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Static Analysis of Tunnels in Urban Areas for Metro Construction

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***Abstract*— Rapidly developing urban cities like Chennai, Bangalore, Kolkata, etc. are becoming densely populated day by day and it may induce heavy traffic all over place. Out of many options for alternate means of transportation, utilizing the underground space for metro tunnel proves to be more effective. The aim of this project is to analyze the stability of underground metro tunnel in Bangalore (East-West Zone) subjected to various static loads. The static loads may arise due to self-weight of the soil around the tunnel, hydrostatic pressure and live load due to traffic movement on the ground surface. ANSYS software used here is a finite element package which numerically simulates the effect of insitu stresses on the tunnel face. Analysis is done for linearly elastic geometry under isotropic conditions and validated with Kirsch solution. Similarly, Bray's solution is adopted for validation of non-linear analysis. This validation procedure helps us to implement it on our practical field problem under anisotropy with various parameters. Thus, this project brings out the comparison of elastic and elasto-plastic model for both 2D and 3D simulation with the help of suitable graphs.**

Keywords*— *ANSYS; Kirsch; Bray; underground metro; yield criteria;

I. INTRODUCTION

Nowadays, due to increased population in urban areas and lack of space in busy central junctions, the constructions of infrastructure are mostly concentrated on the underground space. Static analysis is mainly done to know how the soil will react by its self weight and also for other static loads. The water table is the main criterion which is at a distance of 5m below the ground surface. So, the hydrostatic pressure should also be included in analysis. If there is any heavy loaded vehicle passing through that area, its effect will be on the tunnel face. Static analysis is mainly done to give any remedial measures while construction, when the soil will not withstand the load and to provide temporary support in the areas till lining is done. Before constructing the tunnel, suitable size of lining can be selected and to know how the soil will react before and after lining. Static analysis will also ensure that the structure will withstand steady-state loading conditions.

II. LITERATURE STUDY

T G Sitharam et al (2008) develops the soil profile data along various parts of Bangalore. This paper deals with the geotechnical and geophysical site characterization in Bangalore, to develop microzonation maps by using MASW technology.

P Anbazhagan et al (2008) describes the properties of the soil layer with various depths using MASW component. MASW is used to study the behavior of soil and embankments. This paper describes the methodology of Multichannel Analysis of Surface Waves to obtain the soil properties such as density, Poisson's ratio and young's modulus for different layers of soil situated in and around Bangalore. Rayleigh surface waves generated in this are captured by using SURFSEIS software package to arrive at the soil properties for the location.

TABLE I. SOIL PROPERTIES IN BANGALORE

Layer depth	Density (Kg/m^3)	Young's modulus (N/m^2)	Poisson ratio	Cohesion (Kpa)	Friction angle (deg)
0- 3.2m Clayey sand	2000	3.25 x10^8	0.3	5	35
3.2 - 8m Clayey sand + Gravel	1900	1.11 x10^8	0.3	20	30
8-28.5m Silty sand + Gravel	2000	4.08 x10^8	0.3	15	35
> 28.5m Hard rock	2000	5.23 x10^8	0.2	4000	42

M. Sekhar et al (2009) explains in detail about the topography, groundwater level, depth of hard rock and the tunnel alignment along the east-west section of the metro rail project. It deals about the impact of groundwater system for proposed metro tunnel. From the studies, it has been concluded that the ground water table will be at a depth of 5m approximately which will have a greater influence on the stresses acting on the underground tunnel.

B.S.Sudhir Chandra (BMRC) explains the salient features of twin tunnel construction along the east – west corridor for

18.1kms and north-south corridor for 24.2kms. In a total length of 42.3kms, the elevated section is 33.48kms and underground section is 8.82kms. The dimension of the tunnel's inner diameter is 5.6 m and boring diameter is 6.44 m with a reinforced concrete lining thickness of 280mm. The depth of the tunnel from the ground level is 15 to 18.3 m approximately and centre to centre distance of the twin tunnel is 15.04 m. Tunnelling is done by using slurry TBMs and earth pressure balanced TBM method and cut and cover method is used for stations. Two drilling machines namely Helen and Margarita are used for tunnelling this section which has a drilling capacity of 11m per day.

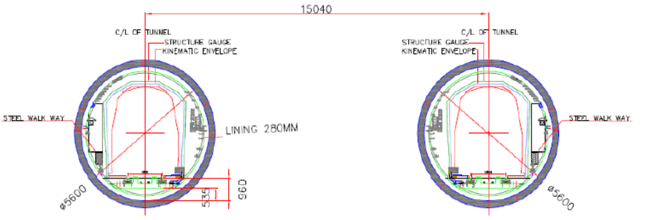


Fig. 1. Bangalore underground tunnel c/s

III. VALIDATION OF ANSYS

The validation of ANSYS for elastic solution using a solved example problem is carried out and checked for approximation of results with theory proposed by Kirsch. The material is homogenous throughout and has linear mode of failure. A rectangular plate with dimension of 200x100mm is taken and has a hole of radius 10mm at the center. Its young's modulus and Poisson's ratio values are 210,000N/mm^2 and 0.3 respectively and its density is 1900kg/m^3. Kirsch equations are used to solve the problem and identify the stresses and the results are tabulated below. The same parameters are adopted in ANSYS for the model generation and quad-free meshing with smart size = 2 are used. Roller support is provided on left and bottom face and the other 2 sides are subjected to loads. . A point located at polar coordinates r,θ near an opening with radius 'a' has stresses

Radial stress,

$$\sigma_r =0.5(\sigma_v+ \sigma_h)(1-a^2/r^2)+0.5(\sigma_v- \sigma_h)(1+3a^4/r^4-4a^2/r^2)\cos 2\theta \quad (1)$$

Tangential stress,

$$\sigma_\theta =0.5(\sigma_v+\sigma_h)(1+a^2/r^2)-0.5(\sigma_v- \sigma_h)(1+3a^4/r^4)\cos 2\theta \quad (2)$$

Shear stress,

$$\tau_{C\theta} =0.5(\sigma_v-\sigma_h)(1-3a^4/r^4+2a^2/r^2)\sin 2\theta \quad (3)$$

The graph obtained from ANSYS and Kirsch solutions are plotted in MS Excel and checked for accuracy. The graph obtained from the result are shown below

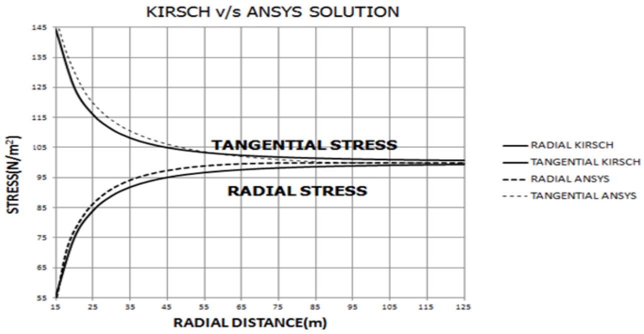


Fig. 2. Comparison of Kirsch vs. ANSYS graph from results

By using Bray's solution, ANSYS is validated for elasto-plastic solution. The same example problem is taken and its results are compared with ANSYS results for accuracy. All the elastic properties are same as specified while the angle of internal friction is 30^0, cohesion is 3.45MPa and dilatancy angle is 0^0. If plastic zone radius around an opening is of radius 'r$_o$ then, plastic zone stresses are given by

Radial stress, $$\sigma_r = m_3 . r^{(m_1 - m_2)} \quad (1)$$

Tangential stress, $$\sigma_\theta = m_4 . r^{(m_1 - m_2)} \quad (2)$$

Where,

$$m_1 = 2 \sin\Phi / (1-\sin\Phi)$$
$$m_2 = C \cos\Phi / \sin\Phi$$
$$m_3 = m_2 / r_0^{m_1}$$
$$m_4 = m_3 (1+\sin\Phi) / (1-\sin\Phi)$$

The plastic zone equation is given below:

$$r_p = r_0 [(P+C.\cot\Phi)(1-\sin\Phi) / (C.\cot\Phi)]^{((1-\sin\Phi) / 2 \sin\Phi)} \quad (3)$$

Similarly, in ANSYS, Drucker-Prager model is used. The same parameters along with the above given parameters are adopted with quad-free meshing of smart size = 2 along with the same boundary conditions as specified above. The graph obtained from the result is shown below.

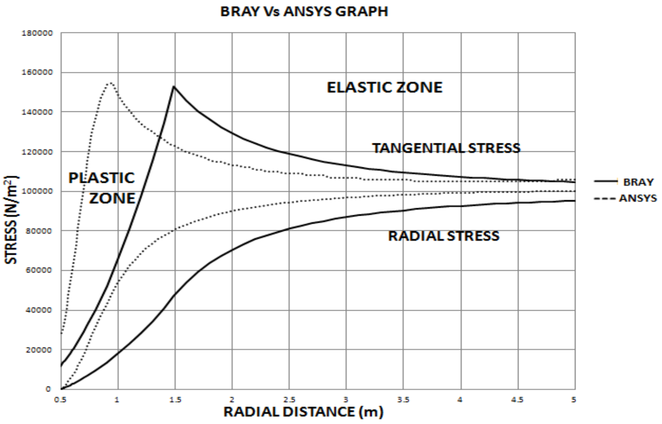


Fig. 3. Comparison of Bray vs. ANSYS graph from results.

The optimum dimension is taken as 3times the diameter on either sides of the model and the meshing adopted is quad-free type for further calculations.

IV. STATIC ANALYSIS OF BANGLORE METRO TUNNEL

4.1 Elastic analysis

Homogeneity and isotropy assumptions are not applicable in field problem of Bangalore metro. It consists of 4 different layers of soil obtained from literature and each layer is of varied thickness and contains different properties. The Bangalore underground metro tunnel lies in the third layer which is subjected to hydrostatic pressure apart from gravity. Linear analysis means that the material will react like elastic as there is no yield point. Numerical FEM using ANSYS is used to simulate the linear elastic model by using the constants like density of soil, Poisson’s ratio and young’s modulus. **Main Menu> Preprocessor> Material Props> Material Models> Structural> linear> elastic** is used to define the type of elastic model to be used in ANSYS. The soil modeling meshing and boundary conditions can be adopted from the previous chapters. **Main Menu> Solution> Define Loads> Apply> Structural> Inertia> Gravity> on global** is used to specify the gravity load acting on negative Y-direction with a value of **9.81m/s^2**. To apply live load **Main Menu> Solution> Define Loads> Apply> Structural> pressure>on line** command is used and a value of **6kN/m^2** is specified. Hydrostatic pressures acts due to the presence of water table below 5m from the ground level. Thus, the second, third and fourth layers are subjected to hydrostatic pressures. Its value is also given in the form of pressure acting on the whole layer uniformly. A value of **29.43KN/m^3** is applied for the second layer and **166.67KN/m^3** for the third layer. As fourth layer lies below the tunnel, its hydrostatic pressure may not affect the tunnel. The thickness of concrete lining is 280mm. It is made of reinforced concrete with a young’s modulus of 3e10N/m2 and a Poisson ratio of 0.2. The lining is provided simultaneously after boring some portion of the tunnel in order to reduce the stresses and results in tunnel stability. The results for single and twin tunnels with and without lining are tabulated below along with their images.

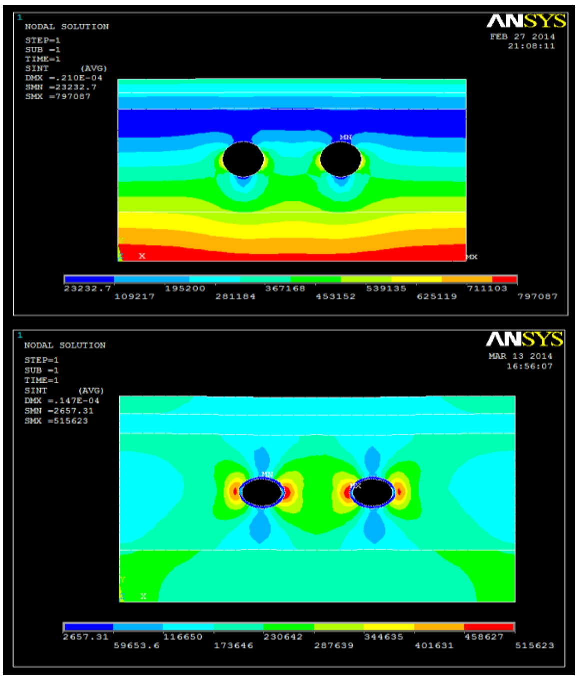


Fig. 4. Stress intensity image for without and with lining.

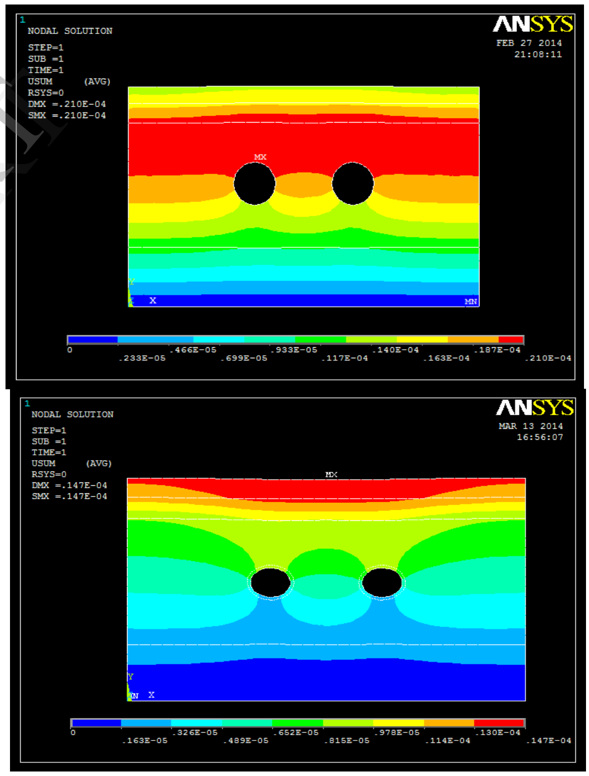


Fig. 5. Displacement image for without and with lining.

TABLE II. RESULTS FOR 2D TWIN TUNNEL

Results	Gravity	Gravity + Hydrostatic	Gravity + Hydrostatic + Live load
Without lining			
Max. Displacement (m)	$0.115X10^{-5}$	$0.206X10^{-4}$	$0.210X10^{-4}$
Max. Radial stress (N/m^2)	501.642	161713	163830
Max. Tangential stress (N/m^2)	457.221	614239	631491
Max. Stress intensity (N/m^2)	28021	780146	797087
With lining			
Max. Displacement (m)	$0.115X10^{-5}$	$0.143X10^{-4}$	$0.147X10^{-4}$
Max. Radial stress (N/m^2)	324.772	114526	118975
Max. Tangential stress (N/m^2)	418.384	509252	515623
Max. Stress intensity (N/m^2)	28016.3	509252	515623

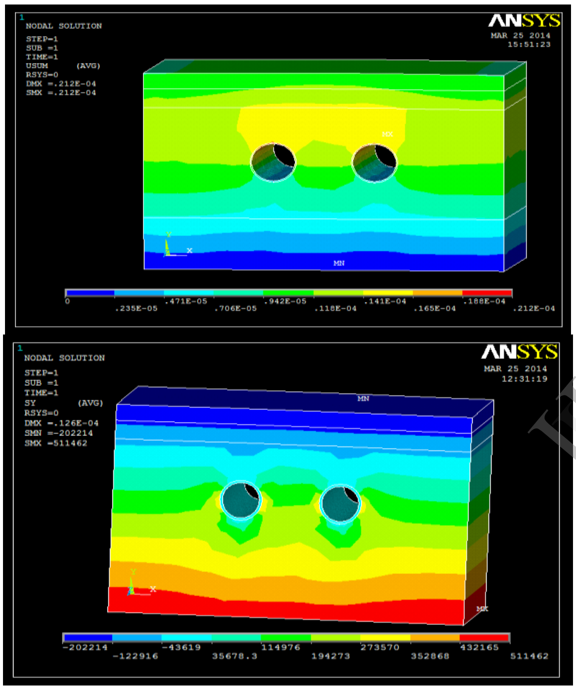


Fig. 6. Displacement image for without and with lining.

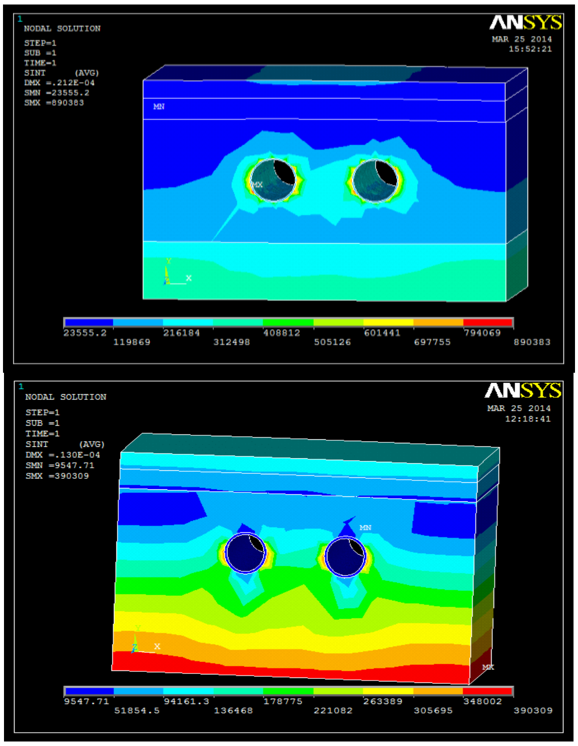


Fig. 7. Stress intensity image for without and with lining.

TABLE III. RESULTS FOR 3D TWIN TUNNEL

Results	Gravity	Gravity + Hydrostatic	Gravity + Hydrostatic + Live load
Without lining			
Max. Displacement (m)	$0.71X10^{-6}$	$0.208X10^{-4}$	$0.212X10^{-4}$
Max. Radial stress (N/m^2)	20457.9	196481	199060
Max. Tangential stress (N/m^2)	9792	544222	560956
Max. Stress intensity (N/m^2)	28021	780146	797087
With lining			
Max. Displacement (m)	$0.680X10^{-6}$	$0.126X10^{-4}$	$0.130X10^{-4}$
Max. Radial stress (N/m^2)	18794.8	140827	143633
Max. Tangential stress (N/m^2)	9027.38	511462	517828
Max. Stress intensity (N/m^2)	30256.8	385477	390309

4.2 Elasto-plastic analysis

To solve the elasto-plastic model in ANSYS, Drucker-Prager model is used. This model is the most appropriate among all nonlinear models which are used to get accurate results. In this model we have to give both elastic and plastic properties for generating the model. For 2D analysis, PLANE42 element is used and for 3D analysis, SOLID65 element type is used as it is applicable to use in Drucker-Prager model as per ANSYS database. As seen in previous chapters, plastic model implements constants like cohesion value, angle of internal friction and the dilatancy angle. The dilatancy angle should be specified a least value of 10. PLANE42 can be used either as a plane element or as an axisymmetric element. This element is defined by four nodes having two degrees of freedom at each node. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. Similarly, SOLID65 is capable of cracking in tension and crushing in compression. It can be used to model concrete lining or model soil apart from its reinforcement behavior. Each of the 4 layers have different set of elastic and plastic properties to be specified separately using different material number. The static loads and boundary conditions are specified as in case of elastic analysis and solved to get the results. The comparison of results for single and twin tunnel with lining and without lining are tabulated below with suitable images.

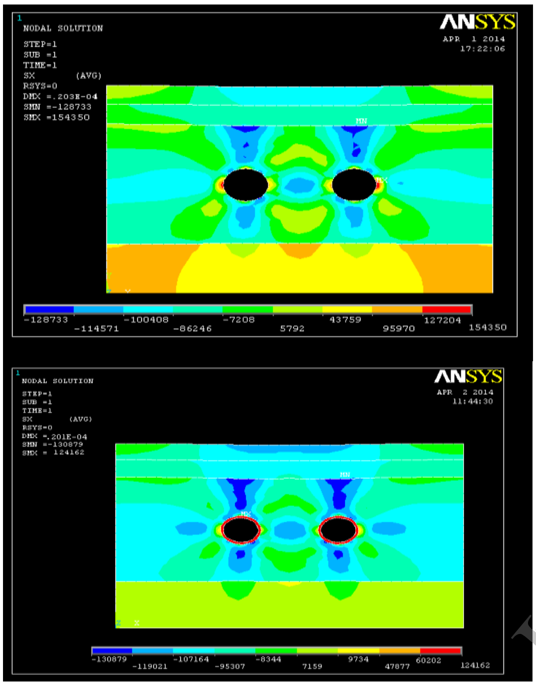


Fig. 8. Radial stress image for without and with lining.

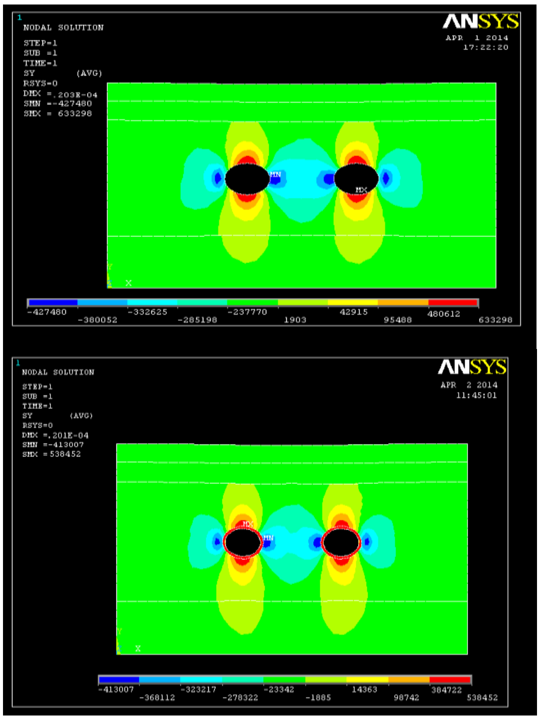


Fig. 9. Tangential stress image for without and with lining.

TABLE IV. RESULTS FOR 2D TWIN TUNNEL

Results	Gravity	Gravity + Hydrostatic	Gravity + Hydrostatic + Live load
Without lining			
Max. Displacement (m)	$0.970X10^{-6}$	$0.197X10^{-4}$	$0.203X10^{-4}$
Max. Radial stress (N/m^2)	552	149785	154350
Max. Tangential stress (N/m^2)	474.362	614747	633298
Max. Stress intensity (N/m^2)	25637	368171	377214
With lining			
Max. Displacement (m)	$0.970X10^{-6}$	$0.197X10^{-4}$	$0.203X10^{-4}$
Max. Radial stress (N/m^2)	552	149785	154350
Max. Tangential stress (N/m^2)	474.362	614747	633298
Max. Stress intensity (N/m^2)	25637	368171	377214

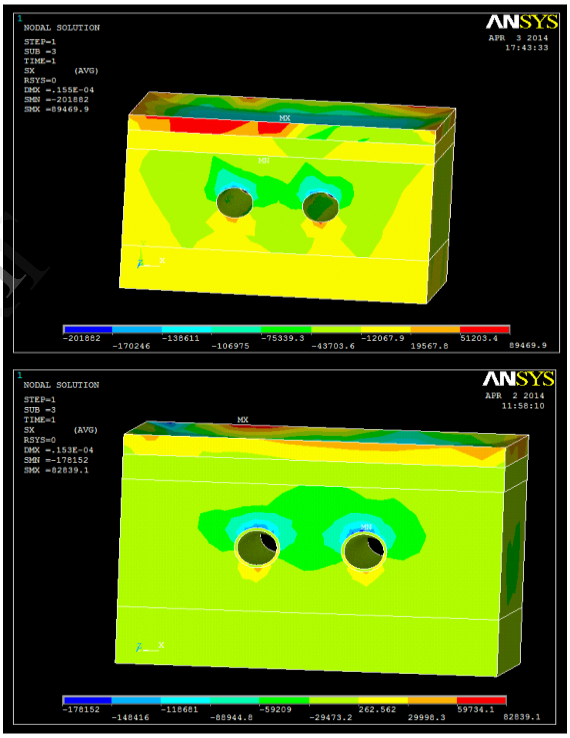
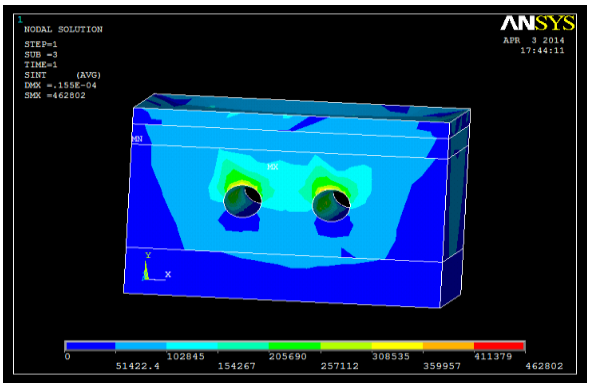


Fig. 10. Radial stress image for without and with lining.



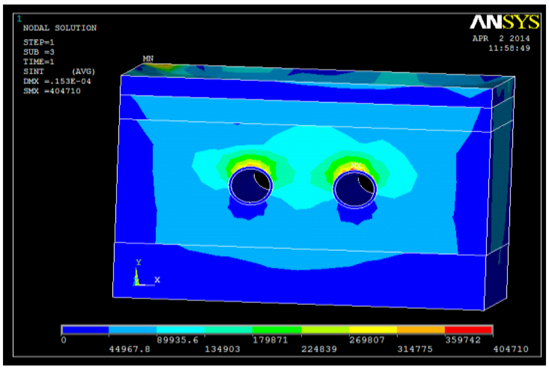


Fig. 11. Stress intensity image for without and with lining.

TABLE V. RESULTS FOR 3D TWIN TUNNEL

Results	Gravity	Gravity + Hydrostatic	Gravity + Hydrostatic + Live load
Without lining			
Max. Displacement (m)	$0.671X10^{-6}$	$0.150X10^{-4}$	$0.155X10^{-4}$
Max. Radial stress (N/m^2)	3812.86	87888.9	89469.9
Max. Tangential stress (N/m^2)	3699.42	87293.8	89069
Max. Stress intensity (N/m^2)	16493	448020	462802
With lining			
Max. Displacement (m)	$0.671X10^{-6}$	$0.150X10^{-4}$	$0.155X10^{-4}$
Max. Radial stress (N/m^2)	3812.86	87888.9	89469.9
Max. Tangential stress (N/m^2)	3699.42	87293.8	89069
Max. Stress intensity (N/m^2)	16493	448020	462802

V. RESULTS AND DISCUSSION

The respective graphs for Kirsch and Bray solution calculated using ANSYS is shown below. The presence of yield point on Bray's graph is clearly depicted. As this model consists of various layers of soil with different set of properties, it accounts for anisometry and hence the radial and tangential stress lines in Kirsch solution graph does not coincide at a point.

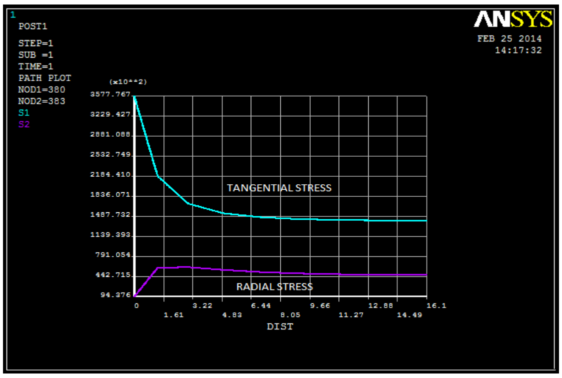


Fig. 12. Kirsch solution graph for Bangalore Metro Tunnel

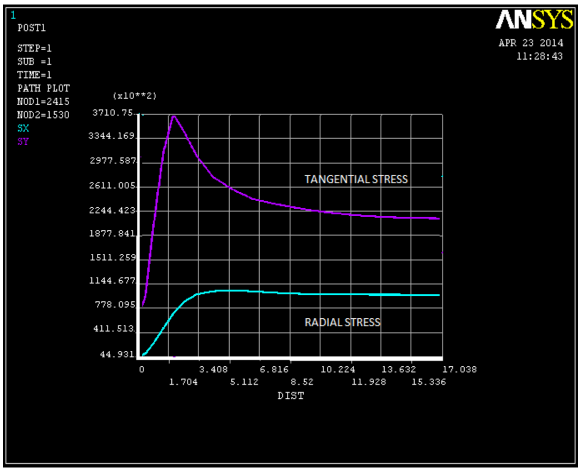


Fig. 13. Bray solution graph for Bangalore Metro Tunnel

Soil around the tunnel is weak in Bangalore underground metro tunnel and the water table is at a higher level. Therefore, the influence of load due to hydrostatic pressure will be a major issue to be taken care of. Elasto-plastic results are more accurate when compared with elastic results as they include the concept of yielding. Tunnel support system reduces the overall settlement caused due to various in-situ stresses and traffic loads acting on the underground structure. Therefore, provision of suitable lining thickness for safety against static loads, live loads and uplift pressure can be modeled and checked using the ANSYS numerical simulation tool. The possibility of the software to simulate dynamic, electrical, thermal, magnetic problems makes it a powerful finite element software.

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