Study on Stress-Deformation Characteristics of Tunnel in Jointed rock

Vinutha. S[1] and Muttharam.M[2]

[1] Student, Anna University, CEG Campus Chennai.
[2] Professor, Anna University, CEG Campus, Chennai
saravinu2667@gmail.com

Abstract. Numerical modelling of the behaviour of jointed rock is quite tedious process as the discontinuities not only require special modelling consideration, but also require alternate treatments that depends upon the degree of problem. This study deals with the influence of joint parameters to analyse stress-deformation characteristics around the tunnel profile. For such study, the joint orientations and number of joint sets are varied in the rock mass in which tunnel excavation is being adopted. In the present study, joint dip angles (30°,60°,90°) and number of joint sets (1- 3 sets) are varied to ascertain stability in each case. The numerical study for such analysis is proposed to be carried through PLAXIS 3D. In these simulations after the full face tunnel excavation process, the behaviour of jointed rock mass without any tunnel support is analysed. In comparison with tunneling in intact rock mass, the difference in variation of maximum radial stress concentrations in JRM with three joint sets is found to be 68%. The influence of dip angle on the failure mechanism is also investigated. It is also observed that the Joint dip angle 60^0 in case of one joint set, has adverse effect around the periphery of tunnel irrespective of its shape. In addition to this, the strike of sliding plane of rock mass is necessary to be ascertained in accordance with the alignment of tunnel that varies as per the project specification. From the analysis, it is being evident that the tunnel alignment which is parallel to the strike of joints has detrimental effects on determining stress- deformations around the tunnel.

Keywords: *Joint Dip angles; Joint sets; Plastic points; Stress-deformation around tunnel without supports*

1 Introduction

Tunnels are underground artificial passages that are constructed to allow rapid transport facilities and also used for diverting water for power generation. During tunneling, deformability characteristics should be taken into account because deformability in rock means capacity of the rock to strain under applied loads or in response to unloading after excavation. The strain in rock are more concerned even when there is a little chance of rock failure because large displacements locally can impose stresses within the structures. When the plane of weakness are closely spaced in large number, it appropriately modify the properties of rock mass. Moreover, the location of joints and orientations affects the shape of tunnel adversely. It is common that complex geological conditions have a significant adverse impact on tunnel engineering. Particularly, jointed rock exhibits complex mechanical behaviour such as anisotropy, dilatancy which is generally associated with the existence of joints and its propagation (Madkour.H 2012). Moreover in tunnel construction, collapse is considered as dangerous geological disasters, which needs an urgent engineering problem to be solved. Thus, geological strata are considered to be highly influential in case of tunneling. Based on different purposes and nature of project, tunneling work in various stratigraphy has some adverse conditions. Hence, study on stress-deformation characteristics around tunnel in jointed rock is necessary to be well defined and discussed under the influence of joint parameters.

2 Study on presence of discontinuities

During Tunnel Excavation, one of the serious problem is the unexpected accidental failure of rock blocks, which are formed by intersection of tunnel surface and the discontinuities present on it. Hamed and Bujang et al, (2011), analysed the effect of discontinuities on stability of rock blocks in tunnel which outlines the case study of 'Railway Tunnel in the eastern part of Iran' that has operated in sandstone with vertical bedding which is 250m length. This study has represented the results of an investigation that was carried out using important parameters such as discontinuities in rock block that explains instability in tunnel.

As per Jaeger and Cook et al, (1979), the discontinuities are structures such as bedding planes and joints with usually several sets in very different directions which separate the rock mass into discrete but interlock pieces. In this review, features like Rock Quality Designation (RQD), rock mass rating classification (RMR), stress and strain, and distributions of discontinuities in a sample tunnel were evaluated. RQD was calculated as more than 80 and RMR value has been calculated that designates the rock mass of tunnel as desirable.
Even though, significant parameters were suggested for the purpose of tunnelling, tunnel has been collapsed at 150 to 160m of its length. Fig 1 represents the collapsed tunnel with vertical bedding.

Fig 1 Tunnel with vertical bedding in sandstone rock mass (After Hamed, 2011)

While investigating the analysis of stresses and displacements, indicated around critical zone, it seems that because of lack of ground water table and good rock condition around collapse area, induced stresses after tunnelling caused deformation. Further on analysis, it is being evident that the "Stepped over Fractures" were recognised between the bedding. These are joints found to be on either side of the bedding contacts. Bedding contact strength controls the resulting intersection type of fracture. The rock blocks can have possibility to slide around the wall located near critical zone. In other words, it will be splitting out as wedge blocks. In addition to this, the evaluation of stability in tunnel roof displayed that toppling was created by intersection points of discontinuities in critical area. It is generalised that the fracture termination which often gives sliding and movement of blocks, is likely to occur at weak bedding contacts and it propagates straight through strong contacts and these fracture terminate more likely to occur under shallow burial depth condition in tunnelling process.

2.1 Numerical Simulation Models

Finite element analysis helps in modelling tunnel with many aspects of stability. Joint properties in layered and jointed rock mass is prominent in tunnel mechanics. Hence, Minggao Zhang et al, (2011) considered dip angles, joint distance and lateral pressure coefficient and outlined numerical study on tunnel mechanics in jointed rock mass with FEM analysis.

In the present study, jointed rock mass surrounding the area of Giaxiaba Tunnel in Chongqing city was considered. The tunnel media considered was full of joints in which 3 set models are adopted for stability condition. Surrounding rock was being divided into 8,306 elements and assumed as homogenous elastic –plastic Mohr coulomb criteria. They have projected one prominent joint set at 45^{o} with average spacing of 0.7m. The boundary model considered in which size of model is kept as 3 times the tunnel diameter.

At first, No Joint tunnel model is investigated where plastic zone is elliptical in shape. The plastic zone and total displacement are approximately symmetrical distribution because of the symmetry of model and initial stress.

In case of dip angle variation, 25^{o}, 45 ^{o}, 90 ^{o} are being chosen to be applied on the model. Graphical method to differentiate sliding and bending zones are showcased, by Goodman (1989), as shown in Figure 2. This method was found to be easy, but lateral pressure coefficients were not considered in this case.

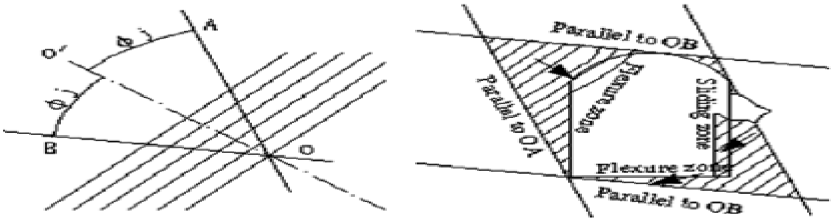


Fig 2 Graphical method to distinguish the sliding zones and bending zones (After Minggao Zhang et al, 2011)

In case of Joint distance, to investigate the tunnel mechanics under different loading conditions, three joints distance of 0.35, 0.75and 1.5m are being applied on the model, respectively. For joints distance of 0.35m, the plastic zones and total displacement are obvious in nature which exhibited the anisotropic behavior and for the 1.5m joint distance, it is worth noting that the plastic zone and total displacement are similar to no joints model. They made variations in Lateral pressure coefficients also and studied plastic zone and displacements. The dip angles, distances of joints have significant effect and forms a vital role in tunnelling process. It has been evident that with increase in joint distance, tunnel model behaved as no joint condition and if the Joint distance decreased, it showed anisotropy behaviour.

3 Numerical Analysis

To investigate the effect of joint induced stress-deformation patterns, numerical implementation using constitutive model has been simulated to model a tunnel excavated from rock mass containing one joint set, two joint set and three joint set.

The parameters of joint model, intact rock mass properties and other inputs are summarised in Table 1 which are considered from the paper, “Parameters identification of tunnel jointed surrounding rock based on Gaussian process regression optimized by Difference Evolution Algorithm” by Annan Jiang et al(2021).

Table 1 Model Parameters considered for analysis

PARAMETERS	VALUES	UNITS
E	1.2×10^6	kN/m²
ν	0.2	-
C_j	75	kN/m²
φ_j	25	^{0}
G	5×10^5	kN/m²
ψ	22.5	^{0}
σ_t	40	kN/m²
C	1000	kN/m²
φ	30	^{0}

Rock type – Every rock has its own level of anisotropic behaviour based on the lithified strata. Most prominent joints in weathered quartzite are taken for the current study in which advancement of tunnel is made.

Size of Tunnel- Length of tunnel = 50m, Elliptical shape (width= 10m, height= 8m)

The Variation of parameters considered for the analysis are shown in Table 2

Table 2–Variation of Parameters for analysis

<table>
<tr><td>MODEL USED</td><td colspan="4">JOINTED ROCK MODEL (JR)</td></tr>
<tr><td rowspan="2">JOINT PARAMETERS</td><td>JOINT SETS (n)</td><td>One joint set</td><td>Two joint set</td><td>Three joint set</td></tr>
<tr><td>JOINT DIP ANGLES (α)</td><td>30^0
60^0
90^0</td><td>30^0 , 60^0
30^0 , 90^0
60^0 , 90^0</td><td>30^0 , 60^0,90^0</td></tr>
<tr><td>SHAPE OF TUNNEL</td><td colspan="4">ELLIPTICAL SHAPE</td></tr>
</table>

3.1 Model size and Mesh Convergence Analysis

In Finite element modelling, the model size is considered to be an important factor which is to be ensured that the size of the model chosen should not influence to change the in-situ stress at the outer boundary. In addition to this, Jointed Rock (JR) model is continuum and the effects of discontinuities are smeared out. Hence the model size has to be increased until outer in-situ stresses are unchanged during the excavation process. For Jointed rock model, the model size should be adopted, at least 5D on either side of the tunnel (where D is the size of tunnel). Thus, the model size adopted in the analysis is 14D x 14D.However, the trial analysis for 11D x11D and 12.5D x 12.5D was made. The stress contour for the model size 14Dx14D is shown in Fig 3 in which stress contours are elevated around excavation and the outer in-situ stress was effectively found to be unchanged with this model size.

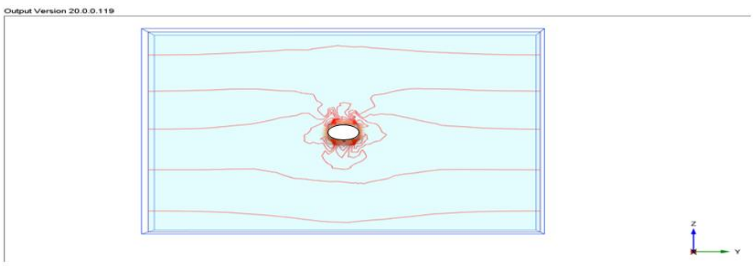
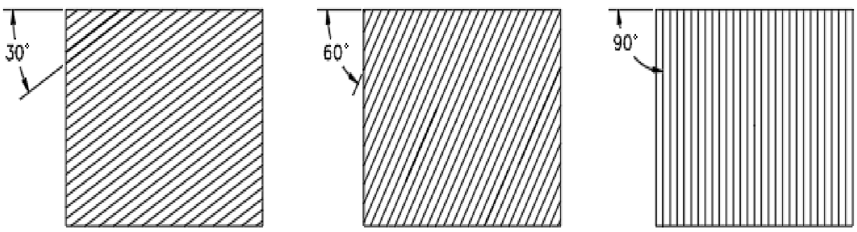
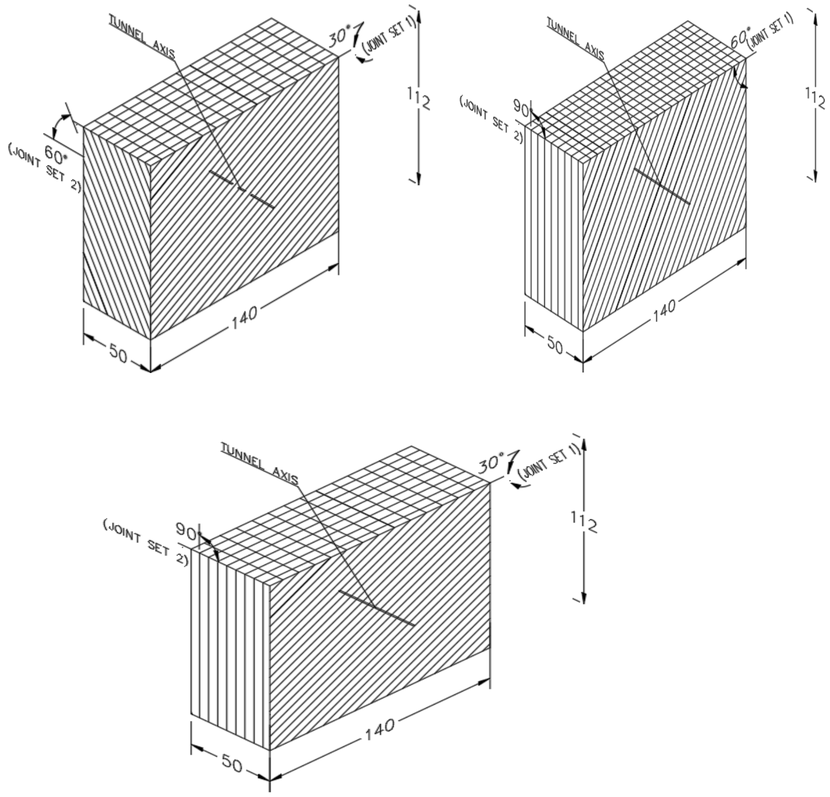


Fig 3 Contour of Stress for the model size 14Dx14D

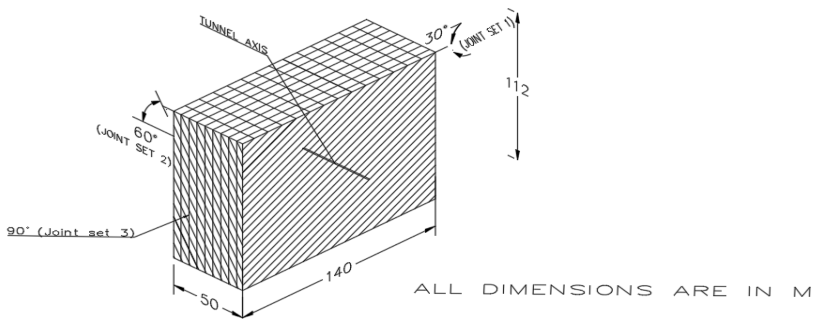
The Mesh convergence analysis is necessary to be performed for computing efficiency with accuracy. In Plaxis 3D, the relative element size is being adopted based on the model size. Coarser mesh having an average element size of 13.96m, was chosen from the convergence analysis. For the optimum mesh chosen, the local refinement can be made by varying coarseness factor around the tunnel excavation. The jointed rock mass with various dip angles and the joint sets considered are shown in Fig 4.



(a)



(b)



(c)

Fig 4 Jointed rock mass with various dip angles and the joint sets (a) One Joint set (b)Two Joint set (c) Three joint set

4 Results and Discussions

The variation of joint dip angles and the joint sets, across the elliptical cross section of tunnel are analysed and the results are discussed with various interpretations. The tunnel was located at 50m from EGL and the overlying strata from the ground level is converted into equivalent loads. The size of the model as per the analyses are 140 x 112 x 50m. The insitu stress ratio (k_0) for the rock mass is taken as 1. The elliptical tunnel of width 10m and height 8m is advanced through the jointed rock which is favorable with dip, is simulated in Plaxis 3D. The generated mesh is as shown in Fig 5.

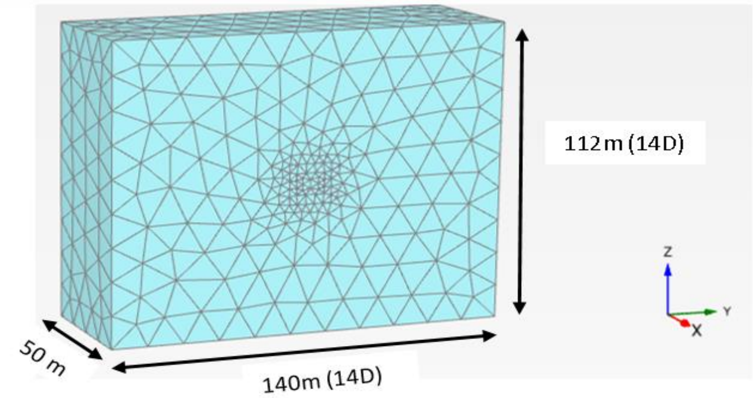


Fig 5 Generated mesh

4.1 Influence of One joint set

The deformation values around tunnel for different combinations of joint parameters are plotted in graphical form to study its influence. Graph is plotted between the joint dip angles and maximum displacements around tunnel as shown in Fig 6. From the graph, it is observed that one joint set with dip angle 60° has maximum displacement of 34.44 cm at the tunnel roof. With dip angle 30°, 90° the maximum displacement is found to be 23.27cm and 20.61cm respectively. It is evident that the joint dip angle of 60° shows higher deformation value around the tunnel profile, in case of one joint set which is observed as critical criteria.

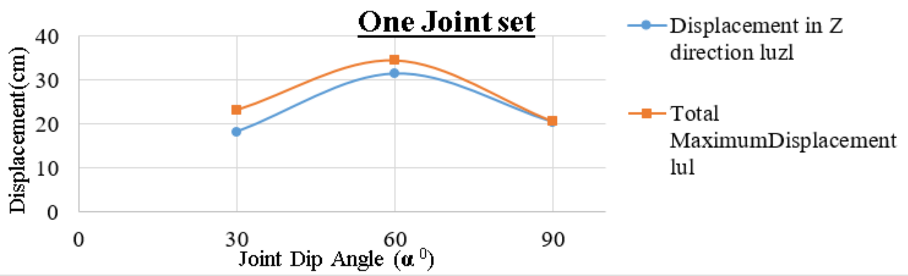


Fig 6 Displacement Vs Joint dip angles around Elliptical tunnel

JRM in which tunnel is advanced, is being compared with considering the rock mass to be intact. Graph is plotted between radial stress at crown and invert with r/b, in which r is the distance of point from the centre of tunnel and b is the width of elliptical tunnel (ie, major axis) as in Figure 7

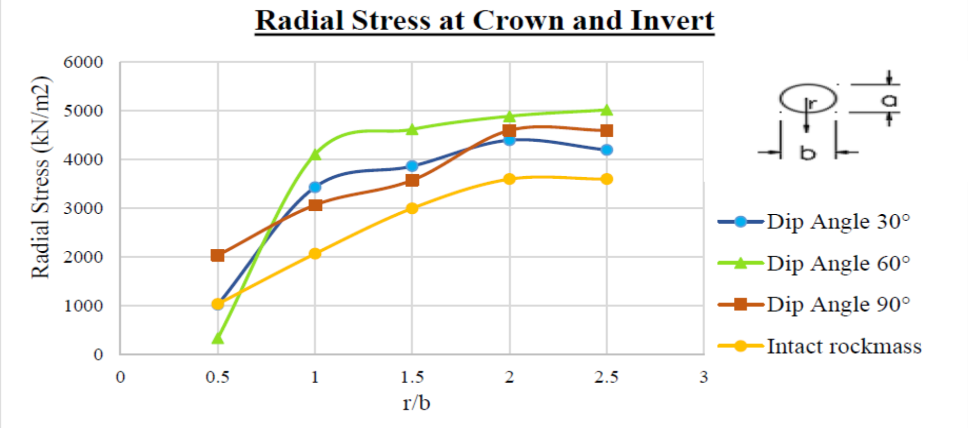


Fig 7 Radial Stresses around Elliptical boundary at roof and Invert

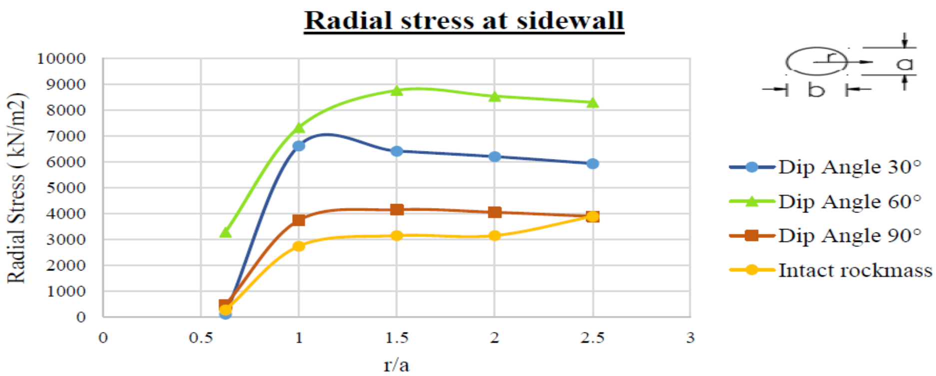


Fig 8 Radial Stresses around Elliptical boundary at Sidewall

Radial stress at sidewall and r/a is plotted as in Fig 8 in which r is the distance of point from the centre of tunnel and a is the height of elliptical tunnel (ie, minor axis). The variation of radial stresses are minimum along the boundary since it is a free surface. In comparison with intact rock mass, at r/a =1 the JRM with dip angle 90° has percentage variation of radial stress as 50.2%, JRM with dip angle 30° has percentage variation of 41.17% and with dip angle 60° the percentage variation of radial stress at crown and invert portion of tunnel is 33.3%. Likewise, in sidewall, the radial stress is maximum for tunnelling in joint dip angle 60° with respect to intact rock mass. From these graph, radial stresses are found to increase steadily across the tunnel and significant higher radial stresses are observed at sidewalls than the crown and invert portion.

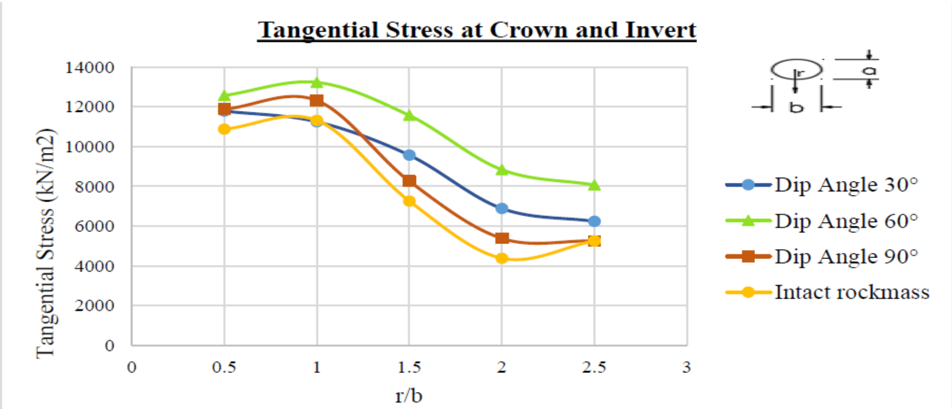


Fig 9 Tangential Stresses around Elliptical boundary at crown and invert

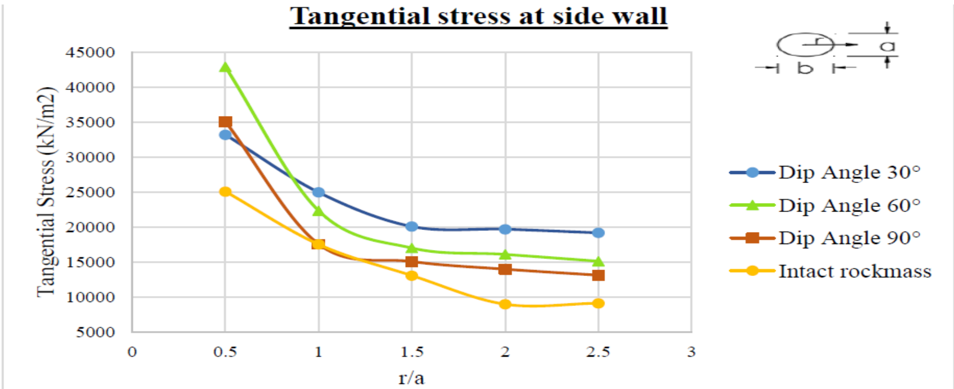
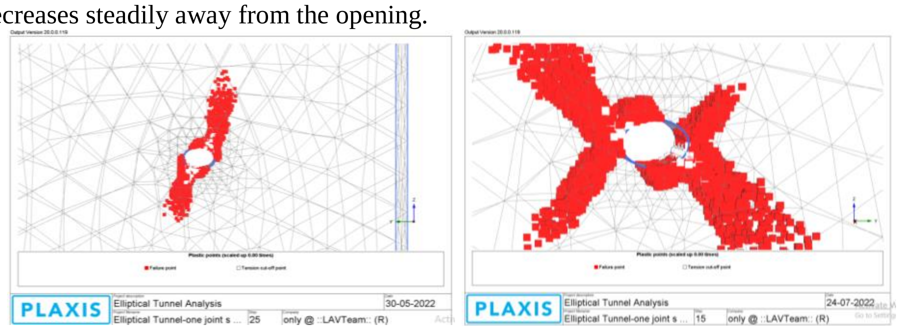
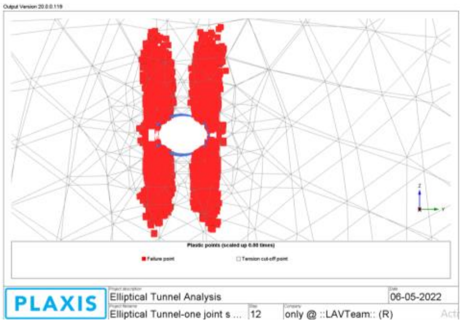


Fig 10 Tangential Stresses around Elliptical boundary at Sidewall

Tangential stresses along the tunnel periphery are important to be ascertained since it decides the violent breakout during excavation process. Graph is plotted between tangential stresses at roof and invert with r/b, in which r is the distance of point from the centre of tunnel and b is the width of elliptical tunnel (ie, major axis) as in Fig 9. For joint dip angle 60° and 90°, the tangential stress at crown and invert portion, is found to increase initially and then decreases. The tangential stresses at sidewall of tunnel as in Fig 10, is also observed with r/a. At sidewall, the tangential stress decreases steadily away from the opening.



(a) (b)



(c)

Fig 11 Plastic Points around Elliptical boundary (a) one Joint set 30^0 (b) one Joint set 60^0 (c) one Joint set 90^0

For the stability analysis and for support design, the plastic points around the tunnel is necessary to be considered. The Plastic zone exists up to the excavation influence and have some detrimental effects along the sliding plane of JRM. Such plastic points occurrence around the elliptical tunnel is shown in Fig 11. Since the rock strata considered to be dipping, the potential sliding is determined from the zone of interbed separation and most crucial in case of joint dip angle 60°.

4.2 Influence of Two and Three Joint sets

The Jointed rock mass with two joint sets are analysed same in case of one joint set, in which strike of joint sets are considered in parallel and perpendicular to the tunnel alignment.

Graph is plotted between two joint sets with combination of joint dip angles and maximum displacements around tunnel as shown in Fig 12. From the graph, it is observed that two joint set with dip angle (30°, 90°) has maximum displacement of 34.4cm at the tunnel roof. With dip angle (30°, 60°), the displacement is found to be 33cm and combination of joint dip angle (60°, 90°) has less displacement of 17.94cm.

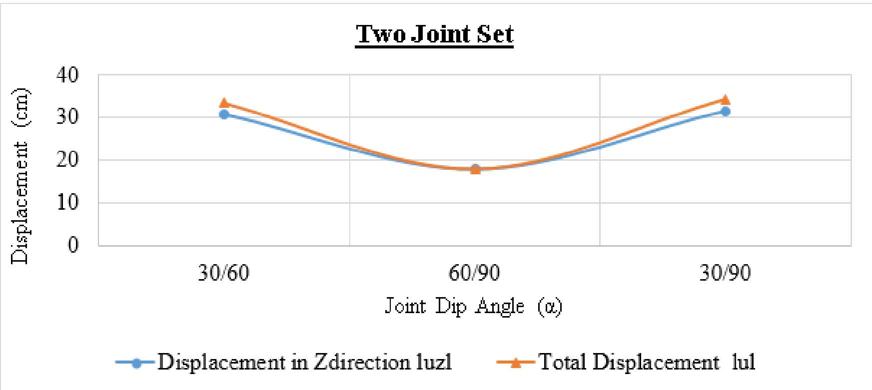


Fig 12 Two joint set-Displacement Vs Joint dip angles around Elliptical tunnel

Radial stresses are traced along crown and sidewall of elliptical tunnel by considering the points along the periphery and away from the excavation in which r is the distance of point from the center of tunnel and a is the height of elliptical tunnel (ie, minor axis) and b is the width (major axis) of tunnel. From the analysis, it is found that along side wall, radial stress is maximum at r/a=1, for tunnelling in joint dip angle 30°/60° which differs by 62.5% in comparison with the stress concentration at crown and invert portion of elliptical tunnel. It is also evident that in case of joint dip angle 30°/90°, radial stress at sidewall found to increase steadily beyond r/a=1. The stress influence at sidewall is most prominent upto r/a =1.5 and beyond that the elastic zone can be significant. Away from the tunnel boundary, in both cases, the tangential stress is found to decrease steeply.

When the number of discontinuities are more with in rock mass considered, the strength of it decreases eventually. Hence for the stability analysis and for the external support design, the plastic points around the tunnel is necessary to be taken into account.

The underground opening can be monitored effectively by measuring relative displacements of points along the tunnel boundary. The maximum significant deformation in tunnelling with three joint sets is found as in case of one joint set and observed as 33.5cm.

With the increase in distance of a point from the tunnel boundary, the radial stresses at crown and sidewall increases .The percentage variation of maximum radial stress at side wall and crown portion of elliptical tunnel is found to be 44%.Tangential stress at crown and invert of tunnel, are found to decrease as same as JRM with one and two joint sets. In all cases, along the sidewall of elliptical tunnel, the tangential stress is higher than the crown portion.

5 Conclusions

By analyzing stress and deformation characteristics around tunnel, with variation of joint parameters, the following conclusions are made.

1) In case of failure mechanisms of an excavation in a jointed rock mass, the number of joint set is an influencing parameter for the failure of a rock fragment. From the analysis made, it is observed that tunnelling in rock mass that has three joint set (n =3) shows phenomenal results.
2) With respect to tunnelling in intact rock mass, the difference in variation of maximum radial stress concentrations at sidewalls of tunnel in JRM with one joint set is found to be 62.5%, with two joint sets it is found as 63.41% and with three joint sets, the difference in variation is 68%
3) The strike and dip angle of the joints of rock mass are necessary to be considered in accordance with the alignment of tunnel which varies as per the project specification and has major impact. It is observed that the tunnel alignment parallel to the strike of joints has detrimental effects on determining stress-deformations around the tunnel.
4) Either in case of one or two joint sets, the combination of Joint dip angle 90^{o} does not have much significance, since its behaviour is approximately same as intact rock mass.
5) From the result and analysis, for the condition of surrounding rock with joints, bolt- grouting combined support may be preferred around the excavation in order to improve the stability of tunnel and condition of surrounding rock parameters.

References

1. Amit K. Verma and T. N. Singh (2010) 'Assessment of tunnel instability-a numerical approach'-Arab J Geosci,Vol 3,pp.181–192
2. Annan Jiang, Xinping Guo, Shuai Zheng and Mengfei Xu (2021)-'Parameters Identification of Tunnel Jointed Surrounding Rock Based on Gaussian Process Regression Optimized by Difference Evolution Algorithm'- Tech Science Press-Computer Modeling in Engineering & Sciences Vol.127,No.3,2021, pp.1177-1199
3. Channabasavaraj.W and Visvanath.B (2013) 'Influence of Relative Position of the Tunnels: A Numerical Study on Twin Tunnels'- Proceedings of International Conference on Case Histories in Geotechnical Engineering, Chicago.
4. Hamed A. Keykha and Bujang B. K. Huat (2011) 'The effect of discontinuities on stability of rock blocks in tunnel'-International Journal of the Physical Sciences Vol. 6(31), pp. 7132 – 7138.
5. Imran Ahmad Khan and Kumar Venkatesh, R.K. Srivastava (2016) 'Elasto-plastic finite element analysis of twin interacting deep horse shoe tunnels' – Proceedings of Indian Geotechnical Conference IGC2016,IITM,Chennai.
6. Ing (2017) 'Behaviour of jointed rock masses: numerical simulation and lab testing' – Proceeding of Phd thesis To the Faculty of Geosciences, Geoengineering and Mining, Freiberg University, Germany.
7. Jegadeesh Kumar T., Muttharam M. (2022) 'Numerical Study on the Influence of In-Situ Stress Ratio on Stress and Deformation Characteristics of Rock Tunnel'- Stability of Slopes and Underground Excavations- Lecture Notes in Civil Engineering, Vol 185. Springer, Singapore.
8. Madkour.H(2012) 'Parametric Analysis of tunnel behaviour in jointed rock' -Ain Shams Engineering Journal-Vol 3, 79–103
9. Minggao Zhang and Hengbin Wu, Zeping He and Tingqiang Zhou (2011) 'Numerical Study on Tunnel Mechanics in Jointed Rock Mass with Finite Element Method'-Applied Mechanics and Materials -Vol. 99-100 -pp 790-795
10. Suman Panthee, P.K. Singh, Ashutosh Kainthola, T.N. Singh (2016) ' Control of rock joint parameters on deformation of tunnel opening'- Journal of Rock Mechanics and Geotechnical Engineering- Volume 8, Issue 4, August 2016,Pages 489-498
11. Tai-Tien Wang, Tsan-Hwei Huang(2013) 'Anisotropic Deformation of a Circular Tunnel Excavated in a Rock Mass Containing Sets of Ubiquitous Joints: Theory Analysis and Numerical Modeling'- Springer-Rock Mechanics and Rock Engineering -Issue 2/2014
12. Wanrong Liu, Chao Peng and Baoliang Zhang (2021) 'Study on Influence of Joint Distribution on Surrounding Rock Failure of an Underground Tunnel'-Hindawi , Geofluids Volume 2021, Article ID 3621040,
13. Goodman RE (1980) Introduction to Rock mechanics- Wiley: New York
14. John A.Hudson and John P.Harrison (1997) - Engineering Rock Mechanics-An Introduction to the Principles –Pergamon, An imprint of Elsevier Science: UK