Finite element analysis of tunnels in various scenarios and their stabilization using bolts and shotcrete

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***Abstract*: In this study, FEM is used to analyse such excavations with the help of PLAXIS 2D and RS2 software. A total of 5 models have been analysed, namely – 1. Settlement due to tunnel construction, 2. NATM tunnel construction, 3. Horseshoe-shaped tunnel with and without support, 4. Tunnel and surface excavation, and 5. A half tunnel. In the third model, a horseshoe-shaped tunnel is analysed for different diameters, lengths, spacings and tensile capacities of the bolts. It is also analysed for different thicknesses and Young's Moduli of the liner. Different modifications are made in the model by changing spans and heights, and the most suitable modification is suggested.**

The results showed that the most critical areas of the tunnel are the crown and the spring line when the tunnel is circular. In the case of a d-shaped tunnel, the shoulder and the spring line are found to be critical. Whereas for the tunnel excavated in the rock, the base is a critical location. In addition, for the horseshoe-shaped tunnel in the rock, it was found that a diameter of 15mm is the most suitable. The liner thickness of 0.35 mm and Young's modulus of 3100 MPa were found to be most suitable based on the analysis. The design of the half tunnel, which has a span of 13 meters and a height of 14.1 m, was found to be the most stable, although it requires a considerable amount of excavation.

***Index Terms*— Tunnels, Finite Element Method, PLAXIS 2D, Young's modulus.**

I. INTRODUCTION

Through the ages, tunnels have been essential to the development and survival of humankind. Since cave formation, tunnelling has evolved for various uses, including water management, underground transportation, mineral extraction, and warfare. Initially done by hand using simple instruments like chisels, hammers, spades, and shovels, civil engineering tunnelling technology has advanced significantly. The peak of tunnelling technology has been reached as a result of the ever-growing needs of the modern human race. A tunnel's construction necessitates extensive rock and soil excavation. Excavation and backfilling have been simpler thanks to the accessibility of modern equipment like the New Austrian Tunnelling Method (NATM) and Tunnel Boring Machine (TBM). They are described below.

Finite Element Analysis (FEA) is a computational method used to analyse and predict the behaviour of structures or systems under different conditions. It is commonly employed in engineering and physics to solve intricate problems associated with stress, heat transfer, fluid flow, and other physical phenomena.

FEA divides complex geometries into smaller subdomains known as finite elements, which are interconnected at specific nodes. By applying mathematical equations and principles, FEA simulates the behaviour of the system by dividing it into discrete elements and solving equations for each element. The outcomes are then combined to obtain an overall understanding of the system's behaviour.

The process of finite element analysis typically involves several steps:

1. Pre-processing: This involves creating a finite element model of the structure or system. The geometry is divided into finite elements, and material properties, boundary conditions, and loads are assigned to the model. Meshing, which is the process of dividing the geometry into finite elements, is also performed in this step.
2. Formulating equations: In this step, governing equations are formulated for each finite element based on the behaviour of the material and the type of analysis being performed. These equations describe the relationships between forces, displacements, and other variables.
3. Assembly: The individual equations from each finite element are combined to form a system of equations that represents the entire structure or system. This involves assembling the stiffness matrix, which relates the displacements and forces at each node.

4. Solution: The system of equations is solved to obtain the displacements and other quantities of interest. Various numerical techniques, such as matrix inversion or iterative methods, are used to solve the equations.
5. Post-processing: Once the solution is obtained, the results are extracted and interpreted. This may involve visualizing the displacements, stresses, strains, or other variables of interest. Post-processing also includes evaluating the validity of the results and assessing the performance of the structure or system.

Finite Element Analysis enables engineers and scientists to study the behaviour of complex systems and structures, optimize designs, and predict their performance under different conditions. It finds applications in various fields, including structural engineering, mechanical engineering, aerospace engineering, automotive design, civil engineering, and others.

II. OBJECTIVES OF PRESENT STUDY

This study consists of various tunnel excavation models in soil as well as rock. They are analysed in different conditions such as near a pile foundation, adjoining a trench excavation, with bolts and liner as a support. The objectives of this study are as follows:

- To Obtain the settlement due to the excavation process and its effect on the adjoining pile foundation.
- To find out the critical areas in the tunnel lining regarding maximum deformation, axial forces and bending moments for circular as well as free-shaped tunnel.
- To analyse a horseshoe-shaped tunnel excavation in rock material.
- To analyse the stability of a tunnel with bolts as a support for different diameters, lengths, spacings and tensile capacities of bolts.

III. FINITE ELEMENT MODELLING

A. Settlement due to tunnel construction

This model focuses on analyzing the impact of constructing a shield tunnel in medium soft soil on a piling foundation, considering the tunnel's structure. The construction process of a shield tunnel involves the excavation of earth in front of a tunnel boring machine (TBM) and the subsequent installation of a tunnel liner behind the TBM. In practice, the excavation often goes deeper than necessary, resulting in a finished tunnel lining that occupies a smaller cross-sectional area compared to the volume of earth removed.

Despite attempts to fill the remaining space, stress redistributions and soil deformations are unavoidable during tunnel construction. To prevent potential damage to existing structures or foundations above the soil, it is crucial to forecast these consequences and take appropriate precautions. The finite element method can be employed to conduct such an analysis, allowing for a comprehensive understanding of the anticipated effects and enabling the implementation of necessary preventive measures.

B. Soil Stratigraphy

The analysis covers a tunnel with a diameter of 5 meters and an average depth of 20 meters. The soil profile consists of four different layers:

Upper Layer: The upper section, reaching up to a depth of 13 meters, comprises soft clay-type soil. The stiffness of this clay soil rises in a nearly linear fashion as we move deeper.

Sand Layer: Below the clay layer, there lies a 2.0-meter-thick layer of fine sand. This layer acts as the foundation for the wooden piles on which ordinary brick homes are erected.

Piling Foundation: Adjacent to the tunnel, the piling foundation of such a construction is modelled. It is vital to prevent any shifting of these piles to avoid inflicting structural damage to the building.

Lower Layer: Beneath the sand layer, there is a 5-meter-deep layer of rich loamy clay.

C. Structural Elements

In this model, both the tunnel and the building are treated as structural elements. Specifically, the model focuses on the right half of a circular tunnel. The tunnel is composed of curved plates or shells, while the building is represented by a rigid plate supported by piles. This representation allows for the analysis of the structural behavior and interactions between the tunnel and the building.

All the material data sets are taken from the Tutorial manual of PLAXIS 2D.

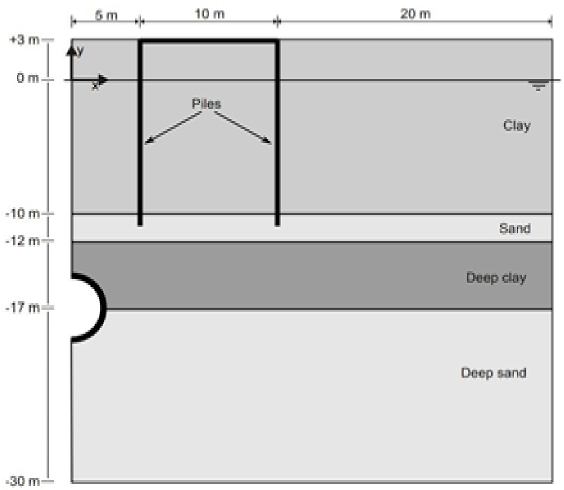

Fig. 1: Geometry of the Tunnel

Here, the Normal stiffness of the tunnel lining is 1.4. 107 kN/m whereas the Flexural rigidity is 1.43. 105 kNm^2/m. The weight of the tunnel lining is 8.4 kN/m/m. The weight of the building is 25 kN/m/m.

D. Generated Mesh

Fig. 2 shows the generated mesh where the mesh is refined near the pile foundation and tunnel. At all other places the grading of mesh is coarse.

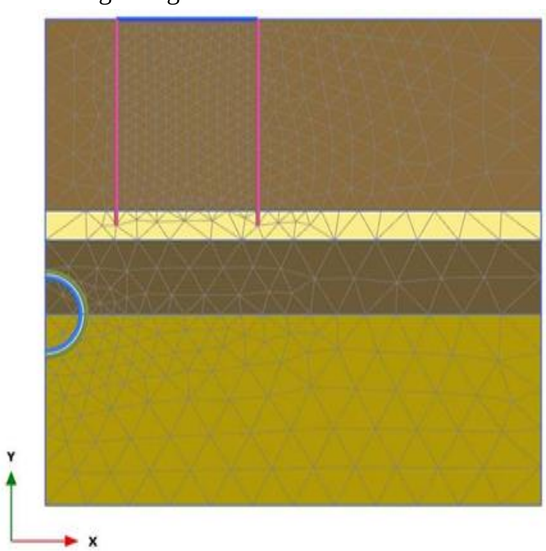

Fig. 2: Generated Mesh of the Tunnel Geometry

III. MATERIAL PROPERTIES

The material properties of the soil with a high frictional strength value are imported from the tutorial file of Rocscience Phase 2. The soil is 'Till' that has a unit weight of 20 KN/m^3.

A. Distributed Load

The distributed load of 0.2 MN/m2 is applied uniformly to the segment of the ground surface exactly above the tunnel.

Finished Model

The model is analysed in 3 stages. In Stage 1 only the tunnel is excavated. In Stage 2 trench is excavated and in the third stage the distributed load is applied just above the tunnel. The finished model at the third stage is shown in Fig. 3.

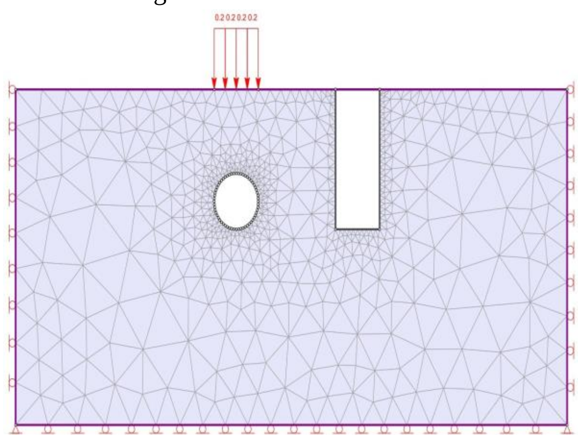

Fig. 3: Finished Model showing surface excavation and tunnel excavation

IV. RESULTS AND DISCUSSIONS

This section includes the results of all the models that have been described in the previous chapter. For every model, a deformed mesh is generated that shows the displacements of all the structures with the maximum displacement. For the excavations that are modelled in PLAXIS 2D, the forces in the lining of the tunnel are also shown. For the models in Rocscience Phase 2, the number of yielded elements of the material, bolts and lining are also shown.

A. Settlement due to Tunnel Construction

Fig. 4 shows deformed mesh at phase 2. During the phase of removing soil and water from the tunnel, the surrounding soil undergoes stress redistributions, resulting in settlement. The tunnel lining also experiences deformation as it adapts to the changing conditions and stress distribution in the soil.

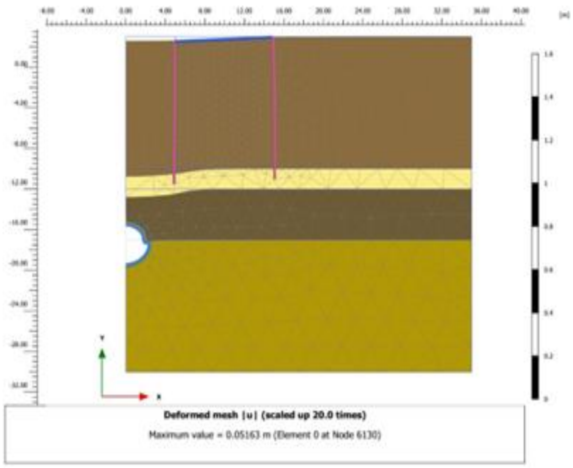

Fig. 4: Deformed mesh of settlement due to tunnel construction

Node 6130 is at the crown of the tunnel lining. The value of the maximum deflection is 51. 63mm, as can be seen in Fig. 4.

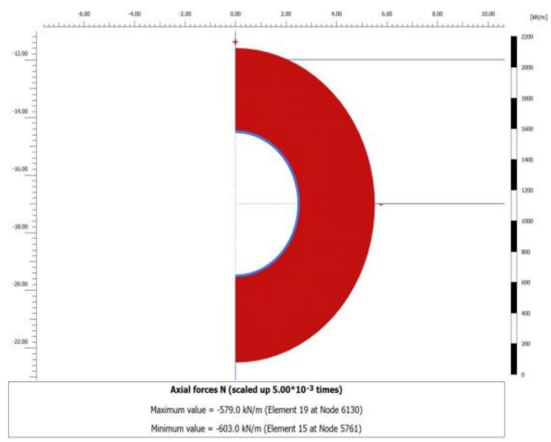

Fig. 5: Axial forces in the tunnel lining

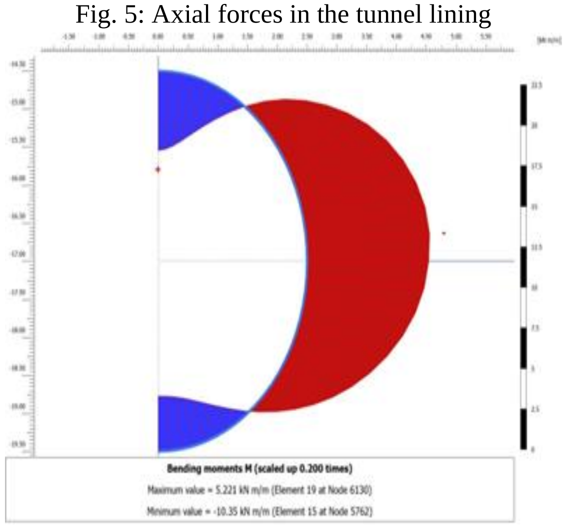

Fig. 6: Bending Moment in the tunnel lining

Figures 4.2 and 4.3 show the Axial Forces and the Bending Moments in the tunnel lining, respectively. It can be seen that the axial force is approximately constant throughout the lining but is maximum at the centre. Whereas, the ultimate bending moment is obtained at the centre with a negative value of 10.35 kN m/m and a positive value of 5.221 kN m/m at the crown of the tunnel lining.

As a result of the settlement at the tunnel excavation level, a tilt of 0.215% which is 1:465.8, is observed in the structure.

V. CONCLUSIONS

The following conclusions can be drawn from the analysis of all the tunnel excavation models in the previous chapter.

- After the tunnel excavation is completed, the displacement is observed in the tunnel lining which is the highest at the crown of the tunnel.
- A settlement is observed at the ground surface that results in the tilt of the structure founded on the vicinity of the tunnel.
- In case of circular tunnel, the maximum value of Axial forces is obtained at the crown as well as the spring line of the tunnel as a result of the excavation.
- The maximum value of the Bending Moment is obtained at the crown and the spring line of the tunnel.
- From the above two points it can be inferred that the crown and the spring line of the tunnel are critical locations regarding the deformations, forces and bending moments.
- In the case of D shaped tunnel, the axial forces are maximum at the shoulders of the tunnel and the Bending Moment is maximum at the spring line.
- For the horseshoe-shaped tunnel excavated in rock, the maximum displacement is obtained at the base of the tunnel.
- For the horseshoe-shaped tunnel supported by the bolts, the diameter of 15mm is found to be the most suitable as the maximum displacement is near to the minimum and the number of yielded bolt elements is lesser than that for the diameter of 20mm which produces the least maximum displacement.
- It has been found that the maximum displacement decreases with increasing tensile capacity.

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