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Behavior of Underground Tunnel under Strong Ground Motion

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Abstract. The design of the tunnel demands an adequate analysis to access the possible damage to the tunnel under different conditions of loading. A huge amount of research studies has already been reported by many investigators, over the performance of the tunnel under static loading conditions. However, their performance under dynamic loading is still very rare. The present paper discusses the response of the tunnel under varying levels of seismic loading. The finite element analysis has been used to understand the behavior of underground tunnel under three different earthquakes input motions, i.e., 0.3g, 0.5g, and 0.7g, in addition to varying load from the superstructure constructed over it. The study has been performed using the finite element software OPTUM G2. The thickness of the tunnel lining has been kept constant as 250 mm, which is widely accepted in many tunneling projects. The cross-section and diameter of the tunnel adopted in the study are 50m x 54m and 6.35m respectively with 18m of depth of overburden. An Elasto-plastic constitutive material model has been used to model the tunnel lining and the surrounding soil. As the seismic intensity increases, it prompts the catastrophic change in the behavior of tunnel. The magnitude of the earthquake for which the tunnel is being designed must be considered based on past earthquake history of the region. This paper highlights the behavior of tunnel lying in the northern region of India.

Keywords: Tunnel, Seismic loading, Finite element analysis, Elasto-plastic, OPTUM G2.

1 Introduction

Tunnels have nowadays become the crucial elements for the modern infrastructural advancements of the country. Because of their sophisticated outlook and the fact that they connect most of the naturally disconnected locations, separated by natural barriers like mountains, construction of these underground structures is gaining popularity. The underground structures, due to their overall connectivity to the ground are considered safer and more resistant to the cyclic loading as compared to the surface structures. However, the static and dynamic loads on the tunnel must be properly addressed during the design and if neglected, it may result in damages such as ground subsidence or even total collapse of tunnel [1-10], which may further prove uneconomical in terms of amount of money and cost of labour. Most of the tunnels are situated at the locations which are vulnerable to the disasters such as earthquake, landslide etc. and are even subjected to blasting and explosions during the construction stage as well. Therefore, the study of the behavior of tunnels under these dynamic loadings has become a preferred choice for the research introspection [11-16]. The other types of tunnel damages are due to the ground liquefaction, which occurs predominantly if the tunnel is constructed in soft grounds [17-19]. The research of the tunnels can be accomplished by three 3 approaches viz. experimental, analytical and numerical. The Numerical approach because of improved computing performance is widely followed to analyses the problems of tunneling for different loading types [20-23].

The metro tunnels in the urban sector of a country are constructed at shallow depths and are thus prone to seismic loading. Further, these tunnels are also subjected to the lithostatic pressure of the buildings and other infrastructural elements constructed above them. Therefore, there is a need of the research over the response of tunnels due to combined effect of static and dynamic loading to ensure their long-term stability.

The present study introduces the numerical analysis of the Delhi metro tunnel for different earthquake loading in addition to the load of superstructure. The study has been performed using finite element based software, OPTUM G2. The results have been plotted in the form of stress and displacement at different sections of the tunnel due to combined effect of earthquake and the static load of the superstructure. The research study highlights the behavior of tunnel lying in the northern part of India, and the concluding remarks of the study will be considered for the general design purposes of such tunnels.

2 Numerical Modelling and Analysis

Finite element study has been carried out to understand the behavior of Delhi metro tunnel under varying earthquake loading. The OPTUM G2 software has been adopted for the analysis and modelling [24]. The model has 50m of width and 54m of height of the model. Moreover, the whole model has five different layers of varying thickness as 10m, 10m, 15m, 15m and 4m. These layers were divided based on Young's Modulus of the soil surrounding the concrete lining. The tunnel has an |overburden depth of 18m and lies in between layer 2 and layer 3. Moreover, the shallow foundation has been assumed in the form of raft footing placed above the tunnel. The tunnel has an opening of diameter 6.35m and concrete lining has thickness of 0.25m. The center of the footing and the tunnel lies in a line. The footing of the super structure has 12m of width. Fig 1 shows the detailed diagram of the tunnel model.

The present Delhi metro tunnel has Delhi silty-sand as the surrounding soil. The properties of the silty-sand and the concrete lining are shown in Table 1[25]. Stratification of the soil varies in vertical direction and is shown in Table 2. The soil is cohesionless and follows the associated flow rule. The mesh adaptivity has been considered for the accuracy of results having frequency of three adaptive iterations in every iteration. Fig 2 shows the meshing and boundary condition of the finite element model. The 6-node Gauss element has been adopted for meshing and 10000 number of element were formed. Further, the base of the model has fixed support and the vertical sides of the model have roller support. This is termed as standard fixities in OPTUM G2.

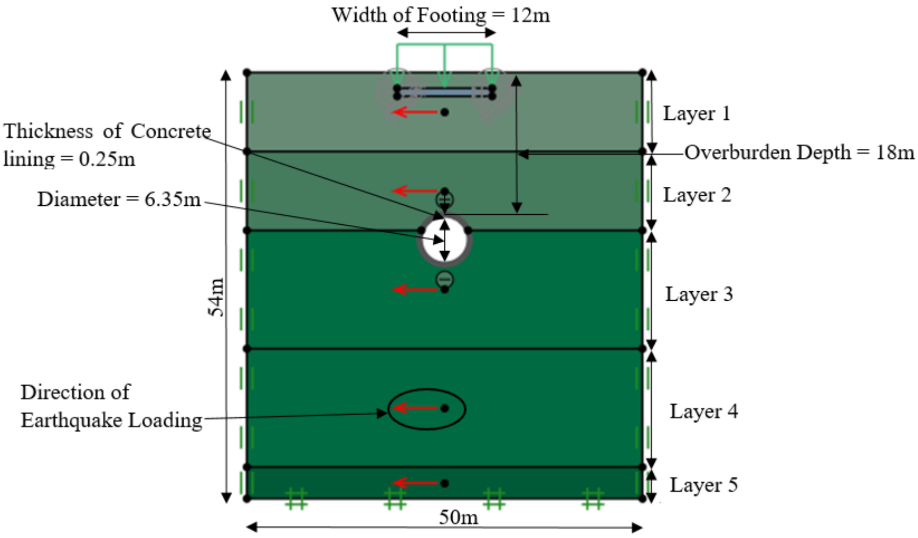


Fig. 1. Detailed geometry of the tunnel having footing of superstructure

Table 1. Properties of Soil and Concrete Lining [25]

Delhi Silty Sand	
Bulk density	18 kN/m^3
Saturated Density	20 kN/m^3
Poisson Ratio	0.25
Friction angle	35
Dilation angle	5
Concrete Lining	
Density	25 kN/m^3
Young Modulus	3.16 × 10^7 kPa
Poisson Ratio	0.15
Sectional area	2500 cm^2/m
Plastic section modulus	15625 cm^3/m
Moment of Inertia	130208.33 cm^4/m
Yield strength	30 MPa
Weight	625 kg/m/m

Table 2. Young Modulus of Delhi silty sand at the various depth

Depth (m)	Young Modulus (kPa)	Layer
0-10 m	7500	Layer 1
10-20 m	15000	Layer 2
20-35 m	30000	Layer 3
35-50 m	40000	Layer 4
50-54 m	50000	Layer 5

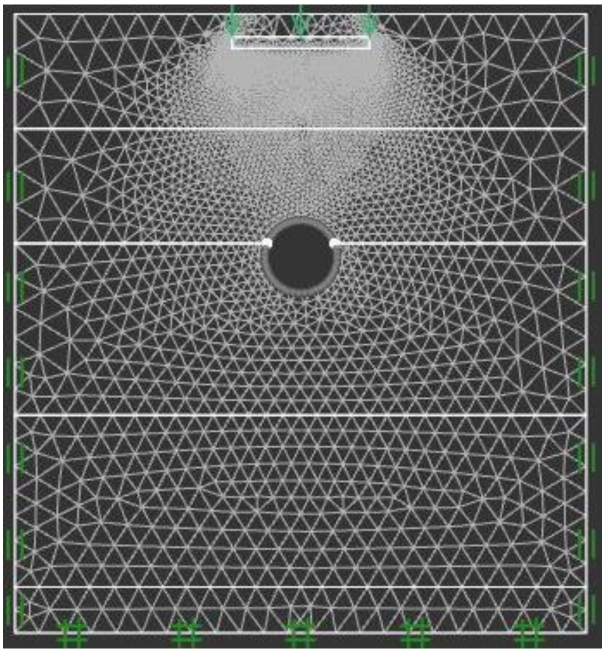


Fig. 2. Meshing and Boundary conditions of the model

2.1 Steps of analysis

The analysis was performed to simulate the real field conditions in five stages:

1. Stage I: In this stage initial stress analysis has been carried out. It has similar soil field conditions and also known as green field condition simulating the field conditions.
2. Stages II: The elastoplastic analysis has been performed for the simulation of excavation of tunnel. Based on user manual of OPTUM G2, the tunnel is fully supported and excavation was carried out with full support [24].
3. Stage III: Supports were provided in this stage in the form of concrete lining.

4. Stage IV: Elastoplastic analysis was performed by providing a raft foundation at a depth of 3m from the ground and a uniformly distributed load, due to the superstructure, was applied at its top extending from 0 kN/m^2 to 30 kN/m^2.
5. Stage V: Multiplier Elastoplastic analysis was performed for the earthquake loading for different magnitude i.e., 0.3g, 0.5g and 0.7g.

3 Results and Discussion

This study deals with the stability and serviceability analysis of the Delhi metro tunnel having raft foundation of the super structure. The load of the superstructure has been varied from 0 kN/m^2 (Self load of foundation only) to 30 kN/m^2. The simulation has been carried out using OPTUM G2 software. The displacement, stresses, shear force and bending moment results were obtained and discussed in the present section. Fig 3 shows the variation of displacement of the Crown Point in different cases. It has been observed that displacement increases with the increase in load from super structure. Similarly, as the magnitude of an earthquake increases it leads to rise in displacement. It concludes that load from the super structure and magnitude of an earthquake has significant role in the serviceability of the tunnels in soil. However, the change in displacement is negligible but for high-rise structure, this is a point of concern. Moreover, load per unit area must be incorporated during earthquake resistant designing of underground tunnels in soil. Similar trend of results were obtained for the springer of the tunnel as shown in Fig 4.

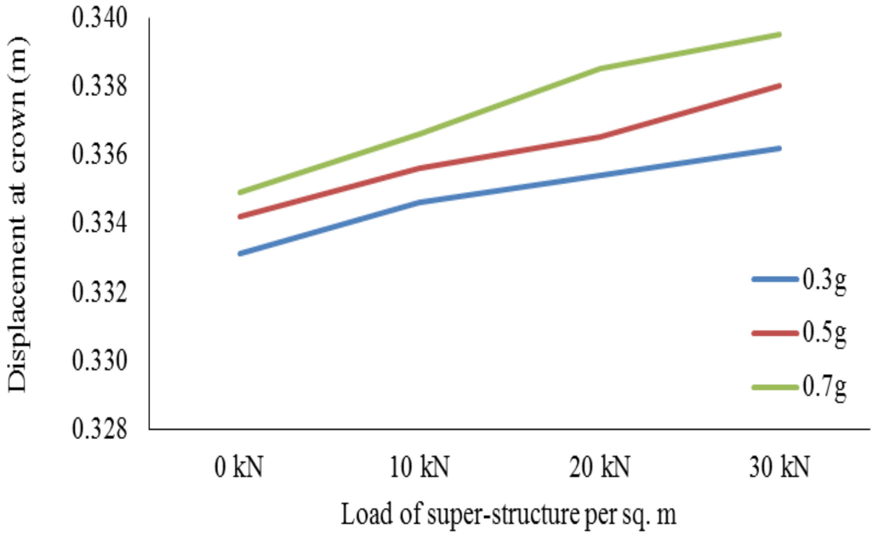


Fig. 3. Displacement at the crown for different magnitude of earthquake loading with increasing super structure load

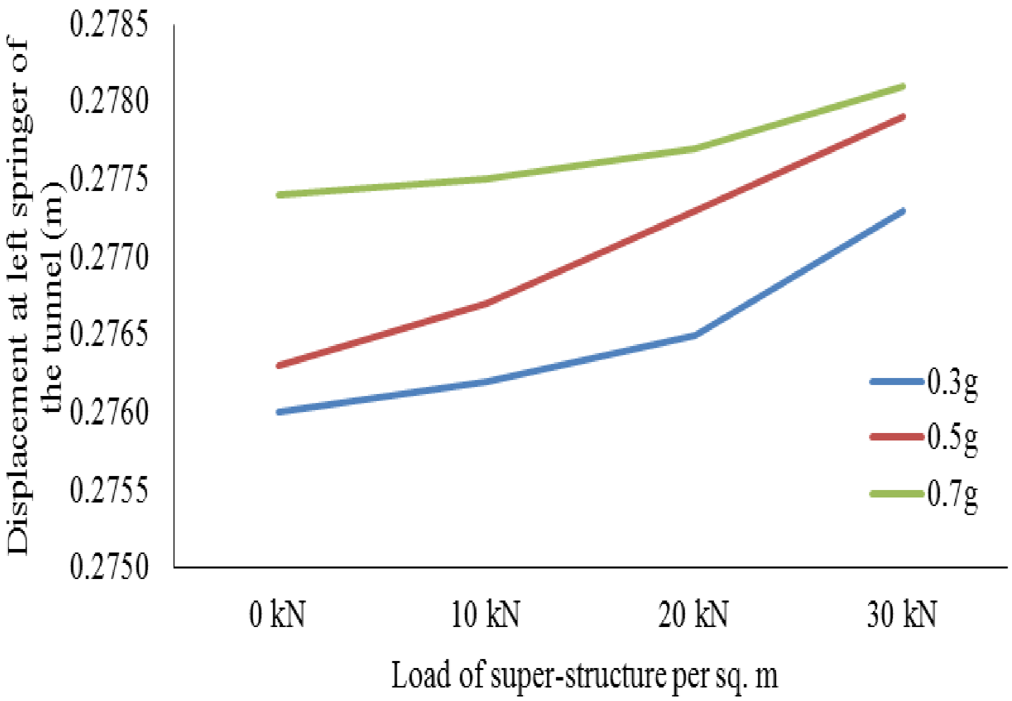
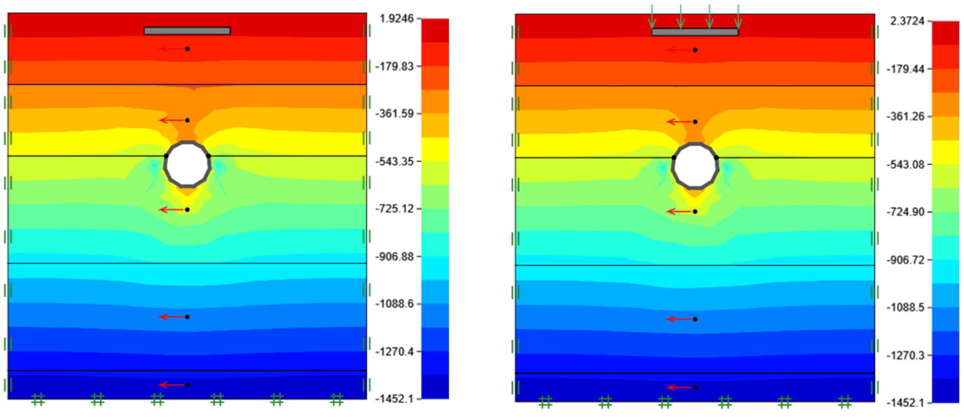
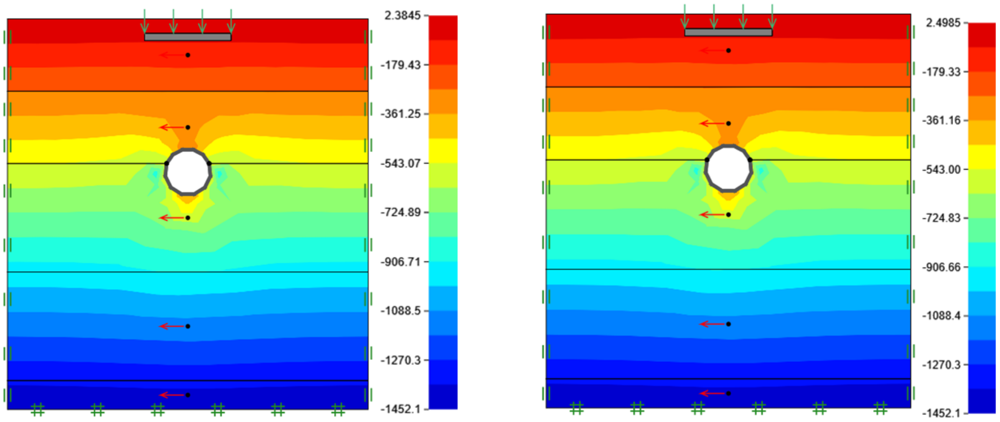


Fig. 4. Displacement at the springer for different magnitude of earthquake loading with increasing super structure load



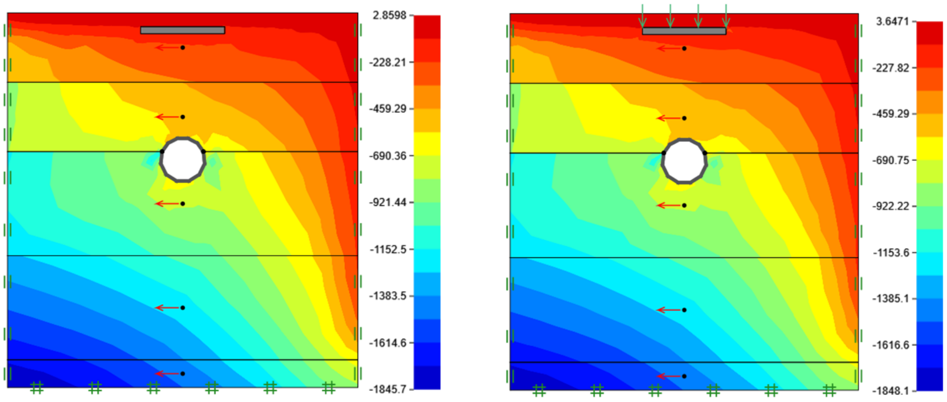
(a) (b)



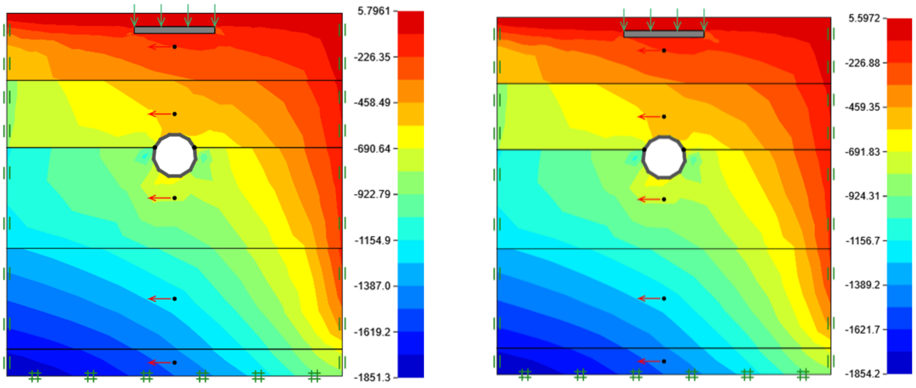
(c) (d)

Fig. 5. Contours of initial stress for (a) 0 kN/m^2, (b) 10 kN/m^2, (c) 20 kN/m^2 and (d) 30 kN/m^2 load of super structure before 0.7g of earthquake loading

The stresses developed in the soil surrounding the tunnel opening shows the load dispersion in the medium. Fig 5 and Fig 6 are shown for the initial stresses and final stresses after 0.7g magnitude of earthquake loading respectively. The initial stress observed for the 0kN/m^2, 10kN/m^2, 20 kN/m^2 and 30 kN/m^2 load of super structure is 1924.6 Pa, 2372.4 Pa, 2384.5 Pa and 2498.5 Pa respectively. After 0.7g of earthquake loading 2859.8 Pa, 3647.1 Pa, 5796.1Pa and 5597.2 Pa stresses were obtained for 0 kN/m^2, 10 kN/m^2, 20 kN/m^2 and 30 kN/m^2 load of super structure respectively. Therefore, stresses near the foundation increase as the load from the superstructure increases and hence it has to be incorporated in addition for the stresses in the tunnel lining.



(a) (b)



(c) (d)

Fig. 6. Contours of final stress for (a) 0 kN/m^2, (b) 10 kN/m^2, (c) 20 kN/m^2 and (d) 30 kN/m^2 load of super structure after 0.7g of earthquake loading

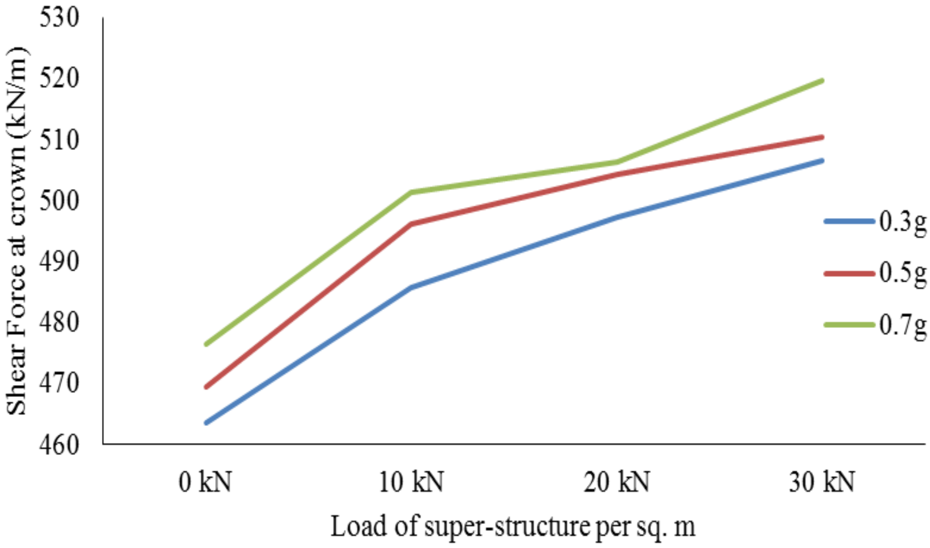


Fig. 7. Shear force at the crown for different magnitude of earthquake loading with increasing super structure load.

Fig 7 shows the variation of shear force at the crown of the tunnel for different magnitude of earthquake with increasing load from super structure. Almost linear behavior has been observed in all the cases, therefore, in addition to displacement and stresses, shear force has also significant role in the stability of the soil tunnel during an earthquake event. Fig 8 shows similar results as observed in Fig 7. It has been concluded that shear force must be calculated from the analysis before going for the construction.

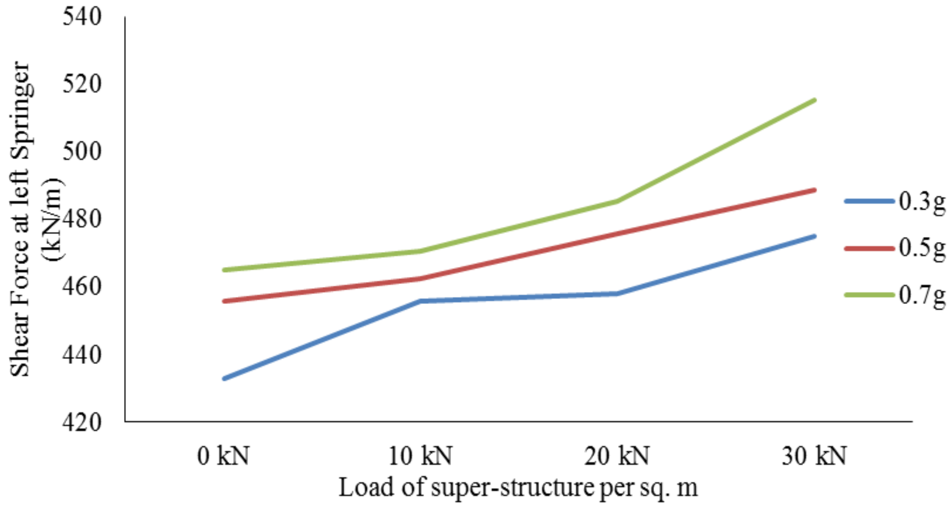


Fig. 8. Shear force at the springer for different magnitude of earthquake loading with increasing super structure load

4 Conclusions

The present study has been carried out to understand the behavior and the response of tunnel constructed in three different seismic zones. The displacement, shear force and stresses have been compared and discussed in the previous section. The major conclusions from the present study are:

1. The magnitude of displacement varies linearly with the amount of load from the superstructure in all the cases of earthquake events, i.e., 0.3g, 0.5g and 0.7g.
2. The stresses and shear force at the crown and springer of the tunnel found has significant influence of load from superstructure and the magnitude of earthquake event.
3. The change in the value of stresses around the periphery of the tunnel opening has significantly increases with the amount of load; however, the magnitude of earthquake has higher impact on the tunnel stability.

References

1. Zaid, M., Mishra, S. & Rao, K. S. Finite Element Analysis of Static Loading on Urban Tunnels. in IGC-2018 (2018).
2. Zaid, M., Shah, I. A. & Farooqi, M. A. Effect of Cover Depth in Unlined Himalayan Tunnel: A Finite Element Approach. in 8th Indian Rock Conference 448–454 (2019).

3. Athar, M. F., Zaid, M. & Sadique, M. R. Stability of Different shapes of Tunnels in Weathering Stages of Basalt. in Proceedings of National Conference on Advances in Structural Technology 320–327 (2019).
4. Ali Khan, M., Sadique, M. R. & Zaid, M. Effect of Stratification on Underground Opening: A Numerical Approach. in Lecture Notes in Civil Engineering vol. 34 133–142 (Springer, 2019).
5. Naqvi, M. W., Zaid, M., Sadique, M. R. & Alam, M. M. Dynamic Analysis of Rock Tunnels Considering Joint Dip Angle : A Finite Element Approach. in 13th International Conference on Vibration Problems (2017).
6. Zaid, M., Mishra, S. & Rao, K. S. Stability of Different Shapes of Himalayan Tunnels Under Blast Loading. in 8th Indian Rock Conference 375–380 (2019).
7. Zaid, M. & Sadique, M. R. Dynamic Analysis of Tunnels in Western Ghats of Indian Peninsula: Effect of Shape and Weathering. in INTERNATIONAL CONFERENCE ON RECENT TRENDS AND INNOVATIONS IN CIVIL ENGINEERING (ICRTICE-2019) (2019).
8. Zaid, M., Naqvi, M. W. & Sadique, M. R. Stability of Arch Tunnel in Different Magnitude of Earthquake with Effect of Weathering in Western Ghats of India. in Indian Geotechnical Conference (IGC2019) (2019).
9. Gahoi, A., Zaid, M., Mishra, S. & Rao, K. S. Numerical Analysis of the Tunnels Subjected to Impact Loading. in 7th Indian Rock Conference, (IndoRock2017) (Indorock2017, 2017).
10. Zaid, M., Athar, M. F. & Sadique, M. R. Effect of Rock Weathering on the Seismic Stability of Different Shapes of the Tunnel. in Indian Geotechnical Conference (IGC2019) (2019).
11. Wang, J. N. (1993). Seismic design of tunnels: a state-of-the-art approach, monograph, monograph 7. *Parsons, Brinckerhoff, Quade and Douglas Inc, New York*.
12. Brady, B. H., & Brown, E. T. (1993). *Rock mechanics: for underground mining*. Springer science & business media.
13. Hashash, Y. M., Hook, J. J., Schmidt, B., John, I., & Yao, C. (2001). Seismic design and analysis of underground structures. *Tunnelling and underground space technology*, *16*(4), 247-293.
14. Oraee, K., Hosseini, N., & Gholinejad, M. (2010). Seismic analysis of horseshoe tunnels under dynamic loads due to earthquakes. In *10th Underground Coal Operators' Conference 2010* (pp. 140-145). The Australasian Institute of Mining and Metallurgy.
15. Mishra, S., Rao, K. S., Gupta, N. K., & Kumar, A. (2017). Damage to shallow tunnels under static and dynamic loading. *Procedia engineering*, *173*, 1322-1329.
16. Manouchehrian, A., & Cai, M. (2017). Analysis of rockburst in tunnels subjected to static and dynamic loads. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(6), 1031-1040.
17. Liu, H., & Song, E. (2005). Seismic response of large underground structures in liquefiable soils subjected to horizontal and vertical earthquake excitations. *Computers and Geotechnics*, *32*(4), 223-244.
18. Azadi, M., & Hosseini, S. M. M. (2010). The uplifting behavior of shallow tunnels within the liquefiable soils under cyclic loadings. *Tunnelling and Underground Space Technology*, *25*(2), 158-167.
19. Zhao, K., Wang, Q., Wu, Q., Chen, S., Zhuang, H., & Chen, G. (2020). Stability of immersed tunnel in liquefiable seabed under wave loadings. *Tunnelling and Underground Space Technology*, *102*, 103449.

20. Mroueh, H., & Shahrour, I. (2003). A full 3-D finite element analysis of tunneling–adjacent structures interaction. *Computers and Geotechnics*, *30*(3), 245-253.
21. Pakbaz, M. C., & Yareevand, A. (2005). 2-D analysis of circular tunnel against earthquake loading. *Tunnelling and Underground Space Technology*, *20*(5), 411-417.
22. Shahin, H. M., Nakai, T., Zhang, F., Kikumoto, M., & Nakahara, E. (2011). Behavior of ground and response of existing foundation due to tunneling. *Soils and foundations*, ***51***(3), pp. 395-409.
23. Zaid, M., Irfan, S., Farooqi, M.A. (2019). Effect of Cover Depth in Unlined Himalayan Tunnel: A Finite Element Approach. In the proceeding of *8th Indian Rock Conference,* Indian International Centre, New Delhi, India, 03-04 March 2019, ISBN No. 81-86501-27-1.
24. Krabbenhoft, K., Lyamin, A., & Krabbenhoft, J. (2015). Optum computational engineering (OptumG2). *Computer software]. Retrieved from https://www. optumce. com.*
25. Singh, M., Viladkar, M. N., & Samadhiya, N. K. (2017). Seismic analysis of Delhi metro underground tunnels. *Indian Geotechnical Journal*, *47*(1), 67-83.