

Mechanical Response of Segmental Tunnels Subjected to Reverse Faulting: Physical and Numerical Modeling

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ABSTRACT

Underground tunnels crossing active reverse faults are highly vulnerable to permanent ground deformation, which may significantly affect their structural integrity and operational performance. This study investigates the behavior of segmental tunnels subjected to reverse-fault displacement using an integrated approach combining centrifuge testing and three-dimensional finite element modeling. The numerical model developed in ABAQUS was verified against centrifuge experiments, showing excellent agreement with the experimental observations, with prediction errors of only 2% for maximum ground settlement and 4% for maximum tunnel crown displacement. Following model validation, a comprehensive parametric study was conducted to evaluate the influence of reverse fault angle (60°, 75°, and 85°), soil stiffness, tunnel overburden (10-20 m), soil friction angle, and tunnel diameter (5-10 m) on tunnel performance. The results demonstrate that increasing the reverse fault angle substantially intensifies ground settlement, tunnel crown displacement, tunnel S-shaped deformation, and lining ring rotation while expanding the fault-affected zone. Increasing soil stiffness reduces ground settlement but promotes more complete upward propagation of fault rupture and increases localized tunnel deformation. Increasing tunnel overburden decreases both ground settlement and tunnel displacement by dissipating fault-induced deformation within the surrounding soil mass. In contrast, changes in the soil friction angle alone have only a negligible influence on tunnel behavior. Furthermore, increasing tunnel diameter has a limited effect on global settlement but reduces the plastic strain concentration above the tunnel and modifies the fault rupture path.

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1. Introduction

Natural disasters cause a lot of damage to human society annually, and earthquakes are of great importance, especially in most countries like Iran. According to an old belief, underground structures are by far the most secure against earthquakes. However, there are many reports of earthquake-induced damage to tunnels, mines, and underground spaces, so seismic events are considered one of the major risk factors in tunnelling today [1]. The use of tunnels in urban communities is currently expanding. Among the applications of tunnels are road, railway, subway, sewage collection, high-voltage power cables, and drinking water transmission tunnels, which are known as lifelines. Many major cities in the world are built on sediment deposits and fault zones. Many world-class standards have only recommended avoiding the construction of structures adjacent to active faults as an engineering solution [2]. There are numerous lifelines in urban and non-urban areas that may be severely damaged by major earthquakes, and their rupture can aggravate earthquake damage. A study of the history of damage caused by destructive earthquakes in the world shows

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that the share of damage to lifelines is considerable. For example, in the 1989 Loma Prieta earthquake, 90% of the damage was related to direct and indirect effects of damage to lifelines; in the 1994 Northridge earthquake, more than 80%; in the 1995 Japanese Kobe earthquake, 75%; and in the 1999 Turkish Izmit earthquake, over 85% of damage was related to direct and indirect effects of damage to lifelines. When a subway line that is considered an important lifeline is damaged by an earthquake, it can have significant indirect effects on human life as well as on a nation's comprehensive transportation system. Earthquake-prone countries like Iran are witnessing several large and small earthquakes each year and must take action practically and seriously to be safe in the face of these damages to structures such as tunnels, bridges, roads, and pipelines called lifelines [3]. These lines compulsorily cross a wide geographical area, so they face different environmental and sub-terrestrial factors due to earthquake forces. The design and analysis of these lines requires recognition of the behaviour of related parameters in terms of structural engineering, and a lack of familiarity with them can face the design and execution with irreparable damage and hazards, especially due to earthquakes. Therefore, it is not always possible to avoid tunnelling through an active fault. Tunnel passing through a fault is the most important part of tunnel design in the face of earth rupture. Faults can cause lots of damage to tunnels in case of high activity. The study of tunnel behaviour when passing through faults during earthquakes is an almost unknown topic. In this case, the tunnel must be capable of withstanding fault displacement and only cause trivial damage. Investigation of passing through faults in underground structures, especially tunnels excavated in the soil, is very complex. The experience of surface faulting in recent earthquakes has led to paying more attention to the serious damage to infrastructure due to permanent deformation of the earth (especially surface faulting). In the meantime, the effect of the fault on important lifelines is of great importance due to its large extent and, consequently, the possibility of interaction with any particular fault. This research will examine the behaviour of buried structures located at the fault site using numerical modelling. For this purpose, various parameters such as tunnel diameter, applied overburden, and fault angle are considered as variables, and the effect of each parameter will be investigated by considering each of the other parameters as constant.

The theoretical foundations for evaluating continuum soil media under large plastic shear deformations were established through limit analysis and finite element theorems by Bottero et al. [4]. Concurrently, physical modeling of fault rupture propagation through alluvial soil deposits gained momentum through the physical centrifuge experiments of Roth et al. [5]. Empirical observations of seismic damage and dynamic structural responses in underground openings were documented by Dowding and Rozen [6]. Further parameterizations regarding influence zone geometry, strain localization, and surface rupture patterns in alluvial deposits overlying active dip-slip faults were comprehensively detailed by Cole and Lade [7]. As urban infrastructure expanded into seismically active regions, physical centrifuge testing was adapted to evaluate buried structures. Burrige et al. [8] performed landmark centrifuge tests to evaluate the physical performance of tunnel linings intersecting fault zones. In structural geology, Twiss and Moores [9] established comprehensive geometric and kinematic classifications of fault slip mechanisms. Bray et al. [10] developed non-linear finite element procedures and empirical frameworks to model earthquake fault rupture propagation through cohesive soil embankments. Boundary element formulations for faulted rock masses and excavations adjacent to non-linear faults were advanced by Beer and Poulsen [11], Fotoohi and Mitri [12]. Reconnaissance studies following major earthquakes in the late 1990s and early 2000s highlighted severe structural vulnerabilities in transportation lifelines. Asakura and Sato [13] reported tunnel lining failures following the 1995 Kobe earthquake. Allen and Cluff [14] updated engineering recommendations for active faults in dam foundations. Post-earthquake field evaluations by Ulusay et al. [15] in Turkey, damage assessments by Kontogianni and Stiros [16], and physical scale modeling by Jeon et al. [17] confirmed that underground conduits experience massive stress concentrations, cross-sectional ovalization, and severe bending moments near active fault crossings. During the 2000s and 2010s, physical centrifuge modeling transitioned into highly instrumented 3D testing paired with numerical simulations. Lee and Hamada [18] investigated rupture propagation through sandy deposits under variable overburden densities. Lin et al. [19] studied overburden soil deformation induced by thrust fault slip, while Johansson and Konagai [20] correlated ground surface deformation in wet and dry soils with tunnel damage. Gazetas et al. [21] formulated design recommendations for dip-slip fault-foundation interactions. For shallow urban subways, Kun and Onargan [22] presented a case study of the Izmir metro tunnel using continuum modeling across fault zones. Oettle and Bray [23] examined fault propagation through previously ruptured soil [23]. Baziari et al. [24] conducted centrifuge and 3D numerical studies on reverse faulting interactions with continuous and segmental tunnels [25]. In rock tunneling, Zhao et al. [26] simulated TBM excavation in brittle rock near fault zones for the Brenner exploratory tunnel. Normal faulting interactions were evaluated by Liu et al. [27], who analyzed rupture propagation through loose strata and its impact on mountain tunnels. Kiani et al. [2] performed centrifuge tests on segmental shallow tunnels in alluvial deposits affected by normal faults. Ghalandarzadeh et al. [28] synthesized centrifuge data for geotechnical structures crossing active faults. Varnosefaderani et al. [29] analyzed cylindrical tunnels under near-fault seismic excitations combined with reverse faulting. Further geotechnical, foundation, and lifeline mitigation strategies were developed by Ashtiani et al. [30], Garcia and Bray [31], Manouchehrian and Cai [32], Yang and Mavroeidis [33], Yeganeh Khaksar et al. [34], Cai et al. [35], Tali et al. [36], and Wang et al. [37]. The era from 2020 to 2026 marked significant progress in shallow continuous tunneling, advanced limit analysis, and machine learning risk frameworks. Sabbagh and Ghalandarzadeh [38, 39] published benchmark centrifuge and 3D FE numerical studies on continuous shallow tunnels intersecting normal and reverse faults. Interaction mechanisms were expanded by Tohidifar et al. [40], Shen et al. [41], Agalianos and Anastasopoulos [42], Han and Li [43], Nabizadeh and Mojtahedi [44], and Yao et al. [45]. Mitigation mechanics using upper bound finite element limit analysis (UBFELA) were developed by Firouzeh et al. [46], Firouzeh et al. [47], and Nalkiashari et al. [48] for foundations crossing dip-slip faults. Su et al. [49] studied karst cave tunnel deformation, while Wang et al. [50] modeled reverse faulting impacts on mountain tunnels. Specifically regarding shallow continuous tunnels, Amini et al. [51] established numerical simulations modeling shallow continuous tunnels subjected to active dip-slip faults, providing detailed evaluations of longitudinal lining stresses, sinkhole formation, and overburden ratios (H/D). Amini and Khoshrou [52] integrated machine learning algorithms with non-linear numerical datasets to predict failure risks, structural vulnerability, and stress concentration zones for shallow continuous tunnels subjected to dip-slip faulting. Recent state-of-the-art studies by Aghamolaei et al. [53], Vasef et al. [54],

Wang et al. [55], Wang et al. [56], and Zhou et al. [57] highlight current engineering directions in fault-foundation interaction, resilient seismic design, and sensitivity analysis.

Despite substantial progress in previous experimental and numerical investigations, a key gap remains: the "mechanism-based, quantitative characterization of deformation transfer in segmental tunnel linings subjected to reverse-fault displacement". Previous studies have successfully established the importance of tunnel location, tunnel rigidity, fault geometry, overburden, lining properties, and soil conditions. However, the relative importance of these parameters and their influence on different components of the tunnel-ground response are not yet consistently ranked within a unified three-dimensional framework. In particular, the relationship between fault rupture propagation in the soil and the resulting longitudinal deformation, segment-ring rotation, and localized joint response requires further systematic investigation. Accordingly, the objective of the present study is not to re-examine the existence of reverse fault-tunnel interaction, which has already been established, but to provide an integrated experimental-numerical characterization of the deformation mechanisms of **segmental tunnels** under reverse-fault displacement. A centrifuge-based physical model is first used to assess the ground and tunnel response, followed by a three-dimensional finite-element model in ABAQUS [58] that is verified against the experimental observations. The numerical framework is then employed to systematically examine the effects of fault dip angle, soil stiffness, tunnel overburden, soil friction angle, and tunnel diameter on ground deformation, tunnel crown displacement, longitudinal S-shaped deformation, segment-ring rotation, joint response, and fault-zone propagation. In addition, a normalized sensitivity index (NSI) is introduced to quantitatively rank the relative influence of the investigated parameters within the adopted one-factor-at-a-time framework. The main contribution of this study is therefore the **quantitative and mechanics-based synthesis of how fault geometry, soil stiffness, burial depth, and tunnel geometry control the magnitude and localization of deformation in segmental tunnel systems**. Particular attention is given to distinguishing parameters that primarily attenuate global deformation from those that promote localized fault-induced deformation and modify the rupture-transfer mechanism around the tunnel. The resulting framework provides a systematic basis for interpreting the vulnerability of segmental tunnel linings under reverse-fault displacement and for identifying the parameters that should receive priority in seismic assessment and preliminary design.

2. Methodology

Laboratory modelling is generally performed using shake table modelling and geotechnical centrifuge modelling. In these methods, the desired prototype is downsized using scaling criteria, and the model is made at a small scale in the laboratory. Then, using a shake table or centrifuge, the desired acceleration is applied to the model, and the parameters are measured. This research project is a study conducted on the behaviour of buried structures, including lifelines, especially subway tunnels, where these structures pass through existing faults. This will be done by numerical modelling using finite elements in ABAQUS [58]. The results of centrifuge tests will also be used for verification.

2.1. Numerical model

In the present study, the soil environment has been studied using the softening Mohr-Coulomb constitutive model. The parameters of this constitutive model are:

ψ_p : final dilation angle, ψ_{res} : residual dilation angle, φ_p : final friction angle, φ_{res} : residual friction angle, and γ_f^p : octahedral shear strain rate in the final softening step.

In the present study, the parameters of the softening Mohr-Coulomb constitutive model, according to the study by Fadaee et al. [59] and considering the soil type in this paper (Firouzkouh sand #161), are considered as shown in Table 1.

Table 1. Values of softening Mohr-Coulomb model parameters in the present study.

Parameter	Value
ψ_p	12
ψ_{res}	1
φ_p	37
φ_{res}	32
γ_f^p	0.165

The softening Mohr-Coulomb model was adopted to represent the strain-softening behavior of Firouzkouh sand and the associated localization of shear deformation during reverse-fault displacement. The constitutive parameters used in the present study were adopted from the experimental and numerical investigation of Fadaee et al. [59], which specifically considered Firouzkouh No. 161 sand. The selection of these parameters is consistent with the density condition of the physical models, as the centrifuge soil beds were prepared at approximately 60% relative density, representing an intermediate density condition between the loose and dense Firouzkouh sand specimens investigated by Fadaee et al. [59]. However, these parameters should be regarded as literature-based representative parameters rather than as independently calibrated constitutive parameters for the specific stress paths developed during reverse-fault displacement in the present soil-tunnel system. In particular, the experimental program underlying the present study was not designed to provide stress-path-specific element-level constitutive data for independently calibrating the peak-to-residual strength degradation and the associated softening strain. Accordingly, the agreement between the numerical predictions and the centrifuge observations should be interpreted as system-level validation of the overall soil-tunnel response rather than as a

quantitative material-level calibration of the softening constitutive parameters.

Advanced constitutive formulations, such as the pressure-dependent multi-yield-surface (PDMY/PDMY02) models, provide a more comprehensive framework for representing nonlinear and stress-dependent soil behavior, particularly under cyclic loading and liquefaction-related conditions. Recent studies have demonstrated the application of PDMY02 in three-dimensional nonlinear analyses of liquefiable soil deposits and ground-improvement systems [60, 61]. In particular, Asgari and Forcellini [60] demonstrated the use of PDMY02 for different sand states and calibrated the corresponding parameters using field information and undrained cyclic simple-shear test data, highlighting the importance of stress-path-relevant experimental calibration when advanced constitutive models are employed. Asgari et al. [61] further demonstrated the application of PDMY02 within three-dimensional coupled hydro-mechanical analyses of liquefiable sandy soils and ground-improvement systems. These studies illustrate the potential advantages of advanced constitutive formulations while also emphasizing their dependence on sufficiently constrained laboratory and field data.

In the present study, a dedicated sensitivity analysis of the key softening parameters, particularly the peak-to-residual strength degradation and the softening strain, was not performed. Although a sensitivity analysis of the principal geometric and soil parameters is presented later in the manuscript, this analysis does not directly quantify the uncertainty associated with the softening parameters. Introducing arbitrarily selected alternative values for these parameters without independent experimental constraints could result in physically unsupported constitutive parameter combinations. Therefore, this limitation is explicitly acknowledged, and the numerical results are interpreted within the range supported by the adopted literature-based formulation. A systematic sensitivity analysis of the softening parameters, combined with stress-path-specific laboratory testing, is recommended for future work to quantify their effects on fault-rupture propagation, shear-band localization, and tunnel deformation.

2.2. Laboratory model

Soil behaviour is a function of its confining stress. An important point in geotechnical modelling is to equalize soil stress in the real model and the scale. The most important goal of the geotechnical centrifuge device is to eliminate the weakness of modelling in 1g environments due to the reduction of confining stresses in the soil. In other words, by downsizing the model to n times smaller in the laboratory, the all-round stresses are reduced by the same proportion in 1g modelling. In geotechnical centrifuge modelling, this weakness is compensated by imposing a centripetal force as a result of rotating the test sample around a fixed axis. Therefore, the sample rotation speed is adjusted so that the acceleration is equal to the ratio of the similarity of the large-scale to the small-scale model. A geotechnical centrifuge from Tehran University was used for the experiments in this research. This device is of the C67-2 model with a cantilever beam and a suspending basket, and its arm length is 3 meters. It is capable of accelerating between 5 and 130 times the acceleration of the Earth's gravity. To model the tunnel, asbestos-cement pressure pipes were used. This ensured the uniformity of the materials. The thickness determined by the similarity relations for the model tunnel was less than that of the produced pipes; however, the pipes were reduced in thickness after the turning operation, and the pipes were divided into 6 segments by cutting and drilling to form model tunnel rings. As the embankment aligned with the tunnel axis, the embankment was stopped, and the tunnel entered the soil (Fig. 1). After placing the tunnel, the embankment continued to reach the ground level as before. Fig. 2 shows the construction process of the segmental tunnel. For all experiments, 60%-density soil was used. The method for building the model was the wet compression method. In this method, 5% water was added to the dry sand, and a moist, homogeneous soil was obtained by mixing it. In the present study, the soil was poured into 3 cm layers and compacted by a tamper to achieve complete homogeneity throughout the soil reservoir. The number of poundings to reach the desired density in the pilot experiments was determined.

The numerical simulations were implemented using the ABAQUS/Explicit [62] solver to accurately capture the complex, highly non-linear interactions and the dynamic response during the fault displacement process. The computational domain was designed to be sufficiently large relative to the tunnel diameter (D) to minimize potential boundary interference. To model the soil medium, the domain was discretized using 8-node linear brick elements with reduced integration (C3D8R), which are specifically chosen to prevent volumetric locking and enhance computational efficiency in geotechnical problems. A refined mesh was strategically applied in the vicinity of the fault plane and the tunnel lining, where the maximum element size was optimized to ensure a clear representation of the plastic shear bands and stress gradients. The accuracy of this discretization was further verified through mesh convergence checks, ensuring that the maximum ground settlement and tunnel crown displacement reached stable values. Regarding the boundary conditions, the bottom of the model was fully constrained in all degrees of freedom, while the lateral boundaries were configured to allow vertical movement while preventing lateral translation, thereby simulating far-field soil behavior. The interaction between the segmented lining and the surrounding soil was governed by a surface-to-surface contact algorithm, utilizing a Coulomb friction law to permit realistic sliding and separation at the soil-lining interface. Furthermore, the segmented tunnel lining was modeled to account for its structural flexibility, allowing for the transfer of normal confining pressures and the development of localized relative rotation and shear displacement among the rings, which is critical for capturing the behavior of segmental linings under fault-induced deformations. The tunnel lining was modeled as a series of discrete segmental rings rather than as a continuous lining. Accordingly, adjacent rings were not assumed to behave as a continuously rigidly connected structure, allowing relative deformation between neighboring rings under fault-induced ground movement. The discrete representation permits localized relative rotation, shear displacement, and opening between adjacent rings, which are subsequently used to characterize the segmental response of the tunnel. The soil-lining interface was modeled using a surface-to-surface contact formulation with Coulomb friction, allowing relative sliding and separation between the surrounding soil and the tunnel lining. It should be noted that the present model does not employ an experimentally calibrated nonlinear moment-rotation constitutive law for the segmental

joints. Therefore, the calculated joint opening and ring rotation should be interpreted as indicators of the relative deformation of adjacent discrete rings rather than as a detailed constitutive prediction of joint moment-rotation behaviour.



Fig. 1. Images of the construction process of the segmental tunnel using asbestos-cement pipe.

Table 2 summarizes the similitude relationships adopted in the centrifuge modeling, where the scaling factors are defined as a function of the centrifugal acceleration level, N . In total, 32 experimental tests were performed, of which 18 were for normal fault and 14 for reverse fault. Of these, 20 were original experiments, and the rest evaluated the performance of the fault simulator box, model measurement tools, testing issues, and result repeatability. Table 3 provides a general overview of each experiment.

Table 2. Common coefficients in centrifuge modeling.

Parameters	Scale (model/prototype)
Length (diameter and thickness)	$1/N$
Density, stress, and strain	1
Velocity	1
Force (compressive and shear)	$1/N^2$
Bending moment	$1/N^3$
Young's modulus (E)	1
Flexural stiffness (EI)	$1/N^4$
Axial stiffness (EA)	$1/N^2$

Table 3. General overview of the experiments in the study.

No.	Fault	Fault angle	Acceleration (g)	Overburden/tunnel Diameter (H/D)	Internal diameter of prototype tunnel (m)
1	Reverse	60	60	1	6
2	Reverse	60	50	1	5
3	Reverse	60	50	0.75	5
4	Reverse	60	50	0.75	5
5	Reverse	60	50	0.75	5
6	Reverse	60	50	1	5
7	Reverse	75	50	0.75	5
8	Reverse	75	50	0.75	5
9	Reverse	75	50	1.3	5
10	Reverse	60	50	1	5
11	Reverse	60	50	1.5	5
12	Reverse	60	35	1	4.2
13	Reverse	60	35	Free field	Free field
14	Reverse	60	35	0.75	4.2

In this section, one of the physical models created in a centrifuge device is selected to evaluate the accuracy of the numerical model. The numerical model was developed in ABAQUS [58] using the soil parameters reported by Fadaee et al. [59] for Firouzkuh No. 161 sand. The applicability of the adopted parameters within the present soil-tunnel configuration was subsequently assessed through comparison with the available centrifuge experimental results. In making the physical models, a box with an external diameter of $50 \times 60 \times 110$ cm is used, which is capable of modelling faults with angles of 45, 60, 75, and 90 degrees. It also considers the tunnel burial operation in its experiments between 0.75 and 1.5 times the tunnel diameter. The tunnel diameter in this modelling set is considered to be 4.2 m and 5 m. Fig. 2 illustrates the physical model.

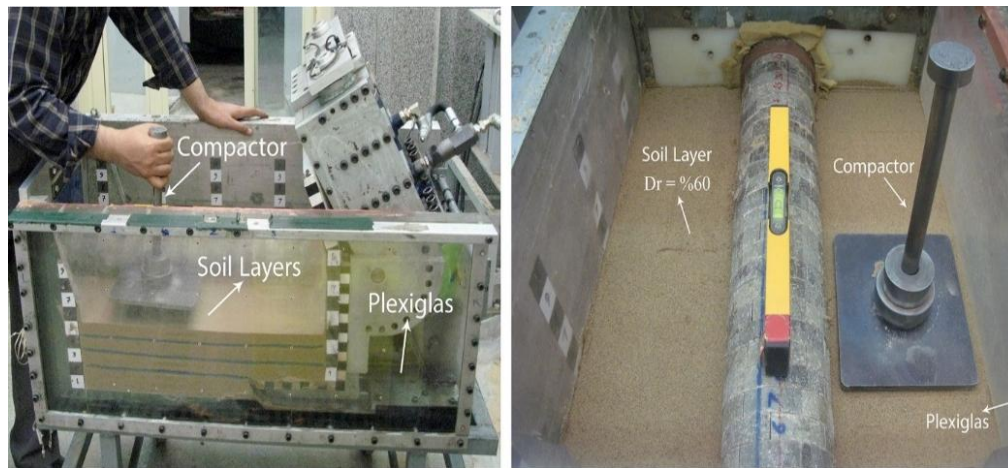


Fig. 2. The physical model.

The models selected for numerical model verification and assessment of modelling accuracy are models 2 and 21 of the physical models that have specifications as shown in Table 4.

Table 4. Geometric properties of physical models used for numerical verification.

Parameter	Model 2	Model 21
Tunnel diameter (D)	5 m	Free field
Overburden	1 D	Free field
Fault type	Reverse	Reverse
Fault angle	60	60
Centrifuge acceleration	50 g	35 g

To enhance the universality of the findings, the numerical results for tunnel displacements (u) and fault-induced deformation zones are normalized with respect to the tunnel diameter (D) and burial depth (H). This dimensionless approach (expressing as u/D and H/D) allows for a more comprehensive comparison of the structural interaction mechanism across different configurations, facilitating the application of these findings to tunnels with varying geometric scales.

3. Results

3.1. Verification of numerical model

To verify the numerical model results used in the analysis of the behaviour of these tunnels due to fault displacement near the fault zone, it is necessary to compare the results of numerical modelling with the experimental results on physical models and to ensure the accuracy of the numerical model. The laboratory results and numerical model are summarized in Table 5, and Fig. 3 also shows the parameters used for verification.

Table 5. Quantitative comparison between the experimental and numerical results for model 2.

Parameter	Laboratory model	Numerical model 2	Error (%)
Peak ground settlement (cm)	98	96	2%
End of tunnel crown level (maximum tunnel crown upward displacement) (cm)	+92	+88	4%
Beginning of the tunnel crown level (minimum tunnel crown downward displacement) (cm)	−5	−17	240%
Ratio of ground settlement to the end of tunnel crown level	1.06	1.09	3%
Differential tunnel crown vertical displacement (cm)	97	105	8%

Note: The error is calculated as the absolute difference between the numerical and experimental values divided by the absolute experimental value:

$$Error = \frac{|Max - Min|}{|Min|} * 100$$

A relatively large percentage difference of 240% is observed for the minimum settlement at the beginning of the tunnel crown level. However, this value should be interpreted with caution because the percentage error is calculated relative to the experimental value of −5 cm. The corresponding numerical prediction is −17 cm, resulting in an absolute difference of 12 cm. Thus, the large percentage value is primarily associated with the small magnitude of the experimental reference value and the sensitivity of relative error calculations to small reference values. This local discrepancy does not represent the overall performance of the numerical model. In fact, the remaining deformation parameters show close agreement between the experimental and numerical results, with errors of 2%, 4%, 3%, and 8% for the peak ground settlement, settlement at the end of the tunnel crown level, settlement ratio, and settlement difference, respectively. The overall consistency of these parameters indicates that the numerical model adequately captures the principal deformation characteristics of the tunnel-ground system. The larger discrepancy in the minimum crown settlement is therefore considered a localized difference that may be related to the sensitivity of the initial deformation state and local soil-tunnel interaction to the numerical idealization.

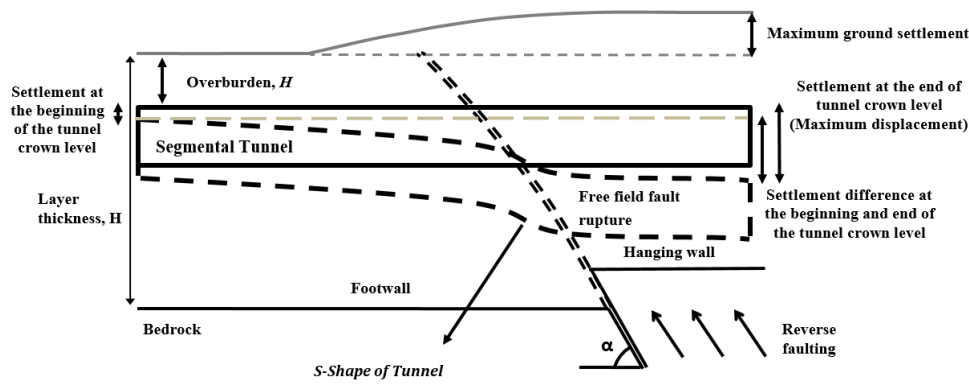


Fig. 3. Schematic of the modelled tunnel and the parameters affecting the model verification.

To verify the numerical modelling results, the distribution of the fault zone in the soil has been compared with experimental results. A comparison of the deformation in the tunnel rings is shown in Fig. 4. The visual comparison effectively demonstrates a strong agreement between laboratory observations and numerical simulations. The physical deformation of the segmental lining – specifically the joint opening and rotation – aligns closely with the structural response predicted by the Explicit numerical model. Furthermore, the correlation between shear-band propagation in the soil and the corresponding plastic shear strain contours provides additional evidence that the numerical framework captures the principal deformation mechanisms observed in the physical model. Overall, the comparison indicates that the adopted numerical framework can reproduce the main characteristics of the soil-tunnel response, including ground deformation, tunnel crown displacement, and localized deformation of the segmental lining. However, this system-level agreement should not be interpreted as an independent quantitative calibration of the adopted softening constitutive parameters.

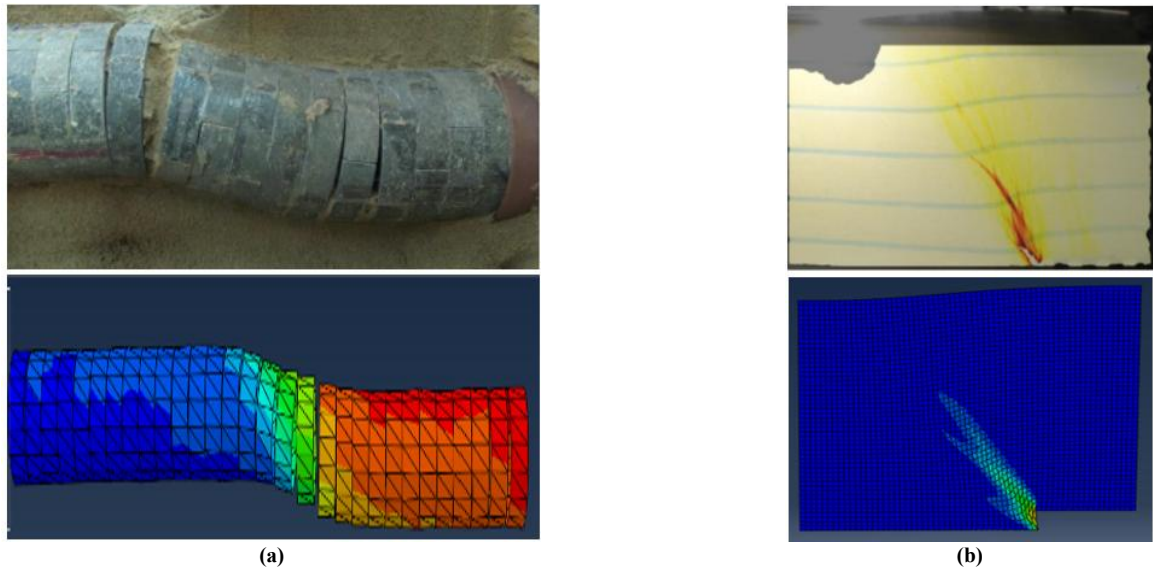


Fig. 4. (a) Deformation of tunnel rings in numerical model 2 with the Explicit method; and (b) numerical model and image analysis in model 21, Explicit method.

3.2. Parametric sensitivity analysis

A series of controlled one-at-a-time (OAT) sensitivity analyses was performed to investigate the influence of the principal geometric, loading, and soil parameters on the interaction between the reverse fault and the segmental tunnel (Table 6). The investigated parameters include tunnel diameter, fault dip angle, burial depth, soil elastic modulus, and friction angle. The OAT approach was deliberately adopted to isolate the effect of each parameter while maintaining the remaining parameters at their reference values. Therefore, the results should be interpreted as single-parameter sensitivity scenarios rather than as independently calibrated physical soil states.

To provide a quantitative comparison of the relative influence of the investigated parameters, a normalized sensitivity index (NSI) was introduced as Eq. 1.

$$NSI = \frac{\frac{\Delta Y}{Y_{ref}}}{\frac{\Delta X}{X_{ref}}} \quad (1)$$

where X denotes the investigated input parameter, Y represents the selected tunnel-response measure, and the subscript “*ref*” denotes the reference model. In the present analysis, the difference between the tunnel-crown displacements at the beginning and end of the tunnel was selected as the response measure because it directly characterizes the differential deformation induced by fault movement. The NSI therefore provides a dimensionless measure of the relative response variation associated with a normalized change in each input parameter. The calculated NSI values in Table 7 indicate that the fault dip angle has the strongest relative

influence on the selected tunnel response ($NSI = 0.434$). The soil elastic modulus and tunnel overburden exhibit intermediate sensitivity, with NSI values of approximately 0.102 and 0.113, respectively. Tunnel diameter has a comparatively lower influence ($NSI = 0.051$), whereas the independently varied soil friction angle produces a very limited response ($NSI = 0.017$). These results quantitatively support the observed trends in the individual parametric analyses. It should be emphasized that these sensitivity indices quantify the isolated influence of individual parameters and should not be interpreted as measures of genuine parameter interaction. In particular, the present OAT analysis does not allow direct estimation of interaction terms between soil stiffness, friction angle, tunnel geometry, burial depth, and fault dip angle. Such effects would require a factorial, response-surface, or other multi-parameter experimental design in which two or more variables are varied simultaneously. Accordingly, the term “interplay” is used only in a qualitative mechanistic sense, and the present results are explicitly distinguished from statistically quantified interaction effects.

Table 6. Characteristics of the studied models for parameter analysis (reverse fault).

Model No.	Tunnel diameter, meter (D)	Angle of friction (ϕ)	Overburden, meter (H)	Elasticity modulus, MPa (E)	Reverse fault angle (α)
1 ref. model	5	37	10	25-50, moderate soil	60
2	5	37	10	25-50, moderate soil	75
3	5	37	10	25-50, moderate soil	85
4	5	37	10	75-50, hard soil	60
5	5	37	10	12.5-25, soft soil	60
6	5	37	15	25-50, moderate soil	60
7	5	37	20	25-50, moderate soil	60
8	5	25	10	25-50, moderate soil	60
9	5	30	10	25-50, moderate soil	60
10	7.5	37	10	25-50, moderate soil	60
11	10	37	10	25-50, moderate soil	60

Table 7. Normalized sensitivity indices for the investigated parameters.

Parameter	Investigated range	Response range (cm)	Normalized sensitivity index (NSI)	Relative influence
Fault dip angle (α)	60-85°	177-209	0.434	High
Soil elastic modulus (E)	12.5-75 MPa	163-184	0.102	Moderate
Overburden depth (H)	10-20 m	158-178	0.113	Moderate
Tunnel diameter (D)	5-10 m	168-177	0.051	Low
Soil friction angle (ϕ)	25-37°	176-177	0.017	Very low

Note: The NSI represents the normalized single-parameter sensitivity within the adopted one-factor-at-a-time framework. The index is not an interaction coefficient and therefore does not quantify multi-parameter interaction effects.

Table 8 shows the displacement values created in the models. Also, Fig. 8 plots the distribution of faults in the soil for different models of reverse faults.

Table 8. Displacement values created in the numerical models.

Model No.	Ground vertical displacement (cm)	Beginning of the tunnel crown level (minimum tunnel crown downward displacement) (cm)	End of tunnel crown level (maximum tunnel crown upward displacement) (cm)	Ratio of ground settlement to the end of tunnel crown level	Differential tunnel crown vertical displacement (cm)
1	216	27	204	1.05	177
2	236	20	229	1.03	209
3	230	27	236	0.97	209
4	215	21	205	1.04	184
5	198	30	193	1.02	163
6	209	19	197	1.06	178
7	179	18	176	1.01	158
8	216	28	205	1.05	177
9	216	28	204	1.05	176
10	195	18	186	1.04	168
11	210	23	196	1.07	173

3.3. Investigation of the fault angle effect

In this paper, the behaviour of near-fault tunnels under three angles, 60, 75, and 85 degrees for reverse faults has been studied.

As shown in Fig. 5a, as the fault angle increases in a reverse fault, the maximum vertical displacement in the tunnel crown increases. By examining Fig. 5b, it can be seen that the maximum settlement created at ground level in a reverse fault increases by

20 cm, and it remains almost constant as the fault angle increases. As shown in Fig. 5c, by increasing the fault angle in the reverse fault from 60 to 75, longitudinal S-shaped tunnel deformation increases, and then this amount remains constant as the angle increases from 75 to 85.

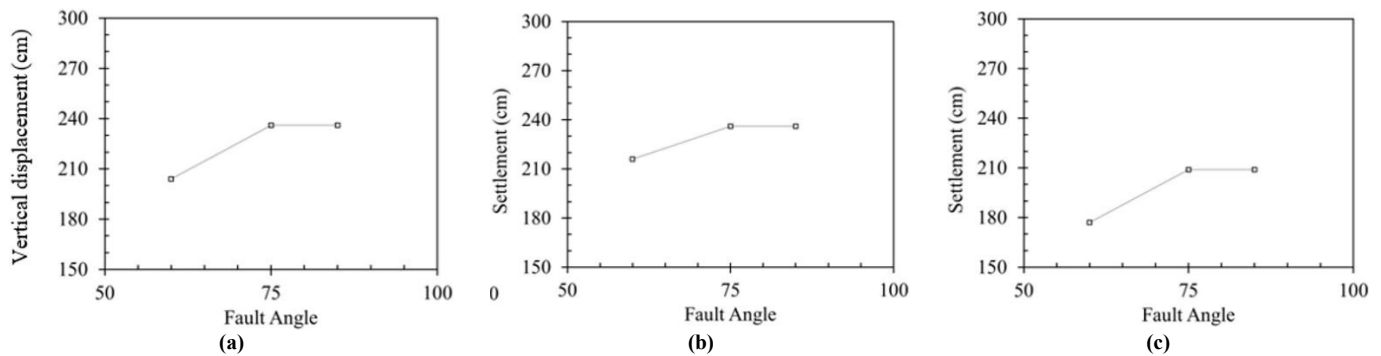


Fig. 5. Effect of fault angle on tunnel: (a) tunnel crown; (b) ground level; and (c) S-shaping of tunnel (tunnel diameter = 5 m, friction angle = 37°, moderate soil, and overburden = 10 m).

Fig. 6 illustrates the influence of the fault dip angle on the propagation of the rupture zone within the soil medium and the corresponding structural response of the tunnel lining under reverse faulting conditions. As observed, increasing the dip angle shifts the rupture pattern from a relatively planar shear band towards a distinct bilinear path, causing localized strain concentration near the ground surface and the tunnel crown. Furthermore, higher fault angles exacerbate the structural deformation of the tunnel lining. This is evidenced by a more pronounced S-shaped longitudinal deformation, coupled with severe relative rotation between adjacent segmented rings, which consequently leads to increased joint opening and potential loss of structural integrity.

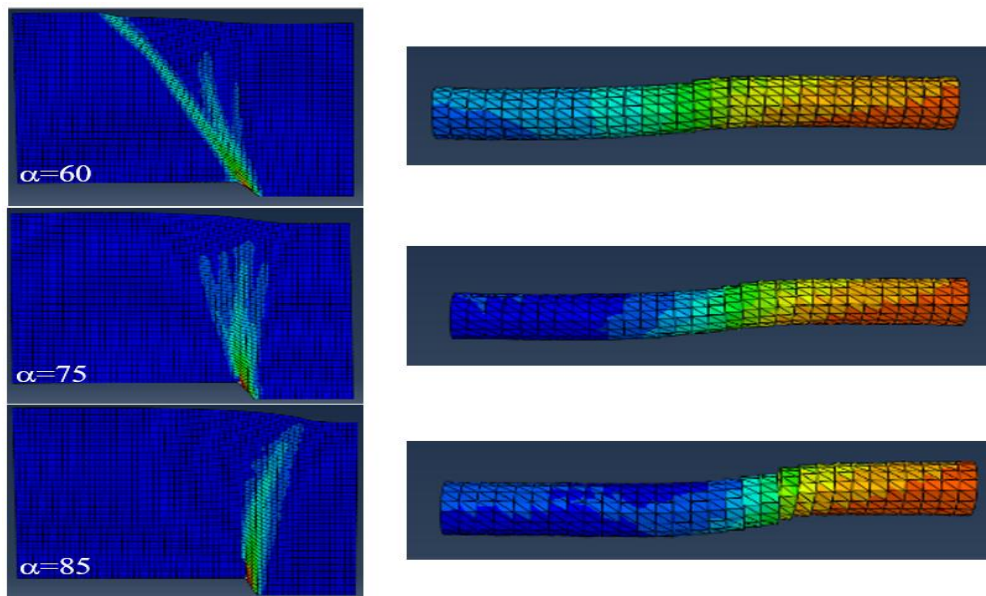


Fig. 6. Changes in fault distribution with fault angle variation under a reverse fault (tunnel diameter = 5 m, friction angle = 37°, moderate soil, and overburden = 10 m).

3.4. Investigation of the effect of soil elasticity modulus

The elastic modulus was varied from 12.5 to 75 MPa while the remaining soil, tunnel, and fault parameters were kept unchanged. This analysis was performed to isolate the influence of the stiffness level of the surrounding soil on fault-induced deformation and shear-band localization. The results indicate that increasing the soil elastic modulus reduces the overall deformability of the ground surrounding the tunnel and produces a more concentrated and continuous localized deformation zone. Conversely, lower stiffness results in a broader and more distributed deformation zone and greater tunnel deformation. These observations demonstrate the important role of ground stiffness in controlling the transfer and localization of fault-induced deformation around the tunnel.

By examining Fig. 7a, it can be seen that the amount of vertical displacement created at the tunnel is similar to that of the subsidence at ground level and has an optimum value for the soil elasticity modulus. Therefore, as the hardness of the soil increases, the amount of subsidence created in the vertical direction due to gravity decreases; at the same time, due to complete transfer of bedrock displacement to the whole soil, the displacement resulting from the fault increases. In this study, the behaviour of near-fault tunnels placed in three types of soft, moderate, and solid soils in a reverse fault has been investigated. The following are the diagrams for each. As shown in Fig. 7b, as soil type changes from soft to moderate in reverse faulting, the amount of displacement created at the surface decreases because of increasing soil hardness, and then this value remains constant. Therefore, it can be said that the elasticity modulus of soil has an optimum value, and an increase in soil hardness from a certain amount will not have any effect on the amount of displacement created at ground level. As shown in Fig. 7c, with increasing soil hardness in reverse faults, the opposite is true, and as hardness increases, the displacement difference at the beginning and end of the tunnel crown level increases.

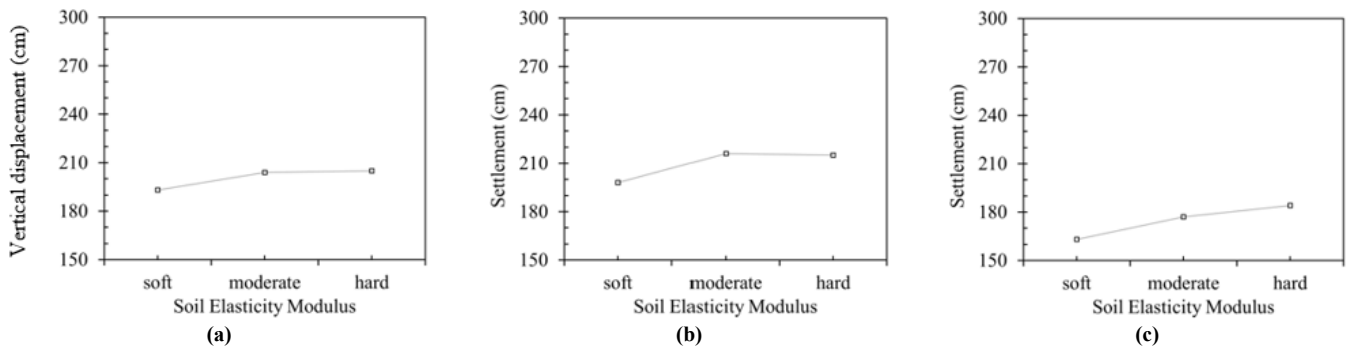


Fig. 7. Effect of soil type on tunnel: (a) tunnel crown; (b) ground level; and (c) S-shaping of tunnel (tunnel diameter 5 m, friction angle 37° , fault angle 60° , and overburden 10 m).

As illustrated in Fig. 8, increasing soil stiffness (elastic modulus) significantly influences both the rupture band propagation within the soil medium and the structural behavior of the tunnel lining under reverse faulting. In softer soils, the shear zone tends to diffuse and branch out with irregular patterns, partially attenuating before reaching the surface. Conversely, as the soil stiffness increases from soft to hard, the rupture plane develops fully and propagates continuously up to the ground surface along a well-defined, localized shear band with minimal branching. Regarding the structural response of the tunnel, higher soil stiffness induces greater soil-structure interaction constraints, exacerbating the localized shear forces on the lining. Consequently, a more pronounced S-shaped longitudinal deformation is observed in stiffer ground conditions. Furthermore, the increased ground resistance intensifies the relative displacement and rotation between adjacent segment rings, leading to a substantial increase in joint opening and joint dislocation.

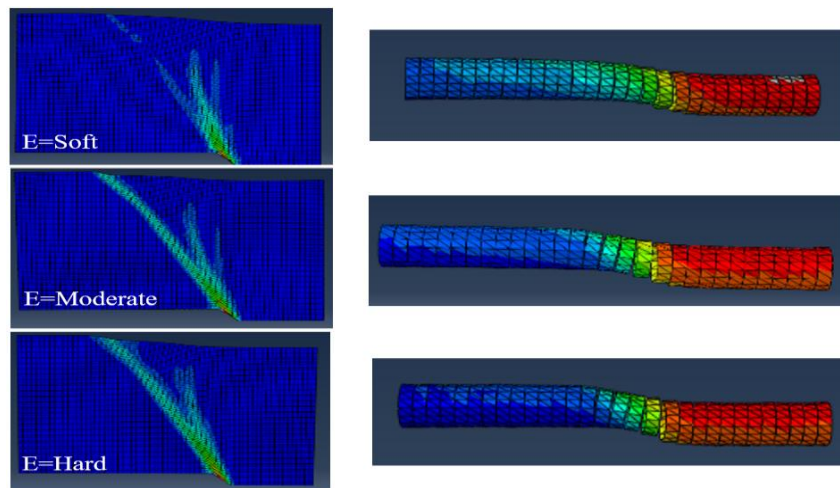


Fig. 8. Changes of fault distribution with changes in soil hardness in a reverse fault (tunnel diameter = 5 m, friction angle = 37° , fault angle = 60° , and overburden = 10 m).

3.5. Investigation of the effect of overburden

To investigate the effect of tunnel depth, three values, 10, 15, and 20 m, are considered for tunnel overburden, and then the results for reverse faults are investigated. It is observed that as the tunnel depth increases, the amount of displacement created at the surface for reverse faults decreases. The notable point is that the slope changes with an increase in tunnel overburden. The amount of displacement created at the tunnel crown level is similar to the surface behaviour according to Fig. 9, and changes increase as slope depth increases. This may be due to the increase in soil mass due to the increase, and consequently a decrease in the fault force for displacement across the whole section of soil.

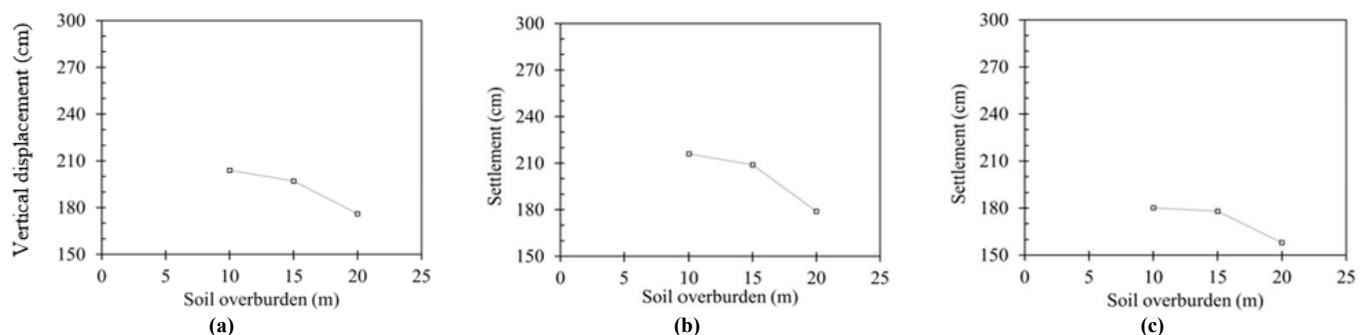


Fig. 9. Effect of overburden on tunnel: (a) tunnel crown; (b) ground level; and (c) S-shaping of tunnel (tunnel diameter = 5 m, friction angle = 37° , moderate soil, and fault angle = 60°).

As shown in Fig. 9, by increasing the tunnel overburden in a reverse fault, the displacement difference at the beginning and end of the tunnel crown decreases because of an increase in tunnel depth.

As illustrated in Fig. 10, the overburden depth plays a critical role in controlling both the fault rupture propagation through the soil and the structural deformation of the tunnel lining under reverse faulting. With increasing overburden depth (from $H = 10$ m to 20m), the confinement around the tunnel increases significantly, which alters the soil-structure interaction mechanisms. As a result of higher confinement at greater depths, the tunnel experiences higher shear forces, leading to a more pronounced S-shaped longitudinal bending deformation. Conversely, the increased surrounding soil pressure suppresses excessive relative movement between adjacent segment rings, thereby reducing the joint openings (gaps) and ring offsets compared to shallow overburden conditions. From a mechanical perspective, the observed reduction in crown displacement with increasing overburden (H/D ratio) is attributed to the enhanced soil confinement. As the overburden increases, the lateral earth pressure coefficient and the resulting normal stress state around the lining rise significantly. This increase in confinement limits the rotational degrees of freedom at the segmental joints, thereby reducing the joint opening magnitude. Furthermore, the higher overburden acts as a stiffness buffer, effectively attenuating the fault-induced shear strain before it propagates to the lining interface. The internal force analysis confirms that under higher overburden, the bending moments (M) are redistributed more uniformly along the tunnel perimeter, preventing localized stress concentrations that typically lead to larger displacements.

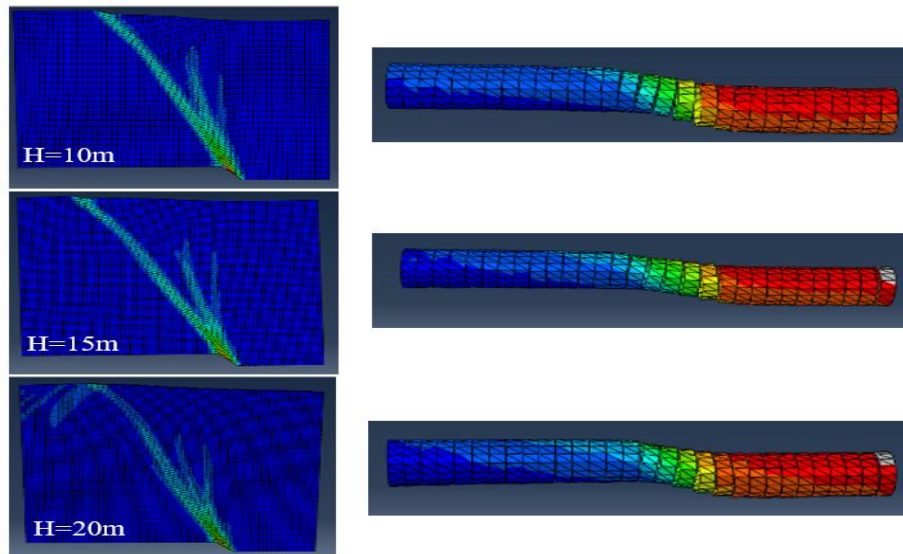


Fig. 10. Fault distribution changes with increasing overburden under a reverse fault (tunnel diameter = 5 m, friction angle = 37° , moderate soil, and fault angle = 60°).

3.6. Investigation of the effect of friction angle of soil grains

In the present study, this parameter was changed independently, and with other soil parameters kept constant, it was observed that the parameter did not change the numerical modelling results independently. The following is an example of a diagram of the maximum vertical displacement created at the tunnel crown level by reverse faulting in Fig. 11.

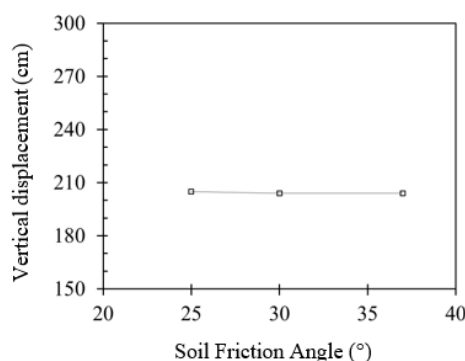


Fig. 11. Effect of friction angle on maximum vertical displacement at tunnel crown level (tunnel diameter = 5 m, moderate soil, overburden = 10 m, and fault angle = 60°).

By examining Fig. 11, it can be seen that the maximum vertical displacement created at tunnel crown level is not independently dependent on the friction angle of the soil. To study the effect of this parameter, its effect on other parameters of the soil behavioural model should be considered. Mere increasing the friction angle while keeping other parameters constant has very little effect on the fault-affected area and slightly changes the thickness of that area. It can also be seen that the variability of the mere friction angle of soil grains does not affect the S-shaping value and the tunnel ring orifice.

3.7. Investigation of the effect of tunnel diameter

In this study, three diameters, 5, 7.5, and 10 m, are modelled and studied for the tunnels. By increasing the diameter in reverse faulting, the displacement initially decreases and then increases (it has a relative minimum). According to Fig. 12, the behaviour of the tunnel is similar to that of the earth's surface. It is also seen from Fig. 12c that the effect of tunnel diameter on its S-shaping is

negligible, with a 50% increase in tunnel diameter only causing a 9 cm decrease and then a 5 cm increase in the S-shaping value of the tunnel.

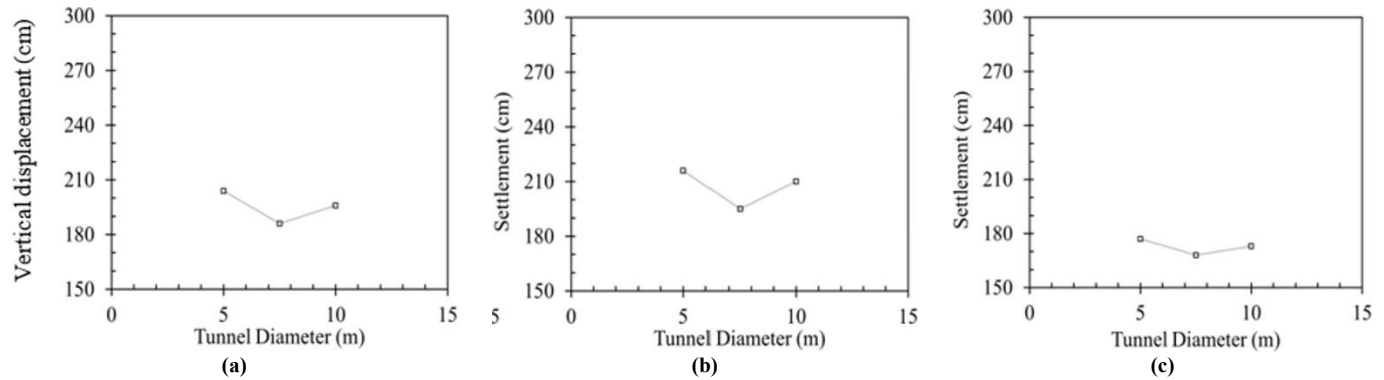


Fig. 12. Effect of tunnel diameter: (a) tunnel crown; (b) ground level; and (c) S-shaping of tunnel (friction angle = 37°, moderate soil, overburden = 10 m, and fault angle = 60°).

Fig. 13 illustrates the influence of tunnel diameter (D) on shear band propagation within the soil medium under reverse fault movement. As observed, increasing the tunnel diameter significantly alters the rupture propagation path due to the enhanced stiffness and blockage effect provided by the larger tunnel structure. In smaller diameters ($D = 5$ m), the primary rupture path easily propagates upward toward the hanging wall block and reaches the ground surface along a continuous shear zone with secondary vertical branches. However, as the tunnel diameter increases to $D = 10$ m, the larger cross-section acts as a rigid barrier, redistributing localized strains around the tunnel boundary. Consequently, rupture transfer into the hanging wall side is substantially suppressed, resulting in a more localized and constrained shear zone around the tunnel crown and primary fault trace. The influence of tunnel diameter on fault-induced deformation is governed by the structural flexural rigidity (EI). While global surface settlement remains relatively insensitive to diameter variations, the tunnel's structural response is highly dependent on the D parameter. Increasing the diameter enhances the tunnel's cross-sectional moment of inertia, which initially decreases the magnitude of differential displacements across the fault plane. However, the subsequent increase in displacement for larger diameters observed in our model is linked to the larger contact area with the soil, which facilitates the transmission of shear forces. A mechanics-based assessment of the axial force and bending moment profiles reveals that larger diameters induce a more complex S-shaped bending pattern, as the tunnel lining experiences higher differential loading across the fault-soil interface. These observations suggest that fault-displacement transfer is influenced not only by tunnel geometry but also by the relative stiffness-to-diameter characteristics of the tunnel lining. However, this observation represents a mechanistic interpretation of the single-parameter analysis rather than a direct quantification of parameter interaction.

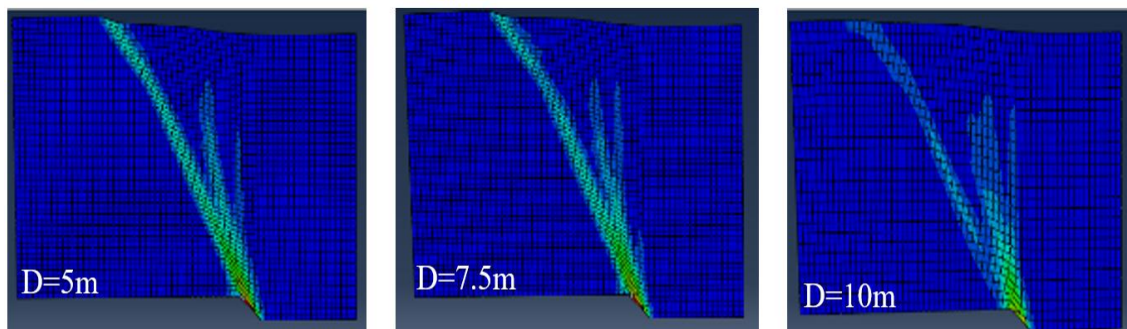


Fig. 13. Changes in fault distribution with increasing tunnel diameter under reverse fault (friction angle = 37°, moderate soil, overburden = 10 m, and fault angle = 60°).

4. Limitations and future research

The present study provides a detailed investigation into the interaction between reverse faults and segmental tunnel linings. While the deterministic approach offers high-fidelity insights into the deformation mechanisms, the following limitations should be noted:

- **Scope of fault configurations:** This study focuses on a specific reverse-fault geometry and displacement magnitude. The interaction mechanism – specifically the transition between structural bending and shearing – is highly dependent on the fault dip angle and the tunnel-fault crossing angle. Future parametric studies should investigate a broader range of crossing angles (e.g., 30° to 90°) and fault types, including strike-slip and normal faults, to derive more universal design charts.
- **Geotechnical and environmental factors:** The current model assumes a specific soil density and drainage condition. Variations in groundwater pressure and soil hydraulic conductivity can significantly alter the pore-water pressure response during fault movement, which should be incorporated into future constitutive modeling.
- **Scaling relationships:** The validity of our centrifuge model results relies on the application of appropriate scaling laws. We verified our prototype behavior by ensuring the similarity in stiffness-to-geometry ratios (EI/D^4) and soil-lining interface

friction. However, we acknowledge that the scaling relationship between centrifuge fault displacement and real-field prototype behavior is non-linear. Future work will involve a series of comparative simulations to refine the scaling factors for different lining stiffnesses.

5. Conclusions

This study investigated the behavior of segmental tunnels subjected to reverse fault displacement through an integrated experimental and numerical approach. Centrifuge modeling was first employed to reproduce the complex soil-tunnel interaction under reverse faulting, and the developed finite element model was subsequently verified against the experimental observations. The close agreement between the numerical predictions and centrifuge test results confirmed the capability of the adopted numerical model to accurately capture the deformation mechanisms associated with fault rupture, providing a reliable framework for conducting comprehensive parametric analyses. The results demonstrated that tunnel response is governed by the combined influence of fault geometry, soil mechanical properties, and tunnel burial conditions rather than by any individual parameter. Among the investigated variables, the reverse fault angle was identified as one of the most influential factors controlling tunnel performance. Increasing the fault angle intensified ground settlement, tunnel crown displacement, and S-shaped tunnel deformation while simultaneously enlarging the fault-affected zone and increasing tunnel ring rotation. These observations indicate that steeper reverse faults generate more concentrated deformation fields and consequently impose greater structural demands on segmental tunnel linings. The mechanical properties of the surrounding soil also played a significant role in determining tunnel behavior. Increasing soil stiffness reduced the magnitude of ground settlement due to the enhanced resistance of the soil mass against vertical deformation. However, stiffer soils transferred bedrock displacement more efficiently toward the ground surface, resulting in clearer and more continuous fault rupture propagation and greater localized deformation around the tunnel. Therefore, although hard soils may reduce overall settlement, they can increase the concentration of fault-induced deformation and should be carefully considered during seismic design. Tunnel burial depth considerably influenced both the magnitude and distribution of deformation. Increasing the overburden reduced surface settlement and tunnel displacement because the thicker soil cover dissipated a larger portion of the imposed fault movement before it reached the ground surface. Nevertheless, deeper tunnels exhibited more pronounced S-shaped deformation patterns, indicating that increasing burial depth modifies the deformation mechanism rather than eliminating the adverse effects of reverse faulting.

The parametric analyses further showed that varying the soil friction angle alone produced only a marginal effect on tunnel response when other constitutive parameters were maintained constant. This finding suggests that the friction angle cannot be considered an independent governing parameter and should instead be evaluated together with the complete constitutive behavior of the surrounding soil. Likewise, tunnel diameter exhibited only a limited influence on global settlement; however, increasing the tunnel diameter altered the distribution of plastic strains above the tunnel and modified the upward propagation of the fault rupture. Therefore, although tunnel diameter has a relatively minor effect on overall deformation, it may significantly influence the local failure mechanism within the fault zone. From an engineering perspective, the outcomes of this research emphasize that the design of tunnels crossing active reverse faults should explicitly consider the combined effects of fault angle, soil stiffness, and tunnel overburden. The numerical model verified against the centrifuge observations provides an efficient tool for evaluating tunnel performance under different geological conditions and can support engineers during the preliminary design and risk assessment of underground lifeline infrastructures located in fault-prone regions. Furthermore, the findings suggest that mitigation strategies such as adopting flexible segmental linings, improving joint ductility, optimizing tunnel alignment with respect to the fault trace, and applying localized ground improvement techniques may substantially reduce structural damage caused by reverse fault displacement. Beyond geometric and structural design modifications, advanced strengthening techniques may provide additional opportunities for improving structural resilience under severe deformation demands. Recent experimental research has demonstrated that prestressed fiber-reinforced polymer (FRP) confinement can enhance the load-carrying capacity, initial stiffness, and deformability of damaged reinforced-concrete members compared with conventional passive confinement [63]. Although this strengthening approach has primarily been investigated for reinforced-concrete members rather than tunnel linings subjected to fault displacement, its active confinement mechanism provides a potentially relevant concept for future tunnel retrofit applications. In particular, prestressed FRP-based strengthening may be investigated as a potential future technique for controlling localized damage and enhancing the residual structural capacity of tunnel lining components following severe deformation. Further experimental and numerical studies are required to evaluate its applicability to segmental tunnel linings under fault-induced deformation. Although the proposed methodology provides reliable predictions of tunnel behavior under reverse faulting, the present study was limited to specific soil conditions, tunnel geometries, and quasi-static fault displacement. Future investigations should extend the proposed framework to three-dimensional numerical analyses, dynamic earthquake loading, nonlinear segmental joint behavior, groundwater effects, and different geological environments. Incorporating probabilistic risk assessment and performance-based design methodologies would further improve the reliability and practical applicability of underground structures constructed across active fault zones.

Although the present study focuses on the deformation response of segmental tunnels subjected to reverse-fault displacement, the proposed fault-tunnel framework can be extended in future studies to investigate time-dependent and impulsive loading conditions. In this context, analytical studies of transient structural response, such as the dynamic response of a transverse beam under slamming excitation based on Wagner theory [64], provide a useful perspective for interpreting dynamic deformation transfer and structural demand. Such analytical approaches may offer a complementary basis for understanding the temporal evolution of deformation and internal forces in tunnel linings subjected to rapidly varying ground or fault-induced loading. Future investigations could therefore integrate transient dynamic formulations with the present fault-tunnel framework to evaluate the effects of loading

duration, excitation characteristics, and structural inertia on tunnel response.

Statements & declarations

Author contributions

Majid Kiani: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

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Consent to participate: Not applicable.

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