

STABILITY AND FAILURE ANALYSIS OF EXCAVATIONS USED FOR
UNDERGROUND MINING OF BATI RAMAN OIL FIELD

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UNDERGROUND MINING OF BATI RAMAN OIL FIELD**

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ABSTRACT

STABILITY AND FAILURE ANALYSIS OF EXCAVATIONS USED FOR UNDERGROUND MINING OF BATI RAMAN OIL FIELD

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Batı Raman holds the Turkey's proven largest oil reserve (1.85 billion barrels). The reserve is located at an average depth of 1450 m within a fractured limestone. This heavy oil has a 12° API gravity and a viscosity of 200-2000 cp. A future plan for this reserve is to use a "mining assisted heavy oil production" method. The idea behind this method is to reach the reserve by a decline from the surface and continue opening up galleries beneath the reserve from which fan shape up holes will be drilled in the reserve. Steam will be injected from these up holes to decrease the viscosity of heavy oil and production will be done by gravity drainage. In this thesis, stability of all the openings based on the scenario above is carried out using a numerical modelling code, FLAC. In the first stage, tunnel openings were first investigated based on analytical solutions, then 2D and 3D analyzes were carried out. It has been shown that the 20m wall-to-wall pillar, which is planned to be left between the tunnels, will remain stable. Then, the effects of boreholes to be used in oil production in the reservoir were modelled, and it was determined that the extends of the failure zones occurred along the tunnel and in the regions where the boreholes were opened. It was compared with a physical model test made with the found failure zones, and it was

concluded that 2.23% of the heavy oil production determined in the experiment was due to borehole openings. A parametric study was conducted by analyzing a total of 15 models by following the ratio found, and Excavation Induced Damage Production Ratio (EIDPR) was defined. As a result of the parametric study, a regression model was created, and the model's equation was shared.

Keywords: Heavy Oil, Deep Tunnels, TBM, Stability, Batı Raman, MAHOP



ÖZ

BATI RAMAN PETROL SAHASI MADENCİLİĞİNDE KULLANILAN YERALTI AÇIKLIKLARININ DURAYLILIK VE YENİLME ANALİZİ

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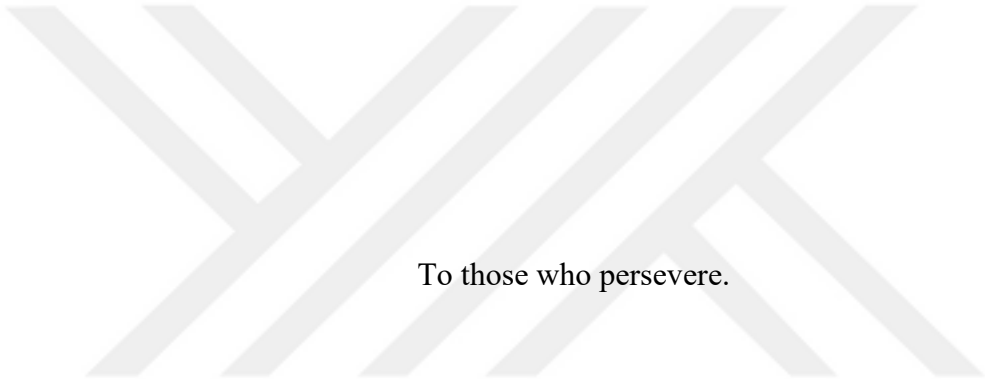
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Batı Raman, Türkiye'nin kanıtlanmış en büyük petrol rezervine (1.85 milyar varil) sahiptir. Rezerv, çatlaklı bir kireçtaşı içinde ortalama 1310 m derinlikte yer almaktadır. Bu ağır petrol, 12° API kütle ağırlığına ve 200-2000 cp viskoziteye sahiptir. Bu rezerv için gelecekteki bir plan “madencilik yardımlı ağır petrol üretimi” yönteminin kullanılmasıdır. Bu yöntemin arkasındaki fikir, yüzeyden desandrelerle reserve ulaşmak ve rezervin altından üzerinde fan şeklinde delikler bulunan galerileri açmaya devam etmektir. Ağır petrolün viskozitesini azaltmak için bu deliklerden buhar gönderilecek ve yer çekimi drenajı ile üretim yapılacaktır. Bu tezde, yukarıdaki senaryoya göre tüm açıklıkların duraylılığı, FLAC adlı sayısal bir modelleme kodu kullanılarak gerçekleştirilecektir. İlk aşamada, tünel açıklıkları önce analitik çözümlere dayandırılarak incelenmiş, ardından 2 boyutlu ve 3 boyutlu analizler yürütülmüştür. tüneller arasında bırakılması planlanan 20 metrelik topuğun duraylı kalacağı gösterilmiştir. Ardından, petrol üretiminde kullanılacak olan kuyuların rezervuar içindeki etkileri modellenmiş ve yenilen bölgelerin tünel boyunca ve kuyuların açıldığı bölgelerde oluştuğu tespit edilmiştir. Bulunan yenilmiş bölgeler ile Batı Raman Sahası için yapılmış fiziksel model deneyi karşılaştırılmış ve deneyde tespit edilmiş olan ağır petrol üretiminin %2.23'ünün kuyu

açılmasından kaynaklı oluşan yenilmiş bölgelerden olduğu sonucuna ulaşılmıştır. Aynı karşılaştırılmaya devam edilerek toplamda 15 adet model analiz edilmiş ve bir parametrik çalışma yürütülmüştür. Kuyu çapı ve boyuna bağlı olarak Kazı Kaynaklı Tahribat Üretim Oranı (KKTÜO) tanımlanmıştır. Yürütülen parametrik çalışma sonucu bir regresyon modeli oluşturulup modele ait denklem paylaşılmıştır.

Anahtar Kelimeler: Ağır Petrol, Derin Tüneller, TBM, Duraylılık, MYAPÜ





To those who persevere.

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LIST OF ABBREVIATIONS

ABBREVIATIONS

API – American Petroleum Institute

EOR – Enhanced Oil Recovery

EIDPR – Excavation Induced Damage Production Ratio

FDM – Finite Difference Method

FEA – Finite Element Analysis

FEM – Finite Element Method

FLAC – Fast Lagrangian Analysis of Continua

GRC – Ground Reaction Curve

LDP – Longitudinal Displacement Profile

LVDT – Linear Variable Differential Transformer

MAHOP – Mining Assisted Heavy Oil Production

MC – Mohr-Coulomb

SAGD – Steam Assisted Gravity Drainage

TBM – Tunnel Boring Machine

VAPEX – Vapour Extraction

CHAPTER 1

INTRODUCTION

Batı Raman is a strategically important heavy oil field for Turkey. Considering the oil production activities in Batı Raman to date, it is seen that it has not reached its full potential. It is planned to produce with the Mining Assisted Heavy Oil Production (MAHOP) method in the field, where various conventional and advanced oil production techniques have been applied, thus revealing its potential. As the name suggests, MAHOP is a method based on mining principles and developed to take advantage of excavatability and drillability through an oil reservoir. In this context, it is vital to correctly plan the mining activities to be used in the MAHOP method, examine them from the perspective of stability, and provide the necessary design parameters for the method's applicability. The applicability of MAHOP is broadly similar to the stability of a deep underground mine. Contrary to the usual, in this method, some borehole drilling works are carried out in addition to the galleries in order to access the reserve and to ensure the maximum possible fracture and failure within the reservoir rock mass for oil production. For this reason, it will not be sufficient to deal with the aimed excavations only in terms of tunnelling and excavation stability only.

Many factors affect the applicability of the MAHOP method. Some of these factors have been studied since the first exploratory studies were carried out and identified by petroleum engineers when the previous oil production methods were applied. Reservoir rock engineering studies focus on porosity and permeability parameters of rocks for conventional or non-conventional oil production. These rock parameters are definitely not sufficient for the MAHOP method. Since this method deals with rock mass, rock type, operation type, strength, and many other factors that affect rock mass behaviour should be considered. Although some studies have been carried out

in this direction, a comprehensive evaluation is not available. Long-term experience, development and successful examples in mining and tunnelling disciplines will undoubtedly be beneficial in providing and supporting oil production by opening galleries and mining excavations. The opportunity to carry out these activities is possible thanks to the developing technology. Tunnelling and deep tunnel excavations are easily carried out today, primarily using Tunnel Boring Machines (TBM). Tunnelling activities have developed considerably with the rapid support application offered by these machines, the principle of continuous progress, and the wide range of tunnel sizes offered. The excavations used for MAHOP include a wide variety of possibilities. Any additional excavation creates deformations and stress changes, starting with the declines used to reach the reservoir. This flexibility allows operations to adopt underground mining methods for oil production. Drilling upwards and changing the boreholes' angle, length, or diameter can be extensively modelled and analysed with today's technology. The capabilities of computer-aided numerical modelling tools are very advanced and are widely used in geotechnical designs. With the application of numerical modelling codes, soil degradation, stability of tunnels, fracture mesh formation or rock mass behaviour, in general, can be easily modelled, studied and visualised. Therefore, it is crucial to construct realistic and predictive numerical models to understand rock mass behaviour. While these design and analysis studies are being carried out, the primary purpose of this application must be taken into consideration, which is heavy oil production.

Heavy oil production requires an unconventional and comprehensive approach, even if only current oil production methods are used. Therefore, these problematic conditions must be well understood. One of these conditions is heavy oil production which cannot be produced by conventional methods. Crude oil in the Batı Raman Field with API gravity of 12° is classified as heavy oil that is heavier than water and sinks and requires heavy oil recovery techniques to be adopted to be produced. Oil production methods, which are called primary and secondary recovery methods, have largely lost their validity for the Batı Raman field, and tertiary recovery

methods are needed. Numerous heavy oil recovery methods are in use, such as drilling vertical wells, pumping water, CO₂ or steam and creating a high-pressure difference on oil. However, the recovery rates of conventional methods are highly inefficient.

For this reason, different technologies are adopted to create efficient solutions such as thermal and cold methods by targeting two factors; gravity and the viscosity of heavy oil. These unconventional methods include the vapour extraction (VAPEX) method, which creates a vapour chamber in the reservoir by injecting vaporised solvents, steam-assisted gravity drainage (SAGD) method that makes the oil more mobile by injecting hot steam from one of the two parallel wells and collecting less viscous oil from the other. In general, steam usage in heavy oil production gives the most favourable recovery rates, even if these methods have their own unique challenges.

1.1 General Remarks and Definitions

Batı Raman and Garzan, these two terms are used interchangeably in some parts of the study. It should be understood that the reservoir rock mass belonging to the Batı Raman field in the Garzan formation has been studied, which means that the mentioned region is the same. The major rock type is the Garzan Limestone in the area.

This study was carried out based on the geomechanical properties of the field, and the presence of fluids was not taken into account. Also, the steam injection operation is not simulated. For this reason, the recommendations and inferences made for future studies on the created model are shared with the reader in the conclusion part. Some assumptions were made in order to carry out this study. The Batı Raman field is considered to be composed of oil-saturated reservoir rock only. In the modelling and analysis process, the Raman field was assumed to be composed of oil-saturated reservoir rock, Garzan Limestone, homogeneous, non-discontinuous, isotropic and under homogeneous hydrostatic stress.

Numerical modelling of the excavations and boreholes were carried out for stability and oil producibility reasons for various borehole geometries.

1.2 Problem Statement

Conventional methods cannot be used in heavy oil production, so non-conventional methods have been developed. MAHOP is one of these methods. This method creates complex geometries in terms of mining and tunnelling. The reason for this is that the deep mining and drilling activities in a hot oil-saturated limestone environment create complex stability problems that are not yet well-studied. Deep TBM tunnelling in a heavy oil reservoir, maintaining the stability of these galleries and pillars, drilling boreholes above the galleries for high pressure, high temperature steam injection, and inducing the necessary deformation to create a mechanically induced steam chamber within the reservoir suitable for steam injection are parts of this complex problem.

1.3 Research Objectives and Scope of the Study

The main focus of this study is to build representative numerical models of the Batı Raman field and provide a reliable analysis of the stability of the excavations used in the mining assisted heavy oil production method and compare different borehole geometries to investigate the steam chamber formations above the galleries by parametric numerical modelling scenarios.

The research objectives of this study are described as follows;

1. Determining geomechanical strength parameters of Garzan Limestone in a laboratory environment
2. Developing FLAC 2D and 3D numerical models of MAHOP that represent the rock mass behaviour of Batı Raman Heavy Oil Reservoir
3. Evaluating the stability of the galleries, pillar and borehole excavations

4. Analyzing the failure zone induced by galleries and boreholes for various borehole geometries by carrying out a parametric numerical study in FLAC 3D.
5. To form a relationship of failure zone as a function of borehole length and borehole diameter by regression analysis.
6. Suggest a borehole geometry for future MAHOP applications.

It is essential to consider the scope when conducting this study. The thesis study is limited to the examination of the effects of the underground tunnel, and steam injection wells excavations, which are included in the mining assisted heavy oil production method planned to be carried out in the Batı Raman oil field, on the reservoir rock mass and the analysis of the formation of the yielded zones as a result of these excavations. In the study, the design of the support system, the steam injection to be made for the execution of oil production or the modelling of the oil flow were excluded from the scope. Therefore the scope is limited to underground excavations and their effects.

1.4 Research Methodology

The methodology followed in this thesis study consists of a quantitative approach at each stage.

1. Conducting a throughout literature review of deep tunnelling, oil mining, and Batı Raman oil production
2. Determining geomechanical properties of the Garzan limestone samples by carrying out deformability and triaxial tests in the laboratory environment
3. Developing 2D and 3D models in a computer-aided design environment
4. Validating the models according to the obtained strength parameters
5. Performing numerical analyses on finite difference method solver code FLAC and FLAC^{3D} for the acquisition of strain increments, plasticity indicators, stress states and displacements data from the simulation results

6. Carrying out a parametric study of fifteen MAHOP models (for five different borehole lengths and three different diameters) for investigation of failure zone above galleries.
7. Developing statistical correlations between failure zone, borehole length and diameter.

1.5 Thesis Outline

This thesis study is written in five chapters. In the first chapter, Introduction, a general overview of the objective and scope of the study is provided. In Chapter 2, a summary of the literature consisting of numerous previous scientific studies that constituted the backbone of this thesis is provided. In Chapter 3, testing procedures and obtained rock mechanical parameters of Garzan Limestone are presented. In Chapter 4, the basis of finite difference methods is explained. Then, three closed-form solutions for single circular tunnel plasticity were discussed. By evaluating each of these solutions, some computer programs were introduced. Finally, from the verification of a solution FDM method started and by generating the conceptualised numerical models of MAHOP openings are developed for 2D and 3D analyses, and the results are presented. In the final chapter, Chapter 5, conclusions and recommendations based on the acquired results of the numerical studies are listed. The outline of this thesis can be seen in Figure 1.

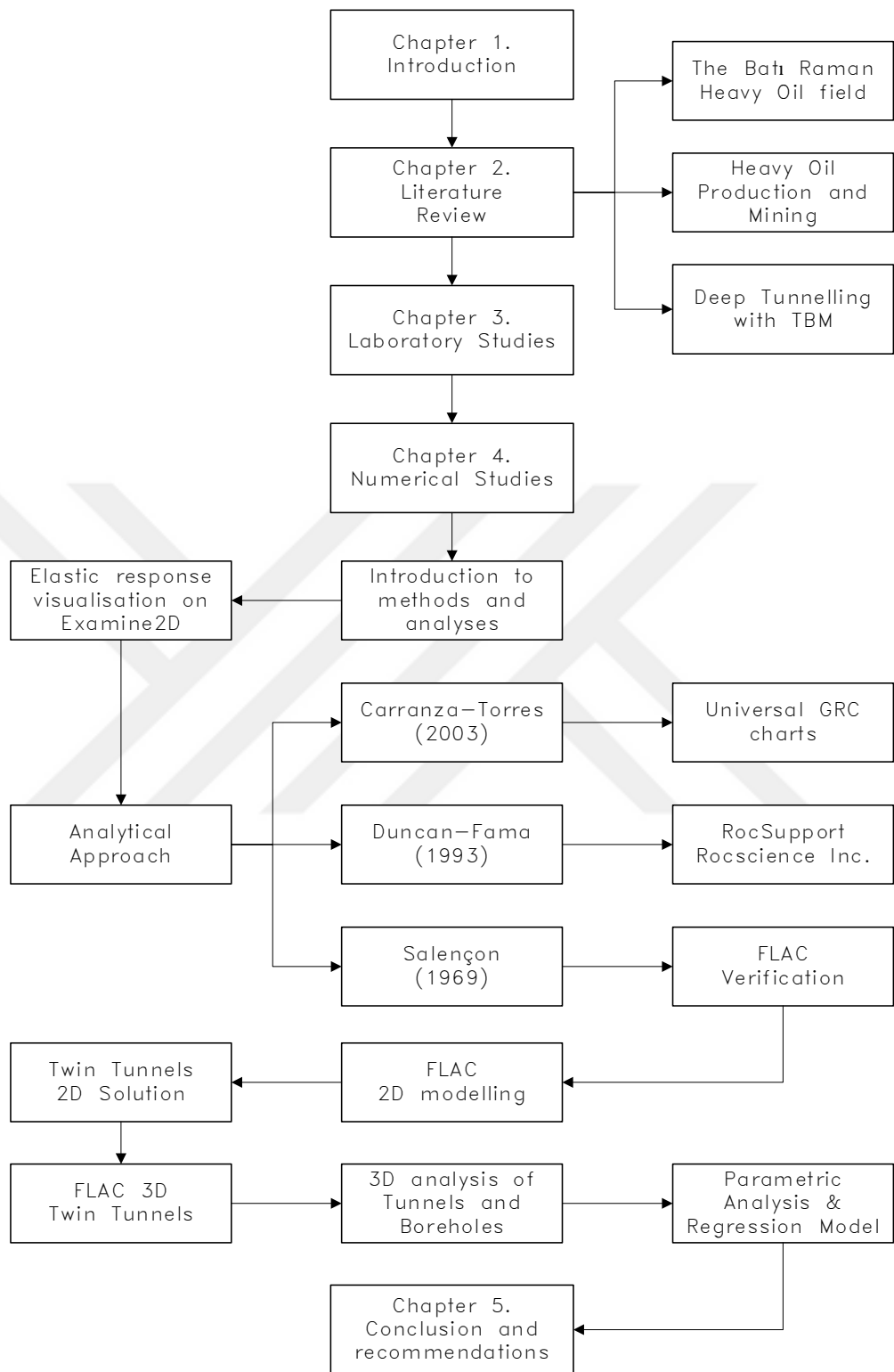


Figure 1. Thesis flowchart

CHAPTER 2

LITERATURE REVIEW

This chapter includes a general overview of the literature on the site characteristics of Batı Raman Oil Field, studies on heavy oil production, tunnelling works at deep levels and numerical studies of TBM tunnels.

2.1 Batı Raman Oil Field

In order to carry out a study on the Batı Raman oil field, it is necessary to have an understanding of the nature and characteristics of the site. For this reason, first of all, the information about the field is presented in chronological order. Then, the studies that have been implemented or planned to be implemented in the field are briefly mentioned. The point to be noted here is that the studies were carried out by the petroleum and geological engineering disciplines.

There are geological mapping studies, including the Garzan formation and the Batı Raman field. Ala & Moss (1979) produced a stratigraphic map covering the southeast of Turkey and northeast of Syria. The part of this map that includes the Garzan formation is shown in Figure 2. In the same study, the oil fields in the southeast of Turkey were also indicated. As can be seen from the stratigraphic map, the Garzan formation is composed of moderately porous fractured limestone. It is stated that the accumulations in the Garzan formation are mostly undersaturated, and the heavy oil produced has a gravity of 13.4° API. It has also been noted that the layer above and below the pay zone of the field is Germav Shale (Ala & Moss, 1979). Alsharhan & Nairn (1997) has done another study in which geological definitions and information about the Garzan formation and the Batı Raman field can be obtained. The site was evaluated in terms of structural geology in this study, and

major faults were mapped. The structural geological map of the Garzan formation is given in Figure 3 and Figure 4 (Alsharhan & Nairn, 1997). It can be seen from these maps that the geological formation that seals the Garzan formation is the Germav shale. The location of the Batı Raman field was also marked in Figure 5.

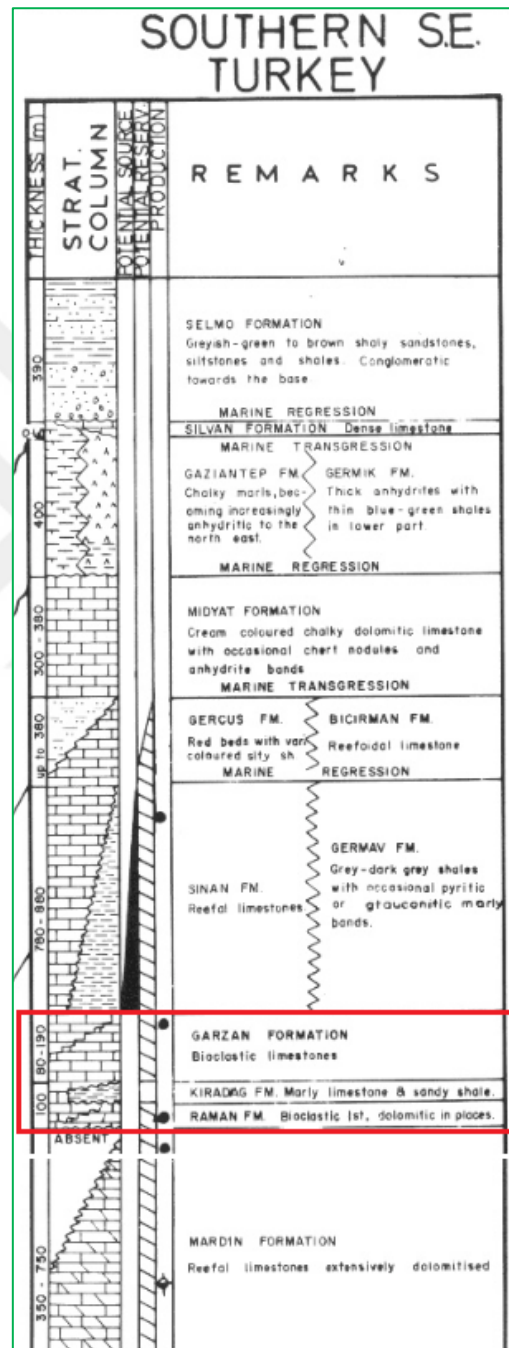


Figure 2. Stratigraphic location of the Garzan formation (Ala & Moss, 1979)

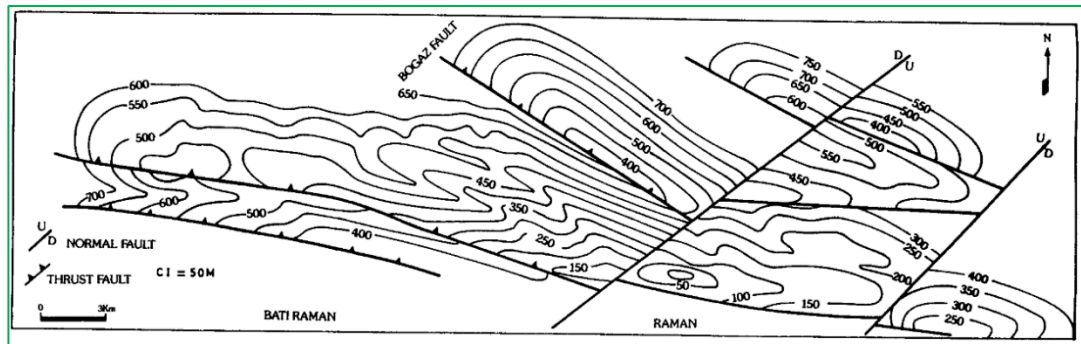


Figure 3. Major faults in the Garzan formation (Alsharhan & Nairn, 1997)

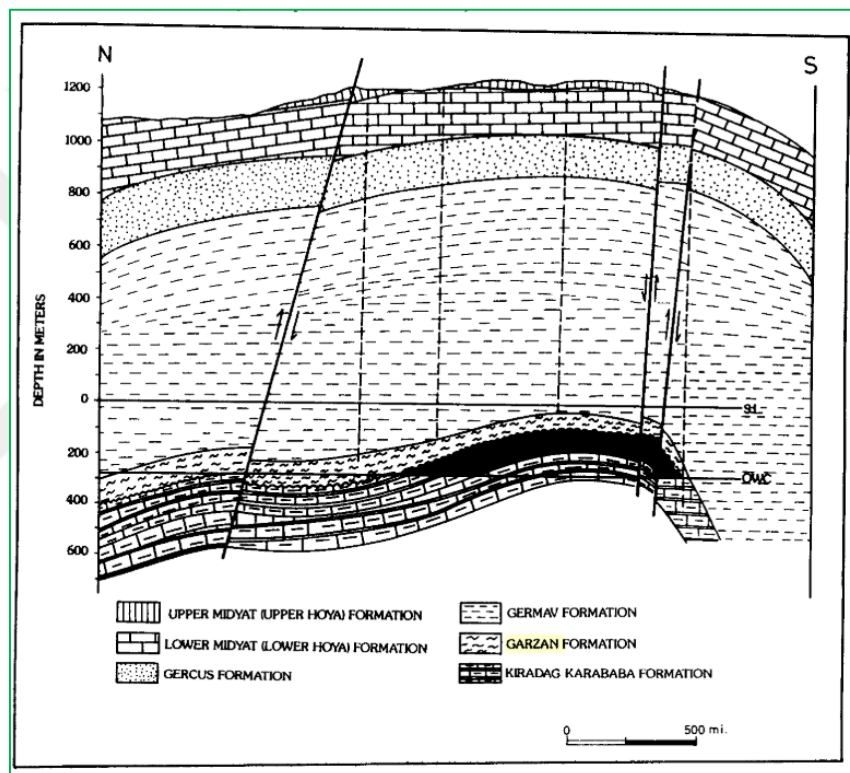


Figure 4. The structural cross-section including the Garzan formation (Alsharhan & Nairn, 1997)

The Batı Raman field is the largest oil field in Turkey, with 1.85 billion barrels of oil. The field was discovered and started operating in 1961 and is located in the southeast of Turkey (Figure 6). The primary production was estimated to be 1.5% of the oil in place (Kantar *et al.*, 1985; Sahin *et al.*, 2007).

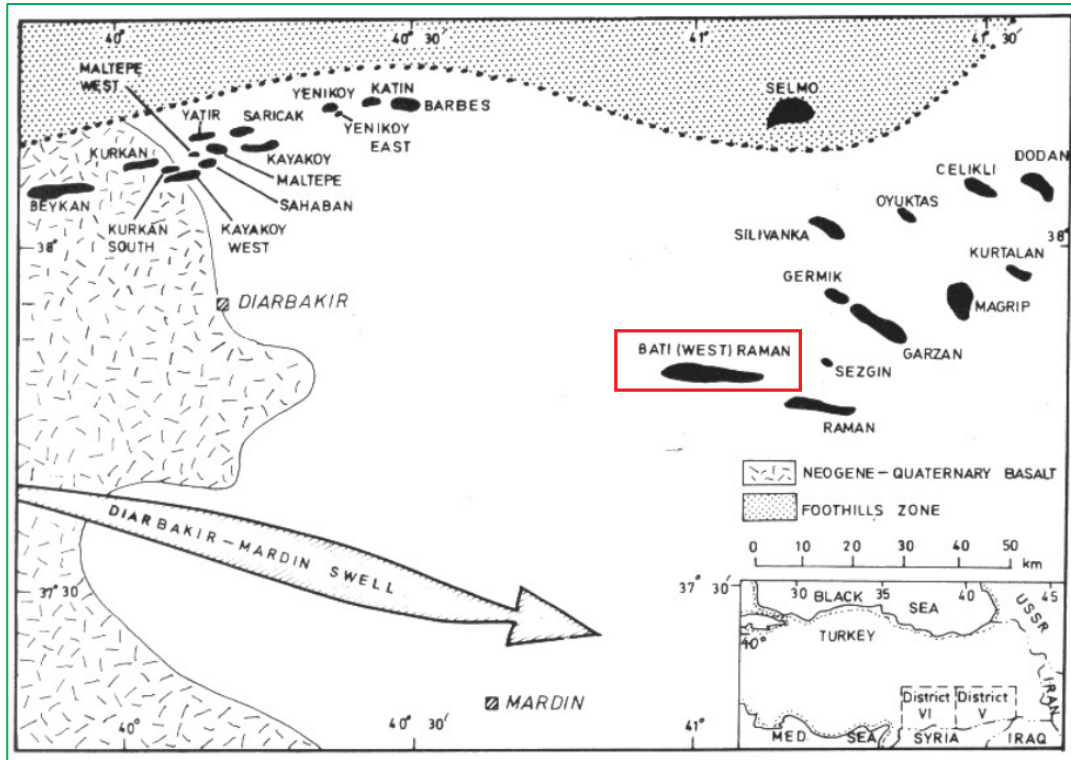


Figure 5. Oil fields in SE Turkey and the Batı Raman field (Ala & Moss, 1979)

Noticeable improvement was experienced between 1965-1970 by increasing the number of production wells. Production with 20 wells was experienced due to intense drilling activity from the well, reaching the level of 130 barrels/day. Production in 1969, after reaching 9000 barrels/day peaked in, tended to decrease. In 1974, the daily production was halved with a decrease in field pressure (Sahin *et al.*, 2012). After 1986, carbon dioxide injection, one of the secondary production techniques, was applied and continues to be applied. In this way, 6% of the oil was produced in the reservoir (Kantar *et al.*, 1985). As a result of all these applications with the current carbon dioxide injection, the site is foreseen to reach a maximum of 10% recovery (Sahin *et al.*, 2012). In the study conducted according to the field's characteristics, a steam injection was applied using horizontal wells in the laboratory environment. Then steam compression experiments were carried out with a physical model, and successful results were obtained by observing the effects. The recovery amount has reached up to 60% (Canbolat *et al.*, 2004).

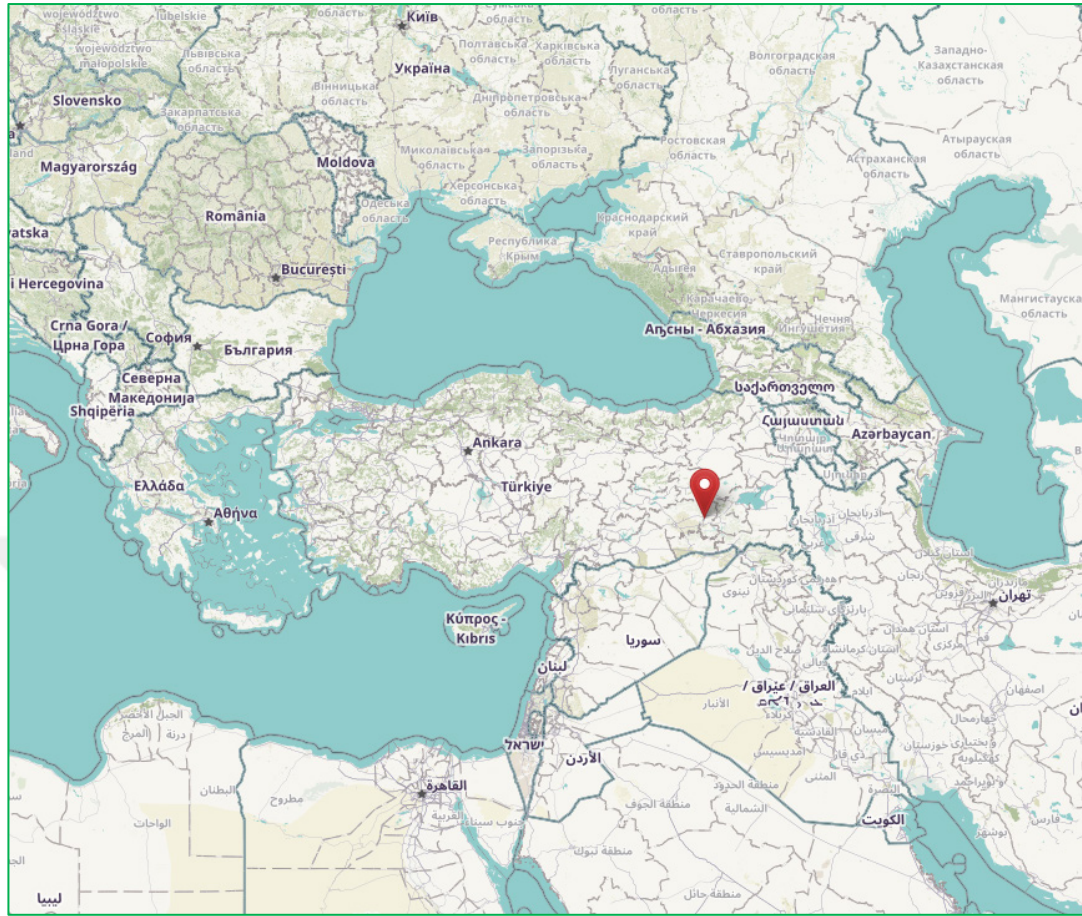


Figure 6. Location of the Batı Raman Field in the Middle East

The methods that have been tried in the Raman field and the ongoing work should be mentioned. For this reason, some prominent studies have been highlighted. It is noteworthy that the common feature of these studies is to deal with the oil reservoir only through flow dynamics and to evaluate production based on flow only.

The most promising study in the field was the application of CO₂ injection. Issever *et al.* (1993) evaluated the CO₂ injection application, which is an enhanced oil recovery application, performance in the Batı Raman field in the fifth year of the application. In their study, the results of improved flow performance and increased reservoir pressure due to CO₂ injection compared to before injection period were shown in the treated pilot area of 33 wells (Issever *et al.*, 1993). The most comprehensive study examining the history of CO₂ injection studies conducted in

the Batı Raman field was presented by Sahin *et al.* (2008). This study, conducted on the 25th anniversary of the CO₂ injection process, examines CO₂ injection in detail. The study particularly draws attention to how the immiscible flooding technique works in a heavy oil reservoir with a fractured limestone matrix.

Another point that draws attention is that the reason why these sweeping and gas-drive processes cannot reach high efficiency is the operational problems. In another study, the researcher focused on how CO₂ injection had a decreasing trend over the years and the necessity of starting steam injection (Sahin *et al.*, 2014). This study is essential because steam injection application, also known as SAGD, is an application that can give successful results for heavy oil fields and can be said to be somewhat expected. The pilot wells in which steam injection trials were made in the Batı Raman field are shown in Figure 7. In the conclusion part of the study, the researcher attributes success in some wells but not in others. The same study also revealed that the quality of the steam injected into the wells plays a prominent role (Sahin *et al.*, 2014). Canbolat *et al.* (2002) has examined whether the presence of gases in the field will have an effect on the transition of the field to SAGD application after the injection applications and revealed that injecting pure steam into an existing gas-injected site produces similar results as injecting a steam-gas mixture. Several studies have also been carried out to increase the efficiency of the ongoing CO₂ injection EOR production method. Safran and Kok (2022) investigated the carbon dioxide injection in a stabilised nanoparticle in foam form. The authors suggested that foam application will increase production and achieve successful results if the necessary conditions are met. One of the most important studies on bitumen recovery and heavy oil production in the mentioned region and examining the relationship between vapour and heavy oil is the study of Kok *et al.*. In this study, various solvents added to water Vapor Extraction (VAPEX) and different injection rates were compared, and a noticeable increase in production was obtained when the injection rate reached 80ml/min (Kok *et al.*, 2009).

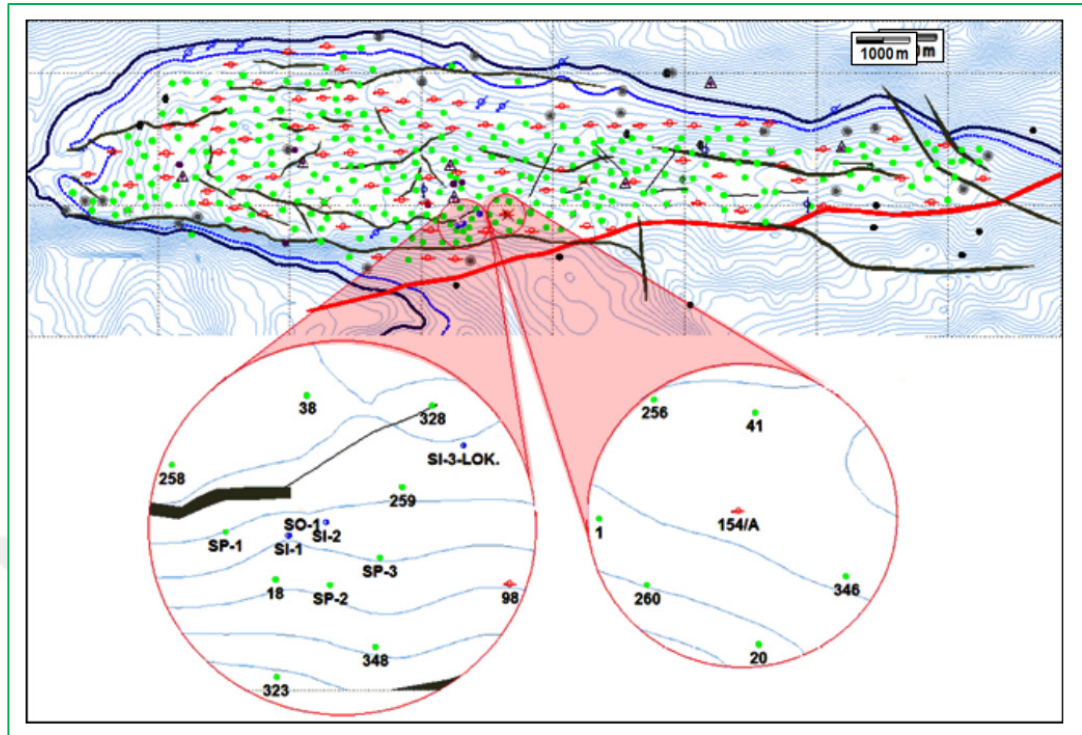


Figure 7. Locations of the pilot steam injection wells in the Batı Raman field

Arslan *et al.* (2007) built a comprehensive static model in 2D and 3D environments to evaluate the Batı Raman Field characterisation in terms of seismic, sedimentologic and fracture properties. The study revealed significant fracture regions by the utilisation of the models created and presented the matrix properties. The distinguishing feature of the study was that it also included the possibility of a triple porosity system in the vug structure of the Batı Raman Field (Arslan *et al.*, 2007). Babadagli *et al.* (2009) have suggested different types of injections that can be applied after the ongoing CO₂ injection and when this method is not sufficient.

To sum up, there is still an unrevealed potential in the Batı Raman field. In light of the studies mentioned in this section, it shows that the applications made to increase the field's efficiency still have not gained a final long-lasting form.

2.2 Mining Assisted Heavy Oil Production

In order to evaluate and classify new methods in oil production, it is necessary to explain the production types of the common petroleum terminology that is accepted worldwide. Oil production is generally classified into three types. These are primary, secondary and tertiary production methods. The primary production methods are those where the reservoir pressure and natural energy can be considered sufficient for production, where a natural flow can be achieved. However, over time, the energy of the reservoir decreases, the natural flow slows down or becomes insufficient. In such cases, an external influence must be made on the area where the production is made. The methods in which these externally applied, driving and activating forces are used are called secondary methods. These repulsive forces are mainly based on the displacement principle. The water or gas injected into the reservoir causes the displacement of the oil to be produced. That is, the forces acting from the outside constitute the primary mode of production.

In some cases, secondary production methods are also insufficient, so enhanced flows need to be developed in addition to the primary natural reservoir energy and the displacement effects used in secondary methods. In this case, tertiary methods are needed, and these methods are based on changing the nature of the oil, physically operating on the reservoir, or creating chemical and thermal reactions (Stosur *et al.*, 2003). Tertiary methods are also known as enhanced oil recovery. The common point of these methods is that they emerge after or in addition to secondary production types. In the light of this classification, it is clear that the required and needed method in Batı Raman is a tertiary method, and MAHOP is one of these methods.

The literature that directly serves the MAHOP method examined in this thesis study is relatively limited. A recent study examined the effects of mining excavations included in this study on oil production by constructing a physical model for the Batı Raman Field, which is the primary motivation for this thesis (Canbolat *et al.*, 2020a). It would also be correct to include the studies made for the fields where the MAHOP method is used similarly.

Canbolat *et al.* (2020b) estimated the total average capital cost of MAHOP, including surface and underground facilities, is \$ 2.75 billion, and the total operational cost of MAHOP (including mining, steam, ventilation, facility, etc.) is \$ 12 / barrel. Canbolat *et al.* (2020a) designed a model for the Batı Raman field. This model planned to enter the reservoir by opening TBM tunnels in the Batı Raman field. This design aimed to perform steam injection with boreholes to be opened to the crests of these tunnels serving in the reservoir and thus to produce mobilised oil. One of the factors that make this work different from the others is that, unlike typical applications, steam production will be able to be done inside the tunnel, and in this way, the steam loss will be reduced to almost zero. The distance the steam will travel is eliminated as it will be produced in the reservoir, and the pure, high pressure and high temperature steam can directly contact the reservoir rock. The author prepared a physical model using limestone with similar characteristics to that of the Batı Raman field and heavy oil samples from the Batı Raman field. In this physical model, the tunnels planned to be built in the field and the boreholes planned to be opened on the tunnels were placed, and high pressure water vapour was injected into these structures. It was numerically modelled and compared how much the steam sweeping the reservoir pay zone through boreholes would increase the production. As a result of this physical model experiment, it was revealed that up to 70% could be achieved in the field by transferring the steam pressure and heat directly to the reservoir rock through the tunnels. The sketch of the physical model and dimensions can be seen in Figure 8.

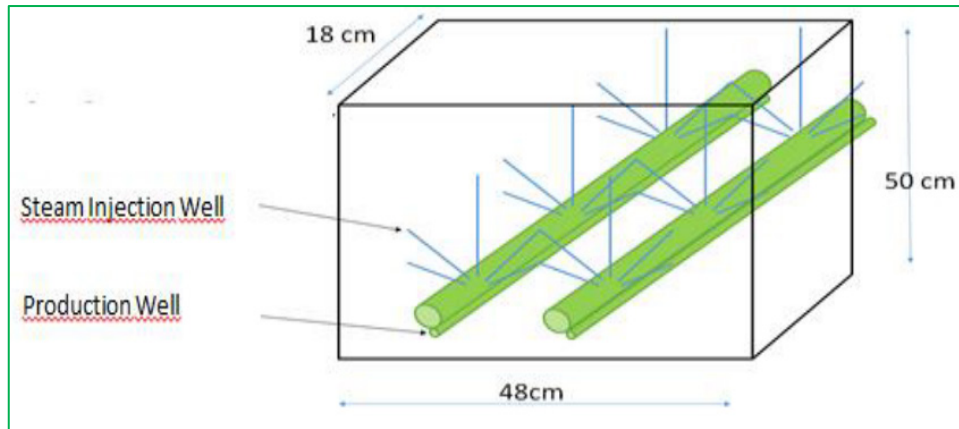


Figure 8. Experimental setup (Canbolat *et al.*, 2020a)

An application involving mining activities was carried out in the Kern River field, which contains heavy oil with an API gravity of 14 in California. In this area, a shaft was descended into the middle of the reservoir, and horizontally extending boreholes were drilled. With the help of these boreholes, steam was injected into the field and production was achieved (Borg, 1982). The diagram showing this production is given in Figure 9.

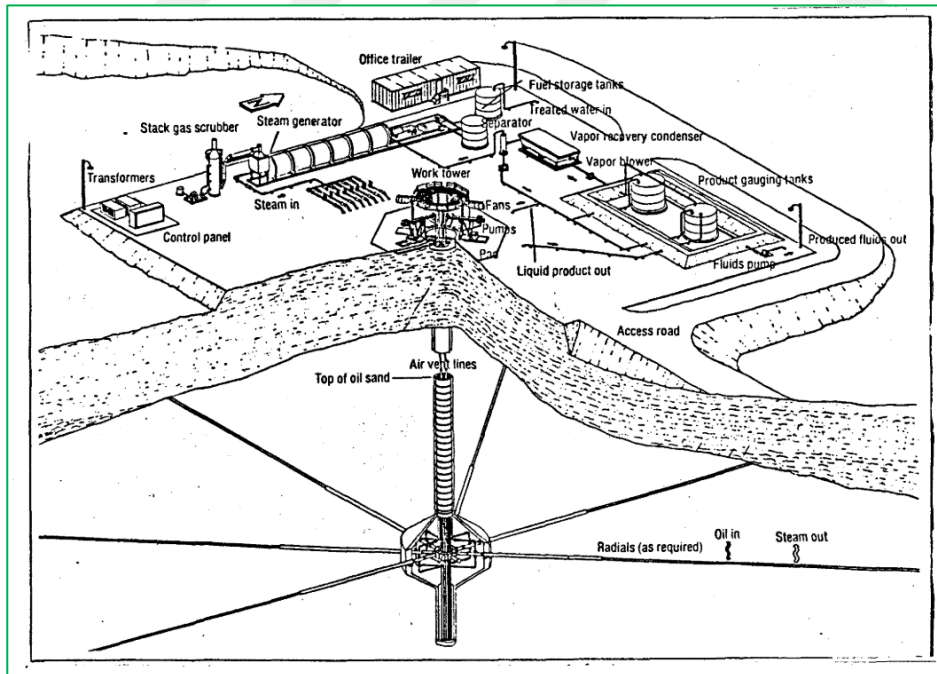


Figure 9. The application in the Kern River Field (Borg, 1982)

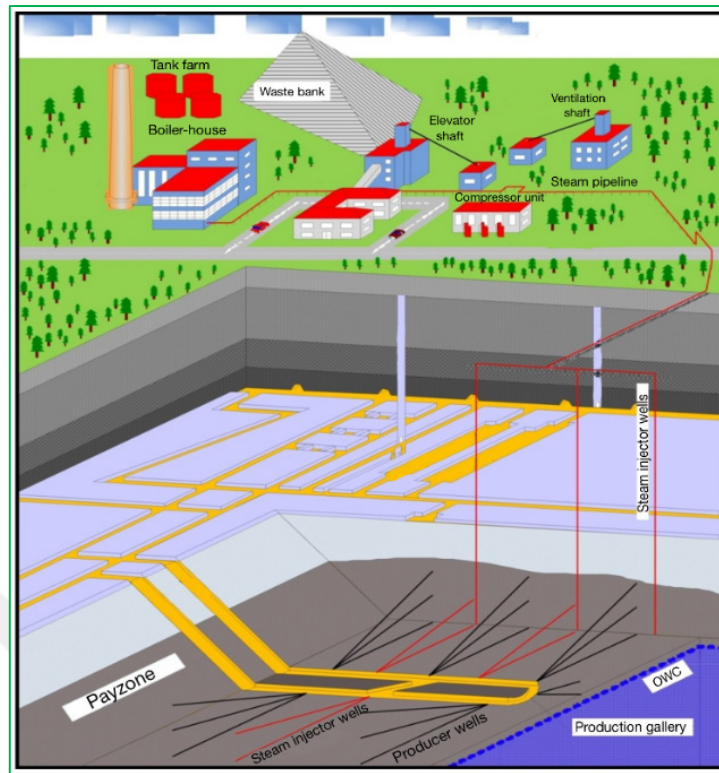


Figure 11. Mining scheme in Yarega Oil Field (Abzaletdinov, 2018)

So far, nearly ten different systems have been adapted to the Yarega field. The most successful of these methods are hot steam injections made from the surface due to the proximity of the reservoir to the surface. A study of thermal rod integration, drilled from the surface and through the gallery, was also carried out by Durkin *et al.* (2017). A study is conducted to measure reservoir rocks' thermal properties and thermal conductivity and evaluate these properties for heavy oil reservoirs (Chekhonin *et al.*, 2012). The most extensive examination of thermal and mining applications in the Yarega heavy oil field can be found in Abzaletdinov's (2018) thesis and the paper by the same author (Durkin *et al.*, 2017). The fishtail well design specified by the author can be seen in Figure 12 (Abzaletdinov, 2018).

Emci and Ozturk (2021), on the other hand, modelled the MAHOP openings in 3D and evaluated the proposed geometry for the first time in terms of mining and tunnelling.

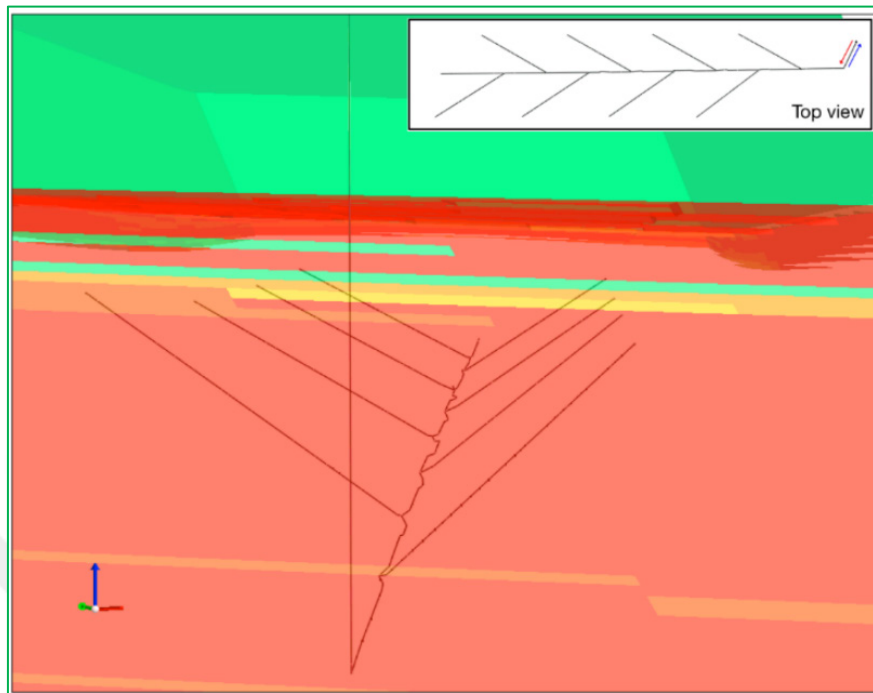


Figure 12. Fishtail well design (Abzaletdinov, 2018)

2.3 Deep Tunnelling with Tunnel Boring Machines

Tunnel Boring Machines (TBM) have many uses today. It has been possible to overcome many difficult underground conditions by employing these machines. For this reason, it is clear that the purpose of tunnelling in the reservoir examined and studied in this thesis will be one of these problematic conditions. In this section, some case studies in which these difficult conditions have been overcome in the field of TBM tunnelling and some studies that demonstrate the practicality of TBM tunnelling are shared.

Since the tunnels planned to be opened in the Batı Raman field will be twin tunnels in the first stage, Islam & Iskander's (2021) work on twin tunnel applications has an important place. In this study, the effects of twin tunnels built in the past decades on the ground settlement are reviewed. By examining different tunnel positions, the effects on the surface during tunnelling and the effects of the tunnels on each other were examined. As a result of the tunnel positioning examined in the study, it has been revealed that the side-by-side opening of the twin tunnels has the least effect on the strata above the tunnels. In line with these examples, it is the right choice to plan the tunnels to be opened side by side in the Batı Raman field.

One of the most critical difficulties brought by deep tunnelling is the in situ stresses that occur as the overburden height increases. There are examples of tunnelling where such difficulties have been overcome. The most important of these is the opening of the Yacambu tunnel, which has a precedent character (E. Hoek & Guevara, 2009). The tunnel is planned to be 1270 meters below the ground and 5 meters in diameter. For the opening of this tunnel, which is planned to be built to transport water under the Andes Mountains, 8 different contracts have been worked out for 32 years. Different types of supports and excavation methods were tried in the tunnel, but the applications were insufficient. In 2008, these problematic conditions were overcome by using yielding supports, and the tunnel was started to be used successfully.

Another work under similar conditions belongs to Diederichs *et al.* (2013). In this study, the factors that played a role in the successful opening of the Olmos tunnel in Peru under the effect of high in situ stresses 2500 meters below the ground are given. Among the lengths of the tunnels reaching 20 kilometres, 12.5 kilometres of them were opened with TBM. Therefore, the Olmos tunnel is an important example of the importance of using TBMs in deep tunnelling. Rock bursting was the most challenging factor in this tunnel study (Diederichs *et al.*, 2013).

There are many examples where TBMs are used and planned for deep tunnelling. Considering the working principle of TBM, one of the reasons for this is the ability to place supports and the continuity of the operation quickly. Another example in this respect is the work of Goel (2016). Taking as an example the 14.75-kilometre tunnels opened in India to serve the hydroelectric project; It is planned to open a TBM tunnel that passes under the Himalayan mountains. In this study, the risks and difficulties that may be encountered in the planned tunnels are revealed (Goel, 2016).

As can be seen from the studies mentioned above, many difficulties can be encountered in TBM tunnelling. However, it should not be forgotten that what will be encountered underground is not always predictable. Likewise, when an idea of the geological structure of the underground is obtained, different unexpected conditions may arise, such as changes in extreme conditions, a hard rock a few meters above a soft rock boundary, or the presence of groundwater. In such variable conditions, it may be necessary to take different measures in the application of TBM. Considering the working principles of TBMs, the operational effects of variable geological conditions and the classification of the measures to be taken against these effects were studied by Gong *et al.* (2016).

One of the most critical risks in TBM tunnelling is TBM jamming. In the study of Xu *et al.* (2021) on this subject, the solution of the compression problem encountered in the Gaoligongshan tunnel and the examination of the operational methods followed in the hard rock structure are given. In this study, it was stated that TBM selection plays the most critical role in TBM compression. In the continuation of the

study, the steps to be taken to avoid the problem of TBM jamming are given step by step.

With the development of TBM tunnelling, side operations have also gained importance. Therefore, the importance of automation in terms of tunnelling has emerged. The variety of equipment, both for tunnelling and assisting, has increased. As a result, new equipment types are also being developed in line with the TBM operating logic. Different machines have been produced that work similarly to these principles. An example of the equipment that can be considered to be used for tunnelling in the Batı Raman can be given. One of them is the Epiroc Mobile Miner machine. These machines provide continuity as their working principle and aim to give promising results in hard rock types. These machines, which have high automation power, can dig tunnels up to 5.5 meters in diameter and provide operational convenience for applying appropriate support types (Epiroc, 2021).

CHAPTER 3

LABORATORY STUDIES

Investigating the behaviour of naturally occurring materials requires the utmost applicable attention in a modelling study. Experiments carried out in a laboratory or a field study establish a crucial link between natural conditions and simulated models. Therefore, as a starting point for the thesis study, several tests were performed on representative rock samples from the Batı Raman Reservoir.

3.1 Garzan Limestone Rock Samples

Rock strength parameters were obtained from the tests conducted on 7 core specimens. Specimens had very different characteristics in terms of containing heavy oil. The grouping was done based on visual inspections and provided taken depth data tests were done on the specimens. Preparation of specimens was done by using an NQ2 impregnated diamond core bit. Prepared specimens photogrammetrically modelled with textured wireframes over a thousand photos for further studies. These samples, which were modelled in the computer environment, can be seen in Figure 13.

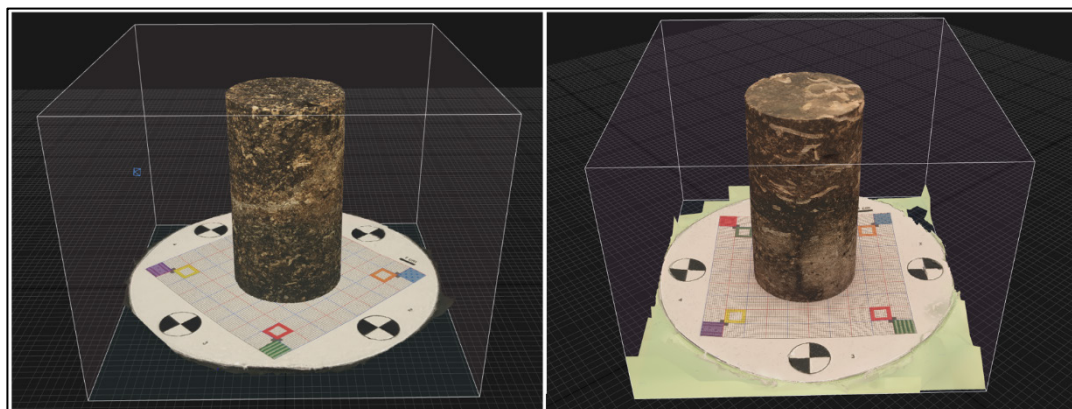


Figure 13. Photogrammetrically modelled Garzan Limestone specimens

3.2 Testing of Rock Samples

These specimens were divided into two groups for triaxial compressive strength test to obtain Cohesion (c) and internal friction angle (ϕ) of Garzan Limestone, and remaining specimens are tested in static deformability tests to observe the material behaviour under uniaxial loading and get elastic modulus (E) and Poisson's ratio (ν) of the Garzan Limestone.

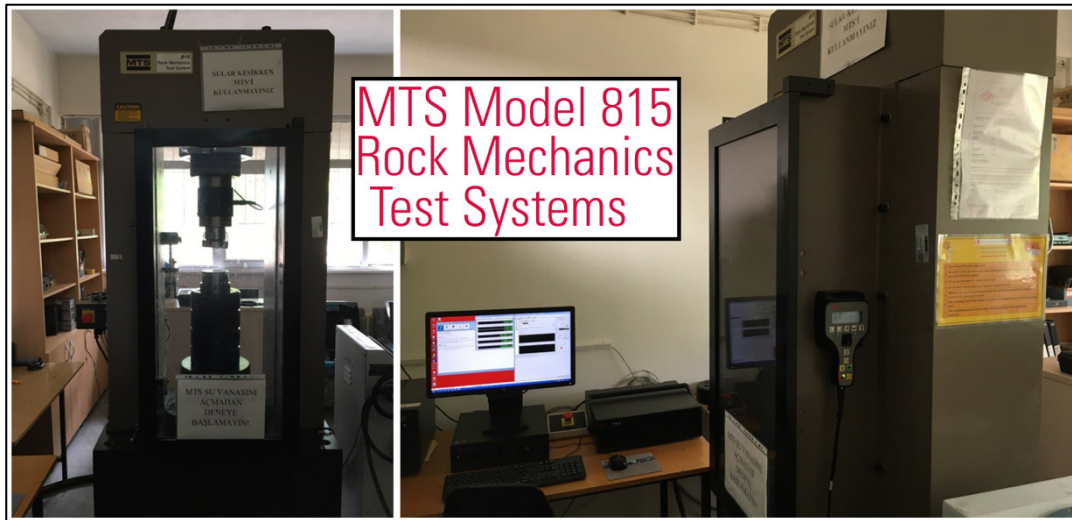


Figure 14. MTS 815 Rock Mechanics Test System

Deformability tests were conducted in MTS Model 815 Rock Mechanics Test system. MTS Model 815 is servo-controlled testing equipment that can be programmed for specific testing procedures, including different loading rates at different strain increments or different load paths such as cyclic loading. MTS testing system contains an embedded LVDT that records the displacement. The main loading frame and data logger device can be seen in Figure 14.

All tests were operated according to the suggested methods in ISRM's compilation of rock characterisation, testing and monitoring standards, the Blue Book. Triaxial compressive strength tests applied were made according to the standards created by Kovari et al. (1983). The applied static deformability test was carried out according to the standards set forth by Bieniawski & Bernede (1979).

3.2.1 Static Deformability Tests

The primary purpose of the static deformability test is to obtain a complete force(or load)-displacement curve of the tested specimen. The "complete stress-strain curve" term means the total recorded displacements that start at the first point of the elastic region with the initial loading to the peak value and finish when the post-peak behaviour is established and determined. Testing systems and control apparatus for conducting the test vary. The most practical and suggested one is measuring the displacements with lateral and axial extensometers. Other methods include using external LVDTs, attaching conventional electrical resistance strain gauges or utilising strain measurement transducers (Fairhurst & Hudson, 1999).

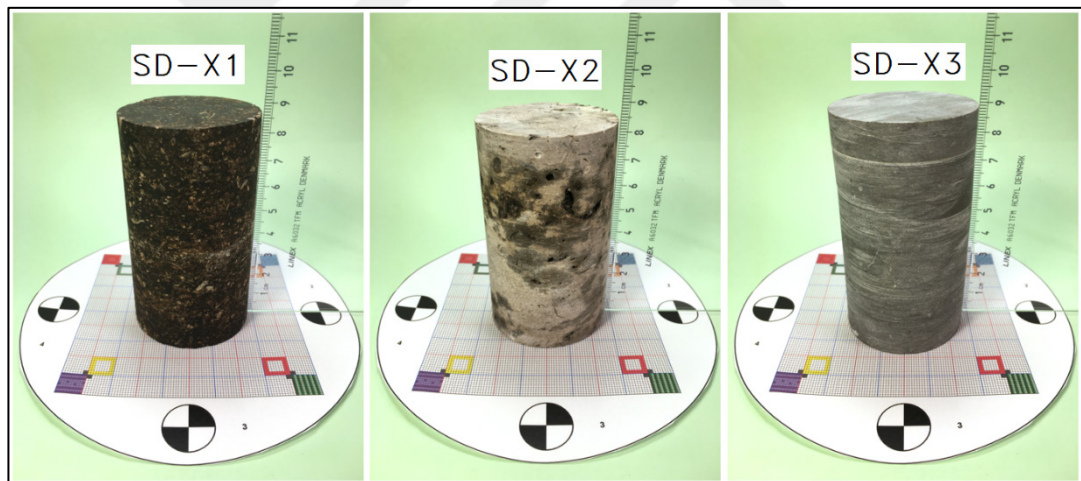


Figure 15. Static deformability test specimens

Three static deformability tests were done on the specimens in Figure 15. Measurement of displacements was done by utilising a dual axial extensometer kit and a circumferential extensometer kit. The computer system of the MTS815 was used for acquiring data. The two extensometer kits and embedded LVDT displacements were stored on the same data file from a single channel. Positioning of the extensometers and size adjustment of the circumferential extensometer's chain

can be seen in Figure 16. As suggested in the standards, loading was programmed and conducted at 0.001 mm/mm/s axial strain rate.

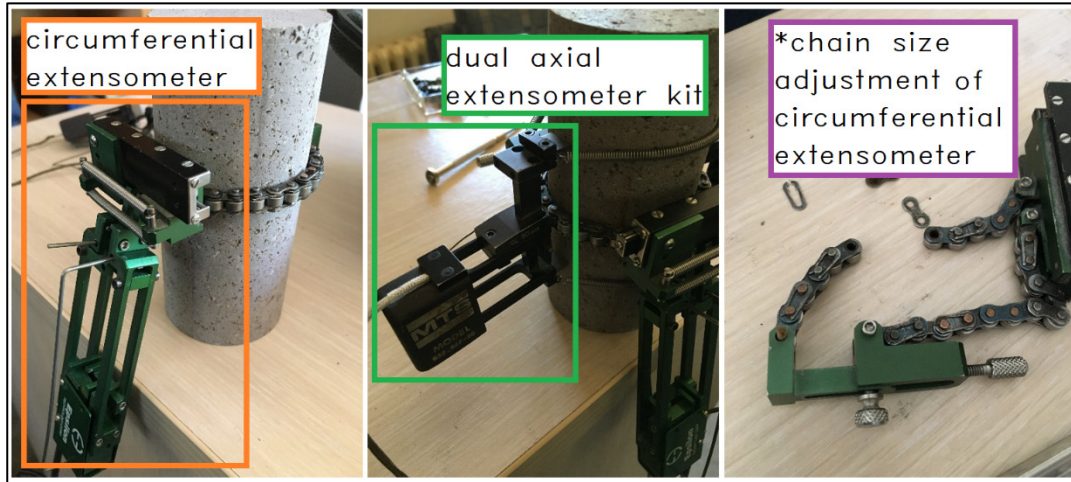


Figure 16. Positioning of extensometers

3.2.2 Triaxial Compression Strength Tests

Triaxial compression tests are done to calculate the relation between confining pressure and the strength of a cylindrical rock sample. There are three test types that differ from each other by means of utilising different failure envelopes. These are individual tests, multiple failure state tests and continuous failure state tests (Kovari *et al.*, 1983). In the scope of this study, individual tests were employed. Another critical point was to determine the confining pressure. The determination was done by considering the real sample locations and within the limits of the hydraulic line that feeds the triaxial cell with oil. Thus 10 MPa, 15 MPa and 20 MPa confining pressures were applied during the tests. As suggested in the standards, the load rate was adjusted to execute failure within the 5-15 minutes loading range. Figure 17 and Figure 18 show the set-1 and set-2 of specimens used in triaxial compression tests. As can be seen from the figures mentioned, the samples in the first set are oil-saturated fractured limestone samples representing the structure of the reservoir. On

the other hand, the specimens in the second set are limestone samples that do not contain any petroleum. For this reason, the parameters obtained from the specimens consisting of the form in the first set were used for the representation of the reservoir in the study.

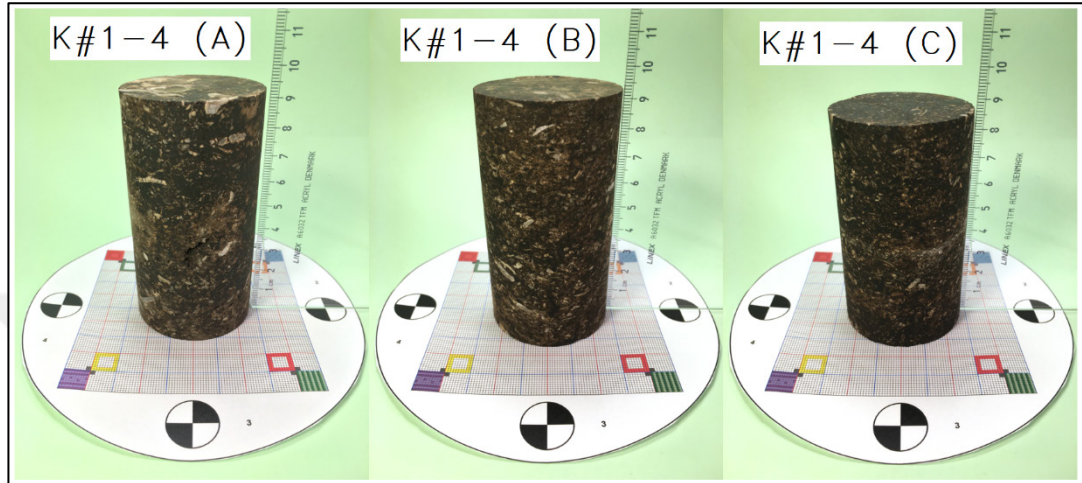


Figure 17. Triaxial compression test specimens (set-1)

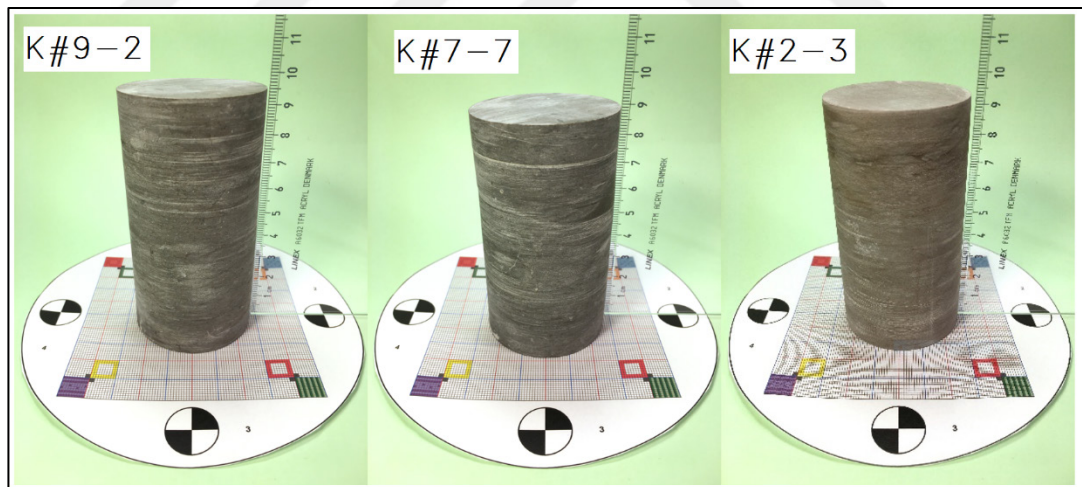


Figure 18. Triaxial compression test specimens (set-2)

3.2.3 Test Results

The stress-strain graphs for the deformability tests and Mohr-Coulomb failure envelopes were drawn according to the measured and calculated quantities. The Mohr circles representing the envelopes for the two sets are given in Figure 19 and Figure 20. The failure envelopes of the sets created as a result of the experiments carried out and the parameters obtained from these envelopes are given in Table 1.

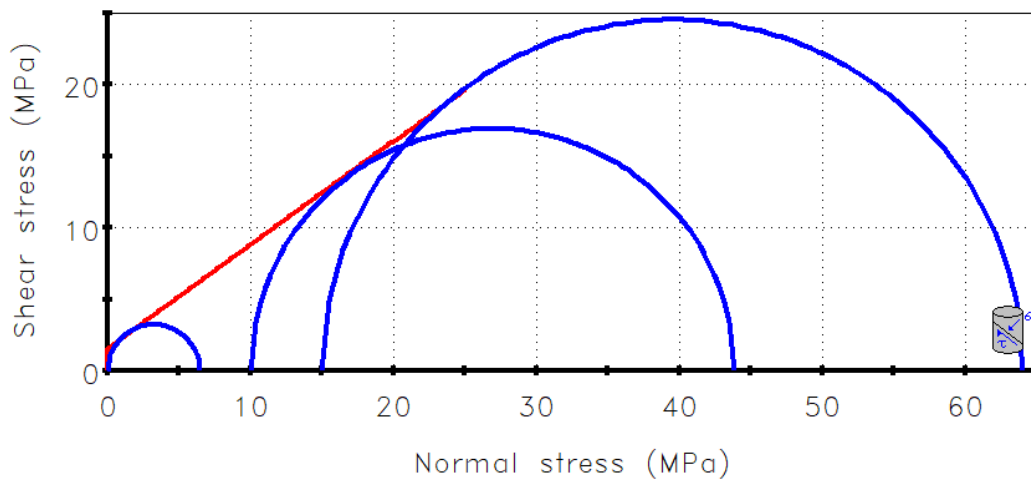


Figure 19. Mohr-Coulomb failure envelop of the set-1 specimens

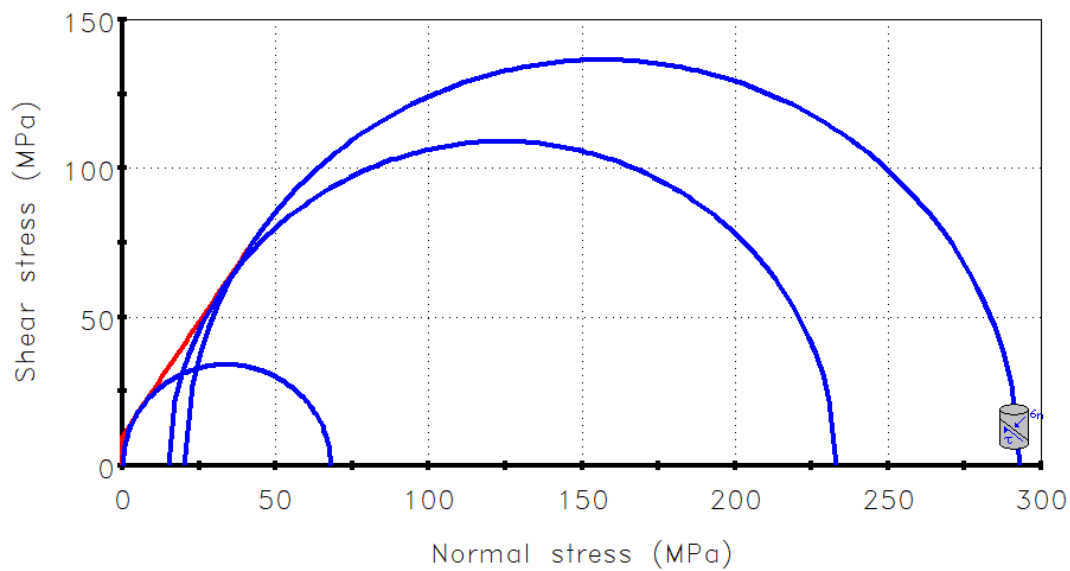


Figure 20. Mohr-Coulomb failure envelop of the set-2 specimens

Table 1. Triaxial compressive strength test results

Set ID	Cohesion	Friction angle	UCS
	C (MPa)	Φ (°)	σ_{ci} (MPa)
Set-1	1.6	34	6.2
Set-2	10.1	56	67.4

From the inspection of deformability test results in two samples, SD-X1 and SD-X2, strain-softening behaviour indicators were observed in the post-peak region. Figure 21 and Figure 22 shows the complete stress-strain graphs of the specimens. Non-linearity in the elastic part of the curve was observed for SD-X2. The elastic region, peak point and post-peak behaviour can be seen in the figures. Post-peak behaviour of the SD-X3 could not be observed.

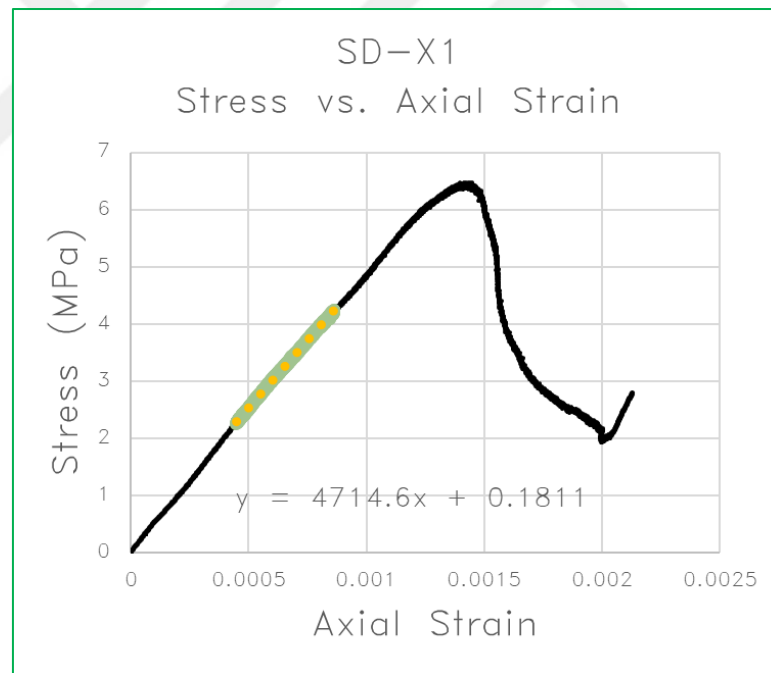


Figure 21. Complete stress-strain curve of the SD-X1

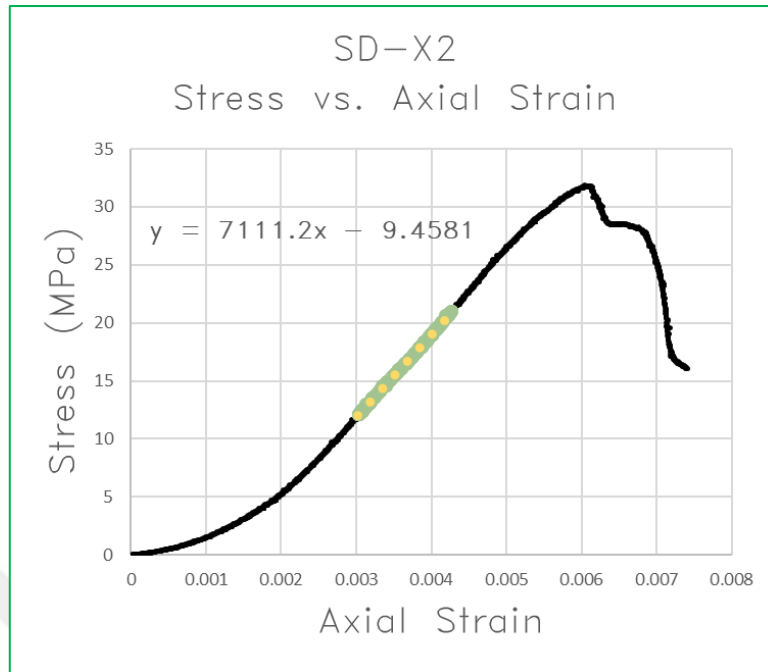


Figure 22. Complete stress-strain curve of the SD-X2

The static deformability test results are given in Table 2. Due to the limited sample size, sufficient data could not be produced for statistical study. When the test results are compared with visual observations, it can be concluded that the UCS value of the samples containing more oil will be lower. On the other hand, when post-peak behaviours are considered, it should be necessary to select the models to be made accordingly and carry out more experiments for constitutive model calibration.

Table 2. Static deformability test results

Specimen ID	UCS	Young's modulus	Poisson's ratio	Mass density
	σ_{ci} (MPa)	E_i (GPa)	ν	γ (kg/m ³)
SD-X1	6.4	4.7	0.24	2166
SD-X2	31.8	7.1	0.21	2462
SD-X3	68.6	5.3	0.26	2702

It should be noted that observation of post-peak behaviour can be difficult when measuring strains with extensometers. Due to rock behaviour, sudden changes in the form of the specimen can cause the extensometers to slip. Similarly, if the data collection sampling rate is kept low, this can result in information loss.

It has been observed that it is possible to interpret the results in two main branches. In this respect, it can be concluded that the samples with high saturation with oil diverge considerably from the reference limestone values and their strengths are quite low. On the other hand, it can be deduced that the samples with little or no oil saturation are close to the mean reference values and in accordance with the predictable limestone behaviour. It should be kept in mind that the values obtained as a result of these studies are obtained from a limited number of samples and cannot represent the whole Batı Raman heavy oil reservoir. It is worthwhile to note that in the following numerical modelling chapter, set-1 laboratory test results have been taken into account, thinking that it represents the Batı Raman Oil field better based on visual oil content comparison.



CHAPTER 4

NUMERICAL STUDIES

This chapter first covers a preliminary investigation for elastic responses of tunnels by using the boundary element method. Then, a brief introduction to the analytical convergence confinement method (CCM) and ground reaction curves of the tunnel are introduced. Lastly, the theory of finite difference methods (FDM) is introduced, and 2D and 3D twin FLAC tunnel model results are presented.

4.1 Introduction

Tunnel stability analysis has been addressed in many ways and can be evaluated with different approaches. It is possible to divide these approaches into three: empirical methods, analytical methods and numerical methods. The most frequently used analytical methods, the convergence confinement method and the FDM numerical method, were studied in this thesis.

The study was started by utilising conventional approaches to make decent predictions and determine elastic solutions for the modelled geometry. Different pillar widths were modelled with examine2d, an elastic boundary method solver program designed for this purpose. The study then turned to analytical methods to examine the rock mass behaviour under hydrostatic stress in single tunnels. After these analytical results were presented together, the FDM program FLAC was verified by these results. In the verified FLAC model, 2D plane strain analysis was performed, and as a result of this analysis, the plastic zone width in the twin tunnels and the stresses and displacements on the pillars were shown. The same analyses continued by switching to FLAC^{3D}, and the strain, stress and displacement amounts in the crest and wall regions of the tunnels were modelled and analysed in 3D. As a final step, Canbolat *et al.*'s (2020a) experiment was modelled in metric scale in the

3D model, and the effects of drilled boreholes over the tunnels were examined. As a result of this, the failure zone was calculated, and an inference was made to determine the production amount based on the relationship between the failure volume and the total volume. It should be noted that in the numerical modelling no support for the tunnels and no casing for the boreholes were assumed.

The parameters used in the study were determined as a result of the experiments and in accordance with the parameter determination principles (Hoek & Brown, 1997; Kang *et al.*, 2017).

The input parameters for the problem of the Batı Raman tunnel scenario can be stated as follows;

- Circular tunnel with a radius, $a = 2$ m
- Insitu hydrostatic stress state, $\sigma_o = 33$ MPa (at the depth samples were taken)
- Internal pressure, $p_i = 0$ (for the unsupported case)
- Uniaxial Compressive Strength of the intact rock, $\sigma_{ci} = 6.2$ MPa
- Shear Modulus, $G = 1.9$ GPa (from the relationship $E=2G(1+\nu)$)
- Poisson's ratio, $\nu = 0.24$
- Young's Modulus, $E = 4.7$ GPa
- Internal Friction Angle, $\phi=34^\circ$
- Cohesion, $c = 1.6$ MPa (Mohr Coulomb medium)
- Dilation angle ($\psi=0^\circ$ for non-associated flow, $\psi=\phi$ for associated flow)

4.2 Elastic model visualisation

The analysis started with utilising a 2D plane strain boundary element modelling tool for the elastic stress analysis of circular twin tunnels. The boundary element method creates meshes for the boundaries of underground openings and modelled rock mass. The resultant graphical representation of elastic model stress analysis can be visualised by making simple manipulations of parameters for the model. For this purpose, Examine 2D (Rocscience, 2013) program was used to establish preliminary

parametric elastic designs. Examine 2D is a restricted tool that assumes plane strain condition as the basis and the modelled material as homogenous, isotropic, and linearly elastic. Based on the selected failure criterion, quantitative analytical results, including strength factor, principal stress difference, can be obtained for the contour patterns in the model. These results can indicate possible plastic deformations by calculating the ratio between analytic rock mass strength and induced stresses of the selected points. In short, the program was used to get a starting point for the numerical analysis work and to have an insight into possible locations where induced stresses can overrun the MC failure envelop (Fraldi & Guarracino, 2011).

In Examine 2D, the twin circular tunnels were created. The properties for the elastic boundary element stress analysis are set as follows; Field stress type assumed constant, elastic material behaviour assumed isotropic, and the failure criterion for the rock was selected as Mohr-Coulomb. Elastic rock mass properties are used according to the static deformability test results, including elastic modulus and Poisson's ratio. The failure envelop for the MC constitutive model is defined according to the triaxial test results. The stress field is assumed hydrostatic (Ebell *et al.*, 2017). Strength Factor values in elastic boundary element solutions obtained according to the entered parameters are given for 4 pillar widths: 20m, 15m, 11m and 5m from Figure 23 to Figure 26. Strength factor calculations in Examine2D represent only the ratio between the material strength and the induced stress if the SF is less than 1, which tells that the material would fail under the prescribed stress state.

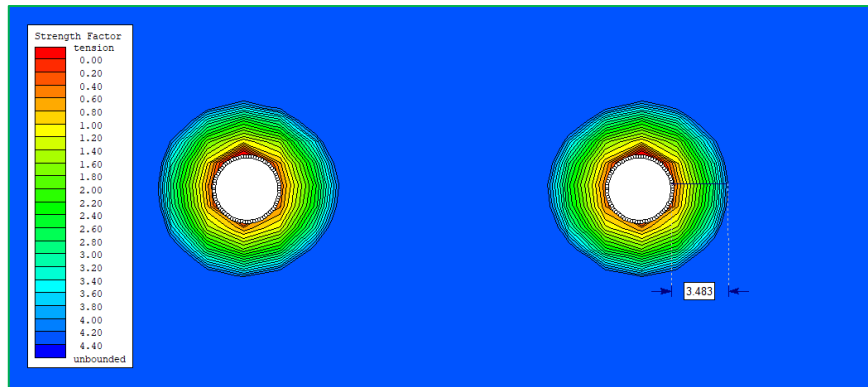


Figure 23. 20m pillar width

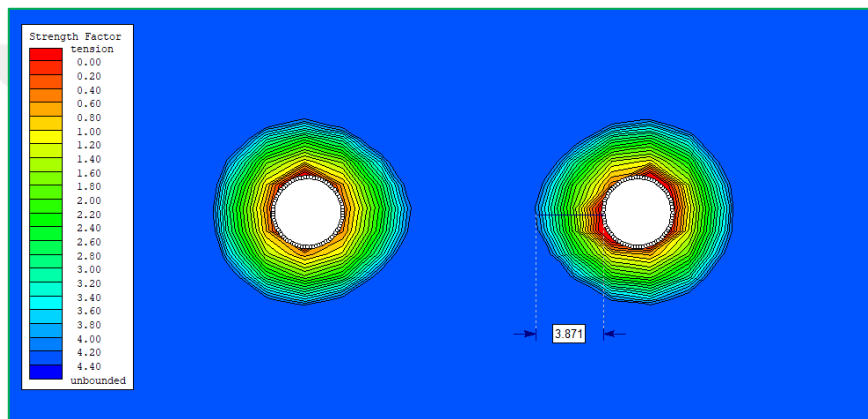


Figure 24. 15m pillar width

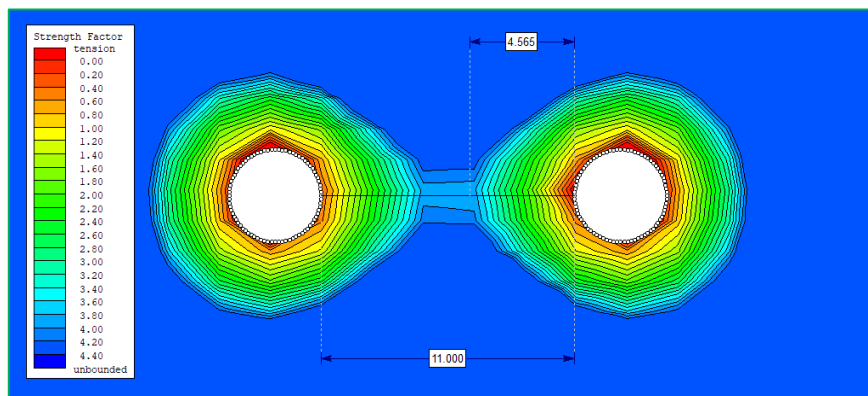


Figure 25. 11m pillar width

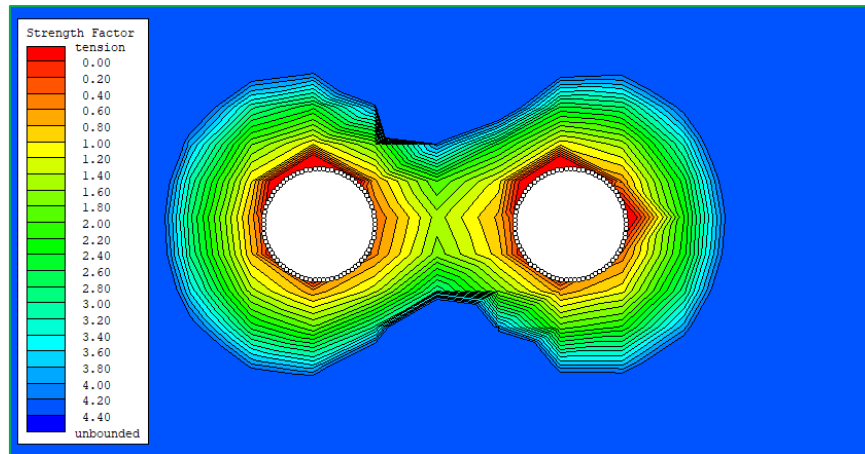


Figure 26. 5m pillar width

From the results of the elastic analysis, it can be assumed that pillar width can be acceptable with 20 m width. Another interpretation is that, as a rule of thumb, the minimum distance between two tunnels should be approximately equal to the diameter of the larger tunnel (Evert Hoek, 2007). According to the results of this analysis, stability is expected to be lost when the distance between the tunnels decreases to 11 meters.

4.3 Analytical investigation of the Circular Tunnel

Determination of plastic zone extents and radial converge around a circular opening in underground is one of the fundamental problems in underground rock mechanics. This problem has been investigated for a long time, and there are numerous approaches and proposed solutions for the problem (Carranza-Torres, 2003). Many authors have been focused on single tunnel calculations (Detournay, 1986; Duncan Fama *et al.*, 1991; Panet, 1995; Salencon, 1969). Other authors presented analytical solutions for twin tunnels (Wang *et al.*, 2017).

In this part, three of the presented analytical solutions will be studied for the Batı Raman tunnels. Analytical solutions will be limited to a single tunnel investigation. However, exact solutions will be used in the verification of 2D single tunnel cases.

For this reason, based on the solution presented by Carranza-Torres (2003) for Mohr-Coulomb material.

From the definition of the MC yield criterion, principal stress can be stated as follows.

$$\sigma_1 = K_\phi \sigma_3 + \sigma_{ci} \quad (1)$$

where K_ϕ stands for passive reaction coefficient and σ_{ci} stands for the UCS of the rock mass. K_ϕ and σ_{ci} can be calculated as follows,

$$\begin{aligned} K_\phi &= \frac{1 + \sin \phi}{1 - \sin \phi} \\ \sigma_{ci} &= 2c\sqrt{K_\phi} \end{aligned} \quad (2)$$

At this point it the volumetric response of the elasto-plastic material should be stated. Materials can experience volumetric changes once they are in the plastic region. Depending on the material characteristics, the dilation angle controls this volumetric change. Basically, if it is assumed as there will not be any volumetric changes, the flow in the plastic range is classified as non-associated. Similarly, if volumetric changes occur and the dilation angle is taken as equal to the internal friction angle, then the plastic flow is classified as associated (Carranza-Torres, 2003). It should be remembered that geomaterial behaviour is influenced by many different factors, and the responses vary. Three main mechanisms that cause damage and volumetric changes are pore collapse occurrence due to hydrostatic stress state and microcrack formation due to tensile and shear failures (Huang *et al.*, 2021). Fossum and Brannon (2006) showed that the mechanisms mentioned above could be observed and investigated due to the porous and microcrack bearing structure of limestone samples from the results of triaxial compression tests.

In order to visualise the volume expansion phenomenon, shear failure volume increase and pore collapse can be seen in Figure 27.

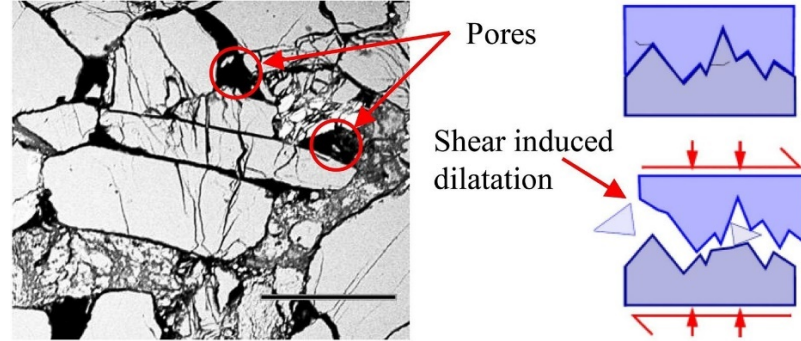


Figure 27. Volume increase in shear failure and pore collapse (Brannon *et al.*, 2009; Huang *et al.*, 2021)

Considering an underground tunnel in porous rock that is saturated with this damage, considerations must be made. Thus, overall high overburden pressure and hydrostatic stress state assumption and the focus on porous limestone material determined the choice of plastic potential function selection. The role of dilatancy in the MC model can affect the estimation significantly. Determination of the degree of dilatancy, dilation angle can be achieved by results of volumetric strain and axial strain charts of multiple triaxial tests (Maranha & Maranhã des Neves, 2009).

For the consistency in this study, no further investigations were made on the dilatancy characteristics of Garzan Limestone. In this analytic solution, associated plastic flow-rule is used. Failure envelop of Garzan Limestone is given in Figure 28. When the following transformation in (3) is made, the cohesion value in the envelope can be hidden (Anagnostou & Kovari, 1993) and hence simplified form of the envelope can be written. Both envelopes can be seen in Figure 28.

$$\begin{aligned} S_1 &= \sigma_1 + \frac{\sigma_{ci}}{K_\phi - 1} \\ S_3 &= \sigma_3 + \frac{\sigma_{ci}}{K_\phi - 1} \end{aligned} \quad (3)$$

$$S_1 = K_\phi S_3 \quad (4)$$

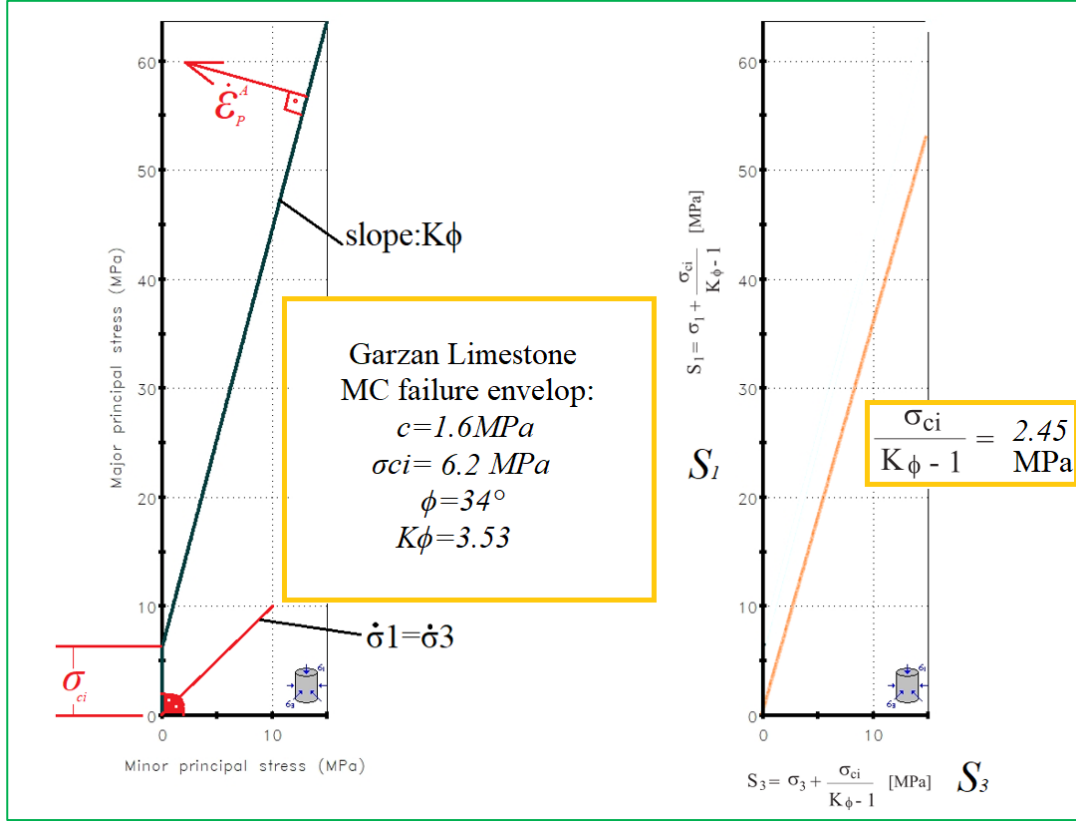


Figure 28. MC failure envelop (left), and transformed Cohesion hidden envelop (right) of Garzan Limestone

After making this simplification and transformation of principal stresses, the transformation of insitu stress, internal pressure and critical value of internal pressure are also made (5) (Carranza-Torres, 2003).

$$\begin{aligned} S_o &= \sigma_o + \frac{\sigma_{ci}}{K_\phi - 1} \\ P_i &= p_i + \frac{\sigma_{ci}}{K_\phi - 1} \\ P_i^{cr} &= p_i^{cr} + \frac{\sigma_{ci}}{K_\phi - 1} \end{aligned} \quad (5)$$

The critical value of internal pressure now can be defined in terms of transformed parameters (6) . In this way, critical internal pressure can be calculated. Then the radius of the plastic zone can be evaluated (7).

$$\frac{P_i^{cr}}{S_o} = \frac{2}{K_\phi + 1} \quad (6)$$

$$\frac{R_{plastic}}{a} = \left[\frac{P_i^{cr}}{P_i} \right]^{\frac{1}{(K_\phi - 1)}} \quad (7)$$

Then, the radial convergence at the wall is given by the following equation (8) .

$$\begin{aligned} \frac{u_r^a}{a} \cdot \frac{2G}{S_o - P_i^{cr}} = & \frac{(K_\psi - 1)(K_\phi - 1) - 2C}{(K_\psi + 1)(K_\phi - 1)} + \frac{2(K_\psi + K_\phi) + 2C}{(K_\psi + 1)(K_\psi + K_\phi)} \cdot \left(\frac{R_{plastic}}{a} \right)^{K_\psi + 1} \\ & + \frac{2C}{(K_\psi + K_\phi)(K_\phi - 1)} \cdot \left(\frac{a}{R_{plastic}} \right)^{K_\phi - 1} \end{aligned} \quad (8)$$

where C equals to (9),

$$C = (1 - \nu)(K_\phi K_\psi + 1) - \nu(K_\phi + K_\psi) \quad (9)$$

If these equations are solved with the Garzan parameters, the following results are obtained (10).

$$\begin{aligned}
K_\phi &= 3.53, \frac{\sigma_{ci}}{K_\phi - 1} = 2.45 \text{ MPa} \\
S_o &= \frac{\sigma_o + \sigma_{ci}}{(K_\phi - 1)} = 35.45 \text{ MPa} \\
p_i &= \frac{p_i + \sigma_{ci}}{(K_\phi - 1)} = 2.45 \text{ MPa} \\
P_i^{cr} &= \frac{2S_o}{K_\phi + 1} = 15.65 \text{ MPa} \\
p_i^{cr} &= 13.2 \text{ MPa} \\
R_{plastic} &= 4.2 \text{ m} \\
\frac{U_r^a}{a} &= 3\%, (\psi = 0^\circ) \\
\frac{U_r^a}{a} &= 15\%, (\psi = \phi)
\end{aligned} \tag{10}$$

Carranza-Torres (2003) also provides a series of pretty practical charts to use for simple hand calculations. It must be noted that the wall convergence charts are suitable for a single Poisson's ratio. The utilisation of the charts can be seen in Figure 29, Figure 30, Figure 31 and Figure 32. Corresponding values of Garzan Limestone analysis are marked on each chart.

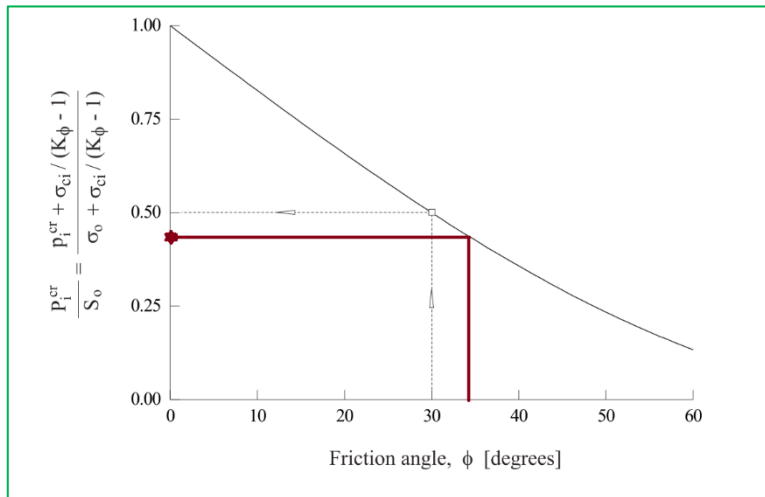


Figure 29. Critical internal pressure calculation

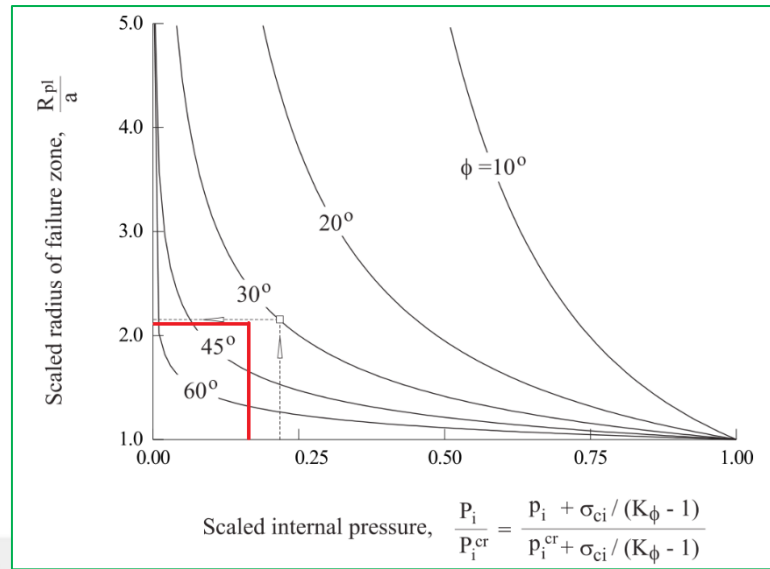


Figure 30. Plastic zone radius

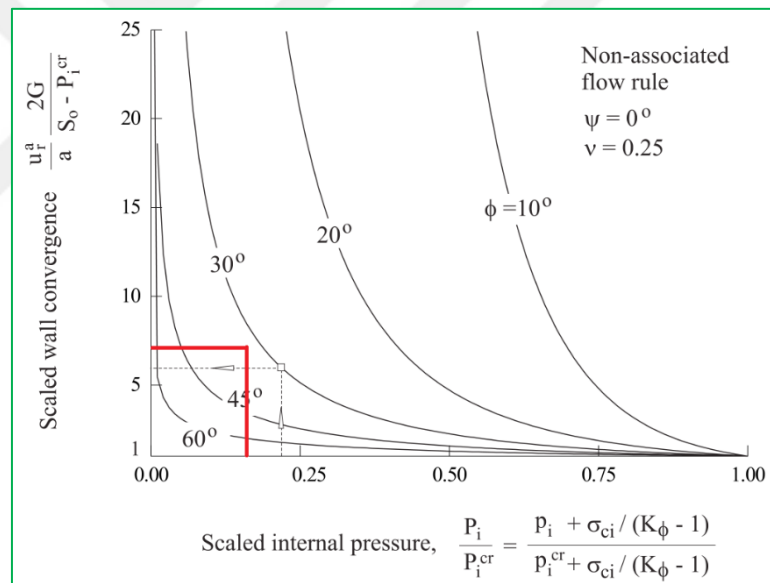


Figure 31. Wall convergence (non-associated flow)

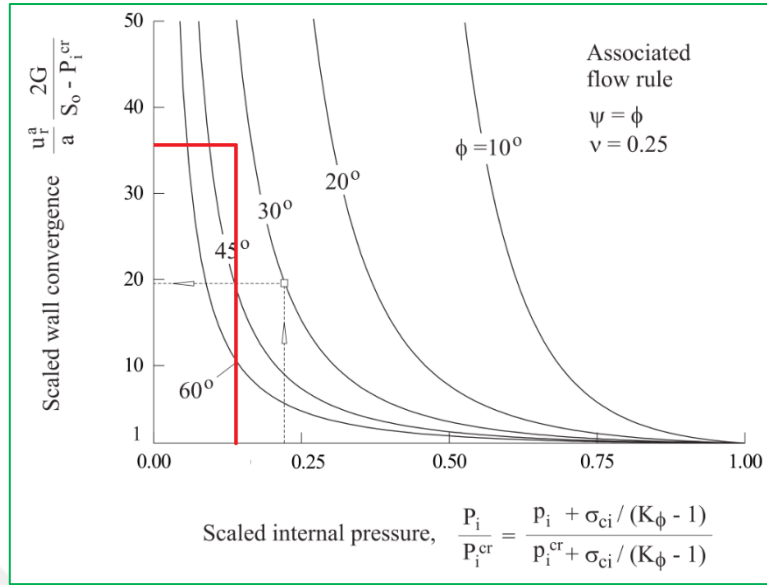


Figure 32. Wall convergence (associated flow)

As a final remark for the solution, Carranza-Torres (2003) presents universal charts to calculate GRC that can be used to determine the tunnel behaviour at given parameters. The ground reaction curves for Garzan Limestone based on the Carranza-Torres solution is given in Figure 33.

Another analytical solution that allows obtaining a ground reaction curve is given by Duncan Fama (1993). The Duncan Fama solution is another analytic approach based on MC failure criteria. The parameters used in the solution are the strength of rock mass, Poisson's ratio, elastic moduli, and internal friction angle (Duncan Fama, 1993).

The Duncan Fama analytical solution is implemented into the Rocsupport program by RocScience Inc., with a very user-friendly interface. For this reason, calculations based on the Duncan Fama solution were conducted on RocSupport software. Ground reaction curves were obtained for a single circular tunnel in the elasto-plastic Garzan limestone rock mass under hydrostatic insitu stresses.

Initially, the radius of the plastic zone and critical internal pressure for the same parameters are calculated by entering the same parameters used in Carranza-Torres (2003)

solution. Results of the Duncan Fama (1993) solution and comparison with Carranza-Torres solution results can be seen in Table 3.

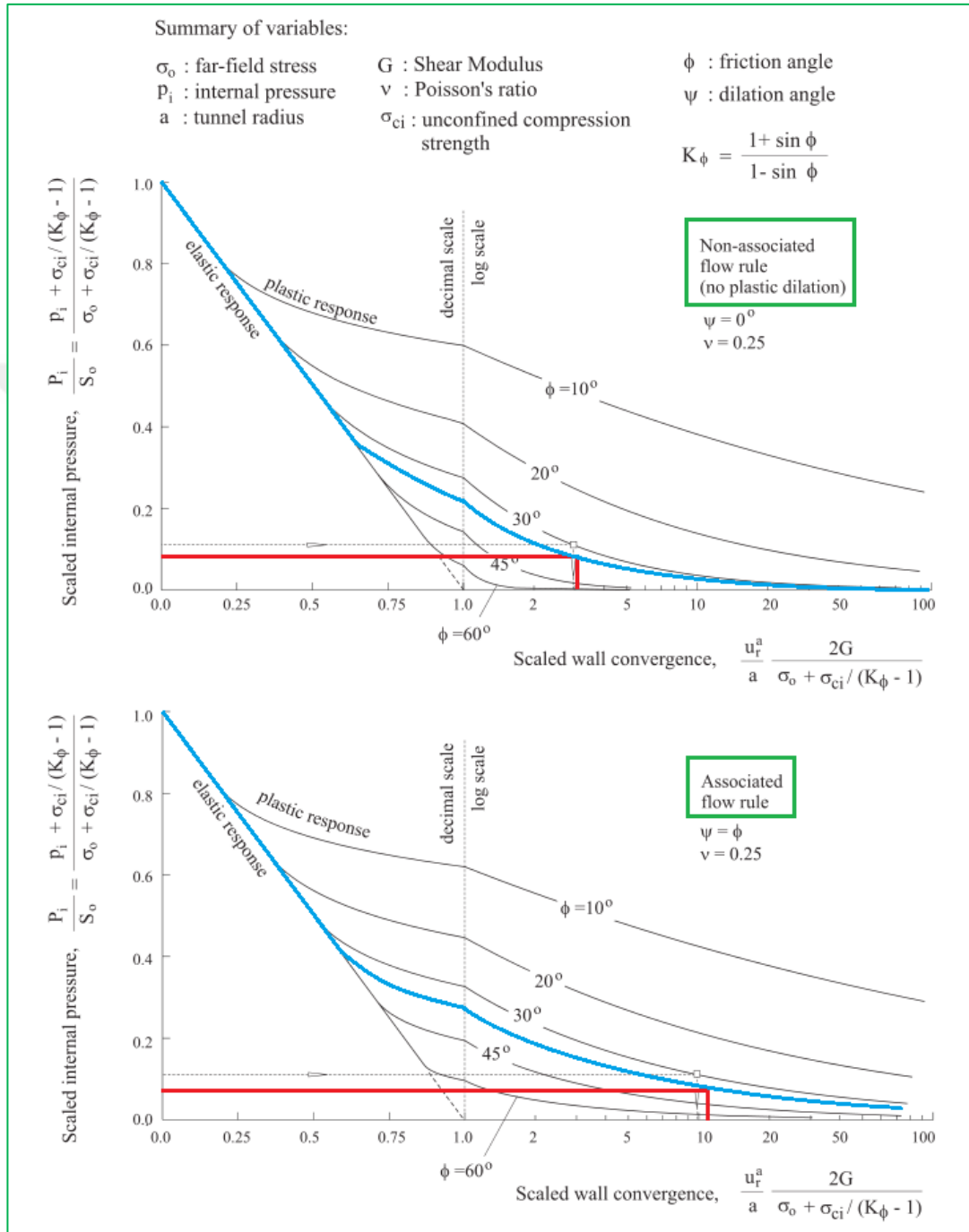


Figure 33. GRC based on Carranza-Torres (2003)

Table 3. Comparison of analytical solutions

	Plastic zone radius	Critical internal pressure	Wall/tunnel convergence
	$R_{plastic} (m)$	$P_i^{cr} (MPa)$	(%)
Carranza-Torres (2003)	4.17	13.20	3
Duncan Fama (1993)	4.16	13.18	3

At this stage, the support requirements and the stability of the circular tunnel can be preliminarily estimated. Some researchers presented guidelines in terms of tunnel convergence and rock mass strength ratio to estimate possible squeezing problems (E Hoek & Marinos, 2000). When these guides are utilised for the Garzan problem, severe squeezing problems can be expected for the tunnel operations (Figure 34).

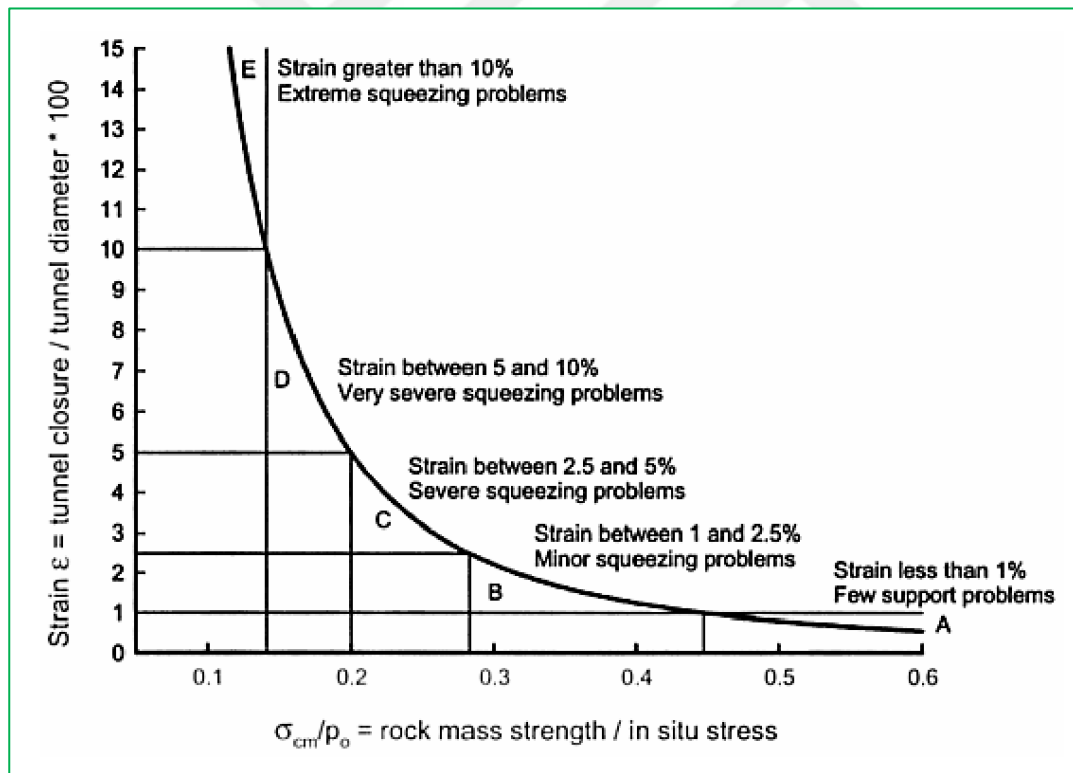


Figure 34. Relationship between tunnel convergence and strength

As it can be observed from Figure 34, depending on the tunnel closure amount and rate, problems can occur. For this reason, the time for adding supports is critical for the problem. The authors also suggest support types for each class indicated in Figure 34. For the severe or minor squeezing issues category, it is recommended to apply rapid supports and support the tunnel face in worse cases (Hoek & Marinos, 2000). This recommendation can be obtained as valid reasoning for TBM usage in Batı Raman tunnels. The face support of TBMs and rapid support installation rate in sequential lining operations can justify the selection of the tunnelling method in Batı Raman.

Support system design is another crucial point in the stability of tunnels. However, in the scope of this study, a detailed investigation of support parameters, types, or market availability for specific supports is not included. Still, a brief evaluation in RocSupport is conducted to provide a starting point for further studies. A safety factor is defined in RocSupport as the ratio between maximum support pressure of the support and equilibrium pressure which is the intersection of GRC and support reaction curves. A FoS should be greater than 1 to satisfy the stability of the tunnel. The ground reaction curve calculated based on the Duncan Fama (1993) solution can be seen in Figure 35. By activating the add support option, support parameters, support installation time regarding the strain occurrence or distance between the face and supports can be selected. In TBM tunnelling, permanent supports start behind the shield between excavation and support installation (Nematollahi & Dias, 2019). TBM shield supply temporary supports. Considering a double TBM shield length and segmental concrete linings suitable distance from the tunnel face can be selected. For demonstration purposes, one scenario can be presented. In a system, 5 MPa maximum available support pressure and 1% max. avg. strain concrete segmental lining can be applied 2 meters away from the tunnel face. In this way, tunnel convergence can be decreased from 2.98% to 1.96% and plastic radius from 4.16m to 3.47 m. The resultant FoS for the support can be calculated approximately as 3.5. The GRC – SRC relation can be seen in Figure 36. Designing a robust TBM support system requires more investigations rather than only the required support pressure,

including interlocking of the segments, segment shapes, trailer, shield and cutter pressures (Nematollahi & Dias, 2019). RocSupport also enables the user to calculate long term GRC for a project which gradually reduces the strength of the rock mass. This phenomenon should also be considered when designing a proper support system. For example, in the given support scenario, if 30% strength reduction is applied for long term calculation, final convergence increases from 2.98% to 5.61% for the unsupported case, and the supported case increases from 1.96% to 2.26%. The FoS for the supported case decreases dramatically over the strength reduction and moves from 3.53 to 1.71.

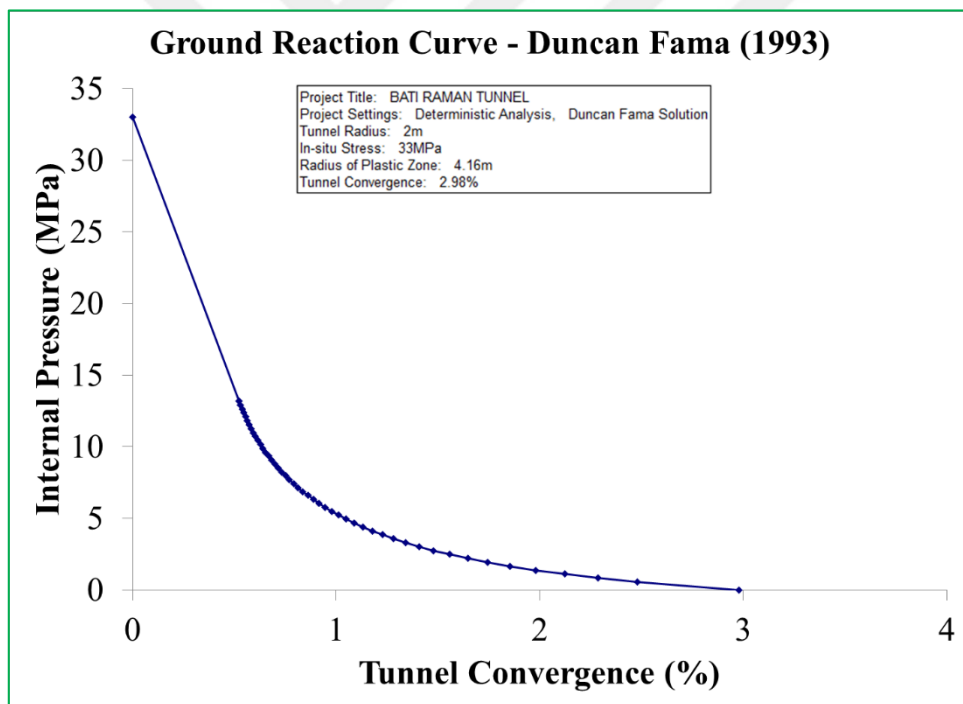


Figure 35.GRC based on Duncan Fama (1993)

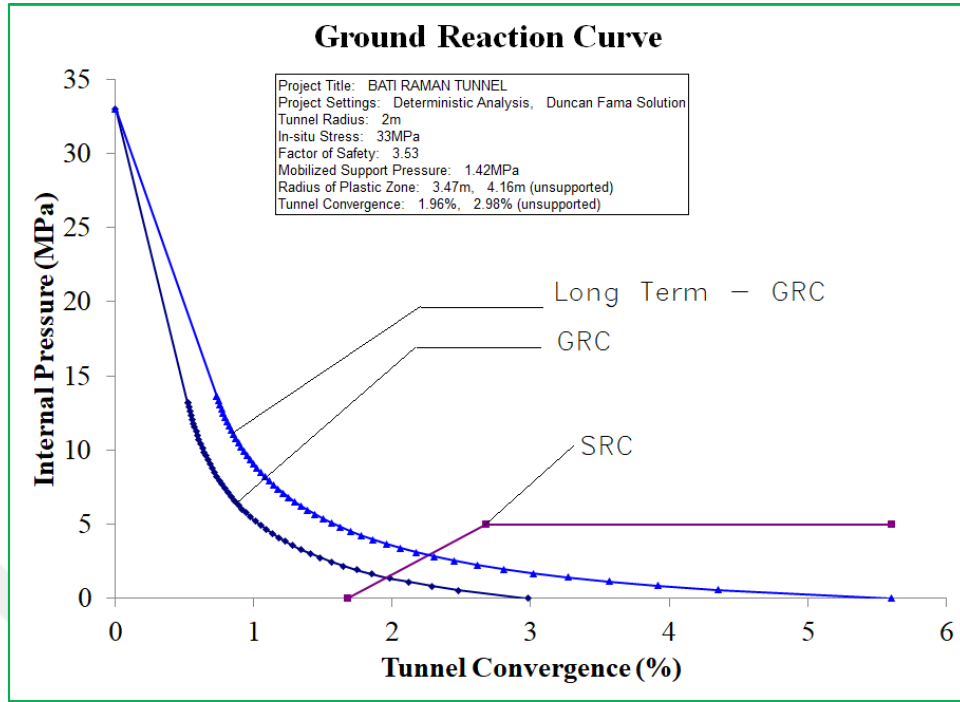


Figure 36. GRC-SRC for support evaluation

Another exact solution can be obtained by Salençon (1969). In this study, this solution is used in the verification of the FLAC finite difference solver.

Firstly, the closed-form solution of Salençon (1969) is given and calculated with previous parameters for Garzan as follows;

$$R_o = a \left[\frac{2}{K_p + 1} \frac{P_o + \frac{q}{K_p - 1}}{P_i + \frac{q}{K_p - 1}} \right]^{\frac{1}{(K_p - 1)}} \quad (11)$$

$$K_p = \frac{1 + \sin \phi}{1 - \sin \phi}$$

where R_o = plastic zone radius

a = tunnel radius

$q = 2.c.\tan(45+\phi/2)$

P_o = insitu stress

P_i = internal pressure

Radial stress at the plastic radius can be calculated as follows,

$$\sigma_{re} = -\frac{1}{K_p + 1}(2P_o - q) \quad (12)$$

Stress values inside the plastic region from a distance "r" away from the tunnel centre can be calculated as follow,

$$\begin{aligned} \sigma_r &= \frac{q}{K_p - 1} - \left(P_i + \frac{q}{K_p - 1} \right) \left(\frac{r}{a} \right)^{K_p - 1} \\ \sigma_r &= \frac{q}{K_p - 1} - K_p \left(P_i + \frac{q}{K_p - 1} \right) \left(\frac{r}{a} \right)^{K_p - 1} \end{aligned} \quad (13)$$

The displacements and stresses in the elastic zone can be obtained as follows,

$$\begin{aligned} \sigma_r &= -P_o + (P_o - \sigma_{re}) \left(\frac{R_o}{r} \right)^2 \\ \sigma_\theta &= -P_o - (P_o - \sigma_{re}) \left(\frac{R_o}{r} \right)^2 \\ u_r &= - \left(P_o - \left(\frac{2P_o - q}{K_p + 1} \right) \right) \left(\frac{R_o}{2G} \right) \left(\frac{R_o}{r} \right) \end{aligned} \quad (14)$$

Similarly, plastic region displacements and stresses,

$$u_r = -\frac{r}{2G}\chi$$

$$\begin{aligned}\chi = & (2\nu - 1) \left(P_o + \frac{q}{K_p - 1} \right) \\ & + \left(\frac{(1 - \nu)(K_p^2 - 1)}{K_p + K_{ps}} \right) \left(P_i + \frac{q}{K_p - 1} \right) \left(\frac{R_o}{a} \right)^{(K_p - 1)} \left(\frac{R_o}{r} \right)^{(K_{ps} + 1)} \\ & + \left((1 - \nu) \frac{(K_p K_{ps} + 1)}{(K_p + K_{ps})} - \nu \right) \left(P_i + \frac{q}{K_p - 1} \right) \left(\frac{r}{a} \right)^{(K_p - 1)}\end{aligned}\quad (15)$$

$$K_{ps} = \frac{1 + \sin \psi}{1 - \sin \psi}$$

where ψ = dilation angle, G = shear modulus, ν = Poisson's ratio

by calculating (11) and (12) the critical pressure as 13.22 MPa and the plastic radius as 4.201 m can be obtained. The comparison of all analytical solutions is given in Table 4.

These results were verified with a 2D plane-strain solution of a quarter-symmetry model in FLAC. For this purpose, the model in Figure 37 was generated. The 2m radius and MC constitutive model parameters were applied, initial stress tensors on every grid were set to 33 MPa, boundary conditions were set according to the quarter symmetry.

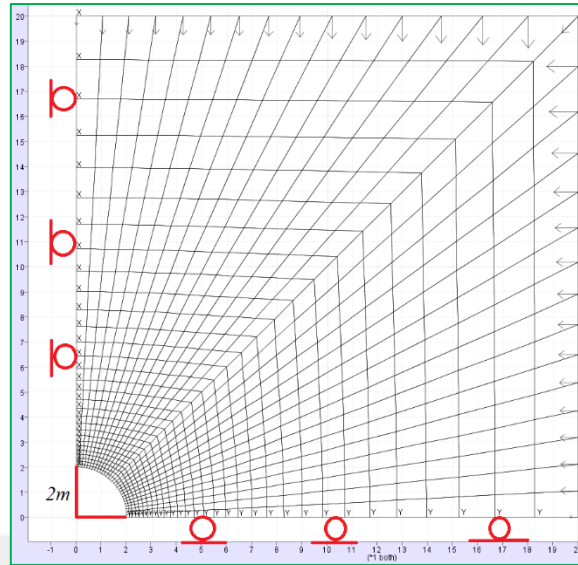


Figure 37. FLAC verification model

The verification results show that the plastic zone radius can be obtained as 4.3m and maximum wall displacement as 60.89 mm that verifies the model according to the exact solutions.

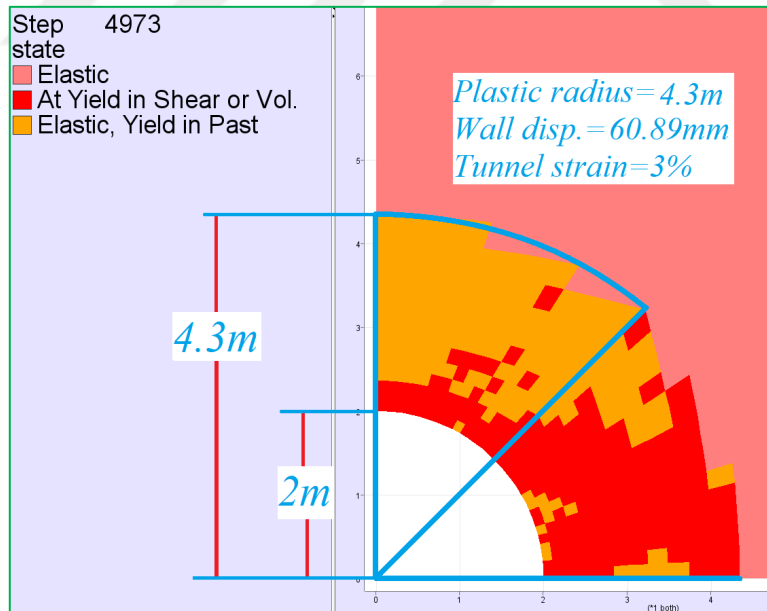


Figure 38. Plastic extends in FLAC

Table 4. Analytical solutions

	Plastic zone radius	Critical internal pressure	Wall/tunnel convergence
	$R_{plastic} (m)$	$P_i^{cr} (MPa)$	(%)
Carranza-Torres (2003)	4.17	13.20	3
Duncan Fama (1993)	4.16	13.18	3
Salençon (1969)	4.20	13.22	3

The ground reaction curves of the Batı Raman tunnel problem drawn in line with analytical calculations and FLAC verification are given in Figure 39.

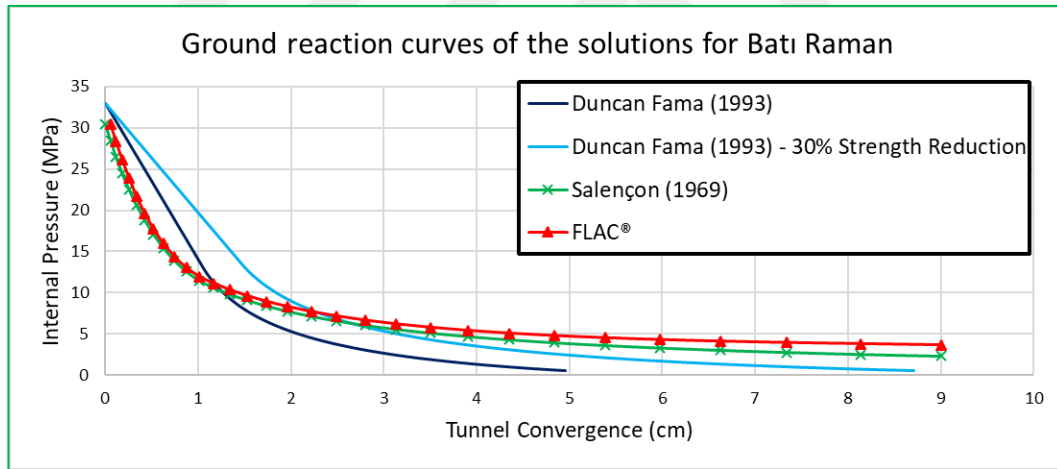


Figure 39. GRCs for the Batı Raman tunnel with 2m radius

4.4 Overview of Finite Difference Methods and FLAC

In this thesis study, numerical solutions for the stability analysis were obtained based on the finite difference method. Its application to geotechnical problems was achieved with the introduction of the code FLAC in 1986 by Itasca Consulting Group, Inc. FLAC (Itasca, 2002), Fast Lagrangian Analysis of Continua is a two-dimensional numerical modelling code which is used for simulating problems and conducting analysis in geotechnical problems of naturally occurring soil, rock, groundwater materials. FLAC also enables the user to analyse different structural elements or ground supports. Later on, FLAC^{3D} was released, which uses the same techniques and method for modelling problems in 3D. These codes are used to analyse, test and design geotechnical problems by different engineering disciplines, mainly in mining, civil and geotechnical applications.

FLAC uses the explicit finite difference formulation to simulate and analyse complex behaviours that contain multiple stages of tunnel excavations, non-linear material response, plastic indicators, and plastic flow characteristics after reaching the post-peak stage. In FDM formulation, the region of interest is discretised by connected nodes and meshed thoroughly, similar to finite element methods. Finite-difference methods (FDM) are numerical techniques used to solve differential equations by approximating derivatives employing finite differences in numerical analysis (Sastry, 1967). The solution's corresponding value at these specified nodes is calculated by solving ordinary or partial differential equations containing finite differences and values from adjacent points. The spatial domain and time step can also be discretised or split into a finite number of steps (Grossmann *et al.*, 2007).

4.5 Plane Strain Analysis of Parallel Twin Tunnels

In order to observe the effects of twin tunnel excavations on each other and on the pillar, an analysis was made in the plastic material model. In this analysis, the hydrostatic stress condition was applied, and the stress of 33MPa was applied to the boundaries of the square model. Considering that the tunnels will be opened sequentially, first the first tunnel and then the second tunnel were opened, and the effects were observed. It took about 18 thousand steps for the model to reach equilibrium. The contours of the induced stresses and the dimensions of the plastic regions that emerged after this simulation are given in the figures below. As can be seen, the plastic zone expands by about 30cm compared to the single tunnel situation, reaching a radius of approximately 4.6 meters in total.

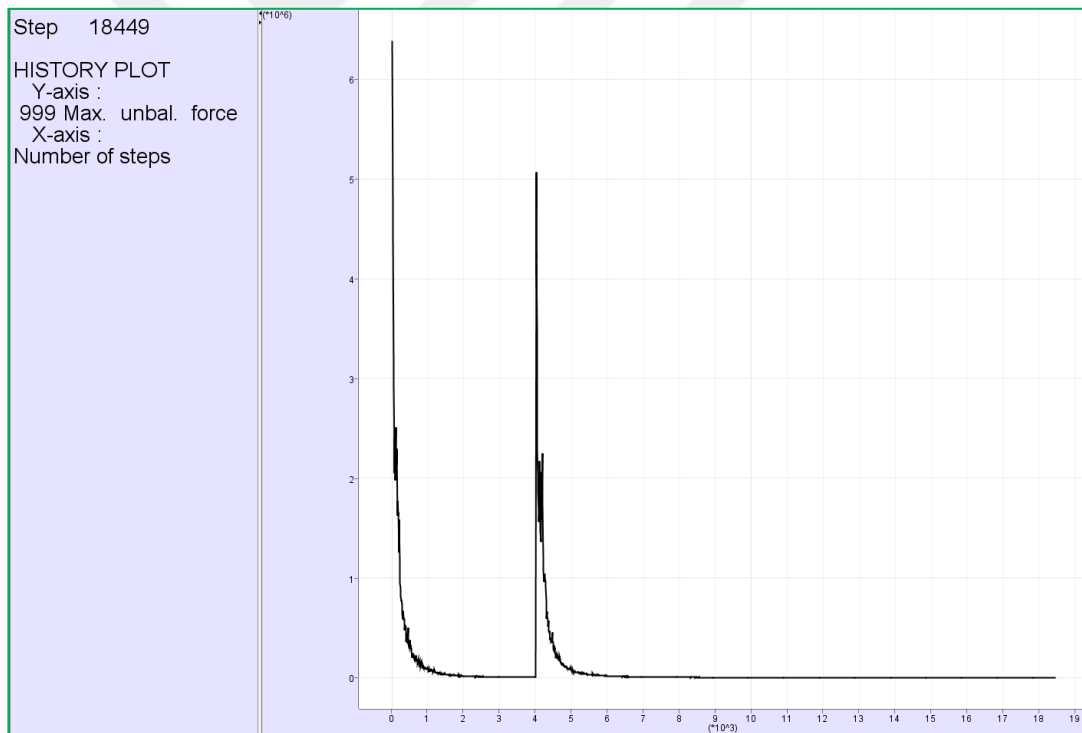


Figure 40. Unbalanced force after the twin tunnel excavation

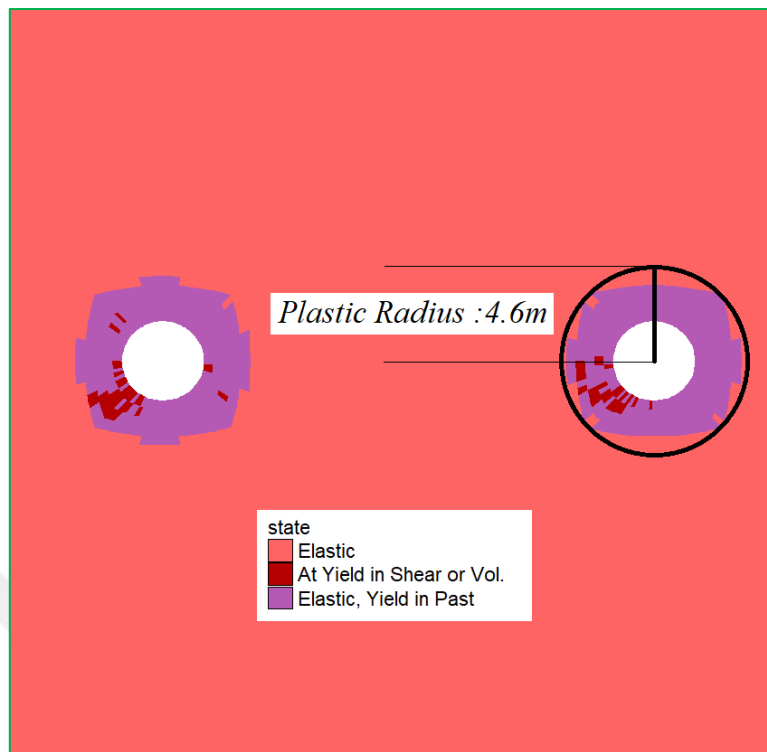


Figure 41. Plastic zones around the tunnels

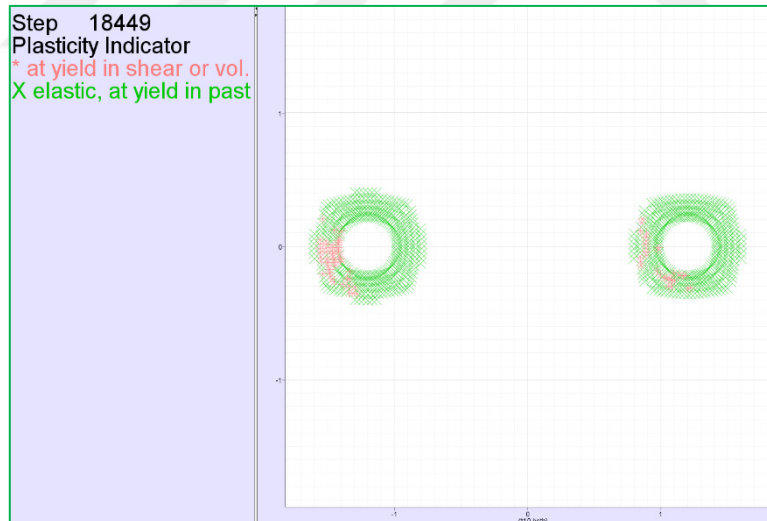


Figure 42. Plasticity indicators around the tunnels

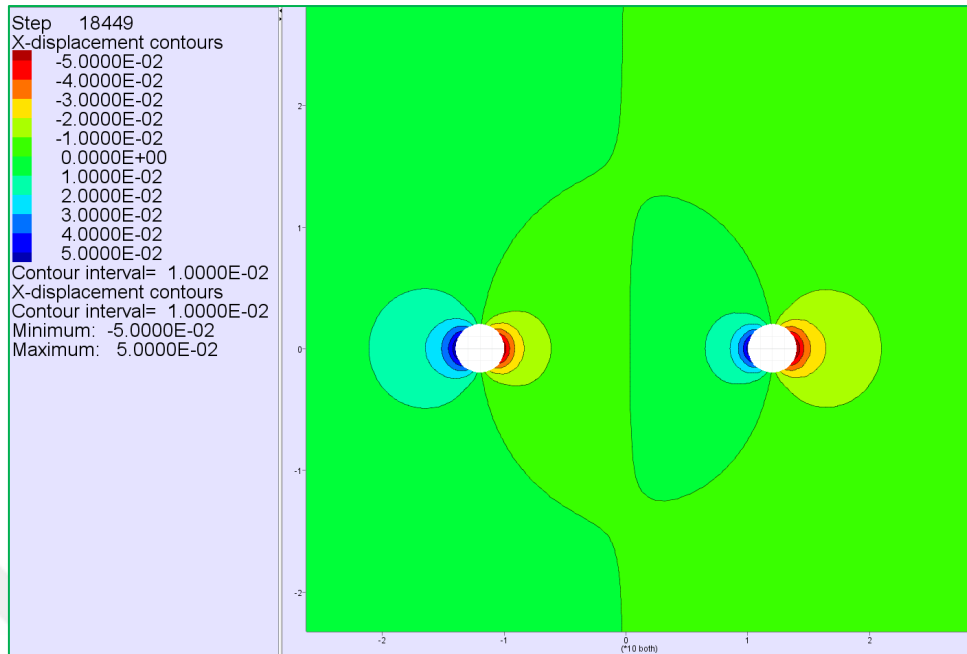


Figure 43. X-displacement contours

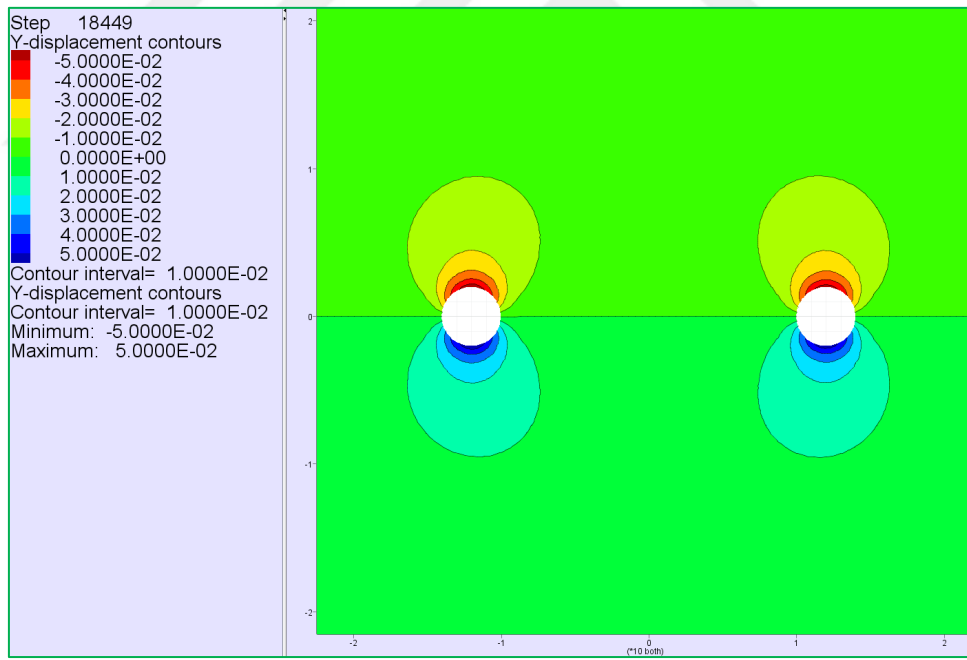


Figure 44. Y-displacement contours

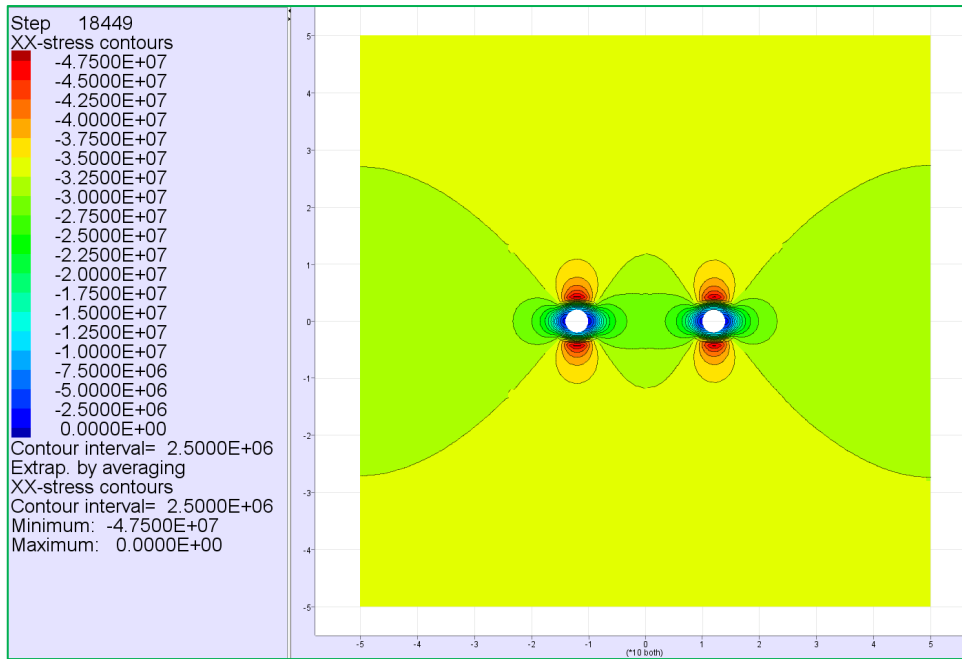


Figure 45. XX-stress contours

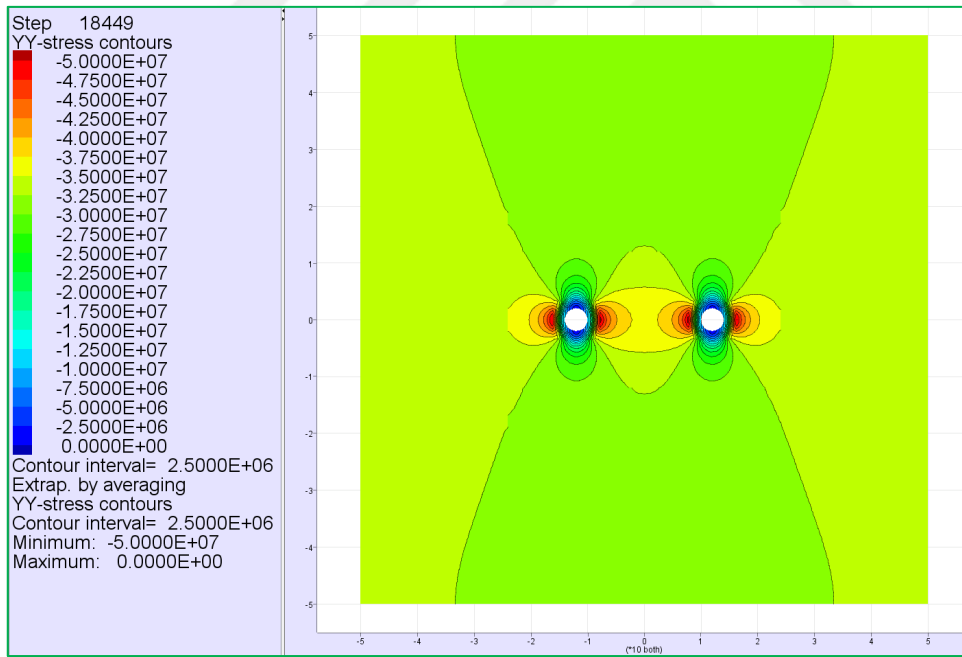


Figure 46. YY-stress contours

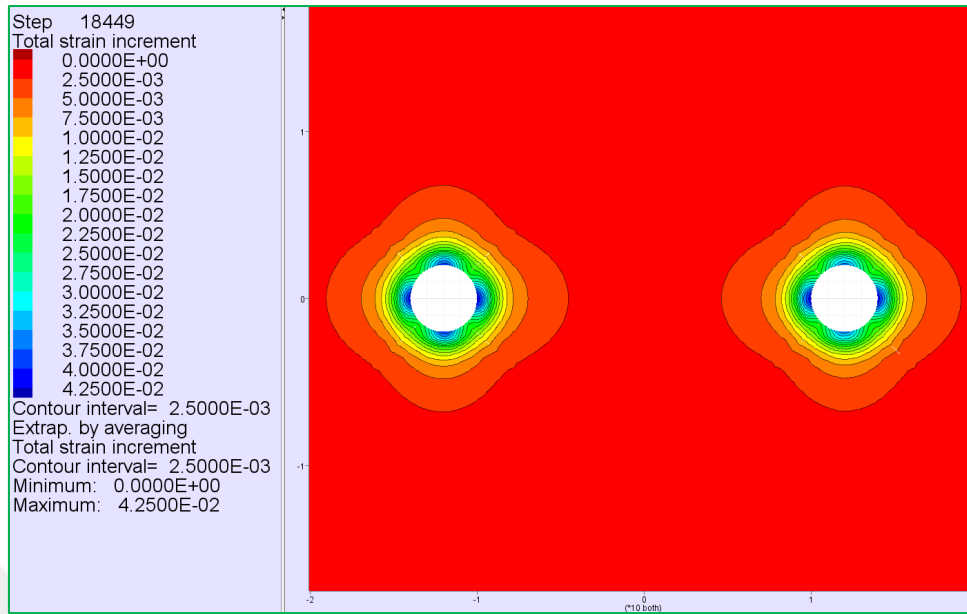


Figure 47. Total strain increment around the tunnels

In the simulation, the first tunnel on the left was opened before the tunnels were waited for the model to reach equilibrium, then the second tunnel on the right was opened. As can be seen from the given contour maps, as a result of the plane strain analysis, a displacement of 5 cm was predicted in the tunnel crown part and the wall part. In addition, it was simulated that the induced vertical stress reached 50 MPa in the tunnel crown, and the induced horizontal stress reached 47.5 MPa in the tunnel wall. When the model reached equilibrium, the strain value in the first tunnel was found to be around 4% in the tunnel wall and crown. The reason why this value differs from the analytical solutions obtained in the previous sections is due to its twin tunnel structure. In order for the obtained values to simulate the actual situation, the tunnel excavation should be examined with the strength reduction method. For this reason, a three-dimensional analysis should be applied. For this purpose, the work continues on the 3D version of the same code, $FLAC^{3D}$.

4.6 3D Analysis of Parallel Tunnels

By using the extrusion function, the model is extruded by 200 meters along the tunnels. In this way, the 3D model for the twin tunnels was created. Model boundaries were assigned as roller boundaries on all sides, and the hydrostatic stress was initialised on all grid points in the model. The roller boundaries were assigned by fixing the velocity to zero perpendicular to the related face. The boundaries can be seen in Figure 48. 3D model boundary conditions

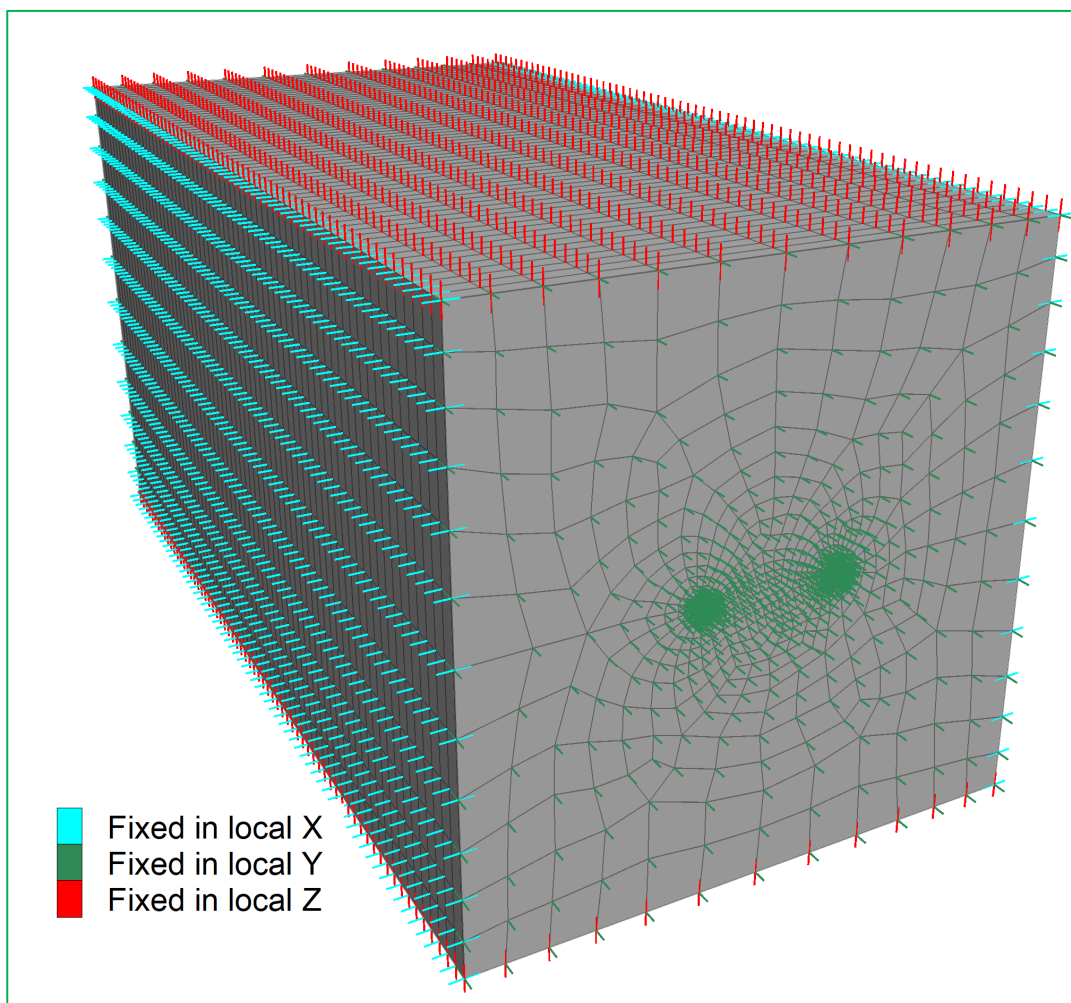


Figure 48. 3D model boundary conditions

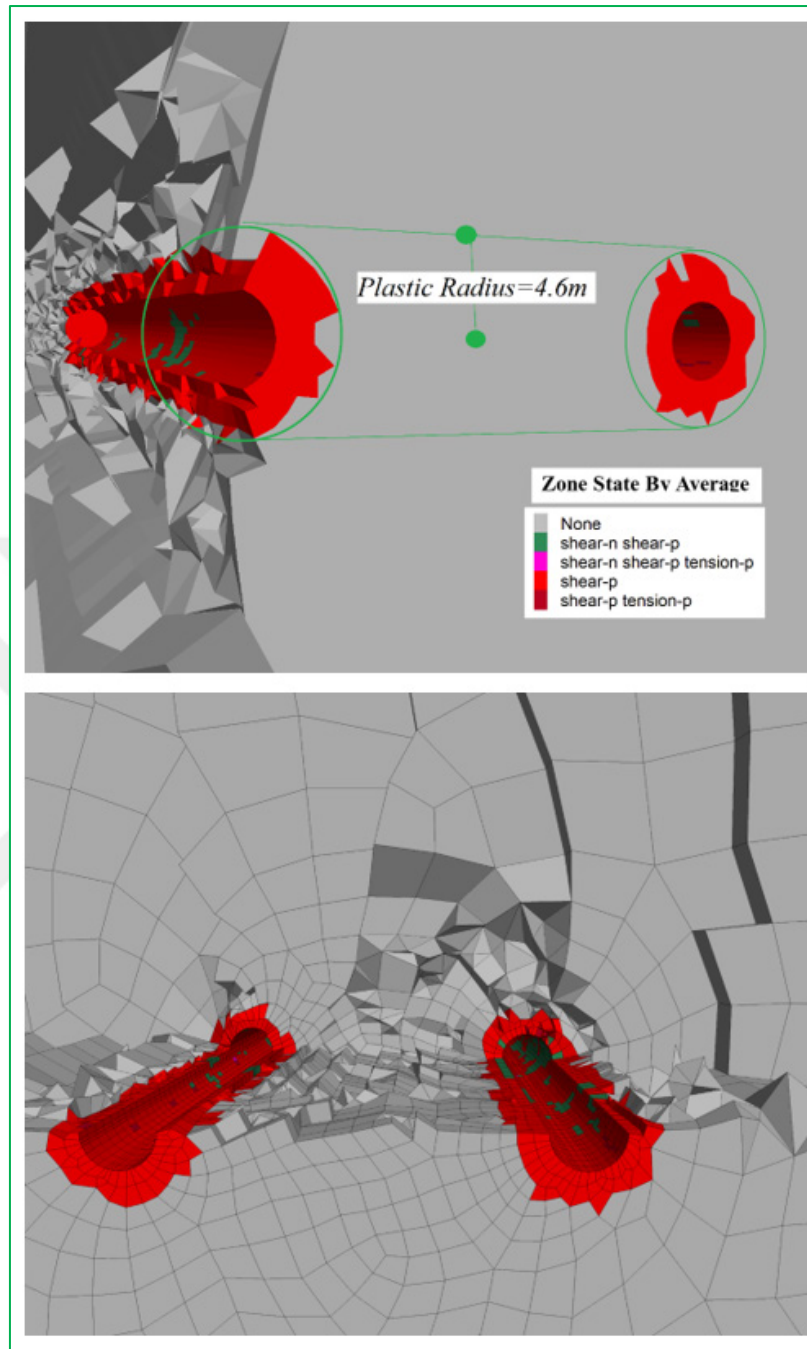


Figure 49. The plastic region around the twin tunnels

As a result of the numerical analysis, no change was observed in the boundaries of the plastic zone formed, and its radius was found to be around 4.6 m (Figure 49).

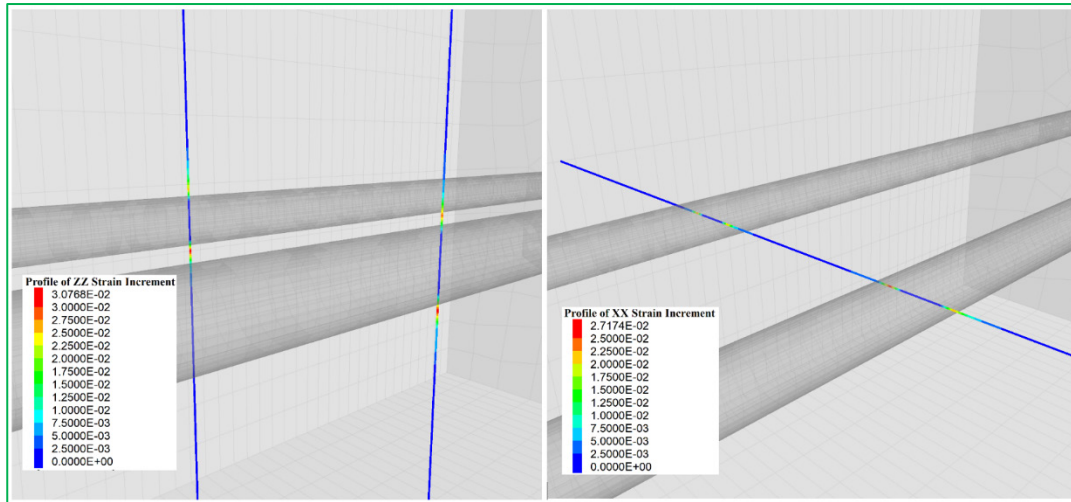


Figure 50. Vertical and horizontal strain profiles in the mid-section of the model

Horizontal and vertical strain profiles on the middle surface of the model of the tunnels are coloured on the linear profiles and shown in Figure 50. The displacement magnitudes and strain rates were compared in line with the information obtained from these points. It has been observed that the results obtained are parallel trends with the analytical and plane strain solutions made up to this stage. When the results are compared, it is noticeable that there are differences. There are two reasons for these differences. The first of these is the linearity of the mesh structure in the modelling in the third axis due to the extrusion action. The second reason is that the density, stiffness, and surrounding stress values of the excavated zones were gradually reduced to zero during the excavation action command in the three-dimensional model. This model relaxation technique is used to simulate a more realistic situation by giving more accurate results since the material does not disappear instantaneously in any real case. The vertical strain graphs obtained from the vertical profiles and the positions of the profiles in the model are given in Figure 51. Some history points were created to visualise the values obtained as a result of the analysis. A ground reaction curve was created in the middle of the tunnel length Figure 53. The contour map of the zone displacement magnitude and some of the history points placed in the model are also shown.

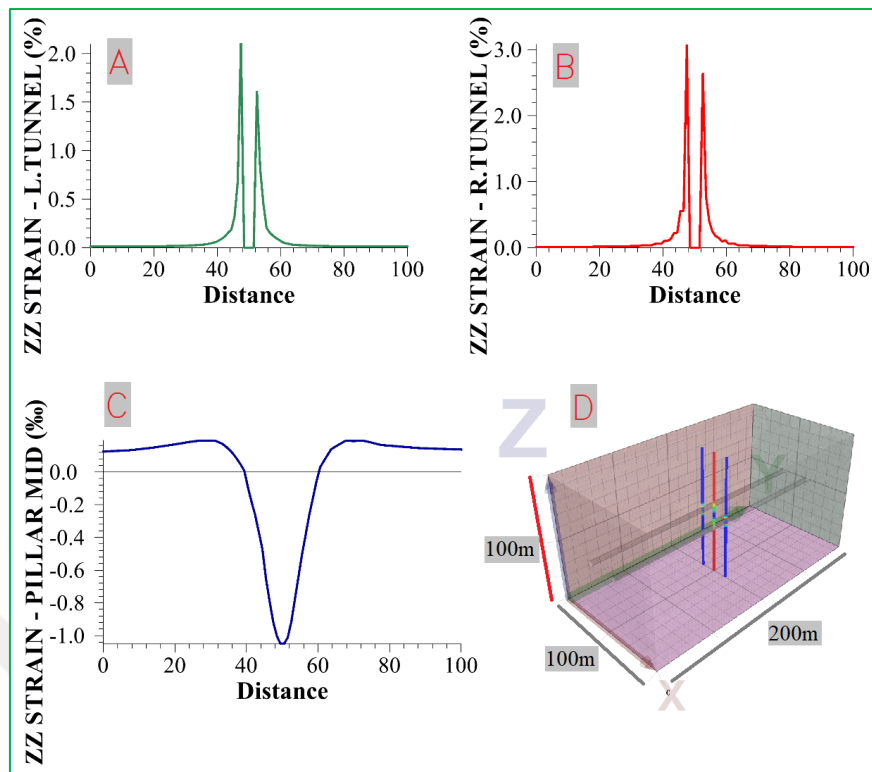


Figure 51. Vertical strain profile of the left tunnel (A), the right tunnel (B), the pillar (C), and the profile locations with the model dimensions (D)

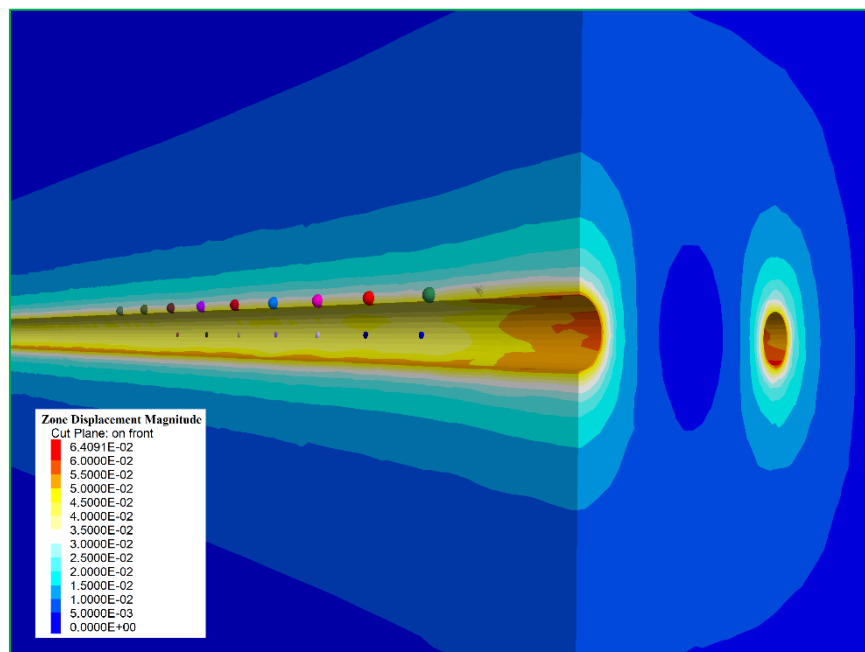


Figure 52. Zone displacement magnitudes and history locations

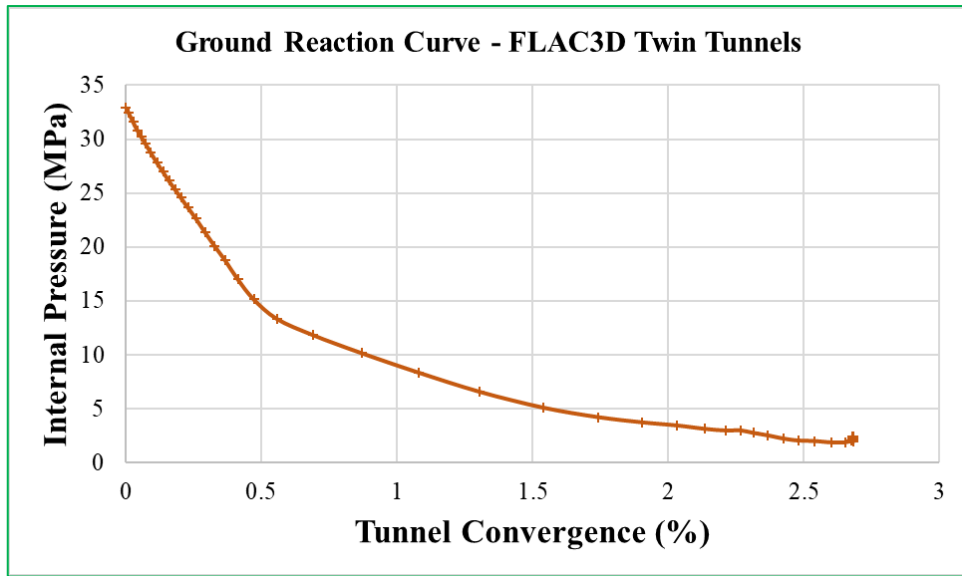


Figure 53. GRC of the tunnels

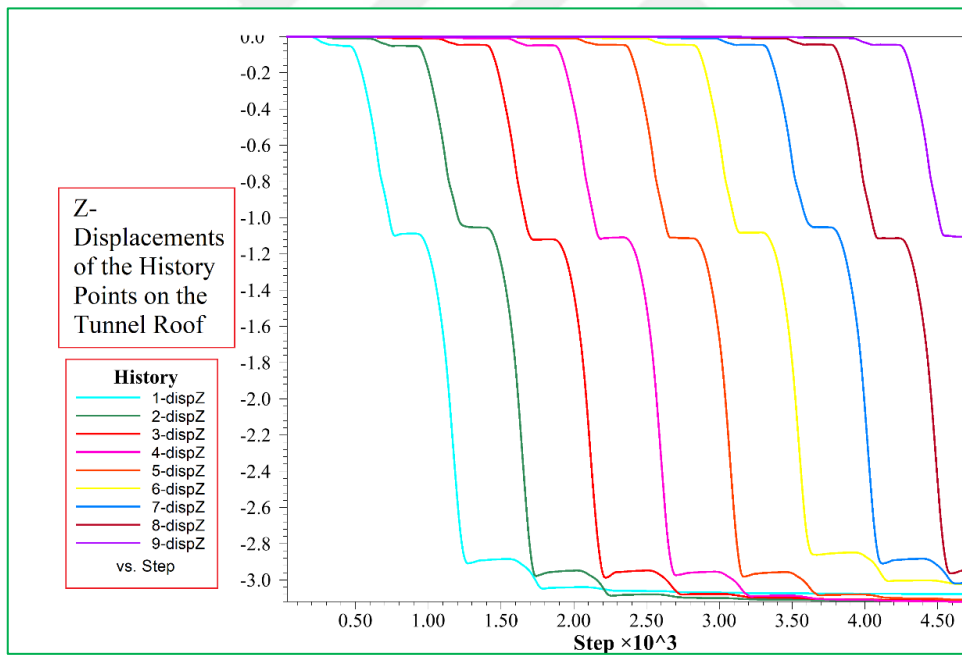


Figure 54. Vertical displacements on the tunnel crown

The modelling has shown that it is possible to open twin tunnels in the Batı Raman oil field in line with the assumptions made. As the number of tunnels increased, the direct effects of the openings excavated in the same plane on each other were observed. Considering the ratio of rock mass strength and in situ stresses, it was expected that the squeezing problem would be encountered, but this probability was low as a result of the numerical simulations. Since it is understood that it is possible to ensure the stability of the tunnels, the modelling of the borehole excavations was made in order to observe the effect of the boreholes to be used for steam injection together with the tunnel excavations.

After this stage, a complex geometry must be created in the third dimension to study the problem. Therefore, a model design was needed to be used in numerical analysis. A validation point is required in order to compare the data to be obtained as a result of this design. For this reason, the physical model created in the MAHOP study mentioned in the literature review section has been imitated (Canbolat *et al.*, 2020a).

4.7 3D Analysis of Parallel Tunnels and Boreholes

Based on the physical model prepared by Canbolat *et al.* (2020a), a model suitable for numerical work was designed. The primary purpose of this design is to determine and observe the reservoir rock mass behaviour and to establish a connection between the rock mass behaviour and oil production through this characteristic excavation situation. It is possible to talk about the actual situation with the metric unit by taking the dimensions of the physical model in meters. The three-dimensional model built for this reason has a height of 50 meters and a width of 100 meters. There are two parallel circular tunnels in the model and a total of 30 boreholes of 15 each on these tunnels. The boreholes are arranged in the form of fans at equal intervals, and their lengths are 11, 14 and 20 meters, and they are positioned at 30, 60, 90 degrees, respectively. The pillar was kept 20 meters between the tunnels as it was studied. Based on the study, the positioning of the tunnels in the model was made 4 meters above the reservoir floor. The reason for this choice is to minimize the effect of the tunnels to be opened in the reservoir on the strata at the bottom of the reservoir and to prevent the tunnels from having an effect on the strata sealing the reservoir. After the computer-aided drawing of the model was made, all quadrilaterals mesh was produced on all surfaces in the model using a 3rd party mesh program. In addition, by producing a conformal hex-dominant volume mesh, the quadrilaterals surfaces in the model were made conformal and interconnected. The ridge angle was kept at 10 degrees for the mesh, thus preventing the boreholes from losing their circularity by remaining relatively minor to the model. In this way, 3,087,598 zones were obtained. Unlike the original model, the purpose of keeping the width of 100 meters was to minimise the effect of boundary conditions. For the same reason, all boundary conditions of the model are covered with roller boundary and the hydrostatic stress area is entered as 33 MPa equally to all gridpoints in the model and using the same parameters used in the previous sections. The material behaviour was assumed to be linearly elastic and perfectly plastic during the analysis process, and the model was solved to comply with the Mohr-Coulomb failure criterion. The placement of the

model on the coordinate plane, the location of the origin, the angles, lengths and positions of the boreholes are given in Figure 55. Conformal model mesh and interior view of the tunnels and boreholes are given in Figure 56 and Figure 57.

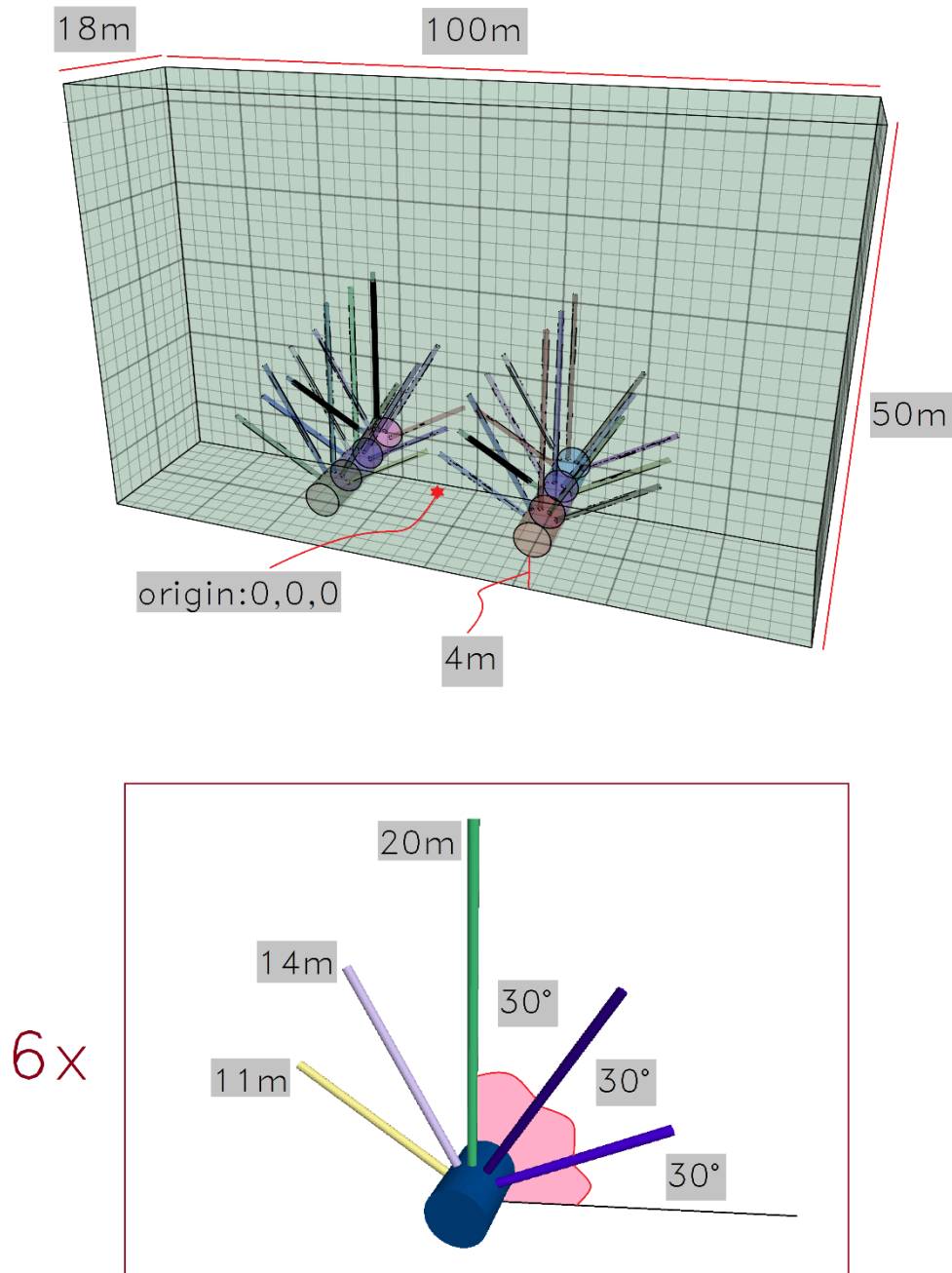


Figure 55. Model dimensions

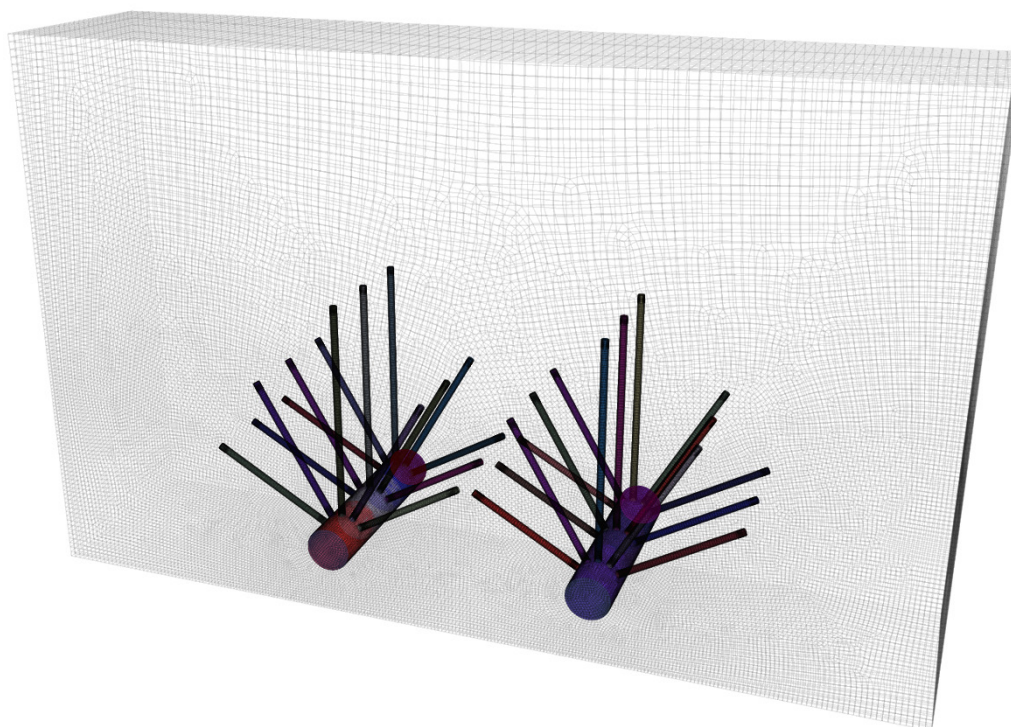


Figure 56. Conformal hex mesh of the model

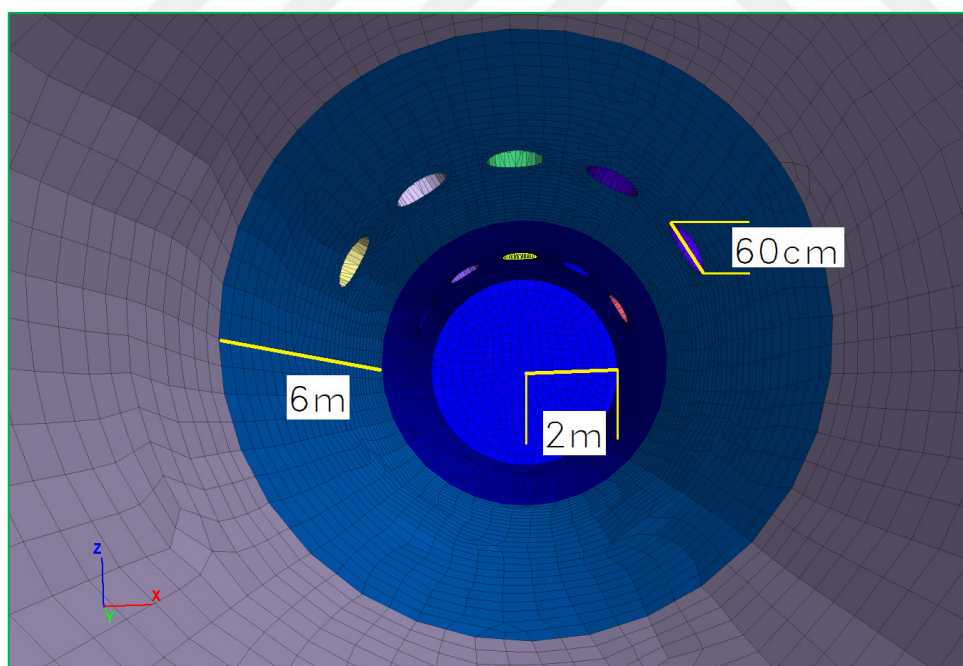


Figure 57. Interior view of the tunnels

As a result of the analysis, the induced stresses formed after the excavations were observed, and contour maps were created for the vertical and horizontal stresses concentrated around the boreholes. Contour maps in the middle plane of the model are given in Figure 58 and Figure 59 for vertical and horizontal stresses.

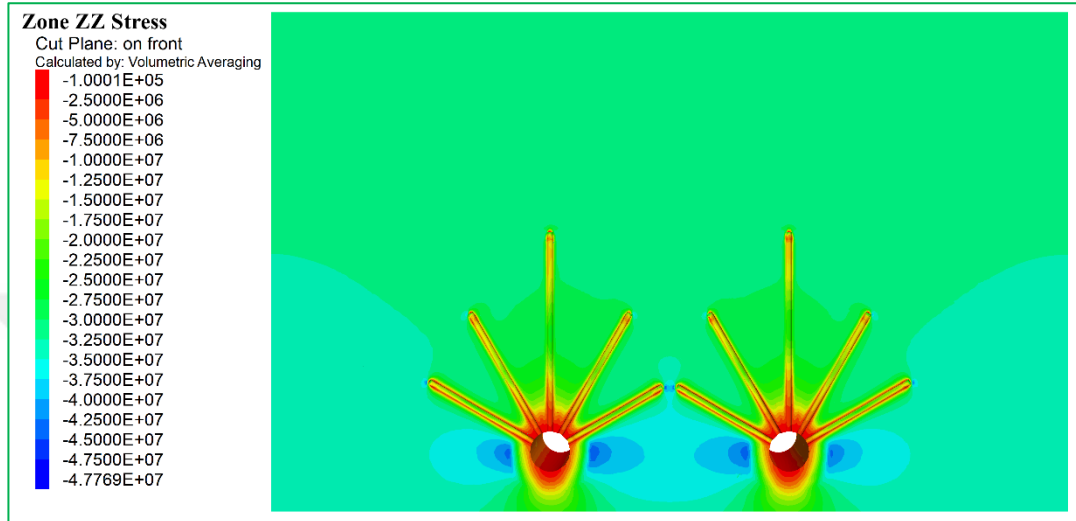


Figure 58. Vertical stresses contour map

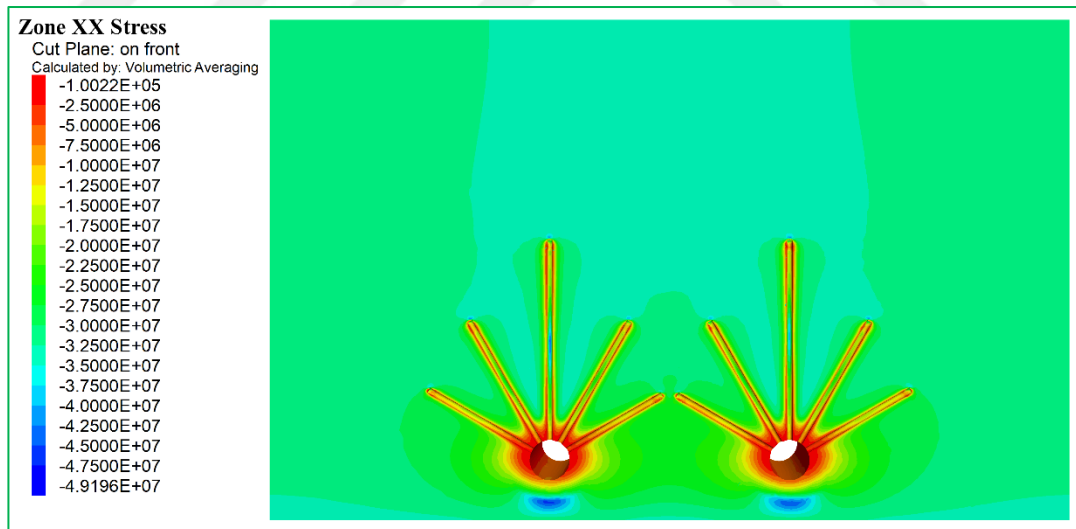


Figure 59. Horizontal stresses contour map

Profiles were created to observe the effects of boreholes opened and record the stress and strain changes in their vicinity. Profiles extend in the vertical direction extending from the base of the model to the top. The first (A) of these profiles, located in the

middle plane of the model, is 10 meters to the left of the tunnel wall, the second (B) is in a position coincident with the longest borehole, and the third (C) passes through the middle of the pillar. Horizontally positioned profiles start by passing through the centres of the tunnels (G) and reach above the boreholes (D) by increasing 10 meters in each profile. The locations of the profiles and the graphs of the stress and strain values recorded along these profiles are given in the figures below.

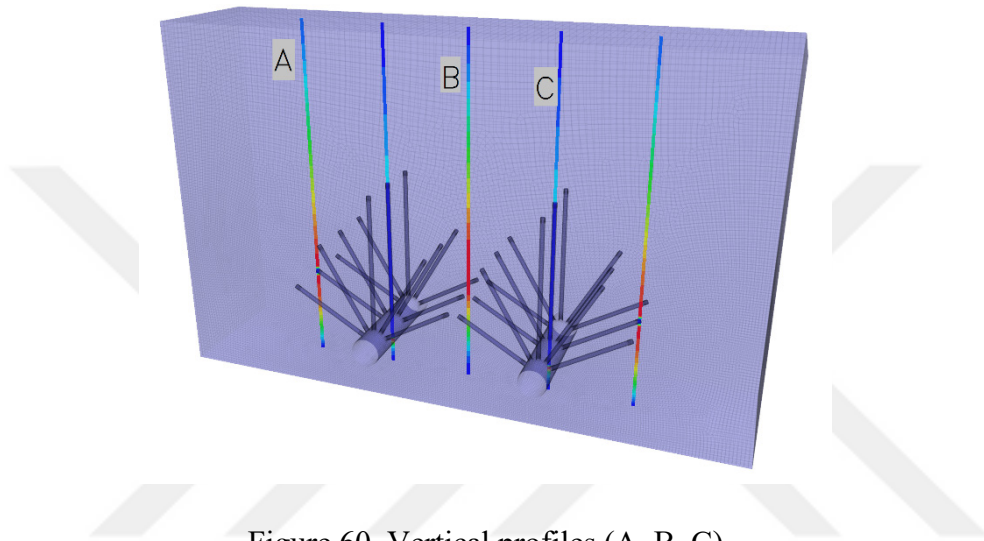


Figure 60. Vertical profiles (A, B, C)

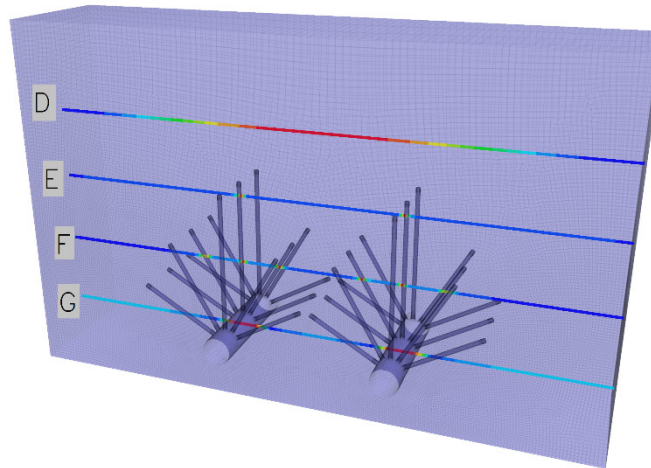


Figure 61. Horizontal profile (D, E, F, G)

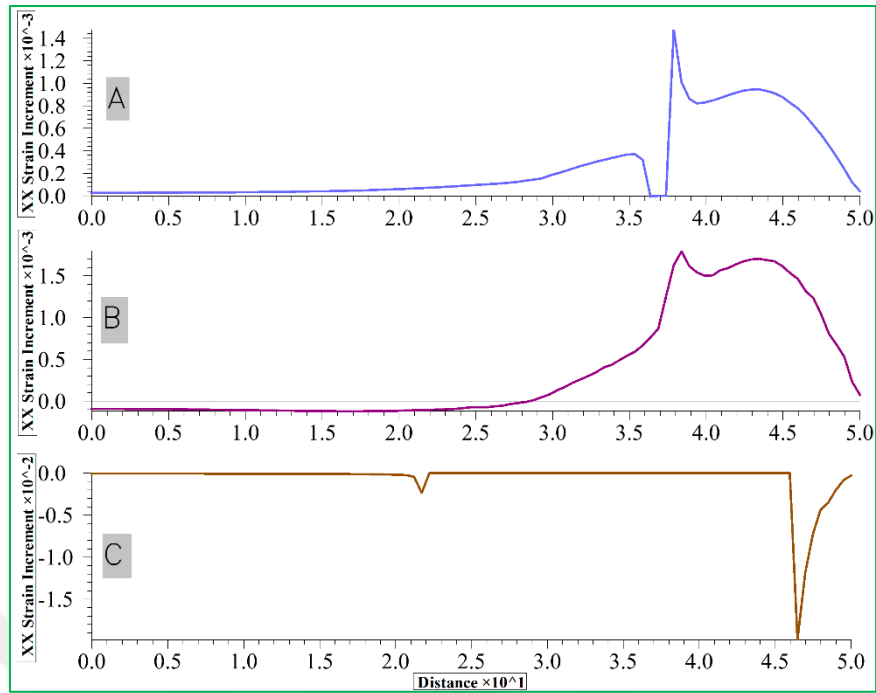


Figure 62. XX strains along vertical profiles

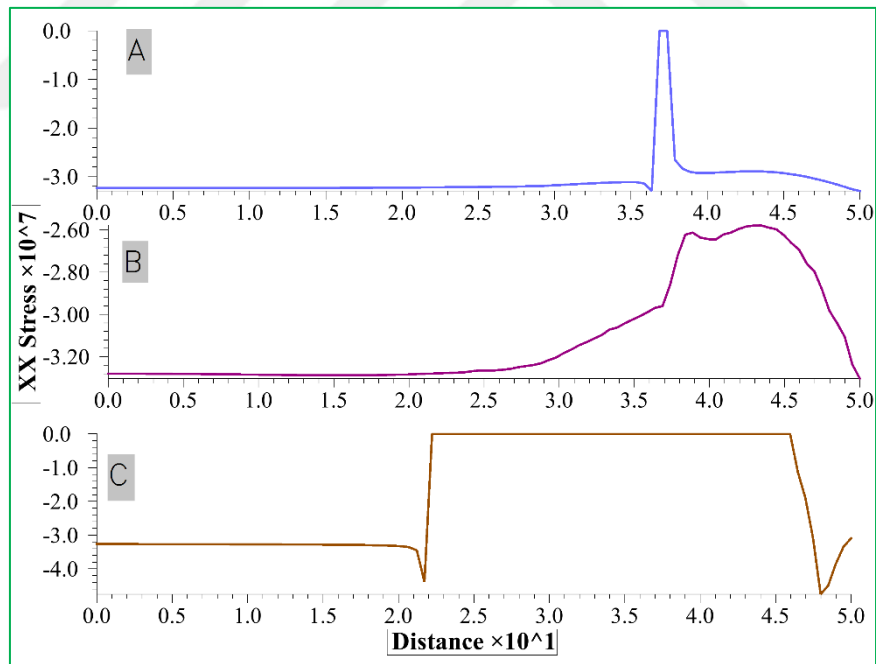


Figure 63. XX stresses along vertical profiles

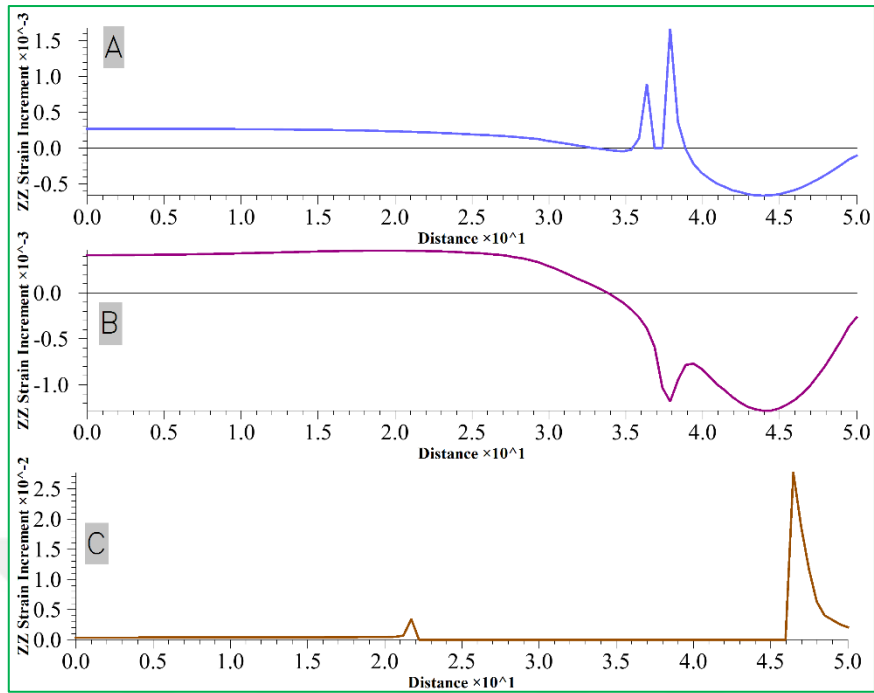


Figure 64. ZZ Strains along vertical profiles

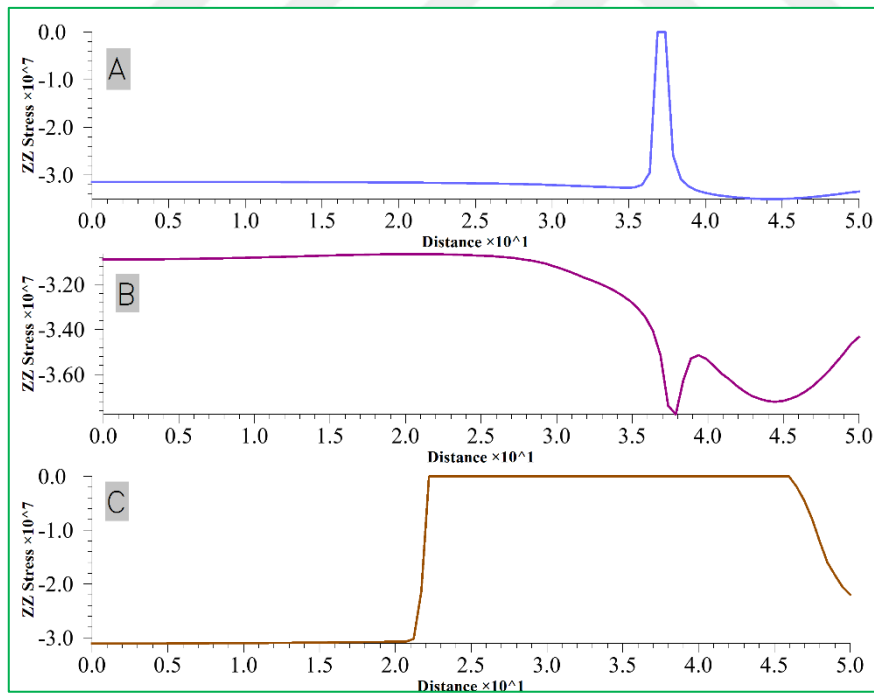


Figure 65. ZZ Stresses along vertical profiles

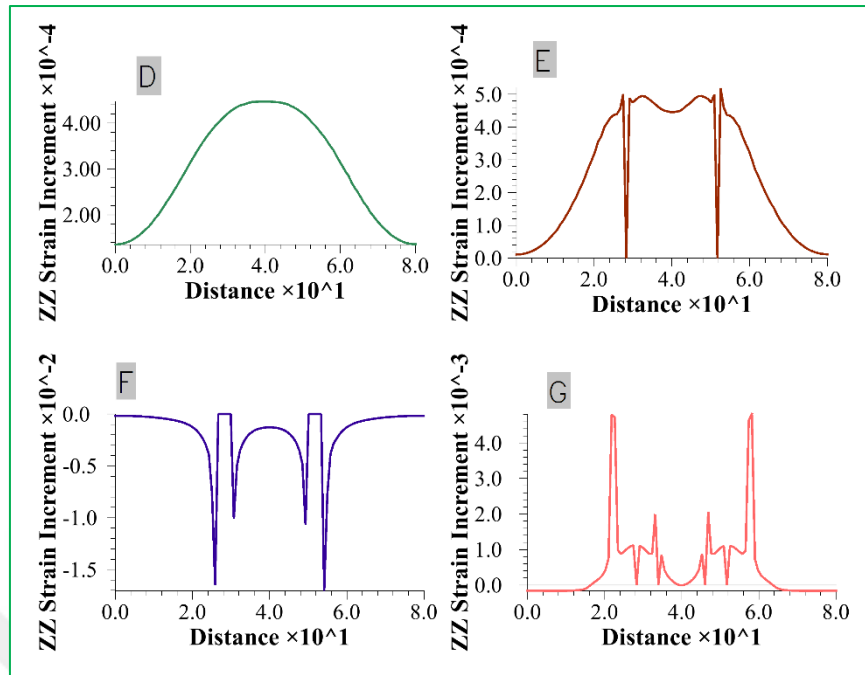


Figure 66. ZZ Strains along horizontal profiles

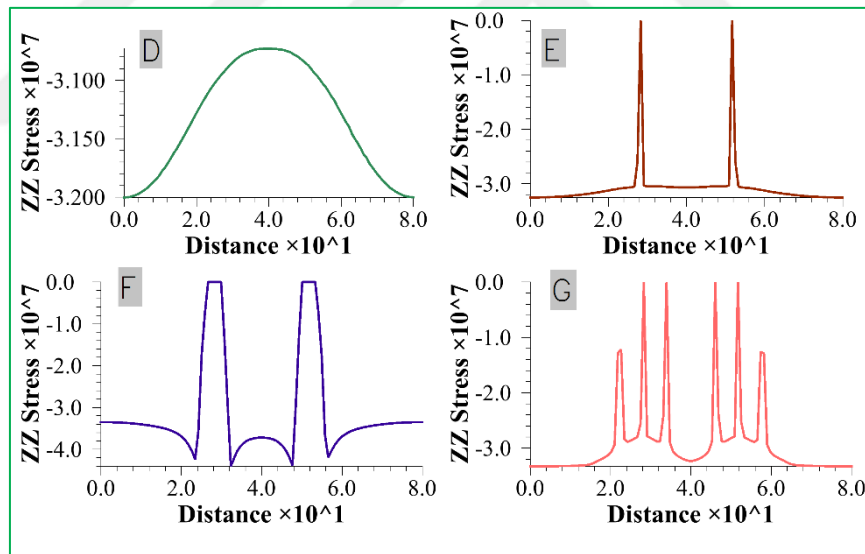


Figure 67. ZZ Stresses along horizontal profiles

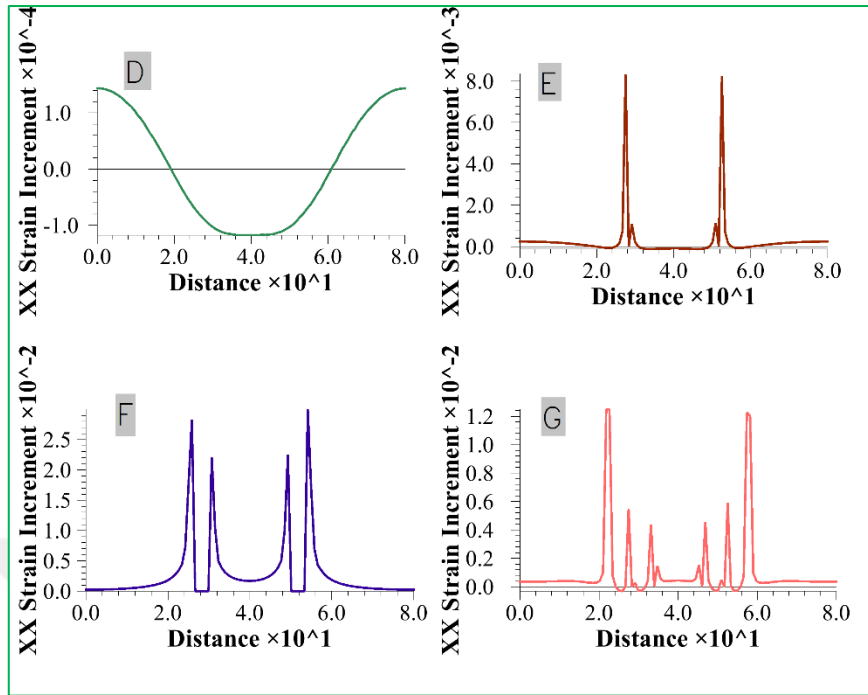


Figure 68. XX Strains along horizontal profiles

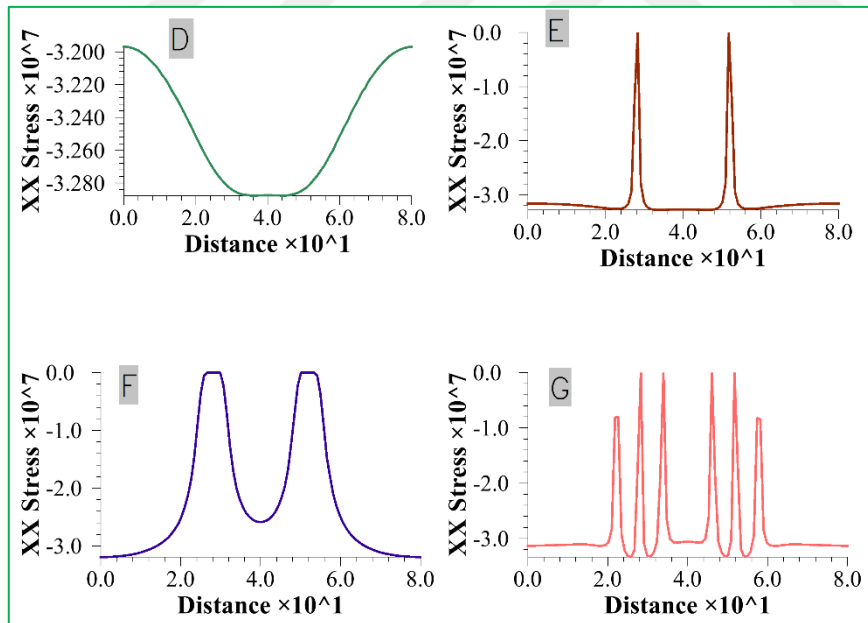
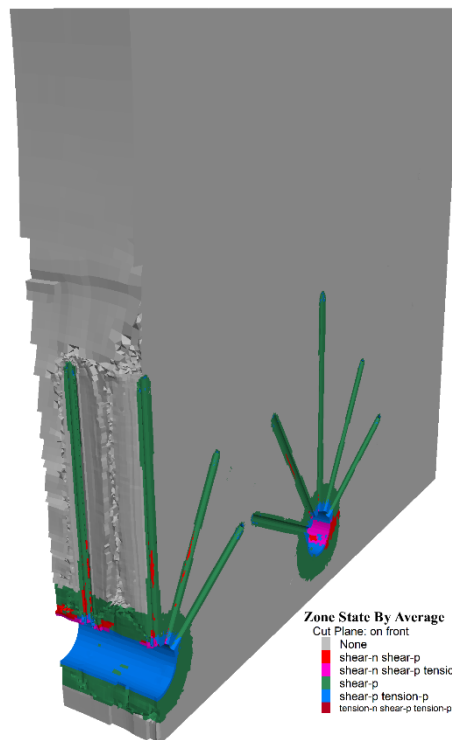
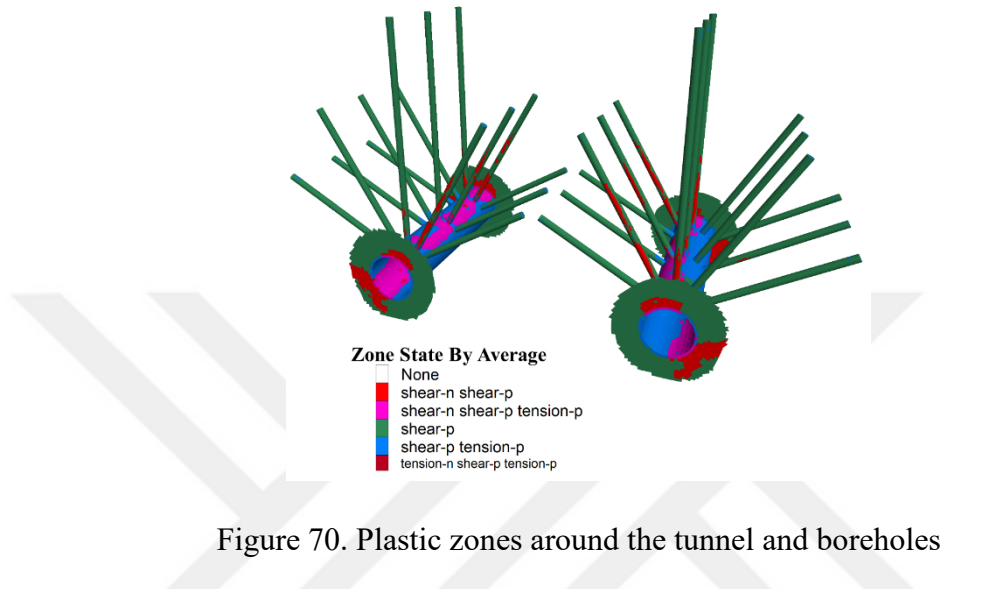


Figure 69. XX Stresses along horizontal profiles

The induced stresses and strains caused by the excavations resulted in the failure of the zones in the model. These failed zones are mainly concentrated on the tunnel wall and the wall of the boreholes. Plastic extends in the model are given in Figure 70 and Figure 71.



Considering the displaced volume, it is seen that the boreholes excavated have a mobility effect, but this displacement does not cause failure in the model. An isosurface containing the displaced zones of 1 cm or more was created and the plastic zones formed in this isosurface are given in Figure 72 and Figure 73.

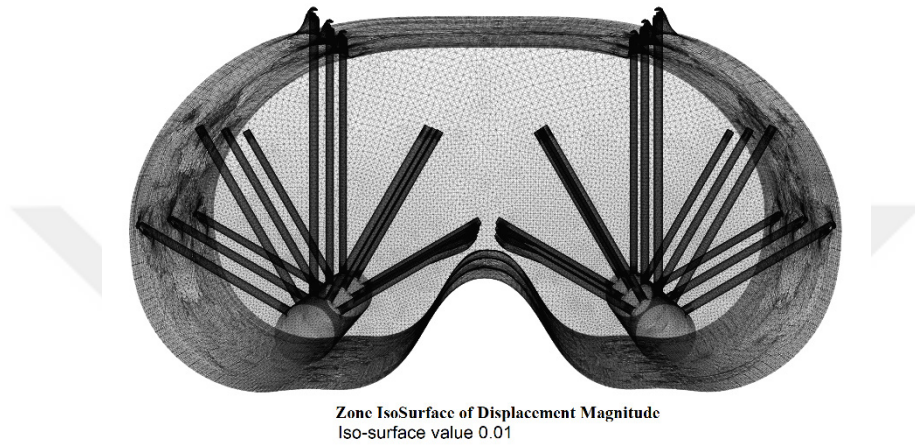


Figure 72. 1cm displacement isosurface

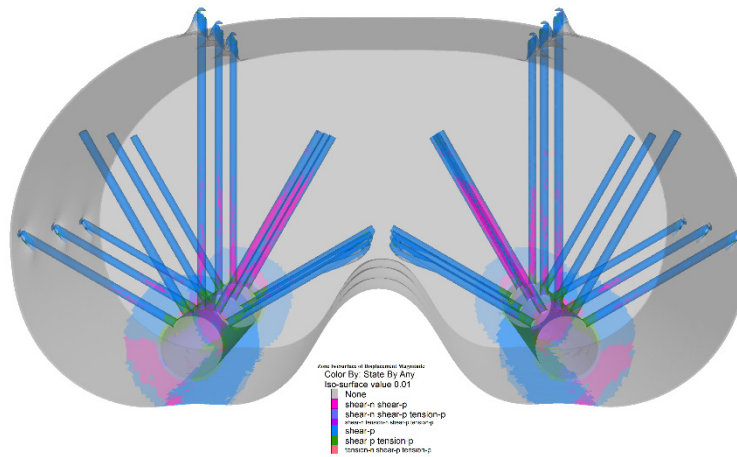


Figure 73. Isosurface and plastic zones

4.8 Parametric Study for Different Borehole Lengths and Diameters

A parametric study was carried out by following the modelling path described in the previous section. For this purpose, 15 models were created. In this parametric study, the plastic volumes formed due to the excavations were recorded and compared by writing a FISH script.

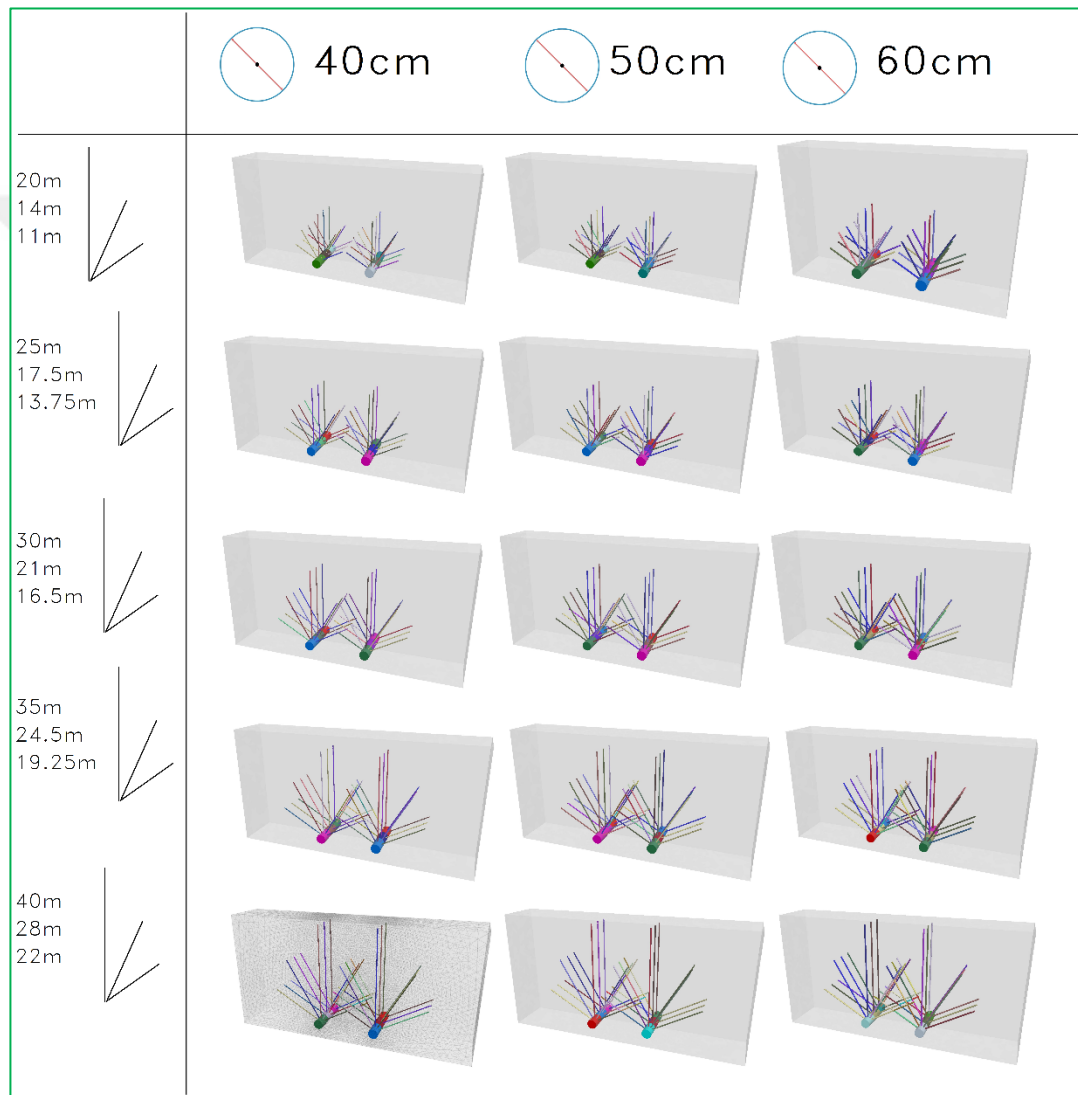


Figure 74. Models used in the parametric study

The parameters of the models created were chosen in a way that connects the two ends. Borehole diameter of 60 cm used in the physical model created can be an extreme condition for underground drilling machines, so the same models were created with boreholes of 50 and 40 cm in diameter. Starting from the same point of view, it is possible to drill longer up holes in underground mining. For this reason, the borehole lengths used in the model are extended proportionally, provided that the angles they make with each other and the ratio of their lengths to each other remain constant. The 15 models created, borehole diameters in these models and borehole lengths in each model are given in Figure 74. In order to compare the volume remaining inside the model after excavation with the plastic volume, the volume of each of the excavations was calculated and subtracted from the total volume. The total plastic volumes found as a result of the analyses are given in Table 5.

Table 5. Parametric models' dimensions and plastic volumes

Model Number	Diameter	90° BH	60° BH	30° BH	Plastic Zone Volume in FLAC ^{3D}
	(cm)	(m)	(m)	(m)	(m ³)
1	60	20	14	11	952.61
2	60	25	17.5	13.75	1011.35
3	60	30	21	16.5	1032.14
4	60	35	24.5	19.25	1299.11
5	60	40	28	22	1340.66
6	50	20	14	11	845.42
7	50	25	17.5	13.75	869.10
8	50	30	21	16.5	896.77
9	50	35	24.5	19.25	897.67
10	50	40	28	22	934.03
11	40	20	14	11	816.86
12	40	25	17.5	13.75	848.00
13	40	30	21	16.5	875.60
14	40	35	24.5	19.25	891.73
15	40	40	28	22	903.77

Canbolat *et al.* (2020a), in their study, claimed that they could recover 70% oil as a result of the physical model experiment from the Batı Raman heavy oil field, which has a porosity value of 35%. While making this calculation, the volume of the limestone sand and heavy oil mixture coming from the Batı Raman field, which the model placed in it, was taken into account. In this study, it is possible to comment on heavy oil recovery by making some assumptions.

If the failed zones determined as a result of the numerical analysis are accepted as the volume where production is provided and if we assume that 35% of this volume is oil and if we accept that the steam injection method applied will save 70% of this volume, the oil volume produced will be as follows:

Table 6. Recovered oil volume from the plastic zones

Model Number	Diameter	90° BH	60° BH	30° BH	Plastic Zone Volume in FLAC ^{3D}	Recovered Oil Volume
	(cm)	(m)	(m)	(m)	(m ³)	(m ³)
1	60	20	14	11	952.61	233.39
2	60	25	17.5	13.75	1011.35	247.78
3	60	30	21	16.5	1032.14	252.87
4	60	35	24.5	19.25	1299.11	318.28
5	60	40	28	22	1340.66	328.46
6	50	20	14	11	845.42	207.13
7	50	25	17.5	13.75	869.10	212.93
8	50	30	21	16.5	896.77	219.71
9	50	35	24.5	19.25	897.67	219.93
10	50	40	28	22	934.03	228.84
11	40	20	14	11	816.86	200.13
12	40	25	17.5	13.75	848.00	207.76
13	40	30	21	16.5	875.60	214.52
14	40	35	24.5	19.25	891.73	218.47
15	40	40	28	22	903.77	221.42

As a result of comparing these volumes with the physical test results of Canbolat *et al.*(2020a), it can be said that 2.23% of the production they have made for the same model (20m-14m-11m borehole lengths and 60cm diameter – model number 1) comes from the plastic zone that will form when opening the tunnel and borehole and that can be defined as the Excavation Induced Damage Production Ratio (EIDPR). Similarly, if the percentages of other numerical models on production are examined, the results in Table 7 can be obtained. The point that should not be overlooked here is that the volume other than excavations also changes for the different models created. While the volumes representing the rock mass of the models are kept constant, the excavated volume changes as the length and diameter of the opened boreholes change, so the volume must be calculated for each borehole pattern.

Table 7. EIDPR values for each model

Model Number	Diameter	90° BH	60° BH	30° BH	Plastic Zone Volume in FLAC ^{3D}	Recovered Oil Volume	Excavation Induced Damage Production Ratio
	(cm)	(m)	(m)	(m)	(m ³)	(m ³)	(%)
1	60	20	14	11	952.61	233.39	2.23
2	60	25	17.5	13.75	1011.35	247.78	2.37
3	60	30	21	16.5	1032.14	252.87	2.42
4	60	35	24.5	19.25	1299.11	318.28	3.05
5	60	40	28	22	1340.66	328.46	3.15
6	50	20	14	11	845.42	207.13	1.98
7	50	25	17.5	13.75	869.10	212.93	2.04
8	50	30	21	16.5	896.77	219.71	2.10
9	50	35	24.5	19.25	897.67	219.93	2.11
10	50	40	28	22	934.03	228.84	2.19
11	40	20	14	11	816.86	200.13	1.91
12	40	25	17.5	13.75	848.00	207.76	1.99
13	40	30	21	16.5	875.60	214.52	2.05
14	40	35	24.5	19.25	891.73	218.47	2.09
15	40	40	28	22	903.77	221.42	2.12

In this way, it is possible to define the excavation induced damage production ratio (EIDPR). The aim of the models made is to observe what the EIDPR will be if the MAHOP method is applied according to the field conditions. For this purpose, a regression analysis was performed. In this analysis, the percentage of EIDPR was taken as the dependent variable, and the borehole lengths and diameters used to separate the models were entered as the variables. As a result of the regression analysis, a statistically appropriate relationship was found over the longest borehole and diameter as a variable. In addition, an optimisation was made and aimed to maximise the EIDPR.

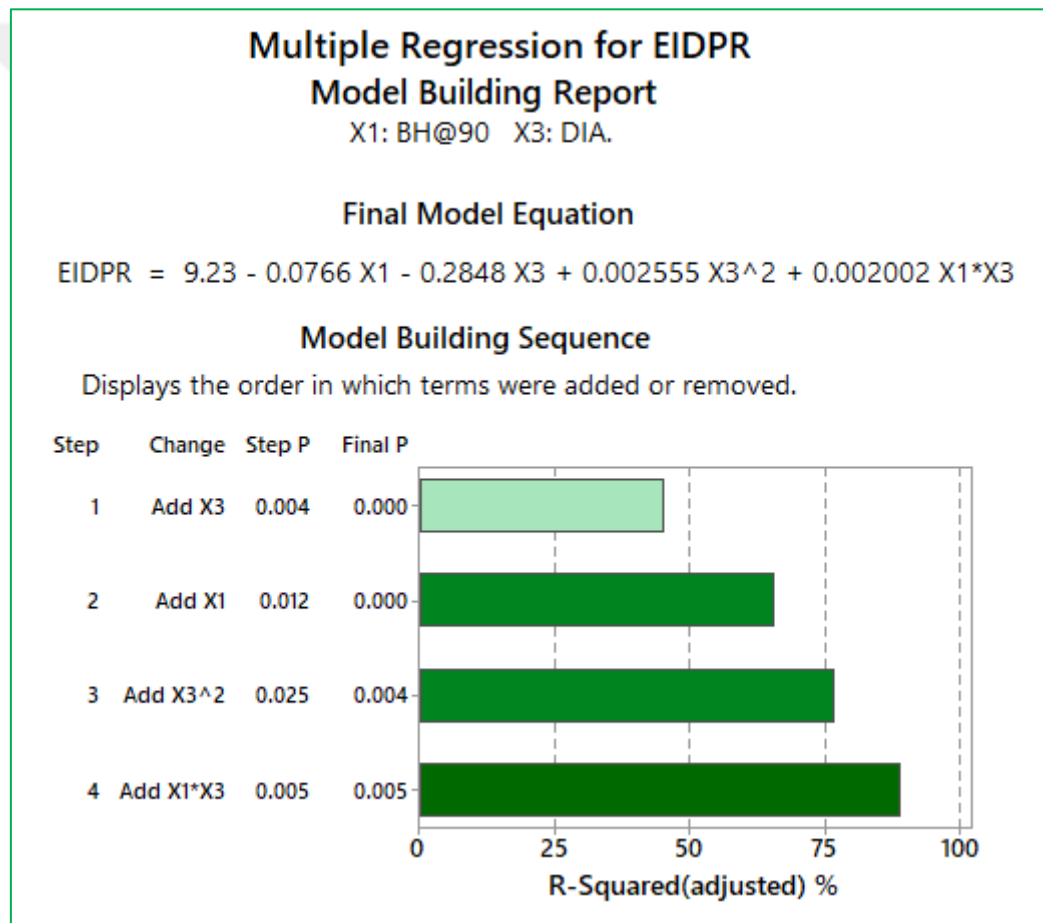


Figure 75. EIDPR Regression model building report

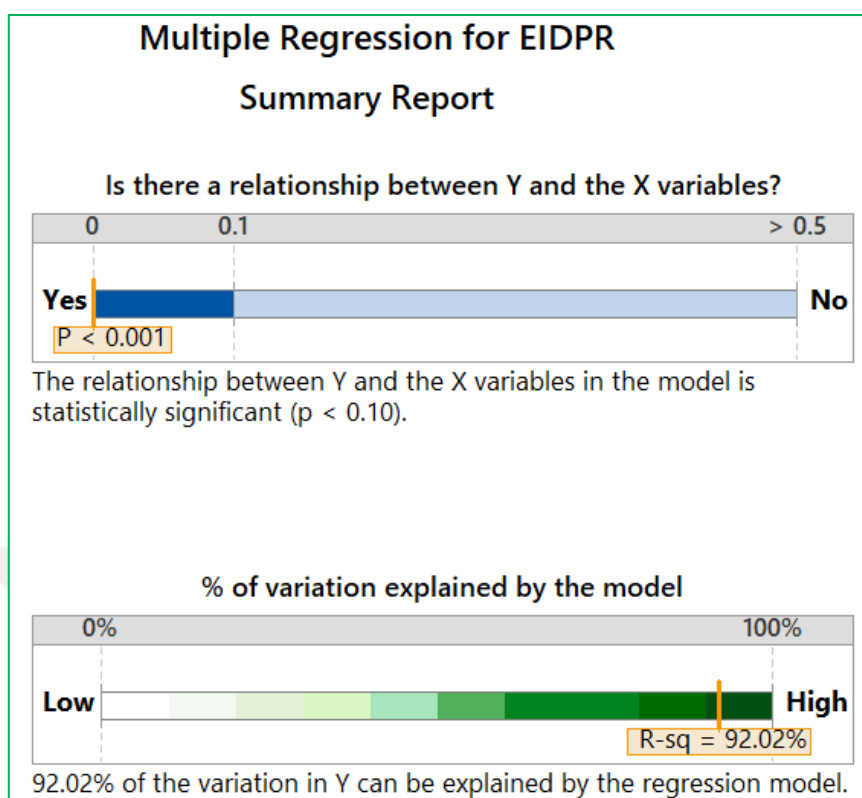


Figure 76. EIDPR regression model P and R-sq values

In the regression model, the variables were added to the model equation with different combinations, and the appropriate combination was sought according to the P-value and R-sq values.

Table 8. Analysis of variance in EIDPR model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	1.7806	0.44515	28.83	0.000
BH@90	1	0.1142	0.11424	7.40	0.022
DIA.	1	0.2543	0.25426	16.47	0.002
DIA.*DIA.	1	0.2176	0.21765	14.10	0.004
BH@90*DIA.	1	0.2004	0.20037	12.98	0.005
Error	10	0.1544	0.01544		
Total	14	1.9350			

As a result of the statistical evaluation, it was revealed that the model had over 90% power in explaining the EIDPR variation (Table 9). In addition, it has been observed that the diameter and length of boreholes have a direct effect on the EIDPR (Table 8).

Table 9. EIDPR regression model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.124262	92.02%	88.83%	83.05%

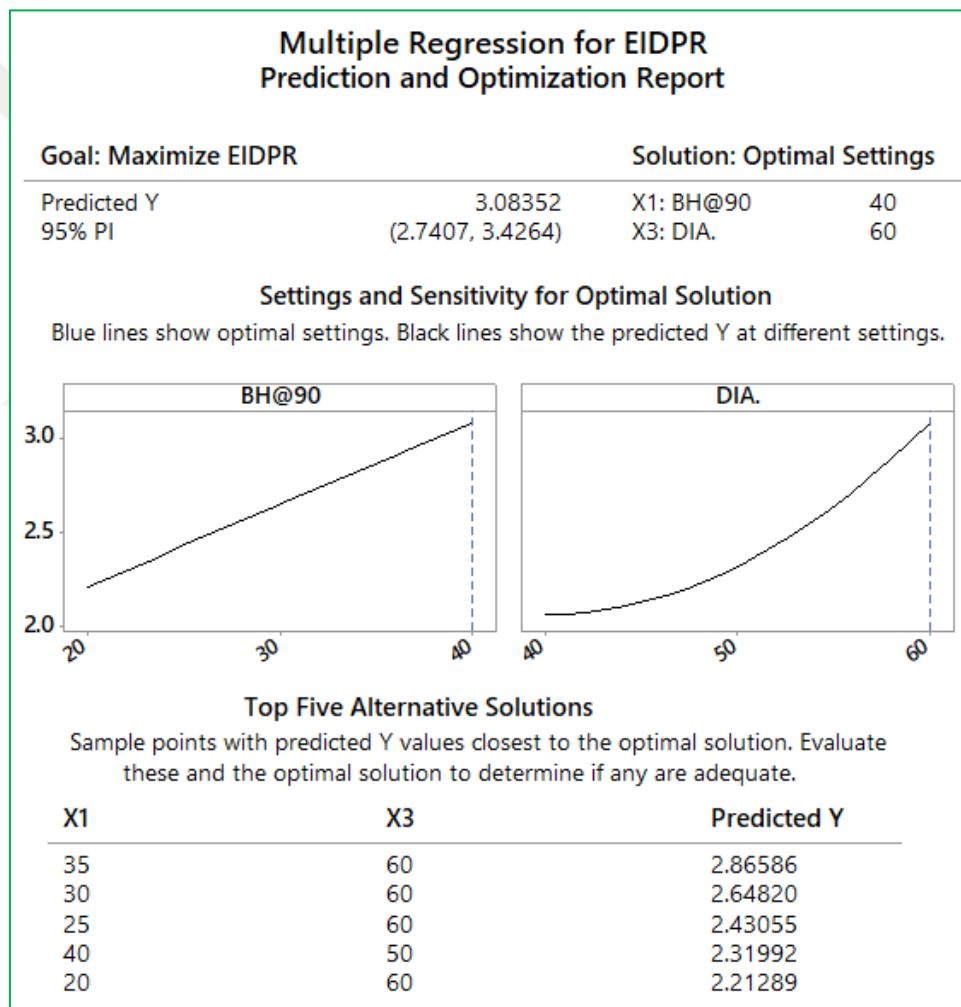


Figure 77. Optimisation report for EIDPR regression model

As a result of the optimisation made on the numerically analysed models, it has been determined that the highest value of EIDPR will be reached as a result of using the 60cm borehole diameter and the vertical borehole of 40 meters length set. In this way, it was found that the EIDPR value would reach 3%. Similarly, it is possible to obtain EIDPR values for the desired length and diameter combination by using the model equation.

$$EIDPR = 9.23 - 0.0766Ax - 0.2848x + 0.002555B^2 + 0.002002AxB \quad (16)$$

where,

- EIDPR = Excavation induced damage production ratio percentage (%)
- A = Vertical borehole length in meters (m) ($20 < A < 40$)
- B = Borehole diameter in centimeters (cm) ($40 < B < 60$)

The surface plot of the equation of the EIDPR multiple regression model is given in Figure 78.

Surface Plot of EIDPR vs DIA., BH@90

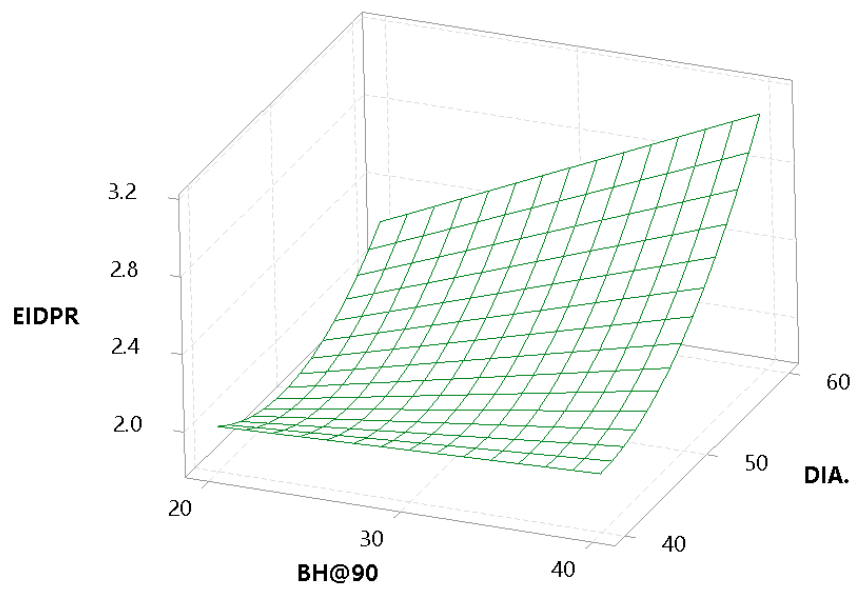


Figure 78. Surface plot of EIDPR multiple regression model



CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The MAHOP method is a promising method for oil production. As examined in this thesis, heavy oil production has never reached sufficient efficiency with the application of conventional methods alone. Considering the increasing energy demand worldwide and the role of oil production in both political and social issues, it is clear that the production of heavy oil reserves will be needed. If the Raman reserve is explicitly examined, it has crucial importance for Turkey with its potential. For these reasons, studies in Raman need to be developed and handled with innovative approaches. The MAHOP method offers an approach that has never been applied or tried before. The most crucial point to be noted here is that this method includes more than one engineering discipline. The vast experience in mining and the long-term study of rock behaviour mean that this accumulation can also be used for oil production.

This study has shown that, if certain conditions are met, the contribution of mining to heavy oil production can be achieved by applying the MAHOP method. The conclusions to be drawn from the study can be presented by classifying them as follows.

1. Geomechanical parameters were obtained from laboratory tests of limestone specimens belonging to the Batı Raman field. As a result of these tests, it was determined that the strength of the reservoir limestone containing oil has significantly lower values. While the average UCS value of the oil-saturated samples was around 6 MPa, the oil-free limestone samples showed a UCS value of over 60MPa.

2. As a result of the deformability tests, strong indications that the rock behaves in a strain-softening manner in the post-peak region were found in the intact rock behaviour.
3. In the analyses made using the elastic material and boundary element method, it has been shown that twin tunnels with a diameter of 4 meters can be drilled stably with a 20-meter wall-to-wall pillar in the rock mass of Garzan limestone.
4. Analytical plastic solutions are applied for a single circular tunnel to be drilled in the reservoir rock mass, and the common results are listed. As a result, it was determined that a plastic zone of approximately 4.2 meters would form around the unsupported tunnel.
5. As a result of the analytical calculations, it has been found that the tunnel diameter will experience a 3% closure if no support is applied. Another critical finding at this point is that it has been observed that this rate will reach 15% if the associated flow rule is applied.
6. Analytical solutions are compared with 2D plane strain analysis, and single tunnel verification is provided. After that, twin tunnels in the same model were examined considering the plastic behaviour, and it was observed that the plastic region expanded and reached 4.6 meters due to the twin tunnel structure. Likewise, it has been determined that the twin tunnel structure without support will undergo a 5% closure.
7. The analyses continued in FLAC 3D, and the relaxation method was applied. In this way, the amount of stress and strain that will occur around the tunnels and in the pillars has been simulated in stages in line with tunnelling practices, and it has been observed that a 2% closure will be experienced in the tunnel wall. In line with these results, it has been found that there will not be a squeezing problem in the tunnel, and the pillar of the tunnel will remain stable.
8. The plastic zones formed around the tunnels and the effects of these boreholes were observed in the model created to examine the boreholes,

tunnels and rock mass behaviour of the Batı Raman heavy oil field. The models created showed that the main element affecting the formation of the plastic zone is the tunnel opening, and plastic zones are concentrated around the tunnels. The contribution of boreholes to the formation of the plastic zone has been limited to their own surroundings.

9. On the other hand, drilled boreholes do not cause failure in the crown of the galleries/tunnels.
10. As a result of the numerical analysis of the compared physical model, it was observed that a plastic volume of 952.61 cubic meters was formed. It has been determined that 233.39 cubic meters of oil can be obtained as a result of the MAHOP oil recovery applied from this volume. The ratio of this volume to the volume determined in the MAHOP study is 2.23%. Accordingly, Excavation Induced Damage Production Ratio (EIDPR) was defined. Furthermore, a parametric study was conducted.
11. When the 15 models used in this parametric study are compared, it is concluded that the case of maximizing the EIDPR value can be achieved when the boreholes with the highest length and the largest diameter are excavated among the models examined. The following equation was obtained through the regression model. However, it should be noted that the linearity of EIDPR with variables A and B does not mean that the borehole diameter and length can be taken as long and as large as possible. There is a practical length and hole diameter limits for underground drilling machines, and likewise, there is a geometrical reservoir rock length limit (average 60 m).

$$EIDPR = 9.23 - 0.0766Ax - 0.2848x + 0.002555B^2 + 0.002002AxB$$

where,

- EIDPR = Excavation induced damage production ratio percentage (%)
- A = Vertical borehole length in meters (m) ($20 < A < 40$)
- B = Borehole diameter in centimeters (cm) ($40 < B < 60$)

12. As a result of the optimisation made on the numerically analysed models, it has been determined that the highest value of EIDPR will be reached as a result of using the 60cm borehole diameter and the vertical borehole of 40 meters length set. In this way, it was found that the EIDPR value would reach 3%.
13. If the Canbolat *et al.* (2020a)'s physical laboratory model is taken as a comparison, it can be concluded that the contribution of the mining operations (tunnels/galleries and fan boreholes) to the MAHOP oil production is not significant. However, one should keep in mind that the physical model does not represent a deep, highly stressed mining environment of Batı Raman.

It is possible to make some suggestions for future studies,

- Reservoir modelling is based on porosity and permeability values in terms of petroleum. Rock mass modelling, on the other hand, is examined by rock mechanical parameters in mining applications. Therefore, the most critical issue in future studies should be the determination of real rock mass behaviour with a coupling of solid-liquid. For this reason, further testing on the reservoir rock should be performed with utmost care for the determination of intact rock strength and post-peak behaviour.
- In underground openings, the in-situ stress condition, which is sometimes not given due attention, should be determined, and the in-situ stresses on the reservoir should be determined. Different scenarios should be created with a probabilistic approach when actual field measurements cannot be made. In addition, structural geological features should be identified, the structures sealing the reservoir should be modelled, and the effect of stress changes in the reservoir on other strata should be observed.

- The tunnels should be modelled with proper support (concrete/ reinforced concrete/rock bolts/ steel arch). Also, the fan holes should be modelled with perforated casing.
- Since the study area is an oil reservoir, it should be kept in mind that the material has a fluid content, and the solid-liquid relationship should be examined with coupled models. With a similar approach, since oil production will be provided by applying high pressure and temperature steam, it should be noted that solid-liquid-gas coupling would be necessary for more realistic modelling.
- Steam Assisted Gravity Drainage (SAGD) heavy oil recovery method is based on forming steam chambers for which induced micro and macro fractures in the reservoir play a crucial role in the conveyance of steam through the reservoir. Therefore, discrete fracture network modelling may be a more appropriate technique for fracture pattern modelling rather than continuum models. Hence, discrete element modelling of the proximity of tunnels/galleries and fan-boreholes might be a more appropriate modelling technique combined with continuum models for the pillar and the rest of the reservoir.
- The excavation arrangement of boreholes at different angles will also change the induced stress distribution, so it is possible to have different effects. Therefore, different approaches can be considered, similar to a knitting pattern in which boreholes intermingle. As an example, a model named “Miner's Braid” was designed.

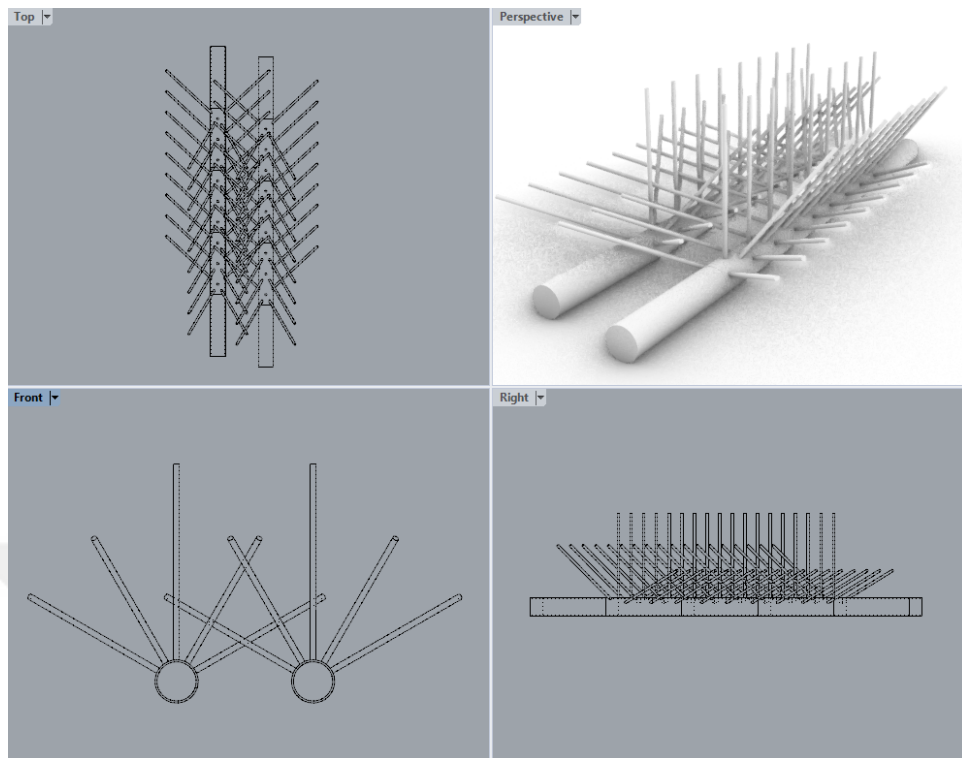


Figure 79. The Miner's Braid borehole design

As a result, the MAHOP method is a heavy oil production method that can be enriched and made more efficient by mining methods, as demonstrated in this study.

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