Effect of Rock Weathering on the Seismic Stability of Different Shapes of the Tunnel

Mohammad Zaid, Mohd. Faraz Athar, and Md. Rehan Sadique

Abstract Tunnels in rock are integral part of contemporary old and modern smart cities in hilly terrain to provide services and transportation. Tunnels have been the lifeline of the metropolitan cities since decades. Tunnelling have reduced the time of travel, saved money, reduced number of accidents and also reduced the human impact on the ecology of the hilly regions. Hilly regions are seismically active zones and have several minor earthquakes at a shorter span of time. Himalayan mountains are young folded mountains and have been affected by several earthquakes of large magnitude in last century. Hence, stability study of tunnels in hills is very crucial. This present study focuses on the effects of rock mass weathering, due to geological and other changes, on the stability of tunnels subjected to earthquakes. The 2D plane strain elastoplastic model has been adopted for the numerical analysis using finite element software. A model of dimensions 42 m x 42 m has been developed having an overburden of 500 m. The different shapes of the tunnel are also varied to understand their stability. Plasticity theory of failure given by Mohr–Coulomb has been incorporated to simulate the constitutive properties of rock mass. The physical properties of basalt have been adopted for this study. The different weathering classes of basalt used in this study are fresh basalt, slightly weathered basalt, medium weathered basalt and highly weathered basalt. The earthquake data of acceleration time history has been taken from the records of the Koyna earthquake, which was a 6.4 M magnitude earthquake. This study will help to understand the stability of the smart city tunnels subjected to the earthquake in hilly regions. This paper concluded that weathering has detrimental effects on the seismic stability of smart city tunnels. The deformations reduce by 34% with the increase in the depth of overburden in case of arch-shaped tunnels, in case of circular-shaped tunnels the deformations reduce by 42% and in case of horseshoe-shaped tunnels deformations reduces by 28% of deformations at shallow depth of overburden.

Keywords Smart city tunnels · Finite element · Mohr–coulomb · Seismic · Koyna

---

M. Zaid · Mohd. F. Athar (✉) · Md. R. Sadique
Department of Civil Engineering, ZHCET, Aligarh Muslim University, Aligarh, U.P, India
e-mail: faraz.athar12@gmail.com

S. Patel et al. (eds.), *Proceedings of the Indian Geotechnical Conference 2019*,
Lecture Notes in Civil Engineering 137,
https://doi.org/10.1007/978-981-33-6466-0_59

1 Introduction

Among the major civil engineering structures, underground tunnels are considered of utmost importance due to its vast uses and strategic importance. Development of smart cities is an ambitious project of twenty-first century [1]. In India also, few cities on hills such as Munnar (Kerala), Shillong (Meghalaya), Kodaikanal (Tamil Nadu), Ooty (Tamil Nadu), Mussoorie (Uttarakhand), Nainital (Uttarakhand), Darjeeling (West Bengal), etc., has been selected to be developed as a smart city. In this pursuit of establishing smart cities, Tunnels may serve different purposes depending upon the requirements of the particular area. The effect of dynamic loading on the stability of rock tunnels had been studied by reseachers in available literature [2–5].

Due to rapid urbanization in the Indian subcontinent and Government projects like "smart city", several cities are being converted into metropolitans at a very high pace. This process in old cities where availability of land is a major problem can easily be sought out by constructing underground tunnels for metros, subways, underpasses, etc.

The structure with that much of importance requires high precision and accuracy while constructed, the stability of tunnels when constructed in the rock mass is also very important aspect before actual construction of the tunnel. Albino et al. [6] had presented a comparative study on the definitions of smart city provided by different sources and concluded that many cities calling themselves as smart, lack universality. In the modern world fast transportation facility is a prerequisite for any developed country. Underground tunnels play a vital role in achieving the fast transportation facilities. Metro-rail, bullet train, high-speed highways can only be made possible by constructing underground tunnels to ensure uninterrupted traffic movement. Most of the underground tunnels are situated in metropolitans and on hills, thus, their structural safety must be ensured. The vulnerability of lands on hills to seismic events cannot be discarded.

Many researchers in the past have studied seismic vulnerability of underground tunnels [7–15]. Carlos A. Jaramillo et al. [16] shows the seismic design impact on tunnels in rock through various case histories. Several researchers carried out the study for the damage caused by an earthquake on tunnel stability [8, 16, 17]. The underground tunnels constructed in soil-mass are considered to be more resistant toward seismic attacks than tunnels that are constructed in rockmass [16]. Corigliano et al. [18] shows the seismic stability of deep tunnels situated in rock mass. Stratification in soil-mass also affects the stability of tunnels when subjected to dynamic loads such as earthquake [19]. Naqvi et al. [20] shows the seismic stability of tunnels constructed in jointed rock mass.

Above studies conclude that it is important to study the seismic stability of underground tunnels before going for their construction. The weathering effect of rock mass is an important consideration while constructing any structure in rock mass [21–23]. Ki-II Song studied the behavior of underground structures under the effect of spatially variable weathered rock mass and shows that the spatially variable rock-mass induces large deformation as compared to the homogenous rockmass on ground surface [24].

Tunnels are of various shapes ranging from circular to horseshoe to box, etc. Navid Hosseini et al. [25] analyzed the seismic stability of horseshoe tunnel for different type of rock mass. Somnath Mondal et al. [26] also carried out seismic analysis of horseshoe tunnel in soil, in both the cases numerical modelling is adopted to solve the problems. Arash Rostami et al. [27] studied the effect of different shapes of tunnel gates on the settlement of soil, their study shows that the rectangular shape has maximum settlement and circular shape has least settlement. Although, horseshoe shape has settlement similar to that of circular shape. Yamamoto et al. [28] carried out the static stability of different shapes of tunnels under the surcharge loading constructed in cohesive soil whereas Elshamy et al. [29] take the case of different shapes of twin tunnels and their behavior under soft clay soil. These studies establish that shape of the tunnel is a crucial factor for ensuring its safety against various static and dynamic conditions. Finite element analysis has been widely accepted as main tool for the design and analysis of the complex structures like tunnels [30].

In past, different parameters were adopted for the stability of tunnel by different researchers. The problems of seismic stability of tunnels on account of rock weathering along with different shape of tunnels are very rare. In this study, authors will be dealing with seismic effect under the influence of rock weathering in case of different shaped tunnels. There are many methods to analyze the problems, one can do it either by the experimental approach, or analytical approach or numerical approach, etc. The experimental work requires sophisticated machineries and models to analyze the problem. On the other hand, numerical simulation is a very effective way of solving real-life problems with a mere application of computing system. The effectiveness of numerical techniques is that, it proves to be economical as a single parameter can be varied or changed at any point of analysis without much affecting the cost of study and for any geometry or condition. The availability of digital computing system and dedicated numerical modelling software made the task easier for researchers to solve these complex real-valued problems easily and accurately. The numerical approach has been adopted for solving out the current problem. Numerical solution may be done in different ways like domain reduction method (DRM), used by Corigliano et al. [18], finite difference method used by Ki-Il Song et al. [24], boundary value problem, finite element method, etc. Naqvi et al. [20] and Abakanov et al. [31] used the finite element method to analyze the problem. Naqvi et al. [20] used Abaqus/CAE to analyze the problem, whereas Abakanov et al. [31] used Ansys software for numerical solution of their problem. The finite element method is a bit easier to deal with, in comparison to the other numerical techniques available. The authors have adopted a finite element technique to carry out the present study.

In this study, a 2D elastoplastic model of the tunnel is generated through Abaqus/CAE. The analysis is carried out for various tunnel geometries such as circular, horseshoe, and arch shape tunnels. The analysis has been performed for Basalt rock on different stages of weathering. Stages of weathering considered are fresh basalt, slightly weathered, medium weathered, to highly weathered basalt. The seismic analysis has been done consideringKoyna earthquake (1967) of magnitude 6.4 M on Richter scale under different depth of tunnel. The analysis is carried out for the depth of 5 m, 10 m, 17.5 m from the crown to the ground level.

2 Numerical Modelling and Analysis

A 2D elastoplastic model of the tunnel is generated through finite element software Abaqus. The tunnel box is of the dimensions 42 m x 42 m and the tunnel has the diameter of 7 m in all the three geometrical cases. The circular, horseshoe and arch shape tunnel lining has also been adopted in the study, the thickness of the tunnel lining is taken as 120 mm, the height of tunnel from crown to invert in all the cases is 7 m. The tunnel geometries for circular, horseshoe and arch shape tunnel are shown in Fig. 1.

Mohr-Columb elastoplastic constitutive material model is adopted for the material properties of the tunnel. The material parameters for finite element modelling are shown in Table 1. The concrete lining is modelled as linear elastic in Abaqus/CAE. The properties of 2D plain strain finite element model have been taken up from Gahoi et al. [21–23,32–36].

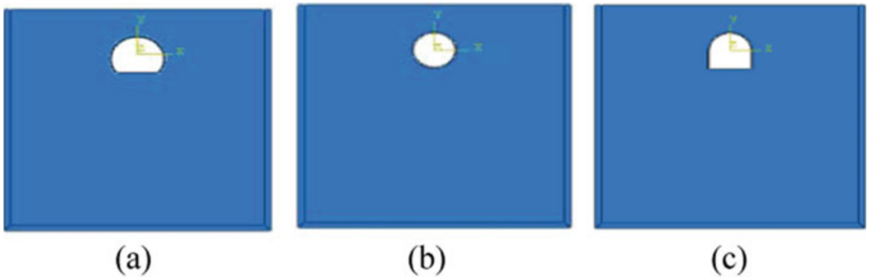


Fig. 1 Geometry of **a** Arc, **b** Circular and **c** Horse Shoe tunnels

Table 1 Input parameters of the numerical model

Weathering stage	Density (kg/m^3)	Young Modulus (GPa)	Poisson's Ratio	Friction Angle (°)	Cohesion (MPa)
W_0	2960	46.5	0.186	63.38	26.25
W_1	2740	20.6	0.260	53.71	18.50
W_2	2470	2.80	0.272	33.33	8.08
W_3	1820	0.6	0.272	43.87	1.64
Concrete	2400	31.6	0.150	-	-

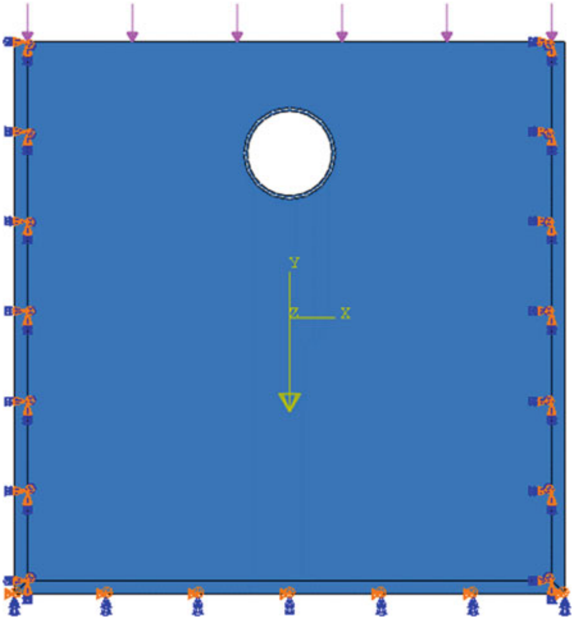
3 Analysis

The analysis has been carried out in two steps using Abaqus. The first is Static General step and second one is Dynamic Implicit Step. The Static step analyzed the settlement of the tunnel under self-weight during static conditions with an overburden of 500 m at the top. Whereas, in dynamic step earthquake loading has been applied and its effect on the tunnel geometry are analyzed. Earthquake loading is assigned by providing an accelerating boundary condition to the base of the model in Dynamic step. The duration of the earthquake is taken as the step time (step time = total time of earthquake occurrence) for the analysis in Dynamic step. Static step has been considered for 1 s in each case. The base of the model has been fixed in all directions in the Static step and the sides have applied for roller support by allowing deformation in the vertical direction. Figure 2 shows the loading and boundary conditions applied to the model. In Dynamic step, boundary condition at the base has been discarded for the application of earthquake.

The model has been meshed by element type CPE3R- 3 Node Linear triangular, reduced integration, and hourglass control for Rockmass excluding boundaries. The boundary elements are meshed with element type CINPE4- 4 Node Linear quadrilateral, reduced integration element in Abaqus/Standard. The meshed geometry is shown in Fig. 3.

In the present study, effects of Koyna earthquake (11 December 1967) were considered. The magnitude of the earthquake as recorded on Richter scale is 6.4 M reported by Indian Metrological Centre. The earthquake is the consequence of the

Fig. 2 Load and boundary condition assembly



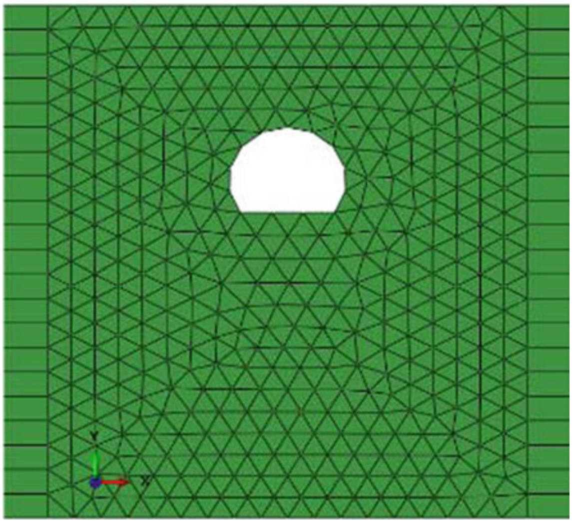


Fig. 3 Mesh of the model

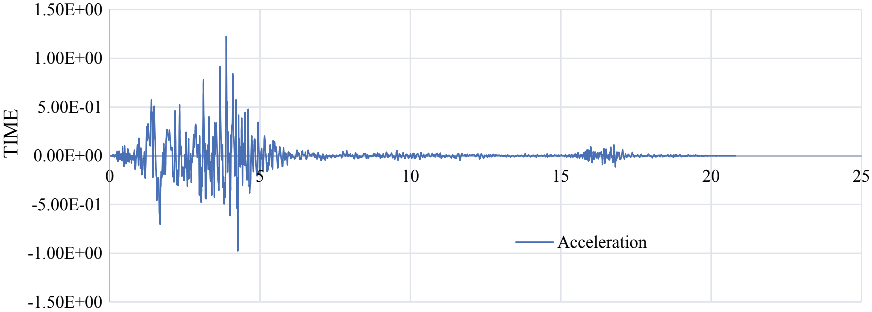


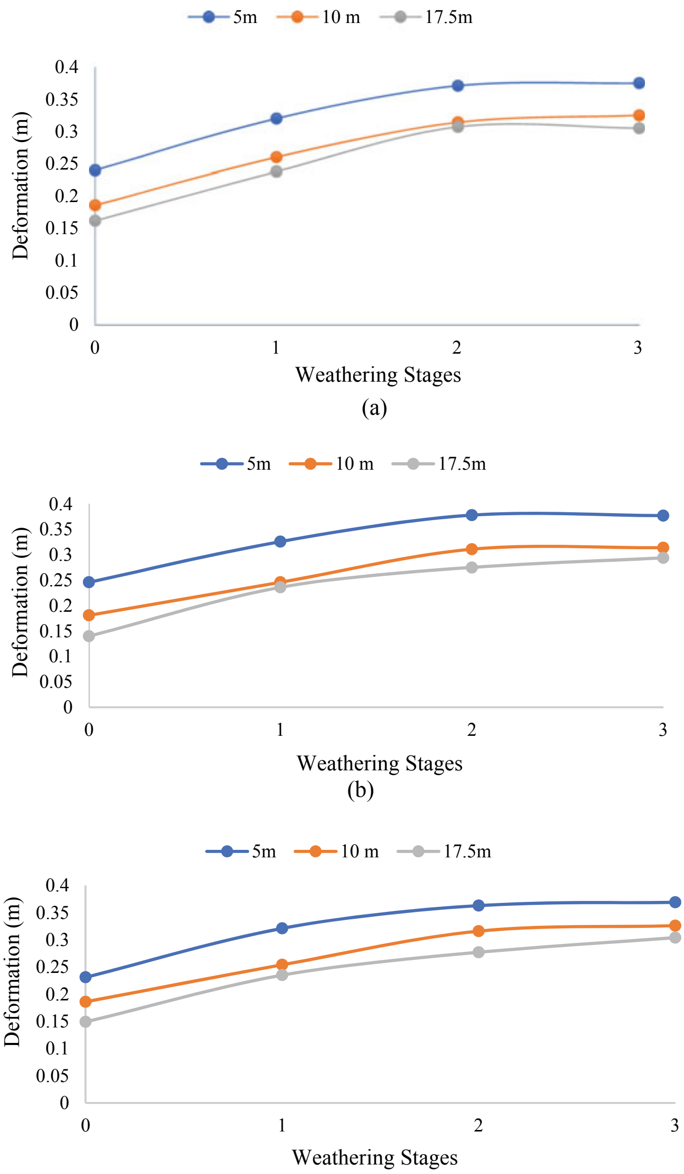
Fig. 4 Acceleration versus Time History of Koyna Earthquake 1967 [37]

fault along the Malabar coast [37]. The acceleration versus time history curve of the earthquake is shown in Fig. 4.

4 Result and Discussion

The study has been carried for the seismic stability of tunnel having different shapes. Weathering effect has also been considered for the stability analysis. Finite element methods analysis has been adopted and Abaqus/Implicit was used for the analysis. The results are as follows.

Figure 5 shows maximum deformation for different stages of weathering in basalt rock with varying depth of overburden for Arch, Circular, Horse Shoe shaped tunnels,



(a)

(b)

(c)

Fig. 5 Graph of Maximum Deformation vs. Weathering Stages for Different Depths of Tunnel at the crown of **a** Arch, **b** Circular and **c** Horse Shoe Tunnel respectively. The graphs depict that as the depth of overburden increases the tunnels leads to stability. There is increase in magnitude of deformation as the rock leads to higher stage of weathering.

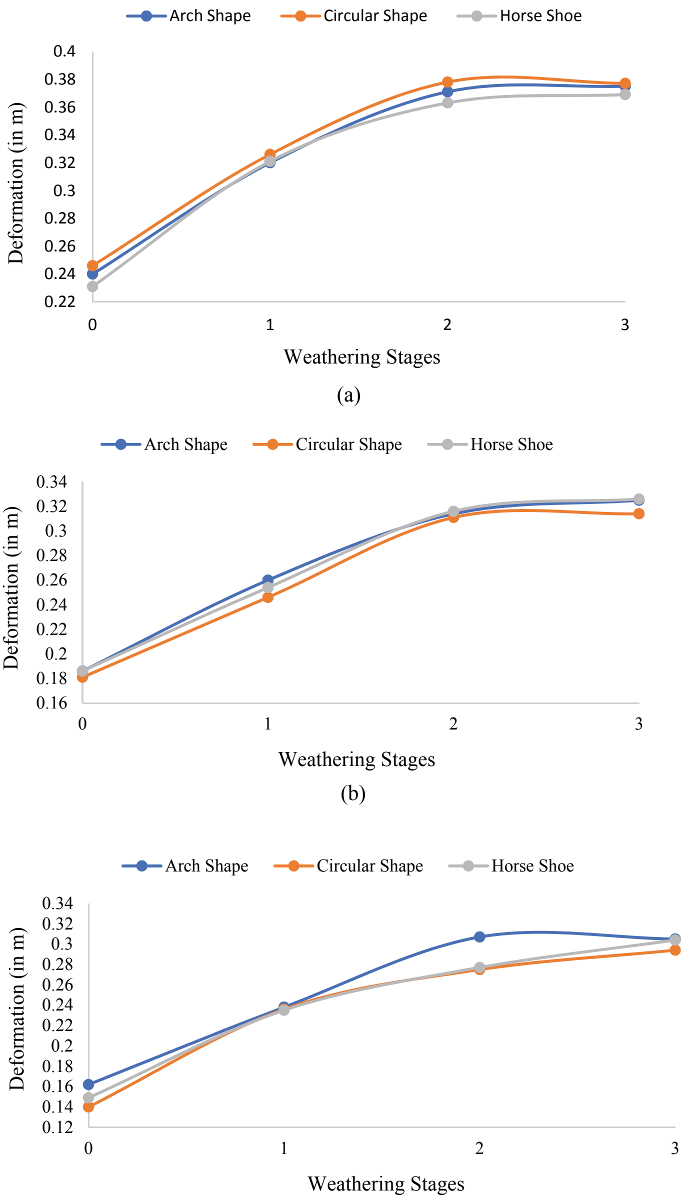
The comparison of different shapes of tunnels for different weathering stages of basalt is plotted in Fig. 6. It shows the deformation behavior for different shaped tunnels with varying stages of weathering and for different depth of overburden. The figure shows that the magnitude of deformation increases with increase in stage of weathering. Thus, tunnel becomes stable for a particular depth if it is being constructed in fresh rock. For shallow tunnels (5 m depth of overburden), horseshoe-shaped tunnels are more stable as compared to arch-shaped and circular-shaped tunnels and the circular shape tunnels are most unstable. For intermediate depth tunnels (10 m depth of overburden), circular-shaped tunnels are most stable and for deep tunnels (17.5 m depth of overburden) also circular tunnels show more stable behavior. Figure 7 has been plotted for the comparison of different stages of weathering of basalt rock at different depth of overburden. The tunnels constructed in highly weathered rocks and medium weathered rocks show similar behavior in terms of deformation. The deformation decreases with depth of overburden for a particular stage of weathering. The tunnels constructed in fresh (no weathering) rock are most stable.

Figures 8 and 9 show different contours for arch and circular tunnels for 10 m depth of overburden for different stages of weathering of basalt rock.

5 Conclusion

The following conclusion can be drawn from the study above:

1. Stability increases with increase in depth of tunnel for all weathering stages.
2. Fresh basalt rock is much stable weathering stage for tunnel stability as compared to the other weathering stages of basalt rock.
3. For shallow depth tunnels, horseshoe-shaped tunnels are much stable as compared to circular and arch-shaped tunnels
4. As the depth of over burden increases tunnel having circular shape becomes more stable in comparison to arch shape and horseshoe shape.
5. Irrespective of weathering stage of a basalt rock, as the depth of tunnel increases, deformations decrease leading to the stability of tunnel

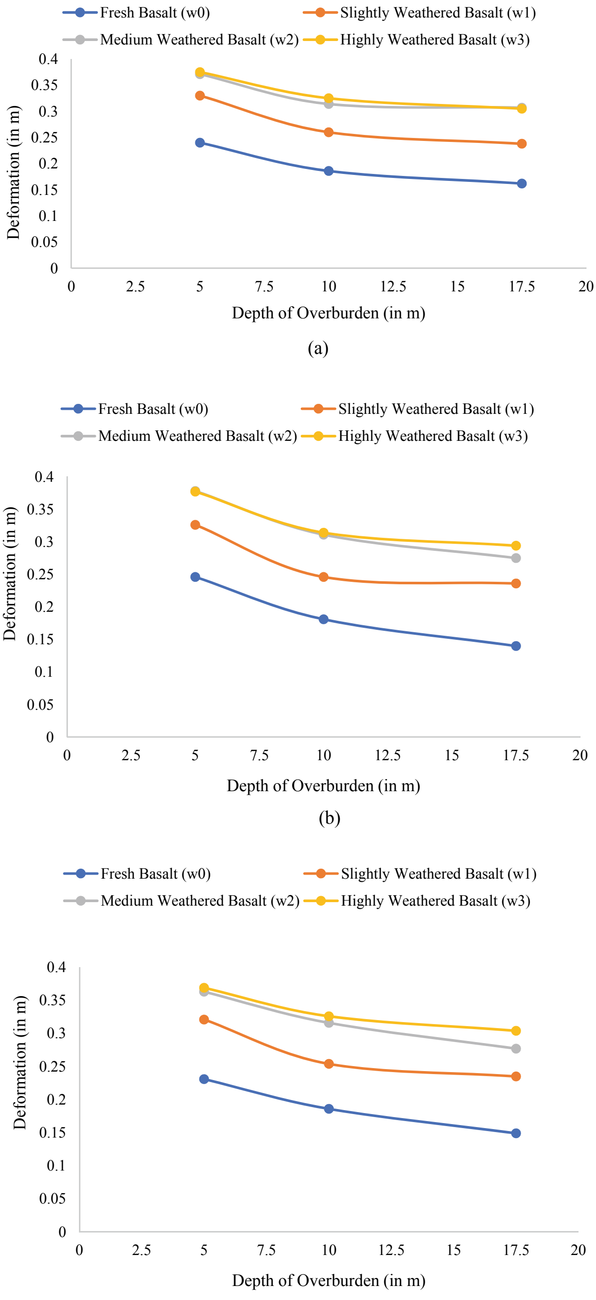


(a)

(b)

(c)

Fig. 6 Deformation versus Weathering Stages for comparison of Shapes of Tunnels for **a** 5 m depth, **b** 10 m depth and **c** 17.5 m depth, of tunnel



(a)

(b)

(c)

Fig. 7 Deformation versus Depth of Overburden for Comparison of Different Weathering Stages for **a** 5 m, **b** 10 m and **c** 17.5 m

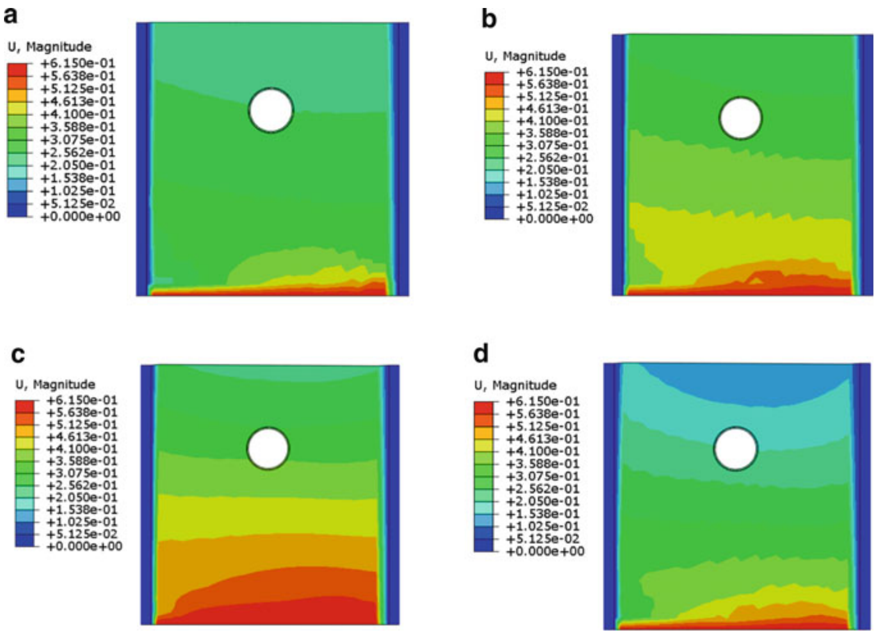


Fig. 8 Contours for Total Maximum Deformation at 10 m of Overburden for Arch Tunnel for **a** Fresh Basalt (w0), **b** Slightly Weathered Basalt (w1), **c** Medium Weathered Basalt (w2) and **d** Highly Weathered Basalt (w3)

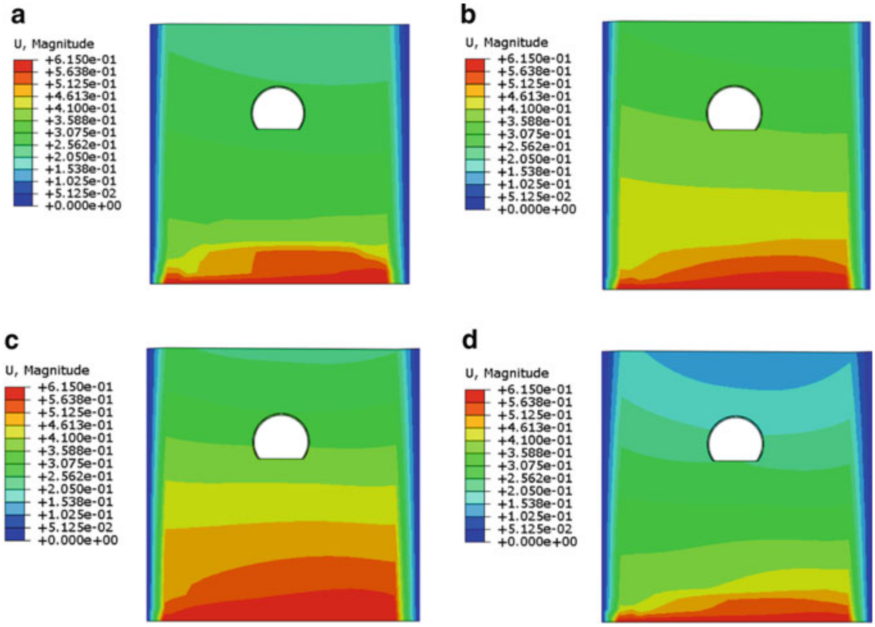


Fig. 9 Contours for Total Maximum Deformation at 10 m of Overburden for Circular Tunnel for **a** Fresh Basalt (W_0), **b** Slightly Weathered Basalt (W_1), **c** Medium Weathered Basalt (W_2) and **d** Highly Weathered Basalt (W_3)

References

1. Harrison, Colin & Abbott Donnelly, Ian. (2011). “A Theory of Smart Cities". 55th Annual Meeting of the International Society for the Systems Sciences 2011.
2. Zaid, M., Mishra, S.: Numerical analysis of shallow tunnels under static loading: a finite element approach. Geotech Geol Eng. (2021). https://doi.org/10.1007/s10706-020-01647-1
3. Zaid, M., Sadique, M.R., Alam, M.M.: Blast analysis of tunnels in manhattan-schist and quartz-schist using coupled-Eulerian–Lagrangian method. Innov. Infrastruct. Solut. **6**, 69 (2021). https://doi.org/10.1007/s41062-020-00446-0
4. Zaid, M., Sadique, M.R., Alam, M.M., Samanta, M.: Effect of shear zone orientation on the stability of rock tunnel subjected to blast loading. Geomech. Eng. **23**(3) (2020). https://dx.doi.org/10.12989/gae.2020.23.3.245
5. Zaid, M., Sadique, M.R.: Numerical modelling of internal blast loading on a rock tunnel. Adv. Comput. Des. (2020). https://dx.doi.org/10.12989/acd.2020.5.4.417
6. Albino, V., Berardi, U., Dangelico, R.: Smart Cities: Definitions, Dimensions, Performance, and Initiatives. J. Urban Technol. **22**, 3–21 (2015)
7. Singh, Manendra & Narayan Viladkar, Manohar & Kumar Samadhiya, Narendra. (2016). “Seismic Analysis of Delhi Metro Underground Tunnels". Indian Geotechnical Journal. 47. https://doi.org/10.1007/s40098-016-0203-9
8. Fabozzi, S., Licata, V., Autuori, S., Bilotta, E., Russo, G., Silvestri, F.: Prediction of the seismic behavior of an underground railway station and a tunnel in Napoli (Italy). Undergr. Sp. **2**(2), 88–105 (2017)
9. Patil, M., Choudhury, D., Ranjith, P.G., Zhao, J.: Behavior of shallow tunnel in soft soil under seismic conditions. Tunn. Undergr. Sp. Technol. **82**, 30–38 (2018)

10. Yu, H., Zhang, Z., Chen, J., Bobet, A., Zhao, M., Yuan, Y.: Analytical solution for longitudinal seismic response of tunnel liners with sharp stiffness transition. Tunn. Undergr. Sp. Technol. **77**(April), 103–114 (2018)
11. Ali Khan, M., Sadique, M.R., Zaid, M.: Effect of stratification on underground opening: a numerical approach. In: Pulugurtha S., Ghosh I., Biswas S. (eds.) Advances in Transportation Engineering. Lecture Notes in Civil Engineering, vol. 34. Springer, Singapore. (2019) https://doi.org/10.1007/978-981-13-7162-2_11
12. Naqvi, M.W., Akhtar, M.F., Zaid, M., Sadique, M.R.: Effect of superstructure on the stability of underground tunnels. Transp. Infrastruct. Geotech. (2020). https://doi.org/10.1007/s40515-020-00119-6
13. Zaid, M., Sadique, M.R.: Blast resistant behaviour of tunnels in sedimentary rocks. Int. J. Protect. Struct. (2020). https://doi.org/10.1177/2041419620951211
14. Zaid, M., Sadique, M.R.: The response of rock tunnel when subjected to blast loading: finite element analysis. Eng. Rep. (2020). https://doi.org/10.1002/eng2.12293
15. Zaid, M., Sadique, M.R., Samanta, M.: Effect of unconfined compressive strength of rock on dynamic response of shallow unlined tunnel. SN Appl. Sci. **2**, 2131 (2020). https://doi.org/10.1007/s42452-020-03876-8
16. Jaramillo, Carlos. (2017). "Impact of Seismic Design on Tunnels in Rock - Case Histories". Underground Space. 2. https://doi.org/10.1016/j.undsp.2017.03.004
17. Lin, Qi., Jun & Qing Fang, Xiao & Long Liu, Jin.: Earthquake Damage Evaluation of Tunnels. Applied Mechanics and Materials. **170–173**, 1402–1409 (2012). https://doi.org/10.4028/www.scientific.net/AMM.170-173.1402
18. M. Corigliano, L. Scandella, G. Barla, C. Lai, and R. Paolucci, "Seismic analysis of deep tunnelsin weak rock: a case study in Southern Italy", in 4th International Conference on Earthquake Geotechnical Engineering, At Thessaloniki, Greece June 2007.
19. D. Miguel M. Ferreira, "Seismic behaviour of shallow tunnels in stratified ground", Dissertation of master degree in Civil Engineering, Institutu Superior Ťechnico, October, 2010.
20. Naqvi, M.W., Zaid, M., Sadique, M.R., Alam, M.M.: Dynamic analysis of rock tunnels considering joint dip: a finite element approach. In: 13th International Conference on Vibration Problems, ICOVP2017, Indian Institute of Technology, Guwahati, India (2017)
21. Gupta, A.S., Rao, K.S.: Index properties of weathered rocks: inter-relationships and applicability. Bull. Eng. Geol. Env. **57**(2), 161–172 (1998)
22. Gahoi, A., Zaid, M., Mishra, S., Rao, K.S.: Numerical analysis of the tunnels subjected to impact loading In: 7th Indian Rock Conference (IndoRock2017), New Delhi (2017)
23. Zaid M., Mishra S., Rao K.S.: Finite element analysis of static loading on urban tunnels. In: Latha Gali M., P. R.R. (eds) Geotechnical Characterization and Modelling. Lecture Notes in Civil Eng. **85**. Springer, Singapore. https://doi.org/10.1007/978-981-15-6086-6_64 (2020)
24. Song, K.-I., Cho, G.-C., Lee, S.-W.: Effects of spatially variable weathered rock properties on tunnel behavior. Probab. Eng. Mech. **26**, 413–426 (2011). https://doi.org/10.1016/j.probengmech.2010.11.010
25. Hosseini, Navid & Oraee, Kazem & Gholinejad, Mehran. (2010). "Seismic analysis of horseshoe tunnels under dynamic loads due to earthquakes". Coal Operators' Conference.
26. S. Mondal and T. Rahman, "A Comparative Study of Seismic Analysis of a Horse Shoe Tunnel for Different Types of Soil," International Journal of Inovative Research in Science, Engineering and Technology (IJIRSET) vol-4 issued-9 pp. 8522–8528, September 2015.
27. Rostami, A., Asghari, N., Ziarati, A., Morteza & Jahani, Saman & Shahi, Bahman. : Investigating Effect of Tunnel Gate Shapes with Similar Cross Section on Inserted Forces on Its Coverage and Soil Surface Settlement. Open Journal of Civil Engineering. **06**, 358–369 (2016). https://doi.org/10.4236/ojce.2016.63030
28. Yamamoto, K., Lyamin, A.V., Wilson, D.W., Sloan, S.W., Abbo, A.J.: Stability of dual square tunnels in cohesive-frictional soil subjected to surcharge loading. Can. Geotech. J. **51**(8), 829–843 (2014)
29. Shaaban, hesham. (2013). Behavior of Different Shapes of Twin Tunnels in Soft Clay Soil. International Journal of Engineering and Innovative Technology (IJEIT) ISSN: 2277–3754. Volume 2. 297–302.

30. V. PA, B. PG, and M. SC, “On a smart use of 3D-FEM in tunnelling,” in 8th International symposium on Numerical models in geomechanics; NUMOG VIII, 2002, pp. 361–366.
31. D. Abakanov, T & B. Begalinov, A & T. Abakanov, A. (2016). Seismic Stability of Tunnels at the Kapchagai Hydropower Plant. Soil Mechanics and Foundation Engineering. 53. https://doi.org/10.1007/s11204-016-9365-9
32. Zaid, M., Khan, M. A. and Sadique, M. R. (2019) “Dynamic Response of Weathered Jointed Rock Slope having the Transmission Tower”, in *Proceedings of National Conference on Advances in Structural Technology*. NIT Silchar, pp. 414–422.
33. Zaid, M., Sadique, M.R.: Effect of Joint Orientation and Weathering on Static Stability of Rock Slope having Transmisison Tower”, in *7th Indian Young Geotechnical Engineers Conference – 7IYGEC 2019 15–16 March 2019, NIT Silchar, Assam.* India SILCHAR, NIT Silchar (2019)
34. Zaid M., Talib A., Sadique M.R.: Effect of joint orientation on the seismic stability of rock slope with transmission tower. In: Latha Gali M., Raghuveer Rao P. (eds) Geohazards. Lecture Notes in Civil Eng. **86**. Springer, Singapore. https://doi.org/10.1007/978-981-15-6233-4_11 (2021)
35. Athar, M.F., Zaid, M., and Sadique, M.R.: “Stability of Different shapes of Tunnels in Weathering Stages of Basalt”, in *Proceedings of National Conference on Advances in Structural Technology*. NIT Silchar, pp. 320–327 (2019)
36. Zaid, M., Talib, A. and Md. Rehan Sadique (2018) “Stability Analysis of Rock Slope having Transmission Tower”, IJRECE, 6(2).
37. Systems, C. of O. for S.-M.O.: Strong Motion Virtual Data Center (VDC).https://strongmotioncenter.org/vdc/scripts/default.plx. Accessed 15th October 2018 (2018)