NUMERICAL ANALYSIS OF TWIN TUNNELS USING PLAXIS 2D

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY

IN

GEOTECHNICAL ENGINEERING

Submitted by:

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2K21/GTE/08

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CANDIDATE'S DECLARATION

I, Itoo Rakshanda (2K21/GTE/08) of M. Tech (Geotechnical Engineering), hereby declare that the Project entitled "NUMERICAL ANALYSIS OF TWIN TUNNELS USING PLAXIS 2D", which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi, submitted in partial fulfilment of the requirement for the award of the degree of Master of Technology is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project entitled " NUMERICAL ANALYSIS OF TWIN TUNNELS USING PLAXIS 2D", which is submitted by Itoo Rakshanda (2K21/GTE/08) of M. Tech (Geotechnical Engineering), Delhi Technological University, Delhi, submitted in partial fulfilment of the requirement for the award of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ABSTRACT

The advancement in urban transport necessitates the creation of dual or new singular tunnels in conjunction with the pre-existing ones. The impact of the twin tunnel location and construction method on soil displacement and the resultant forces exerted on the tunnel lining necessitates a thorough investigation of these factors in relation to tunnel design. The objective of this study is to construct a two-dimensional computational model for the purpose of examining the effects of dual tunnels on the adjacent soil and the tunnel lining. The significance of this lies in the fact that the interaction between the twin tunnels has the potential to induce considerable ground deformation, thereby presenting a potential hazard to structures in close proximity. The research conducted a comparative analysis of the impact of tunnel dimensions, depth of soil covering, and distance between tunnels, on the stability of the surrounding soil and the tunnel lining. The circular and horseshoe tunnel shapes were utilised in the study, which was conducted in geologically weak rock formations. This study examined the impact of various tunnel shapes on ground deformation and forces, including bending moment, axial force, and shear force, in the lining of the tunnel. A comparative analysis was conducted utilising a jointed rock model within the Plaxis 2D software. The findings of this study suggest that circular tunnels exhibit greater settlement in comparison to both horseshoe and rectangular tunnels. Moreover, increasing the dimensions of tunnels while maintaining a constant centre-to-centre distance for both circular and horseshoe-shaped tunnels led to an increase in ground settlement and forces within the tunnel lining. As the overburden increased, the maximum settlement value and forces in the tunnel lining for circular tunnels decreased. The study reveals that in horseshoe-shaped tunnels, there is a decrease in the maximum ground settlement values, whereas the forces in tunnel linings increase with the increase in the overburden. The research findings indicate that an increase in tunnel spacing, for both circular and horseshoe tunnels, resulted in a reduction of ground settlement and forces in the tunnel lining.

ACKNOWLEDGEMENT

I would like to express my profound gratitude and heartfelt appreciation to Prof. Anil Kumar Sahu, Department of Civil Engineering, DTU, Delhi, for his invaluable guidance, unwavering support, and valuable feedback throughout this project. His extensive knowledge and expertise fathered my project work at every stage. Without his encouragement, this task would have been impossible to accomplish.

I am also deeply grateful to Prof. Raju Sarkar, Department of Civil Engineering, DTU, Delhi, for his cooperation, continuous support, and tireless efforts in guiding me through each phase of the project. I would like to express my heartfelt thanks to the Vice Chancellor, Prof. Jai Prakash Saini, DTU and Dean PG, Prof for their invaluable support and dedication.

Furthermore, I would like to extend my sincere appreciation to our Head of Department, Prof. V. K. Minocha, Department of Civil Engineering, DTU, Delhi, for his keen interest, encouragement, and unwavering assistance throughout the duration of my project. His guidance and support have been instrumental in my progress.

I would also like to acknowledge and thank Almighty God, my parents and all my friends for their insightful suggestions, and encouragement during my work. Their contribution has played a significant role in shaping the outcome of this project.

Place: Delhi (ITOO RAKSHANDA)

Date: 2k21/GTE/08

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LIST OF ABBREVIATIONS AND SYMBOLS

TBM	Tunnel Boring Machine
NATM	New Austrian Tunnelling Method
SEM	Sequential Excavation Method
MTBM	Micro Tunnel Boring Machine
EPB	Earth Pressure Balance
FEM	Finite Element Method
NGI	Norwegian Geotechnical Institute
FSM	Fictitious Stress Method
K	Coefficient of earth pressure
EPBM	Earth Pressure Balance Machine
D	Diameter/Width of tunnel
EA	Axial stiffness
EI	Flexural stiffness
T	Lining thickness
W	Self-weight
v	Poisson's ratio
γ_{sat}, γ_{unsat}	Unit weight
E'	Intact elastic modulus
v_1	Intact Poisson's ratio
E_2	Stratified elastic modulus
v_2	Stratified Poisson's ratio
G_2	Stratified shear modulus
C_{ref}	Cohesion
ϕ	Friction angle
ψ	Dilatancy angle
α_1	Bedding angle
σ_t	Tensile strength
α_2	The angle from horizontal

CHAPTER 1

INTRODUCTION

1.1 HISTORY OF TUNNELLING

There is nothing revolutionary about the idea of tunnelling. Throughout human history, many tunnels have been built for a wide range of purposes, including those pertaining to transportation, sewage, water, and electrical supply. The first tunnel under the Euphrates River was created in Babylon in 2180 BC. Its length was close to 900 metres, and pedestrians were the only users of it. Around the year 520 B.C., the famous engineer Eupalinos constructed a water tunnel on the island of Samos in Greece. It was approximately 1,100 metres in length and was driven through limestone. The excavation took place on both sides of the tunnel at the same time, with the two crews coming together in the centre [1]. This was a particularly interesting and peculiar aspect of the case.

At that particular period, manual labour was the sole means of conducting excavations. Gunpowder was used in the post-Middle Ages era. Sophisticated and automated techniques were not employed until the 20th century. The process of excavation is increasingly becoming more efficient in terms of time and safety for workers. Various approaches have been formulated, with the selection of a particular technique being predominantly influenced by features of the terrain and the design of the tunnel. With the aid of advanced technology and past knowledge, tunnels can now be constructed in almost any kind of soil.

In 1841, the initial shield-driven tunnel in history was constructed by French engineer Marc Brunei beneath the river Thames in London. It measured approximately 300 metres in length and was excavated through the London clay. The initial toll of one penny was levied within this tunnel. The London Underground, formerly referred to as the East London Line, acquired this particular section in 1865, which subsequently became integrated into the remainder of the line. The aforementioned railway is recognised as the inaugural subterranean railway system in the world. Subsequent to its inception, over a hundred metropolitan areas have been established globally, with the majority of them exhibiting a tendency towards expansion, even as novel ones are being erected [2].

1.2 TUNNELLING IN URBAN AREAS

The requirement for infrastructure is expected to rise as cities continue to grow. When above-ground space is at a premium, going underground is often seen as the most practical solution for accommodating growing needs. Underground space is widely regarded as the most productive choice for the construction of surplus infrastructure. Lack of surface area is not the only factor driving people towards subsurface solutions. Congestion on the surface is eased by tunnelling and other forms of underground transportation, which also benefit the environment. However, the high cost associated with such endeavours can be a barrier in certain contexts. Tunnelling through an urban environment is a very difficult and complex process. The primary reason for this is that tunnels need to be constructed adjacent to other structures, whether they are above or below ground. In light of this, tunnel engineers need to take necessary precautions to ensure that tunnel-caused ground deformations do not cause considerable damage to other structures that are next to or overlaying the tunnel. This is in addition to guaranteeing the safe construction of tunnels, which is their primary and fundamental objective. To be able to accomplish this, tunnel engineers and designers need to have the ability to create accurate forecasts about ground movements and evaluate the potential harm that these movements could cause to structures in the surrounding area. By using TBMs (Tunnel Boring Machines) and exerting significant pressure at the face of the excavation (for example, using the Earth Pressure Balance method), surface deformations can be controlled, and volume loss can be restricted to less than 1%. This is possible through the use of the Earth Pressure Balance method.

There have been recent developments in tunnelling technology that have led to the development of novel approaches to the construction of underground routes. These new approaches provide advantages in terms of productivity, safety, and cost-effectiveness. The following are some of these methods:

1. New Austrian Tunnelling Method (NATM): This technique, which is also known as the Sequential Excavation Method (SEM), entails excavating the tunnel in short portions while simultaneously providing temporary support using sprayed concrete (shotcrete) and rock bolts. This technique makes use of the inherent strength of the

rocks in the surrounding area and is flexible enough to accommodate varying ground conditions.

2. Cut-and-Cover Method: This method is utilised in metropolitan areas or shallow depths where it is appropriate to do so. The process begins with the digging of a trench, followed by the construction of the tunnel structure and ends with the capping of the tunnel. This method is frequently utilised for the construction of underground utility tunnels and subway systems.
3. Drill and Blast Method: This conventional method entails perforating holes into the rock surface and utilising explosives to achieve fragmentation. Following the process of blasting, the dislodged rock is extracted, and structural reinforcement mechanisms such as rock bolts and shotcrete are implemented to ensure the durability and steadiness of the tunnel. The prevalence of this phenomenon is comparatively lower in metropolitan regions owing to apprehensions regarding ground disturbance and vibrations.
4. Microtunneling: This is a method of installing pipes or conduits with a small diameter, which is accomplished without the need for excavation. The utilisation of a micro tunnel boring machine (MTBM) is implemented, whereby the machine is directed by lasers and operated from a remote location. Microtunneling is a trenchless excavation technique that effectively reduces surface disturbance and is applicable to diverse soil types.
5. Tunnel Boring Machines (TBMs): TBMs are automated devices employed for the purpose of tunnel excavation via the process of rock or soil cutting. Tunnel boring machines are comprised of a cutting head that rotates and is outfitted with either disc cutters or roller bits, a shield that provides support for the tunnel face, and a conveyor system that facilitates the removal of excavated material. Tunnel Boring Machines (TBMs) exhibit a high degree of precision and efficiency, enabling them to function effectively across diverse soil and rock formations. TBMs are further of the following types:
   i) Earth Pressure Balance (EPB) TBMs: These TBMs utilise a balance of earth pressure and mechanical support to excavate tunnels. EPB TBMs are specifically engineered to operate in cohesive soils and soft rocks, where they utilise the excavated soil as a means of support while maintaining balanced pressure. Additives, commonly in the form of bentonite, are incorporated into the excavated material to enhance its stability during transportation.

ii) Slurry Shield TBMs: These TBMs are considered suitable for ground conditions that are characterised by high water content or instability, such as mixed faces or soft clay. These TBMs operate within a pressurised chamber that is filled with a stabilising slurry. The slurry serves to offset the pressure exerted on the ground, while concurrently facilitating the conveyance of excavated material to the surface for subsequent separation.

iii) Hard Rock TBMs: These TBMs are utilised for excavating tunnels through complex rock structures. With the aid of disc cutters or roller bits, the rock is crushed and fractured. Tunnel face stabilisation may necessitate the implementation of supplementary support systems such as rock bolts or shotcrete.

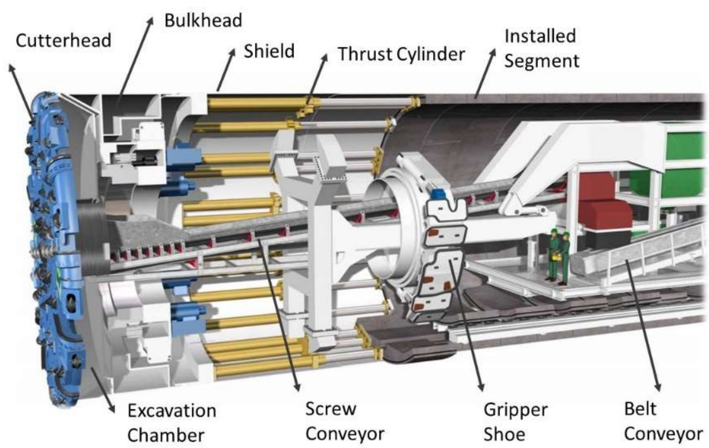


Fig. 1.1 Components of Tunnel Boring Machine. *(Source: rail system.net/tunnel boring machine)*

1.3 TWIN TUNNELS

In the context of transportation infrastructure, the term "twin tunnels" most commonly refers to the concept of building two tunnels in tandem with one another. Generally speaking, these tunnels are put to use for a variety of functions, such as roadways, trains, or underground transportation networks. The design of the twin tunnel offers various advantages over the design of the single tunnel. These advantages include higher capacity, greater security, and more efficient maintenance. Some key features of twin tunnels are:

- The utilisation of twin tunnels enables the segregation of traffic flow, thereby resulting in a higher capacity as compared to single tunnels. The implementation of dual tunnels facilitates the concurrent passage of a greater number of vehicles or trains, thereby mitigating traffic congestion and enhancing the efficacy of transportation.

- The establishment of twin tunnels provides an increased level of security through the provision of backup. In the event of tunnel unavailability resulting from maintenance, accidents, or emergencies, the alternative tunnel can serve as a means of facilitating traffic flow. The implementation of redundant service serves to mitigate interruptions and maintain an uninterrupted flow of transportation.
- The utilisation of twin tunnels enables the execution of maintenance tasks on one tunnel while the other tunnel continues to operate. This practice serves to mitigate the necessity of total shutdowns and alleviate the inconvenience experienced by commuters. Furthermore, enhancements and advancements can be executed in a single tunnel while the other remains operational, guaranteeing a seamless transition and uninterrupted transportation activities.
- The implementation of twin tunnels facilitates improved ventilation and safety mechanisms. In the event of emergencies, it is possible to mitigate the impact of smoke or pollutants by installing distinct ventilation systems in each tunnel, which would facilitate adequate air circulation. Similarly, the incorporation of personal safety mechanisms, such as fire suppression and evacuation protocols, can be executed in every tunnel to augment safety precautions.
- The construction costs associated with twin tunnels are typically higher in comparison to single tunnels, primarily due to the requirement for redundant structures and systems. Nevertheless, the enduring advantages in relation to enhanced capability, safety, and maintenance effectiveness frequently surpass the initial capital outlay.
- The integration of twin tunnels into urban landscapes can be accomplished with greater efficacy than that of larger single tunnels. A reduction of surface area and visual prominence may provide benefits in safeguarding the aesthetic worth of the surrounding areas and augmenting the possibilities for urban planning.
- The implementation of twin tunnels has the potential to improve the driver experience and increase comfort levels. This can be achieved through the provision of distinct, properly designed tunnels that feature suitable lighting and road conditions. This phenomenon has the potential to enhance the level of

comfort experienced by drivers, mitigate driver fatigue, and ultimately enhance overall satisfaction.

Fig. 1.2 Thane-Borivali Twin Tunnel. *(Source: Swarajyamag.com/Thane Borivali twin tunnel)*

1.4 INTRODUCTION TO FEM

The utilisation of Finite Element Methods (FEM) is a prevalent practice in the analysis of tunnelling, as it enables the simulation of intricate soil, rock, and tunnel structure behaviour. FEM is a numerical approach that involves splitting of the problem domain into smaller elements. This technique enables the estimation of continuous systems by means of a discrete representation. This section provides a brief summary of various programmes that are considered appropriate for simulating tunnel construction. This overview was generated through a comprehensive analysis of programme manuals, website content, and relevant literature pertaining to the programme in question.

1.4.1 PLAXIS

PLAXIS is a prevalent software tool based on the finite element method, which is commonly employed for the purpose of geotechnical engineering analysis. The application of this method is frequently observed in the examination and planning of subterranean passages, along with other geotechnical constructions such as footings, ridges, etc. PLAXIS provides customised functionalities and capabilities that are specifically designed to address the distinctive intricacies and difficulties that are inherent in tunnelling endeavours. PLAXIS offers several notable attributes for tunnelling analysis, such as:

a) The PLAXIS software facilitates the generation of accurate and authentic 3D representations of tunnel configurations, which encompass diverse geological and structural details. This enables precise modelling and evaluation of tunnel performance in varying loading scenarios.
b) The PLAXIS system takes into account the soil-tunnel interface. Realistic evaluation of stress distribution, deformations, and probable surface settlement is made possible through the modelling of various tunnel lining types.
c) Groundwater flow and its effect on a tunnel's structural integrity can be analysed with the use of PLAXIS. The different hydrological states that can be modelled with this tool include steady-state and transient flow, seepage forces, and pore pressure growth. In order to determine the effects of water intake and create effective dewatering methods, this information is essential.
d) With PLAXIS, you can model the tunnelling and constructing procedure beforehand. Sequential excavation, tunnel face stability, ground reinforcing methods and tunnel support system instalments may all be modelled using this software. Engineers can better evaluate the consequences of various methods of construction and fine-tune the design for safety and efficiency by simulating the construction procedure.
e) The PLAXIS software package integrates non-linear rock and soil constitutive models, enabling the accurate portrayal of material behaviour. It is imperative to account for various factors which include strain softening, consolidation, and shear strength degradation in order to comprehensively comprehend the intricate reaction of rocks and soils during tunnel excavation.
f) The PLAXIS software offers functionalities to evaluate ground subsidence resulting from tunnel excavation operations. This technology enables engineers to assess the possibility of surface and subsurface distortions, estimate the degree of settlement, and scrutinise their effects on neighbouring infrastructure and facilities.

1.4.2 ABAQUS

Abaqus is a versatile software tool that finds extensive usage in diverse engineering domains such as structural analysis, thermal analysis, and fluid dynamics. In addition to these applications, Abaqus can also be employed for the purpose of tunnelling analysis. The analysis of tunnelling generally encompasses the examination of the performance of tunnels and how they interface with the adjacent soil or rock formations. Abaqus offers a range of features and capabilities that can be employed for the purpose of tunnelling analysis. The Abaqus software facilitates the generation and simulation of the tunnel's geometry, encompassing its morphology, measurements, and intricate attributes. The characterization of the rock or soil encompassing the tunnel can be accomplished by utilising suitable material models that are accessible in Abaqus. The models under consideration are capable of capturing nonlinear behaviour, including but not limited to plasticity or nonlinear elasticity, as well as time-dependent properties, such as creep or consolidation. Abaqus provides meshing capabilities for the purpose of discretizing the tunnel and the adjacent soil or rock into finite elements.

1.4.3 ANSYS

Tunnelling is one of the many engineering challenges that can be analysed and modelled with the help of ANSYS, which is a popular engineering simulation programme that delivers extensive capabilities. Even though ANSYS provides a wide variety of tools and modules for various applications, the company does not provide a module that is specifically designed for tunnelling. On the other hand, the structural analysis and geomechanical skills that ANSYS possesses make it a tool that may be utilised quite successfully for tunnelling analysis. The ANSYS software facilitates the simulation of the interaction between the tunnel and the soil, enables the assessment of the structural soundness of tunnel linings, permits the analysis of groundwater flow, optimises excavation sequencing, evaluates risks, and simulates tunnel ventilation, thereby providing engineers with a comprehensive tool for tunnel design.

1.5 AIM AND OBJECTIVES

The objective of this research work is to examine the impact of various parameters on tunnel interactions. In order to achieve this goal, the project is guided by the following set of objectives.

a) To model the construction of a twin tunnel using Plaxis 2D
b) To investigate the settlement characteristics of twin tunnels as well as forces generated in tunnel linings by varying;
   (i) Tunnel shape
   (ii) Tunnel size
   (iii) Tunnel overburden
   (iv) Tunnel spacing

1.6 THESIS LAYOUT

In Chapter 1, an introduction to the topic and a comprehensive overview of the subject matter are provided.

In Chapter 2, a literature study is conducted on tunnelling-induced ground deformations utilising numerical approaches. In addition to this, it explains various tunnelling techniques that are available and in use nowadays.

In Chapter 3, the methods, materials, geometry, and boundary conditions that were used to carry out the research are dissected and discussed.

In Chapter 4, the outcomes of each of the four different modelling conditions are presented.

In Chapter 5, the conclusions are presented, along with some recommendations for further study.

The study concludes with a comprehensive list of references that acknowledges and credits the sources used and cited throughout the paper.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH GAP

2.1 LITERATURE REVIEW

Khabbaz et. al [3] conducted a study on the potential hazards associated with tunnelling beneath Martin Place in Sydney, and the additional loads that such tunnelling may impose on surrounding buildings. The principal objective of this study was to enhance comprehension of the interactions between tunnels and rock piles, to advance sustainable development. For the purpose of predicting the interaction between the construction of tunnels and piled foundations, a model based on finite element analysis has been established. The discrete constituents of the tunnel, rock, and pile are subjected to individual scrutiny before their integration into a unified model. The desktop study was utilised to develop the model, which is founded on the features of Hawkesbury Sandstone. The piles have been designed in accordance with the established norms of Australia and have integrated valuable knowledge acquired from the erection of high-rise structures. The step-by-step procedure of a tunnel-boring apparatus is used to predict the construction of tunnels. Research is carried out to investigate the correlation between the location of the tunnel, basements, and piles after the combination of various elements According to the findings of this study, the process of tunnelling might result in an increase in both the flexural and axial loads of piles. The increase in load has the potential to exceed the structural capacity of certain piles, particularly those located in close proximity to basement walls. Through the implementation of parametric analysis, a noteworthy association was identified between the tunnel's depth and the magnitude of stress exerted on the lining. Nevertheless, the correlation between the magnitude of the load and the depth of the tunnel exerted on the piles remains ambiguous.

Chehade and Shahrour [4] conducted a numerical study to examine twin tunnels, with a specific focus on optimising the construction technique and relative positioning of the tunnels. Parametric research was conducted to examine the effects of tunnel construction on soil settlement and internal forces by analysing these two factors.

The research commences by introducing a numerical model, which is subsequently utilised to conduct analyses on three distinct twin tunnel arrangements: horizontal alignment, vertical alignment, and inclined alignment. The aforementioned statement demonstrates the correlation between construction methodology and its influence on both ground settlement and internal forces. The researchers concluded that the excavation of the uppermost tunnel first results in increased bending moment and settlement. The vertical alignment of tunnels is associated with the highest degree of soil settlement, whereas tunnels that are horizontally oriented are associated with the lowest degree of soil settlement. The construction of twin tunnels necessitates the consideration of environmental and subsurface congestion constraints. Numerical modelling is a valuable tool for considering these constraints and identifying optimal solutions for the construction of dual tunnels.

Vinod and Khabbaz [5] carried out computational modelling on circular and rectangular twin tunnels in order to determine the ground settlements and bending moments in the tunnel linings. The primary factors that will be considered in this investigation are the impacts of the volume losses, relative placements of the twin tunnels, critical distances, overburden, and tunnel widths for both circular and rectangular tunnels. The authors came to the conclusion that rectangular twin tunnels have a lower surface settlement range than circular twin tunnels at shallow depths; but, for larger depths, circular twin tunnels settle less than rectangular twin tunnels do. This was found to be the case when the authors analysed the two types of tunnels side-by-side.

Zhang et al. [6] performed Finite element (FE) analyses on an anisotropic soil model that was developed by the Norwegian Geotechnical Institute (NGI) utilising the Active-Direct Shear-Passive concept. The study examined 682 cases to explore how five primary factors influence the structural forces of twin tunnels. These parameters included the depth of burial, the distance between the tunnel centres, the soil strength, the stiffness ratio, and the degree of anisotropy. The prediction model developed can be utilised by engineers to accurately assess the structural response of twin tunnels, thereby achieving project-specific reliability indices. The study's findings suggest that the augmentation of burial depth results in a significant amplification of the thrust pressures that exert force on the linings of a parallel twin tunnel. The authors arrived at the conclusion that these factors have a significant impact on the structural integrity of the tunnel system. The influence of soil stiffness on the structural responses of twin tunnels is negligible. The anisotropic nature of soil properties exerts an influence on tunnelling reactions. If anisotropic soil behaviour is disregarded in favour of assuming isotropic soil behaviour, it could lead to an underestimation of the maximum bending moment and thrust force in the twin-tunnel linings. The explicit computation of twin tunnel structural forces through basic regression algorithms is characterised by a lower degree of precision.

Banerjee and Chakraborty [7] examined the deformation of twin tunnels in this study under the influence of several physical parameters, including the mutual position of tunnels, changes in the level of the water table, and the impact of utilising liners of varied stiffness was evaluated. The outcomes were specified in terms of deformation or settlement characteristics appropriate for tunnels. The finite element-based software Abaqus was used to carry out a thorough parametric analysis. The material attributes were stated in terms of equivalent cohesion and friction angle for rock, with the tunnels being assumed to be situated within weathered granite rock. The conclusion of the study was that for the upper tunnel, the influence of s/D on d/D was relatively strong for its lesser values up to 1. For the lower tunnel, the effect of s/D on d/D was greatest at H/D = 1 and increased as the tunnel depth below the ground level reduced. Both the upper and lower tunnels' deformation behaviour was significantly impacted by the falling water table. Variation in the vertical distance between the parallel tunnels had a negligible impact on the deformation ratio (du/D) in the upper tunnel as a result of a lowered water table. The change in liner rigidity had a significantly greater impact on the lower tunnel than on the upper tunnel. In porous, weathered granite boulders, consolidation-related deformation is unlikely. Finally, it can be stated that the predicted liner deformations can assist designers in determining an appropriate liner thickness to allow for safe deformations.

Hamdy et al. [8] examined a case study on the first phase of Greater Cairo metro line No. 4. The design of twin tunnels encompasses both vertical and horizontal alignments, as well as diagonal orientations. There are two instances of diagonal alignment, one of which involves the construction of tunnels beneath the river Nile. Furthermore, there exist two instances of horizontal alignment, wherein one of them involves the tunnel being situated above the bottom clayey soil. The appropriate spacing between twin tunnels was determined based on displacement and internal forces within the tunnels. The study has provided data on both horizontal and vertical displacements in relation to twin tunnels and the adjacent soil. The analysis is conducted through the utilisation of the PLAXIS programme, employing two-dimensional numerical models. Furthermore, the methodologies pertaining to the construction of the dual tunnels have been deliberated. The study conducted by the authors revealed that the maximum surface settlement exhibits a decreasing trend as the distance between tunnels increases, for varying tunnel alignments. The spacing between tunnels has a significant impact on the soil displacement and internal forces experienced by the tunnel lining. Specifically, when the distance between tunnels is less than 2.20 times the tunnel diameter for horizontal alignment, 1.80 times the tunnel diameter for diagonal alignment, and 1.25 times the tunnel diameter for vertical alignment, the effects are particularly pronounced. When the distance between twin tunnels exceeds 2.20 times their diameter, the impact of their interaction can be disregarded.

Agbay and Topa [9] carried out the research to present a methodology for deriving a modification factor that incorporates the impact of a pre-support system and the quality of the rock mass. The data utilized in this work has been sourced from the Eurasia Tunnel, which was constructed through the utilisation of the New Austrian Tunnelling Method. Additionally, the excavation process was reinforced through the implementation of the fore poling and umbrella arch method. To revise the geological profile, numerical analyses were performed on 12 cross-section lines along the tunnel in the current study. A parametric study was carried out on the pre-support systems with varying distances between pipes. Furthermore, a statistical formula was derived to demonstrate the reduction in maximum surface settlement due to the pre-support system. The authors concluded that the impact of the cohesion parameters and friction angle on the surface settlement induced by twin tunnels was found to be minimal. The alteration of settlement values is influenced by important factors such as Poisson's ratio and the deformation modulus of the rock mass. The deformation modulus and Poisson's ratio of the rock mass are significant factors that contribute to the alteration of settlement values. This is due to the fact that the stress-strain states of the tunnel's surrounding medium primarily govern settlement.

Wang et al. [10] conducted a study on the excavation of a twin tunnel with a large diameter, situated at a shallow depth in soft soil. The excavation process was carried out through the utilisation of two distinct methods, namely the four-step method and the Cross Diagram method. This study examines the impact of construction and environmental factors on ground surface settlements, The study analyses the effects of tunnelling methods, construction speed, soil conditions, and rainfall on settlement outcomes. The authors concluded that surface settlement in muddy silty clay is large and long-lasting. Tunnel excavation effects range from 0.5 to 4 times the diameter of the tunnel. Ground surface settlement is influenced by the construction methods employed for tunnels as well as the soil conditions. If the surface settlement caused by the first tunnel has not yet stabilized, the excavation of the second tunnel can lead to a significant settlement. Therefore, the second tunnel should be excavated after the first tunnel-caused surface settlement stabilises.

Shinde et. al [11] performed a study to assess the impact of the surrounding soil on tunnelling operations by monitoring the deformation of the soil mass. Plaxis 2D software was utilised in the present study to analyse the effects on the tunnel. To validate the findings of this study a comparative analysis was conducted between the values obtained from this research and those reported in prior literature. The validation results exhibited variability within a range of 10 to 15 percent in comparison to the findings reported in prior research publications. Therefore, the software is deemed suitable for performing an analysis of the tunnel. Consequently, the software can be utilised to conduct additional analysis on the impact of adjacent soil and structures on the tunnel.

Choi et al. [12] conducted a series of experimental model tests to examine the mechanical behaviour of existing and new tunnels. The researchers set out to determine how factors including tunnel diameter, tunnel centre-to-centre distance, and earth pressure coefficient (K) affect tunnel performance. Testing was done by excavating a new tunnel next to an already existing tunnel and measuring the resulting displacement and crack propagation. The authors concluded that beyond a certain distance, which varies with tunnel size, displacements surrounding tunnels decrease and attain a stabilised state. Additionally, it was noticed that the influence zone of the old tunnel on the excavation of the new tunnel diminishes as the size of the existing tunnel decreases. The authors also concluded that as the earth pressure coefficient, K increases, pillar region displacements reduce irrespective of the tunnel centre-to-centre distance. Thus, as the earth pressure coefficient increases the pillar's stability is assured.

Phadke and Titirmare [13] investigated several cutting-edge approaches to tunnelling. Tunnel construction is typically quite pricey, but it is time and labour efficient, and it offers a more comfortable environment. The construction of a tunnel requires a significant excavation of the surrounding ground, rock, or other material. The process of excavation and backfilling has become much simpler as a result of the availability of contemporary technology. The authors concluded that increased mechanisation of tunnels can lead to a reduction in construction time and facilitate early revenue generation. The Tunnel Boring Machine (TBM) has the potential to attain a higher production rate while utilising a reduced labour force in comparison to the New Austrian Tunnelling Method (NATM). The utilisation of Tunnel Boring Machines (TBM) is considered a safer option due to the presence of a shield that safeguards the working area. Moreover, the absence of explosive blasting, which is a characteristic of the New Austrian Tunnelling Method (NATM), renders TBM a relatively safer alternative. As TBM blasting is not a part of the process, there is no need to worry about vibrations or overbreak. Nevertheless, the use of Tunnel Boring Machines (TBM) incurs significant expenses due to the high initial capital cost and extended mobilisation time. The primary drawback associated with Tunnel Boring Machines (TBM) is their limited adaptability to varying geological conditions and tunnel shapes. The power demand is substantial, and often the Tunnel Boring Machine (TBM) cannot be repurposed for other projects due to the potential for disparate requirements and demands.

Singh et al. [14] investigated a total of ninety simulations to examine the crucial spacing of the twin tunnel within a granitic rock mass. The diameter of twin tunnels varies from 2 metres to 10 metres, while the distance between them varies from 0.2 to 2 times the tunnel diameter. Based on the results, it is suggested that the distance between tunnels be at least 0.8 times the tunnel diameter. The study revealed that the impact of small-diameter tunnels is limited to the near field, whereas large-diameter tunnels have an effect on both the near and far fields. It is recommended that the vertical aperture, measuring approximately 3 metres in diameter and containing a canister of radioactive waste, be drilled at intervals exceeding 2.4 metres. The authors arrived at the conclusion that the tunnel's stability and sustainability performance is directly correlated with its displacement. The attainment of optimal stability in a structure is based on the minimal displacement of its components. The research indicates that the impact of spacing and tunnel dimension on stress levels is minimal. The magnitude of the induced stress zone is inversely proportional to the spacing of twin tunnels, while it is directly proportional to the diameter of the tunnels. The identification of the plasticity of the host zone is necessary to evaluate the fractured zone and deformed structure. Plasticity is a crucial parameter for distinguishing between the elastically deformed zone and the permanently deformed zone.

Chu et al. [15] conducted experimental simulations on twin circular tunnels in homogeneous material, bi-layered and tri-layered formations. During the excavation process, the induced displacements and strains around the tunnel openings were measured. Using the Fictitious Stress Method (FSM), a two-dimensional numerical simulation has been made to study the mechanical properties of a twin tunnel in formations comprising multiple layers. At the interface, the continuity equation for displacement and stress is taken into account for conducting simulations. Various values of initial stress, modulus ratio, and coefficient of earth pressure (K) have been taken into account. The analysis pertains to the distributions of displacement in the vicinity of tunnels that lack support. The determination of fractured zones surrounding tunnels is based on the application of Hoek and Brown's failure criterion across a range of configurations. The authors came to the conclusion that the numerical findings are in good accordance with the results of the model test, with the difference falling between 2% and 4%. This indicated that the FSM model was capable of being utilised to solve the mechanical behaviour of a tunnel that had been excavated in a multi-layered formation. For two-layered formations, in the case of a stiffer formation, there will be less settlement at the tunnel crown. But if the rock formation above the tunnels is weaker, the area around the upper tunnel will displace more. For three-layered formations, the stiffer formations on top and bottom cover the tunnels and make them more stable. On the other hand, as the tunnels are surrounded by weaker rocks, the displacements at the uppermost and lowermost parts of the tunnel will get higher.

Kamal et al. [16] conducted a systematic analysis of the horizontal twin tunnels of Cairo Metro Line No. 4. This was achieved by using finite element analysis Plaxis 2D. The tunnels were subjected to both static and earthquake dynamic loads, with the latter being simulated using the Dahsour Earthquake 1992-time real history. The present study has incorporated both static and dynamic analyses to assess the impact of soil-structure interaction on the horizontally situated twin tunnel’s static and dynamic behaviour. An investigation was also carried out on the horizontally aligned twin tunnels of Cairo Metro Line No. 4 under various factors, which included tunnel depth, the distance between tunnel centres (s), and the stiffness of soil (E). The findings indicate that soil structure interaction is anticipated to govern both static and dynamic analysis.

The parameters under study hold significant importance in the design of tunnels subjected to static and dynamic loads.

Fu et al. [17] presented an analytical solution for issues related to the determination of displacements and stresses in the vicinity of deforming twin-parallel tunnels situated in an elastic half-plane. The solution is based on the utilisation of complex variable theory. For the purpose of the study, it was postulated that a consistent radial displacement would serve as the boundary condition for both tunnels. The proposed analytical approach was utilised to gain a comprehensive understanding of the interaction between twin-parallel tunnels by closely examining the impact of tunnel depth and spacing on surface movement. Significant emphasis was placed on this aspect of the study. The study indicates that the impact of twin tunnel interaction on surface displacements decreases as the depth of the tunnels and the distance between them increase. The analytical solution presented in this study demonstrates that the principle of superposition can be utilised to ascertain the surface deformation of twin-parallel tunnels with considerable depth and spacing. However, if the tunnels are not spaced at a certain distance, the interaction effect between them must be considered to accurately predict ground movement.

Dias et al. [18] presented the outcomes of an analysis of two cross-tunnel sections. The subterranean construction was executed for the purpose of establishing a metropolitan railway system within an urban locality situated in Lyon, France. Upon comparing the measurements of various projects, it can be inferred that the primary causes of short-term settlements are the face instability and the annular gap that were detected subsequent to the release of the shield. The present study involves an analysis of the horizontal and vertical movements that occur during the excavation of a tunnel using a slurry pressurised tunnel boring machine. The obtained observations are subsequently compared with various numerical approaches. The 2-dimensional numerical methodology employs the principle of volumetric reduction and is implemented for every phase of excavation. The simulation approximates the observed movements; however, it necessitates the utilisation of empirical coefficients to depict the three-dimensional problem in 2D. The utilisation of the three-dimensional approach enables a more direct consideration of the physical aspects of the problem, thereby facilitating the incorporation of various factors such as the shield conicity, slurry pressure at the tunnel face, the grout consolidation and the grout injection in the annular void.

Afifipour et al. [19] investigated the interaction between twin tunnels that cross beneath an underpass using a three-dimensional finite element modelling approach. The study placed particular emphasis on the effects of TBM construction parameters, such as grout pressure, face pressure and thrust jacks force, on the interaction between the tunnel and the structure. Additionally, the study examined the variations in bending moment and axial force of the subway members during tunnel excavations. The study performed an in-depth analysis of the influence of twin tunnel construction on the alteration of bending moments and normal forces of the structural elements of the subway and the initial tunnel lining. The findings indicate that face pressure had a greater influence on the settlement of the subway when compared to grout pressure and thrust force. The displacement rate varied significantly as a result of the incremental adjustment of EPB operation parameters at the tunnel crown, in comparison to the surface and piles toe of the underpass. The magnitudes of bending moments in the underpass exhibited lesser variation compared to normal forces The impact of the construction of a second tunnel on the first tunnel, specifically in terms of alterations to normal forces, bending moments, and displacements resulted in an increase of less than 10%.

Mirhabibi and Soroush [20] investigated the impact of various three-dimensional modelling techniques for surface buildings on the ground settlement caused by twin tunnelling. The present study involved the analysis of 23 three-dimensional finite element models utilising field data from Shiraz Metro line 1 and the ABAQUS code. The objective was to evaluate the impact of various building modelling techniques. The study examined four distinct categories of building models, namely: (a) models that solely incorporate structural elements, (b) models that include structural elements and all walls that are situated along the beams, (c) models that comprise both structural and facade box components, and (d) models that integrate structural elements, facade, and partition walls conducted in order to analyse the structural behaviour of buildings and open spaces under various loading conditions. The findings indicate that the use of a three-dimensional modelling approach results in significant differences when compared to a two-dimensional modelling approach, as demonstrated by the outcomes of the finite element model. The utilisation of two-dimensional plane strain modelling has been observed to result in an overestimation of building stiffness, consequently leading to reduced settlement amounts when compared to three-dimensional models. The process of constructing three-dimensional building models that solely take into account the structural elements such as columns, beams, and slabs, leads to settlements that are highly adaptable and closely resemble the green-field scenario. Moreover, the stiffness of the building has a negligible impact on the settlement trough. The incorporation of facade and partition walls into the finite element models yields increased stiffness, thereby leading to reduced settlement and flexibility of the settlement trough.

Fang et al. [21] investigated the soil surface settlement profiles resulting from the implementation of closely-spaced twin tunnels through the shallow tunnelling method. The area of interest, where the twin-tunnelling was executed in both offset and stacked configurations, involved the consistent monitoring of ground deformation across a total of 18 cross-sections throughout the construction process. Various reinforcement schemes, including partial face, full face, and fore poling, were implemented to accommodate the diverse conditions of the twin tunnels in the relevant area. This study presents and depicts the documented ground settlements and settlement troughs of three representative sections. The Gaussian function is utilized to fit the ground settlement troughs caused by individual tunnels. This study presents and compares the factors that define such surface settlement troughs. These parameters include empirical trough width, ground loss percentage, maximum settlement, and trough width parameters. The authors concluded that the characteristics of a surface settlement trough, including the width of the trough and the percentage of ground loss, are significantly impacted by the ground reinforcement strategies employed. The ground settlements produced by each of the twin tunnels tend to increase maximally with a decrease in the burial depth while maintaining the same reinforcement schemes.

As the distance between tunnel centres decreases, the percentage of ground loss induced by the second tunnel decreases. However, these losses are typically greater than those induced at corresponding sections by the first tunnel.

Chena et al. [22] examined the deformation and stress characteristics of twin tunnels in Changsha, China, caused by close-proximity EPBS under-crossing in sandy soil stratum. The Metro Jet System (MJS) technology was employed to build horizontal columns that stabilised the sandy soil beneath the twin tunnels already in place. The stress and deformation of old tunnels that were impacted by the construction of new tunnels were thoroughly tracked. Hoop stress and deflection of existing tunnels was kept within permissible limits.

Do et al. [23] used the FLAC3D finite difference element programme to incorporate significant impacts of segment joints and tunnel distance on the structural lining forces generated in twin tunnels. The construction procedure of the second tunnel significantly impacts the induced structural lining forces in the first tunnel across different phases. The values acquired from a continuous lining are consistently larger than those obtained from a segmental lining. However, the influence on the structural forces produced in the first tunnel due to the distribution of joints in the second tunnel is insignificant. To avoid any critical influence the minimum separation distance between the tunnels is approximately twice the diameter of a single tunnel. The research findings show that a rise in the tunnel distance leads to a reduction in the impact of the second tunnel on the normal force experienced in the first tunnel. A continuous lining is comparatively less vulnerable to the effects of the subsequent tunnel construction than a segmented lining. At a distance of approximately two tunnel diameters, the alterations in the normal forces generated in the initial tunnel as a result of the collision with the second tunnel can be disregarded, regardless of whether the tunnel is reinforced with segmental or continuous lining. The bending moment and normal force in the first tunnel aren't affected much by the way the joints are placed in the second tunnel.

Chakeri et al. [24] investigated the impacts of the interaction between twin tunnels mostly opened in fault zones and mixed ground using surface settlement measurements taken with an Earth Pressure Balance Machine (EPBM) as the primary data source for this study. In this investigation, both numerical and empirical techniques were employed. The authenticity of the results generated by three-dimensional numerical simulation is tested using observed data. Good agreement was found between numerical results and experimental data. The authors concluded that tunnel spacing and fault spacing greatly affect maximum surface settlement and surface settlement curve shape. Numerical models approximated the field-measured surface settlement data. The Herzog technique is good for evaluating the influence of twin tunnel spacing on maximum surface settlement, even though its results differ from numerical models and observable data. An intensive interaction would be seen on the surface settlement curve if the twin tunnels were built with a spacing of less than 3D. When the tunnel spacing exceeds three times the tunnel diameter, the surface settlement takes on a form resembling the curve of two independently operating tunnels. When distances are greater than 4D, the interaction factor also approaches 0. Maximum surface settlement is heavily influenced by the fault zone thickness and the tunnel face material. Substituting limestone for very dense sand on the tunnel face raises the maximum surface settlement value by a factor of 4.

2.2 RESEARCH GAP

On the basis of the literature review mentioned above, the following research gaps are observed:

1. Despite extensive research on the numerical modelling of twin tunnels in various soil types, little investigation has been undertaken to simulate twin tunnels in distinct rock strata using Plaxis 2D.
2. The majority of research studies using numerical modelling of twin tunnels through Plaxis 2D have focused on TBM tunnels, which are typically circular in shape and less frequently rectangular due to the relative ease of modelling such tunnels. However, a comprehensive evaluation of distinct tunnel geometries achievable through the NATM excavation method has yet to be conducted using Plaxis 2D.

CHAPTER 3

MATERIALS AND METHODS

3.1 GENERAL

Numerical analysis using plaxis 2D was conducted on twin tunnels in weak rocks. Modelling was carried out on 15 node system using a jointed rock model to evaluate ground settlements and forces generated in the tunnel lining.

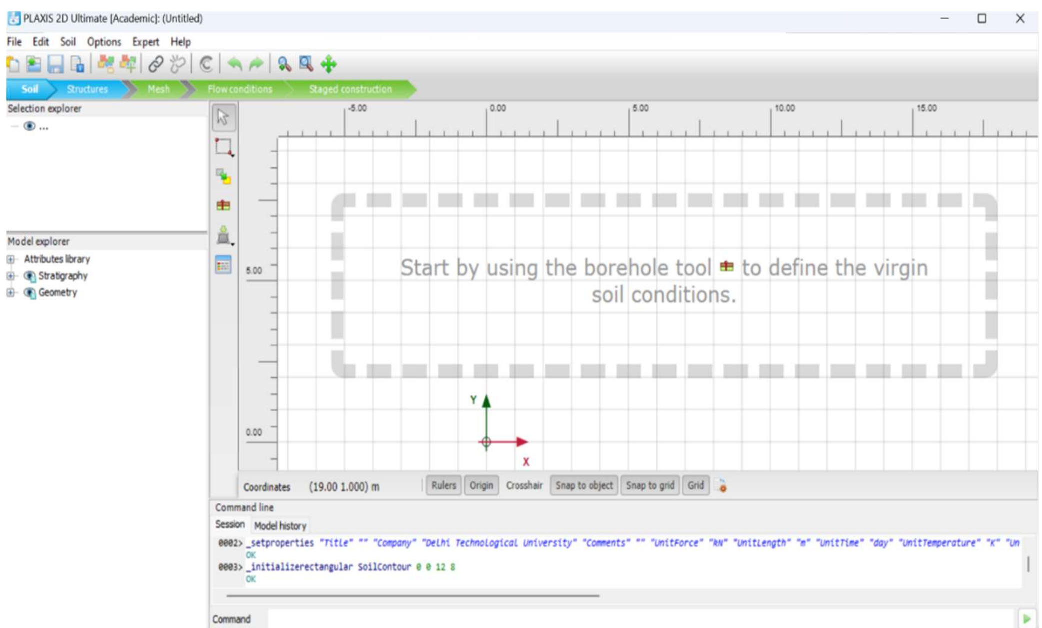


Fig. 3.1 Basic Layout of Plaxis 2D

3.2 STAGES FOR CALCULATION

Numerical analysis using plaxis 2D was conducted on twin tunnels in weak rocks. Modelling was conducted on 15 node system using a jointed rock model to evaluate ground settlements and forces generated in the tunnel lining. Modelling was carried out in three phases:

(i) the initial phase before the excavation of tunnels,
(ii) the construction of a single tunnel and its lining and,
(iii) the construction of a nearby tunnel including its lining.

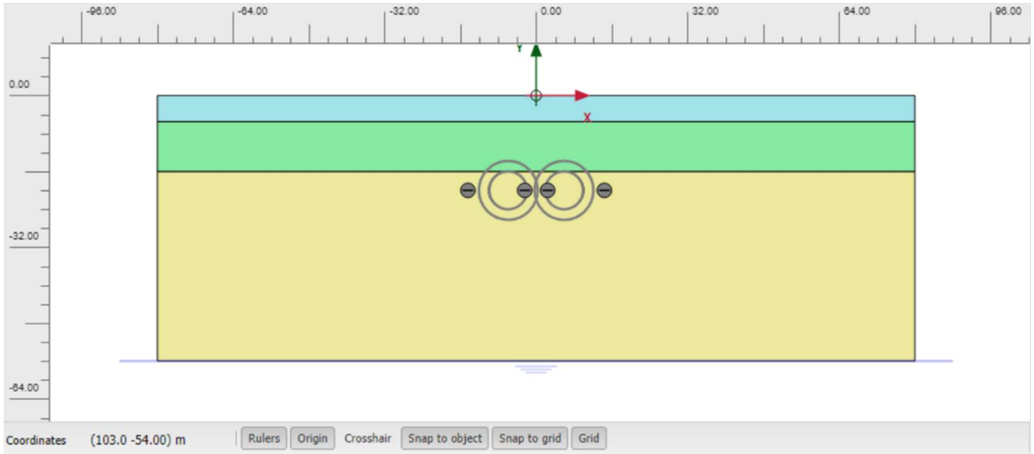


Fig. 3.2 Initial phase before the excavation of tunnels.

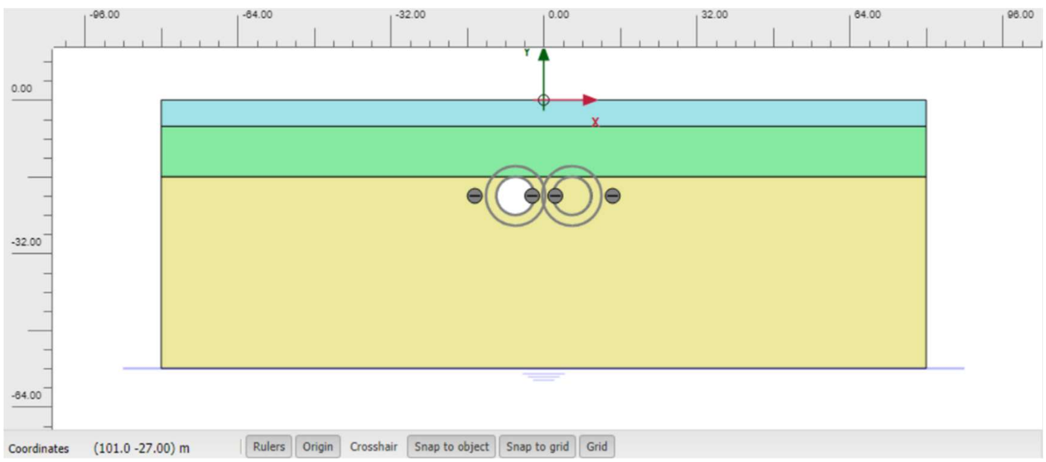


Fig. 3.3 Excavation of the first tunnel.

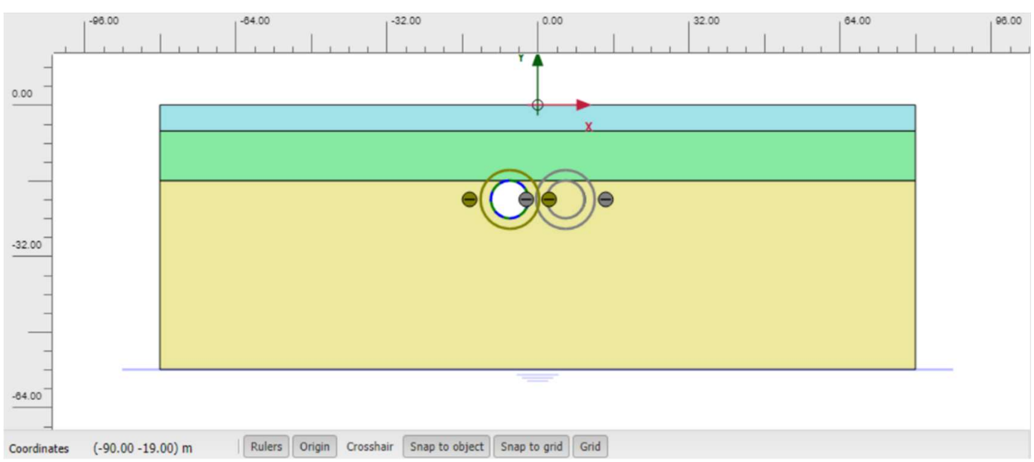


Fig. 3.4 Activation of lining for the first tunnel.

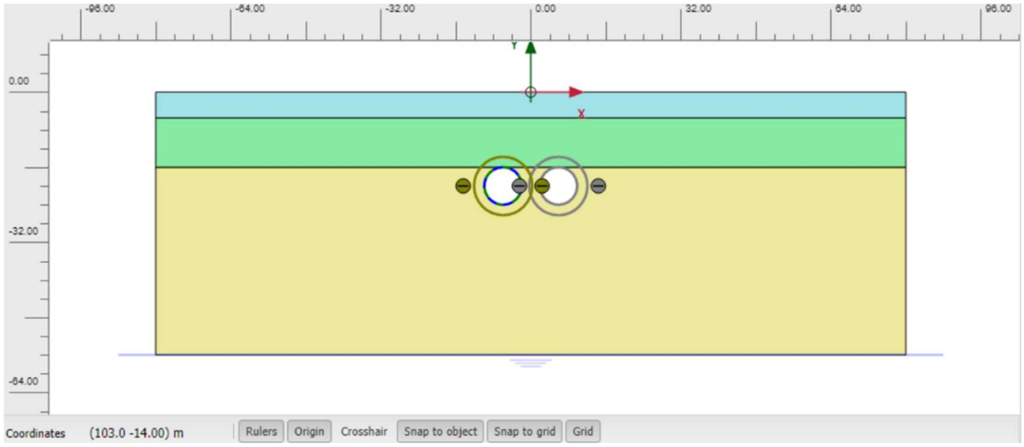


Fig. 3.5 Excavation of the second tunnel.

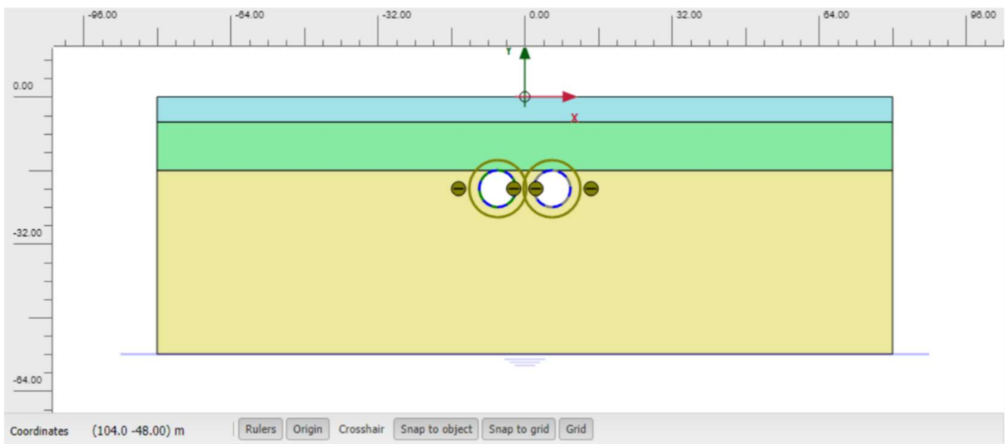
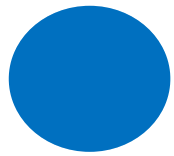
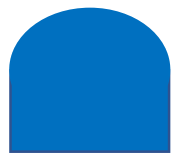


Fig. 3.6 Activation of lining for the second tunnel.

3.3 GEOMETRY AND BOUNDARY CONDITIONS

The tunnels considered in the analysis were assumed to be circular, horseshoe and rectangular tunnels. The width of the boundary for the analysis was fixed as 20d and the depth as 7d, where d is the diameter in the case of circular tunnels and width in the case of a horseshoe and rectangular tunnels, which was maintained as 8 m. Since the diameter of circular tunnels was equal to the width of horseshoe/ rectangular tunnels, the term “diameter of the tunnel” is utilised to represent both the diameter of circular tunnels and the width of horseshoe/ rectangular tunnels. The height of the horseshoe tunnel was taken equal to the diameter of the circular tunnel whereas the height of rectangular tunnels was maintained at 5.5m because a minimum clearance of 4.6 m is to be provided for trucks [5].

Table 3.1 Shape and Dimensions of twin tunnels considered in the analysis

Shape of Twin tunnels		Dimensions
Circular		Diameter (5 – 8) m
Horseshoe		Width (5 – 8) m Height (5 – 8) m
Rectangular		Width 8 m Height 5.5 m

3.4 MATERIALS AND DATA

The rock and tunnel lining properties used in this analysis were taken from previous research work [3]. The ground profile comprised three layers of class IV, class III, and class II sandstone as shown in Table 3.2. The tunnel lining and rock properties are presented respectively in Tables 3.3 and 3.4 below.

Table 3.2 Preliminary ground model [3]

Geological formation	Depth (m)
Class IV Sandstone	0 to -5.5 m
Class III Sandstone	-5.5 to -16 m
Class II Sandstone	> -16

Table 3.3 Tunnel lining properties [3]

Parameter	Value
Axial stiffness, EA (KN / m)	8.75×10^6
Flexural stiffness, EI (kNm^2 / m)	7.5×10^4
Lining thickness, t (m)	0.3
Self-weight, w $(kN / m / m)$	7.5
Poisson's ratio, v	0.2

Table 3.4 Rock parameters for jointed rock model [3]

Property	Class II Bertuzzi (2014)	Class III Bertuzzi (2014)	Class IV Bertuzzi (2014)
Unit weight γ_{unsat} (kN/m^3)	24	24	24
Unit weight, γ_{sat} (kN/m^3)	24.5	24.5	24.5
Intact elastic modulus, E' $(kN\ /\ m^2)$	6×10^6	4×10^6	3×10^6
Intact Poisson's ratio, v_1	0.25	0.25	0.25
Stratified elastic modulus, E_2 (kN/m^2)	5×10^6	3.5×10^6	2×10^6
Stratified Poisson's ratio, v_2	0.25	0.25	0.25
Stratified shear modulus, G_2 (kN/m^2)	600×10^3	400×10^3	100×10^3
Cohesion, C_{ref} (kN/m^2)	50	35	15
Friction angle, ϕ (°)	30	25	20
Dilatancy angle, ψ (°)	12	7	5
Bedding angle, α_1 (°)	0	0	0
Tensile strength, σ_t (kN/m^2)	50	35	15
Cohesion, C_{ref} (kN/m^2)	50	35	15
Friction angle, ϕ (°)	30	25	20
Dilatancy angle, ψ (°)	12	7	5
Angle from horizontal, α_2 (°)	80	80	80
Tensile strength, σ_t (kN/m^2)	50	35	15

The following figures 3.7, 3.8 and 3.9 illustrate the connectivity plots for circular, horseshoe, and rectangular twin tunnels, with circular tunnels having a diameter of 8 m, horseshoe and rectangular tunnels having a width of 8 m.

The floors of all three tunnels are consistently maintained at a level of 3d from the ground, where 'd' represents the diameter or width of the aforementioned tunnels.

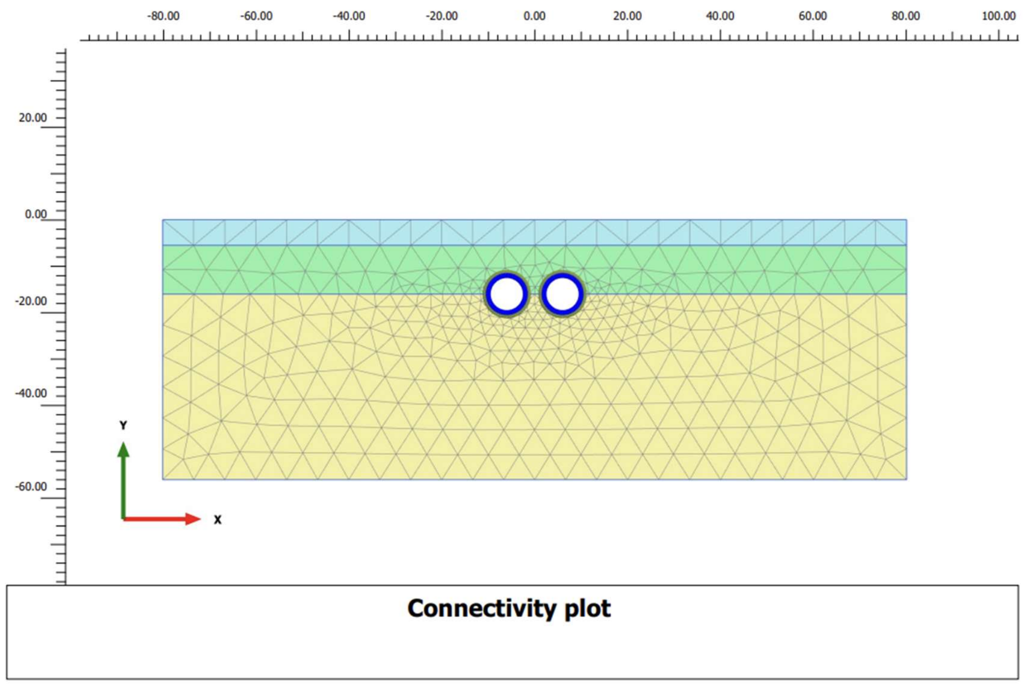


Fig. 3.7 Connectivity plot for circular twin tunnels.

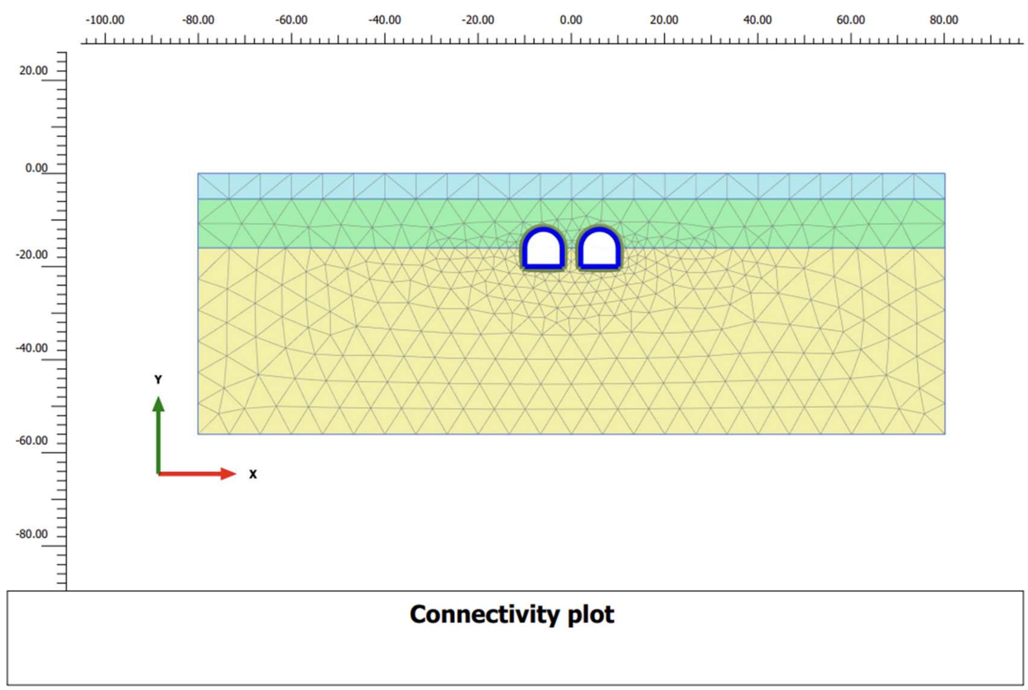


Fig. 3.8 Connectivity plot for horseshoe twin tunnels.

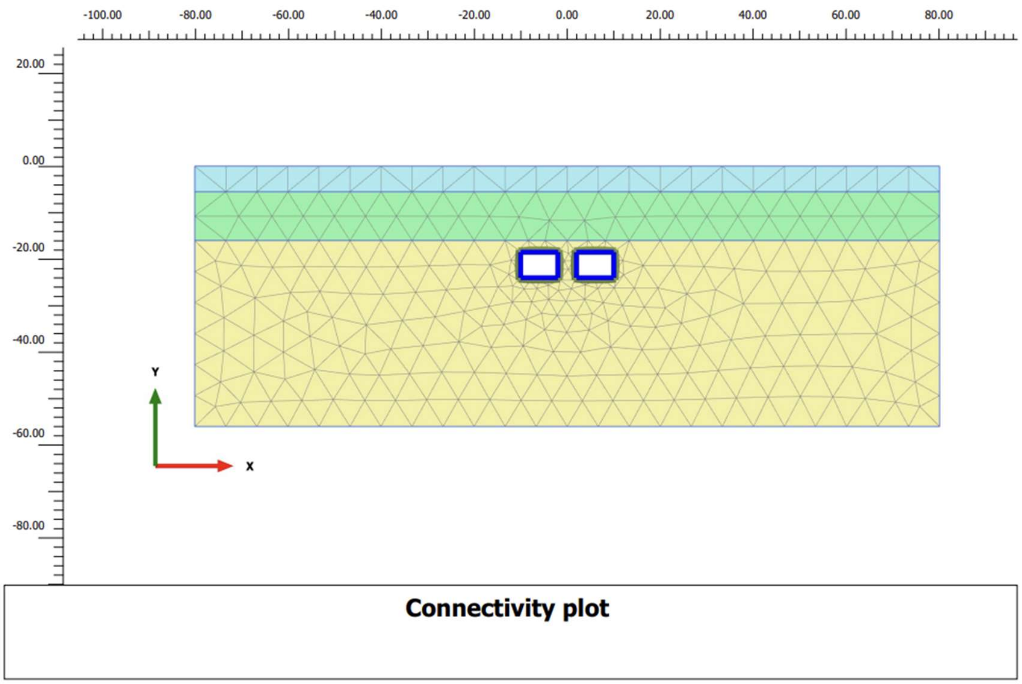


Fig. 3.9 Connectivity plot for rectangular twin tunnels.

3.5 MODELLING CONDITIONS

In this study effect of tunnel shape, tunnel size, and overburden on the ground settlement and forces generated in tunnel lining were analyzed using plaxis 2D.

1) Shape of tunnels

The shapes of the tunnels analyzed in this study were circular, horseshoe and rectangular. To study the effect of the shape of tunnels on the ground settlement and forces in tunnel linings, the diameter of the circular tunnels was fixed at 8 m, for rectangular tunnels, the width was taken equal to 8 m and the height was fixed as 5.5 m and for horseshoe tunnels, the width, as well as height, was taken equal to 8 m. The centre of the tunnels was maintained at 2d, where d is the diameter of the tunnel.

2) Size of tunnels

Numerical analysis was performed on circular and horseshoe twin tunnels to study the effect of tunnel sizes on ground settlement and forces in tunnel linings. The various tunnel sizes considered for the analysis were 5 m, 6 m, 7 m, and 8 m. The spacing between the tunnels was maintained at 12 m centre-to-centre and the depth of the tunnel centres was maintained at 2.5d, where d is the tunnel diameter on which the analysis was carried out.

3) Overburden on tunnels

The circular and horseshoe tunnels investigated for change of overburden were fixed at a centre-to-centre distance of 1.5d where d is the diameter of the tunnel and was maintained at 8 m. The overburden on tunnels varied as 1.5d, 2d, and 2.5d.

4) Spacing between tunnels

To investigate the effect of spacing between tunnels on ground settlement and forces in tunnel lining, the analysis was performed on circular and horseshoe twin tunnels. The spacings in terms of centre-to-centre distances between tunnels considered for the analysis were 1.7d, 2.5d, and 3d. The tunnel size was maintained at 5 m and the depth of the tunnel centres was maintained at 2.5d, where d is the tunnel diameter on which the analysis was carried out.

CHAPTER 4

RESULTS AND DISCUSSION

Tunnels were analyzed for the following configurations;

- Tunnels with varying shapes
- Tunnels with varying sizes
- Tunnels with varying overburden
- Tunnels with varying spacing

4.1 EFFECT OF SHAPE OF TUNNELS

Numerical analysis was done on circular, rectangular, and horseshoe tunnels using plaxis 2D keeping all other parameters such as spacing, diameter and overburden fixed.

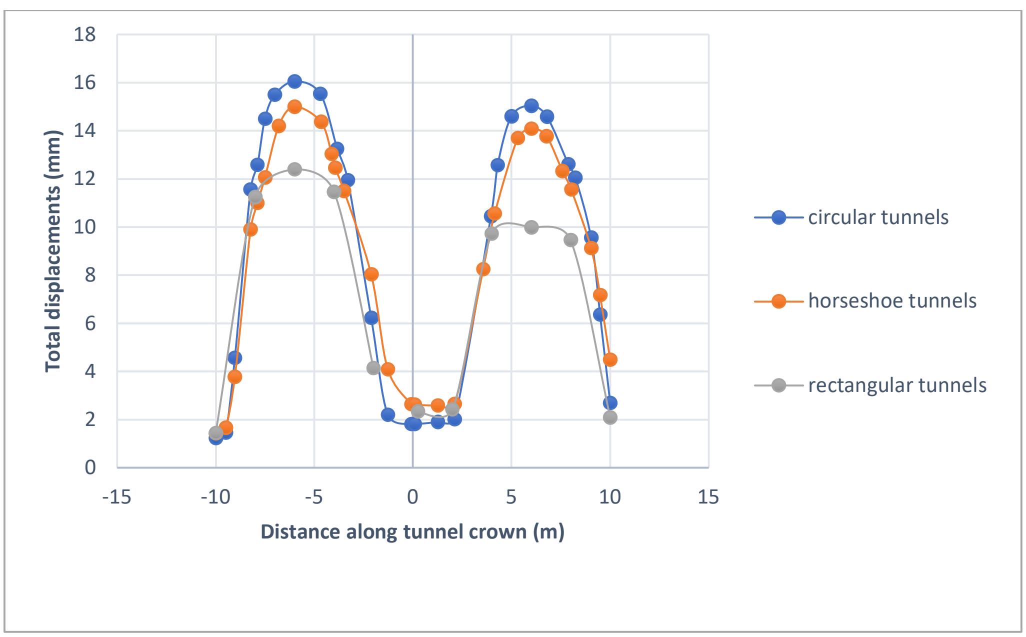


Fig. 4.1 Total displacement at tunnel crown for different shapes of tunnels.

The data presented in Figure 4.1 indicates that maximum settlement values in the case of circular twin tunnels and horseshoe twin tunnels are approximately the same and greater than the maximum settlement value obtained in the case of rectangular tunnels. This is due to the fact that, in the case of circular and horseshoe tunnels, the overall settlement is concentrated directly above the tunnels, but, in the case of rectangular tunnels, the settlement is dispersed over a considerable region. The highest degree of settlement was observed at the crown of the tunnel.

The study findings indicate that circular tunnels have maximum settlement value of 16.05 mm, as illustrated in Figure 4.2. Horseshoe tunnels as depicted in Figure 4.3, have a maximum settlement value of 15.67 mm, while rectangular tunnels, as shown in Figure 4.4, have a maximum settlement value of 12.39 mm. All these settlement values are established at the crown of each tunnel.

Similar results were obtained by Vinod and Khabbaz [5] while carrying out their research on, " Comparison of rectangular and circular bored twin tunnels in weak ground".

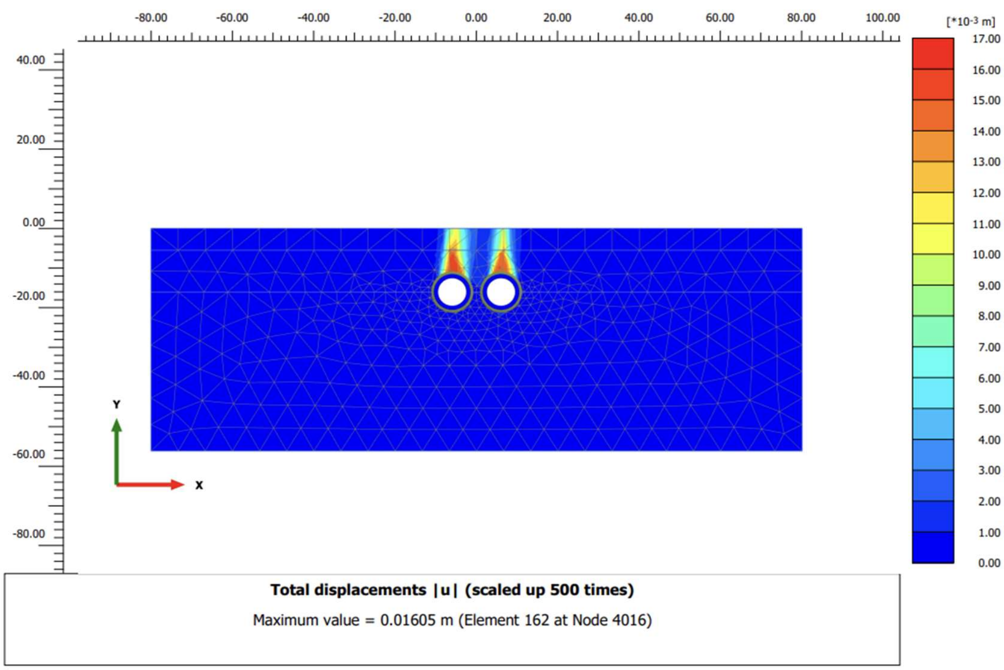


Fig. 4.2 Total displacement at tunnel crown for circular twin tunnels.

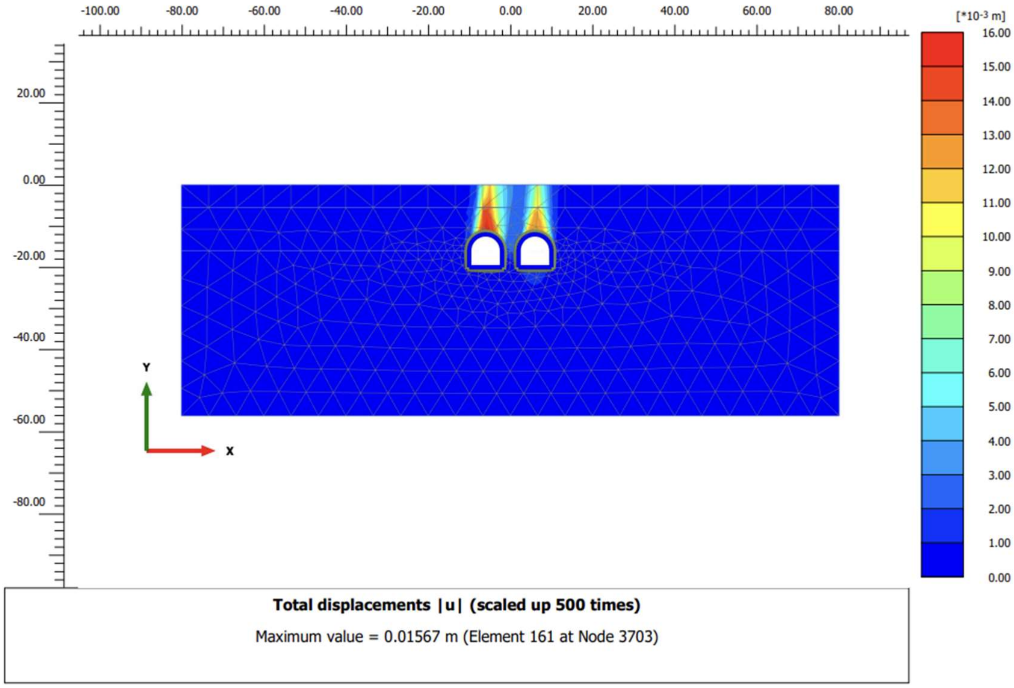


Fig. 4.3 Total displacement at tunnel crown for horseshoe twin tunnels.

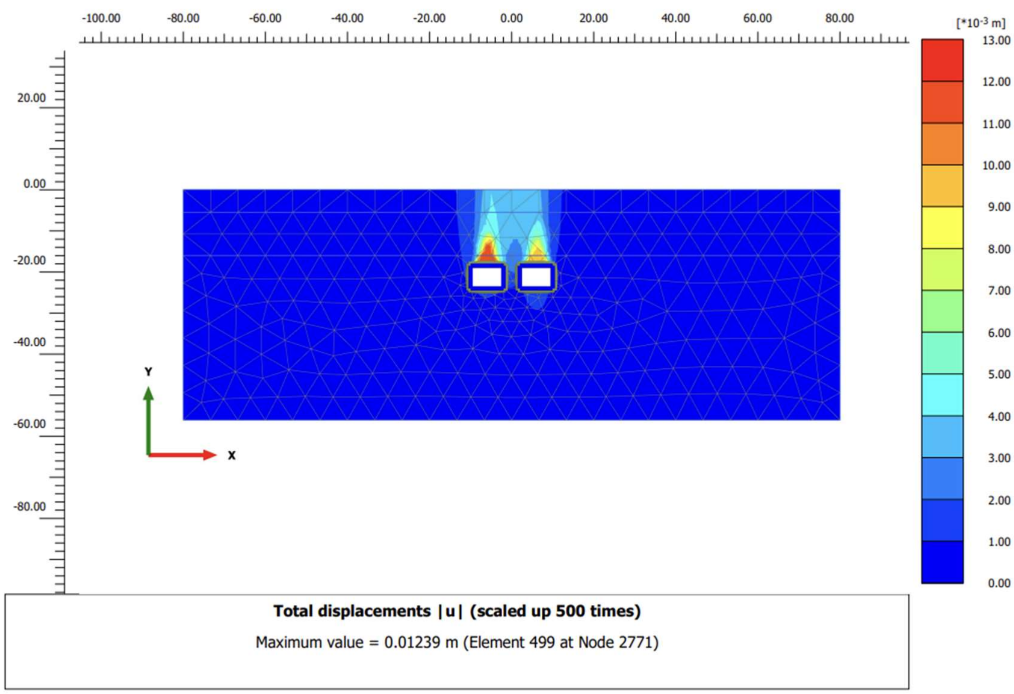


Fig. 4.4 Total displacement at tunnel crown for rectangular twin tunnels.

Figures 4.5 to 4.11 given below illustrate the distribution of axial force, shear force, and bending moment, respectively, for the aforementioned tunnel shapes.

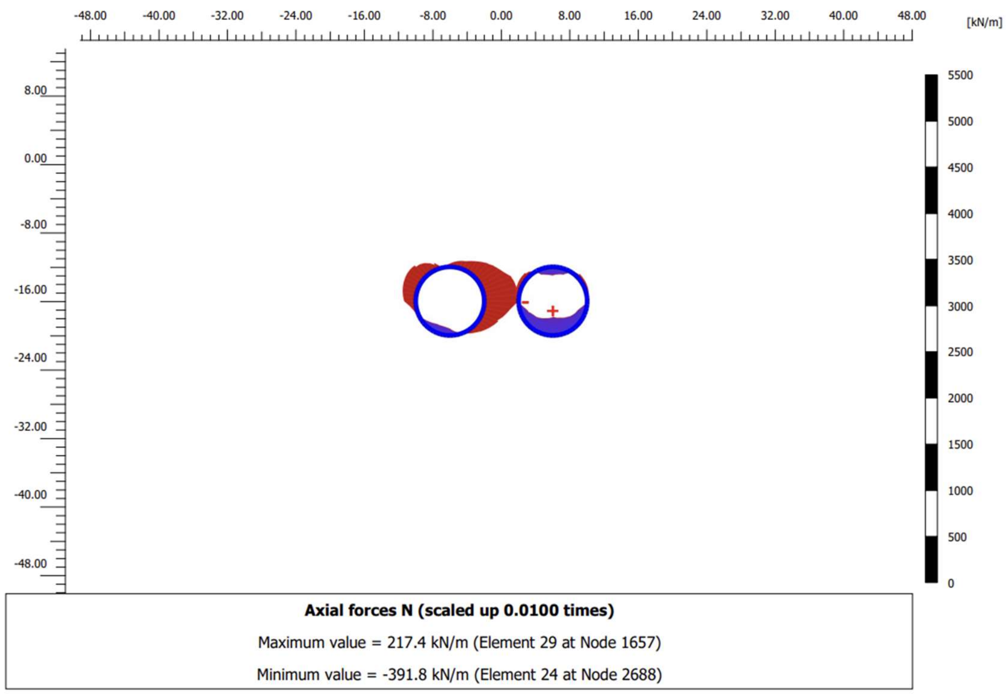


Fig. 4.5 Distribution of axial forces generated in tunnel linings for circular twin tunnels.

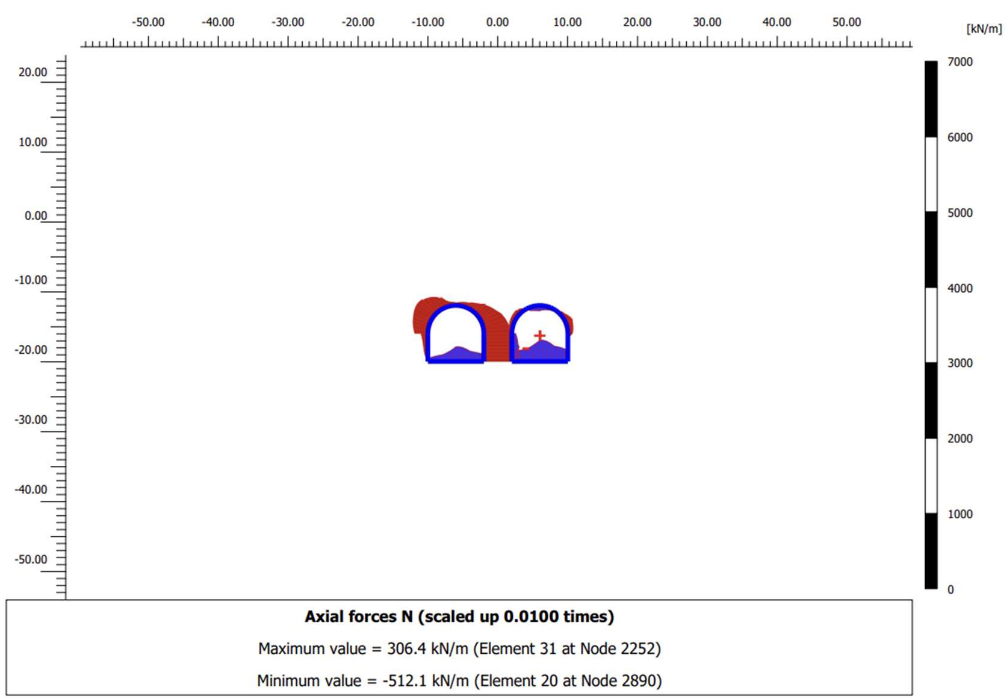


Fig. 4.6 Distribution of axial forces generated in tunnel linings for horseshoe twin tunnels.

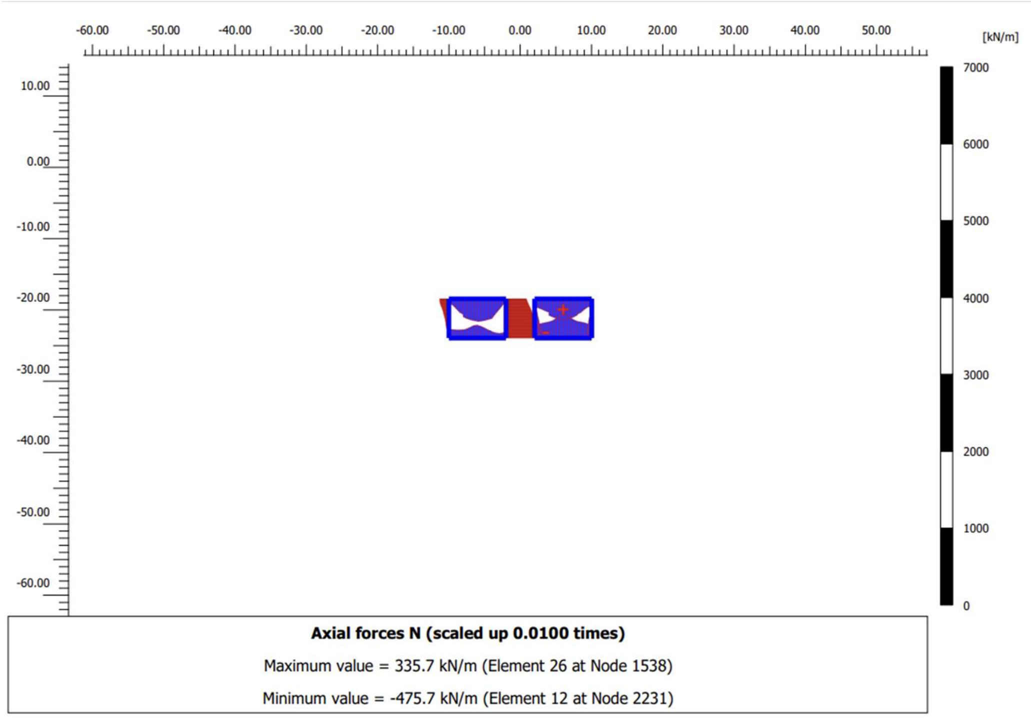


Fig. 4.7 Distribution of axial forces generated in tunnel linings for rectangular twin tunnels.

In Figures 4.5, 4.6, and 4.7, the axial force distribution can be observed. This distribution provides insight of the variations in axial force in the tunnel linings for different shapes.

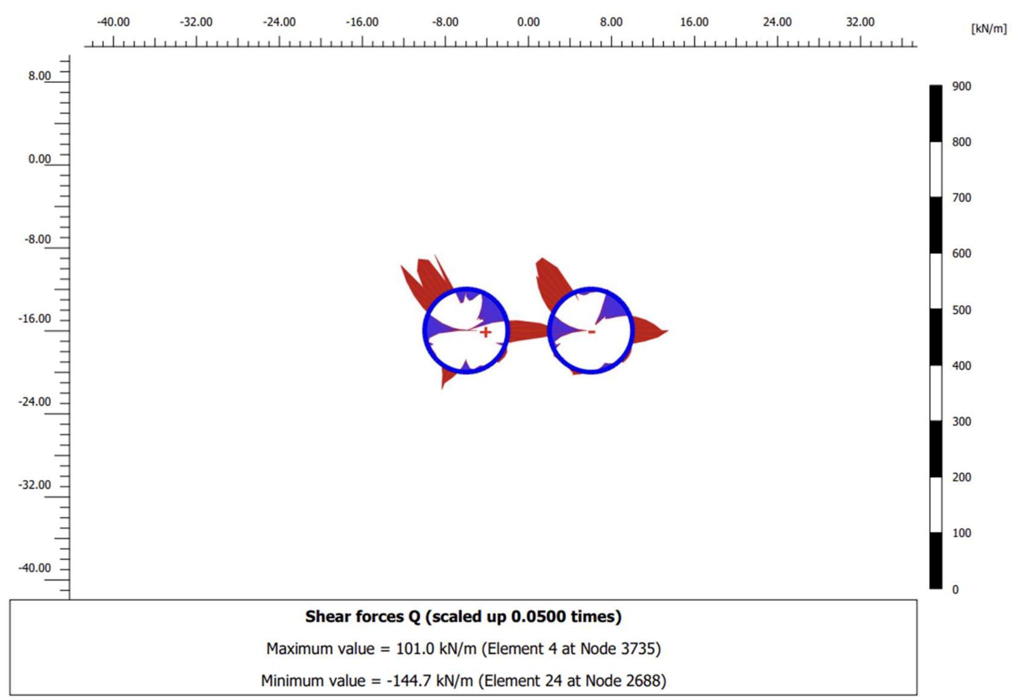


Fig. 4.8 Distribution of shear forces generated in tunnel linings for circular twin tunnels.

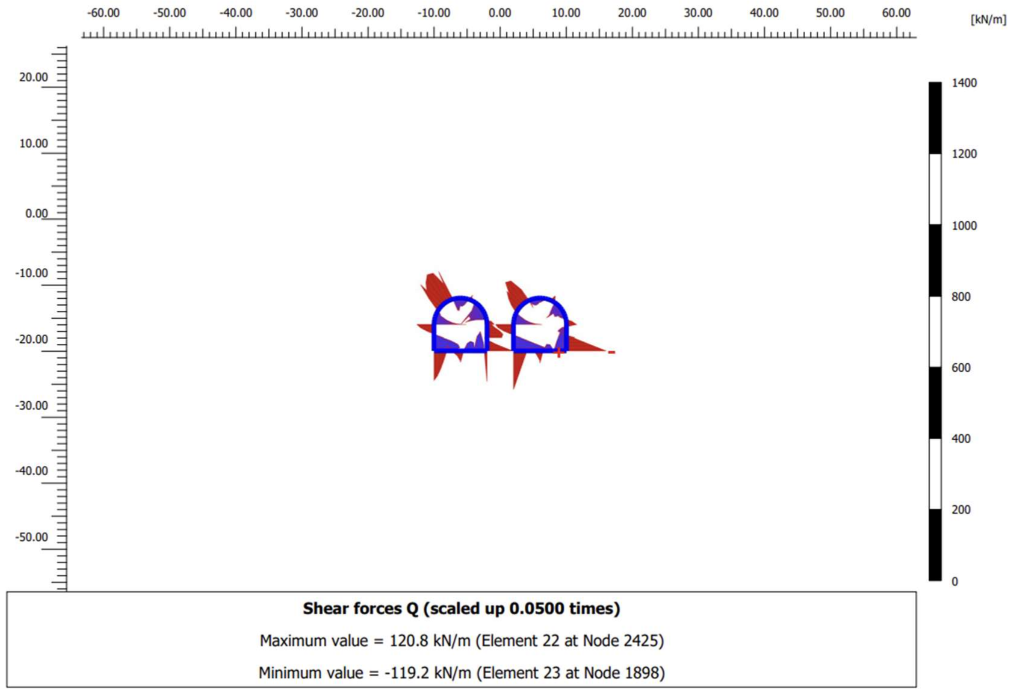


Fig. 4.9 Distribution of shear forces generated in tunnel linings for horseshoe twin tunnels.

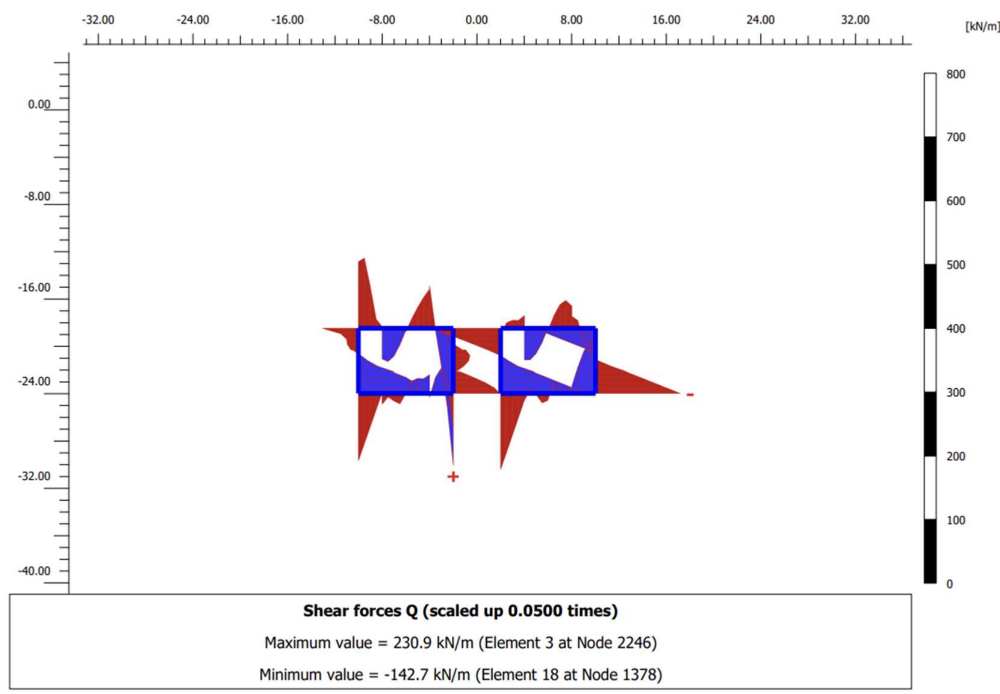


Fig. 4.10 Distribution of shear forces generated in tunnel linings for rectangular twin tunnels.

Figures 4.8, 4.9, and 4.10 presents the distribution of shear force, showcasing how the shear forces acts within the tunnel lining.

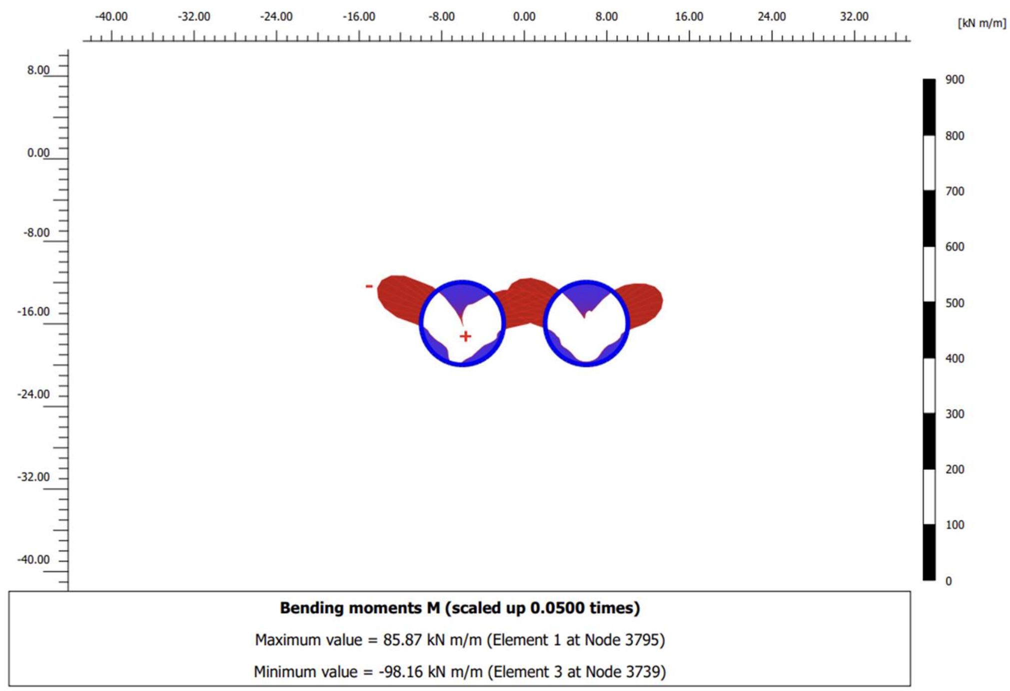


Fig. 4.11 Distribution of bending moment generated in tunnel linings for circular twin tunnels.

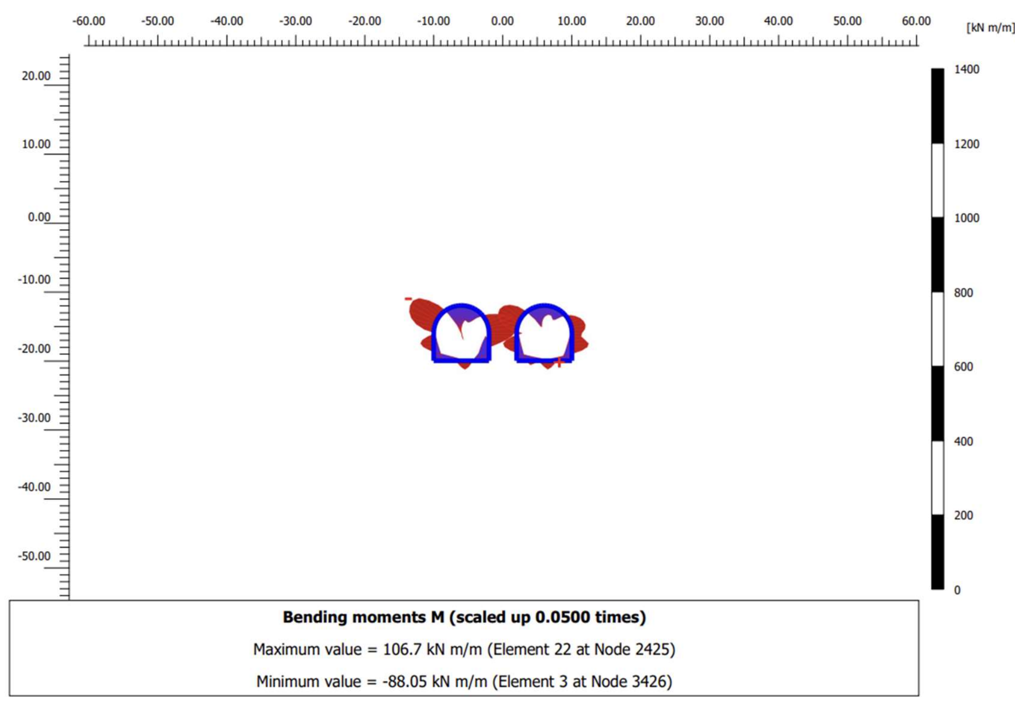


Fig. 4.12 Distribution of bending moment generated in tunnel linings for horseshoe twin tunnels.

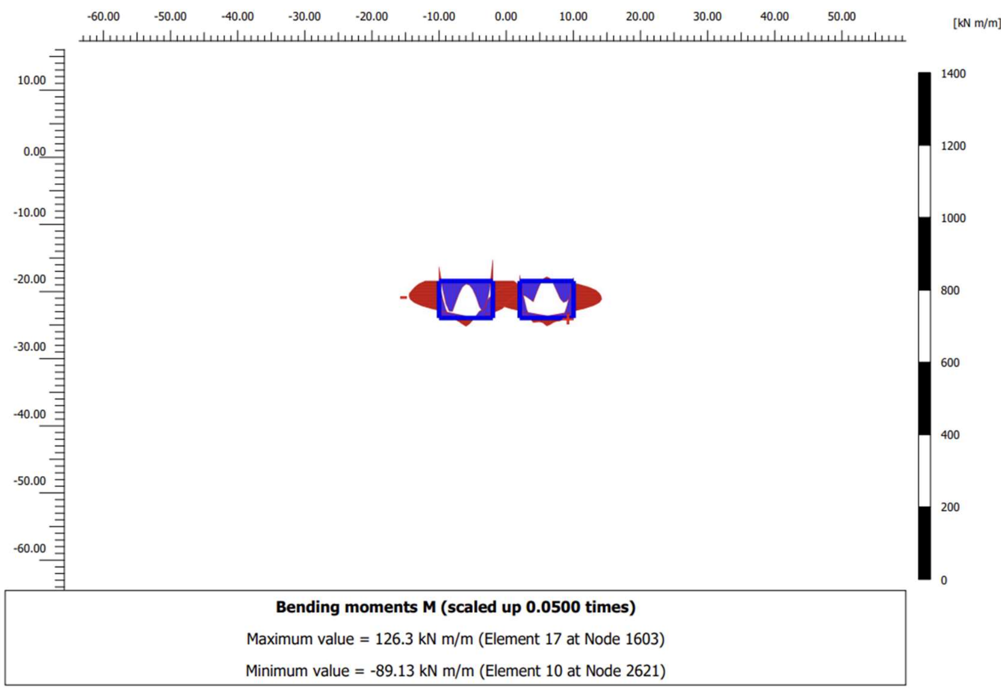


Fig. 4.13 Distribution of bending moment generated in tunnel linings for rectangular twin tunnels.

Figures 4.11, 4.12, and 4.13 display the distribution of bending moment, illustrating the bending effects exerted on the tunnels. The distribution demonstrates the variations in bending moment magnitude and direction within the tunnel lining. It is clear from the above figures that the bending moment obtained in the case of circular tunnels is the least, thus possessing a significant advantage over rectangular tunnels.

4.2 EFFECT OF SIZE OF TUNNELS

Four tunnel sizes were considered for both horseshoe and circular tunnels to evaluate the effect of tunnel sizes on the ground settlement and forces in tunnel lining. The centre-to-centre spacing between tunnels was kept constant. Thus, larger tunnels have a less clear distance between them. The settlement of ground and forces produced in tunnel lining in the case of circular and horseshoe tunnels is shown in the figure below.

For circular tunnels, the ground settlement is slightly higher than in horseshoe tunnels. The larger diameter tunnels have a higher amount of maximum settlement. For both circular as well as horseshoe tunnels moment increases with an increase in the tunnel size. However, the moment produced is more in horseshoe tunnels.

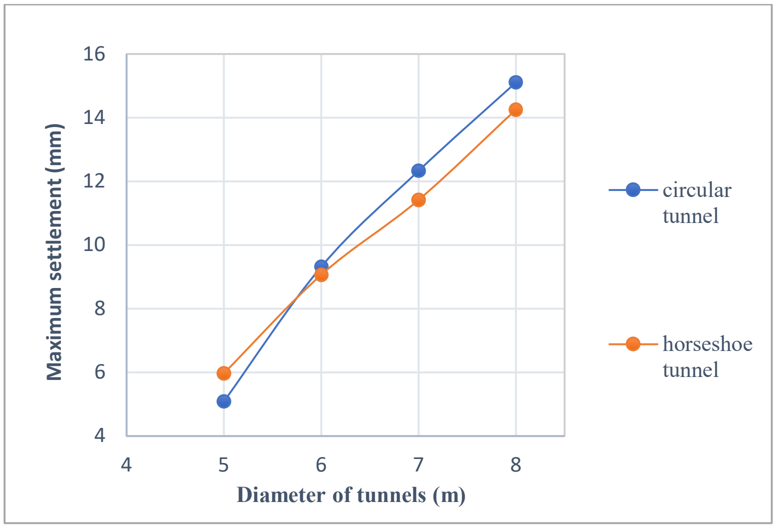


Fig. 4.14 Effect of diameter on maximum ground settlement for circular and horseshoe twin tunnels.

Figure 4.14 illustrates the relationship between tunnel size and settlement for both circular and horseshoe tunnels. The figure demonstrates that as the size of the tunnels increases, the settlement also increases. This phenomenon can be explained by considering the interaction between the tunnels. As the size of the tunnels grows larger, the interaction between them becomes more significant. This interaction is a result of the overlapping of the pressure bulbs associated with each tunnel. The pressure bulb represents the zone of influence around the tunnel where the ground is subjected to stress and deformation. When the pressure bulbs of two adjacent tunnels overlap, the stress and deformation caused by one tunnel can affect the neighbouring tunnel. This overlapping of pressure bulbs leads to increased settlement in both tunnels. Consequently, as the size of the tunnels increases, the overlapping of pressure bulbs intensifies, resulting in higher settlement values.

The findings presented in Figure 4.14 emphasize the importance of considering tunnel size and its impact on the settlement during tunnel design and construction. It highlights the need to account for the interaction between adjacent tunnels to accurately assess settlement and ensure the stability of the tunnel system.

Figures 4.15, 4.16, and 4.17 given below display the variations of bending moment, axial force, and shear force, respectively, in relation to the diameter of tunnels. These figures illustrate that the values of bending moment, axial force, and shear force increase as the diameter of the tunnels increases, regardless of whether they are circular or horseshoe-shaped.

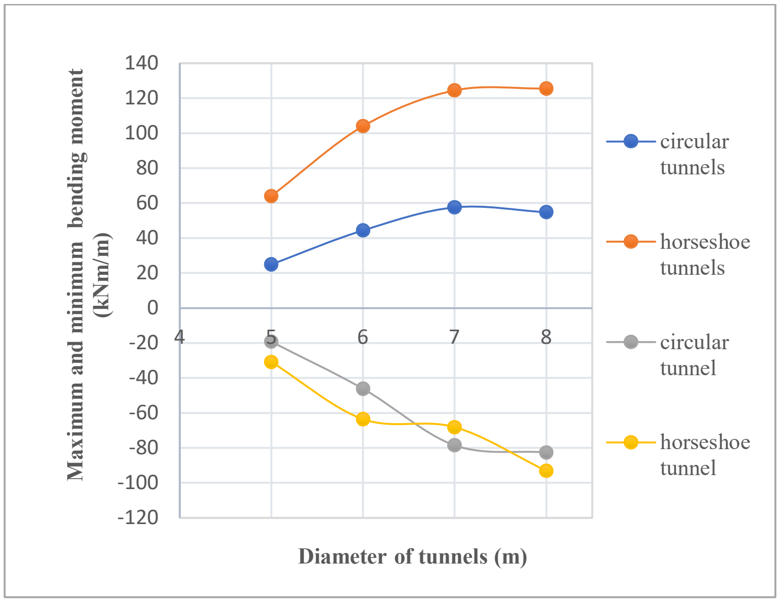


Fig. 4.15 Effect of diameter on bending moment generated in tunnel lining for circular and horseshoe twin tunnels.

The above figure, 4.15 demonstrates the variation of bending moment with tunnel diameter. It reveals that larger tunnel diameters result in higher bending moments. This is because an increase in tunnel diameter increases the interaction between tunnels, resulting in a greater resistance to bending forces.

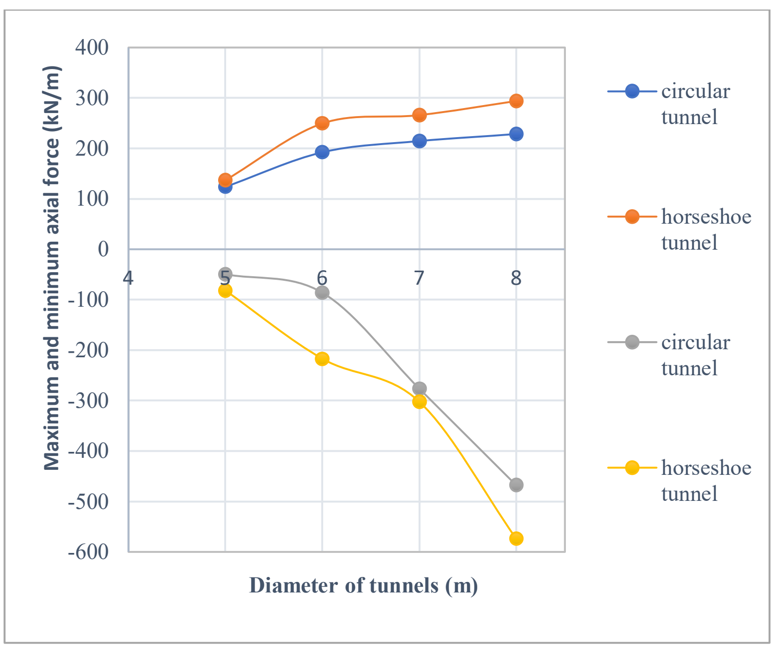


Fig. 4.16 Effect of diameter on axial forces generated in tunnel lining for circular and horseshoe twin tunnels.

In Figure 4.16 and 4.17 the variation of axial force and shear force with tunnel diameter respectively is depicted. It can be observed that as the diameter of the tunnels increases, the axial force as well as shear force increases. This is because a larger tunnel diameter corresponds to a greater surface area, resulting in increased axial forces acting on the tunnel and also because of the increased interaction between the tunnels, both shear and the axial forces increase.

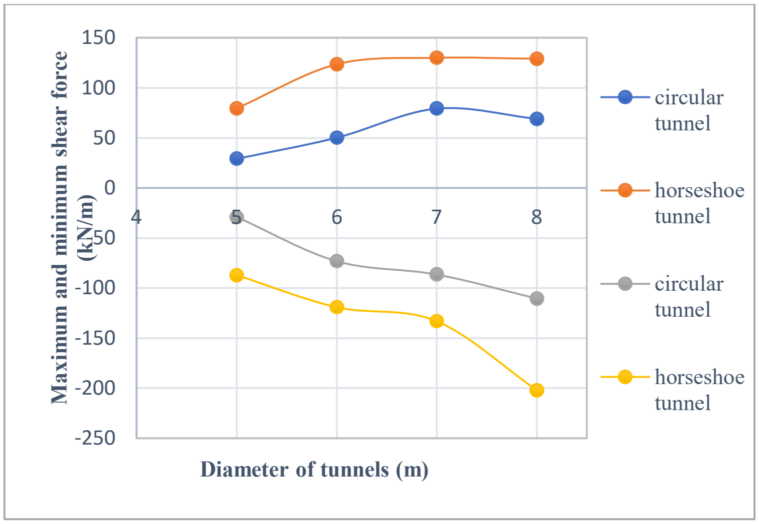


Fig. 4.17 Effect of diameter on shear forces generated in tunnel lining for circular and horseshoe twin tunnels.

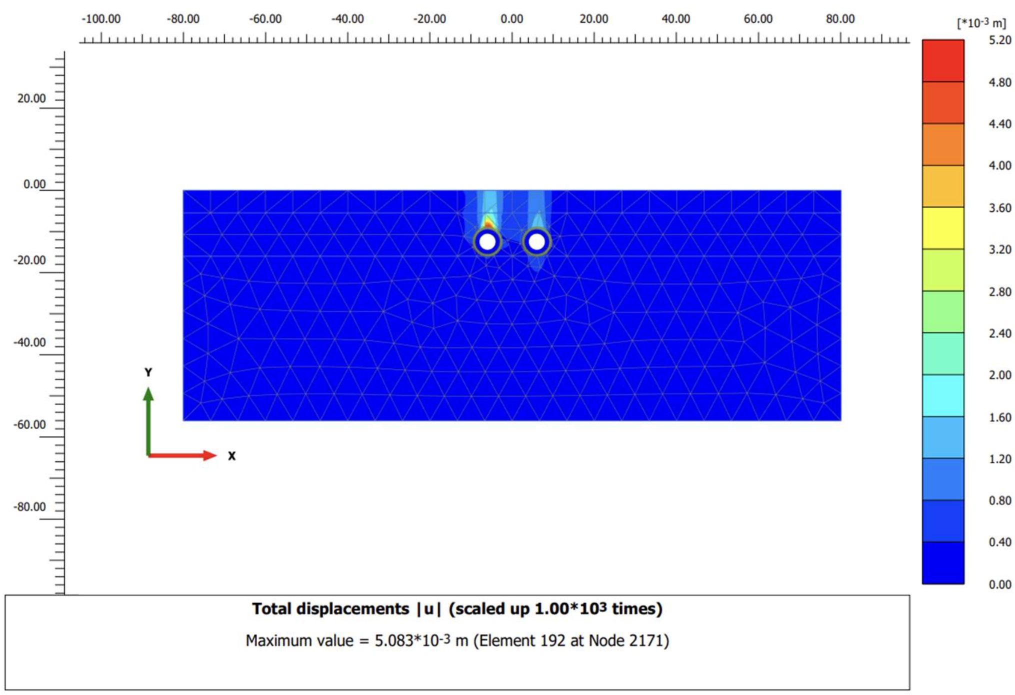


Fig. 4.18 Total displacement at tunnel crown for circular twin tunnels of diameter 5 m, spacing 12 m and overburden 2d from crown.

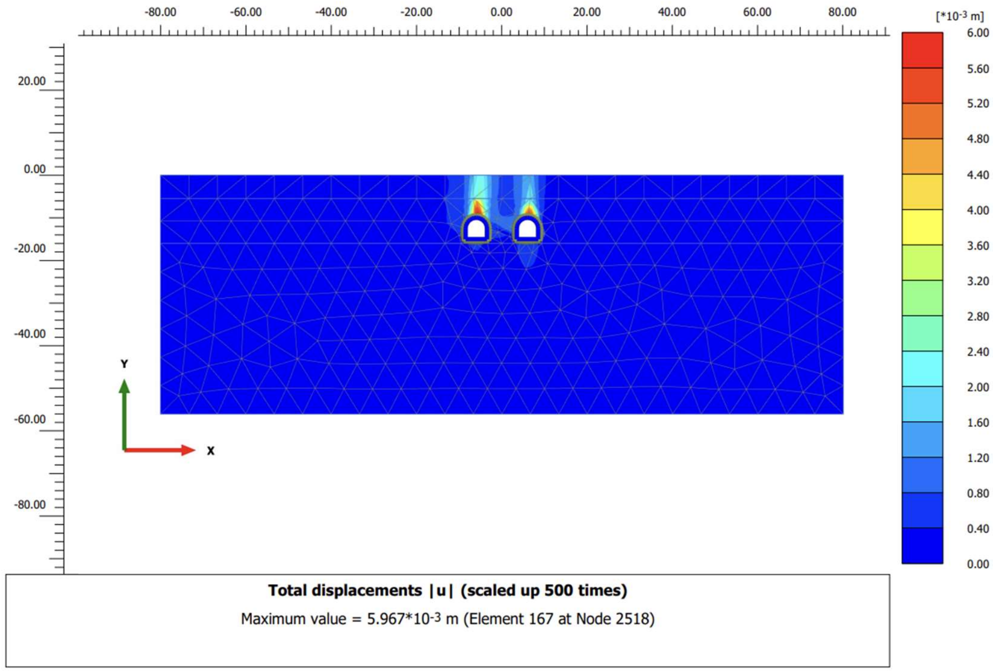


Fig. 4.19 Total displacement at tunnel crown for horseshoe twin tunnels of diameter 5 m, spacing 12 m and overburden 2d from crown.

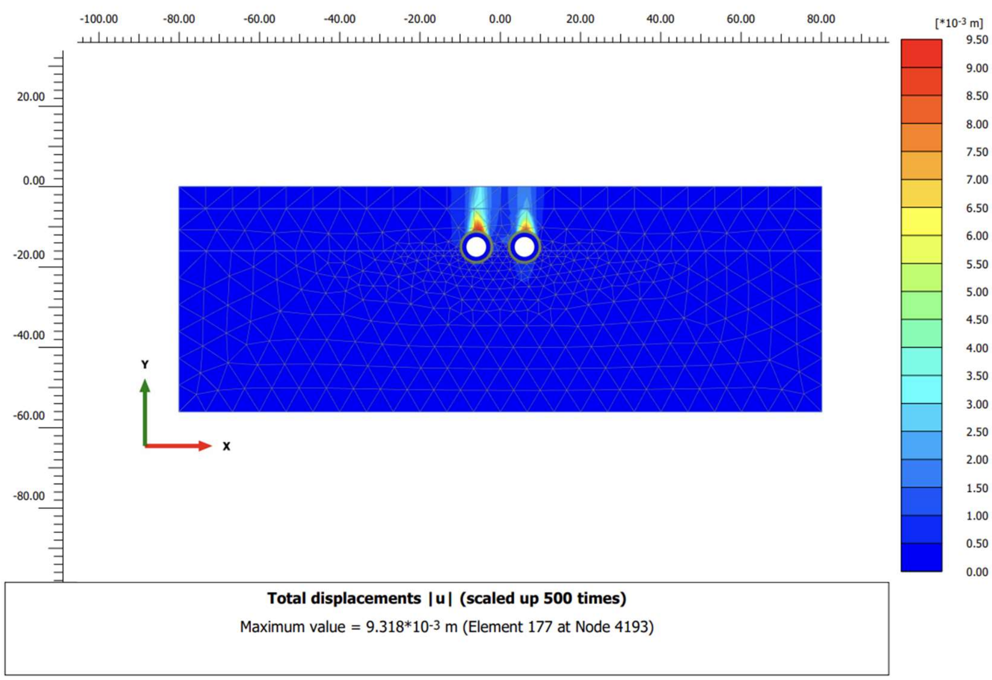


Fig. 4.20 Total displacement at tunnel crown for circular twin tunnels of diameter 6 m, spacing 12 m and overburden 2d from crown.

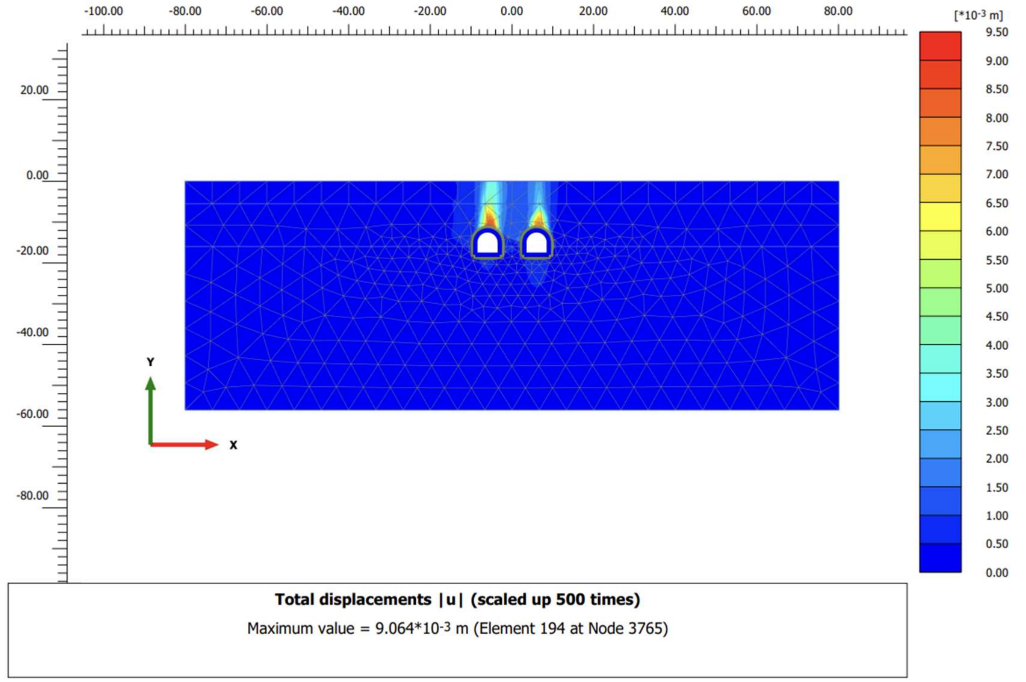


Fig. 4.21 Total displacement at tunnel crown for horseshoe twin tunnels of diameter 6 m, spacing 12 m and overburden 2d from crown.

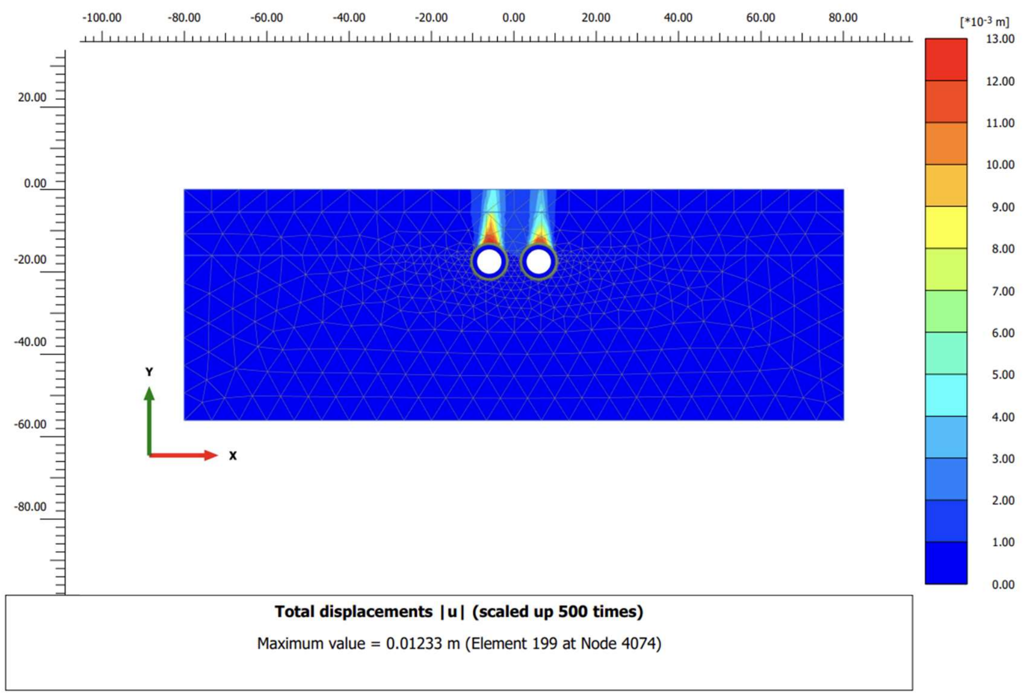


Fig. 4.22 Total displacement at tunnel crown for circular twin tunnels of diameter 7 m, spacing 12 m and overburden 2d from crown.

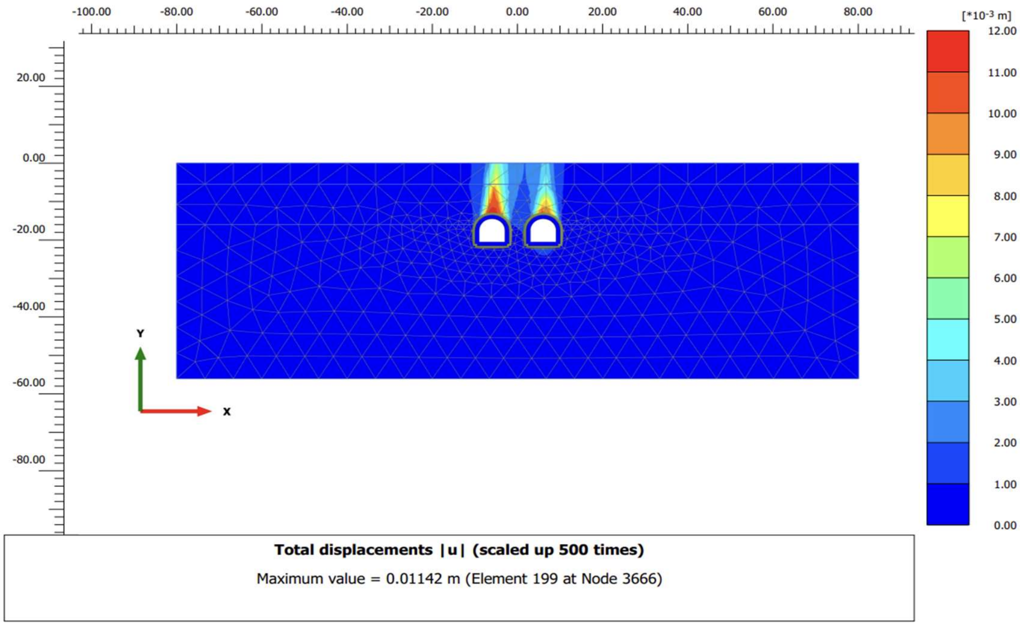


Fig. 4.23 Total displacement at tunnel crown for horseshoe twin tunnels of diameter 7 m, spacing 12 m and overburden 2d from crown.

4.3 EFFECT OF OVERBURDEN ON TUNNELS

The analysis was performed by varying the overburden on tunnels as 1.5d, 2d, and 2.5d. It was found that for both circular as well as horseshoe tunnels a minimum overburden of 1.5d was required for safe construction. Results were plotted in terms of cover-to-diameter ratio. As the cover-to-diameter ratio increased, the maximum settlement was reduced. This is because of the arch action that takes place when cover to diameter ratio is more and thus increases the stability of tunnels.

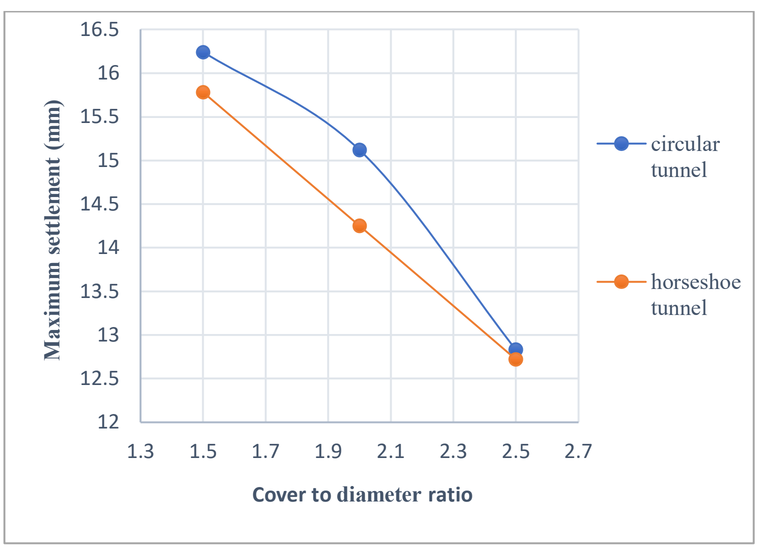


Fig. 4.24 Effect of overburden on maximum ground settlement for circular and horseshoe twin tunnels.

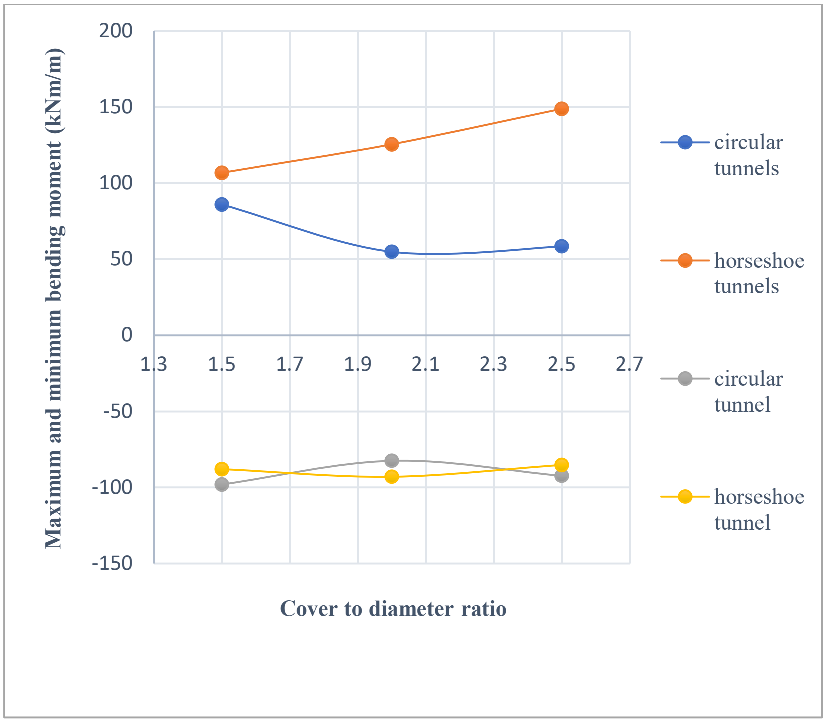


Fig. 4.25 Effect of overburden on bending moment generated in tunnel lining for circular and horseshoe twin tunnels.

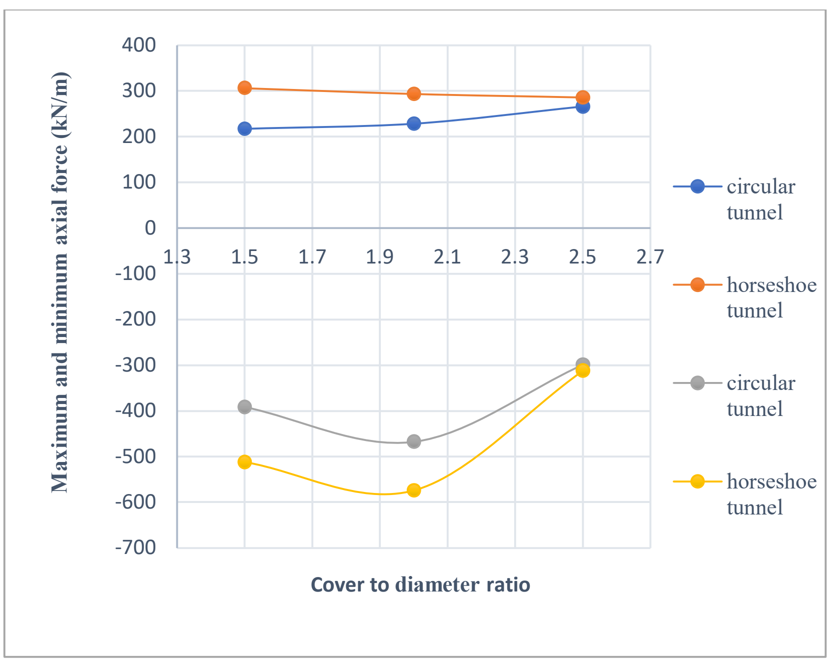


Fig. 4.26 Effect of overburden on axial forces generated in tunnel lining for circular and horseshoe twin tunnels.

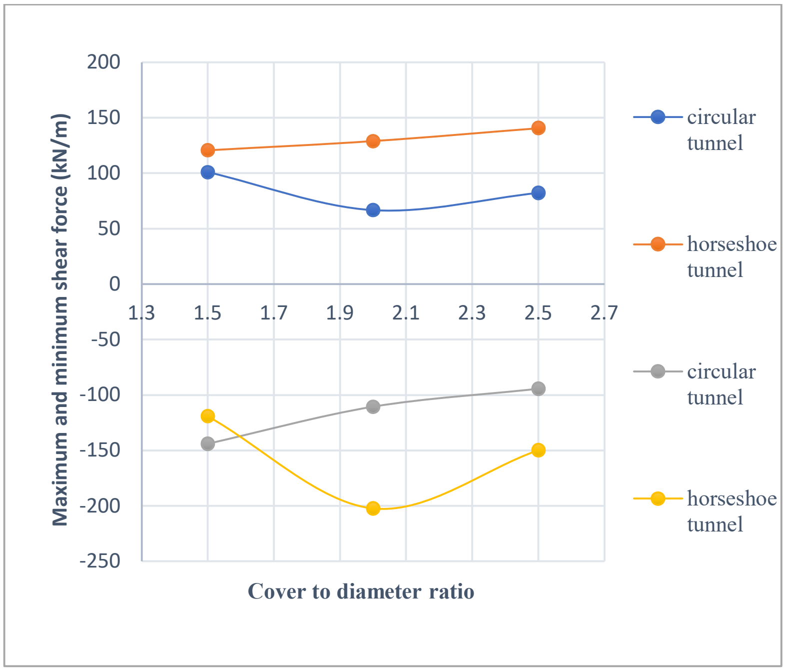


Fig. 4.27 Effect of overburden on shear forces generated in tunnel lining for circular and horseshoe twin tunnels.

Similar results were also obtained by Vinod and Khabbaz while doing research on, " Comparison of rectangular and circular bored twin tunnels in weak ground" [5].

O'Reilly and New (1982) also obtained similar results while doing their research on, "settlements above tunnels in the United Kingdom - their magnitude and prediction" [25]. In this study as well the stability of tunnels increases with an increase in the overburden.

4.4 EFFECT OF SPACING BETWEEN TUNNELS

The analysis was performed by varying the distance between tunnel centres as 1.7d, 2.5d, and 3d. The critical distance for circular tunnels was found equal to 2d, as for distances less than 2d settlements as well as forces generated in tunnel lining increased. For horseshoe tunnels, a critical distance of 2.5 d was required for safe construction. Figures 4.28, 4.29, 4.30, and 4.31 provide insights into the variation of settlement, bending moment, axial force, and shear force for both circular and horseshoe tunnels, considering the spacing between the tunnels.

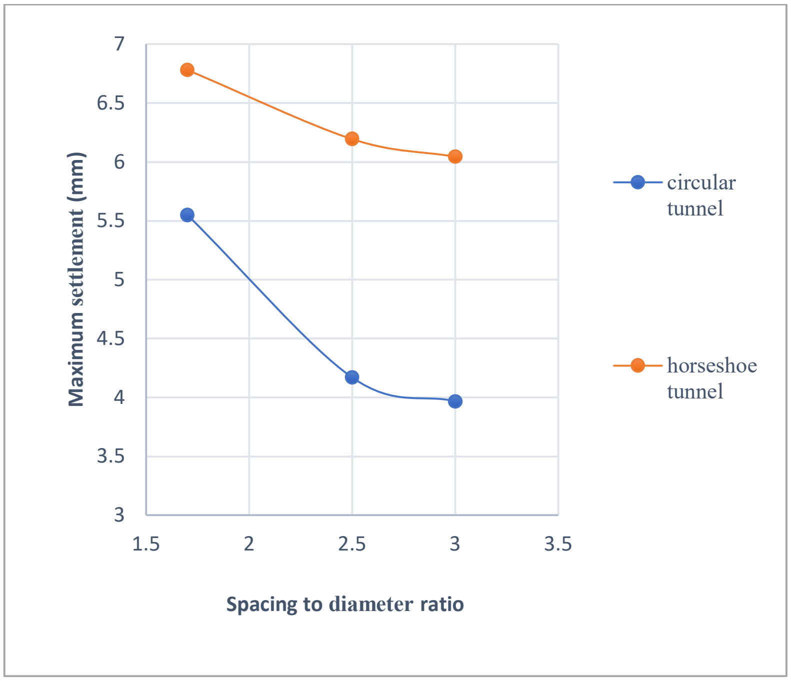


Fig. 4.28 Effect of spacing on maximum ground settlement for circular and horseshoe twin tunnels.

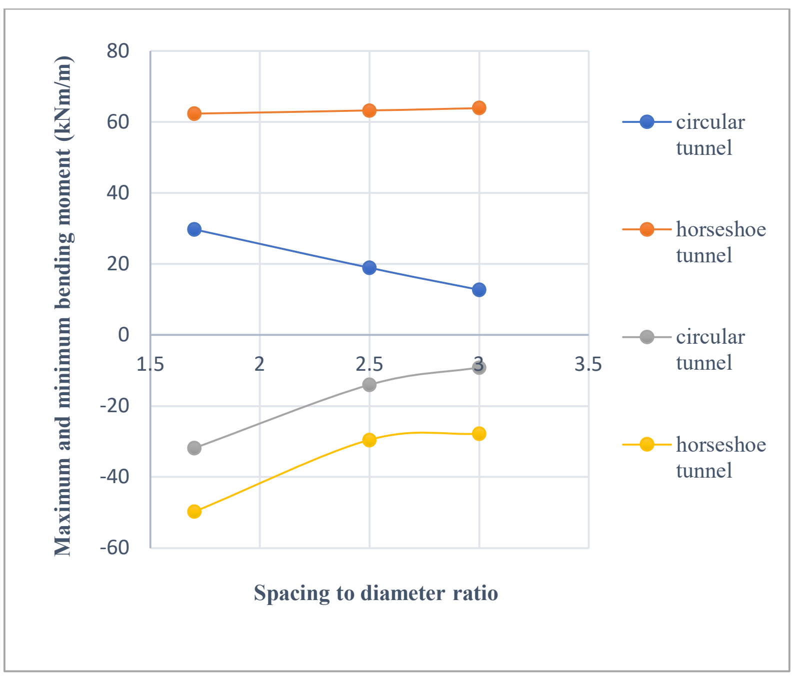


Fig. 4.29 Effect of spacing on bending moment generated in tunnel lining for circular and horseshoe twin tunnels.

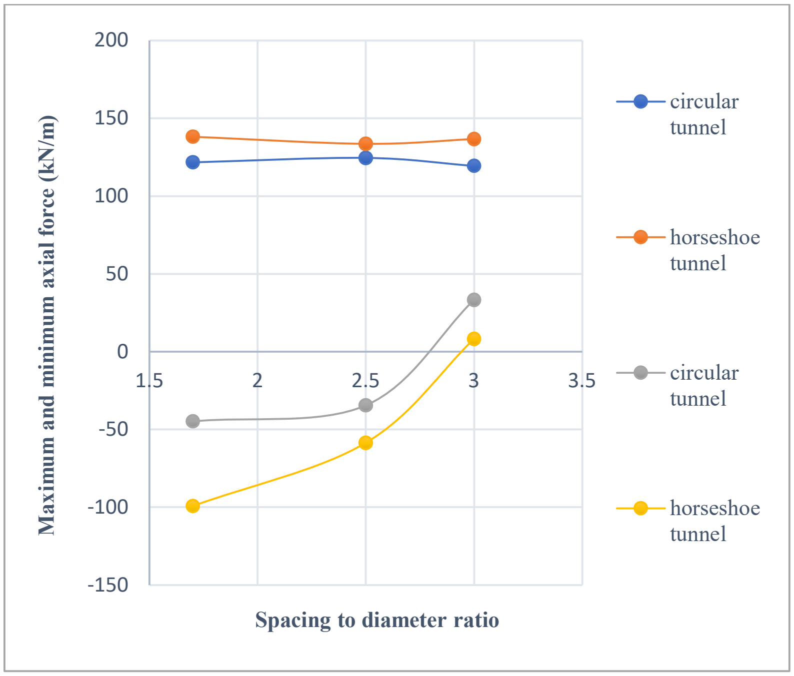


Fig. 4.30 Effect of spacing on axial forces generated in tunnel lining for circular and horseshoe twin tunnels.

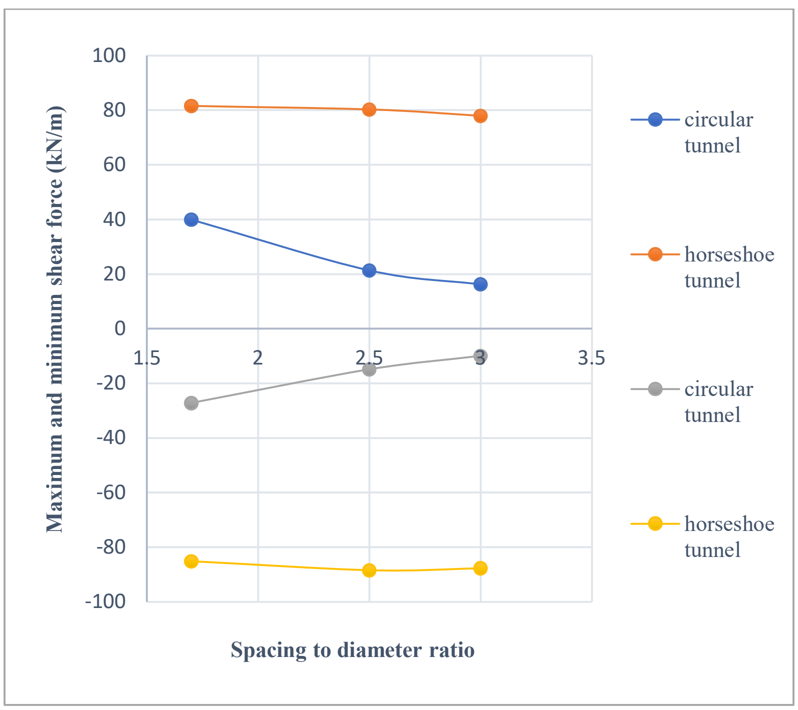


Fig. 4.31 Effect of spacing on shear forces generated in tunnel lining for circular and horseshoe twin tunnels.

Figure 4.28 demonstrates that as the spacing between tunnels increases, the settlement reduces. This can be attributed to the fact that increased spacing allows for a greater separation between the tunnels, resulting in less interaction and overlap of the pressure bulbs around each tunnel. As a result, the settlements are reduced.

Figure 4.29 shows the variation with respect to the tunnel spacing. While the specific trend is not mentioned, it is common for an increase in tunnel spacing to lead to a decrease in bending moments. This is because larger spacing reduces the interaction and mutual influence between tunnels, resulting in lower bending moments.

Figure 4.30 displays the variation of axial force with spacing between tunnels. Similarly, larger spacing generally leads to decreased axial forces. The reduced interaction between tunnels allows for a more independent response to external loads, resulting in lower axial forces.

Lastly, Figure 4.31 illustrates the variation of shear force with tunnel spacing. Increased spacing typically results in lower shear forces. The diminished interaction between tunnels leads to less transfer of shear forces between adjacent tunnels, thus reducing the overall shear forces.

These findings highlight the influence of the spacing tunnel on settlement, bending moments, axial forces, and shear forces. They suggest that increasing the spacing between tunnels can help mitigate settlement and reduce the magnitudes of bending moments, axial forces, and shear forces in both circular and horseshoe tunnels.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

5.1 CONCLUSION

Finite element analysis was employed to study the interaction between the twin tunnels in weak rocks under a jointed rock model using plaxis 2D. This paper investigates the effect of tunnel shapes, tunnel sizes, overburden, and spacing on the ground settlement and various forces generated in tunnel lining. The following conclusions were drawn from the study:

1. Effect of shape of tunnels: The results show that the settlement was maximum for circular tunnels followed by horseshoe tunnels and least for rectangular tunnels. However, the forces generated in the lining of circular tunnels were the least.
2. Effect of size of tunnels: For both circular as well as horseshoe tunnels, the surface settlement, as well as the forces in the tunnel lining, increased with an increase in the tunnel size. The bending moment and shear forces produced in the horseshoe tunnels were significantly more compared to that in circular tunnels.
3. Effect of overburden on tunnels: The value of maximum settlement decreased with an increase in the overburden for both circular as well as horseshoe tunnels. In the case of circular tunnels increasing the overburden on tunnels decreased the maximum bending moment produced in tunnel lining but for horseshoe tunnels bending moment increased with an increase in the overburden.
4. Effect of spacing of tunnels: The study also concluded that for both circular as well as horseshoe tunnels, the surface settlement as well as the forces in the tunnel lining decreased with an increase in the tunnel spacing. The maximum settlement, bending moments, shear and axial force produced in horseshoe tunnels is more compared to circular tunnels .

5.2 RECOMMENDATIONS FOR FUTURE WORK

Numerical analysis using Plaxis 2D can facilitate a comparative study of twin tunnels by employing diverse material models. This approach can enable the identification of the most appropriate model for the given strata.

The potential for further extension of this research attempt lies in conducting an analysis utilising Plaxis 3D, followed by a comparative evaluation of the outcomes.

Various material models provided in the Plaxis software can be utilised to conduct an analysis on diverse rock and soil strata.

Studies can be conducted to stimulate the behaviour of soil and rock interaction with tunnels more realistically by using advanced material models to determine stress dependency, anisotropy, strain hardening and softening, creep, swelling, and shrinkage.

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