Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Numerical Study on the Influence of In-Situ Stress Ratio on Stress and Deformation Characteristics of Rock Tunnel

T. Jegadeesh kumar[1] and M. Muttharam[2]

[1]PG Student, Division of Soil Mechanics and Foundation Engineering, Civil Engineering Department, College of Engineering Guindy, Anna University, Chennai – 600025.
[2]Professor, Division of Soil Mechanics and Foundation Engineering, Civil Engineering Department, College of Engineering Guindy, Anna University, Chennai – 600025.

Abstract. Numerical study on rock tunnel is to determine the influence of the In-situ stress ratio to understand and estimate the rock state stress, which has become increasingly important. The state of intact stress in rock mass changes while excavating the tunnel. On the other hand, it establishes a new form of stress and deformation in a tunnel. For this study, different in-situ stress ratio values (0, 0.5, 1, 1.5, 2, 3) are considered, and different shapes of the tunnel (circular, elliptical, and D-shaped) are used for analysis. Two other models are used (Mohr-Coulomb and Hoek-Brown Model), and their responses are compared. PLAXIS 3D Finite Element Software is used for Numerical analysis. The result shows that the crown's deformation is more if the in-situ stress ratio is less, and deformation in the sidewall is more if the in-situ stress ratio is high. Among these three shapes, the elliptical shape shows more deformation for both Mohr-Coulomb and Hoek Brown models. While comparing the Mohr-Coulomb and Hoek Brown model, the Hoek Brown model shows more deformation because it considers the Rock Mass properties like GSI, Disturbance factor, etc. and the failure envelope or strength envelope is not linear. Whereas in the case of Mohr-Coulomb strength envelope is linear.

Keywords: In-situ stress ratio, Deformation, Rock mass properties.

1 Introduction

Rapid urbanization and economic development increase the usage of land. So, to reduce the traffic and for ease of transportation, tunnels are constructed nowadays. Tunneling in the rock is a complicated process. Rock at the depth was subjected to stress because of the weight of overlying strata, tectonic plate movements, soil erosion, construction of the building, etc.. an excavation or opening in rock may disrupt the stress field new set of stresses are induced in the rock opening. The presence of joints or discontinuities also plays a significant role in the change of the in-situ stress ratio values. The presence of discontinuities may increase the risk of stability on the tunnel by creating more deformation (Keykha et al. (2011)) [5]. Knowledge and magnitude of in-situ stress and induced stress is an essential component in the rock tunneling. In-situ stress ratio is the ratio of the horizontal stress to the vertical stress. Stress values in the tunnel can be determined by various methods like Hydraulic fracturing, flat jack method, over coring, and under the coring method. The tunnel's size and shape also influence the tunnel's deformation characteristics, which with an increase in tunnel dimension, there is an increase in deformation of the tunnel (Lollino et al., (2015))[4]. Different shape of the tunnels is used based upon the needs. In this study, three different shapes of the tunnels are analyzed (circular, elliptical, and D shape), and different in-situ stress ratios (0, 0.5, 1, 1.5, 2, 3) are considered. As it is difficult to perform an analytical study by creating models and applying stress values. Different methods can be adopted for analysis, they are the Coupled FEBEM method (Singh. R.B. (1985))[11], Boundary Element Method (Varadarajan et al.,(1983))[17] and displacement-based back analysis method (Zhang et al.,(2019))[19] and some of the studies analyzed by using Finite Element Method. Among them, Finite Element method, analyzing the entire volume of the soil were as Boundary Element Method solves only the unknowns of boundaries. So, this study has been performed numerically by using PLAXIS 3D finite element software. Two different models, Mohr-Coulomb and Hoek Brown models are considered for the study. In Mohr-Coulomb, the soil parameters like cohesion and angle of internal friction are used. In Hoek Brown, it incorporates both intact and discontinuities in rock, such as joints, Geological strength index, disturbance factor, etc..

2 Literature review

Aravind Kumar Jha (2013) analyzed the circular opening in which with the increase in in-situ stress ratio, deformation at the sidewall increases when k>1.5 and also performed the analysis by increasing the size of the tunnel, with the increase in the size of excavation the deformation is large which varies linearly**. Zhang et al. (2019)** studied the stress field distribution and deformation around the tunnel excavation in soft rock. The short bench construction method is used and shows that it effectively controls the deformation around the tunnel in the case of soft rock. **Meguid and Rowe (2005)** analyzed the stability of D shaped tunnel by using the Mohr-Coulomb model shows that at a high in-situ stress ratio, the deformation of the tunnel wall increases with the inward displacement of springline and upward displacement at the crown. **Zuo et al. (2012)** undergone a case study in Baozhen tunnel Hubei china. The tunnel is analyzed using ADINA software. This shows that the tunnel's roof settlement becomes stable after a while due to the adjustment of stress and strain energy after the tunnel's excavation. **Srivastava (1985)** analyzed single and interacting tunnel using the Finite Element method in which sequential excavation and simultaneous excavation have been undergone by considering rock as elastic and elastoplastic. Results obtained show that the sequential excavation leads to more deformation when compared to simultaneous excavation. It may be because in sequential excavation tunnel bored on the left side influences the right side of the tunnel. The deformation at tunnel boundary at spring level on the pillar side is least for the elastic case compared to the elasto-plastic case. Their difference is reflected more in the case of a smaller in-situ stress ratio 0.5. **Sing (2009)** studied tunnel instability in the Bansagar region by using the Finite Element Method. Mohr

Coulomb's model is used for the analysis. The crown and bottom of the tunnel show more deformation compared to the tunnel's sidewall. Based on this study, the following methodology is adopted.

3 Methodology

The major part of the tunnel lies under the Earth as the tunneling work is done in different places for different stratigraphy for various purposes. The determination of stress and deformation around the tunnel is necessary. In this study, numerical analysis is performed using PLAXIS 3D, employing a 10-noded tetrahedral element. In Chennai, the most abundantly present rock type is charnockite. So, charnockite rock is used for analysis. Rock considered here is intact, homogenous, and isotropic. The size for different shape of the tunnel and model parameters are listed below (see Table 1). For which the mesh size is taken as 24 x 24 x 24 m. If the mesh size is two times the diameter, the stress and deformation overlapped up to the boundary. So, a mesh size of 3 times the diameter has been taken for analysis and tunnel is running towards the length of 24 m. Based on the literature study, the most commonly used model in literature is the Mohr-Coulomb model. In this study, Mohr-Coulomb and Hoek-Brown models are considered for analysis. The values are taken from the literature study done by Ademeso and Olaleye (2014) [9]. The Hoek-Brown criterion in a form that has been found practical in the field and that appears to provide the most reliable set of results for use as input for methods of analysis in current use in rock engineering.

Table 1. Dimensions for different shape of the tunnel and model parameters

Shape and Dimensions of the tunnel	Mohr-Coulomb model parameters	Hoek - Brown model parameters
Circular (8 m diameter) Elliptical (8 m width and 6 m height) D shape (8 m width and 6 m height)	Cohesion = 34.323 MPa Angle of internal friction = 50.57^0	Intact Uniaxial Compressive Strength = 250 MPa Geological Strength Index = 95 Disturbance factor = 1 Intact modulus = 12000Mpa m_i = 28, m_b = 19.591 s = 0.4346 a = 0.5

Where mb, s, and a are Hook and Brown constants. Different in-situ stress ratio values are considered for analysis by using two different models for each shape of the tunnel. The models are compared based on the stress and deformation values to understand which model shows more deformation and stress.

4 Results and Discussion

Deformation and stress values for different shapes and different in-situ stress ratio values are determined by considering two different models using PLAXIS 3D finite element software. A model of 24x24x24 m is created in the PLAXIS in which lining is not provided to get the exact deformation around the tunnel. The results obtained are plotted in the form of a graph to show the influence of the in-situ stress ratio in the rock tunnel's stress and deformation characteristics.

3.1 Mohr-Coulomb model

Three different shapes of the tunnel are analyzed with different in-situ stress ratio values. The results obtained are discussed below with the graph for different shape of the tunnel.

Circular tunnel. A circular tunnel of 8 m diameter is simulated in the PLAXIS (see Fig 1)**.** The deformation and stress values for the different in-situ stress ratio values of the circular tunnel are plotted in the form of a graph to clearly show the influence of the in-situ stress ratio on stress and deformation characteristics of the tunnel. The graph plotted between displacement vs. in-situ stress ratio shows that, for in-situ stress ratio values 0 to 1, the deformation in the vertical direction is more (i.e., displacement in the z-direction), and for in-situ stress ratio values 1 to 3, the deformation is more in horizontal direction (i.e., displacement in the x-direction) (see Fig. 2). When vertical stress is high, the deformation at the crown and bottom increases. But when horizontal stress increases, the deformation at the sidewall of the tunnel get increases.

When the in-situ stress ratio value is 0, a plastic zone is formed at the tunnel's sidewall, and with an increase in horizontal stress, the plastic zone moves towards the crown of the tunnel.

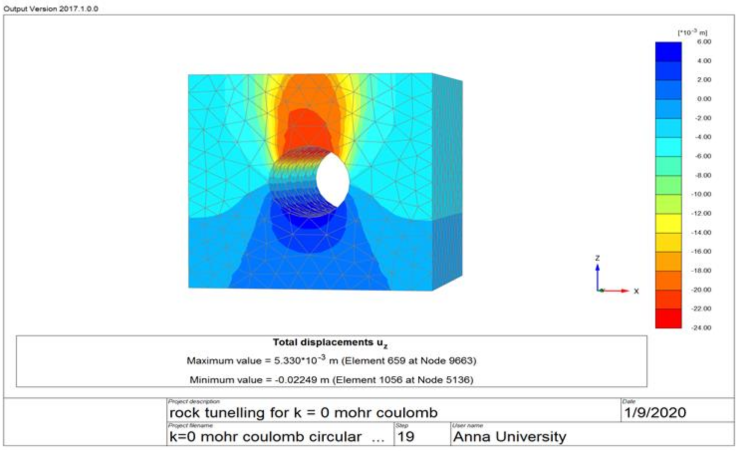

Fig. 1. Total displacement in the z-direction of the circular tunnel for k = 0

The graph plotted between Radial stress and Radial distance (from the center of the tunnel) shows that the radial stress is more in sidewall when the in-situ stress ratio is 0, and radial stress at the roof is more when the in-situ stress ratio is 3. It shows that radial stress increases with an increase in the radius of influence, but the radial stress at the tunnel boundary is zero (see Fig. 3 & 4). The graph plotted between hoop stress and radial distance shows that hoop stress is maximum in sidewall when the in-situ stress ratio lies from 0 to 1, and it is maximum at the roof when the in-situ stress ratio value lies from 1.5 to 3. When comparing hoop stress and radial stress, hoop stress is a major stress that has high-stress values than radial stress.

The hoop stress rises to the distance of 2 times the diameter, and then it gets decreased (see Fig. 5). Where r is the radius of influence, r_i is the tunnel radius, and k is the in-situ stress ratio represented in the graph. Radial stress and hoop stress increase with the increase in the radius of influence because when the radius is equal to the plastic zone radius, the hoop stress reaches the maximum. As radial stress increases with an increase in radius, but the increase rate gradually decreases. Finally, both approach the value of in-situ stress.

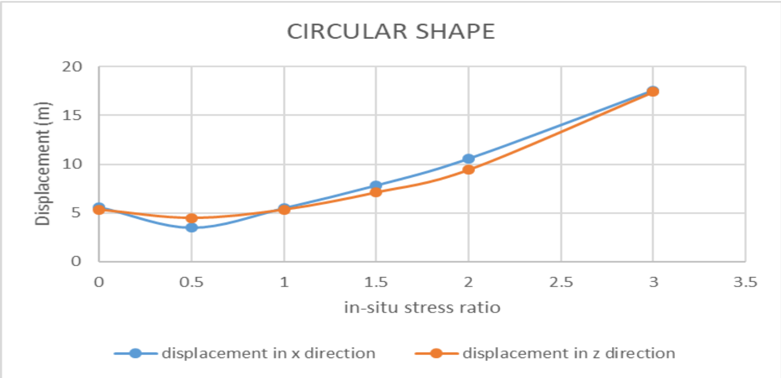

Fig. 2. Displacement vs. in-situ stress ratio for circular tunnel

Elliptical tunnel. Elliptical tunnel of width 8m and height 6m is simulated in PLAXIS (see Fig 6). The graph plotted between displacement, and in-situ stress ratio shows the same displacement pattern as that of the circular tunnel (see Fig 7). But when compared to the circular shape, displacement is more in the case of elliptical shape because of the height to width ratio. As the tunnel (8 m) width is more than the height (6 m), the deformation is more vertical. Graphs plotted between radial stress vs. radial distance (from the center of the tunnel) and hoop stress vs. radial distance follows the same pattern as that of the circular tunnel. But the stress values are high when compared to the circular tunnel.

D shaped tunnel. D shaped tunnel of 8 m width and 6 m height is simulated in the PLAXIS (see Fig 8). The graphs show the same variations as that of the circular and elliptical tunnel. But due to the corner effect, deformation in the x-direction is less than the deformation in the z-direction for an increase in the in-situ stress ratio (see

Fig. 9). Graphs plotted between radial stress vs. radial distance (from the center of the tunnel) and hoop stress vs. radial distance shows the same pattern as that of the circular and elliptical tunnel. But the stress concentration at the sharp edge of the D shape is high, and with an increase in horizontal stress, the stress concentration effect also increases.

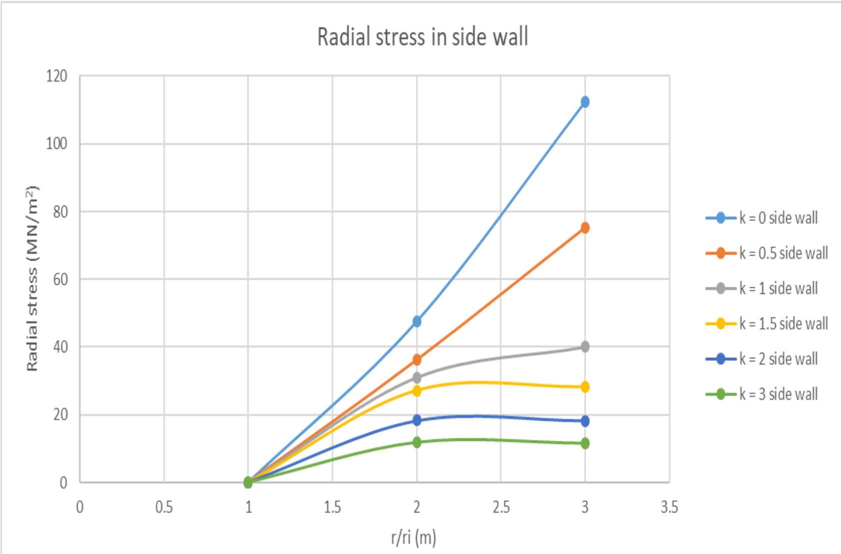

Fig. 3. Radial stress vs. Radial distance (r/r_i) for the circular tunnel.

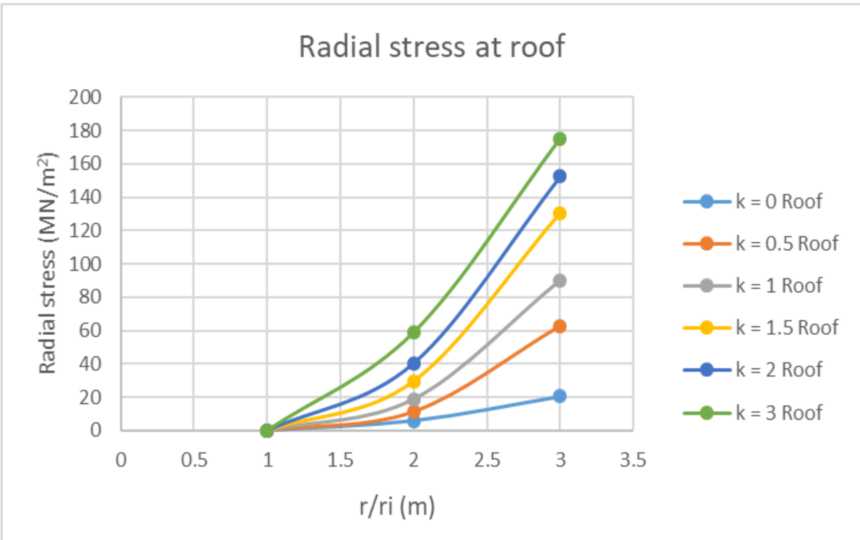

Fig. 4. Radial stress vs. Radial distance (r/r_i) for the circular tunnel.

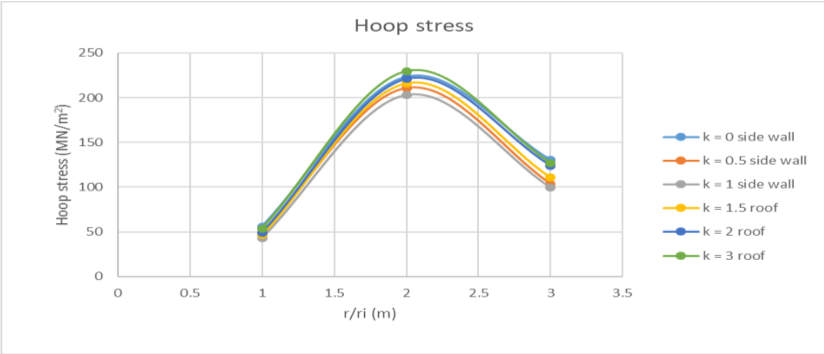

Fig. 5. Hoop stress vs. Radial distance (r/r_i) for the circular tunnel.

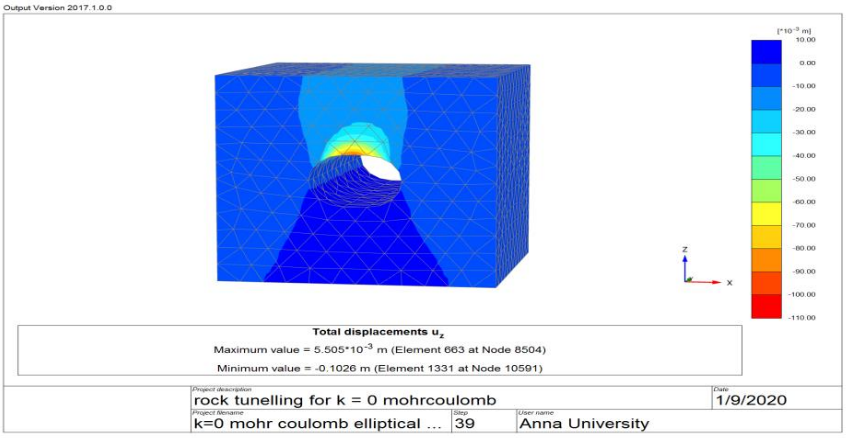

Fig. 6. Total displacement in the z-direction of the elliptical tunnel for k = 0

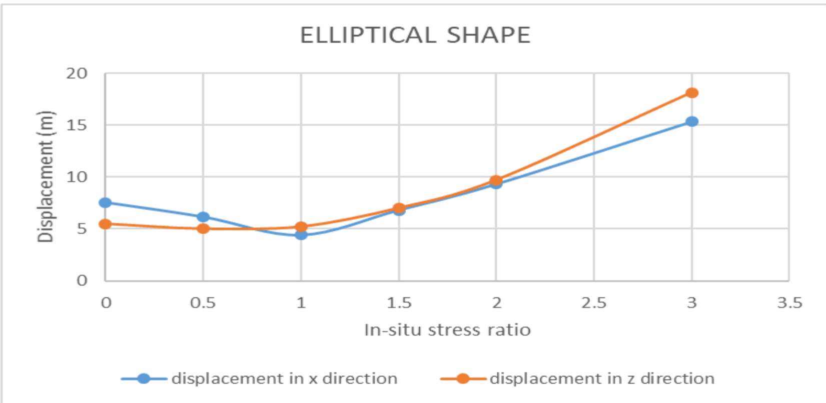

Fig. 7. Displacement vs. in-situ stress ratio for the elliptical tunnel.

3.2 Hoek – Brown model

In the Hoek – Brown model, the tunnel's size and shape are the same as that of the Mohr-Coulomb model, but parameters for analysis are different. Hoek- Brown criterion includes the rock mass properties like GSI, Disturbance factor, etc.,

Circular tunnel. A circular tunnel of 8 m diameter is simulated in PLAXIS. The graph plotted between displacement and in-situ stress ratio shows the same deformation pattern as that of the Mohr-Coulomb Circular tunnel. But the deformation values obtained are different. For the in-situ stress ratio value 0, the displacement in the vertical direction for Hoek-Brown is 65.9 mm, and for Mohr-Coulomb, it is 5.55 mm.

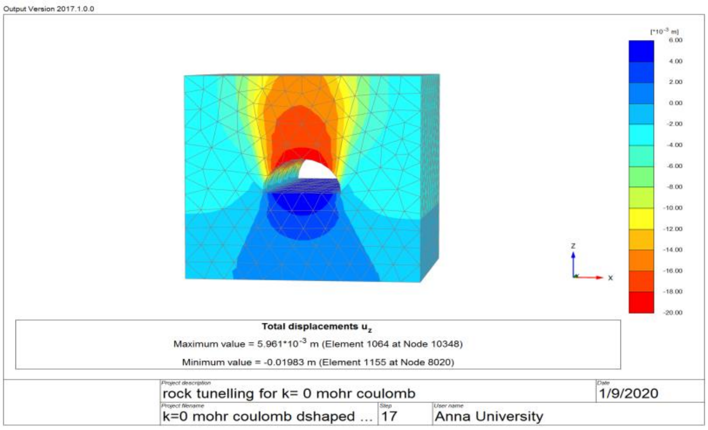

Fig. 8. Total displacement in the z-direction of the D shaped tunnel for k = 0

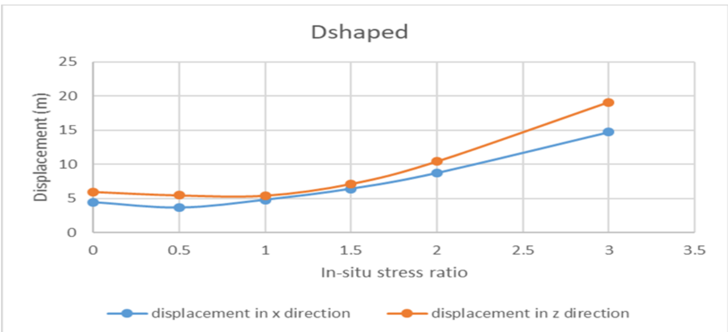

Fig. 9. Displacement vs. in-situ stress ratio for the D shaped tunnel

Mohr-Coulomb gives more conservative results because the strength envelope for the Hook-Brown model is not a straight line. It curves down. Whereas in Mohr-Coulomb, it is a straight line. The radial and hoop stress vs. radial distance pattern for Hoek-Brown also shows the same way as that of the Mohr-Coulomb, but the stress values obtained are high in the case of Hoek-Brown. The graph plotted between radial stress and radial distance (from the center of the tunnel) shows the influence of stress in x and z-direction. The graph plotted between hoop stress and radial distance shows that up to two times the tunnel's diameter, the hoop stress value increases, and then it decreases (see Figs. 10, 11 & 12). Where r is the radius of influence, r_i is the tunnel radius, and k is the in-situ stress ratio. Radial stress and hoop stress increase with the radius's increase. when the radius is equal to the plastic zone radius. The hoop stress reaches the maximum and then begins to decline as radial stress increases with an increase in radius, but the increase rate gradually decreases. Finally, both approach the value of in-situ stress.

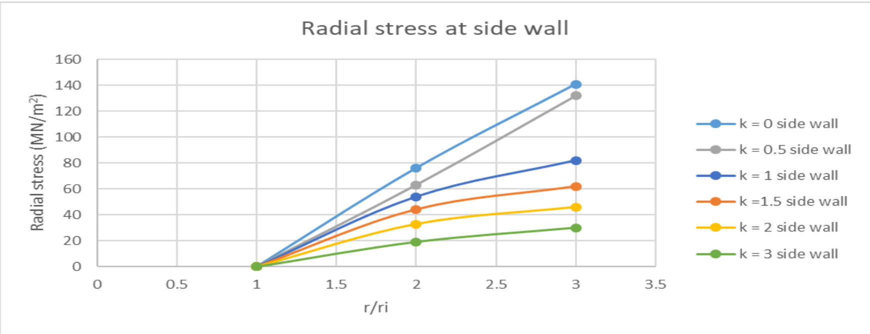

Fig. 10. Radial stress vs. Radial distance (r/r_i) for the circular tunnel

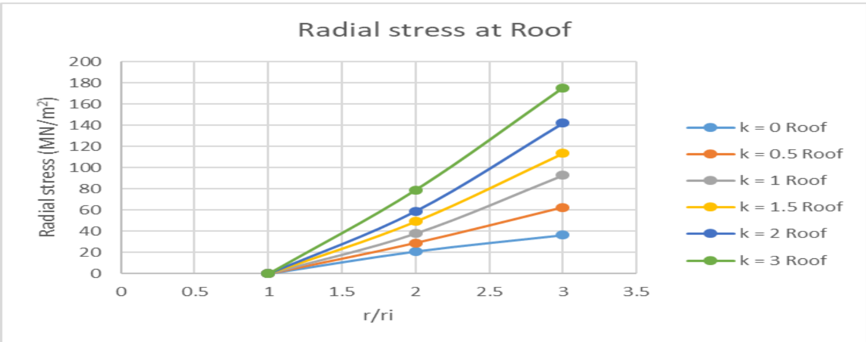

Fig. 11. Radial stress vs. Radial distance (r/r_i) for the circular tunnel.

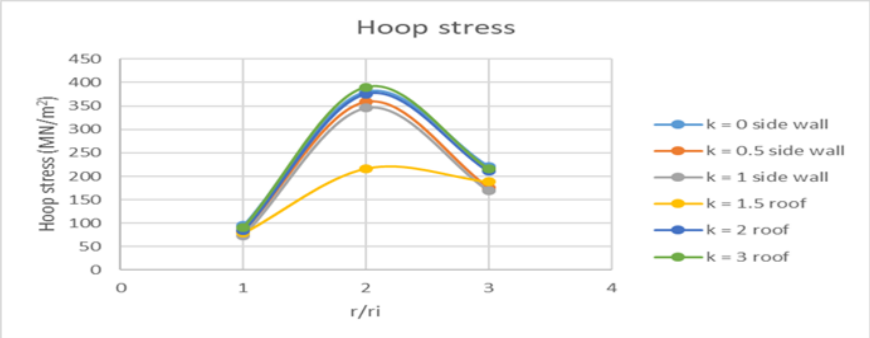

Fig. 12. Hoop stress vs. Radial distance (r/r_i) for the circular tunnel

Elliptical tunnel. Elliptical tunnel of width 8 m and height 6 m is simulated in PLAXIS. The graph plotted between displacement, and in-situ stress ratio shows the same deformation pattern as that of Mohr-Coulomb's deformation, and the values are different. The deformation or displacement in the Hoek-Brown and Mohr-Coulomb model's vertical direction is 78.07 mm and 5.88 mm, respectively, for in-situ stress ratio 0. The graph plotted between radial stress vs. radial distance (from the center of the tunnel) and hoop stress vs. radial distance follows the same pattern as that of Mohr-Coulomb but compared to the stress values of Mohr-Coulomb, Hoek- Brown stress values are higher.

D shaped tunnel. D shaped tunnel of width 8 m and height 6 m is simulated in PLAXIS. The graph plotted between displacement and in-situ stress ratio shows the same pattern as that of Mohr-Coulomb, but the deformation values are different. The displacement in the vertical direction for Mohr-Coulomb and Hoek-Brown is 6.24 mm and 75.20 mm, respectively. The graph plotted between radial stress vs. radial distance (from the center of the tunnel) and hoop stress vs. radial distance follows the same pattern as that of Mohr-Coulomb, but when compared to the stress values of Mohr-Coulomb, Hoek- Brown stress values are higher.

Total displacement. For the in-situ stress ratio 0, the total displacement for the elliptical, circular, and D-shaped tunnel is 138.3 mm, 24.12 mm, and 21.35 mm, respectively shows that deformation is more for elliptical tunnel because of the width to height ratio of the tunnel. When comparing the total displacement of Mohr-Coulomb and Hoek-Brown, the total displacement is more in the case of Hoek-Brown. For the circular tunnel, the total displacement for in-situ stress ratio 0 for Mohr-Coulomb and Hoek-Brown is 24.12 mm and 76.81 mm. The difference in the displacement values is 68.5 %. For elliptical shape, the displacement values of Mohr-Coulomb and Hoek-Brown for the in-situ stress ratio 0 are 138.3 mm and 150.3 mm, respectively. For the D-shaped tunnel, the displacement values for Mohr-Coulomb and Hoek-Brown for in-situ stress ratio value 0 are 21.3 mm and 105.3 mm, respectively. It is clear from the graph that the Hoek-Brown model shows more deformation than that of the Mohr-Coulomb model (see Fig 13).

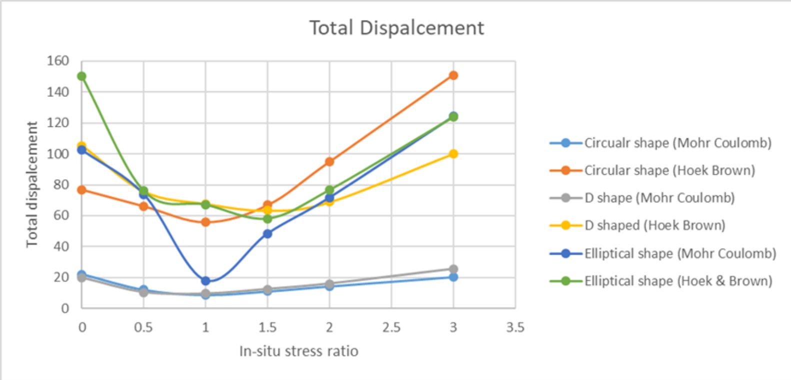

Fig. 13. Total displacement vs. in-situ stress ratio

5 Conclusions

The following conclusions were made by analyzing the above variations like different in-situ stress ratio values for different tunnel shapes by using different models.

1. Mohr Coulomb's results for deformation give conservative results when compared to Hoek-Brown results. Because the strength envelope is not a straight line in the case of the Hoek- Brown model. It curves down, so it gives a low strength estimate than the Mohr-Coulomb model.
2. The results obtained clearly show that with increased in-situ stress ratio, the deformation in vertical direction decreases, and horizontal direction increases. This is because, with an increase in horizontal stress, the deformation in vertical direction decreases.
3. The total displacement is maximum in the case of an elliptical tunnel. If there is a need to provide an elliptical tunnel, a proper support system like bolt grouting support can be provided. The elliptical shape shows more deformation due to height to width ratio as the tunnel's width is more when compared to the height, the deformation in the vertical direction is high when vertical stress is high.
4. D-shaped tunnel suffers high-stress concentration at their sharp bent edges, i.e., critical stress concentrations increase as the boundary's relative radius of curvature decreases. Openings with sharp corners should therefore be avoided.
5. The proper support system for the tunnel which has high deformation and stress values can also be determined with the help of the Ground Response Curve.

References

1. Aravind Kumar Jha ‘Elasto-Plastic Analysis of Circular Openings for underground Excavation in Hoek–Brown and Mohr-Coulomb Criteria’, Thesis of Department of Geotechnical Engineering, Institute of Engineering, Pulchowk Campus, Tribhuvan University, Nepal (2013).

2. Archana ‘Rock Support Interaction Analysis in Underground Structures’, M. Tech. Thesis, submitted to the Department of Civil Engg., IIT Delhi, India (2007).
3. Dongming Zhang, Zixiong Chen and Xiaohan Qi ‘Analysis of Monitoring and Measurement of Small Clear Spacing Tunnel in the excavation by NATM’, Advanced Materials Research Vol. 482-484 pp 581-584 (2012).
4. G. Lollino, C.T. Davie, and C.O. Okogbue ‘Numerical Analysis of the Influence of Tunnel Dimensions on Stress and Deformation Around Tunnels’, in Rocks Engineering Geology for Society and Territory – Vol. 6 (2015).
5. Hamed A. Keykha, Bujang B. K. Huat, Afshin Asadi and Hossein Moayedi ‘The effect of discontinuities on stability of rock blocks in tunnel’, International Journal of the Physical Sciences Vol. 6(1) (2011).
6. Heng Zhang, Liang Chen, Yimo Zhu, Zelin Zhou and Shougen Chen ‘Stress Field Distribution and Deformation Law of Large Deformation Tunnel Excavation in Soft Rock Mass’, thesis on Appl. Sci. (2019).
7. L.Q. Zhang, Z.Q. Yue, Z.F. Yang, J.X. Qi, F.C. Liu ‘A displacement based back-analysis method for rock mass modulus and horizontal in situ stress in tunneling – Illustrated with a case study’, Tunneling and Underground Space Technology pp: 636–649 (2006).
8. M.A. Meguid, R.K. Rowe ‘Stability of D-shaped tunnels in a Mohr–Coulomb material under anisotropic stress conditions’, Published on the NRC Research Press Website (2006).
9. Odunyemi Anthony Ademeso and Boluwaji Muraina Olaleye ‘Physicomechanical Characteristics of Charnockitic Rock of Akure, Southwest Nigeria’, General Scientific Researches, Vol (2), No (1), pp. 31-37 (2014).
10. Qingjun Zuo, Li Wu, Amoussou Coffi Adoko, Zhongle Lu ‘Analysis of Surrounding Rock Mass Deformation Characteristics: Case Study of BaoZhen Tunnel, Hubei China’, Article in Electronic Journal of Geotechnical Engineering, China (2012).
11. Singh. R.B ‘Coupled FEBEM Analysis of Underground Openings’, PhD. Thesis submitted to Indian Institute of Technology Delhi, India (1985).
12. Srivastava. R.K ‘Elasto-Plastic Finite Element Analysis of Single and Interacting Tunnels’, PhD. Thesis submitted to Indian Institute of Technology Delhi, India (1985).
13. Srivastava. R.K., Sharma. K.G. and Varadarajan. A ‘Elasto-Plastic Finite Element Analysis of Horse-Shoe Tunnels’, Indian Geotechnical Journal, 17(2), pp. 159-182 (1987).
14. T.N.Singh ‘Assessment of tunnel instability-a numerical approach’, Department of Earth Science, Indian Institute OF Technology, Bombay. Arabian Journal of Geoscience, pp:181–192 (2009).
15. Tran Tuan Minh, Nguyen Duyen Phong, Nguyen Viet Dinh ‘Research On Stress State And Deformation Around Big Tunnels With Excavation Stages In Bedding And Nonhomogeneous Rock’, International conference "Advances in mining and tunneling", At Ha Noi university of mining and geology (2012).
16. Varadarajan. A. and Sharma. K.G ‘Finite Element Analysis of a Powerhouse Cavern in Gujarat’, Gujarat (1948).
17. Varadarajan. A., Sharma. K.G. and Singh. R.B ‘Analysis of Tunnels by Boundary Element Method’, Indian Geotechnical Journal, pp. 249-268 (1983).
18. Yadav. H.R ‘Geotechnical Evaluation and Analysis of Delhi Metro Tunnels’, Ph.D. Thesis submitted to Indian Institute of Technology Delhi, India (2005).
19. Zheming Zhu , Yuanxin Li, Jun Xie, Bang Liu ‘The effect of principal stress orientation on tunnel stability’, Tunneling and Underground Space Technology, China (2015).