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Comparative Study of Pseudo-Static Finite Element Analysis and Closed-form Solutions of Circular Tunnels Embedded in Soft Soil and Rock

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ABSTRACT

The occurrence of earthquake events has caused numerous causalities and economic losses within the construction industry in the past and present years. However, people have insufficient knowledge and awareness of the impact of earthquakes, especially in understanding the seismic response of complex underground construction industries such as tunneling. Careful consideration of the impact of earthquakes on such structures is crucial due to previous experiences of catastrophic earthquake events that severely damaged underground structures. This study aims to investigate the effect of different soil material properties (i.e., soft soil and rock) on the seismic response of circular tunnels under increasing earthquake ground motion using simplified pseudo-static analysis, while simultaneously emphasizing the shortcomings of conventional closed-form solutions. To achieve this, a two-dimensional (2D) simplified pseudo-static analysis of a soil-tunnel model embedded at 20m depth was investigated under increasing levels of seismic intensity at the transverse direction of the tunnel axis using PLAXIS 2D software. The tunnel is modeled as a circular shape with a 0.5m thick tunnel lining embedded at a depth of 20 m from the ground surface in two different types of soil profiles i.e. soft soil and rock. The soil is treated as a single-phase medium without excess pore pressure. The six seismic intensities of peak ground acceleration (PGA) ranging from 0.1g to 0.6g were considered in this study. For validation purposes, the numerical results of pseudo-static analyses were verified with the analytical closed-form solution using Wang's method 1993. The findings indicate that the tunnel embedded in soft soil experienced maximum structural forces for bending moments and axial forces compared to rock. Results denoted that the seismic responses of the tunnel increased with the increment of earthquake magnitude and its epicenter. Notably, the results of analytical methods seemed to be underestimated compared to numerical analyses.

Keywords: Seismic response; tunnels; soft soil; rock; pseudo-static analysis

INTRODUCTION

The construction and maintenance of underground tunnels are key elements of contemporary infrastructure networks, enabling the effective delivery of transportation, water distribution, and utility services within densely populated areas. The rapid development of urbanization has led to a significant increase in the demand for underground tunneling projects. Nevertheless, tunnels are susceptible to seismic events such as earthquakes, and several factors affect their reaction to ground motion. Earthquakes contributed from the ground motion that refers to the movement of the earth's crust which varies in frequency, size, direction, and duration and can be analyzed as seismic event (Choudhury et al. 2016). Several cases of tunnel damage have been discussed such as the 1995 Kobe earthquake in Japan which resulted in the collapse of a tunnel and subway station (Zhong et al. 2020). Tunnels may be designed without considering the seismicity index of the surroundings which leads them to be vulnerable to damage during earthquakes. It is crucial to construct a resilient infrastructure that can be ensured of its safety and functionality.

Soil characteristics of composition, density, and moisture content influence the reaction of ground in both static and dynamic motion and load. Soil characteristics are of significant importance in the assessment of the dynamic behavior and seismic response of tunnels. The risk of tunnel deformation is high when embedded in loose sand which can amplify the waves of ground motion. Tunnels constructed in soft soil tend to be exposed to higher threats compared to harder soil such as rock. This soil-structure interaction can be observed in the previous event of the Loma Prieta earthquake where it is related to the liquefiable sands (Y. Wang & Orense, 2020). Understanding the factors and behavior of soil-structure interaction is important in designing a strong and adequate underground structure that can withstand the load and its surroundings. This can be done by conducting the seismic analysis that has been done during the construction of the Seikan Tunnel in Japan.

In recent decades, natural occurrences such as earthquakes have played a major role in the safety and socioeconomic impacts (Z. Huang et al. 2022). This can be observed by the unpredictable events that have caused massive loss of life, damage to structures, and environmental climate change. The design process of a structure needs a proper assessment of the seismic environment, regardless of the level of earthquakes. (St John TF Zahrah, 1985). Focusing on the infrastructure, especially the tunnel, it has been agreed that the tunnel is much more earthquake-resistant compared to the aboveground structure [6, 7, 8]. However, the opinion is found to be misleading as the reported cases, such as the 2008 Wenchuan earthquake (Yu et al. 2016), the 1999 Chi-Chi earthquake (T. T. Wang et al. 2021) and the 1995 Kobe earthquake events (Sayed et al. 2019) illustrated that tunnels tend to experience massive damage under earthquake loadings Figure 1.

The surrounding of the underground structure consists of support from soil or rock contributing to the resilience towards any hazard compared to the aboveground structure. However, specific design features, technologies, and seismic analysis in the designing process of underground structures play an important role in enhancing the safety of the structure due to the geological conditions and variety of intensity of earthquakes. It is crucial to construct an adequate tunnel to avoid any hazard by applying current methodologies in assessing the seismicity zone. The combination of geological survey, numerical modeling, and physical testing needs to be implemented in the design and construction phase. Based on the seismic design code and analysis, choosing a good material such as shock-absorbing materials contributed to the safety of the tunnel. Seismic Vulnerability Assessment (SVA) is an approach used in Malaysia previous researchers stated two different methods in evaluating the fragility of the tunnel which are Rapid Visual Screening (RVS) and Vulnerability Index Method (VIM). Other than that, the assessment can be carried out through an analytical approach of linear and non-linear for static and dynamic analysis (Noh et al. 2021).

The increasing intensity and frequency of earthquakes have posed a significant risk to operational tunnels (Z. Huang 2022), and it can be obtained from the recorded seismic ground motion time history (St John TF Zahrah 1985) which includes data on velocity, acceleration, and displacement over time during an earthquake event. The recorded seismic ground motion data can be obtained through the PEER Ground Motion Database. The parameter used in this analysis is the Peak Ground Acceleration (PGA) and its duration to stimulate the tunnel response in dynamic analysis. The underground infrastructure is a complex structure that requires detailed analysis and design. The tunnel can be classified as a multi-purpose infrastructure as it is used for transportation (i.e., subway, railway, light rapid transit) and utilities (i.e., water supply, electricity, sewer pipes). Cui & Nelson (2019) highlighted that the Urban Underground System (UUS) has the potential to reduce traffic congestion above ground, and noise pollution due to high volume traffic, and contribute to an eco-friendly environment. However, the abovementioned earthquake cases involving tunnels have urged experts to evaluate the performance of tunnels subjected to earthquake loadings. The chosen soil materials' properties were influenced by previous cases of seismic events due to tunnel response in different mediums of soil. Geological conditions stimulate different responses of tunnels under the impact of long-duration ground shaking which leads to more comprehensive and effective design analysis. A proper tool to investigate the performance of such structures under the impact of earthquake loads is crucial. The complexity of the tunnel embedded in the earthquake zone contributed to the safety and maintenance during and after the construction phase. Engineers need to construct a tunnel that offers an adequate and functional tunnel in the seismic zones. Previous events affect the current methodologies in evaluating and assessing the soil-structure behavior in the designing process to avoid unfortunate events. The objectives of the study are to investigate the seismic response of a tunnel under earthquake loading with different soil material properties at the same depth of the embedded tunnel using software with a comparison of numerical and closed-form solutions.

METHODOLOGY

To achieve and complete the preceding objectives of the research, the methodology was developed based on the flowchart in Figure 2. This methodology was employed to investigate the seismic response of the tunnel under specified seismic loading conditions while considering two distinct soil material properties.

FIGURE 1. Damages at the Longxi tunnel during the 2008 Wenchuan Earthquake
Source: Yu et al. (2016)

The initial stage of the research involved establishing the parameters of soil, tunnel, and seismic stress. These data are crucial for the modeling procedure using software (Khabbaz et al. 2019). To develop the numerical soil-tunnel model, different earthquake load is considered. The structure of the tunnel, soil materials, loading types, and characteristics will be defined for use in the numerical simulation where the tunnel is embedded in soft soil (Che Osmi & Mohd Ahmad 2016) and rock (Bertuzzi 2014). The specific parameters and materials are considered throughout the study based on previous research papers. The characteristics considered for soil are the shear modulus, Poisson's ratio, density, and 5% damping ratio. Next, the material properties of Young's modulus, Poisson's ratio, and lining thickness are taken into account for the tunnel geometry. The soil-tunnel interaction is affected directly based on the parameter chosen to observe tunnel responses under earthquake load.

A comparison was made between the soil-tunnel interaction data obtained using software utilizing pseudo-static analysis and Wang's solution approach (Ansari et al. 2023). The validation of the analysis provides a better understanding of the seismic behavior of tunnels under seismic loads. The objective of the comparison is to determine the percentage difference between the present and previous closed-form analytical solutions. A small percentage difference indicates the reliability of numerical modeling as an approach for the assessment of the tunnel while further refinement is needed if a larger percentage difference is found. The findings and methodology of this research can be applied in future investigations, while also enhancing awareness and readiness for unpredictable and critical occurrences. Additionally, it also leads to protecting the critical underground structure.

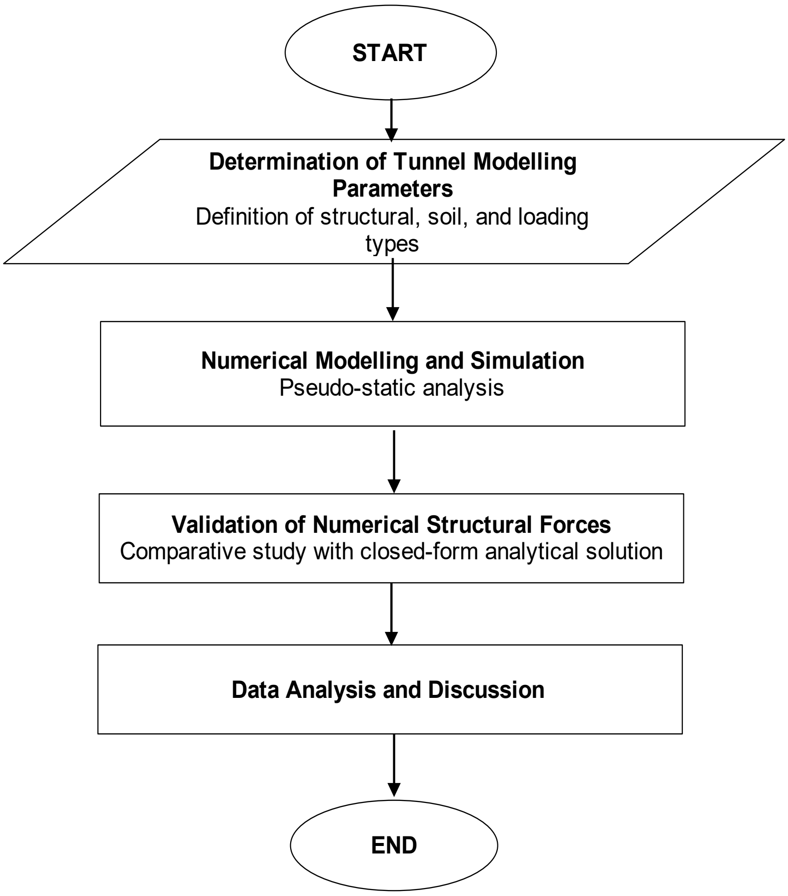

FIGURE 2. Flowchart of research

NUMERICAL MODELLING

SOIL MATERIAL PROPERTIES

Considering the stability of the building, the soil surrounding the subject demonstrates a higher level of inertia which the soil profile has greater resistance to acceleration and deformation when subjected to seismic load (Hashash et al. 2001). Therefore, two different types of soil, including soft soil and rock, were selected and used for the analysis due to their visible behavior under the inertial forces, as indicated in Table 1. Soft soil is chosen due to its instability and larger displacement when amplifying the seismic waves while rock provides a more stable structure under the forces. The sand, which was in a loose state, was classified as Mohr-Coulomb material (Soranzo et al. 2022). It is categorized based on the shear strength, internal friction angle, and cohesion of soft soil which will affect the behavior of the material under shear stress by clarifying whether it will yield or fail. The material properties of soil may indicate larger deformation and influence the stability of the structure. PLAXIS 2D recommended using the Hoek-Brown model for the rock due to its characteristic behavior (Khabbaz et al. 2019). Hoek-Brown is widely accepted by previous researchers based on the assumption to determine the strength and deformation characteristic of fractured rock masses (Hoek & Brown, 2019). The geological strength index (GSI) is a system to estimate the reduction of rock mass strength based on the geological condition that is considered in this research. This model is more accurate to use in the analysis of rock behavior under seismic loading compared to simpler criteria in Mohr-Coulomb. However, it also may lead to inaccuracy of data for other conditions of rocks.

TUNNEL PROPERTIES

A homogeneous soil was excavated to a depth of 20 m from the ground surface to construct a single tunnel with elastic properties. The tunnel lining has a thickness of 0.5 m, a diameter of 10 m, and a damping ratio of 5% (Boldini et al. 2010). The tunnel is built in various soil profiles, each with a modulus of elasticity of 35 x 10^6 (C40/50) (Che Osmi & Mohd Ahmad, 2016). Table 2 displays the characteristics of the tunnel materials.

TABLE 1. Soil Material Properties

Properties	Types Of Soil	
	Soft soil (Che Osmi & Mohd Ahmad, 2016)	Rock (Bertuzzi, 2014)
Element type	2D	2D
Material model	Mohr-Coulomb	Hoek-Brown
Unit Weight, γ (kN/m^3)	17	24
Modulus of elasticity, E (kN/m^2)	10x10^4	30x10^4
Shear wave velocity, Vs (m/s)	149	221.3
Poison ratio, v	0.3	0.25
Cohesion, c (kN/m^2)	10	150
Friction angle, φ (°)	30	35
At-rest earth pressure coefficient, K_0	0.5	0.5
Damping ratio (%)	5	5
Characteristic frictional constant, mi	-	8
Geological strength index, GSI	-	40
Disturbance factor, D	-	0

TABLE 2. Tunnel material properties

Properties	Types of Tunnels
Element type	2D
Material model	Elastic
Unit weight, γ (kN/m^3)	24
Modulus of elasticity, E (kN/m^2)	35 x 10^6 (C40/50)
Poison ratio, v	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

SOIL-TUNNEL MODEL

An analysis of a soil-tunnel model was conducted using PLAXIS 2D software (Khabbaz et al. 2019). The tunnel modeling and geometry in PLAXIS 2D is shown in Figure 3. The construction of the structure included the bedding plane and vertical plane as boundary constraints, with dimensions of 150m and 60m for the x and y axes, respectively with medium element distribution (Che Osmi & Mohd Ahmad, 2016). The boundary condition applied in this modeling free-field condition where the top medium is allowed to move freely and minimal seismic waves pass through. The bottom boundary remains fixed preventing any displacement. The soil-structure interface was used to enable the friction contact of both elements in a seismic event. To examine the impact of soil material characteristics on a tunnel located 20 meters below ground, two scenarios of the model were analyzed using six different earthquakes derived from the previous occurrence (Sayed et al. 2019; *The Imperial Valley, California, Earthquake of October 15, 1979*, n.d.; T. T. Wang et al. 2021).

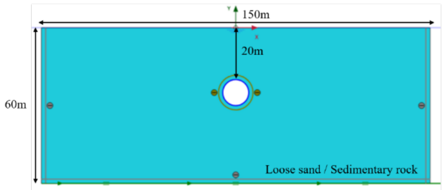

FIGURE 3. Tunnel modeling and geometry in PLAXIS 2D

PSEUDO-STATIC ANALYSIS

Pseudo-static analysis is one of the simplest approaches used in earthquake engineering to analyze the seismic response of soil embankments and slopes. However, the choice of seismic coefficients used in the analysis can be arbitrary and generally lacks rationale. Pseudo-static analysis is a simplified technique used in geotechnical engineering to evaluate the stability of slopes and structures under the influence of seismic forces. This method is specifically used to assess the stability of slopes, retaining walls, and other geotechnical constructions when subjected to ground movements caused by earthquakes. The pseudo-static approach is based on the assumption that the seismic forces acting on a structure can be approximated as static forces, allowing engineers to use familiar static equilibrium principles for analysis. In a real seismic event, the ground undergoes dynamic motion due to seismic waves. Pseudo-static analysis simplifies this dynamic motion by representing the seismic forces as equivalent static forces acting on the structure. Nonetheless, there are significant disadvantages in pseudo-static analysis using the seismic coefficients that should be considered. It lacks evaluation of the ground motion area and the geological condition which leads to conservative and non-conservative analysis and results in unnecessary mischief in construction. The negligence of the ground motion intensity, duration, frequency, and inconsistent engineering practices to simplify the analysis may confuse the designing process and produce an inaccurate seismic response of the tunnel. This can damage the tunnel during a real earthquake event. Consequently, advanced dynamic analysis is required to ensure a reliable and adequate structure in the seismicity zone.

CLOSED-FORM ANALYTICAL SOLUTION (WANG'S METHOD)

The objectives of this study included a comparison between the numerical and analytical solutions for the soil tunnel interaction model with no slip interface condition. The analysis focuses on comparing and investigating the axial force and bending moment resulting from seismic loading. The different types of analysis conducted on underground structures have led to the investigation of the seismic response of these structures concerning their deformation, as it is very responsive to ground motion (J. N. Wang., 1993) which has implications for human safety. However, the maximum thrust and bending moment required compressibility and flexibility in Equation (1) and Equation (2) to find the deformation with a no-slip boundary interface (Siti Khadijah Che Osmi, 2020). In addition, the maximum thrust and bending moment were determined using Equation (3) and Equation (4) of the lining response coefficient. respectively. These values were then substituted into were also Equation (5) and Equation (6) (Ansari et al. 2023)

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

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

$$K1 = \frac{12(1 - v_m)}{2F + 5 - 6v_m} \tag{3}$$

$$K2 = 1 + \frac{F[(1 - v_m) - (1 - 2v_m)C] - \frac{1}{2}(1 - 2v_m)^2 + 2}{F[(3 - 2v_m) + (1 - 2v_m)C] + C\left[\frac{5}{2} - 8v_m + 6{v_m}^2\right] + 6 - 8v_m} \tag{4}$$

$$C = \frac{E_m(1 - v_l^2)r}{E_l t(1 + v_m)(1 - 2v_m)} \tag{5}$$

$$F = \frac{E_m(1 - v_l^2)r^3}{6E_l I(1 + v_m)} \tag{6}$$

Where;
Y_{max}: maximum shear strain of free field soil or rock medium
E_m: Modulus of elasticity of soil or rock medium (kN/m2)
V_m: Poisson's ratio of medium
r: radius of tunnel lining
t: Thickness of tunnel lining
v_l: Poisson's ratio of tunnel lining
I: Moment inertia of tunnel lining
T_{max}: Maximum thrust
M_{max}: Maximum bending moment

However, the value of maximum shear strain was adopted from (Hashash et al. 2001) of its simplified solution due to the absence of specific data. The maximum shear strain was calculated using the following formula:

$$a_s = A a_{max} \quad (7)$$

$$V_s = B a_s \quad (8)$$

$$\gamma_{max} = \frac{V_s}{C_m} \quad (9)$$

The value of A in Equation 7 is the ratio of ground motion at depth to motion at the ground surface, where the tunnel depth of 20 m used in the research was obtained from Table 4, and a_{max} is the peak ground acceleration of the seismic load. Table 5 shows the value of B, the ratio of peak ground velocity to peak ground acceleration at the surface based on the site-to-distance of earthquakes. Based on Equation 9, the maximum shear strain was calculated to be used in further calculations of induced structural forces.

TABLE 3. Ratios of ground motion at depth to motion at ground surface (A) (Karim & Yamazaki, 2003)

Tunnel depth (m)	Ratios of ground motion at depth to motion at ground surface
≤ 6	1.0
6 - 15	0.9
15 - 30	0.8
> 30	0.7

TABLE 4. Ratios of peak ground velocity to peak ground acceleration at the surface in rock and soil (B) (Hashash et al. 2001)

Moment magnitude (Mw)	Ratio of peak ground velocity (cm/s) to peak ground acceleration (g)		
	Source-to-site distance (km)		
	0 - 20	20 - 50	50 - 100
Rock			
6.5	66	76	86
7.5	97	109	97
8.5	127	140	152
Stiff soil			
6.5	94	102	109
7.5	140	127	155
8.5	180	188	193
Soft soil			
6.5	140	132	142
7.5	208	165	201
8.5	269	244	251

DATA ANALYSIS AND DISCUSSION

The seismic response of the tunnel under different soil material properties was conducted with a total of 6 cases each for soft soil and rock. The soil selection was determined by its different qualities, including varying Young's Modulus Elasticity and diverse models such as Mohr-Coulomb and Hoek-Brown, as recommended by the previous researcher. The outcome of the deformation between the soil tunnel interaction using PLAXIS 2D at the node was studied and compared with Wang's 1993 solution method to investigate the seismic response of the structure under the given earthquake load. the empirical data from previous studies were taken into account to conduct this study in order to validate the behaviour of tunnels induced by earthquake loadings and the adequacy of the tunnel's design used in this study. previous research playing a significant role in visualizing how the tunnels react in soft and hard rock soil. This will helps to determine the output range of tunnel's structural forces when subjected to earthquake loadings. Figure 4 and Figure 5 show the outcome of PLAXIS when tunnel lining is in response to seismic ground motion (PGA 0.6g).

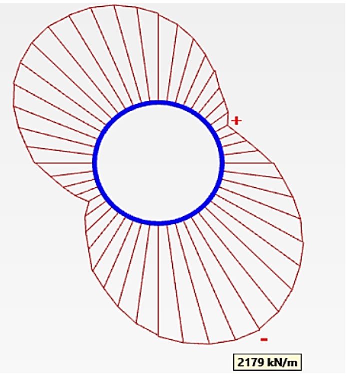

FIGURE 4. Axial force of tunnel lining

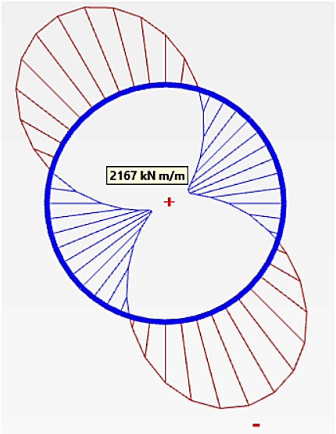

FIGURE 5. Bending moment of tunnel lining

SEISMIC RESPONSE

The result of the analysis for the maximum axial force of both types of soil using software is obtained. The highest induced structural force was observed in the pseudo-static analysis, varying the peak ground acceleration of seismic ground motion from 0.1g to 0.6g. The analysis revealed that the maximum axial force is more pronounced when the tunnel is embedded in rock with a value of 3171 kN/m compared to 2179 kN/m in soft soil when experienced peak ground acceleration of 0.6g. Moreover, the maximum axial force demonstrates an upward trend with the intensification of ground input motion. From the results, tunnels embedded in hard rock experiencing higher values of maximum axial forces compared to tunnels embedded in soft soil. In terms of structural integirty and safety, the structure experienced higher axial forces tend to structural failure such as cracking, spalling, racking and ovalling. It is expected that tunnels embedded in soft soil could resulting to the higher axial forces compared to rock. However, several factors in material properties of soil may influnce the result from analysis. Rock typically has a higher stiffness compared to soft soil. When an seismic event occured, the energy release will produce seismic wave propagation to soil and resulting to the ground shaking. The wave speed often travels faster through denser materials which contributing to the more significant impact forces being imparted to the tunnel in a shorter duration. Moreover, higher deformation of soil also contribute to the increase of axial forces. Low stiffness soil such as soft soil usually experienced larger deformation when subjected to earthquake loadings which can help to reduce energy dissipation, as well as reduce the force acting directly to the structure. Therefore, a careful consideration should take place when designing underground tunnel, especially when it is constructed in seismic prone areas. Figure 6 shows the difference in the maximum axial forces between two soils for the chosen earthquakes. The maximum bending moment for both soil profiles is the second induced structural force that has been measured to investigate the interaction between the soil tunnel and earthquakes. The highest maximum, bending moment for soft soil was experienced at 2198 kN m/m compared to 862.1 kN m/m for rock when subjected to 0.6g ground input motion. The difference in maximum bending moment for the chosen soil is illustrated in Figure 7. For bending moments, the results denoted that tunnels constructed in soft soil experienced higher values compared to rock. The ground deformation induced by seismic loadings forced the structural to bend due to the flexural stresses created in the tunnel lining. Therefore, The results shown gives a significant information for designing tunnels which to ensure that the tunnel's components have sufficient capacity to resist moments without yielding or failing. Moreover, to reduce the excessive bending moment and prevent significant failure such as buckling on the structure, an upgrade in terms reinforcement design should be emphasized. Comprehending shear forces is crucial in structural design. In this study, the maximum recorded shear force occurred when the tunnel was positioned 20m below the ground surface, subjected to a peak ground acceleration of 0.6g, with values of 891 kN/m and 517 kN/m for soil and rock, respectively. This outcome conveyed the increased involvement of soil-tunnel interaction under seismic loading conditions due to the higher shear force values.

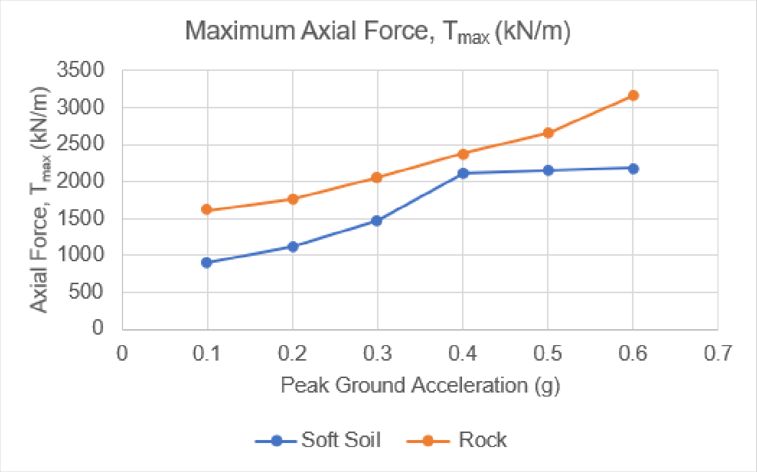

FIGURE 6. Comparison of maximum axial force for soft soil and rock

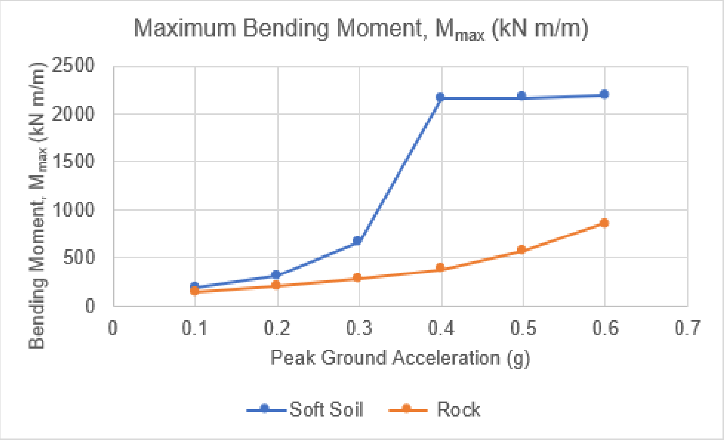

FIGURE 7. Comparison of maximum bending moment for soft soil and rock

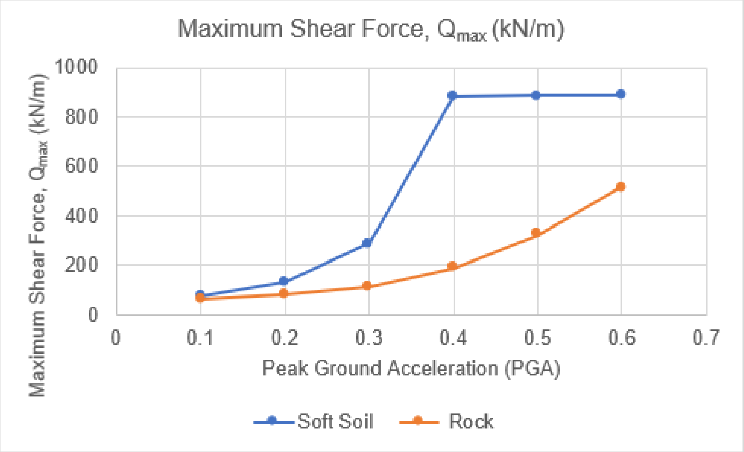

FIGURE 8. Comparison of maximum shear forces for soft soil and rock

COMPARISON OF NUMERICAL AND ANALYTICAL SOLUTION METHOD

The result of the analysis using PLAXIS 2D was compared with the closed-form analytical solution method (Wang's 1993) using the equation above for the induced structural force. Both methods consider a model with no-slip conditions. The absent data for maximum shear strain was also calculated based (Hashash et al. 2001). Tunnel embedded in rock gave the highest induced force when subjected to 0.6g seismic loading for both analysis methods. The difference in the percentage of maximum axial force produced is 60.49% and 64.53% for soft soil and rock respectively which shows a small gap of 4% approximately with a value of 4.22 and 13.16 of flexibility ratio. This data shows tunnels embedded in soft soil experienced higher bending moments and lower induced axial force compared to rock and concluded the different percentages of both soils are acceptable in the analytical solution method. The findings were also affirmed by previous researchers (Akhlaghi & Nikkar 2014; Qingrui et al. 2017).

TABLE 5. Comparison of Numerical and Analytical solution (Wang's 1993)

Types Of Soil	Soft Soil	Rock
Flexibility Ratio, F	4.22	13.16
Compressibility Ratio, C	0.053	0.13

continue ...

... cont.

Maximum Axial Force, Tmax (kN/m)	Numerical Analysis	2179	3171
	Wang's Solution	1167	1624
Maximum Bending Moment, Mmax (kNm/m)	Numerical Analysis	2198	862.1
	Wang's Solution	1043.5	634.9
Percentage Different (%)	T_{max}	60.49	64.53
	M_{max}	71.23	30.35

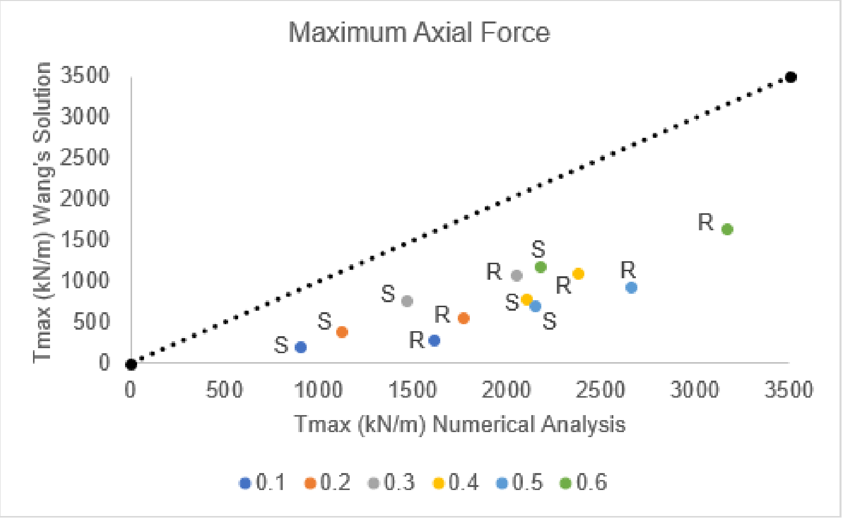

FIGURE 9. Comparison of maximum axial force (Numerical vs Analytical)

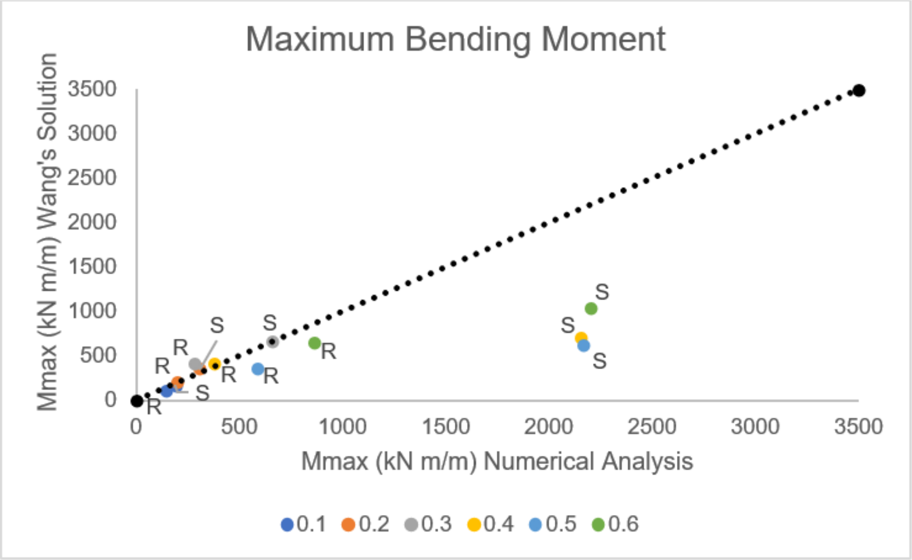

FIGURE 10. Comparison of maximum bending moment (Numerical vs Analytical)

CONCLUSION

Based on the results and case studies, the paper outlines a set of mitigation strategies to minimize the impact of seismic motion on surrounding structures. These strategies encompass pre-excavation surveys, real-time monitoring, adaptive construction methods, and structural reinforcements. The main objective of the research is to study the seismic response of tunnels under different soil material properties. The soil tunnel interaction analysis using PLAXIS 2D resulted in deformation to be used to investigate the response of the tunnel when subjected to seismic input ground motion. A total of 12 cases were studied with two different soil material properties, soft soil and rock. Other than that, pseudo-static analysis has also been conducted with the selected earthquake event from previous literature and the Pacific Earthquake Engineering Research Center Ground Motion Database (PEER). The outcome of the numerical analysis showed the maximum axial forces of 2179 kN/m and 3171 kN/m for soft soil sand and rocks, respectively while the bending moment had a value of 2198 kNm/m and 862.1 kNm/m. The maximum force is when the tunnel collapses in response to the 0.6g peak ground acceleration of the earthquake. This shows that soil material properties play an important role in the tunnel lining response.

Wang's method has also been studied for comparison between numerical and analytical analysis. For each of the forces, it resulted in an acceptable difference in percentage between the two methods. The overall study shows that the seismic response of a tunnel under earthquake loading is affected by the soil material properties of its surroundings from the induced structural forces. This method and comparison can be further investigated and used in the design process, especially for underground structures that are exposed to seismic. In conclusion, this research provides a comprehensive analysis of the seismic response of the tunnel. The findings contribute to the existing knowledge base, offering valuable insights for engineers and stakeholders involved in tunneling projects. By understanding and addressing the factors influencing induced forces, the industry can enhance the safety and sustainability of tunnel construction in urban environments.

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DECLARATION OF COMPETING INTEREST

None.

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