NUMERICAL ANALYSES OF THE KARNAPHULI TUNNEL LINING

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PROJECT REPORT APPROVAL

The thesis titled “Numerical Analyses of the Karnaphuli Tunnel Lining” submitted by Musaddik Hossain, Md. Golam Ahmed and Tonumoy Mustafiz, St. No. 145403, 145425 and 145440 has been found as satisfactory and accepted as partial fulfillment of the requirement for the Degree Bachelor of Science in Civil Engineering.

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DECLARATION OF CANDIDATE

We hereby declare that the undergraduate research work reported in this thesis has been performed by us under the supervision of Professor Dr. Hossain MD. Shahin and this work has not been submitted elsewhere for any purpose (except for publication).

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"Alhamdulillah for every blessing Allah has given us; hidden and apparent. And for everything Allah protected us from, whether we know or don't."

We want to express our indebtedness to Professor Dr. Hossain MD. Shahin for providing us with all the necessary information and guiding us all the way through the research. We also admire his dedication and commendations for our research work. We are also contended to Sultan Al Shafian for his most valuable advice and continuous supervision.

We also place on record, our sense of gratitude to one and all, who directly or indirectly, have contributed to this venture.

ABSTRACT:

Keywords: Finite Element Method, FEM-tij 2D, Mesh, Settlements, Ground Condition, Forces, Beam Spring Model.

Though underground tunnel construction is a common practice in developed countries, it is totally a new concept for a developing country like Bangladesh. This research deals with tunnel project under the river Karnaphuli, Bangladesh. As the soil condition of Bangladesh is not ideal for large scale construction, the construction of Karnaphuli tunnel posses many challenges like – extensive settlement, erosion of river bed, water pressure and proper tunnel lining design.

For numerical analysis of tunnel lining FEM-tij 2D a finite element programme has been used. Soil parameters of Karnaphuli River were collected from the soil investigation report conducted by China Communications Second Highway Survey, Design and Research Institute Co., Ltd. A numerical method Beam spring model was also simulated to compare the results between FEM analysis and BSM. It was observed that in FEM-tij model, simulation of tunnel lining behavior as per practical situation enables higher safety factor comparing the result of beam spring model.

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CHAPTER 1
INTRODUCTION

1.1General

A tunnel is an underground passageway, dug through the surrounding soil/earth/rock and enclosed except for entrance and exit, commonly at each end. A pipeline is not a tunnel, though some recent tunnels have used immersed tube construction techniques rather than traditional tunnel boring methods.

A tunnel may be for foot or vehicular road traffic, for rail traffic, or for a canal. The central portions of a rapid transit network are usually in tunnel. Some tunnels are aqueducts to supply water for consumption or for hydroelectric stations or are sewers. Utility tunnels are used for routing steam, chilled water, electrical power or telecommunication cables, as well as connecting buildings for convenient passage of people and equipment.

A major tunnel project must start with a comprehensive investigation of ground conditions by collecting samples from boreholes and by other geophysical techniques. An informed choice can then be made of machinery and methods for excavation and ground support, which will reduce the risk of encountering unforeseen ground conditions. In planning the route, the horizontal and vertical alignments can be selected to make use of the best ground and water conditions. It is common practice to locate a tunnel deeper than otherwise would be required, in order to excavate through solid rock or other material that is easier to support during construction.

Tunnels are dug in types of materials varying from soft clay to hard rock. The method of tunnel construction depends on such factors as the ground conditions, the ground water conditions, the length and diameter of the tunnel drive, the depth of the tunnel, the logistics of supporting the tunnel excavation, the final use and shape of the tunnel and appropriate risk management.

For designing the tunnel lining engineers have to be concerned about the surrounding earth pressures of tunnel, groundwater condition, consolidation and stresses developed on tunnel lining. The constitutive model should consider typical soil behaviors including positive and negative dilatancy of soils, dependency of density and or confining pressure of soils. Sub loading tij model is one of the constitutive models, which can describe different important characteristics of soils.

1.2 Background

1.2.1 Project Background

The proposed tunnel is located in Chittagong, Chittagong District, Bangladesh. It will connect the east bank with the west bank of Karnaphuli River at the estuary. The Project connects with the Coastal Road under planning at its starting point (at the west bank), then it goes east along the existing Sea Beach Road, and then it crosses N Awalia Road, gate of Naval Academy, and Karnaphuli till the east bank of Chittagong underground. The road goes out from under ground at east bank floodplain, then it rapidly lifts high and becomes Viaduct Bridge and cross the open space between KAFCO and CUFL and KAFCO Fertilizer Plant overhead. It goes down to the ground at the land of east bank, and connects with Banskhali Sarak Road at the terminal point after bypassing KEPZ land and cemetery hills. The planned route is 9,265.971 m long in total.

The main control points of the route are: planned Coastal Road, See Beach Road, Kamal Ataturk Ave Road, N Awalia Road, the Naval Academy, main channel of River Karnaphuli, land of KAFCO fertilizer plant, land of CUFL, conveyor belt of KAFCO fertilizer plant, riverbank, land of KEPZ, martyrs' cemetery hill, villages and buildings, mosques, markets, Banskhali Sarak Road etc. The main parts (tunnel and bridge) of the Project are designed and constructed as expressway standards and the connection roads as urban trunk highway (access control in parts), with the design speed of 80 km/h.

1.2.2 Study Area:

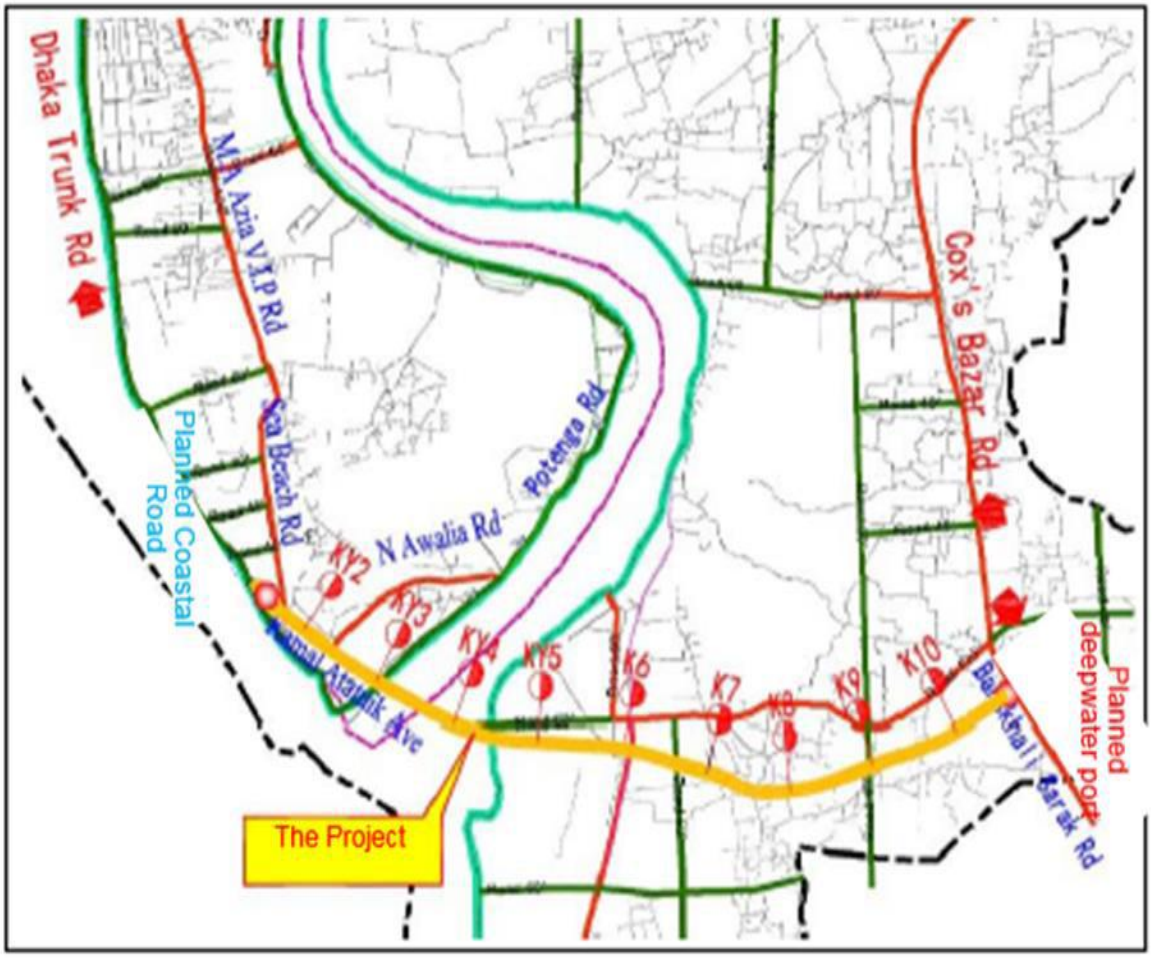


Figure 1.1-1 General Layout of Multi-lane Road Tunnel under the River Karnaphuli Chittagong – Bangladesh

1.2.3 Technical Considerations

1. Technical standard of geometric design
- Design speed: 80 km/h
- Number of lane: Two-way four-lane expressway
- lane Widths: 2×3.65 m
- Lane height: 4.9 m
- Minimum radius of horizontal curve at shield section: 2,550 m
- Maximum longitudinal gradient: 4%.
- Least radius of vertical curves: convex 7,050 m, concave 6,000 m

2. Technical standards of structural design
- Design service life: 100 years
- Design safety grade: first grade
- Impermeability grade of tunnel structure: P12
- Load grade: highway-Grade Ⅰ.
- Seismic peak ground acceleration: 0.15 g
- Tunnel fire control grade: Grade A
- Design flood frequency: 1/100

1.2.4 Geotechnical Investigation

The survey follows Chinese specifications and standards, and the main specifications, standards and

requirements are as follows:

(1) Code for Geotechnical Engineering Investigation (GB 50021-2001) (2009 version)

(2) Code for Highway Engineering Geological Investigation (JTG C20-2011)

(3) Code for Geotechnical Investigations of Urban Rail Transit (GB 50307-2012)

(4) Code for Design of Ground Base and Foundation of Highway Bridges and Culverts (JTG D63-2007)

(5) Specification of Seismic Design for Highway Engineering (JTJ004-89)

(6) Technical Code for Excavation Engineering (DG/TJ08-61-2010)

(7) Code for Design of Building Foundation (GB 50007-2002)

(8) Technical Code for Ground Treatment of Buildings (JGJ79-2012)

(9) Code for Seismic Design of Buildings (GB 50011-2010)

(10) Standard for Soil Test Method (GB/T 50123－1999)

(11) Standard for Engineering Geologic Drilling (CECS240:2008)

(12) Specification for Global Positioning System (GPS) Survey (JTJ／T066－98)

(13) Standard for Hydro geological Investigation of Water-Supply (GB 50027-2001)

(14) Specification of Pumping Test in Borehole for Water Conservancy and Hydropower Engineering (SL320-2005)

(15) Code for Design of Highway Subgrades (JTG D30-2015)

(16) Standard for Classification of Seismic Fortification for Construction Works (GB50223-2008)

And also referred to Shanghai Road Tunnel Design Code (DG/TJ08-2033-2008) and Technical Code for Cross passage Freezing Method.

1.3 Objectives

The objective of this research is:

- ❑ To determine the Water pressure & stress developed in the proposed Karnaphuli tunnel.
- ❑ To determine surface settlement.
- ❑ To determine stresses developed on tunnel lining.
- ❑ To perform an experimental prototype model on the basis of real field conditions that were used in FEM.
- ❑ To compare results obtained from FEM analyses with that obtained from beam spring model.

CHAPTER 2: LITERATURE REVIEW

There are many studies related to tunnel lining analysis. Numerical analysis has been done for different underground structures like Tunneling.

- **Shahin et al.-** Conducted numerical analysis on underground tunnel defining both 2D and 3D parameters.

- **Rostami et al**.- Applied numerical simulation to predict the soil behavior and to determine the probability of shield entrapment in potentially squeezing ground which later in real measurement accurately predicted the effects on the double shield tunnel lining

- **Oreste (2007)-** Developed a code in FEM framework for analyzing mass-structure relation in detail using hyper static reaction method considering geometry of lining and vertical loads that are different from horizontal loads.

- **Hudoba (1997**)- By using FEM 2D and 3D model analyzed the behavior of lining under static loading condition of the surrounding soil during tunneling.

- **Ding et al. (2013)-** through experimental bending test set-up able to simulate both the external loads and the internal water pressure during the tunnel's service life.

- **Tang et al (2013)-** showed the influence of three spring constant 1.shear spring constant, 2.rotation spring constant, 3.pressure spring constant on the design of tunnel lining through beam spring model.

Researches in Perspective of Bangladesh:

Very few research works have been accomplished for underground tunneling system in Bangladesh.

- **Waheed et al. (2008)** has applied Cut and Cover excavation method along the existing rail line passes from Uttara junction to kamalapur junction based on the conventional method of analysis. He recommended performing FEM in this case.

- **Farazandeh et al. (2010)** has revealed that SHIELD tunneling is the safest system in perspective of Bangladesh.

CHAPTER 3: METHODOLOGY

3.1 Methods of Analysis

There are two methods of analysis while designing a tunnel lining

1. Conventional method
2. Numerical method

This research incorporates numerical method of tunnel lining.

3.2 Numerical Method of Tunnel Lining Design.

Numerical analysis is the area of mathematics and computer science that creates, analyzes, and implements algorithms for obtaining numerical solutions to problems involving continuous variables.

There are many applicable models while conducting the analysis of tunnel lining. This research includes two numerical model approaches.

1. Finite element model.
2. Beam spring model.

3.3 Finite Element Model

The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical physics. Typical problem areas of interest include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

FEM is widely used in case of geotechnical purposes because of the following reason-

- Accurate representation of complex geometry
- Inclusion of dissimilar material properties
- Easy representation of the total solution

- Capture of local effects.

There are various kinds of elasto-plastic soil models in FEM 2D analysis. Name of some soil models are:

1. linear elastic constitutive relations;

2. Elasic-plastic Drucker-Prager model;

3. Elasic-plastic Mohr-Coulomb model

4. Elastic-plastic Cap model.

subloading tij model (Nakai and Hinokio, 2004) is an elasto-plastic constitutive model for two-dimensional finite element analysis used in numerical analysis. The Subloading tij model has the following advantages over other constitutive models:

(1) Subloading tij model requires only a few unified material parameters.

(2) This model can describe the characteristics of soils which are as follows:
a) Influence of intermediate principal stress on the deformation and strength of soil.

b) Influence of stress path on the direction of plastic flow is considered by splitting the plastic strain increment into two components.

c) Influence of density and /or confining pressure.

3.4 Beam Spring Model

In this design approach, the vertical earth pressure is estimated from the over-burden pressure and Terzaghi's loosening earth pressure theory. The lateral earth pressure is obtained by multiplying the vertical earth pressure with the coefficient of lateral earth pressure. Beam-spring model is used to estimate deformation and acting stress on the tunnel lining using the vertical and lateral earth pressures.

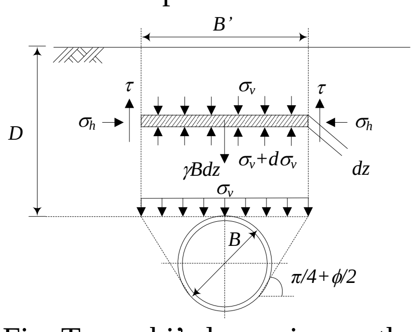


Fig. Terzaghi's loosening earth pressure

CHAPTER 4:MODEL CONSIDERATIONS, SOIL PARAMETERS AND TUNNEL GEOMETRY

4.1 FEM Considerations

 Consider plane strain condition

 Consider iso-parametric element

 Consider soil-water coupling condition

 Consider quadrilateral element (element with 4 nodes)

 Soils are modeled with elasto-plastic constitutive model named -Extended Sub-loading tij model (Nakai et. al., 2011).

4.2 Tunnel Geometry and Design Input (FEM)

1. Tunnel depth- 35 meter from the surface of top soil
2. Tunnel diameter- 5.25 meter
3. Lining thickness- .3 meter
4. Excavation step- 1000
5. Lining step – 200
6. Lining bending modulus (EI)- 4.6x10^8 kgf-sqcm
7. Lining axial modulus(EA)- 6.1x10^6 kgf-sqcm

4.3 Soil Parameters and Geometry:

Soil sample collected from borehole no.23 and parameters are considered as basic design input for FEM simulation.

Basic parameters:

λ = Compression index (or slope of virgin loading curve in e-log p’ curve at the loosest state)

κ = Swelling index (o slope of unloading- reloading curve in e-log p’ curve at the loosest state where, e is void ratio and p’ is consolidation pressure

RCS = (σ1/ σ3)*cs(comp.)* = Critical state stress ratio.

OCR = Over consolidation Ratio.

N or eN = Reference void ratio on normally consolidation line at p=98 kPa & q= 0 kPa (or void ratio at mean principal stresses (p) 98 kPa in e-log p’ curve)

e0 = Initial void ratio.

υ = Poisson’s ratio.

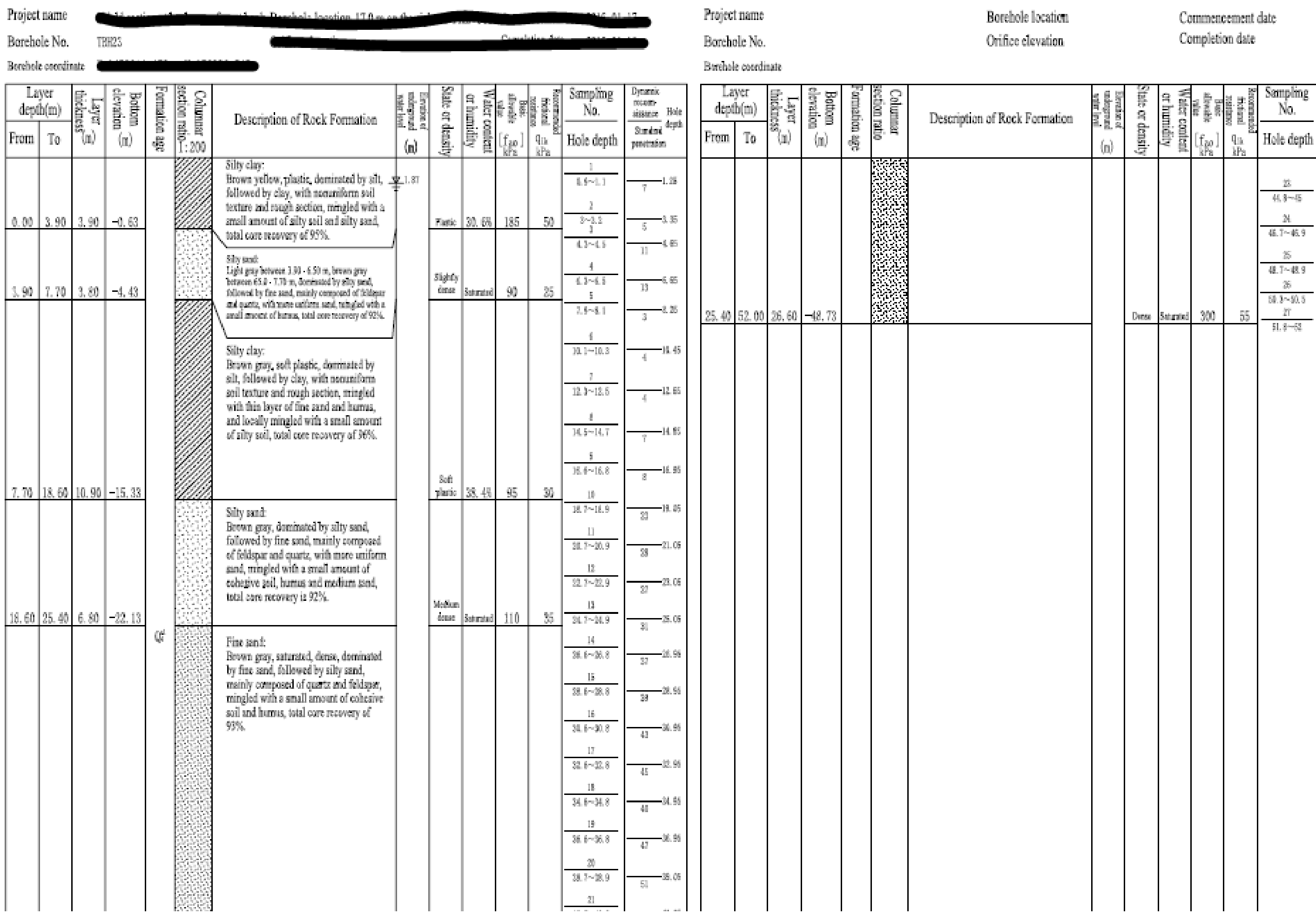
β = Model parameter responsible for the shape of the yield surface.

a = Model parameter responsible for the influence of density and confining pressure.

Table 4.3.1: Basic parameters of soil for FEM analysis

Parameters	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
	Silty Clay	Silty Sand	Silty Clay	Silty Sand	Fine Sand
Depth(meter)	0-4	4-8	8-18	18-26	26-50
Unit weight (saturated)(ton/m^3)	2.13	1.73	2.05	1.83	1.89
Young's Modulus (ton/m^2)	2753.23	1019.72	2243.38	1529.57	2734.16
Poisson's Ratio	.35	.3	.4	.29	.28
Void Ratio(e)	.83	.7	.99	.65	.60
λ	0.1	0.05	0.1	0.05	0.04
κ	0.015	0.0075	0.015	0.0075	0.0063
N(e at p=1kg/cm^2)	1.0	1.1	1.0	1.1	1.1
R_{CS}	3.5	3.2	3.5	3.2	3.2
Permeability(m/day)	.26	3.71	.26	5.44	7

Soil Geometry:



Project name [redacted]

Borehole No. TBH25 [redacted]

Borehole coordinate [redacted]

Layer depth (m) From	To	Layer thickness (m)	Bottom elevation (m)	Formation age	Columnar section ratio 1:200	Description of Rock Formation	Elevation of underground water level (m)	State or density	Water content or humidity	Basic allowable value [f_{a0}] kPa	Recommended frictional resistance q_{ik} kPa
0.00	3.90	3.90	−0.63			Silty clay: Brown yellow, plastic, dominated by silt, followed by clay, with nonuniform soil texture and rough section, mingled with a small amount of silty soil and silty sand, total core recovery of 95%.	1.87	Plastic	30.6%	185	50
3.90	7.70	3.80	−4.43			Silty sand: Light gray between 3.90 - 6.50 m, brown gray between 65.0 - 7.70 m, dominated by silty sand, followed by fine sand, mainly composed of feldspar and quartz, with more uniform sand, mingled with a small amount of humus, total core recovery of 92%.		Slightly dense	Saturated	90	25
7.70	18.60	10.90	−15.33			Silty clay: Brown gray, soft plastic, dominated by silt, followed by clay, with nonuniform soil texture and rough section, mingled with thin layer of fine sand and humus, and locally mingled with a small amount of silty soil, total core recovery of 96%.		Soft plastic	38.4%	95	30
18.60	25.40	6.80	−22.13			Silty sand: Brown gray, dominated by silty sand, followed by fine sand, mainly composed of feldspar and quartz, with more uniform sand, mingled with a small amount of cohesive soil, humus and medium sand, total core recovery is 92%.		Medium dense	Saturated	110	35
25.40	52.00	26.60	−48.73	Q_4		Fine sand: Brown gray, saturated, dense, dominated by fine sand, followed by silty sand, mainly composed of quartz and feldspar, mingled with a small amount of cohesive soil and humus, total core recovery of 93%.		Dense	Saturated	300	55

Sampling No.	Hole depth	Dynamic resistance / Standard penetration	Hole depth
1	0.6~1.1	7	1.28
2	3~3.2	5	3.35
3	4.3~4.5	11	4.65
4	6.3~6.5	13	6.65
5	7.8~8.1	3	8.25
6	10.1~10.3	4	10.45
7	12.3~12.5	4	12.65
8	14.5~14.7	7	14.85
9	16.6~16.8	8	16.95
10	18.7~18.9	33	19.05
11	20.7~20.9	38	21.05
12	22.7~22.9	37	23.05
13	24.7~24.9	31	25.05
14	26.6~26.8	37	26.95
15	28.6~28.8	38	28.95
16	30.6~30.8	43	30.95
17	32.6~32.8	45	32.95
18	34.6~34.8	40	34.95
19	36.6~36.8	47	36.95
20	38.7~38.9	51	39.05
21	[illegible]		[illegible]
23	44.8~45		
24	46.7~46.9		
25	48.7~48.9		
26	50.3~50.5		
27	51.8~52		

Project name Borehole location Commencement date

Borehole No. Orifice elevation Completion date

Borehole coordinate

4.4 Mesh and Drainage Boundary:

The 2D Mesh module is used to construct two-dimensional finite element meshes. The mesh consists of nodes that are grouped together to form elements. Numerous tools are provided for automated mesh generation and mesh editing. 2D meshes are used for SEEP2D modeling and to aid in the construction of 3D meshes.

The 4- noded quadrilateral elements have been used to represent the soil and concrete materials. The 2- noded beam elements have been used to simulated lining, rock bolts and reinforcement in pile. And, the joint interface between pile cap and pile is simulated using the 1- noded joint element**.** Total length of the ground block is 100 meter and height is 50 meter.

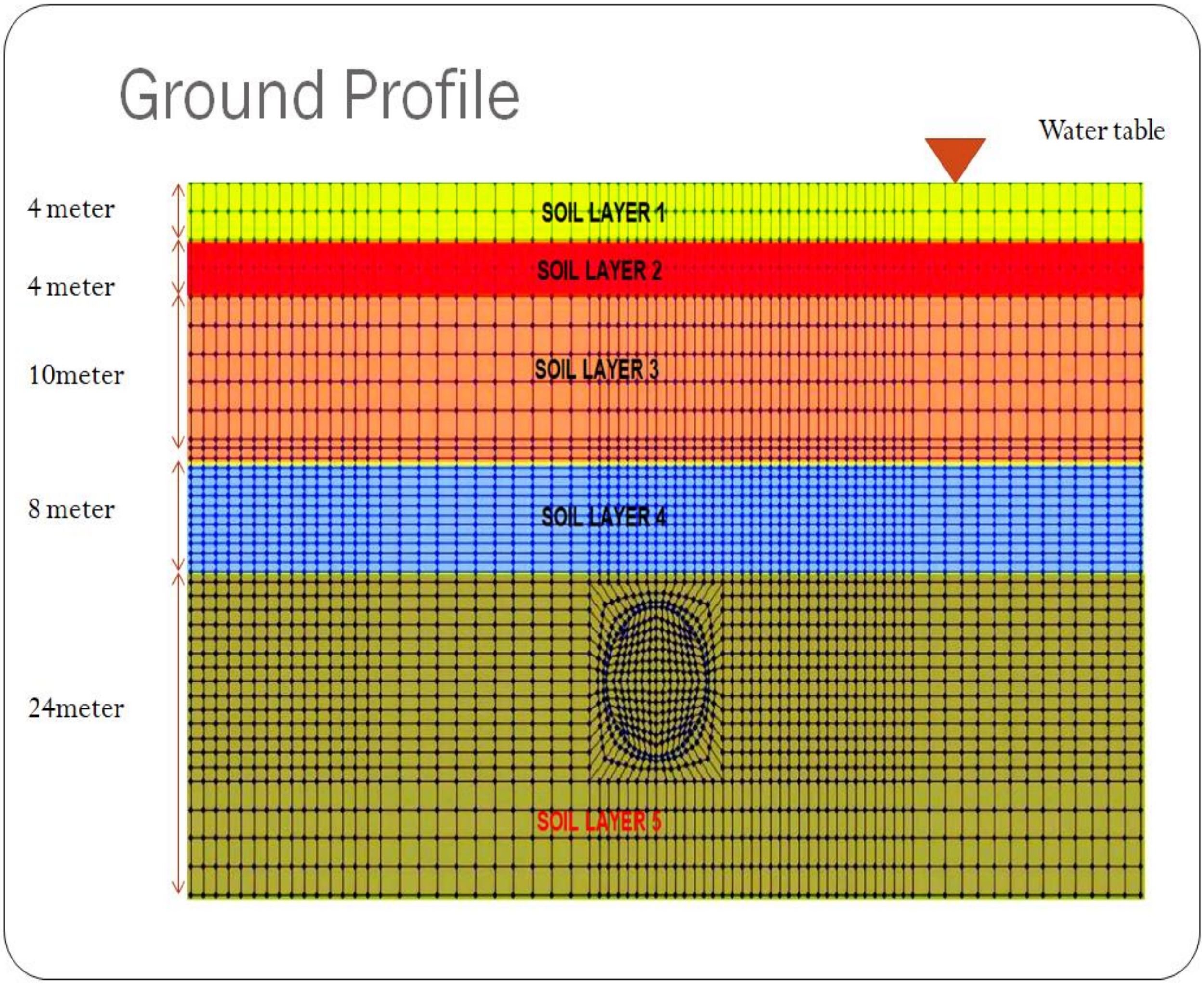


Figure: Mesh of Tunnel

4.4.1 Displacement boundary:

The displacement boundary conditions are as follows:

At bottom: Both vertical and horizontal displacements are fixed.

At left edge: The horizontal displacement is fixed but vertical movement is allowed; i.e., vertical displacement is pinned.

At right edge: The horizontal displacement is fixed but vertical movement is allowed; i.e., vertical displacement is pinned.

4.4.2 Drainage Boundary:

Water table is at the top of the soil layer (as tunnel is situated under river)

At bottom: Undrained

At left and right edge: Undrained

At top: Drained

At lining boundary: Undrained

4.5 Beam Spring Model Basic Inputs and Considerations

Very simple numerical model. Basic input is K which is in real is considered as soil strength parameter as well as beam spring constant in vertical and horizontal direction.

- Soil Strength Parameter K (Horizontal and Vertical) = 80000 kn/m3
- Terrain and water table as defined in Finite Element Model
- Soil unit weight average of all soil layers 19 kn/m^3
- Load factor K0= 0.8
- Lining material modulus of elasticity E= 30000MPA , f'c= 21 MPA

4.7 SOFTWARES FOR TWO MODELS

4.7.1 FEM Notable Softwares

1) FEM-tij 2D.exe- for total calculation

2) Beam_Tunnel_out.exe – for exhibiting the stresses generated on tunnel lining.

3) Micro_AVS.exe - for showing various stresses and settlements graphs.

4) Load_displacement.exe – for showing the data related to surface settlement.

5) Sma4win- for generating graphs.

4.7.2 BSM Notable Softwares

1) Autocad – for drawing the tunnel geometry

2) Gentun.fas- extension for autocad for identifying the tunnel geometry

3) Tunnel_generator.exe- for inputting various soil parameters and defining the ground

4) SAP200- for analyzing stresses exerted on tunnel lining

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 Initial Ground Condition:

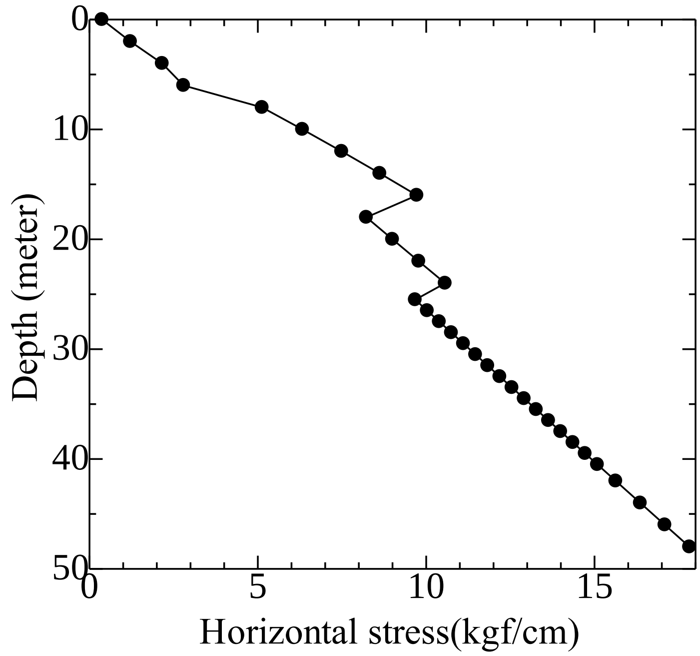


Figure 5.1.1: Horizontal stress along depth

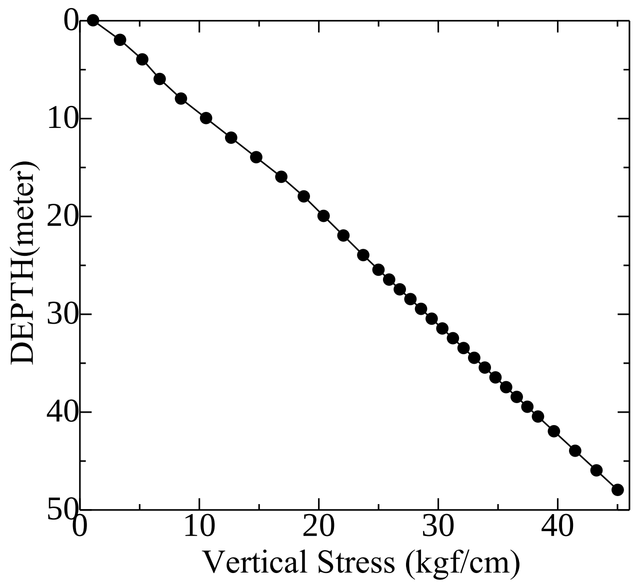


Figure 5.1.2: Vertical stress along depth

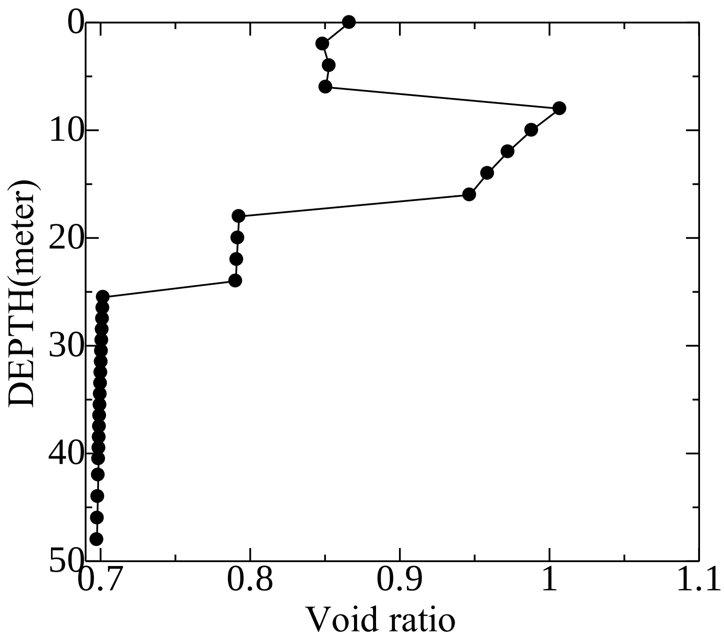


Figure 5.1.3: Void ratio along depth

5.2 Surface Settlement

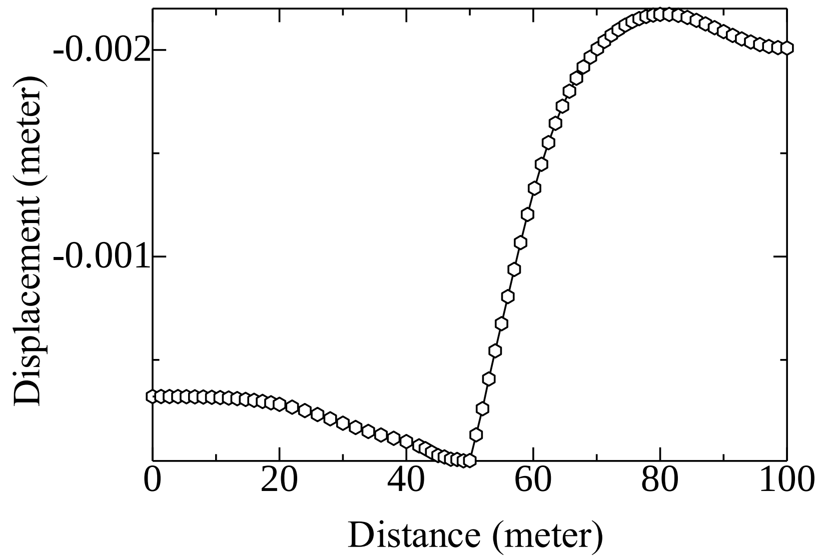


Figure5.2.1: Surface settlement at step 1000

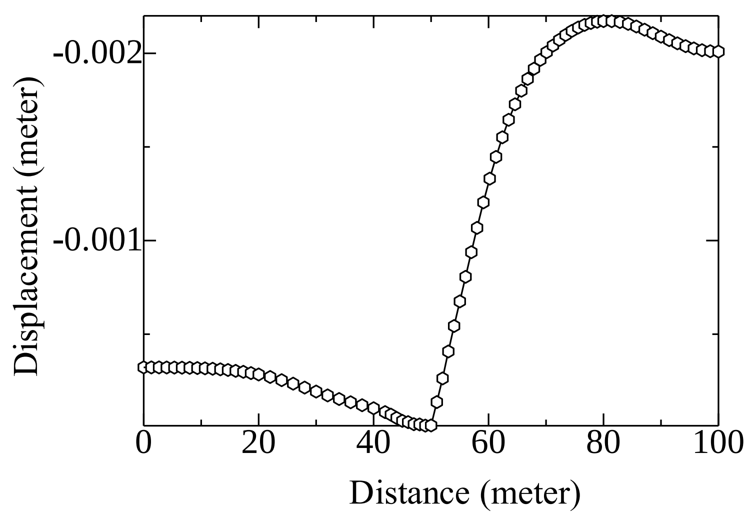


Figure 5.2.2: Surface settlement at step 5000

5.3 Vertical Stress

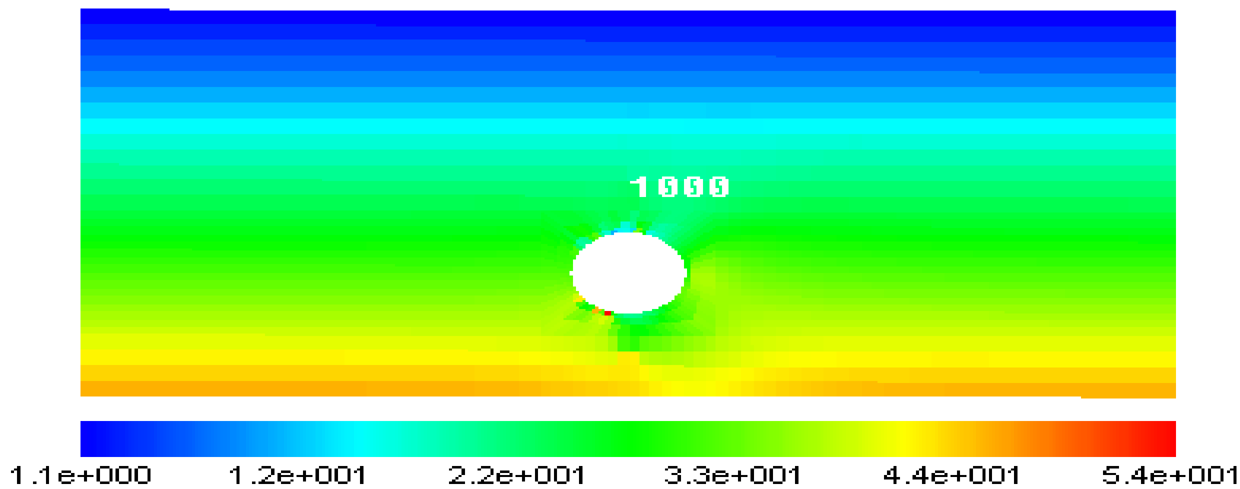


Figure5.3.1: Effective vertical stress after tunnel construction (ton/m2)

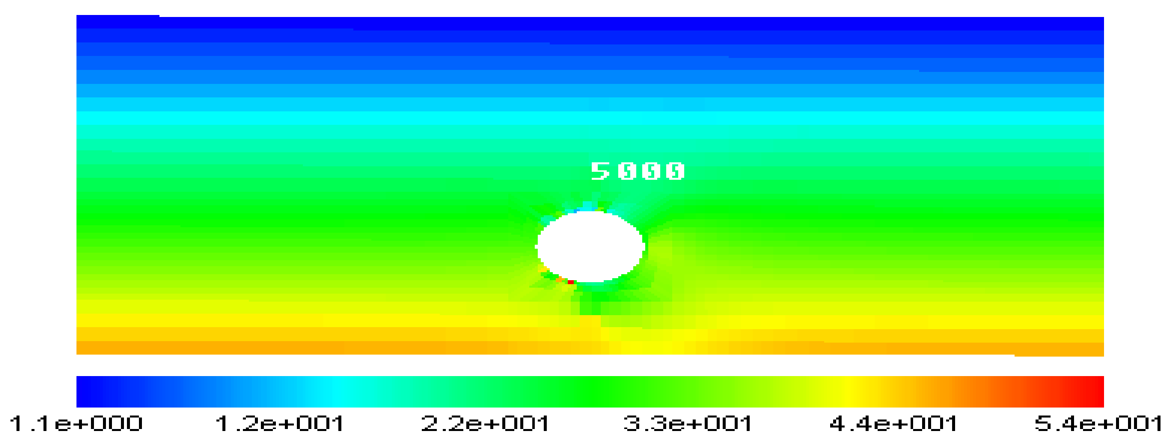


Figure5.3.2: Effective vertical stress at final step (ton/m2)

5.4 Displacement Vector

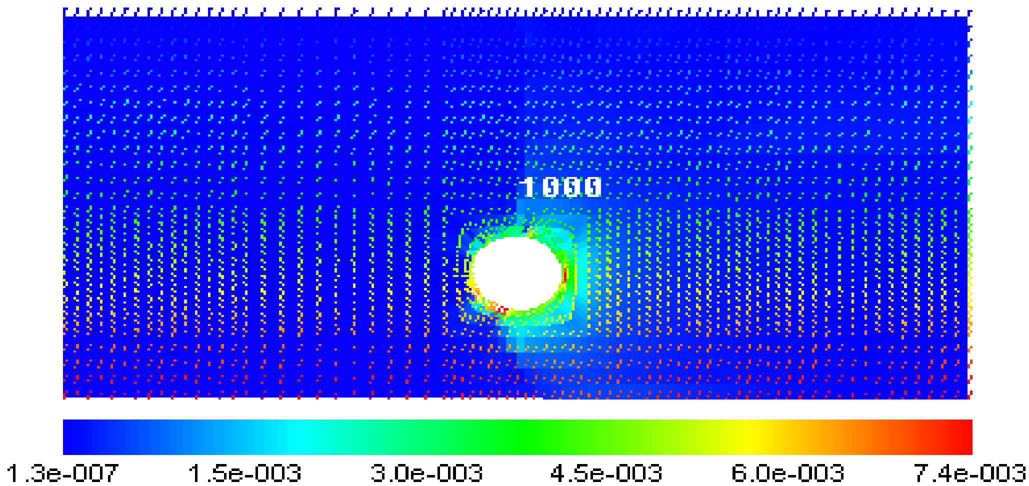


Figure 5.4.1: Displacement vector after tunnel construction

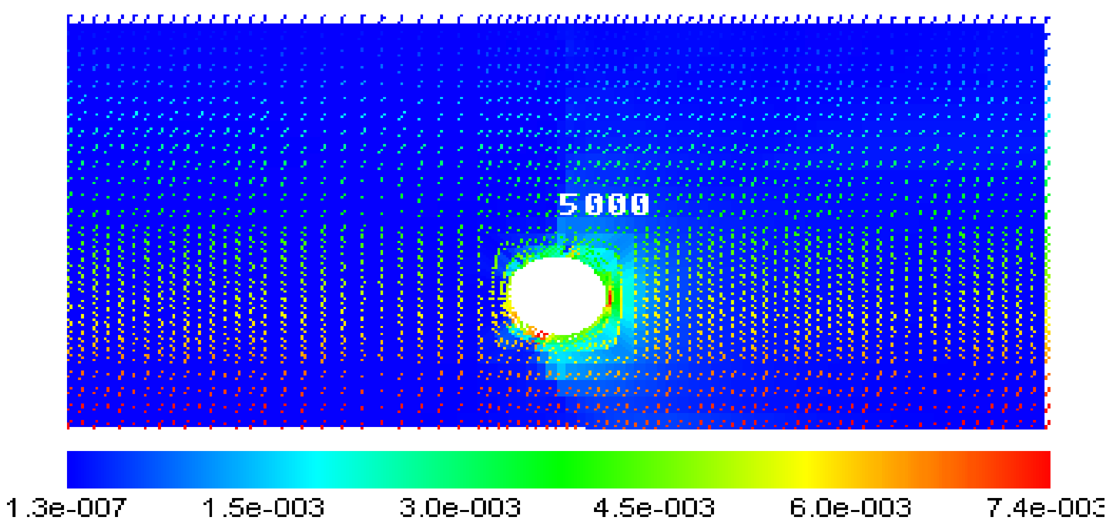


Figure 5.4.2: Displacement vector at final stage

5.5 Pore Water Pressure

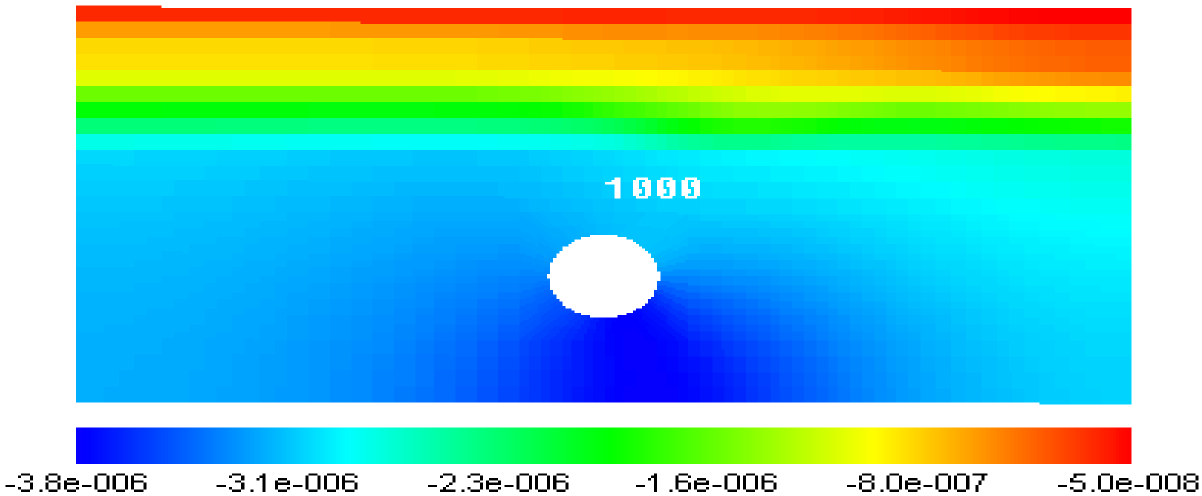


Figure5.5.1: pore water pressure after tunnel construction(ton/m2)

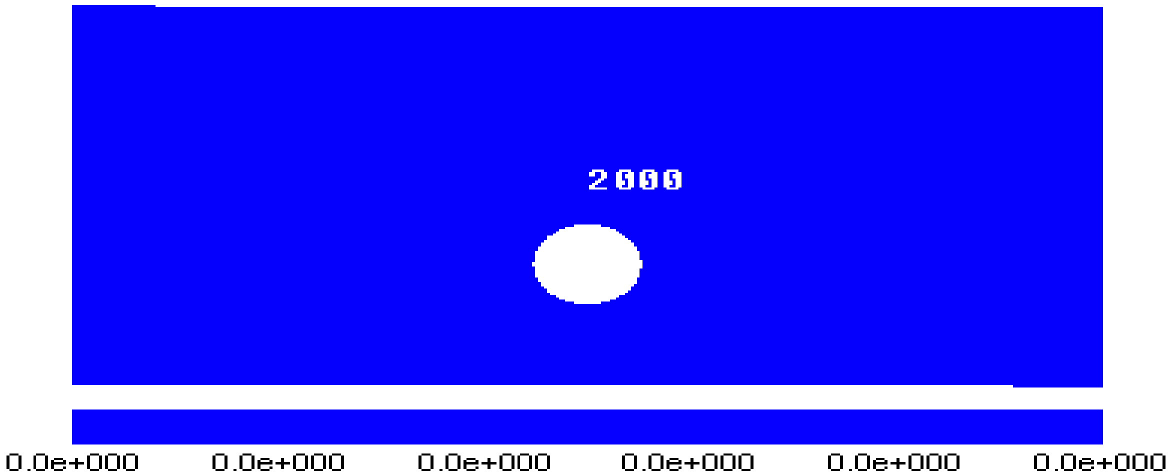
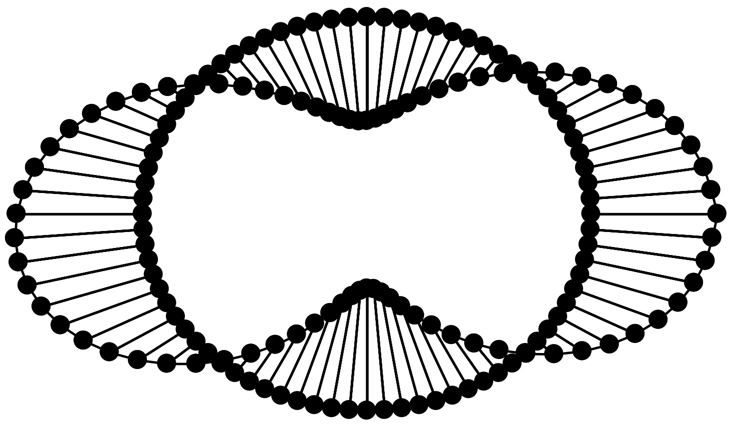


Figure 5.5.2: Pore water pressure at step 2000 (all water has drained out)

5.6 Stresses on Tunnel Lining

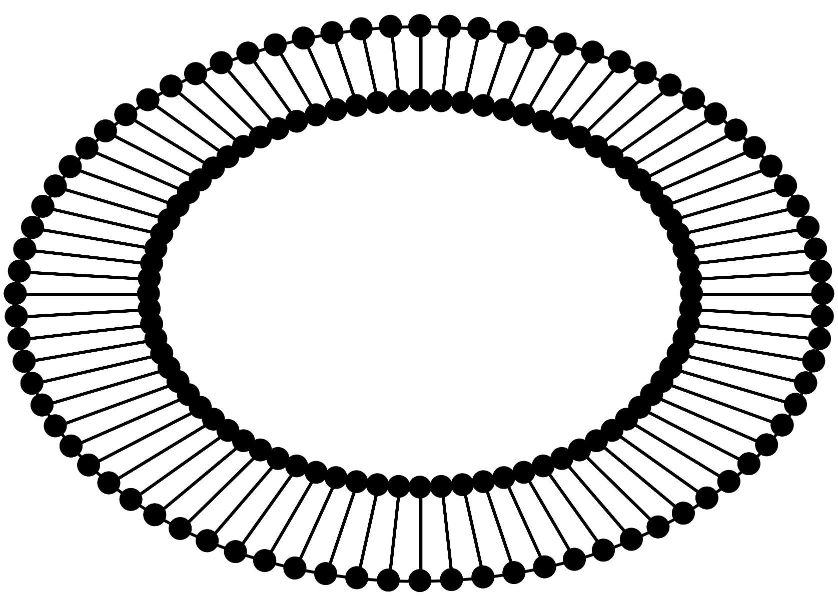
5.6.1 Bending Moment



Maximum Bending Moment = 7.53 ton-m

Figure5.6.1: Bending moment on tunnel lining

5.6.2 Normal Force:



Maximum normal force = 294 ton

Figure5.6.2: Normal force on tunnel lining

5.6.3: Shear Force:

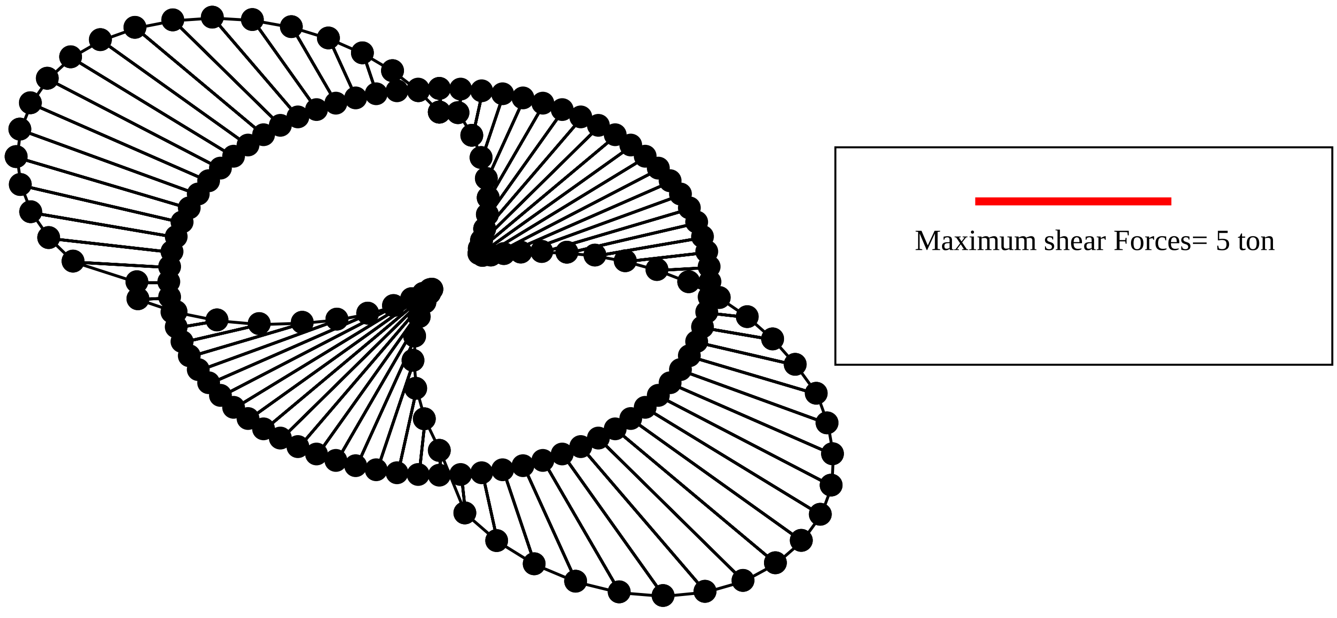


Figure 5.6.3: Shear force on tunnel lining

5.7 Beam Spring Model Stresses:

5.7.1Bending Moment on Tunnel Lining:

Maximum bending moment =80.51 KN-M

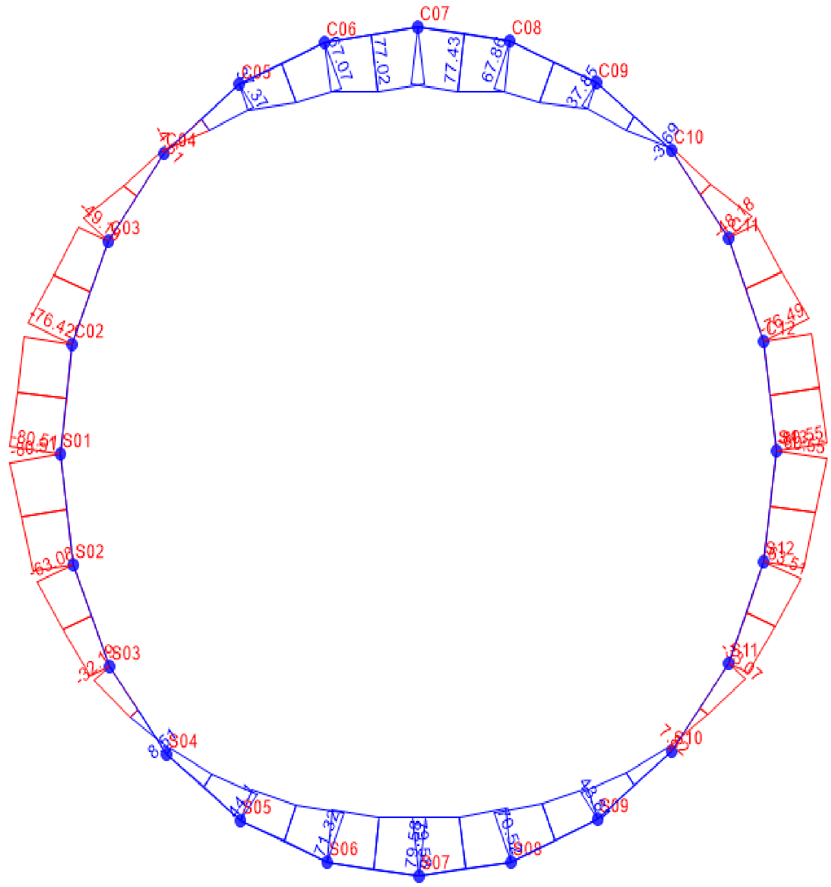


FIGURE 5.7.1 Bending Moment on tunnel lining

5.7.2 Shear Stresses on Tunnel Lining:

Maximum Shear force= 39.62 KN

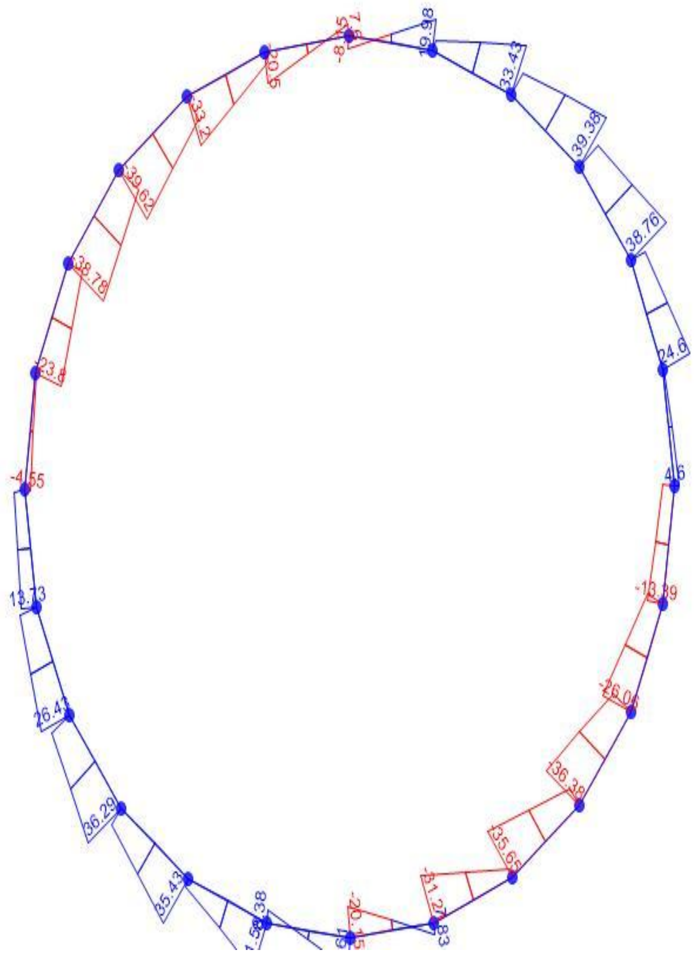


Figure 5.7.2: Shear stresses on tunnel lining

5.7.3 Normal Forces On Tunnel Lining

Maximum normal force = 2122.68KN

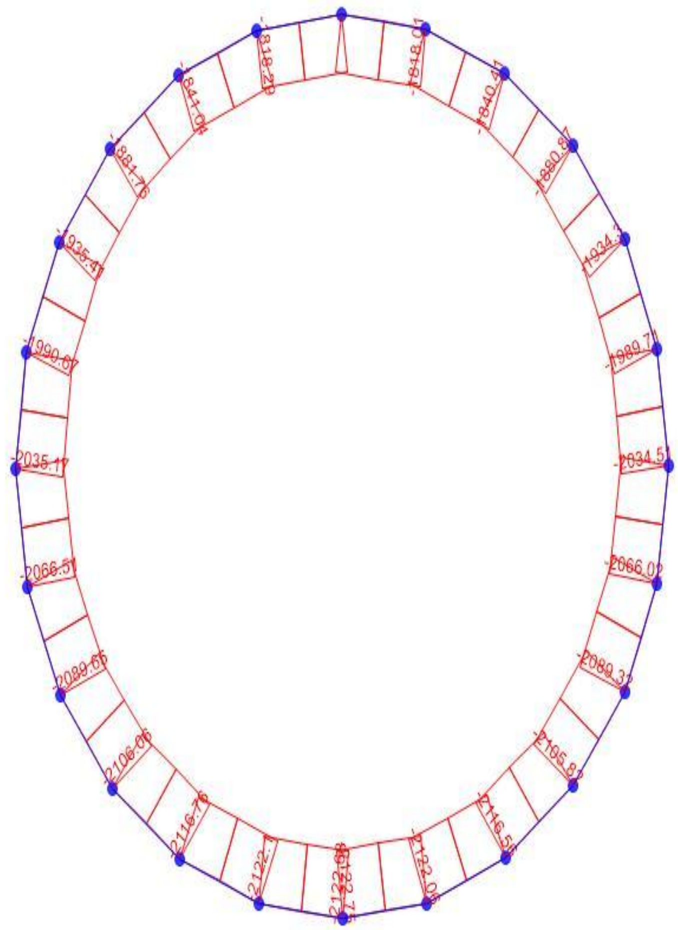


Figure 5.7.3: Normal forces on tunnel lining

CHAPTER 6: COMPARISONS BETWEEN TWO MODELS

FEM and BSM though both models are widely used in tunnel lining design, there are significant differences between them. The differences are mainly based on considerations of soil parameters and tunnel geometry. Tunnel lining design based on FEM should exhibit proper agreement while designing under BSM.

Table 6.1: Stresses comparison between finite element method (FEM) and beam spring model(BSM)

Stresses	Finite Element Method	Beam Spring Method
Bending Moment (Maximum)	**7.53 ton-m=75.3 KN-m**	**80.51 KN**
Normal Force (Maximum)	**294 ton=2940 KN**	**2122.68 KN**
Shear Force (Maximum)	**5 ton = 50 KN**	**39.62 KN**

The comparison between the result of FEM-tij & the BS model was made. It results in following findings:

1. For the predefined considerations that were taken for each of the models, FEM-tij shows higher values of stresses comparing to the Beam Spring model

2. This small differences between two models maybe due to the presence of some boundary conditions or conversion of scale and incorporation of different parameters.

6.2 Why FEM is More Reliable Than BSM

For designing and prediction purpose FEM is more accurate than BSM. Because of the following reasons:

I. BSM only considers the adjacent soil conditions and beam spring constants highly depended on the characteristics of adjacent soil mainly on modulus of subgrade reaction of adjacent soil. On the other hand FEM considers and identify the whole soil layers and take into account of their unique parameters and behavior.

II. BSM does not consider consolidation and therefore neglect surface settlement but FEM take into account the effect of consolidation and surface settlement.

III. BSM is highly depended on the soil strength parameter/modulus of subgrade reaction rather than real field soil parameters such as: shear strength, critical stress ratio, permeability, angle of internal friction, void ratio etc. FEM prioritize real field soil condition while predicting stresses and ground behavior.

IV. BSM does not deal with the displacement boundary and drainage boundary of soil block however FEM considers displacement boundary and drainage boundary in details.

V. Changes in water table during construction and excavation phase is elaborately regarded in finite element method on the other hand neglected in beam spring model.

CHAPTER 7:CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

- Considering all the results and their comparisons we can come to the point that FEM-tij is one of the most accurate model for tunneling excavations and tunnel lining design.
- The finite element analysis carried out showed excellent agreement with the result of observed in beam spring model tests for both stresses and earth pressure. Moreover it can give a guideline for the prediction of deformation pattern inside the ground which beam spring cannot.(6.2)
- In the tunnel excavation considering real ground, for the same soil cover surface settlement due to tunnel excavation depends on the characteristics of soils.

7.2 Limitations and Future Work

1. In this study we have considered the water table at the top of the soil surface. In future we will consider differential water table level for this study.

2. In future, we will consider the dynamic loading which wasn’t considered in FEM-tij model. We will also make a proposal on lining thickness of the tunnel in future.

3. Finally, we will consider a more complex beam spring model which takes into account drainage boundary, displacement boundary and settlement.

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