Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 12, December, 2023

Comparison of Different Combined Multiple Tunnel Complexes in Soft Soil under Seismic Vibrations

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Received 01 September 2023; Revised 12 November 2023; Accepted 23 November 2023; Published 01 December 2023

Abstract

The resilience of underground tunnels has gained paramount importance recently, driven by the need to ensure the safety and functionality of critical transportation and infrastructure systems during seismic events. Underground tunnels are prone to severe damage when the soil condition is poor and located in a high seismic zone. While the behavior of individual tunnels has been extensively studied, the concept of multiple tunnels combined into a large tunnel complex is relatively new, with limited available research focusing on rectangular-shaped tunnel complexes and requiring a more detailed examination. This study parametrically analyzes two novel and unconventional structures in soft soil, i.e., twin and triple tunnel complexes resulting from the combination of closely spaced circular twin and triple individual tunnels. Seismic records from Coyote (US, 1979), Kobe (Japan, 1995), and Kocaeli (Turkey, 1999) have been used to determine the produced surface displacements, tunnel distortions, lateral stresses on the tunnel structures, and the induced seismic forces, including thrusts, shear forces, and bending moments. The results are then compared with the conventional rectangular-shaped tunnel complex, which is also analyzed under the same conditions. The comparison shows that the twin and triple tunnel complexes are comparatively better seismic performers than the conventional rectangular tunnel complex, with reduced ground displacements produced, lesser incurred structural distortions, experienced lateral stresses, and induced seismic forces.

Keywords: Tunnel Complex; Soft Soil; Soil-Structure Interaction; Seismic Response; Finite Element Modeling.

1. Introduction

Urbanization and the population of metropolitan cities require advanced solutions to cater to their needs. This has led to the planning of underground traffic and utility tunnels that not only fulfill the requirements of uninterrupted flow by utilizing the subsurface space but also keep the whole surrounding area compact. Single-individual and closely spaced multiple tunnels are thus constructed nowadays to serve this purpose. A tunnel, being one of the lifeline structures, requires proper evaluation in all regards before its construction. If it is located in soft soil and earthquake-prone regions, it is susceptible to strong vibrations, induced lining forces, and a chance of surrounding soil failure; thus, extra attention is required.

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http://dx.doi.org/10.28991/CEJ-2023-09-12-01

Previously, it was believed that underground structures had a lower chance of damage, but major earthquakes like Loma Prieta (US, 1989), Kobe (Japan, 1995), El Centro (Mexico, 1979), etc. have proved otherwise. The incurred damage depends on various factors like the soil conditions, distance to the fault/epicenter, embedment of the tunnel, magnitude and duration of the ground motion, etc. The case studies of substructure failure compelled the researchers to focus on this topic too. This led to a myriad of research projects on the seismic performance of underground tunnels, either numerically [1–4], analytically [5–8], or experimentally [9–13]. While most of the literature addresses the performance of single individual tunnels of various shapes, in the recent past, closely spaced multiple tunnels have become the subject of study. The effect of soil type, optimum alignment, shape, and influence of the succeeding tunnel on the preceding tunnel and surrounding soil/structures thus been investigated using numerical modeling or experimentation using a shake table and centrifuge [14–18]. Qiu et al. [14] studied the closely spaced twin tunnels in Loess using the centrifuge to investigate the optimum interspacing and other seismic properties.

Kamal et al. [19] numerically performed the parametric study of horizontally aligned bored twin tunnels in alluvial/soft soil that are part of the Cairo metro to evaluate the effect of inter-distance, embedment depth, and soil properties. Alielahi et al. [16] developed amplification coefficients for parallel twin tunnels based on varying embedment depth and interspacing using the boundary element method to modify standard design spectra. Jishnu & Ayothiraman [20] numerically studied the seismic behavior of different construction arrangements, i.e., vertical and horizontally aligned twin tunnels, to determine the effect of pillar width and identify the better performer between them. Azadi & Kalhor [21] also conducted a similar study to evaluate the effect of excavated tunnels on existing tunnels based on embedment, soil cohesion, cementation, etc. Apart from these, many other researchers also performed similar types of studies [22–24]. When the construction of multiple tunnels is carried out in soft soil, it can cause loss of strength and failure of the surrounding ground, which has been reported to happen during construction activity. An example includes the failure of the NATM tunnel at Heathrow Airport [25].

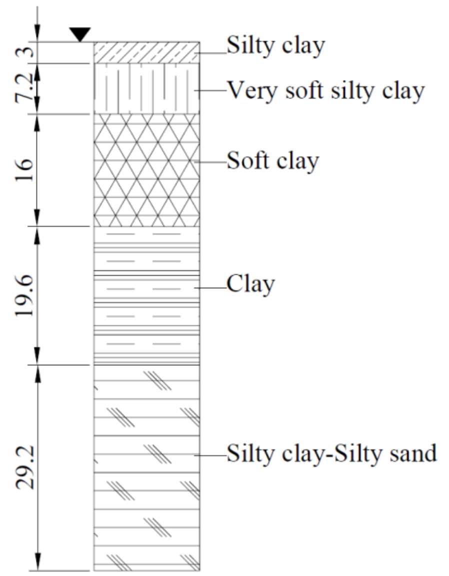
Wu et al. [26] and Chehade et al. [27] concluded that to reduce or avoid the effects of a new tunnel on the preceding tunnel, the center-to-center spacing should be at least 3 times the diameter, while the minimum pillar width should be at least 2 times the diameter for shallower tunnels and 7 times the diameter in the case of deeper tunnels [28]. In soft soil, cement treatment, including jet grout and overlapping cement-admixed columns, is used to improve the surrounding ground. Tyagi et al. [29] and Tyagi & Lee [30] studied the effect of these improved soil mediums on the construction of multiple tunnels of large diameters in close proximity and found that cracks developed when the spacing was less than 2. It is concluded from the centrifuge and numerical results that the minimum distance should be maintained at 3 times the diameter for shallower tunnels and 5 times the diameter for deeper tunnels. Sometimes it is also preferred to combine closely spaced multiple tunnels into a single large tunnel complex, e.g., in the case of metro substations, underground transit systems, etc. This is commonly done in the case of rectangular tunnels.

Zou et al. [31] studied a multi-frame rectangular substation subjected to pseudo-static loading based on a newly developed 1D soil response analysis method. Nguyen et al. [32] studied the seismic behavior of single and multiple rectangular-shaped underground tunnel complexes for a metro system to evaluate their performance based on aspect ratios and incurred shear failure. Chen et al. [33] and Li et al. [34] studied the rectangular tunnel complexes using shake tables and numerical modeling and found that inter-connected columns are the critical sections that are prone to severe damage or collapse during seismic excitations. Similar studies have also been performed by some other researchers for Daikai substation failure analyses [35–37], while Tsinidis et al. [18] summarized the notable work in a review paper as well. Apart from this, attempts have been made to develop the fragility curves—though still in their early stages—for rectangular tunnel complexes in different types of soils, which can help predict the probabilistic damage in the event of a ground motion of a certain amplitude [18, 24, 38]. From the limited literature available, it is evident that the topic of combined tunnel complexes in soft soil needs more research from the point of view of different tunnel cross-sections and probably expected damage patterns during a seismic event.

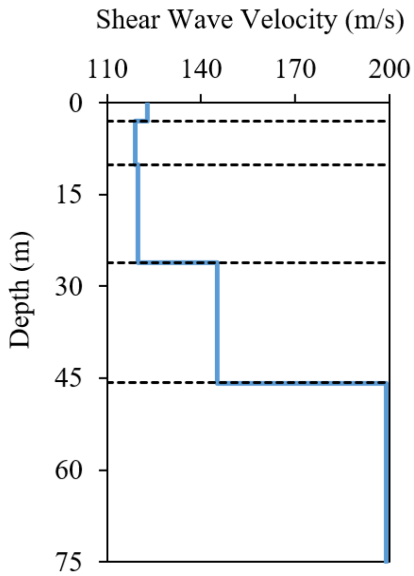
Recently, studies have been performed to evaluate the seismic performance of two novel tunnel complex shapes, i.e., the triple tunnel complex and the twin tunnel complex, resulting from the combination of three and two closely spaced individual tunnels hypothetically proposed to carry multiple underground rail tracks [39–41]. This research is a continuation of comparing parametrically the seismic behavior of these new novel shapes with the conventional combined rectangular-shaped tunnel complex to better understand their behavior and determine the better performer among the three.

2. Soil Constitutive Model and Boundary Conditions

This study considers a stratified soil system consisting of different layers. The uppermost layer comprises silty clay, followed by layers of very soft silty clay and soft clay, with underlying layers of clay and silty clay-silty sand, respectively. According to Eurocode 8, this soil system is categorized as soft soil type 'D' [42]. A detailed overview of the geotechnical soil parameters can be found in Table 1, while Figure 1 illustrates the schematic layered soil profile and shear wave velocity (V_s) profile along with the depth. It is important to note that the ground conditions are assumed to be fully saturated, with the groundwater table (GWT) located at the surface. This soil profile has also been used for similar studies by other researchers [39, 40, 43, 44].



(a)



(b)

Figure 1. (a) Schematic representation of soil profile (in 'm') (b) Shear Wave velocity profile along the depth

This study uses Plaxis 2D, a finite element analysis software, to conduct the analysis. A 2D plain strain numerical model is developed using 15-noded triangular elements. The soil behavior is modelled using a modified Mohr-Coulomb model. A simple Mohr-Coulomb model is an elastic-perfectly plastic model that is insufficient for capturing dynamic wave propagation and its effects. To address this limitation, the model is incorporated with frequency-dependent Rayleigh viscous damping coefficients (α and β) to account for cyclic stresses, resulting in a hysteretic loop with energy dissipation during seismic wave propagation. The equations for these coefficients are as follows:

$$\alpha = 2\omega_1\omega_2 \frac{\omega_1\xi_2 - \omega_2\xi_1}{\omega_1^2 - \omega_2^2} \tag{1}$$

$$\beta = 2\frac{\omega_1\xi_1 - \omega_2\xi_2}{\omega_1^2 - \omega_2^2} \tag{2}$$

while,

$$\omega_1(rad/s) = 2\pi f_1 \tag{3}$$

$$\omega_2(rad/s) = 2\pi f_2 \tag{4}$$

and,

$$f_1(Hz) = \frac{V_s}{4h} \tag{5}$$

$$f_2(Hz) = \frac{3V_s}{4h} \tag{6}$$

here, α and β represent the Rayleigh viscous damping coefficients; ω_1 and ω_2 are the angular frequencies, h stands for the thickness of the specific soil layer, and f_1 and f_2 denote the 1st and 2nd target frequencies. Additionally, ξ_1 and ξ_2 are the corresponding damping ratios, which are assumed to be 10% for soft soil. The tunnel liner is modelled using a Linear Elastic model, with an Elastic modulus (E_l) set at 37 GPa, and the unit weight (γ) and Poisson's ratio (ν_l) are specified as 25 KN/m3 and 0.2, respectively.

Table 1. Soil parameters used in the study

S. No.	Soil Layers	Saturated density (KN/m³)	Shear strength (KPa)	Permeability (m/s)		Rayleigh coefficients	
				Horizontal	Vertical	α	β (×10⁻³)
1	Silty clay	18.4	29.9	5.5×10^{-7}	2.50×10^{-9}	9.660	0.776
2	Very soft silty clay	17.5	27.4	3.5×10^{-6}	1.70×10^{-8}	3.893	1.926
3	Very soft clay	16.9	19.8	5.13×10^{-8}	1.91×10^{-9}	1.771	4.238
4	Clay	18	26.3	3.40×10^{-6}	3.51×10^{-8}	1.744	4.301
5	Silty clay-silty sand	18.1	30	2.13×10^{-5}	2.67×10^{-6}	1.706	4.397

The model's dimensions are kept at 400 × 75 m, employing a very fine mesh to ensure that the wave does not cross more than one element per time step. Free-field boundaries are applied at the lateral ends to absorb incident waves, while a fully reflective boundary is established at the bottom. These boundary conditions are chosen in a way to prevent interference with wave propagation.

3. Research Methodology

To perform this study, twin, triple, and conventional rectangular-shaped tunnel complexes are numerically analyzed using 3 different ground vibrations from past major earthquakes namely Kocaeli (Turkey, 1999), Kobe (Japan, 1995), and Coyote (USA, 1979). The input vibrations used were scaled at 0.4 g unless otherwise stated. The time-history records can be seen along with their spectral acceleration matching with the design spectrum of site class ‘A’ of Euro code 8 in Figure 2.

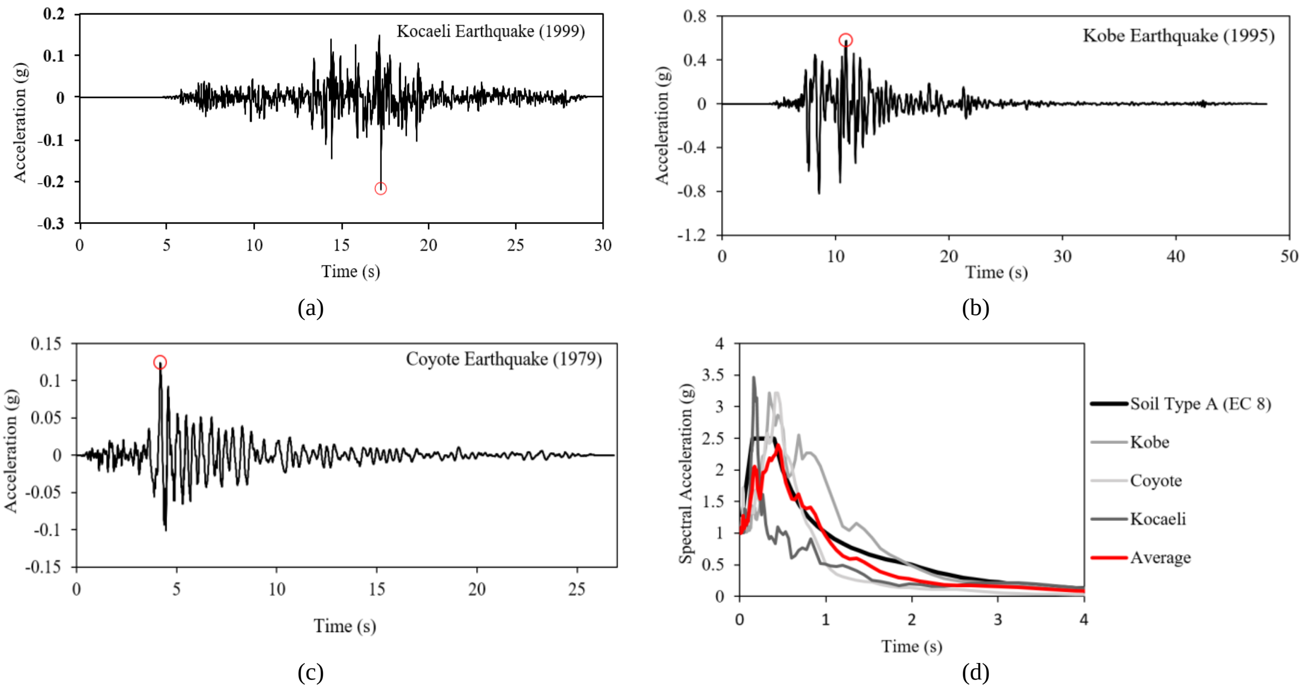
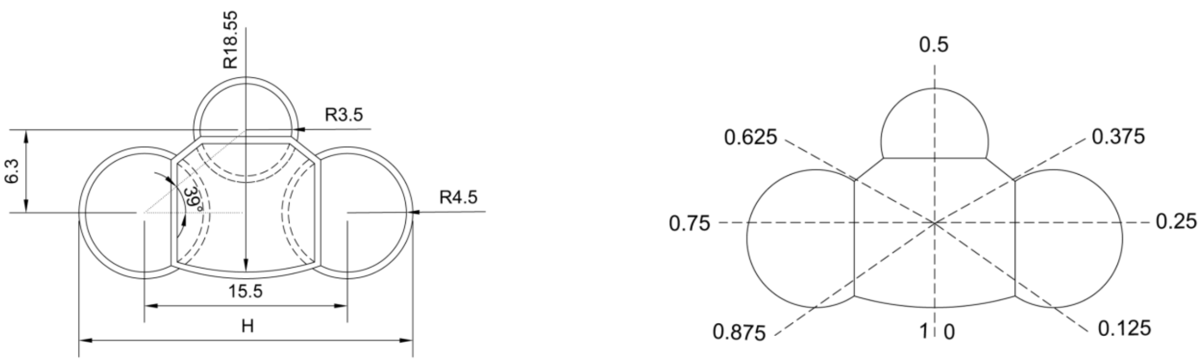
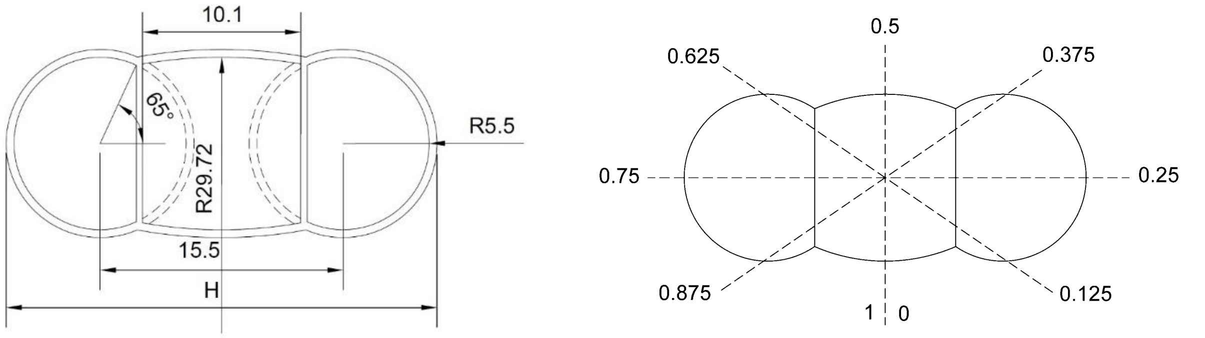


Figure 2. Seismic records of (a) Kocaeli earthquake (1999) (b) Kobe earthquake (1995) (c) Coyote earthquake (1979) (d) spectral matching with design spectrum of site class A (Euro Code 8)

A detailed dynamic analysis is conducted by applying each of the selected time-histories to the soil-tunnel model. The tunnel lining thickness is varied from 0.1 – 2 m and behavior for each case is then parametrically evaluated. These analyses help determine ground displacements, structural distortions, resulting dynamic lateral stresses, and the induced seismic forces. For each of the tunnel complexes, the invert depth is fixed at 23.5 m, corresponding to the embedment ratio (C/H), of approximately 0.5 where ‘C’ represents the cover depth, and ‘H’ denotes the width of the tunnel section. The same procedure is employed to calculate these parameters for the conventional rectangular-shaped tunnel complex too. The results are then inter-compared based on different parameters, including variations in lining thickness, Flexibility ratio (F), produced ground displacements, lateral earth pressures, induced seismic thrusts (T), shear forces (Q), and bending moments (M). This comparison aims to determine the best-performing tunnel shape among the three. Figure 3 displays the tunnel geometries and the normalized tunnel perimeter for the different tunnel shapes, while Figure 4 presents a schematic flow chart diagram illustrating the sequence of the study.



(a)



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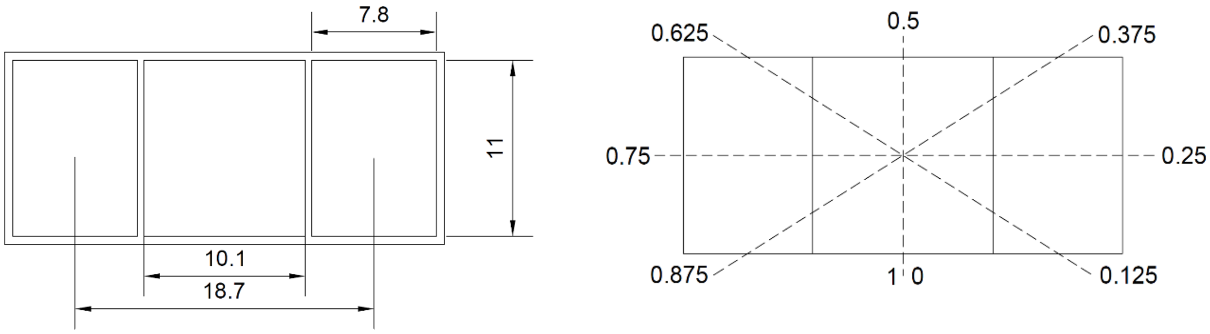

(c)

Figure 3. Geometrical representation (in 'm') and the normalized tunnel perimeter for (a) triple (b) twin (c) rectangular tunnel complexes

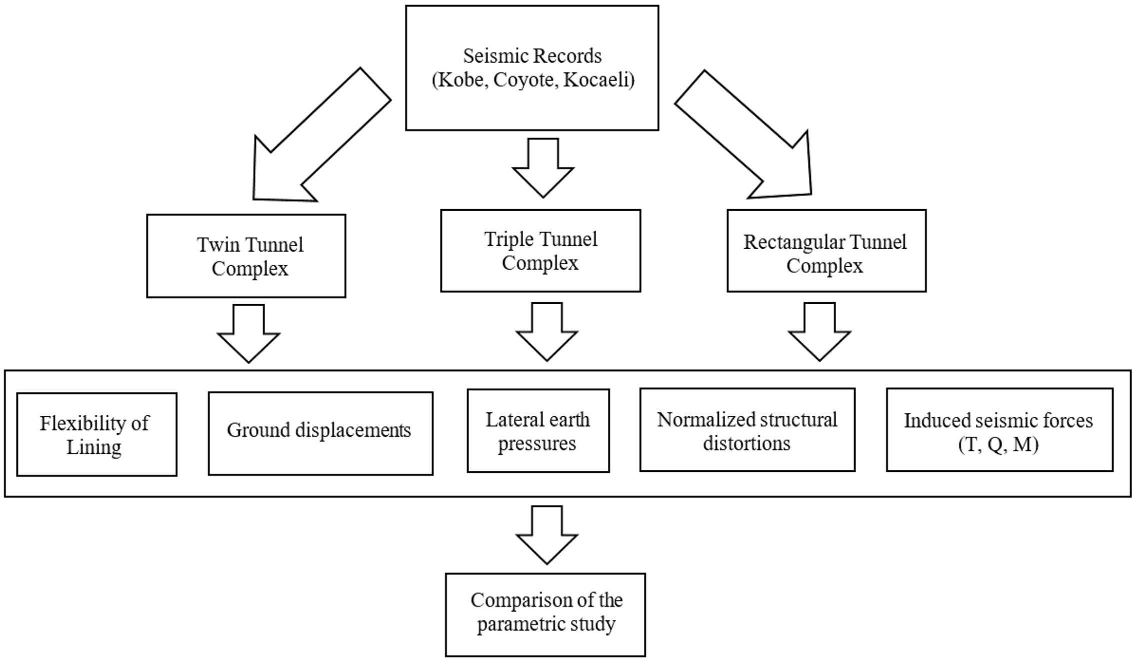

Figure 4. Flow chart diagram representing steps of the study

4. Results and Discussion

4.1. Results Verification

A reference study is performed using a single circular tunnel of 2 m diameter and varying lining thickness from 0.01– 0.2 m under a load of 1 KN/m^3 (Figure 5a). The Linear elastic model is used for both the soil and tunnel plates. The elastic modulus for soil (E_m) and liner (E_l) are taken as 1 KN/m^3 and 10^6 KN/m^3 respectively. Contours for 0.01 m thick liner are shown in Figure 5 (b, c, d). The obtained axial forces, bending moments, and displacements compared well with the well-known analytical solutions of Blake and Roark [45, 46]. The plot of displacement comparison for each case with the Blake solution is shown in Figure 5e which shows the accuracy of results from Plaxis 2D.

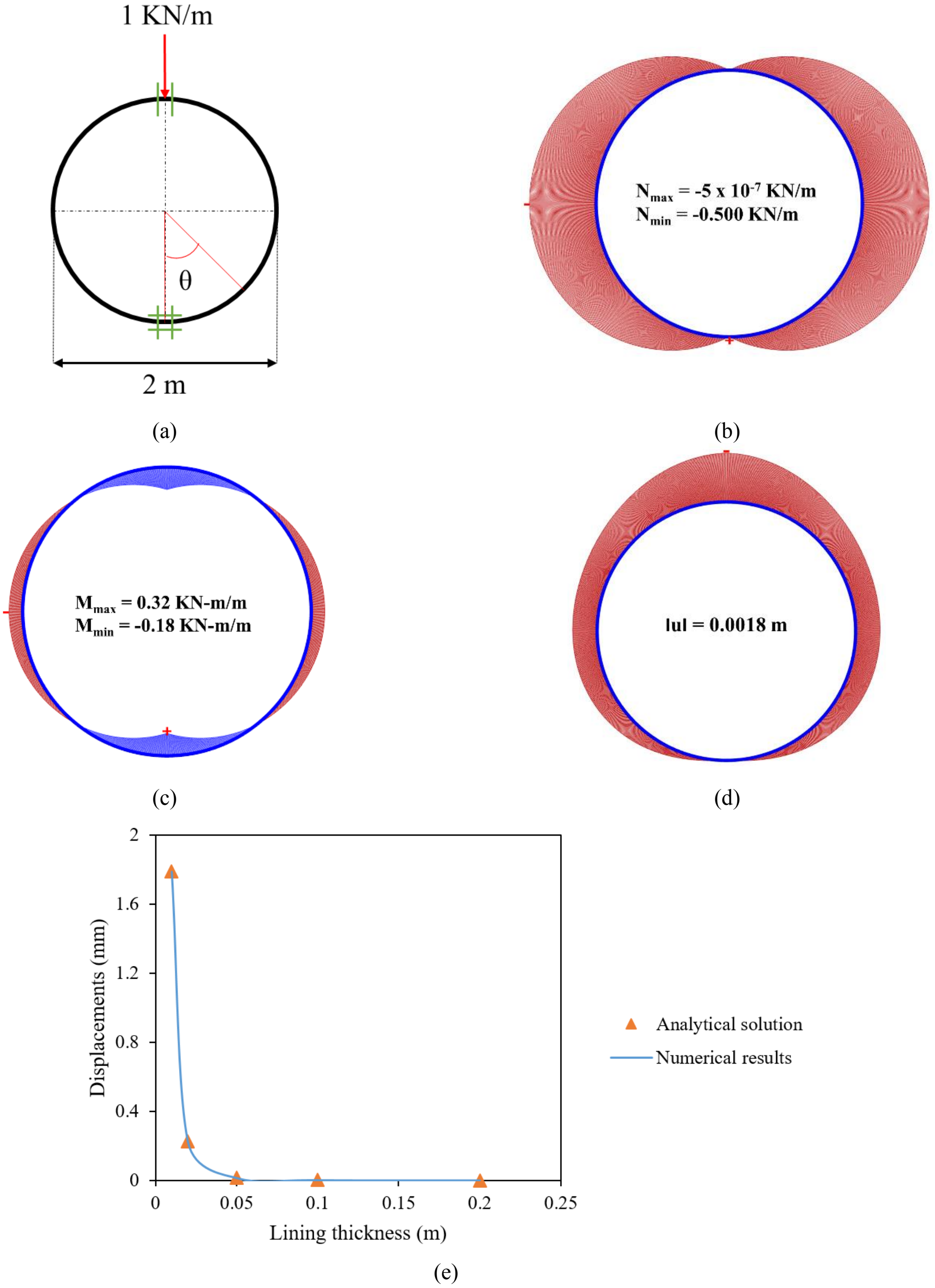

Figure 5. (a) Schematic representation of tunnel (b) Axial force (c) Bending moments (d) displacements (e) comparison plot with analytical solution

A detailed parametric study is then performed and the comparison in terms of varying lining thickness, produced ground displacements, induced seismic forces, and structural distortions is presented in detail.

4.2. Effect of Lining Thickness

Flexibility ratio (F) is defined as the ratio of tunnel distortion to the soil distortion in the free field. To determine F, we subject each lining thickness to ground vibrations and calculate tunnel displacement. Similarly, a 1D soil column in the free field undergoes the same loading, and displacements at tunnel height are determined. Finally, the ratio is calculated. The lining thickness for each tunnel complex is varied from 0.1 m to 2 m to obtain a wide range of F. The obtained F values are then plotted together with the respective lining thicknesses, as shown in Figure 6a. From the figure, it can be observed that the critical section (i.e., F ≈ 1) for twin, triple, and rectangular tunnel complexes is located around 0.2 m, 0.3 m, and 0.5 m, respectively. When keeping other factors constant, such as invert depth, input vibrations, and the thickness of internal connecting members, it becomes evident that a rectangular tunnel behaves as the most flexible, while a twin tunnel is the most rigid for the given lining thickness.

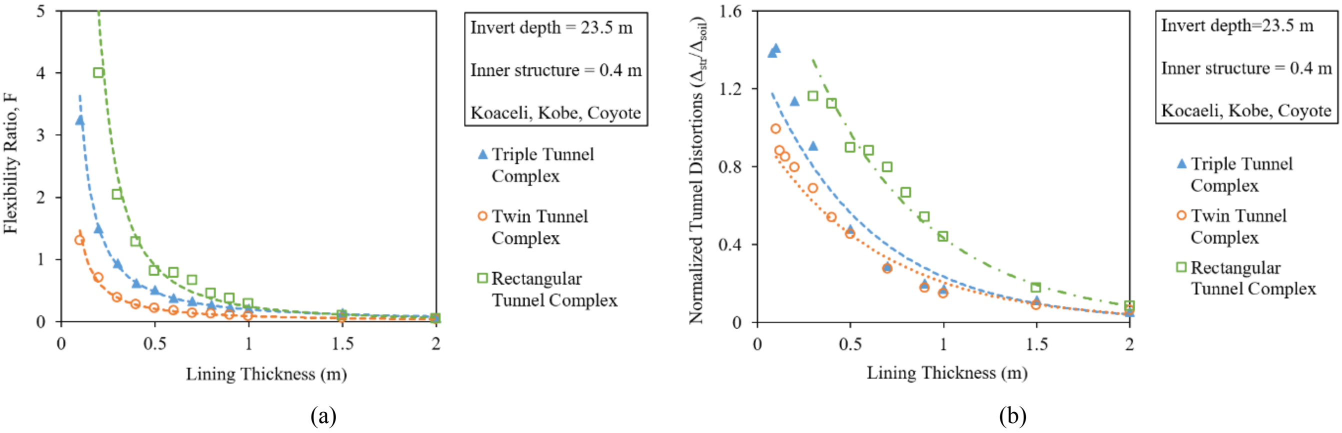

Figure 6. (a) Flexibility ratio w.r.t lining thickness (b) normalized tunnel distortions with variation in lining thickness

From the comparison of normalized tunnel distortions with variation in the lining thickness (Figure 6b), it is also evident that for the same lining thickness, the rectangular tunnel being the most flexible experiences the maximum distortions while the twin tunnel being the most rigid experiences the least distortions among the three tunnel complexes.

4.3. Produced Ground Displacements

A comparison of the produced displacement troughs and the maximum ground displacements for all three input vibrations (Figure 7) reveals that the twin tunnel complex results in the lowest displacements among the three, approximately 1.70 times less than the triple tunnel complex and approximately 2.06 times less than the rectangular tunnel complex. Conversely, the rectangular tunnel complex results in the highest displacements among the three, approximately 1.22 times greater than the triple tunnel complex. This difference can be attributed to the twin tunnel's high rigidity, which resists uplift and induced forces, resulting in minimal ground displacements. In contrast, the rectangular tunnel complex's flexibility leads to greater distortions and uplift, causing maximum ground displacements.

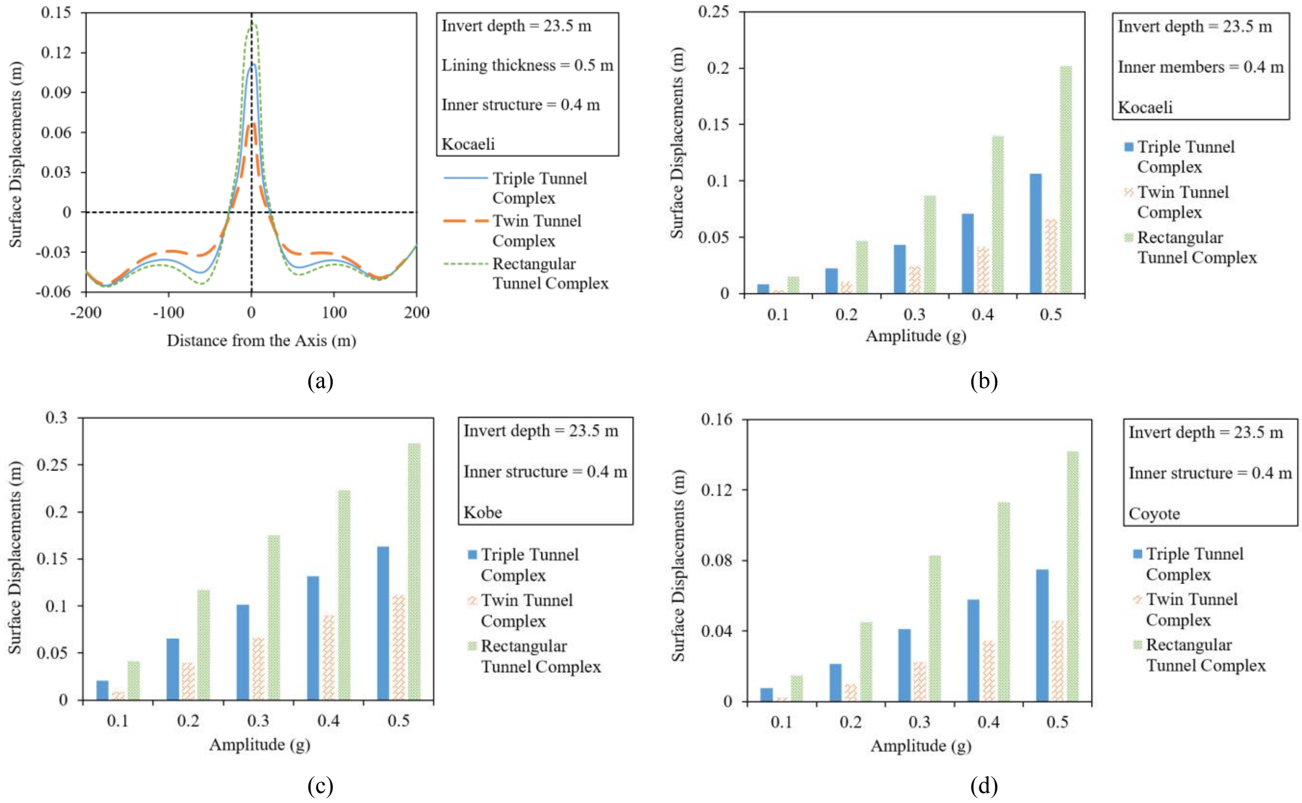

Figure 7. (a) Displacement trough along the axis (b, c, d) surface displacements w.r.t amplitude for different input vibrations

4.4. Lateral Earth Pressures

Figure 8 illustrates a comparison of lateral earth pressures. Keeping all the other parameters constant, it can be noticed that the rectangular tunnel complex experiences maximum stress while the triple tunnel complex has the least stress among the three tunnel complexes. In the case of the rectangular tunnel complex, the maximum stress is approximately 1.23 and 2.03 times higher than in the twin and triple tunnel complexes, respectively. For the twin tunnel complex, the maximum stress is approximately 1.54 times higher than in the triple tunnel complex. This difference is due to the varying curvature along the complex's periphery, with the triple tunnel having more curvature, the twin having intermediate curvature, and the rectangular tunnel complex having no curvature.

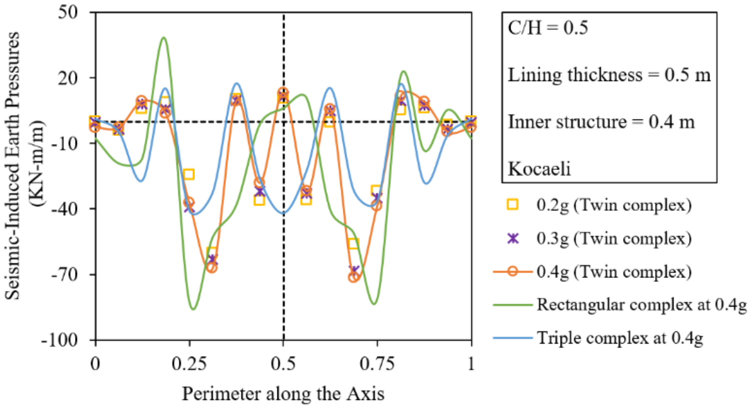

Figure 8. Variation of lateral earth pressures along the normalized perimeter of the tunnel complex

4.5. Induced Lining Forces

The induced lining forces i-e., T, Q, and M for each of the tunnel complexes are evaluated and variation is plotted altogether along the tunnel's normalized perimeter (see Figure 3) which can be seen in Figure 9.

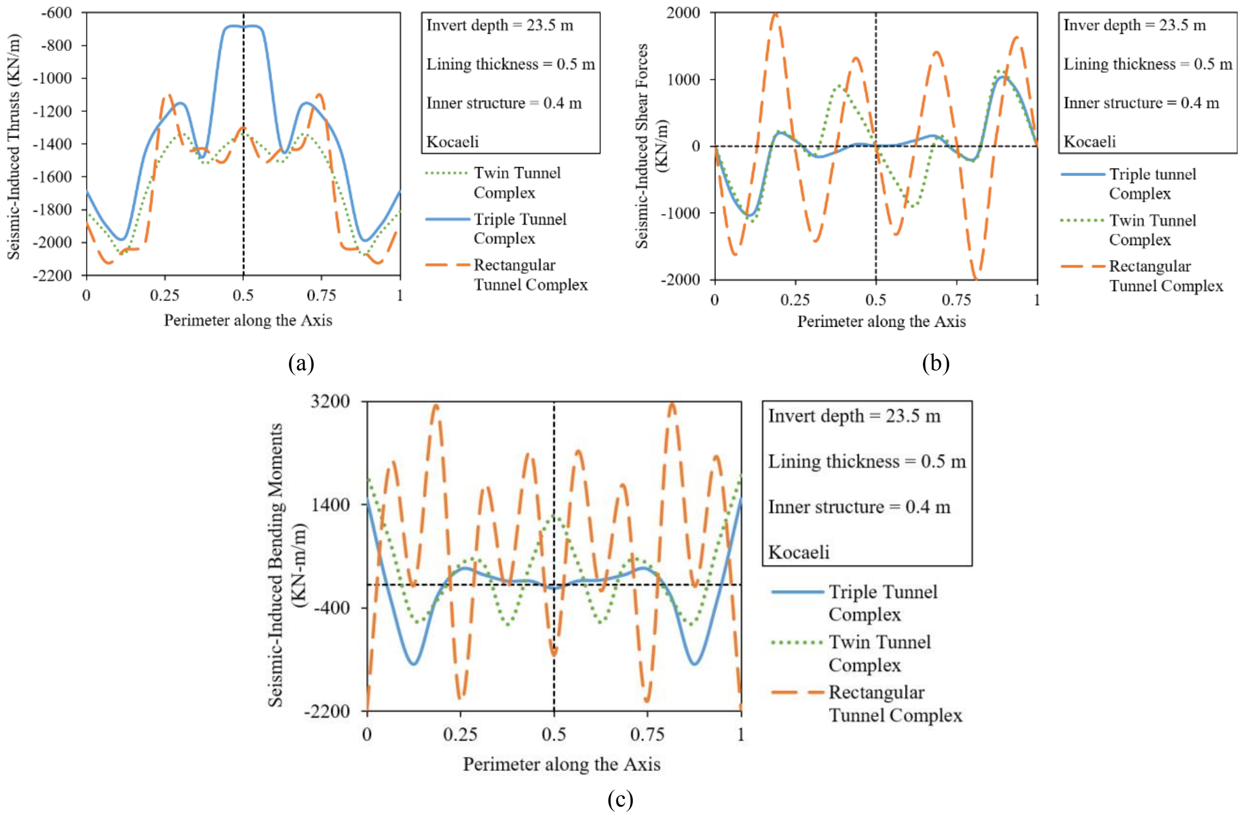

Figure 9. Variation of (a) T (b) Q (c) M along the perimeter of the tunnel complex

Based on the results, it's evident that, while keeping other factors constant and considering the same lining thickness, the rectangular tunnel complex experiences the highest induced forces. The corners, invert (0), and crown (0.5) sections are particularly vulnerable in this configuration. In contrast, the triple tunnel complex experiences the lowest forces overall, with the invert and knee areas (0.125 and 0.875) being the most susceptible points. The twin tunnel complex falls in between, with the invert, crown, and knee areas being the most vulnerable sections.

Specifically, T_{max} in the case of the rectangular tunnel is approximately 1.03 and 1.08 times higher than that in the twin and triple tunnel complexes, respectively. The twin tunnel complex experiences T_{max} about 1.05 times greater than the triple tunnel complex. For Q_{max}, the rectangular tunnel experiences forces approximately 1.81 and 2 times higher than the twin and triple tunnel complexes, respectively. The twin tunnel complex undergoes Q_{max} about 1.12 times more than the triple tunnel complex. In terms of M_{max}, the rectangular tunnel experiences approximately 1.64 and 2.10 times higher forces than the twin and triple tunnel complexes, respectively. The twin tunnel complex experiences M_{max} about 1.28 times higher than the triple tunnel complex.

This discrepancy can be attributed to the greater percentage of curvature along the periphery, with the triple tunnel complex having the highest curvature, followed by the twin tunnel, and no curvature in the case of the rectangular tunnel complex.

5. Conclusions

Twin and triple tunnel complexes represent innovative tunnel structures resulting from closely spaced twin and triple individual tunnels. In this study, a detailed seismic analysis was performed using Plaxis 2D software to assess their performance in terms of ground displacements, dynamic earth pressures, structural distortions, and induced seismic forces. The conventional rectangular-shaped tunnel complex is also included in the study for comparative purposes.

The results reveal that regardless of the lining thickness and while keeping the C/H ratio, the thickness of interconnecting members, and the amplitude of ground motion constant, the rectangular tunnel complex exhibits the most flexibility, the triple tunnel complex falls in between, and the twin tunnel complex displays the highest rigidity among the three. The rectangular tunnel complex, being the most flexible, experiences maximum structural distortions and ground displacements. Conversely, the twin tunnel complex, the most rigid, exhibits minimal structural distortions and ground displacements. A comparison of lateral stresses and induced seismic forces demonstrates that the rectangular tunnel complex undergoes the highest stresses and induced forces, followed by the twin tunnel complex, with the triple tunnel complex experiencing the least. This pattern arises from the fact that the triple tunnel complex features complete curvature, the twin tunnel complex has a smaller curvature percentage, while the rectangular tunnel complex lacks curvature along its periphery.

The obtained results suggest that the twin and triple tunnel complexes perform better in seismic conditions compared to the rectangular-shaped tunnel complex.

5.1. Limitations and Recommendations

As this study is performed using a single soft soil profile, predominantly clay, and limited seismic records, it should not be considered conclusive and applicable to different scenarios. More investigation is required with the evaluation of behavior in other types of soils using a large set of seismic records to refine these conclusions and provide more clarity on the observed behavior. More specifically, a site-specific study is advised based on past seismic records for more accurate results. Apart from this, seismic fragility curves should also be developed and compared to provide more clear insight into the seismic behavior and probable damage during a seismic event.

6. Declarations

6.1. Author Contributions

Conceptualization, Ah.N.; methodology, Ah.N. and M.K.; software, Ah.N. and As.N.; validation, Ah.N. and S.S.; formal analysis, Ah.N.; writing—original draft preparation, Ah.N. and As.N.; writing—review and editing, K.S., S.S., M.K., W.A., and H.B.; supervision, H.B. and K.S.; project administration, H.B.; funding acquisition, W.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this research is available on request from the corresponding author.

6.3. Funding

This research study is funded by Qilu Institute of Technology under grant “QIT23TP001”.

6.4. Acknowledgements

The authors express their gratitude to Ghent University for granting access to their facilities, Qilu Institute of Technology in China for generously funding this specific research under grant “QIT23TP001”, and the Higher Education Commission (HEC) of Pakistan for their support in financing the tunneling research project through the "HRDI-UESTP/UETs Phase 1" grant.

6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

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