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2D FEM Analysis of Tunnel Segment

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***Abstract*: Tunnel is a horizontal passage constructed below the ground level. Tunnels are excavated through different methods, like by manually, by using explosives or by using modern machine tools or use of combination of these methods. Tunnels are designed in such a way that it opposes forces like tension, compression, shear and torsion, tunnels are made of strong materials, like masonry, concrete, iron and steel. Tunnels are broadly categorised in different groups, tunnels for mining purpose, public utilities, and transportation. Tunnels could of many shapes, but general shapes are rectangular, circular, curvilinear or horse-shoe types. There are many challenges are encountered while construction of a tunnel and almost every tunnel has unique solution to its challenges and problems. Challenges can be water bodies, mountains, other natural or manmade obstacles. The method of tunnel construction depends mainly upon the type of soil strata through which it is going to pass. A thorough geological study of the ground are conducted to know the type of material through which the tunnel needs to construct, to access relative risks of different location (like soil and rock types, faults and shear zones, ground water etc.). This paper is to present 2D FEM analysis for segment design for Bored tunnels.**

***Keywords*: Curvilinear, Horse-shoe, Geological, Conventional, Mechanized, Segment, 2D FEM analysis.**

1. Introduction

A tunnel is an underground passageway, which is Dugged through the surrounding of soil/earth/rock and enclosed except for exit and entrance. In today's world due to rapid urbanization in major cities, people from different places and background are getting attracted towards them, for job opportunities and better living standards and basic facilities which are not available in remote villages, this migration of people from small towns/villages to major cities making the cities over-crowded and due to which the vehicular movement also increasing, widening of roads has a limitation since the land is limited, hence traffic jams are occurring every days. So, utilization of underground space has become an important aspect and as a solution and it is becoming popular. Tunnel construction is one of the important and large infrastructure projects (like Underground Metro systems, cross passages, subways etc.), which are important for the development in the transportation networks, in major cities like Mumbai, Delhi, Chennai and Bangalore etc. Tunnel projects requires large budget, construction of tunnel take long duration, it involves high risk, and they are complex. Tunnels are dug in different types of materials varying from soft soil to hard rock, the method of tunnel construction depends on factors such as the ground conditions, the underground water conditions/level, length and diameter of the tunnel, the depth of tunnel, final use and shape of tunnel and approximate risk management. There are several tunnel construction methods are available like Cut and cover method, Conventional method/NATM method and TBM method. Which have been developed in the tunnel construction industry to improve the constructability of tunnels and decrease the impact on surrounding structures and reduce ground settlement conditions with proper supporting system. Depending on the sub-ground strata method of tunnelling is selected. In general, Cut and cover method is used in soft soil, conventional method/NATM and TBM method are suitable for soft soil and hard rock.

Deformation of ground surface due to construction of tunnel beneath ground which effects the structures, monitoring of deformation is very important aspect in the urban area tunnel construction process. Final lining is the concrete structure which comes in contact with the surrounding soil/rock and holds the different loads from surrounding. Final lining of tunnels is designed for various forces, dead load, earth pressure, water pressure, surcharge loads, earthquake load, train and other services load, air pressure, TBM shove ram loads, gasket compression load, handling and stacking loads, grouting loads, and bolts & inserts loads.

The design of final lining pertains to precast concrete segments, diameter of tunnel for a single track is 5800mm (5.8m) including all tolerances and thickness of final lining is 275mm. Analysis of the bored tunnel linings is done considering the interaction between the lining and the ground, the deflection of the lining and the redistribution of the loading dependent upon the relative flexibility of the lining, the variability and compressibility of the ground. 2D FEM analysis are used to understand the soil structure interaction of TBM segment and adjoining rock-mass. The lining behavior as estimated in STAAD analysis is re-evaluated by modeling the actual ground condition in RS2 (RocScience) software.

2. 2D FEM Analysis

A. *By Staad Pro*

A two-dimensional Plane Frame Analyses is performed using the computer program from STAAD Pro. V8i. A near realistic 2D model using beams bedded by radial and tangential

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springs are created and loads applied using STAAD command. Springs have been generated by using Staad command and reference are made to STAAD manual for further details. The bedding is modeled in such a way that the parts of the cross-sections where inward deformation occurs, i.e., where the springs would be subject to tensions, are neglected. The material behavior of ground and lining is generally assumed as being elastic. All forces are applied on the frame model in STAAD Pro and load combination are used for Ultimate Limit State (ULS) & Serviceability Limit State (SLS), and the Members are checked for the load combination for Ultimate Limit State (ULS) & Serviceability Limit State (SLS). The Normal force, bending moment and shear force for all members are taken from the Staad Pro and designed.

Calculation of Spring Constants for Rock-mass:

The lining is modeled as a beam bedded by springs. Multiple beam elements are created along centroidal axis of lining subtending angle of 50 to 100 representing linear 2D structure Beam model spring constants are derived from modulus of sub grade reaction Ks, which is calculated from:

KS = E / (1+ν)×R, where:

E - Young's Modulus of soil/rock

N - Poisson's Ratio of soil/rock mass

R - Radius of Tunnel (with R ≤ 7 m)

The spring constant of a bedding spring representing a certain area A of sub grade is derived as:

Cr = Ks x A

The tangential spring constants Kt is calculated from: $Kt = 0.5 * KS / (1 + \nu)$.

The bending stiffness of the structural element is equal to Ec*Ig. The moment of inertia Ig is based on the modulus of inertia of gross concrete section about centroidal axis, neglecting reinforcement.

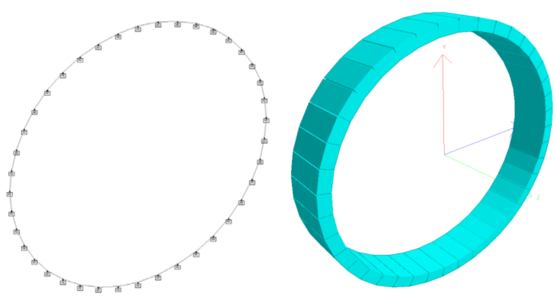

Fig. 1. Idealized model with spring supports and 3D rendered view

Output Diagrams of Staad file:

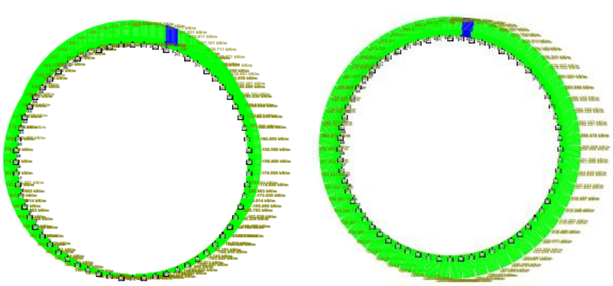

Fig. 2. View of over burden load and extreme water pressure on segment

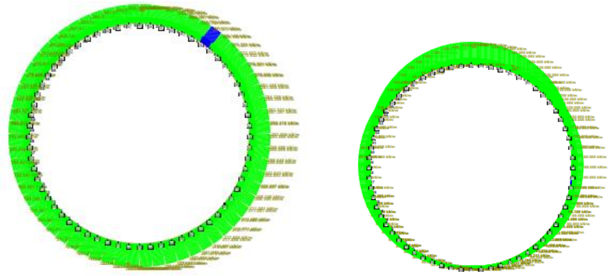

Fig. 3. View of max. water pressure and surcharge load (symmetrical) on segment

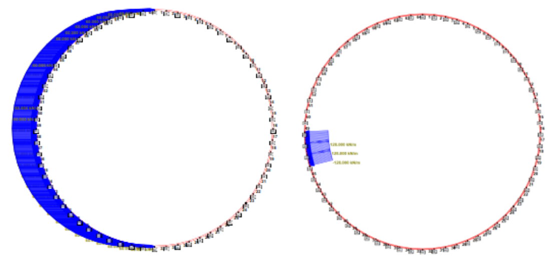

Fig. 4. View of surcharge load (asymmetrical) and derailment load on segment

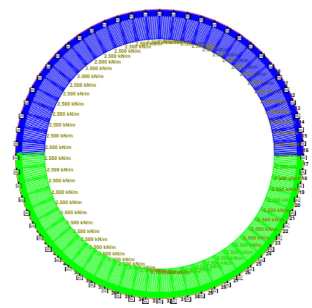

Fig. 5. View of air pressure on segment

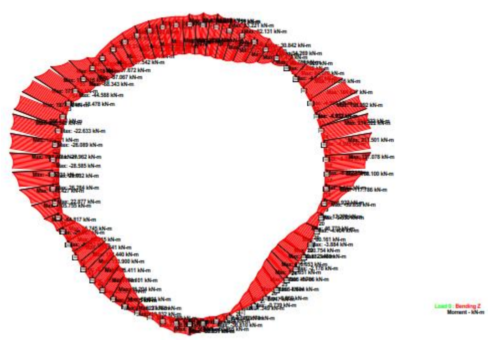

Fig. 6. Bending moment on segment

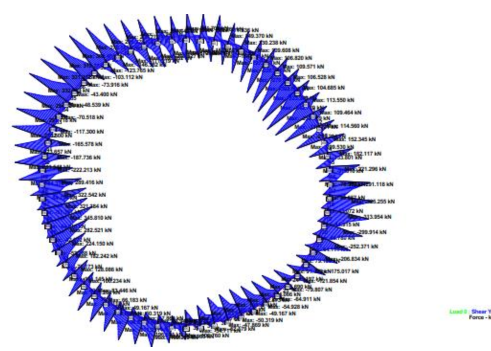

Fig. 7. Shear force on segment

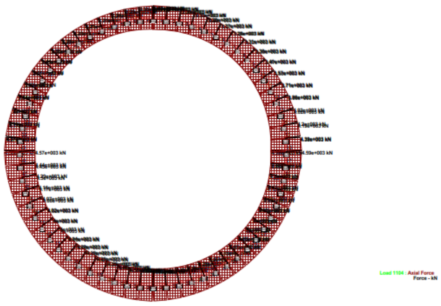

Fig. 8. Axial force on segment

B. By RS2 (RocScience2)

Assumptions considered while performing 2D analysis in RS2:

1. Plain strain condition is assumed; the geotechnical properties are considered assuming homogeneous, isotropic behavior of each layer.
2. The ground layers are modelled with the given properties, and the analyses are performed for drained condition.
3. Water table is assumed at surface.
4. Mohr-Coulomb failure criteria is considered; peak and residual value of shear strength parameters is defined.
5. External boundaries of model are assumed considering the size of tunnel, its cover from the surface and distance between two tubes, and theoretical influence zone. Boundary conditions are modelled as free top boundary (representing ground surface), fully fixed at bottom and vertical roller at the sides.
6. The segmental liner is simulated using structural monolithic elastic beam elements in 2-dimensional plane strain; main parameters defined are modulus of elasticity and moment of inertia. Effective moment of inertia is considered to take effect of joints in the precast segmental using Muir Wood's equation.

RS2 software used to simulate various ground layers and their lateral earth pressure coefficient, modeling the effect of twin tunnels and space between them and also the seismic condition or ordinary design and maximum design case.

Based on the understanding of ground conditions two cases are analyzed:

1. General Case – Having low soil cover and Basalt/ Breccia of grade II at the tunnel level.
2. Worst case – Thick soil cover and grade III Tuff around the at the tunnel level.

Surface loading (Surcharge)

General case = 50kN/m^2

Worst case = 120kN/m^2

Table 1
Four analyses (2x2) are performed using RS2 software

		General Condition	
		General (G)	Worst (W)
Surface Loading	General (G)	Case 1 (GG)	Case 3 (WG)
	Worst (W)	Case 2 (GW)	Case 4 (WW)

The FEM model used for case 1 and 3 are shown in figure 9 & 10 the modeling stages are,

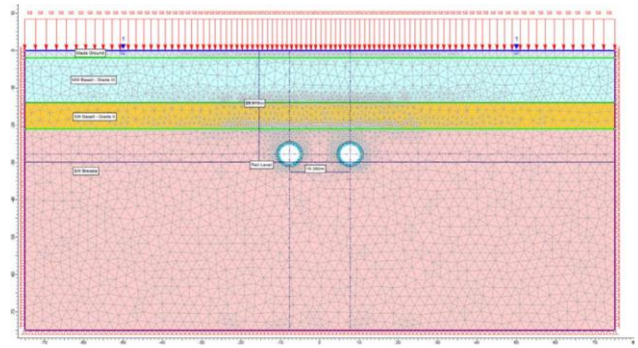

Fig. 9. (Case 1-GG) FEM model showing ground as per General case and Surface loading

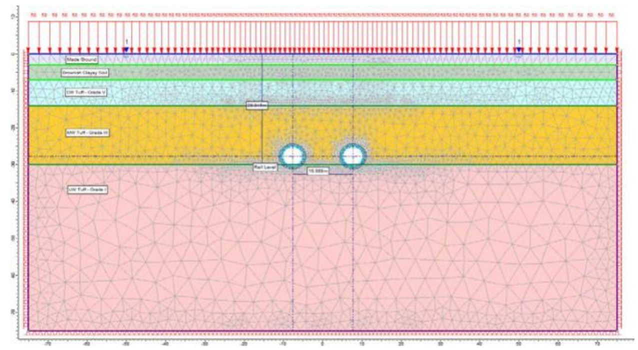

Fig. 10. (Case 3-WG) FEM model showing ground as per Worst case and Surface loading

Steps of modelling as per Construction sequence

Numerical analyses are performed mainly in two stages:

1. Initial stage which simulates the ground condition before construction, and
2. Tunnel excavation and segmental liner installation

Output Diagrams of RS2 file:

A. Maximum Overburden and General ground condition with Surcharge = 50kN/m^2

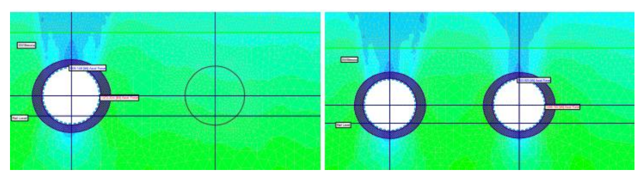

Fig. 11. Axial Force in liner at stage 2 & 3

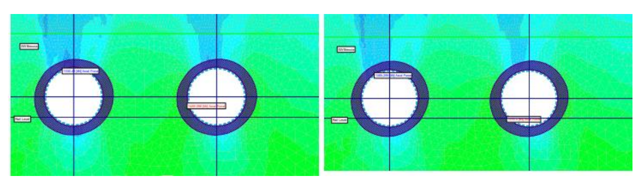

Fig. 12. Axial Force in liner at stage 4 & 5

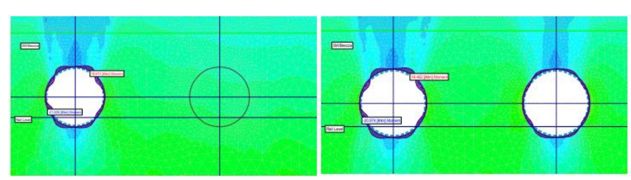

Fig. 13. Bending Moment in liner at stage 2 & 3

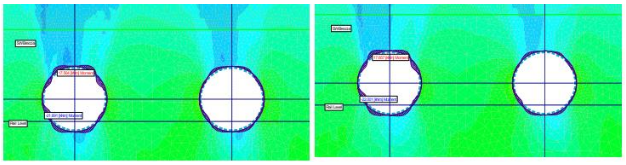

Fig. 14. Bending Moment in liner at stage 4 & 5

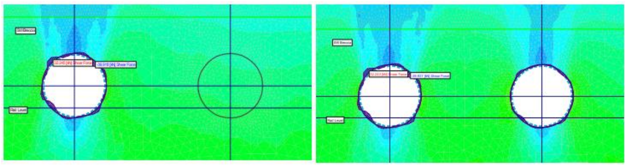

Fig. 15. Shear Force in liner at stage 2 & 3

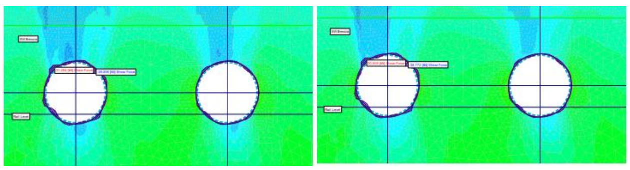

Fig. 16. Shear Force in liner at stage 4 & 5

B. Maximum Overburden and General ground condition with Surcharge = 120kN/m^2

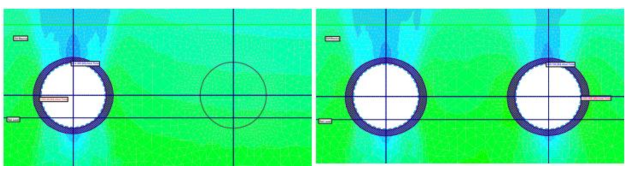

Fig. 17. Axial Force in liner at stage 2 & 3

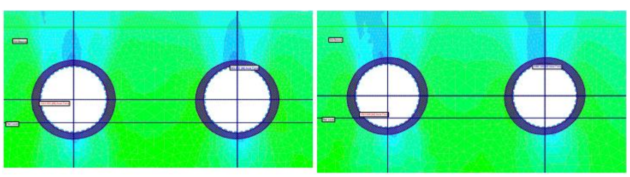

Fig. 18. Axial Force in liner at stage 4 & 5

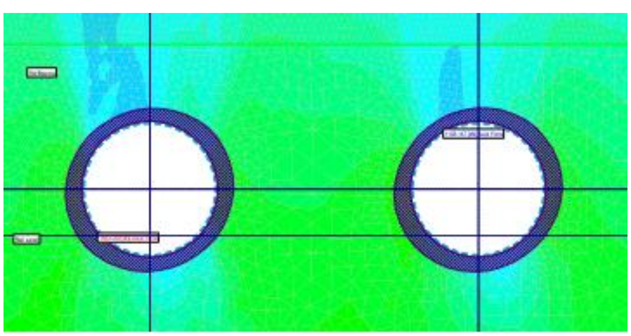

Fig. 19. Axial Force in liner at stage 6

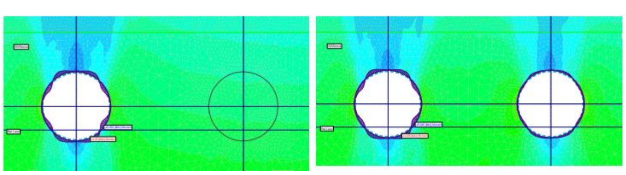

Fig. 20. Bending Moment in liner at stage 2 & 3

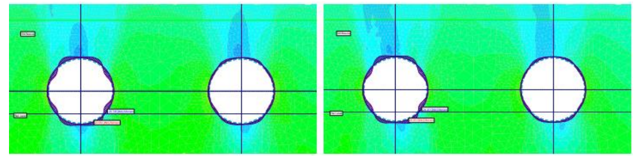

Fig. 21. Bending Moment in liner at stage 4 & 5

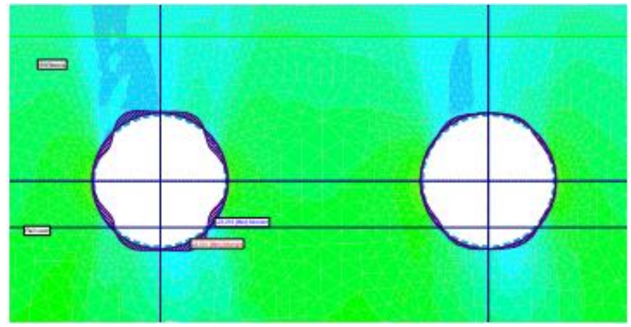

Fig. 22. Bending Moment in liner at stage 6

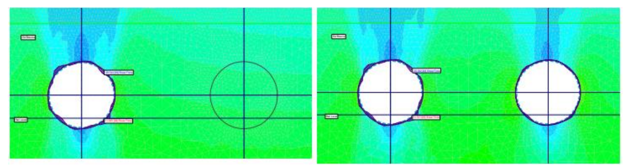

Fig. 23. Shear Force in liner at stage 2 & 3

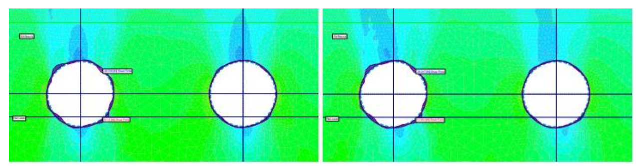

Fig. 24. Shear Force in liner at stage 4 & 5

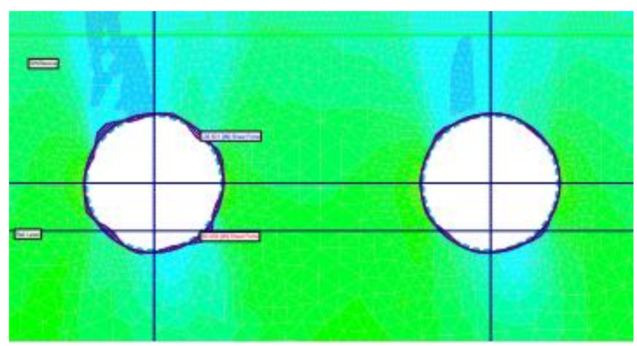

Fig. 24. Shear Force in liner at stage 6

C. Maximum overburden and worst ground condition with surcharge = 50kN/m^2

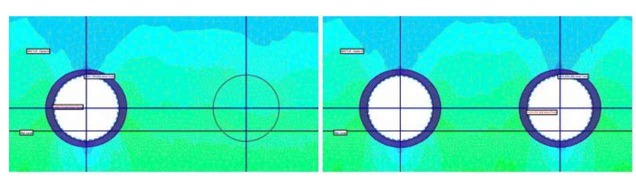

Fig. 25. Axial Force in liner at stage 2 & 3

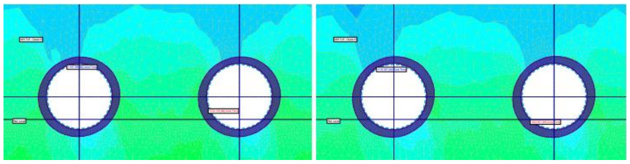

Fig. 26. Axial Force in liner at stage 4 & 5

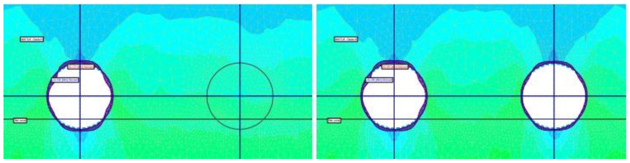

Fig. 27. Bending Moment in liner at stage 2 & 3

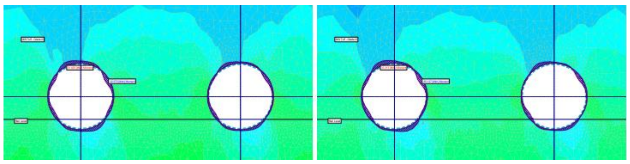

Fig. 28. Bending Moment in liner at stage 4 & 5

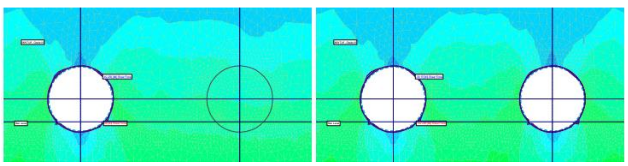

Fig. 29. Shear Force in liner at stage 2 & 3

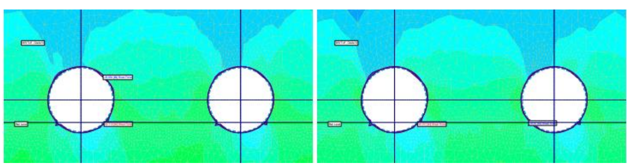

Fig. 30. Shear Force in liner at stage 4 & 5

D. Maximum overburden and worst ground condition with surcharge = 120kN/m^2

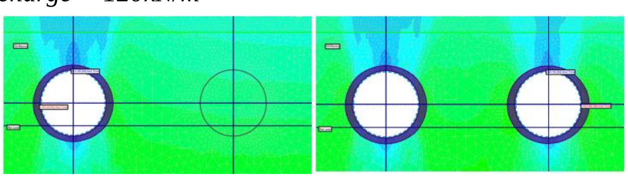

Fig. 31. Axial Force in liner at stage 2 & 3

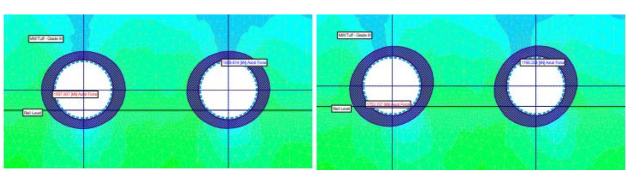

Fig. 32. Axial Force in liner at stage 4 & 5

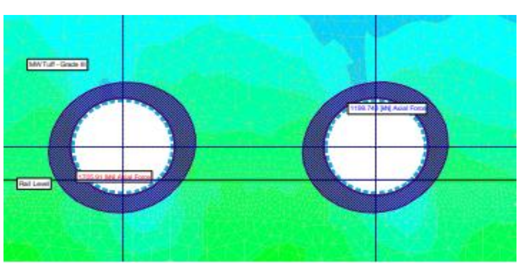

Fig. 33. Axial Force in liner at stage 6

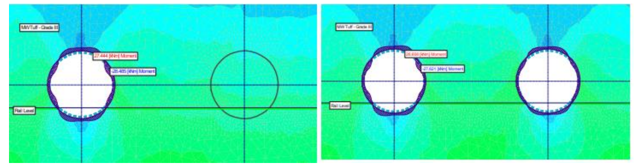

Fig. 34. Bending Moment in liner at stage 2 & 3

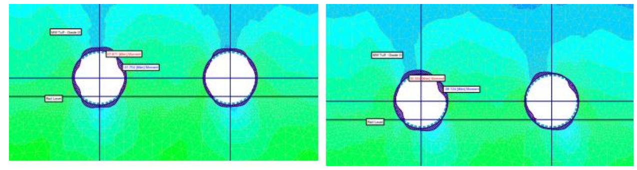

Fig. 35. Bending Moment Force in liner at stage 4 & 5

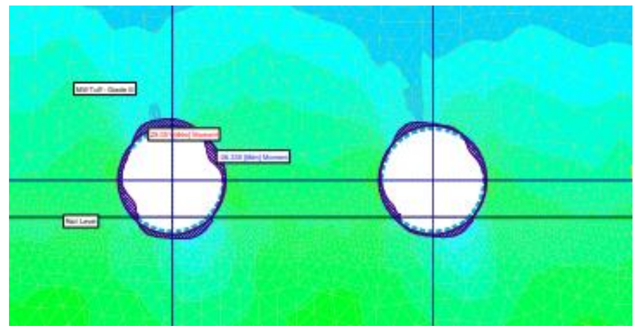

Fig. 36. Bending Moment in liner at stage 6

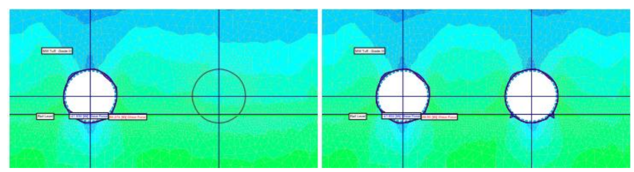

Fig. 37. Shear Force in liner at stage 2 & 3

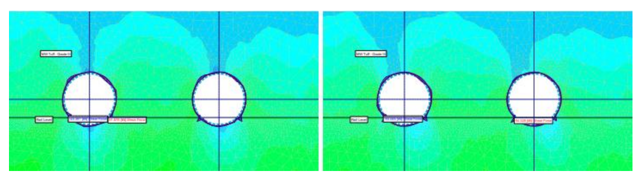

Fig. 38. Shear Force in liner at stage 4 & 5

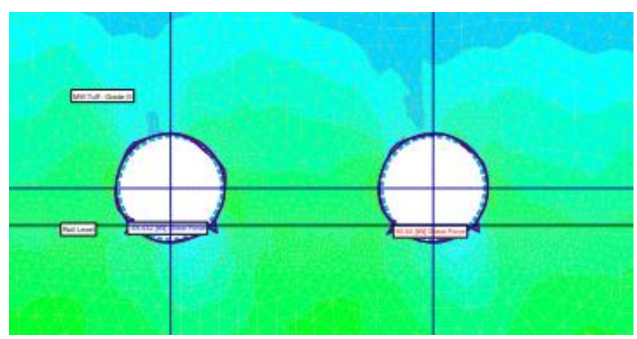

Fig. 39. Shear Force in liner at stage 6

3. Conclusion

Two method of FEM analysis (STAAD Pro and RocScience2) are used to study the behaviour of soil/rock mass surrounding the tunnels. The FEM method made the study of soil/rock masses behaviour much easier and simplified the design of segment for the bored tunnel. Different forces are applied in the model and with the help of possible load combinations the segment is designed for normal and worse load cases. The study of surrounding soil/rock masses the settlement and deformation in the existing adjacent building or any other structure can be anticipated in well advance and which will help the designer to provide additional supports at that particular location to avoid excess settlement.

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