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A NUMERICAL STUDY ON EFFECTS OF DYNAMIC INPUT MOTION ON RESPONSE OF TUNNEL-SOIL SYSTEM

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Abstract

A tunnel is an underground horizontal passage that is constructed to provide services such as transportation, storage places, water, wastewater lines, and the like. Since the tunneling depth in most of the large cities is shallow and lies within the soft ground zone, it is clear that there is a need for a complete understanding of tunnel behavior in soft ground. Underground facilities constructed in soft soils and weak rocks are more vulnerable to earthquake loads when compared to those that are constructed in intact rock. Tunnels experience large stresses, and severe damages may occur when they are subjected to dynamic loading. Hence, proper consideration of an earthquake event in the analysis of tunnels is very important to ensure that these tunnels are safe and stable. In this study, a fully non-linear plane strain analysis was performed using the finite element program, PLAXIS2D AE.02 in order to examine the influence of the dynamic input motion parameters on the behavior of a tunnel during an earthquake. A numerical model is validated by centrifuge test results against tunnel-induced surface settlement in a static condition. The same numerical model is extended to carry out dynamic analyses by using input motions of different amplitudes and frequencies. A parametric study shows that the dynamic axial force and bending moment in a tunnel lining increases with an increase in the magnitude of the earthquake. The results show that the maximum and residual dynamic earth pressure around the tunnel lining is enormously affected by the magnitude and duration of the maximum base acceleration.

Keywords: Seismic behavior; Shallow tunnel; Soft soil; Input ground motion; Numerical analysis

1. Introduction

The demand for public transport has increased with an increase in the population in urban areas. Due to the difficulty in the expansion of surface infrastructure, the construction of underground tunnels for transportation and utilities will be the future demand. In developing metropolitan cities, underground mass rapid transit (MRT) systems are gaining popularity because of their ability to serve as an effective form of transportation. The construction of underground structures is always associated with additional forces that are generated by movements in the surrounding ground. The ground movement that is generated during an earthquake causes damage to sub-surface structures and adjacent existing surface structures. The devastating effects of an earthquake on tunnels are well known. Damages observed in recent earthquake events (St. Fernando earthquake, 1971; Miyagi earthquake, 1978; Kobe earthquake, 1995; Duzce earthquake, 1999; Chi-Chi earthquake, 1999; Niigata earthquake, 2004; Wenchuan earthquake, 2008) have proved that underground structures are vulnerable to earthquakes. The tunnel may experience a large change in the stress state due to deformations or may even collapse under such circumstances [1, 2]. When compared to above-ground structures, the seismic response of underground structures has not been explored much due to inadequate field observations and experimental data [3]. Most of the urban transportation tunnels lie within comparatively soft soil strata at shallow depths. During an earthquake, underground tunnels that are constructed in soft soil or weak rocks at shallow depths experience more damages in comparison to deeper tunnels that are constructed in intact rock. An earthquake results in ground shaking and ground failure, which causes a change in the ground stress-state. This change in the stress state imposes an additional load on the tunnel lining, which can lead to the cracking of the tunnel lining. The damages that have been observed in past earthquakes have necessitated an accurate prediction of earthquake-induced forces in the tunnel lining [4, 5]. A number of past studies have shown a significant increment in tunnel lining forces under seismic conditions [6, 7, 8]. Therefore, an accurate estimation of lining forces, which can minimize the adverse effects of earthquakes, is required in tunneling practices. In the literature, the effect of various parameters such as tunnel flexibility, ground density, and tunnel ground cover on the dynamic behavior of tunnels was studied by centrifuge tests and numerical analyses [9, 10, 11, 12]. Many researchers have investigated the dynamic response of tunnels to seismic shaking by using numerical modeling and have presented the results that were in close agreement with experimental or analytical solutions [12, 13, 14, 15, 16]. Patil et al. [17] presented the summary of various approaches used in the seismic analysis of tunnel. It was found that the effect of the input motion on the stability of the tunnel has not been investigated enough.

The main objective of this paper is to investigate the seismic behavior of shallow tunnels that are constructed in soft soil. The tunnel-soil system was modeled using the finite element-based geotechnical software, PLAXIS2D AE.02 in order to perform the plane strain numerical analysis. Centrifuge test data [18, 19] were used to validate the developed finite element model. In dynamic analyses, the energy dissipation and consequent amount of damping is introduced through the frequency-dependent Rayleigh formulation in terms of viscous damping. A parametric study has been carried out in order to understand the effect of the input ground motion. Numerical modeling is described in detail, and the results are reported in the form of the distribution of acceleration with depth; the distribution of the maximum dynamic earth pressure, the residual earth pressure around the tunnel, and the variation of the axial force and the bending moment in the tunnel lining.

2. Experimental benchmark

Divall and Goodey [18] performed a series of centrifuge tests on small-scale model tunnels in clay, in City University, London. The experiments were conducted in order to investigate tunnel-induced settlements and pore pressure distribution in clay. Two of these successful tests were conducted on the single circular tunnel with three percentage of volume loss; the others were conducted on twin tunnel models. In the present work, the data of a single tunnel centrifuge tests are used to validate the numerical model. The tests were conducted on a reduced scale model at 100g; the model had a 50 mm diameter tunnel at a depth of 100 mm. This is equivalent to a tunnel that has a diameter of 5 m at a depth of 10 m in a prototype scale. The model had a length of 550 mm and depth of 207 mm, which implies a field dimension of a length of 55 m and a depth of 20.7 m at a prototype scale. Speswhite kaolin clay that had an undrained shear strength of 40 kPa was used in the tests. The properties of kaolin clay are as shown in Table 1.

Table 1 – Material properties of Speswhite kaolin clay [20]

Material property	Symbol	Values
Unit weight of soil (saturated clay)	γ_{sat} (kN/m³)	17.5
Specific gravity	G	2.61
Initial void ratio	e_{init}	1.931
Angle of shearing resistance	ϕ	23°
Slope of consolidation line	λ	0.18
Slope of swelling line	κ	0.035
Slope of critical state line	M	0.89
Coefficient of lateral earth pressure	K_0^{nc}	0.49

3. Finite element analyses

3.1 Simulation of centrifuge test

The test for a single circular tunnel is numerically simulated at a prototype scale by using specialized geotechnical finite element (FE) program PLAXIS2D AE.02. The adopted width and depth in the FE model is

55 m and 20.7 m, respectively, which is sufficient to nullify boundary effects. The cover-to-diameter ratio (C/D) is maintained at 2. The circular tunnel has a diameter of 5 m and the soil-structure interface is considered to be around the tunnel contact surface with 0.05 m of virtual thickness. The tunnel axis level was 12.5 m below the ground level and the water table was located at the surface of the ground. Standard boundary conditions were used: fixed at the bottom, free at top, and rotational at vertical side boundaries. The soil exhibits nonlinear behavior, which requires an advanced constitutive model to simulate its behavior. A modified Cam-Clay model has been used to model the soil volume, and the linear elastic model is used to model a tunnel lining that has a thickness of 350 mm. Triangular 15-noded elements were used in the analysis in order to discretize the soil continuum. Geometric modeling consists of a stepwise excavation of a circular tunnel that is supported by a contraction pressure that is equivalent to 3% volume loss on the walls of the newly excavated tunnel. The aim of the analysis was to examine short-term surface settlement in the plane that is perpendicular to the longitudinal axis of the clay tunnel. The results that were obtained in the numerical analysis are compared in the aspect of the prediction of tunnel-induced settlement at the ground surface in the plane that is perpendicular to the longitudinal tunnel axis.

3.2 Parametric study

The calibrated FE model is further extended to perform a nonlinear dynamic analysis by applying harmonic motion at the base of the model. The shear wave velocity of kaolin clay was taken as 100 m/s. Damping ratio is influenced by the plasticity index and cyclic stress-strain parameters of soil. Considering the low strain range in the ground, the material damping for kaolin clay was taken to be 5% [21]. The material damping has been introduced by Rayleigh damping coefficients, as given in Table 2. In the numerical simulation of the dynamic problem, it is necessary to assign absorbing boundaries at the side walls of the soil domain in order to prevent generation of waves during shaking. Therefore, the boundary conditions of vertical side walls were changed to viscous boundaries. Dynamic input motions were applied at the base of the model in the form of a harmonic signal (sinusoidal input motions) at a given frequency, amplitude, and duration.

Table 2 – Dynamic material properties of Speswhite kaolin clay [22]

Material property	Symbol	Values
Shear wave velocity	V_s (m/s)	100
Rayleigh damping coefficient (mass proportional)	α	0.5691
Rayleigh damping coefficient (stiffness proportional)	β	3.295E-3

The amplification in the clay was checked by conducting a sample model run test without tunnel at an input acceleration of earthquake combination P2. The accelerations at a depth of 15 m, 7.5 m, and at the ground surface in the free field were measured in order to check the amplification in the clay. Later, the dynamic analysis of whole tunnel-soil system has been carried out at varied input motions. Various combinations of input motion parameters that were used in the FE analysis are listed in Table 3.

Table 3 – Input motion parameters used in FE analysis

Earthquake ID	Frequency (Hz)	Amplitude (g)	Duration (s)
P1	2	0.1	25
P2	2	0.25	25
P3	2	0.4	25
P4	2	0.25	15
P5	2	0.25	40

A mesh was refined around the tunnel in which the concentration of stress was expected due to the increase in the earth pressure under seismic loading. Fig. 1 shows the FE mesh for the tunnel-soil model. A parametric study has been carried out in order to understand the effect of the input ground motion on the behavior of a tunnel under seismic conditions. Ovaling tunnel deformation, which is desirable under earthquake loading, is observed during shaking. This leads to changes in earth pressures around the tunnel. Also, an additional axial force and bending moment are developed in the tunnel lining due to the ovaling. The axial force (N), the bending moment (M) and the dynamic earth pressure, which are measured at an angle (θ), have been presented in this study. The sign convention used in the measurement of lining forces is shown in Fig. 2. The extreme right point on the circular lining represents θ = 0. The value of θ increases in a counterclockwise direction. The term maximum or residual earth pressure refers to the additional earth pressure that is experienced around the tunnel at a specific point during the earthquake.

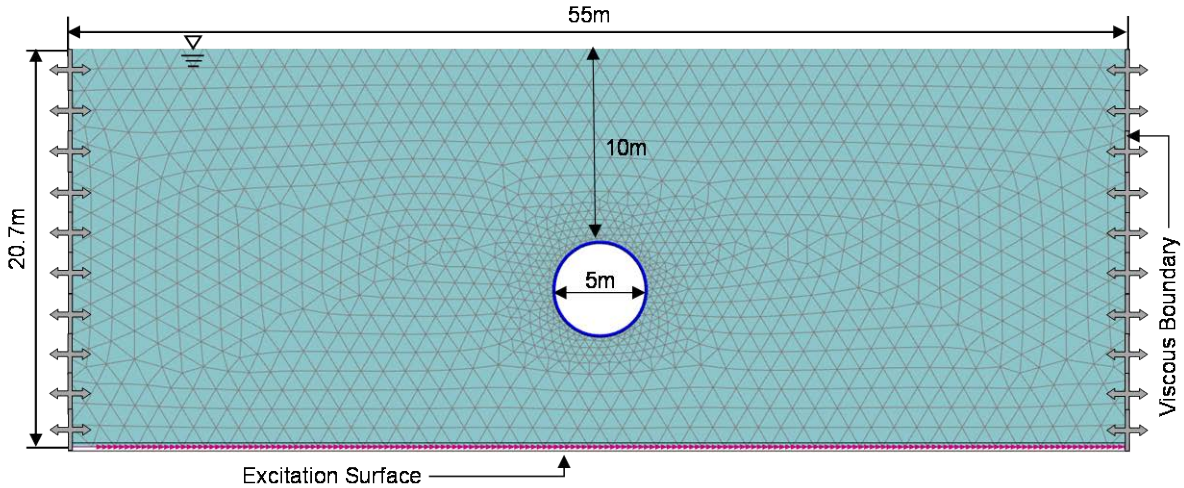

Fig. 1 – FE model of tunnel-soil system

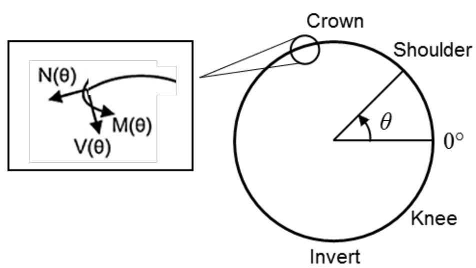

Fig. 2 – Sign convention used to measure lining forces

4. Results

Fig. 3 shows a comparison of the surface settlement profile for a circular tunnel, which was obtained in the centrifuge test, and the FE analysis. It presents the development of surface settlement immediately above the tunnel crown. The settlement values are normalized to the tunnel diameter and plotted around the tunnel center line. The maximum settlement is measured at the tunnel center line. It can be observed that the settlement data in a static condition fit the Gaussian curve described by Grant [20]. The tunnel-induced settlement that is obtained from the numerical analysis is found to be similar to that which is reported by Divall and Goodey [18]. This validates the ability of the numerical model to simulate actual field stress-strain conditions. However, under earthquake loading, the surface settlement profile does not follow the same pattern. The vertical settlement just above the tunnel shoulder under earthquake loading is more than static loading. Heaving is observed beyond a horizontal distance of three times tunnel diameter (3D) from the centerline of the tunnel. The reason behind this phenomenon is that soil softening occurs when it is subjected to cyclic loading for a longer duration. This also indicates that the surface structure within a horizontal distance of 3D from the tunnel centerline may settle further under the dynamic loading. The data that is obtained from numerical analysis does not give a clear understanding of the extent of heaving in the horizontal direction, which needs to be investigated further.

Fig. 4 shows the acceleration time histories that were measured at a depth of 15 m, 7.5 m, and at the ground surface. It can be seen that the input accelerations applied at the base were amplified in a vertically upward direction. The degree of amplification is low up to middle of the model, and then it increases toward the surface. The input acceleration is 0.25g, and the recorded accelerations at a depth of 15 m, 7.5 m, and at the top surface were 0.31g, 0.57g, and 0.79g, respectively.

Earthquake loading induces additional earth pressure on the tunnel. The results of the parametric study are presented in the aspect of the prediction of additional tunnel lining forces and the maximum dynamic earth pressure that is induced during the earthquake. Fig. 5 shows the maximum dynamic earth pressure at various locations around the tunnel lining, which is obtained from FE analysis. The values of the maximum dynamic earth pressure increases with an increase in the magnitude of the input acceleration; however, the location at which it occurs remain same. The largest value of dynamic earth pressure is 30.95 kPa, which is obtained at θ = 225° at a base acceleration of 0.4g. The range of incremental dynamic earth pressure varies between 10 to 25% of that of the static earth pressure.

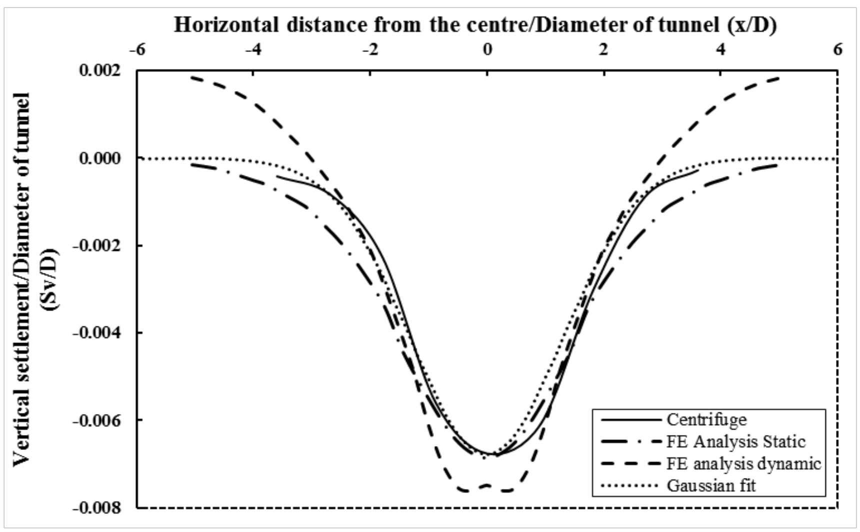

Fig. 3 – Comparison of surface settlement profile of a single circular tunnel

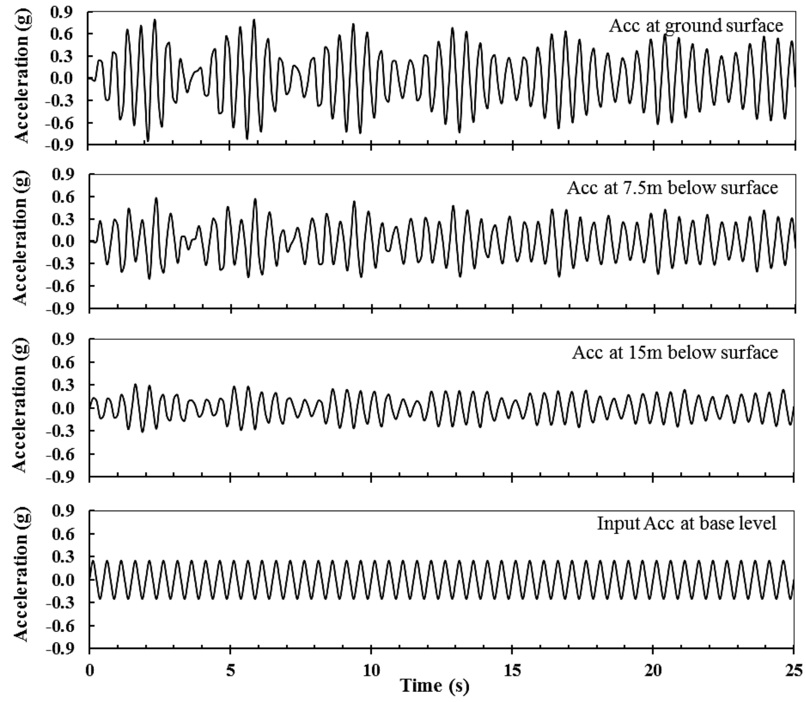

Fig. 4 – Acceleration time histories

The earth pressure changes rapidly during initial load cycles and reaches the maximum value with an increase in the number of cycles. Once the equilibrium is achieved, it starts oscillating around mean value till the end of the earthquake and leaves behind residual earth pressures around the tunnel lining. Fig. 6 shows the variation of the residual dynamic earth pressure around the tunnel lining. The maximum residual earth pressure of 13.75 kPa is obtained at θ = 225° at a base acceleration of 0.4g. The knee part of tunnel lining (between θ = 215° to θ = 325°) has experienced the highest dynamic earth pressure. The obtained results indicate that the maximum and the residual dynamic earth pressure depend on the maximum base acceleration. The higher the magnitude of the base acceleration, the higher will be the earth pressure.

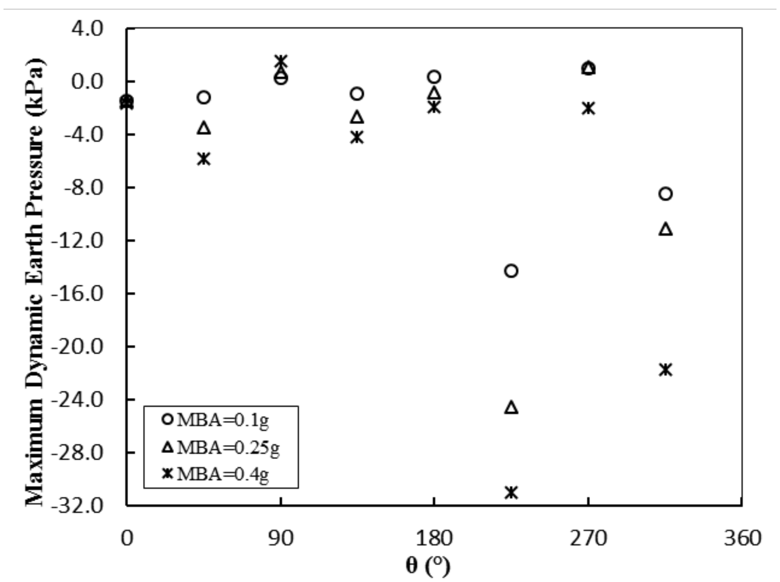

Fig. 5 – Maximum dynamic earth pressures around the tunnel lining at different base accelerations

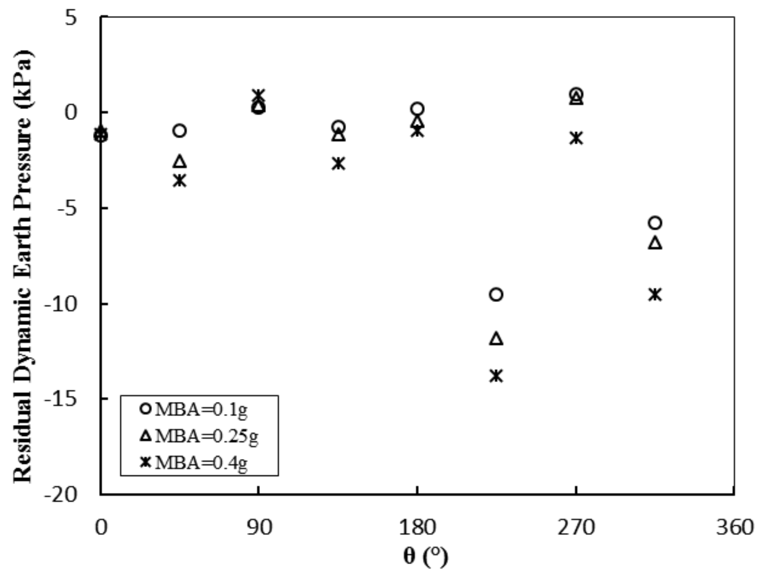

Fig. 6 – Residual dynamic earth pressures around the tunnel lining at different base acceleration

FE analyses have been used to predict the tunnel lining forces at the input motions of earthquake load combinations, P1, P2, and P3. Fig. 7 and Fig. 8 show the comparison between the maximum dynamic axial force and the bending moment around the tunnel at a maximum base acceleration of 0.1g, 0.25g, and 0.4g. An earthquake generates additional earth pressure around the tunnels, which in turn increases stresses in the tunnel lining. The maximum dynamic axial force in the tunnel was observed at θ = 165° to θ = 315° during the earthquake, P3. The percentage increase in the axial force and the bending moment from the maximum base acceleration of 0.1g to 0.4g is 40% and 34%, respectively. This generates a high stress concentration, which may lead to cracking in the tunnel lining. A significant change in the bending moment was observed at θ = 75° and 255°. The results that are obtained in the parametric study show that ovaling may occur at high amplitude earthquake loading.

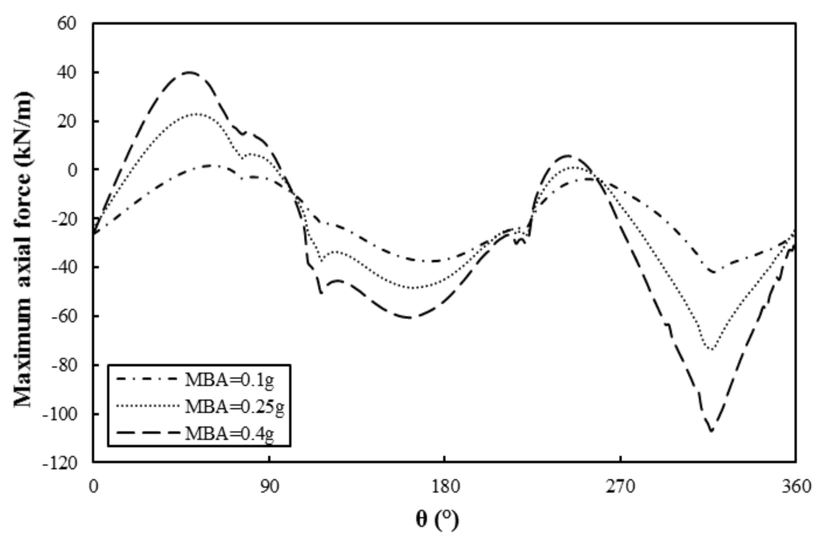

Fig. 7 – Variation of axial force in the tunnel lining at different base accelerations

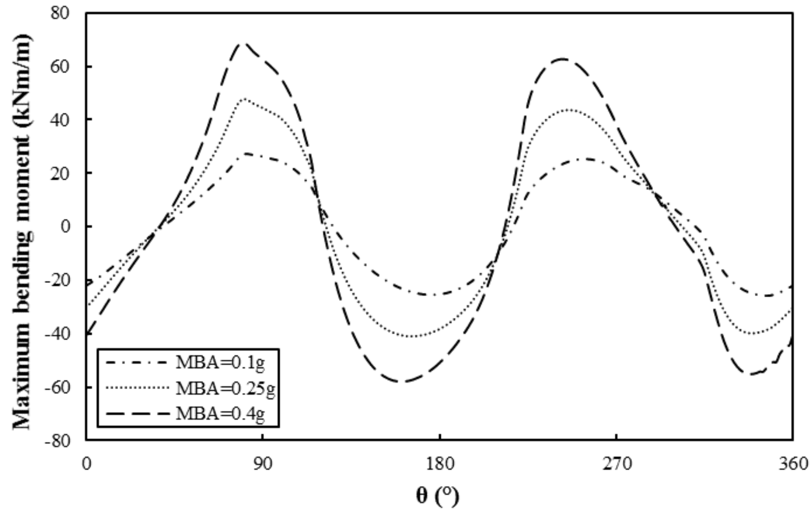

Fig. 8 – Variation of bending moment in the tunnel lining at different base accelerations

Fig. 9 shows the variation of the axial force and the bending moment in the tunnel lining at earthquake load combinations of P2, P4, and P5. It can be seen that the shape distribution envelope changes with an increase in the duration of the earthquake. A maximum axial force of 87.71 kN/m in the tunnel lining was observed during the earthquake loading of 40 sec at an angle of θ = 315°. The maximum bending moment of 65.60 kNm/m in the tunnel lining was observed during the earthquake loading of 40 sec at an angle of θ = 255°. The location of the peak values of the axial force and the bending moment remain the same from the lower to the higher duration of earthquake loading. Cilinger and Madabhushi [11] also reported similar observations on the basis of centrifuge test data. Table 4 gives the maximum and minimum values of the axial force and the bending moment at static loading as well as at the end of the earthquake loading of various durations. A positive axial force and bending moment refer to the compression, that is, contraction in the tunnel lining. Similarly, a negative axial force and bending moment refer to the tension, that is, the expansion in the tunnel lining.

Table 4 – Axial force and bending moment obtained in tunnel lining

Duration of earthquake loading	**Axial Force (kN/m)**		**Bending Moment (kNm/m)**	
	Positive	**Negative**	**Positive**	**Negative**
Static	31.69	---	11.07	-9.539
15 sec	17.03	- 65.56	37.17	- 33.58
25 sec	22.67	- 75.14	47.58	- 40.81
40 sec	27.90	- 87.71	65.60	- 51.40

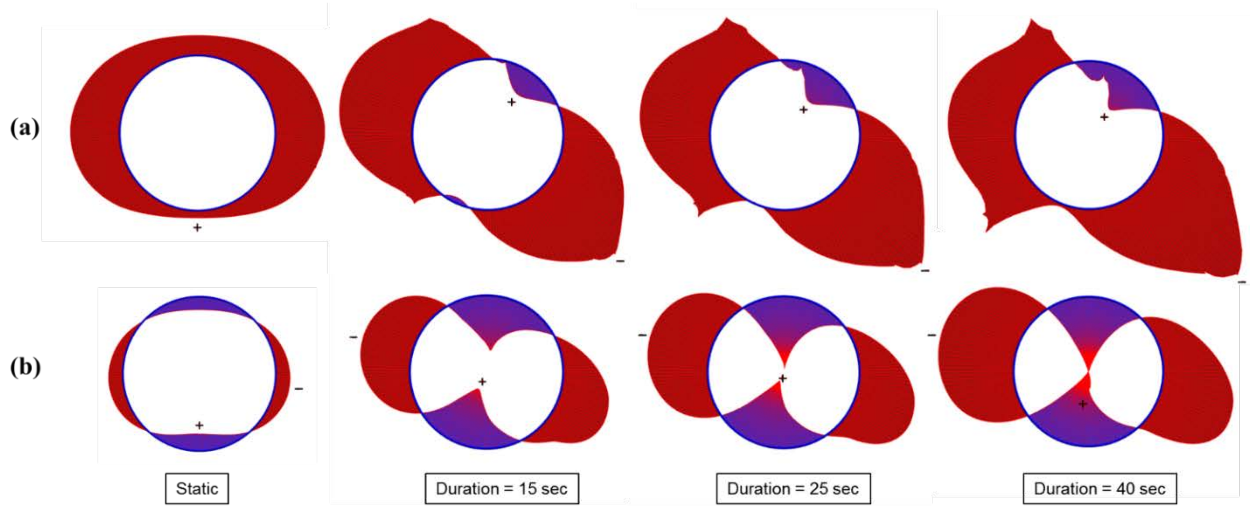

Fig. 9 –Variation in tunnel lining forces under static and seismic loading with duration: (a) axial forces, (b) bending moments

5. Conclusions

A plane strain FE analysis has been carried out to study tunnel-induced surface settlements in clay. The FE model is validated with previously published centrifuge test data that demonstrated the proficiency of numerical model in simulating the actual field condition. The maximum value of the tunnel-induced surface settlement was noted just above the crown. The validated FE model is further used in the fully non-linear analysis in order to investigate the dynamic behavior of a circular tunnel. In nonlinear analysis, the overall response of a system depends on the constitutive model and damping formulation. The assumption of 5% material damping is valid for low shear strain range. Rayleigh damping model generates large damping forces, this results in the underestimation of displacements and overestimation of internal member forces. Under earthquake loading, the maximum value of surface settlement is spotted above the shoulder regions. Soil softening occurs in the clay as a result of cyclic loading. This may lead to heaving at the surface, which is beyond the horizontal distance of 3D from centerline of the tunnel. A parametric study is carried out to examine the effect of the input ground motion parameters such as the amplitude and the duration on the seismic response of the tunnel. An attempt has been made to predict the dynamic behavior of the tunnel-soil system, the amplification in the soil, and the forces in the tunnel lining. These predictions are useful in assessing the effect of dynamic input motion parameters on the dynamic behavior of the tunnel. The earth pressure around the tunnel, the axial force, and the bending moment in the tunnel lining were measured at several locations. An increase in the maximum base acceleration from 0.1g to 0.4g would result in an increase in the axial force and the bending moment by 40% and 34%, respectively. The peak values of the tunnel lining forces lie within the shoulder and knee region. Depending on the various locations, 40 to 70% of these increased earth pressures remain even after the end of the earthquake, which is termed as residual earth pressures. The magnitude of these residual forces depends on the amplitude and duration of the earthquake input motion. Ovaling deformation, which is desirable during an earthquake because it generates supplementary lining forces, has been identified in this study. The tunnel must be designed to resist additional earth pressure and lining forces that the tunnel will experience during an earthquake. The axial force and the bending moment in the tunnel lining increases with an increase in the magnitude of the base acceleration. The location of the maxima and the minima remain unchanged at different acceleration amplitudes. It was found that the parameters of the input ground motion, such as the amplitude and the duration play an important role in the seismic behavior of the tunnel. Therefore, it can be concluded that the tunnel lining forces depend on the magnitude and intensity of the earthquake.

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