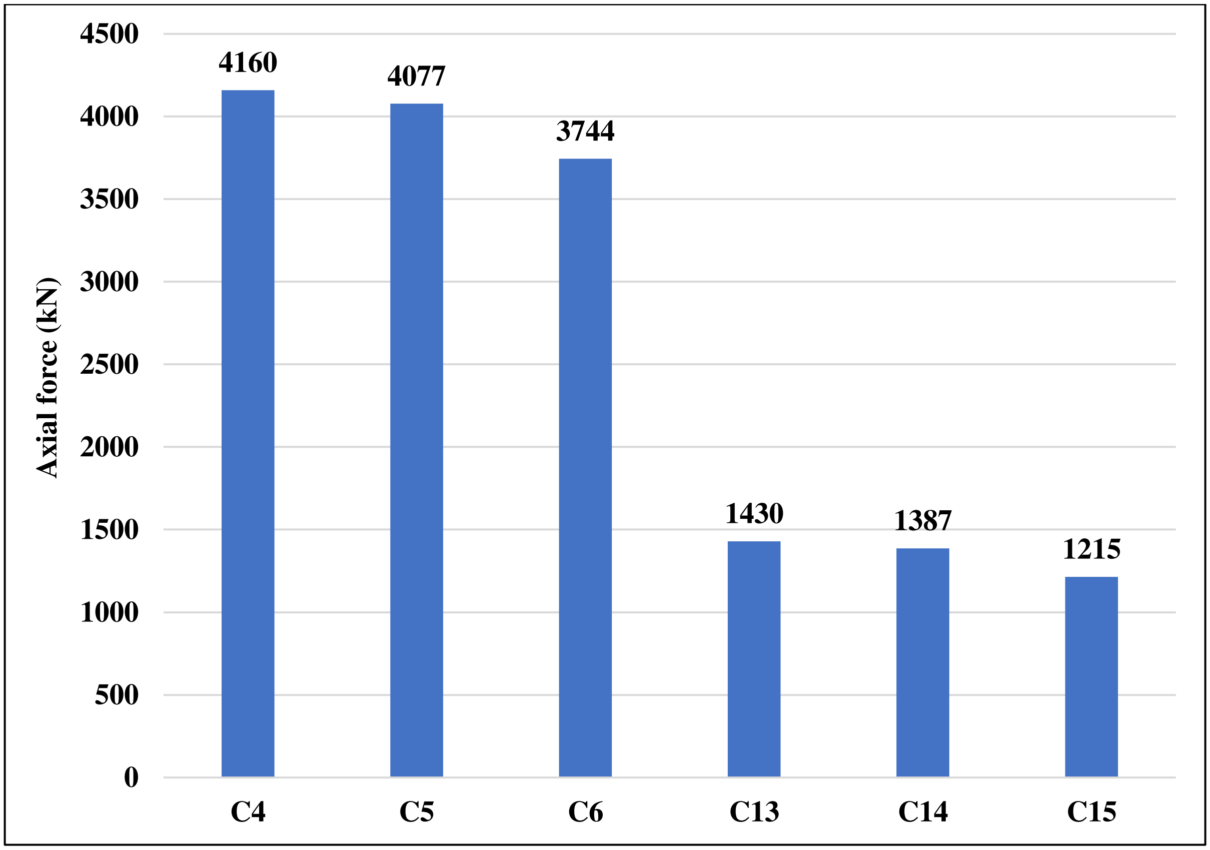


Figure 4.33: Axial force results comparison for BF and SW five floor.

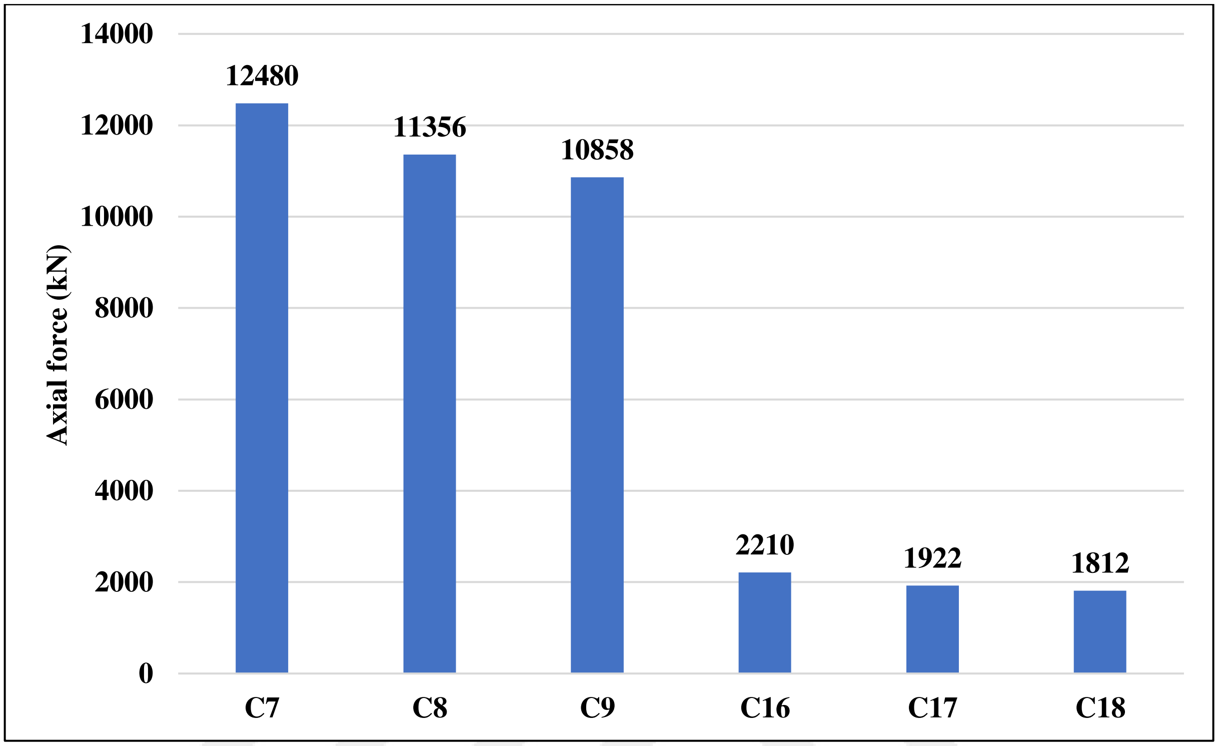


Figure 4.34: Axial force results comparison for BF and SW ten floor.

4.5.3 Displacement Results Comparison Between Building Frame and Shear Wall System

Displacement results comparison between building frame and shear wall system at different floor height are represented in Figure 4.35, Figure 4.36 and Figure 4.37.

The chart shows that the displacement for building frame system is 3000% greater than that of shear wall system at one floor. Meanwhile it is greater by 1400% in building frame system compared to shear wall system in 5 floor building. In addition, results present an increase in displacement by 150 to 180% in building frame system at 10 floors.

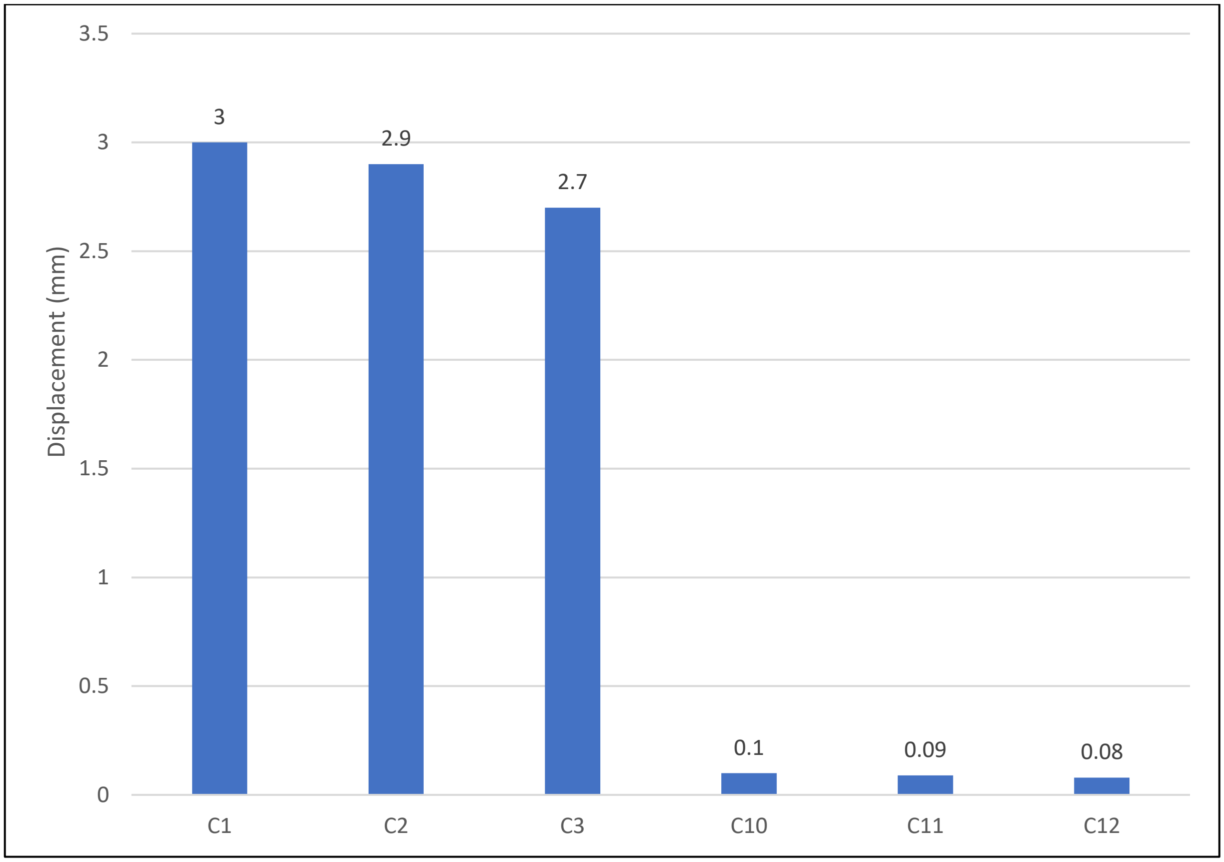


Figure 4.35: Displacement results comparison for BF and SW one floor.

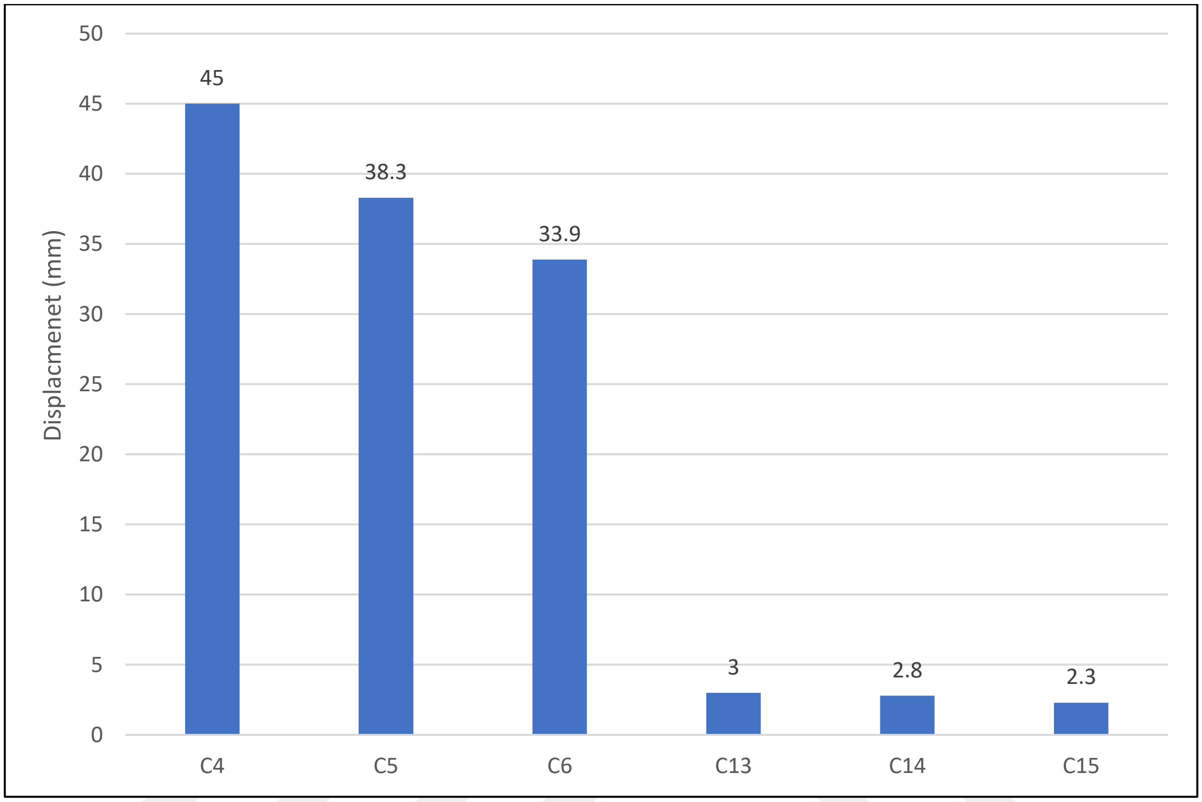


Figure 4.36: Displacement results comparison for BF and SW five floor.

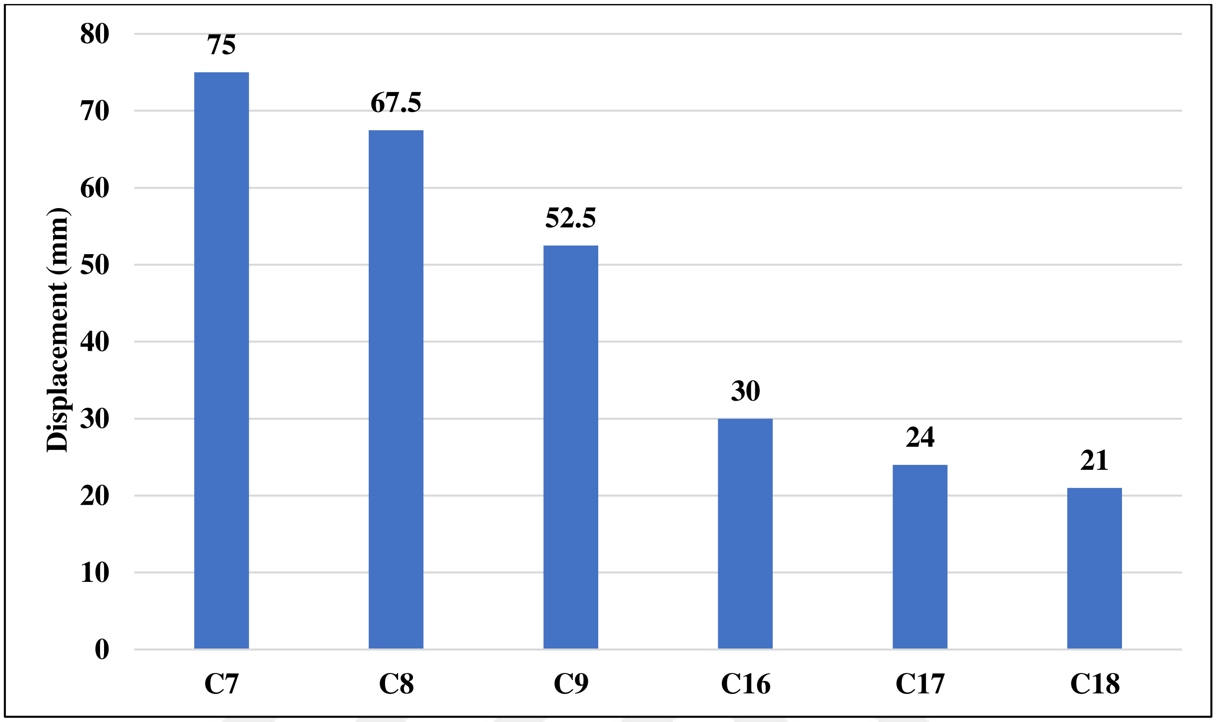


Figure 4.37: Displacement results comparison for BF and SW ten floor.

4.6 DISCUSSION

The results of this study reveal that the dynamic soil-structure interaction is affected by the base shear, axial forces, type of soil, displacement, and moment. Also, the findings indicate that number of floors plays a critical role in influencing the load on soil, which can affect soil stability and performance. These results are consistent with the results found by authors [37]–[42], [49], who conducted an analysis examining the critical role of dynamic soil-structure interaction and major factors that influence soil stability and found that soil characteristics, such as soil structure, soil porosity, overlying structure, the number of soil layers, and the seismic excitation at the seismic rock-outcrop or bedrock can influence the behavior of soil, which in turn, can affect the dynamic soil-structure interaction. They also found that soil humidity, density, stiffness, compaction, damping, porosity, and mass play a critical role in affecting dynamic soil-structure interaction.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CHAPTER GOAL

The previous chapter provided a detailed illustration regarding the critical numerical results and mathematical modeling and simulations conducted using the ABAQUS software tool. This chapter will offer major research conclusions and recommendations that are vital for project managers and civil engineers to consider the employment and investigation of dynamic soil-structure interaction of concrete buildings.

5.2 CONCLUSIONS

This work is executed by identifying major soil characteristics related to the dynamic soil-structure interaction features of a reinforced concrete building. Numerical analysis and simulations were followed and adopted, relying on the ABAQUS® software package to assess the base shear, axial force, moment, and displacement, considering different types of soil. Based on the research work, the following results can be drawn:

A. The base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil. Also, the base shear for a five-floor building frame decreases by 5% from soft to medium soil and by 23% from medium to hard soil.
B. The base shear for a shear wall system with ten stories on medium soil is 20% less than base shear on soft soil. On hard soil, this outcome is lowered by 12%.
C. The axial force for a five-floor building frame decreases by 2% from soft to medium soil and by 8% from medium to hard soil. Additionally, axial forces provide a 9% decrease for medium soil and a 4% reduction for hard soil in a 10-floor building frame resistance system.
D. There is a reduction of 3% from soft to medium soil and a reduction of 12% on hard soil regarding axial force. Meantime, the axial forces are lesser for medium soil by 13% compared to soft soil and less by 6 % for hard soil.

E. The displacement is decreased by 6% in a 5-floor building frame system on medium soil and by 11% on hard soil. However, the displacement of a 10-floor building structure is reduced by 10% on medium soil and 22% on hard soil.
F. Displacement in a five-floor shear wall structure is decreased by 6% and 18% on medium and hard soil. Also, displacement reduces by 20% and 30% on medium and hard soil, respectively.

5.3 RECOMMENDATIONS

Based on the research analysis conducted via the ABAQUS software tool, the researcher recommends some critical and essential suggestions that can help improve the consideration of dynamic soil-structure interaction of concrete buildings. The recommendations include the following aspects:

I- To conduct conferences, workshops, and meetings to encourage the cooperation and consolidation between project managers, civil engineers, and soil experts to investigate and take into account the analysis of dynamic soil-structure interaction in concrete buildings.

II- To carry out further Research and Development (R&D) experiments and analysis to analyze the soil properties and assess its characteristics considering dynamic soil-structure interaction.

III- To increase the level of awareness and knowledge associated with vital practices in civil engineering related to dynamic soil-structure interaction by educating project managers and senior engineers on soil properties principles.

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