

Seismic Response of Tunnels Under Effect of Overburden Depth Using Simplified Pseudo-Static Analysis

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ABSTRACT

Earthquakes are one of the natural occurrences that can lead to massive disasters, either on structures or infrastructure. The seismic response and performance of underground infrastructure such as tunnels against earthquake vibrations is predictably severe due to the complex interaction between tunnels and the surrounding soil, especially one embedded in poor soil material properties. In view of this, previous experiences of tunnel damages subjected to earthquake loads have been reported in the literature. Thus, rigorous analysis is necessary to provide in-depth knowledge and understanding of the seismic response of tunnels which beneficial to engineering practitioners in especially in early design stage in order to avoid the future risk of tunnel damage and failure during an unpredictable earthquake event. The aim of this study is to investigate the effect of overburden depth on seismic response of tunnels using the simplified pseudo-static analysis, while simultaneously to emphasize the shortcoming of conventional closed-form solution. This study presents a two-dimensional (2D) simplified pseudo-static analysis of soil-tunnel model embedded at 10m and 20m overburden depth subjected to increasing levels of seismic intensity at the transverse direction of tunnel axis. The numerical investigation was performed using the finite element program PLAXIS 2D. The circular shaped tunnel lining are assumed to be elastic, while the soil is considered as homogeneous, and isotropic in plane strain condition. Considering the complex soil-tunnel interaction, the tunnel lining and soil interface is assumed as no-slip condition. The numerical result of pseudo-static analyses were compared with the conventional closed-form Wang's analytical solution to verify the reliability of the obtained results. The results denoted that the tunnel embedded at 10 m overburden depth experienced considerable seismic-induced deformation and structural forces than tunnel buried at 20 m depth. The deformation and seismic induced structural forces of tunnel increased with increment on the magnitude of earthquake loadings. Thus, it can be concluded that the shallow tunnel suffered more damages compared to the tunnel embedded at deeper depth. Overburden depth of tunnel plays a significant role in modifying the seismic response of tunnel apart of the imposed magnitude of earthquake loadings. The conventional closed-form analytical method tends to overestimate the seismic response of tunnel compared to numerical pseudo-static analysis.

Keywords: Seismic response; tunnels; overburden depth; pseudo-static analysis

INTRODUCTION

Tunnels have become one of the most important infrastructures in the world as they are commonly used by people as the medium for transportation, solving urbanisation issues such as traffic congestion, land shortage and noise and air pollution, especially in the rapid growth of the population of the world (Cui & Nelson 2019). An

appropriate design of a tunnel is compulsory to avoid any damage and instability of the structure, especially seismic damage as the structure is prone to the issue. Nowadays, many tragedies regarding tunnels exposed to extreme earthquakes have been reported across the world, making the hypothesis that the structures are not immortal from the natural phenomenon rejected. The reported cases such as the Wenchuan Earthquake 2008 (Yu et al. 2016), Chi-Chi

Earthquake 1999 (T. T. Wang et al. 2021) and 1995 Kobe Earthquake (Sayed et al. 2019), (Kontoe et al. 2008) has given good evidence that tunnel is not susceptible to earthquake loads. However, very limited studies have been conducted about the performance of tunnels when subjected to seismic ground motion, subsequently causing to the major damage to the structure and lack of information on how the tunnels react under the extreme hazards. To counter this issue, an in-depth study on the seismic event should be conducted to ensure the appropriate design of structure and to study the pattern and possibility of the structure under the exposure of seismic response using appropriate system.

In earthquake engineering, seismic response analysis has been one of the common studies that evaluate the effect of the earthquake excitation towards the structures. It helps the researchers to visualize the conditions and response of structure or infrastructure in terms of bending moment, axial forces, shear forces and displacement produced when subjected to certain earthquake ground motion. Under the seismic loading, the cross-section of a tunnel will experience axial bending and shear strains due to free field axial, curvature, and shear deformations (Hashash et al. 2001). Mitkees et al. (2020) has conducted the response of segmented tunnel liner under seismic loads by using PLAXIS 2D. The verification of two case studies of continuous tunnel lining and 5 segmented tunnel lining subjected to earthquake loadings has obtained various information on the response of tunnel including the changes of diameter of tunnel, earthquake intensity, number of joints in tunnel lining and tunnel depth leads to the changing the value of bending moment and normal forces. Che Osmi & Mohd Ahmad (2016) evaluated the response of 10-meter diameter of tunnel lining under different geological conditions subjected to various earthquake excitations using Midas GTS NX finite element software. It is noted by the researchers that tunnels constructed in soft soil contribute to the higher values of transverse and longitudinal displacement, as well as the higher PGA value leads to the increment of seismic induced structural forces. From the available previous studies, the understanding on the critical depth experiencing higher seismic effect, the results of the seismic of tunnel and the design of tunnel give a clear sight for this study, as well as the contribution to the earthquake engineering field by providing the information how the infrastructure reacts when induced by seismic effects. The limitation arised from the previous studies cited is that how the underground tunnels react with varying depth in harder soil such as rock. Furthermore, the use of pseudo-static analysis in evaluating the seismic response of tunnel need to be practiced as it is one of the method which reliable and less computational time compared to dynamic analysis. However, In this study,

the geotechnical software, PLAXIS 2D will be used to conduct the numerical modelling for tunnels embedded in different burial depth. The software offering the use of Finite Element Method (FEM) to model various type of geotechnical problem such as soil and rock deformation, stress and strain distribution, pore water pressure, seepage, consolidation and etc. Furthermore, the feature that support various types of loadings and boundary conditions such as gravity, applied forces, displacements, temperature and etc is considered as a suitable tools for the seismic response analysis for this study. Moreover, the output from the PLAXIS 2D can be interpreted in various ways such as contour plots, graphs, tables and animation.

Tunnel damage due to the seismic event is influenced by several factors, one of them is the buried depth of tunnel. According to the previous researchers, it is believed that the shallow tunnel might experience severe damage due to the seismic waves propagation compared to the tunnel embedded in the deeper depth. (Rajyaswori et al.,) 2020, indicated that shallow tunnels are more vulnerable compared to the deep tunnels based on the previous earthquake cases. They also evaluated that degree of damage in underground structures decreased at depths greater than 50 meters, while for depths more than 300 meters, no serious damage occurred. (Judd) 1991, concluded that tunnels constructed less than 50 meters below the ground suffered heavy damage compared to tunnels embedded for up to 300-meter depth. Besides that, Hu et al. (2020) conducted the analysis of different buried depths of tunnel in soft soil summarized that tunnel with 15 meters of buried depth recorded the highest value of bending moment, which indicated to the most vulnerable when subjected to earthquake loadings compared to tunnel embedded in 35 meters of depth.

Considering the important and influenced factors from previous research, this paper aims to capture the response of tunnels in terms of structural forces (i.e., bending moment, axial forces) with different buried depth when subjected to different input ground motion in the homogenous sand soil. The PLAXIS 2D was used to perform the numerical model of the tunnel as the reliability of the software to describe the tunnel behaviour under seismic loads.

METHODOLOGY

The procedure for the seismic response of tunnel under different burial depth has been illustrated as shown in Figure 1. The proposed methodology was started with defining the structural geometry, soil properties and loading types through the previous researchers (Che Osmi & Mohd

Ahmad 2016; Mitkees et al. 2020). In this study, the circular shape tunnel was chosen, embedded in 60 m depth of loose sand soil. The soil-tunnel model was developed in this study by using PLAXIS 2D, a software which is widely used in geotechnical engineering field to elaborate the tunnel behavior under earthquake excitation. The two-dimensional (2D) simplified pseudo-static analysis of soil-tunnel model embedded at 10m and 20m overburden depth subjected to increasing levels of seismic intensity at the transverse direction of tunnel axis. The six seismic intensity of peak ground acceleration (PGA) ranging from 0.1 to 0.6g were considered in this study. As this study conducted a pseudo-static analysis, the seismic excitation applied on the structure is defined manually during the stage construction phase. The circular shaped tunnel lining is assumed to be elastic, while the soil is considered as homogeneous, and isotropic in plane strain condition. The application of pseudo-static analysis use for this study is

due to the simplicity, less-time consuming and relative inexpensiveness of the method. When performing a force-based pseudo-static analysis, the effects of dynamic loading such as earthquake-induced loading were converted to equivalent static loads. These forces are assumed as constant body forces, with their magnitudes proportional to the horizontal or vertical accelerations imposed by the dynamic loading. However, this method may not accurately capture all the dynamic effect perfectly but it can provides at least for the preliminary assessment of the stability of structures against earthquake-induced failure. Considering the complex soil-tunnel interaction, the tunnel lining and soil interface is assumed to be in no-slip condition. The numerical result of pseudo-static analyses was compared with the conventional closed-form Wang's analytical solution (J. N. Wang., 1993) to verify the reliability of the obtained results.

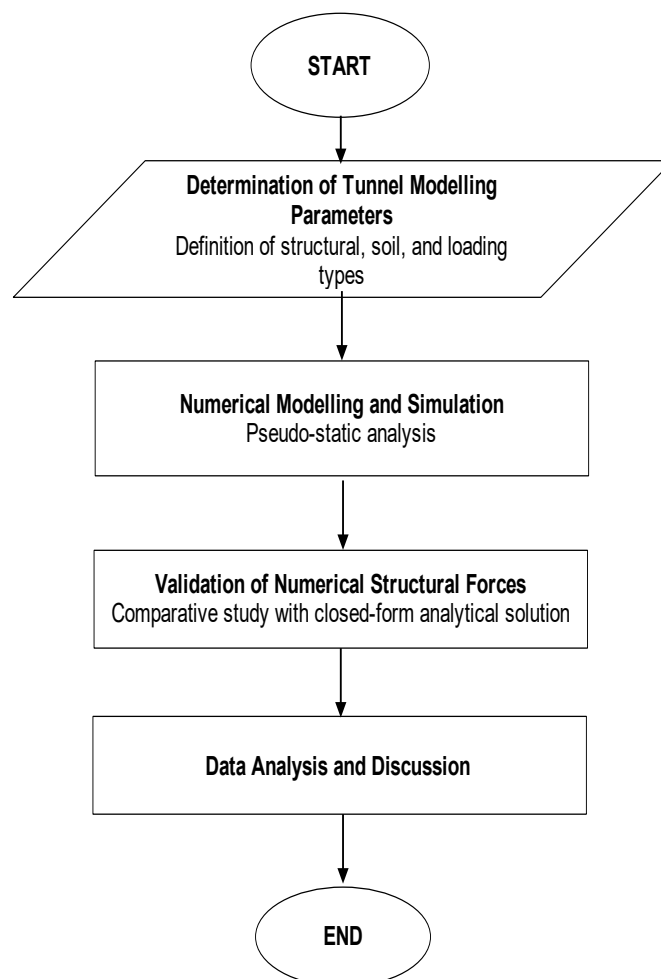


FIGURE 1. Procedure for seismic response of tunnel

NUMERICAL ANALYSIS

The seismic response of tunnels under different burial depths were modeled with the two-dimensional soil-tunnel model by using PLAXIS 2D. In the verification model, the soil was set to 150 m x 60 m of boundary conditions for x and y axis respectively. A total of 60 meters of loose sand soil were constructed. Figure 2 shows the soil-tunnel model used in this study. To avoid non-linearity behaviour of soil during the changes of stress and strain, the Mohr-Coulomb model was used for all the soil and tunnel types and characteristics as it is well-known linear elastic perfectly plastic model. The use of Mohr-Coulomb (MC) model for this study is because of the suggestion from the previous studies on the seismic response analysis. To first estimate soil behaviour, the well-known linear elastic fully plastic model is employed. It is suggested for a preliminary analysis of the current problem. An estimated constant average stiffness is used for the soil layer, allowing for reasonably quick computations and an initial estimate of deformations. The Mohr-Coulomb model effectively

captures two key aspects of soil behaviour: shear strength and frictional resistance. Understanding the interaction between the soil and the tunnel during seismic occurrences requires an understanding of these features. However, the implication of using Mohr-Coulomb model in performing seismic analysis is the inability to capture the real soil behaviour under seismic loading due to the nonlinearity behaviour of soil. The soil stiffness, E_{50} used in the soil layer is constant throughout the elastic zone, until the stress state reaches the plastic zone. Due to the nonlinearity of soil, the soil stiffness is never constant and it changes with the stress level within soil mass. Therefore, the MC model tend to over-predict the ground movement at the stress level less than 50% of the ultimate strength.

The damping ratio was set to 5% for both tunnel and soil to produce an accurate structural response when subjected to seismic loads and because of the traditional values applied by previous research (Atkins & Wilson, n.d.). The staged construction took place by excavating the tunnel and activation of tunnel lining first, followed by the free free vibration and earthquake effect on the structure.

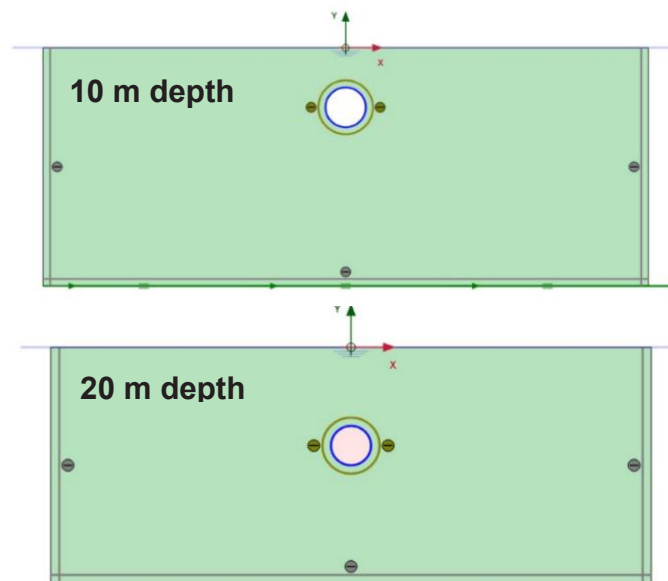


FIGURE 2. Soil-tunnel model of study

SOIL MATERIAL PROPERTIES

In general understanding, tunnels might experience severe damage when embedded in soft soil during seismic events. Considering the important parameters and influencing

factors, a homogenous loose sand were used in this study for the construction of soil-tunnel model. Table 1 shows the soil material properties used in this study following from the previous researcher (Che Osmi & Mohd Ahmad, 2016).

TABLE 1. Properties of hybrid materials

PROPERTIES	TYPES OF SOIL
	LOOSE SAND
Element type	2D
Material model	Mohr-Coulumb
unit weight, γ (kN/m ³)	17
Modulus of elasticity, E (kN/m ²)	10x10 ⁴
Shear wave velocity, Vs (m/s)	149
Poison ratio, ν	0.3
Cohesion, c (kN/m ²)	10
Friction angle, ϕ (°)	30
At-rest earth pressure coefficient, K_0	0.5
Damping ratio (%)	5

TUNNEL GEOMETRY PROPERTIES

In the most cases, tunnel geometry including type of shape, lining properties, and overburden depth playing a vital role in influencing the effect of damage to the structure due to the seismic wave propagation (Chen et al. 2012). In this study, a 10 m diameter single circular tunnel was considered to react with the earthquake ground motion. The tunnel lining had 35×10^6 kN/m² with the poison's ratio of 0.2. The continuous tunnel lining was considered in this study which having the thickness of 0.5 m. the tunnel will embedded in 2 different depth which is 10 m (shallow) and 20 m (deep) to highlight the influence of overburden depth in the seismic response of tunnel. TBM method was taken into consideration which the tunnel has been excavated first in the first stage of construction. Table 2 shows the tunnel geometry properties as suggested by (Mitkees et al. 2020).

CLOSED-FORM ANALYTICAL SOLUTION

The validation of the numerical simulation with closed-form analytical solution has been taking place in order to prove the outcome of the analysis is either accurate or inaccurate. Analytical solutions are useful, relatively quick, and simple to utilize for preliminary seismic design of tunnels even if they are created using strict assumptions and simplifications (Tsinidis et al. 2020). The popular analytical solution, Wang's method (J. N. Wang., 1993) has been considered in this study which it is can give parametric estimation of seismic forces in tunnel lining (Pinnaduwa S W Kulatilake et al. 2022). The maximum thrust, T_{max} and maximum bending moment, M_{max} has been compared under the no slip condition as illustrated in the equation 1 and 2. Furthermore, the estimation of relative stiffness between a circular tunnel lining and the medium is required based on the compressibility ratio (C) and flexibility ratio (F) as shown in eqn. 6 (Hashash et al. 2005; Siti Khadijah Che Osmi, 2020; J. N. Wang 1993)

TABLE 2. Tunnel geometry properties

PROPERTIES	TYPE OF TUNNEL
	SINGLE TUNNEL
Element type	2D
Material model	Elastic
unit weight, γ (kN/m ³)	24
Modulus of elasticity, E (kN/m ²)	35×10^6 (C40/50)
Poison ratio, ν	0.2
diameter, d (m)	10
radius, r (m)	5
thickness of lining, t (m)	0.5
area of tunnel lining, A (m ² /m)	0.5
moment inertia of lining, I (m ⁴ /m)	0.01042
damping ratio (%)	5

$$T_{max} = \pm K_2 \tau_{max} r = \frac{K_2 E_m}{2(1 + \nu_m)} r \gamma_{max} \quad (1)$$

$$M_{max} = \pm \frac{1 K_1 E_m}{6(1 + \nu_m)} r^2 \gamma_{max} \quad (2)$$

$$K_1 = \frac{12(1 - \nu_m)}{2F + 5 - 6\nu_m} \quad (3)$$

$$K_2 = 1 + \frac{F[(1 - \nu_m) - (1 - 2\nu_m)C] - \frac{1}{2}(1 - 2\nu_m)^2 + 2}{F[(3 - 2\nu_m) + (1 - 2\nu_m)C] + C \left[\frac{5}{2} - 8\nu_m + 6\nu_m^2 \right] + 6 - 8\nu_m} \quad (4)$$

$$C = \frac{E_m(1 - \nu_l^2)r}{E_l t(1 + \nu_m)(1 - 2\nu_m)} \quad (5)$$

$$F = \frac{E_m(1 - \nu_l^2)r^3}{6E_l I(1 + \nu_m)} \quad (6)$$

Where;

γ_{max} = maximum shear strain of free field soil or rock medium

E_m = Modulus of elasticity of soil or rock medium

ν_m = poisson's ratio of medium

r = radius of tunnel lining

t = thickness of tunnel lining.

ν_l = Poisson's ratio of tunnel lining

I = Moment inertia of tunnel lining

RESULTS AND DISCUSSION

NUMERICAL RESULTS

The seismic response of tunnel of tunnel influenced by overburden depth has been conducted by using PLAXIS 2D with a total of 12 cases analyses has been considered. four stages of staged construction have been constructed which started with excavation of tunnel through TBM method and activation of tunnel lining, followed by excitation, free vibration and seismic loading stages (NUMERICAL ANALYSIS OF TWIN TUNNELS USING PLAXIS 2D, n.d.; PLAXIS CONNECT Edition V22.02 PLAXIS 2D-Tutorial Manual, n.d.). The criteria considered in evaluating the adequacy of tunnel's bending moment are empirical data provided by previous studies. The increment trend of maximum bending moment of tunnel with different seismic intensities (0.1g -0.6g) were plotted

to analyze which tunnels experienced severe damage with different burial depth. The point is to agree with the previous studies that tunnels embedded at certain depth will produce the highest structural forces.

Moreover, this study has considered the variations of ground motion from 0.1 g -0.6 g and loose sand is because to analyze the effect of seismic intensities, from low to high towards the performance of tunnels and to validate with previous studies how tunnels behave in soft soil in terms of structural forces produced. Figure 3 and Figure 4 illustrated the numerical results obtained from PLAXIS 2D for tunnel in terms of structural forces (i.e., bending moment, shear forces and axial forces). The outcomes from the numerical analysis were tabulated and plotted in terms of structural forces. On top of that, the results from the numerical analysis will be compared with the analytical solution (Wang's method) in order to evaluate the accuracy of results obtained.

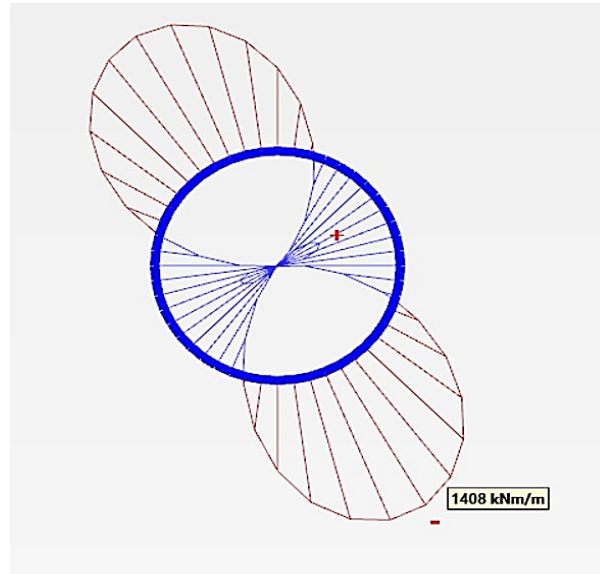


FIGURE 3. Bending moment of tunnel

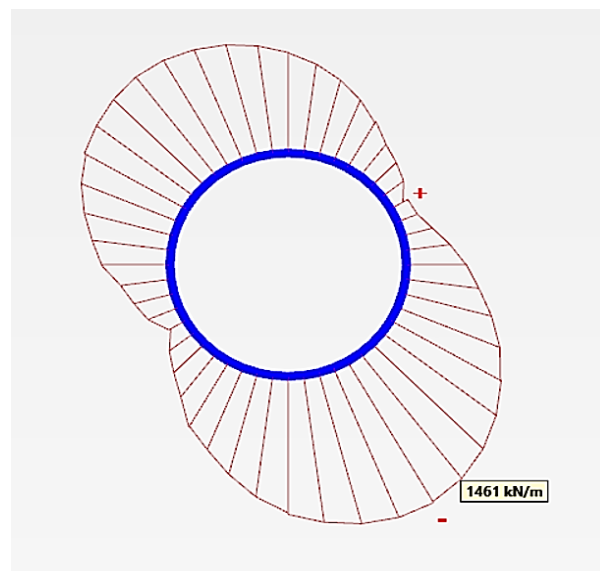


FIGURE 4. Axial force of tunnel

STRUCTURAL FORCES

Figure 5 and Figure 6 show the structural forces for tunnels embedded in 10 m and 20 m depth of sand soil. As illustrated in Figure 5, the highest bending moment recorded for tunnels embedded in 10 m and 15 m depth is 1408 kNm/m and 2230 kNm/m respectively. Both highest bending moments were recorded were at Loma Prieta and Imperial Valley Earthquake. It is noted that the tunnels embedded in 20 m of depth show higher value recorded compared to the 10 m depth due to the influence of overburden depth. Meanwhile, from Figure 6, it is also

recorded the highest value was at Loma Prieta Earthquake. The tunnel buried in 20 m depth recorded the higher value compared to tunnels buried in 10 m depth which is 2159 kN/m and 1461 kN/m respectively.

In another perspective, the structural forces corresponding to tunnel lining segment also been conducted as illustrated in Figure 7, Figure 8, Figure 9 and Figure 10. It can be seen that most of the value for axial forces of tunnel lining in both overburden had the highest value in between 135° to 180° . This means by the critical part of the tunnels occurred on the side part of structure. Meanwhile, for bending moments, the increment trend of the structural forces had the fluctuates values ranging from 45° to 315° .

As it can be seen from the results, most of the highest value contribute from the larger earthquake intensity. It can be clearly said that the seismic intensity measure also plays a vital role in modifying the value of structural forces as reported by previous researchers. The seismic wave propagation and large ground deformation produced a massive ground shaking that triggered structural failure in soil, resulting in the ovaling or racking of the tunnels. (Tsinidis et al. 2020). Apart from that, focusing on the main objective of this study which to investigate the effect of overburden depth in seismic response of tunnel, the results indicated that all of the tunnel in 20 m buried depth has

the highest value in structural forces compared to tunnel buried in 10 m depth. As reported by Mitkees et al. (2020), the highest value recorded was found for tunnel embedded in 15 m, making it is the most vulnerable tunnel constructed when subjected to earthquake loadings. However, the changes of this parameters are not the only factors related to the failure of tunnel lining because of the existence another several factors that also contribute to response and performance of tunnel such as geological conditions, tunnel geometry and earthquake parameters(Che Osmi & Mohd Ahmad 2016; Judd 1991).

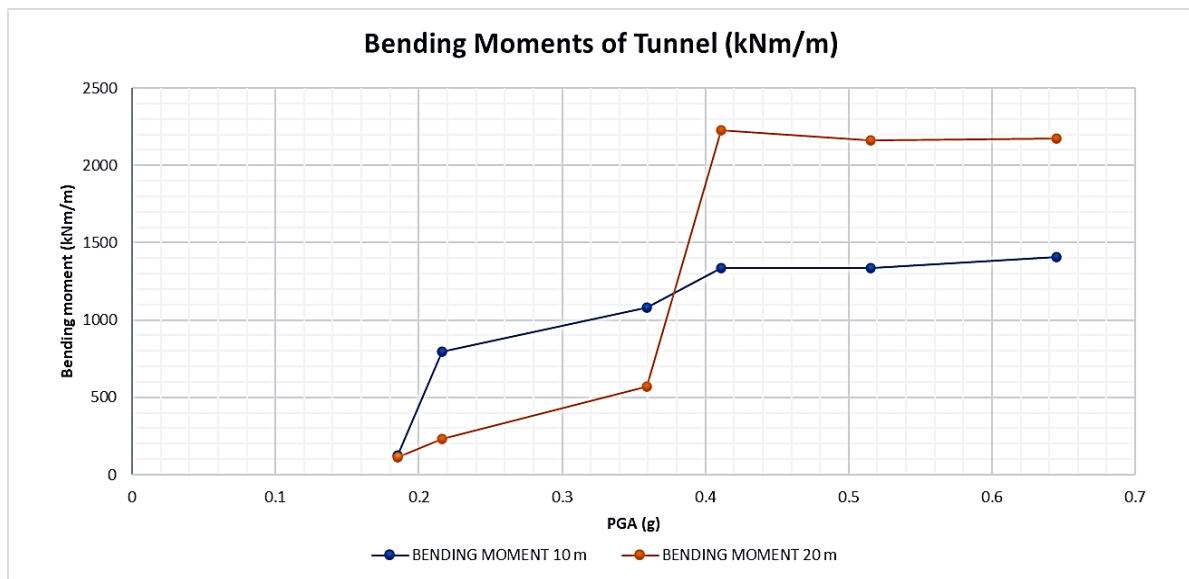


FIGURE 5. Maximum bending moment of tunnels

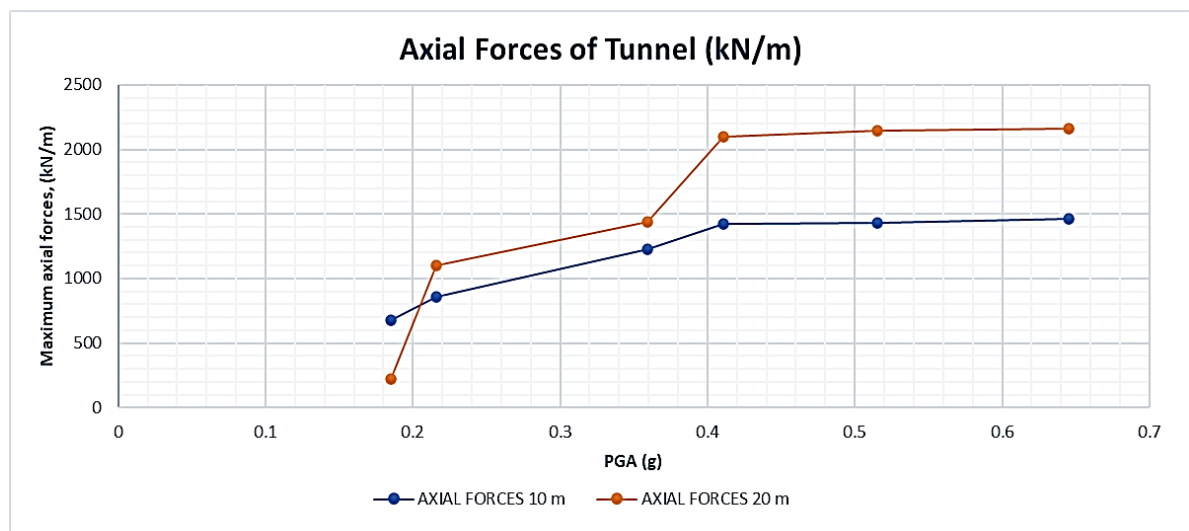


FIGURE 6. Maximum axial forces of tunnel

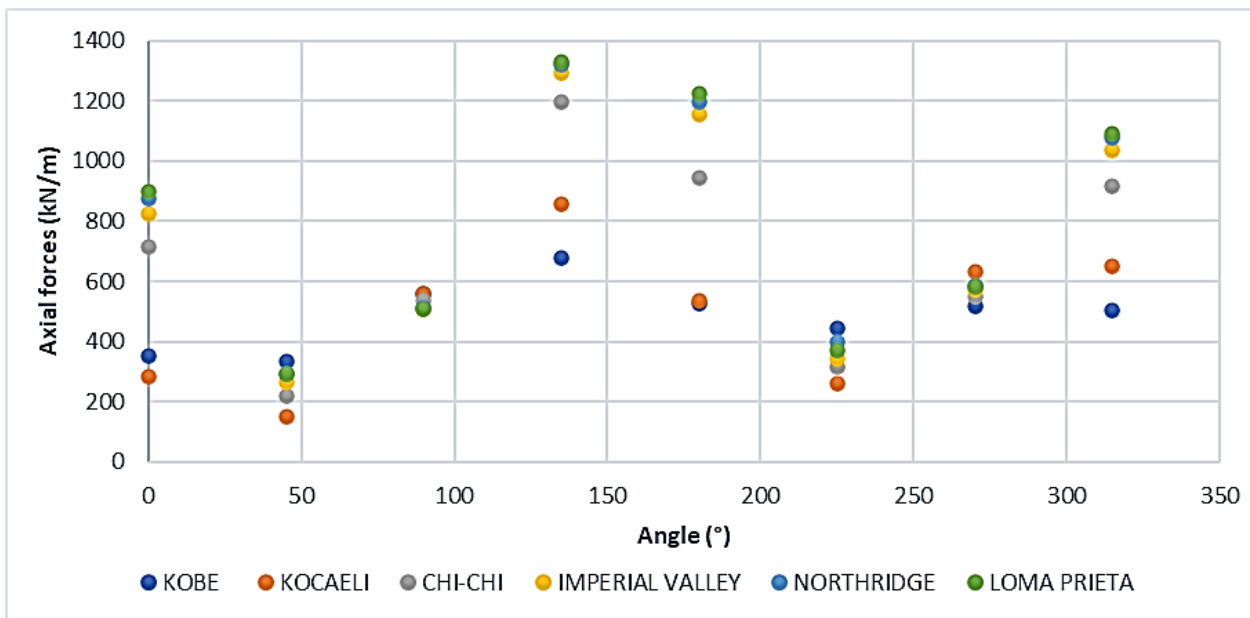


FIGURE 7. Axial forces of tunnel lining in 10 m depth

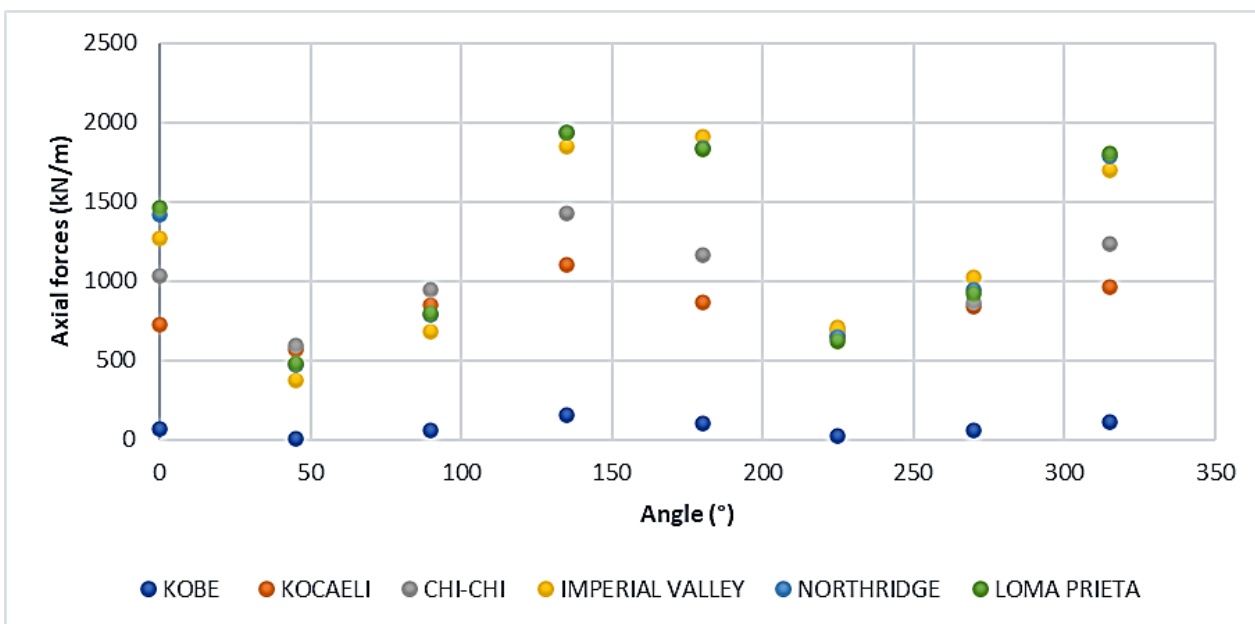


FIGURE 8. Axial forces of tunnel lining in 20 m depth

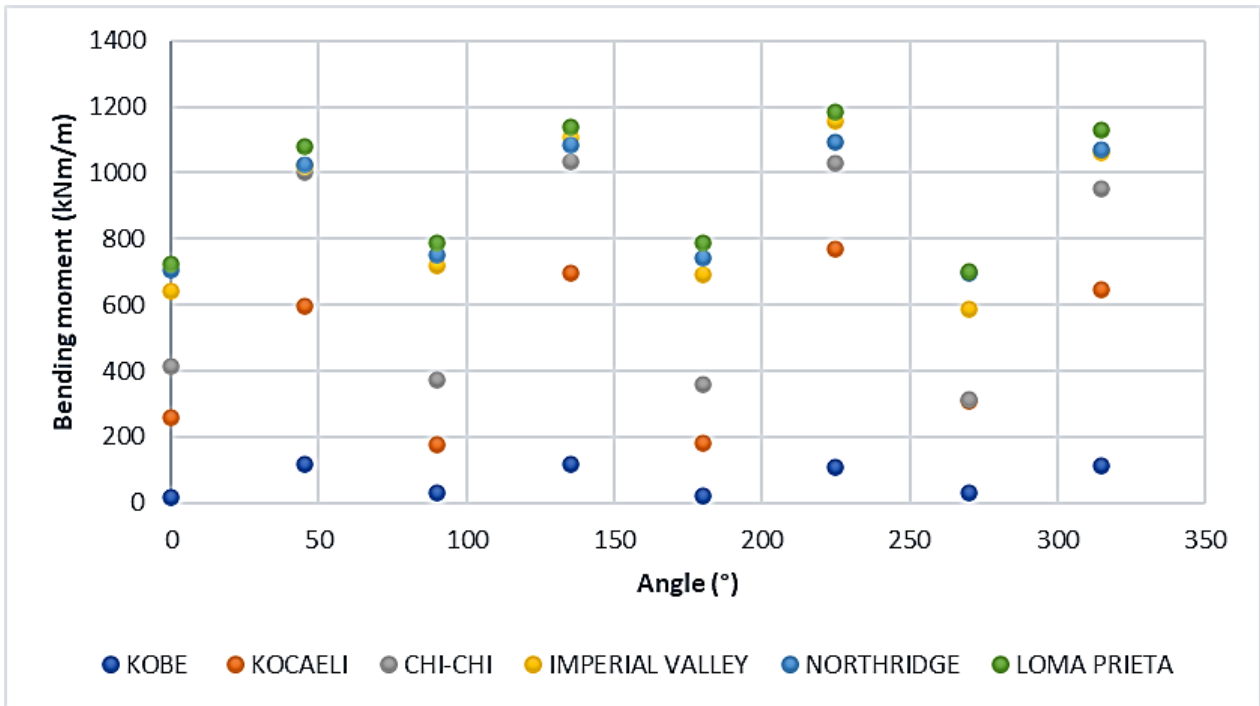


FIGURE 9. Bending moments of tunnel lining in 10 m depth

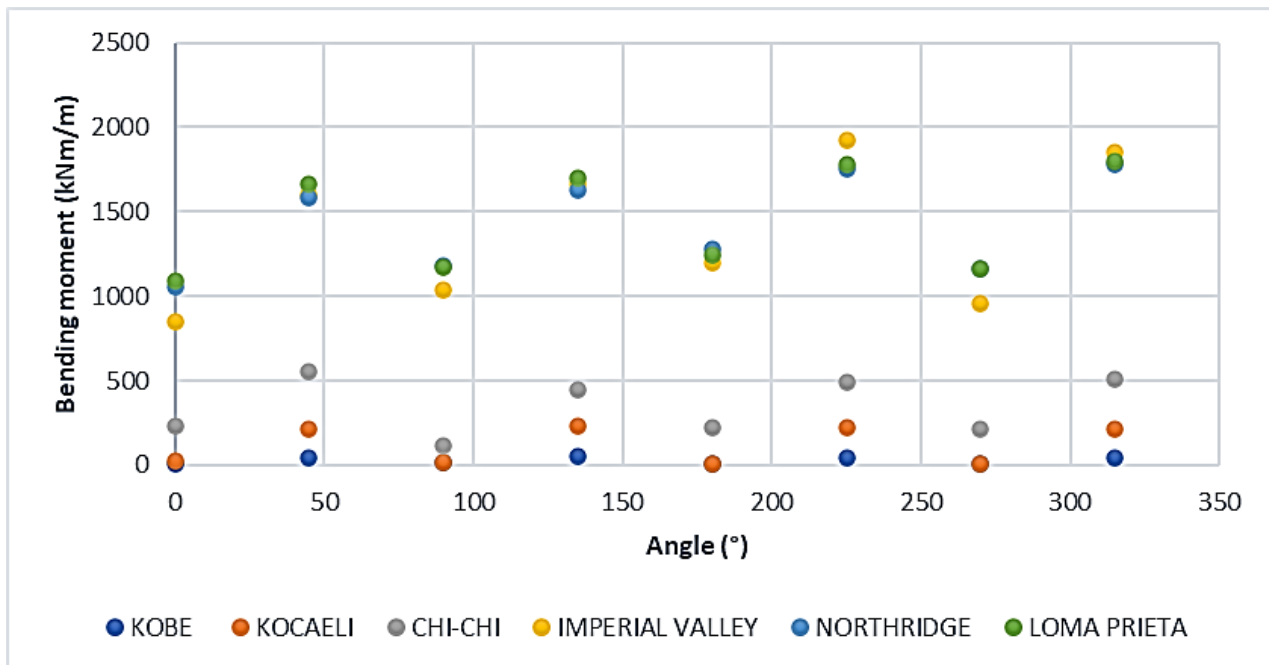


FIGURE 10. Bending moments of tunnel lining in 20 m depth

COMPARISON OF NUMERICAL ANALYSIS AND ANALYTICAL SOLUTION

In order to validate the accuracy of numerical analysis results, a comparison with closed-form analytical solution is required. In this study, the analytical solution from Wang’s method has been used to evaluate the validate the results in terms of maximum bending moment and maximum axial forces. No slip condition between the soil and tunnel lining was considered in this study. The results of analytical solutions have been compared with numerical

analysis in order to validate the accuracy and reliable data. Figure 11 and Figure 12 shows the difference in numerical analysis and analytical solution in terms of maximum axial forces and maximum bending moments, respectively. Both of the results for the structural forces evaluated in numerical analyses and analytical solutions are seems to be agreed and well estimated because of the lower percentage differences appeared and approaching to the 1:1 line. The lowest percentage value of axial forces and bending moments were found in Loma Prieta Earthquake at 10 m depth which produced a value of less than 20% estimation of percentage differences.

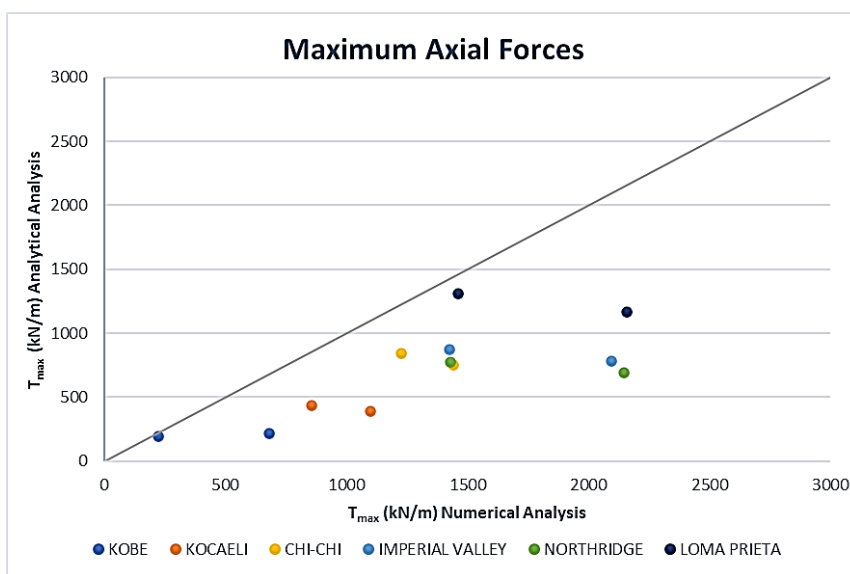


FIGURE 11. Comparison of calculated maximum axial forces between numerical analysis and analytical solution

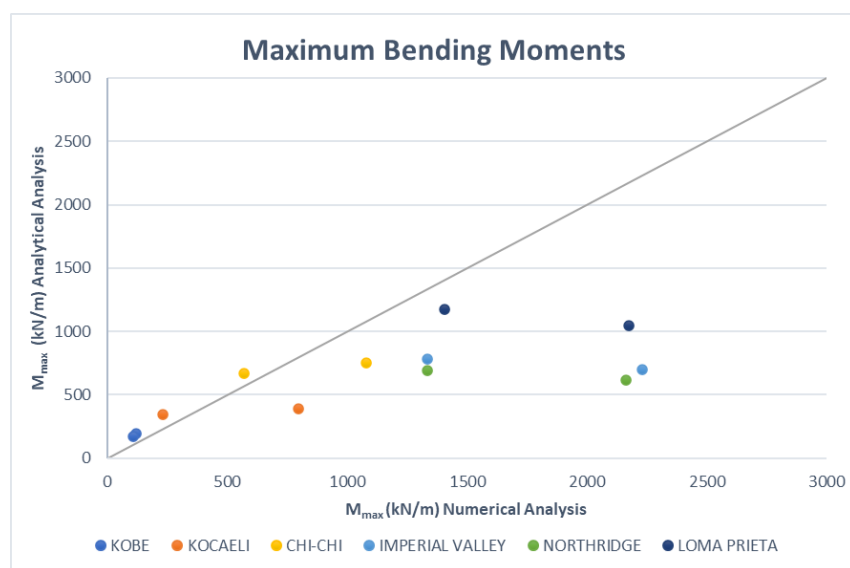


FIGURE 12. Comparison of calculated maximum bending moments between numerical analysis and analytical solution

CONCLUSION

The seismic response of tunnel influenced by burial depth has been conducted by using PLAXIS 2D for numerical analysis and Wang's method for the closed-form analytical solution. The aim of this study is to evaluate the response of tunnels in terms of structural forces when subjected to earthquake loadings by varying the burial depth of tunnel. A circular tunnel embedded in loose sand soil has been subjected to the 6 different earthquake records obtained from PEER. The results obtained from the output of the software have been tabulated and plotted and compared the numerical analysis with the closed form analytical solutions. As the conclusion, the results of the structural forces indicated that the effect of burial depth playing a vital role in influencing and modifying the seismic response of tunnel. The results show that tunnel embedded 20 m below the ground surface has the higher value of structural forces compared to the tunnel embedded at 10 m depth. Apart from that, most of the structural forces value were recorded higher in the PGA is more 0.4 g.

Through this, the earthquake parameters also have been the factor to influence factors in changing the value obtained from the seismic response of tunnel. The analytical solution from Wang's method mere used in this study in order to compare the results between numerical analysis and analytical solution. It can be concluded that the percentage difference between numerical analysis and analytical solution are well agreed when the percentage difference produced a small gap amount. It is safe to say that the analytical solutions do not overestimate the value of structural forces with no slip conditions considered. Overall, the 2D numerical analysis of tunnel using PLAXIS 2D producing a reliable result and give a better understanding on how tunnel reacts under certain seismic loadings. A careful design for the tunnel is required following to the actual seismic design of the tunnel in order to give an accurate results data from the software.

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