Proceedings of the 10th World Congress on Civil, Structural, and Environmental Engineering (CSEE 2025)
Barcelona, Spain - April, 2025
Paper No. ICSECT 145
DOI: 10.11159/icsect25.145

Understanding Material Characteristics and Cover Depth Impact on Urban Metro Tunnels under Seismic Vulnerability: A Numerical Study

Pranav Mahajan[1], B. N. Rao[1]
[1] Structural Engineering Division, Department of Civil Engineering,
Indian Institute of Technology Madras, Chennai, Tamil Nadu, India – 600036
ce23d018@smail.iitm.ac.in; bnrao@iitm.ac.in

Abstract - The behavior of underground tunnels in urban regions requires careful consideration of the complex underground conditions and involves designing the underground tunnel system in vulnerable seismic conditions. Studies have indicated consequences in underground tunnels during and after ground excitation, which needs engineering assessment to ensure structural safety. In the current study, the impact of seismic vulnerability is analysed for site condition variability and overburden depth under different ground motion impacts in x and y directions to understand the tunnel stability and improve seismic resistance. Analysis of seismic vulnerabilities is carried out using three analytical frameworks, which includes linear static, eigenvalue, and nonlinear time history analysis. Simulation of the tunnel behavior under such conditions is carried out using finite element software, MIDAS GTS NX for determining the structural sensitivity to material characteristics variation and overburden pressure for different earthquakes. Acceleration time history analysis of Tokachi and Tohoku Coast earthquakes is used to determine the behavior. The behavior suggested that the maximum settlement, axial force, and bending moment have a significant influence on material characteristics compared to the seismic impact. Increase in tunnel overburden depth also leads to higher axial force and bending moment, which is also influenced by the seismic ground motion observed. These outputs provide comprehension of the tunnel behavior under different materials and overburden depth subjected to different ground motion, which can be utilized for designing the seismic isolators provided between tunnel lining and surrounding soil.

***Keywords*:** Soil-Structure Interaction; Seismic Analysis; Numerical Modelling; MIDAS GTS NX; Non-linear Time History Analysis

1. Introduction

Underground metro tunnels require seismic design consideration in regions subjected to periodic earthquakes of high magnitude or in areas lying under high seismic risk zones. These underground structures should utilize seismic-resistant methods to avoid structural damage in such high-risk zones. Provision of flexible connections, seismic isolators and real-time instrumentation helps in the detection and mitigation of damage by such events [1], [2]. Tunnels with low overburden are more prone to seismic effects, compared to tunnels with high overburden [3]–[5]. Various experimental and numerical studies are carried out to analyze seismic effects on different tunnel components. Detailed geological investigation and safety equipment are essential to decrease earthquake impact on underground structures, leading to reduced damage and more operational service life. Owen and Scholl [6] determined the tunnel deformation mode, which includes axial deformation, ovaling, racking and rocking. Cilingir and Madabhushi [7], [8] analysed the dry sand tunnel behavior under seismic conditions using centrifuge experiments to understand the soil entry effects. Various experimental [9], [10], numerical [11]–[14], and analytical [8], [15] studies determined the tunnel behavior under ground motion.

The Himalayan belt in the Indian subcontinent witnessed large seismic events, as observed by Kashmir earthquake in 2015 (Mw 7.6) and Gorkha earthquake in 2015 (Mw 7.8) [16], [17]. India's national capital, Delhi observed tremors due to earthquakes multiple times. With rapid urbanization, Delhi has large infrastructural projects to be constructed having national importance. Delhi metro system is one such spider web spread over the whole Delhi region and is increasing its limits day by day. The occurrence of any earthquake within the metro zone limits serves as a warning to investigate underground metro tunnel strength and damage resistance. Previously, analysis of material characteristics and tunnel overburden depth is neglected in understanding the tunnel behavior under such conditions. The main objective of the study is to analyze the tunnel systems under different seismic conditions to determine the seismic design requirements and thus prevent any catastrophic design failure.

In this research, numerical modelling of the dynamic behavior of metro tunnels is analysed when subjected to different seismic motions. Material characteristics of the Delhi metro system [18] is considered as the reference. This acts as an inference to the geological conditions under urban transportation system. The behavior obtained, in this study, can be utilized for seismic design of the other metro tunnels under coherent seismic conditions worldwide. The numerical analysis comprehends tunnel behavior and concrete lining reaction subjected to multiple seismic ground motions in different material conditions. Parametric analysis of tunnel subjected to different material conditions and tunnel overburden under different earthquakes is carried out. It is observed that the material characteristics has high impact level on the mechanical structural behavior compared to the seismic effect of earthquake. In contrast, the seismic effect provides high influence to the structural behavioral characteristics in comparison to the material characteristics. So, both parameters affecting the tunnel structure are critical for the seismic analysis. Out of two, material characteristics have a deterministic impact and overburden depth has non-deterministic impact due to its significant dependence on seismic effect.

2. Numerical Modelling

Designing of underground tunnels is extremely challenging in areas prone to high seismic activities [18]. Earlier studies have employed a variety of methodologies to understand the tunnel behavior in seismic conditions. Numerical analysis of such conditions provide in-depth analysis to the structural behavior. Research in lower Himalayan region [19] subjected to Uttarkashi earthquake, 1991 and seismic behavior in liquefiable deposits [20] provides better understanding to the dynamics and response of tunnels under seismic behavior.

In this study, 3D soil-structure model is utilized for simulating the behavior of tunnel structure. The numerical simulation is carried out using finite element software, MIDAS GTS NX to analyze the dynamic behavior of the tunnel under different seismic conditions. The numerical methodology procedure involving geometric modelling, selection of elements type, loading and boundary condition application, and constitutive material model selection is described in the next section. Further, the study aims to determine the impact of the parameters involved and understand the tunnel response under seismic conditions.

2.1. Geometry Modelling

The geometry modelling of a circular tunnel section with diameter of 6.35m and 275mm lining thickness (T1) is generated. The material property for concrete tunnel lining is considered elastic-isotropic. The soil surrounding the concrete tunnel section is modelled under two different overburden depths, 10m and 20m. Therefore, two geometric models of size (60×1×36.35) m, and (60×1×46.35) m in x, y, and z directions respectively are established. Two different types of surrounding soil, highly weathered quartzite (R1) and loose sand (R3) utilizing Mohr-Coulomb failure criterion is used for the constitutive modelling of the surrounding soil. The material properties utilized in the study are obtained from the technical investigation report of the Delhi metro. For the analysis purpose, surrounding soil is assumed to be homogenous and isotropic.

Table 1 depicts the material characteristics of the surrounding soil and tunnel lining utilized for numerical modelling. Figure 1 illustrates the 3D finite element model (FEM) involving 3D hybrid mesh elements for modelling the surrounding soil elements. For tunnel concrete lining, 2D shell mesh elements of uniform thickness are extracted. MIDAS GTS NX, a finite element software is utilized to develop the numerical tunnel model evaluating the soil-structure interaction under seismic conditions. To remove the interacting mesh faces and fuse the different geometry parts, the Boolean auto-connect algorithm is utilized.

2.2. Seismic Loading

Three different time-history datasets, as selected from MIDAS database, are used as ground acceleration motion for different tunnel models. The details of these time-history datasets is provided in Table 2. These selected datasets acts as input for the Non-linear time history analysis of soil-tunnel system to examine their dynamic response subjected under different seismic conditions. Acceleration time history response for the three different seismic conditions are illustrated in Figure 2. These datasets are applied in both transverse and longitudinal direction in reference to the tunnel longitudinal axis. In specific, the time-history data is provided in x-direction and y-direction respectively to determine the variation in dynamic response of the soil-tunnel system under different seismic conditions.

Further, application of geostatic condition causes ovaling in the tunnel concrete lining during insitu stage. This requires detailed analysis of tunnel lining under seismic effects. Later on, to analyse the maximum seismic effect on the tunnel lining, full ground acceleration is provided under extreme seismic conditions.

Table 1: Properties of Materials Utilized

Description	*Highly weathered quartzite (R1)*	*Loose Sand (R3)*	*Lining (T1)*
Unit Weight (γ) (kN/m^3)	25	19	24
Poisson's Ratio (ν)	0.3	0.25	0.2
Elastic Modulus (E) (MPa)	200	60	31600
Cohesion (c) (kPa)	15	10	-
Friction Angle (φ) (degree)	31	30	-
Damping Ratio (%)	5	5	5

Table 2: Selected Earthquakes

Description	*Moment Magnitude (M_w)*	*Year*	*PGA (g)*
Tokachi-Coast, EW	8.3	2003	0.5484
Tohoku-Coast, EW	9.1	2011	0.8105
Tohoku-Coast, NS	9.0	2011	0.7065

2.3. Boundary Constraints

Analysis of tunnel lining under seismic conditions requires free field boundary conditions at the vertical edges of the tunnel section. This provides a semi-infinite medium for the seismic wave to travel within the soil medium. At the bottom, fixed boundary constraint is provided representing a rigid base system. However, the utilization of normal constraints on all the vertical sides will cause reflection of the seismic wave from the tunnel boundary. This leads to additional force and stress on the tunnel lining which is not observed in actual site conditions.

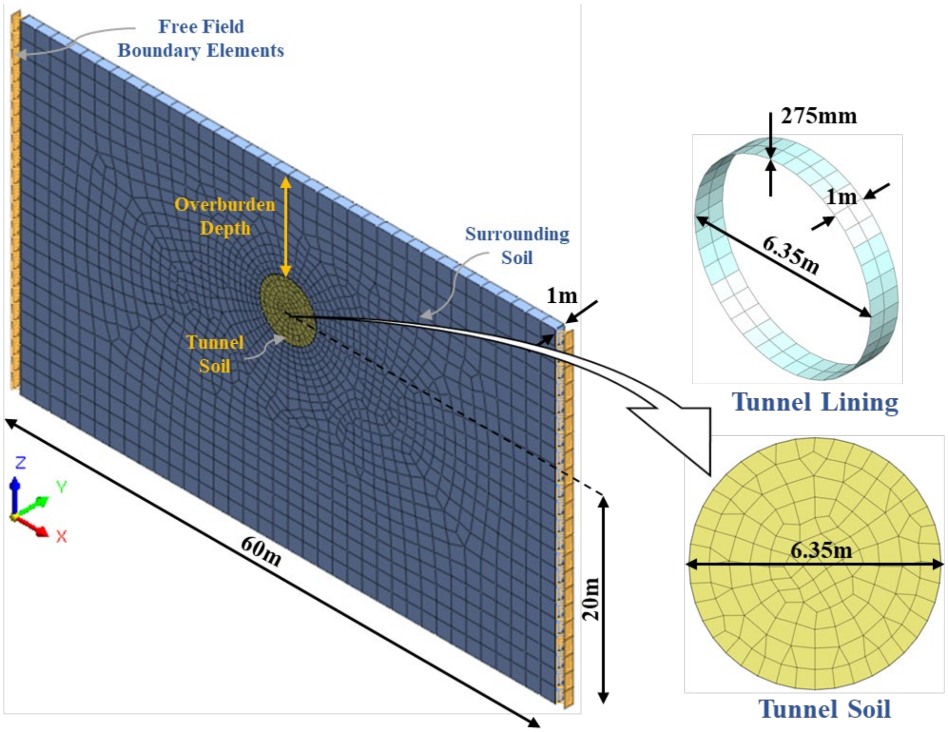

Fig.1: 3D FEM Model of Tunnel components

3. Seismic Analysis

For the present study, the methodology involved in seismic analysis is categorized into six categories: (1) 3D numerical model creation, including material, loading and boundary characteristics, (2) Linear Static Analysis, considering only self-weight, (3) Eigenvalue Analysis, (4) Non-linear time history analysis, for different earthquake dataset considered, (5) Analysis of results, for maximum displacements, axial forces and bending moments, and (6) Sensitivity of the data obtained. The tree diagram depicting the steps involved is shown in Figure 3. This sensitivity analysis is carried out for two major factors, material characteristics and tunnel overburden depth. The analysis provides the determinacy and impact of the parameters under different seismic conditions.

Linear static analysis determines the deformation behavior of the surrounding soil and tunnel lining subjected to self-weight. In order to carry out dynamic analysis, eigenvalue analysis is performed to determine the natural frequencies, time period and mode shape of the tunnel. The analysis has provided the maximum values of the percentage of modal mass in a particular direction where ground acceleration is provided. These values are then utilized for the non-linear time history analysis. In this analysis, simulation in response to different seismic effects is carried out to determine the soil and tunnel lining behavior. This framework comprising six different steps is utilized for the comprehensive assessment of the seismic behavior and its impact on the tunnel lining.

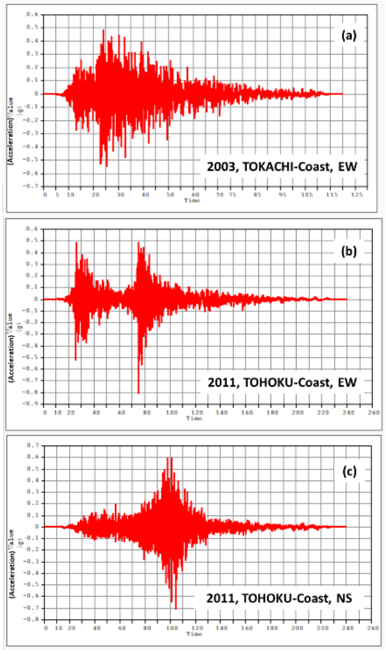

Fig.2: Acceleration time histories of different earthquakes

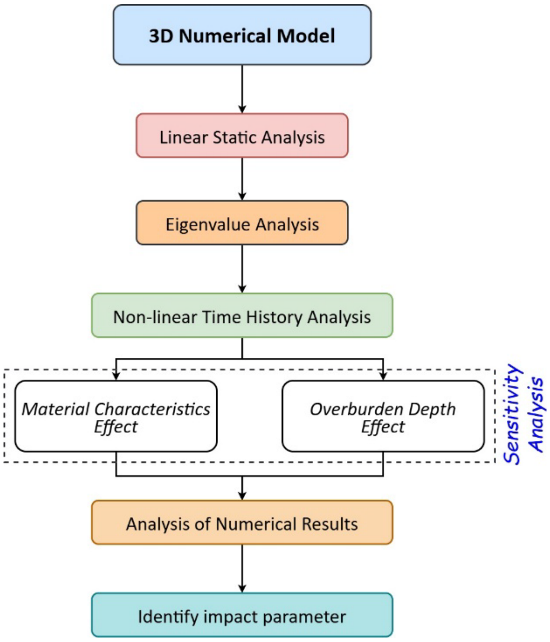

Fig.3: Procedural Methodology for seismic analysis of structure

In eigenvalue analysis, total 50 mode shapes are determined in each analysis. Two mode shapes corresponding maximum percentage of modal mass is used for non-linear time history analysis. In non-linear time history analysis, time step of 0.02 s for total time period of 10 s is carried out. This has generated 500 steps analysis under corresponding seismic response. Maximum settlement, bending moment and axial force under two different material characteristics and overburden depth subjected to three different ground motions are the considered as output data for determination of behavior and impact.

4. Results

4.1. Linear Static Analysis

The structural behavior of the model under self-weight load is analysed using linear static analysis for each case to understand the material and overburden depth effect. The analysis includes determination of axial force and bending moment using results obtained from the numerical simulations. The results obtained for each effect are summarized in Table 3 and 4 respectively. Results showed the decline in values of axial forces by 10.29% and increase in bending moment values by 129.31% when material characteristics changes from R1 to R3. The results indicated the vital impact of surrounding soil material characteristics on the tunnel lining behavior in the insitu analysis. Further, as the overburden depth increases from 10m to 20m, both axial force and bending moment illustrated increase in the values obtained. For the R1 case, the values obtained for axial force and bending moment are increased by 75.70% and 67.05% respectively. For the R2 case, these values are increased by 75.71% and 68.73% respectively.

Table 3: Linear Static Tunnel Behavior under material effect

Material Property Effect		
Maximum Linear Static Response	Material Type	
	R1T1/10m	**R3T1/10m**
Axial Force (kN/m)	-1182.72	-1061.04
Bending Moment (kNm/m)	43.3534	99.4177

Table 4: Linear Static Tunnel Behavior under overburden depth effect

Overburden Effect				
Maximum Linear Static Response	Material Type/Tunnel Depth			
	R1T1/10m	**R1T1/20m**	**R3T1/10m**	**R3T1/20m**
Axial Force (kN/m)	-1182.72	-2078.08	-1061.04	-1864.34
Bending Moment (kNm/m)	43.3534	72.4237	99.4177	167.747

The results depicted the significant impact of overburden depth on the tunnel lining response, defining a correlation between the increased axial forces and bending moment with increasing depth. The contour diagrams for all the different cases under linear static analysis for the axial force and bending moment are provided in Figures 4 and 5 respectively.

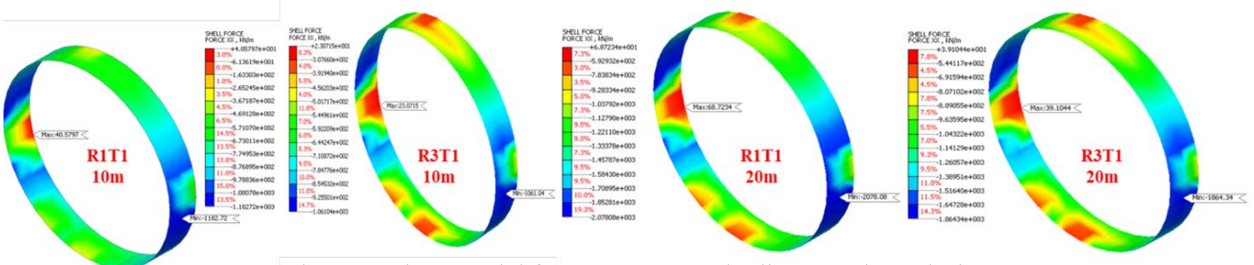

Fig.4: Maximum axial force contours under linear static analysis

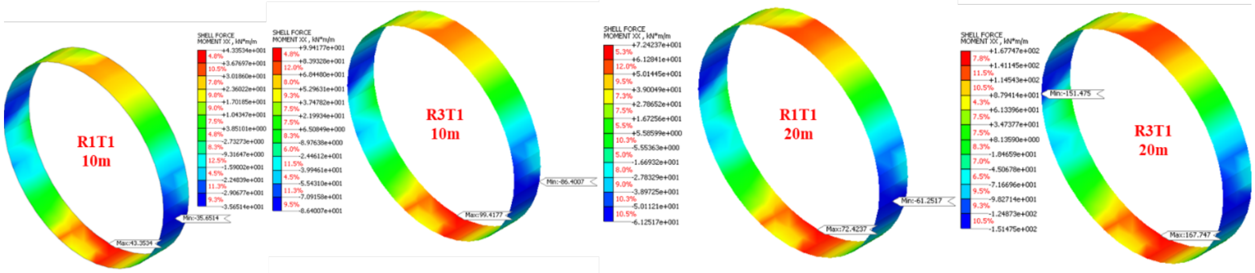

Fig 5: Maximum bending moment contours under linear static analysis

4.2. Eigenvalue Analysis

After determining the linear static behavior, eigenvalue analysis is carried out to determine the dynamic behavior of the soil-tunnel system. This analysis is used to determine the natural frequencies and mode shapes of different models under different seismic earthquakes. Lanczos algorithm is used for the numerical simulation of the eigenvalue analysis. The algorithm is based upon power iteration method, which provides natural frequencies and mode shapes utilizing assumed mode shape in the first iteration. As the iterations converges, exact value of natural frequencies and mode shapes are obtained.

In order to determine the impact of seismicity on the tunnel lining characteristics, seismic motion is provided in x and y direction separately. The eigenvalues obtained under different conditions for seismic effect considered in x and y-direction are provided in Table 5 and 6 respectively. The mode shapes selected for the analysis, represented in Table 5 and 6, are considered based upon the maximum percentage of modal mass. This modal mass percentage accumulates to more than 90% for two modes considered for further analysis. With close to 90% modal mass considered for dynamic response, the accuracy of the model under different conditions provides better accuracy. The eigenvalue analysis depicted that both material characteristics and overburden depth influence the dynamic behavior of tunnel structure. The values obtained for natural frequencies for two modes in each case will be utilized for non-linear time history analysis.

Table 5: Eigenvalue Analysis for seismic ground motion in x-direction

Along x Direction						
Parameter Considered	**Material**	**Lining Thickness**	**Overburden (m)**	**Eigenvalue Analysis**		
				Mode No.	**Cycles**	**Natural period (s)**
Material Property Effect	R1	T1	10	26	1.194434	0.8372169
				75	3.577214	0.2795472
	R3	T1	10	28	0.7653014	1.306675
				76	2.292004	0.4362994
Overburden Effect	R1	T1	10	26	1.194434	0.8372169
				75	3.577214	0.2795472
		T1	20	29	0.936811	1.067451
				79	2.807485	0.3561906
	R3	T1	10	28	0.7653014	1.306675
				76	2.292004	0.4362994
		T1	20	29	0.6002366	1.66601
				79	1.798821	0.5559196

Table 6: Eigenvalue Analysis for seismic ground motion in y-direction

Along y Direction						
Parameter Considered	**Material**	**Lining Thickness**	**Overburden (m)**	**Eigenvalue Analysis**		
				Mode No.	**Cycles**	**Natural period (s)**
Material Property Effect	R1	T1	10	3	0.05290665	18.90121
				9	0.3289339	3.040125
	R3	T1	10	3	0.03251216	30.75773
				9	0.202223	4.945036
Overburden Effect	R1	T1	10	3	0.05290665	18.90121
				9	0.3289339	3.040125
		T1	20	3	0.03259049	30.6838
				9	0.2032394	4.920306
	R3	T1	10	3	0.03251216	30.75773
				9	0.202223	4.945036
		T1	20	3	0.02002835	49.92923
				9	0.1249332	8.004279

4.3. Non-Linear Time History Analysis

The non-linear time history analysis is carried out for three different seismic events. The seismic event details are delineated in Table 2. The analysis is conducted based on two considered factors: (1) Material Property, and (2) Overburden Depth. In the analysis, maximum values of the surface and crown vertical displacements, axial force, and bending moment for different cases are reviewed. All these reviewed parameters are compared for seismic ground motion in both x and y-direction. The observed effect under different material characteristics and overburden depth is reviewed in next sections.

4.3.1. Surface and Tunnel Crown Displacement

The surface displacement and tunnel crown displacement are analysed at the centre of the tunnel section under three different seismic ground motions. The analysis for different material characteristics (R1, R3) and overburden depths (10m, 20m) is carried out for seismic ground motions in the x and y directions. In x-direction, H24_T1-I-1 earthquake leads to maximum ground displacement in range of (215-222) mm. For H24_T1-I-2 and H24_T1-I-3 earthquakes, the displacement values lie in (25-27) mm, as depicted in Fig. 6(a-c). The displacement values observed over tunnel crown and ground surface are approximately equal. However, neither material characteristics nor overburden depth have significantly affected surface displacement. But, variation in seismic effect depicts changes in ground displacement observed in different cases. In y-direction earthquake, the displacement values observed in ground surface is more compared to tunnel crown displacements. These values vary with characteristics of different earthquakes. Further, the displacement values observed over tunnel crown decreases with changing material characteristics for 10m overburden depth. The behavior for 20m overburden depth is vice-versa, as illustrated in Fig. 6(d-f). But, ground displacements always increases with increasing overburden depth. The displacement values increases by 25%, 108%, and 27% for R1T1/10m tunnel when measured at ground in comparison to tunnel crown. However, these values vary significantly for different tunnel studied. Additionally, the displacement values for y-direction earthquake are comparatively smaller than x-direction earthquake. Therefore, significant variation in displacement values are observed for different material characteristics and overburden depth under various seismic ground motions in both x and y directions.

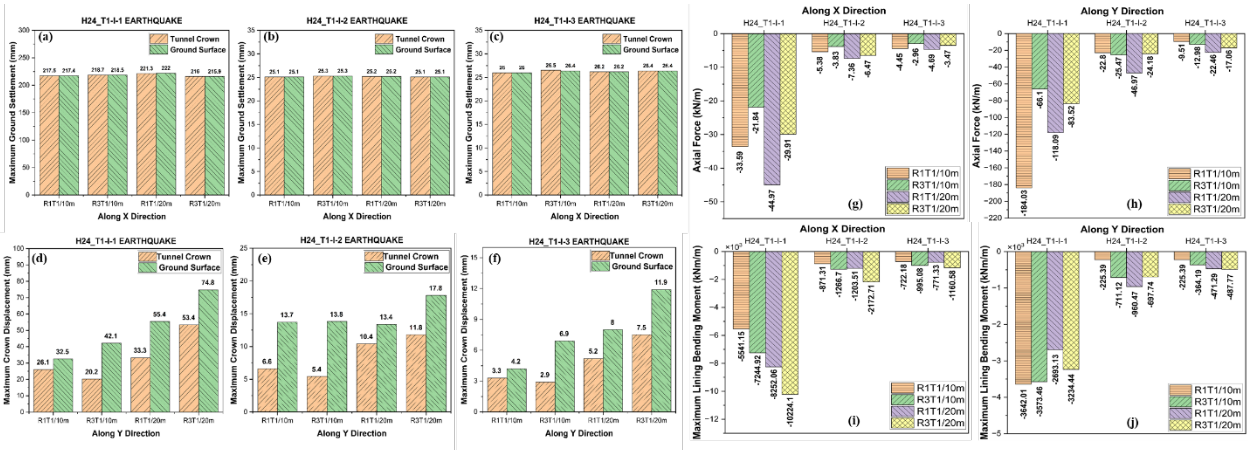

Fig 6: Behavior of Soil-Tunnel System under non-linear time history analysis

4.3.2. Axial Force

To determine the effect of different seismic ground motions on tunnel lining, axial force under different material characteristics and overburden depth is analysed. The impact of H24_T1-I-1 earthquake leads to large values of axial force, compared to others. For this earthquake, the axial force value for R1T1/10m is 33.59 kN, but the surrounding material change for R3T1/10m causes axial force 44.97 kN, which is 34% higher than the former case. This indicates the effect of material strength on the axial force of the tunnel lining, when highly weathered material changes to loose sand. Further, overburden depth causes a decrease in axial force by (33-35) % for same material characteristics. Same behavior is observed when earthquake occurs in y-direction. However, values observed in y-direction are more than in the x-direction. The values observed in different cases are illustrated in Fig. 6(g-h). These values vary for different earthquakes analysed in this paper.

4.3.3. Bending Moment

Bending moment and axial force determine the effect of different behavioral characteristics on tunnel lining. The observed behavior is vice-versa for bending moment as that of axial force. In this, for H24_T1-I-1 earthquake along x direction, the bending moment values increase as material characteristics change from R1 to R3. In the same way, bending moment also increases with increase in overburden depth from 10m to 20m having the same material characteristics. The percentage increase in bending moment amounting 31% and 41% is observed for changes in material characteristics and overburden depth respectively. The maximum value of bending moment is observed in this case. As the value of the seismic ground motion changes, bending moment variation for different cases is observed. However, along the y-direction, the behavior observed in different scenarios is opposite to x-direction behavior. In this, bending moment values decrease with changes in both material characteristics and overburden depth. Fig. 6 (i-j) depicts the bending moment values under different conditions along the x and y directions.

5. Results

This study analyses the dynamic behavior of the tunnel under different seismic ground motions. To determine the behavior, numerical models are studied under different material characteristics and overburden depth. The observed findings are provided as under:

5.1. Material Property Effect

Material properties do not have a significant impact on the displacement characteristics of the ground surface and tunnel crown. This displacement behavior is mostly influenced by the seismic ground motion effect. However, the dynamic behavior of tunnel lining is affected by changes in material characteristics. The axial force and bending moment of tunnel lining depicted more influence of material property than seismic ground motion effects. As material R3 affected the deformation behavior of tunnel lining more than material R1, therefore, the material stiffness needs to be thoroughly investigated to reduce deformation and increase resistance against seismic effects.

5.2. Overburden depth effect

The seismic effect demonstrated more influence than the overburden depth on the axial force and bending moment of the tunnel lining. Also, the axial force and bending moment increases with increase in overburden depth. Therefore, tunnels constructed in high seismic zones need to consider the optimum depth such that the seismic effect by earthquake gets reduced, and not much affected by the overburden depth. This helps in maintaining the structural integrity during the occurrence of seismic events. Therefore, analysis of the soil-tunnel system under different seismic events provided the impact of different material characteristics and overburden depth. The pivotal influence of material properties of surrounding soil and tunnel lining is much more significant than the geometrical effects such as overburden depth. As this overburden depth is largely affected by the seismic effects, tunnel design based on unpredictable seismic effect cannot be provided. Considering the above, for the seismic effect resistance, tunnel lining material stiffness, thickness and optimum overburden depth can lead to reduced stress, structural forces and deformational behavior under different seismic effects.

6. References

[1] K. Aziz, R. A. Mir, and A. Ansari, “Precision modeling of slope stability for optimal landslide risk mitigation in Ramban road cut slopes, Jammu and Kashmir (J&K) India,” *Model. Earth Syst. Environ.*, vol. 10, no. 3, pp. 3101–3117, 2024, doi: 10.1007/s40808-023-01949-2.

[2] J. Ciurlanti, S. Bianchi, and S. Pampanin, *Raising the bar in seismic design: cost–benefit analysis of alternative design methodologies and earthquake-resistant technologies*, vol. 21, no. 5. Springer Netherlands, 2023. doi: 10.1007/s10518-023-01625-x.

[3] J. He, W. Chen, W. Zhao, S. Huang, and Y. Yao, “Numerical test on polystyrene tunnel seismic-isolation material,” *Polish J. Chem. Technol.*, vol. 18, no. 3, pp. 122–127, 2016, doi: 10.1515/pjct-2016-0058.

[4] D. Xu,H.; Li, T.; Xia, L.; Zhao, J.X.; Wang, “Shaking table tests on seismic measures of a model mountain tunnel,” *Tunn. Undergr. Sp. Technol*, no. 60, pp. 197–209, 2016.

[5] X. Liu, Y. Zhuang, X. Zhou, C. Li, B. Lin, N. Liang, Z. Zhong, and Z. Deng, “Numerical study of the mechanical process of long-distance replacement of the definitive lining in severely damaged highway tunnels,” *Undergr. Sp.*, vol. 9, pp. 200–217, 2023, doi: 10.1016/j.undsp.2022.07.007.

[6] Z. Y. Chen and H. Shen, “Dynamic centrifuge tests on isolation mechanism of tunnels subjected to seismic shaking,” *Tunn. Undergr. Sp. Technol.*, vol. 42, pp. 67–77, 2014, doi: 10.1016/j.tust.2014.02.005.

[7] U. Cilingir and S. P. Gopal Madabhushi, “A model study on the effects of input motion on the seismic behaviour of tunnels,” *Soil Dyn. Earthq. Eng.*, vol. 31, no. 3, pp. 452–462, 2011, doi: 10.1016/j.soildyn.2010.10.004.

[8] U. Cilingir and S. P. G. Madabhushi, “Effect of depth on the seismic response of square tunnels,” *Soils Found.*, vol. 51, no. 3, pp. 449–457, 2011, doi: 10.3208/sandf.51.449.

[9] M. Patil, D. Choudhury, P. G. Ranjith, and J. Zhao, “A Numerical Study on Effects of Dynamic Input Motion on Response of Tunnel-Soil System,” *16th World Conf. Earthq. Eng.*, pp. 1–10, 2017.

[10] G. Tsinidis, E. Rovithis, K. Pitilakis, and J. L. Chazelas, “Seismic response of box-type tunnels in soft soil: Experimental and numerical investigation,” *Tunn. Undergr. Sp. Technol.*, vol. 59, pp. 199–214, 2016, doi: 10.1016/j.tust.2016.07.008.

[11] A. Bobet, “Drained and undrained response of deep tunnels subjected to far-field shear loading,” *Tunn. Undergr. Sp. Technol.*, vol. 25, no. 1, pp. 21–31, 2010, doi: 10.1016/j.tust.2009.08.001.

[12] X. Yuanliang, Z. Chao, C. Chun, and Z. Yamei, “Effect of superabsorbent polymer on the foam-stability of foamed concrete,” *Cem. Concr. Compos.*, vol. 127, no. July 2021, p. 104398, 2022, doi: 10.1016/j.cemconcomp.2021.104398.

[13] S. Kontoe, L. Zdravkovic, D. M. Potts, and C. O. Menkiti, “On the relative merits of simple and advanced constitutive models in dynamic analysis of tunnels,” *Geotechnique*, vol. 61, no. 10, pp. 815–829, 2011, doi: 10.1680/geot.9.P.141.

[14] A. Amorosi and D. Boldini, “Numerical modelling of the transverse dynamic behaviour of circular tunnels in clayey soils,” *Soil Dyn. Earthq. Eng.*, vol. 29, no. 6, pp. 1059–1072, 2009, doi: 10.1016/j.soildyn.2008.12.004.

[15] H. Huo, A. Bobet, G. Fernández, and J. Ramírez, “Load Transfer Mechanisms between Underground Structure and Surrounding Ground: Evaluation of the Failure of the Daikai Station,” *J. Geotech. Geoenvironmental Eng.*, vol. 131, no. 12, pp. 1522–1533, 2005, doi: 10.1061/(asce)1090-0241(2005)131:12(1522).

[16] A. Ansari, K. S. Rao, and A. K. Jain, “Seismic Vulnerability of Tunnels in Jammu and Kashmir for Post Seismic Functionality,” *Geotech. Geol. Eng.*, vol. 41, no. 2, pp. 1371–1396, 2023, doi: 10.1007/s10706-022-02341-0.

[17] A. J. Avouac JP, Meng L, Wei S, Wang T, “Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquakeLower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake,” *Nat Geosci*, vol. 8(9), pp. 708–711, 2015.

[18] A. Ansari, K. S. Thadagani, K. Seshagiri Rao, S. Shekhar, and A. E. Alluqmani, “Assessing seismic vulnerability in metro systems through numerical modeling: enhancing the sustainability and resilience of urban underground utilities (3U),” *Innov. Infrastruct. Solut.*, vol. 9, no. 10, pp. 1–26, 2024, doi: 10.1007/s41062-024-01685-1.

[19] M. A. Azad, T. Najeh, A. K. Raina, N. Singh, A. Ansari, M. Ali, Y. Fissha, Y. Gamil, and S. K. Singh, "Development of correlations between various engineering rockmass classification systems using railway tunnel data in Garhwal Himalaya, India," *Sci. Rep.*, vol. 14, no. 1, pp. 1–14, 2024, doi: 10.1038/s41598-024-60289-y.

[20] R. B. Jishnu and R. Ayothiraman, "Seismic behaviour of Delhi metro tunnels in liquefiable deposits," *Nat. Hazards*, vol. 111, no. 3, pp. 2261–2280, 2022, doi: 10.1007/s11069-021-05136-3.