8th International Conference on Seismology & Earthquake Engineering
11-13 Nov. 2019, Tehran, Iran

INTERACTION OF UNDERGROUND TUNNEL AND EXISTING SHALLOW FOUNDATIONS AFFECTED BY NORMAL FAULTS

Sadegh Ghavami
Ph.D. Candidate, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

Alireza Saeedi Azizkandi
Assistant Professor, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

Mohammad Hasan Baziar
Professor, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

Mehrdad Rajabi
Department of Civil Engineering, Islamic Azad University, South Tehran Branch, Tehran, Iran

Keywords: Normal fault, Shallow foundation, Underground tunnel, Interaction

ABSTRACT

In major earthquakes, permanent ground deformations due to fault movements cause serious damage to the foundations and structures. Although many of structural seismic design codes have recommended avoiding the construction of structures in the adjacent to active faults, it is not always a viable option. For example, the lifeline facilities such as gas tunnels, water supply tunnels and transportation tunnels, due to their extensive length, often cannot avoid crossing active faults. Therefore, it is necessary to evaluate the interaction mechanism between structures and fault rupture for effective design to reduce the hazards associated with surface faulting. This study investigates the interactions of underground tunnel and existing shallow foundation affected by normal fault using the finite element method. The results show that the existence of a tunnel changes the fault rupture path and in some cases can increase the foundation rotation. It causes to occur severe level of damage to the structure and increases fear about its instability.

INTRODUCTION

The 1999 earthquakes in Turkey and Taiwan and the 2008 earthquake in China showed that fault movement and propagation of fault rupture through the overburden soil could cause serious damage to surface and subsurface structures (Bray, 2001; Yu et al., 2016). Many of structural seismic design codes only recommended avoiding construction in the vicinity of active faults, and imposed a setback zone from the fault lines to prevent fault rupture surface cross structures (Hart et al., 1999; Boncio et al., 2018). There are many problems in code implementations such as uncertainty related to the mapping of active faults and pattern of fault rupture propagation through soil deposits. Moreover, for long structures, such as tunnels, bridges and pipelines, avoidance of construction across or near active faults is not possible (Ghavami et al., 2018). Therefore, it is necessary to evaluate the interaction mechanism between structures and fault rupture for effective design to reduce the hazards associated with surface faulting.

Available studies on consideration of fault rupture propagation through the overburden soil and its interaction with surface and underground structures can be classified in four main categories: 1) field studies of case histories, 2) experimental modeling, 3) numerical analyses and 4) analytical studies.

The interaction between the shallow foundations and fault ruptures is influenced by many factors, including (a) the position of the foundation relative to the fault outcrop location, (b) The amount of bearing pressure on the foundation, (c) The rigidity and continuity of the foundation, and d) the embedment depth of foundation (Bransby et al., 2008; Ashtiani et al, 2016). A building would fail by either the fault rupture or excess rotation of its foundation (Brennan et al., 2007; Saeedi Azizkandi et al., 2019). Table 1 presents proposed limits for foundation rotation that coincide with structural damage states.

Table 1. Suggested limit states for rigid body rotation due to ground deformations beneath foundations (Baziar et al. 2019)

Foundation rotation	Damage state
0≤θ<1°	Slight
1°≤θ<2°	Moderate
2°≤θ<5°	Severe
θ≥5°	Threatening stability

Due to population growth, tunnels and underground transport facilities are important means of communication. In many cases, they are built in seismically active zones. Therefore, it is necessary to not only evaluate the effects of permanent ground deformation on tunnels but also consider the effect of tunnel presence on the fault rupture path and surface structures. Previous studies have so far confirmed the fact that the presence of a tunnel near active fault can change the zone of large deformations on the ground surface (Lin et al., 2007; Baziar et al., 2014; Saeedi Azizkandi et al., 2019). This study investigates the interactions of underground tunnel and existing shallow foundation affected by normal fault with a dip angle α=60° using the finite element method. The FE software ABAQUS (2014) was used to conduct the numerical study. The numerical analysis of this research was verified with the findings of Bransby et al. (2008) on the normal fault-foundation interaction modeled in centrifuge testing and Nabizadeh et al. (2014) on centrifuge modeling of interaction between normal faulting and tunnel.

NUMERICAL MODELING

The numerical analysis was conducted under two-dimensional plane strain condition by the ABAQUS software. Figure 1 shows the configuration of the numerical model used in this paper. Normal faulting with a dip angle α=60° and a vertical component of displacement h=4m vertical was simulated in a sand deposit of depth H=16m. The foundation width (B) and thickness were 8.5m and 1 m, respectively, and placed in different positions (S/B). Parameter S indicates the distance between the left corner of the foundation and the fault outcrop on the surface in free-field condition. A tunnel with internal diameter of D=4m and thickness of t=0.24m was placed at different coordinates relative to free-field fault rupture path (Figure 1).

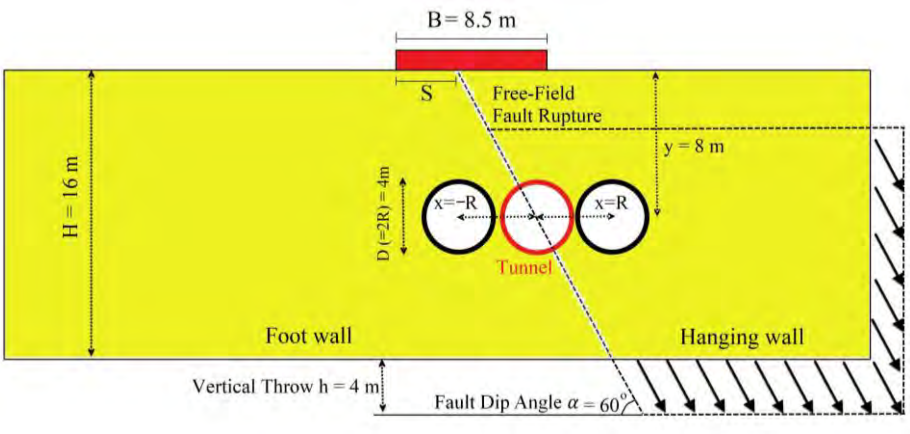

Figure 1. Schematic configuration of the studied problem

An elasto-plastic constitutive model adopted by Mohr–Coulomb as a failure criterion was employed to simulate the soil behaviour. The foundation and the tunnel were modeled as a linear elastic element with high rigidity (steel and concrete, respectively). The interface between the structures and the surrounding soil was modeled as "hard" contact, while a normal behaviour of friction with the friction coefficient was used. The properties of materials adopted in numerical analyses were summarized in Table 2.

The element chosen for soil, foundation and tunnel was quad-dominated with the width of 0.5m or less for a successful numerical simulation. Meshing had dense formation near the tunnel. Figure 2 shows finite element meshing used in the numerical model.

Table 2. The properties of the material adopted in the numerical simulation

Material properties	**Value**
Tunnel:	
Unit weight, (kN/m^3)	24
Elastic modulus, (GPa)	25
Poisson's ratio	0.28
Foundation:	
Unit weight, (kN/m^3)	78.6
Elastic modulus, (GPa)	200
Poisson's ratio	0.35
Soil:	
Unit weight, (kN/m^3)	15.65
Elastic modulus, (MPa)	20
Poisson's ratio	0.3
Cohesion, c (kPa)	0.5
Friction angle, φ (deg)	35
Dilation angle, Ψ (deg)	6
Soil-Tunnel:	
Friction coefficient	0.4
Soil- Foundation:	
Friction coefficient	0.5

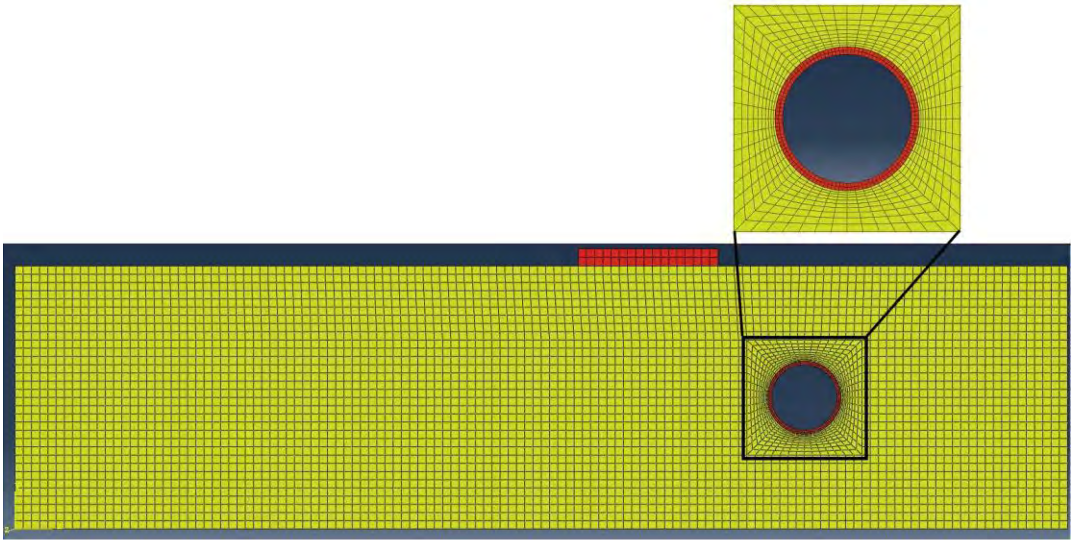

Figure 2. Finite element meshes in the present numerical model

VERIFICATION

The ability of numerical simulations in predicting the faulting effects on surface and underground structures was validated using centrifuge model tests conducted by Bransby et al. (2008) and Nabizadeh et al. (2014).

Bransby et al. (2008) investigated the performance of shallow foundations resting on soil and subjected to normal fault rupture using centrifuge modeling at 115 times Earth's gravity. Direct shear tests were conducted on samples with Dr=60% which gave φ=35° and ψ=6°. Geometrical properties of the experimental model are depicted in Figure 3(a). The foundation was constructed from steel and were of breadth, 87mm (10m at full scale) and thickness 10mm. Normal fault displacement was applied to the sand layer with a dip angle of 60°. The vertical component of the fault displacement in the test selected for the verification was 10 mm (1.15m in prototype).

Figures 4 compare the numerical prediction with the experimental results, in terms of deformed mesh with plain strain contours. As it can be seen, the presence of foundation caused the rupture path to divert towards the footwall. The shear zone and the location of fault outcropping predicted by numerical modeling is quite similar to the experimental results. The foundation rotation in numerical analysis and centrifuge model was about 2°.

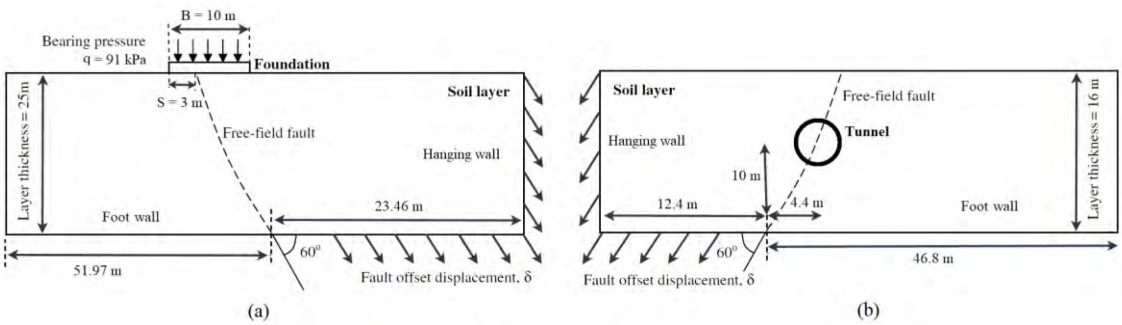

Figure 3. Schematic image of the tests: a) the shallow foundation and fault rupture (after Bransby et al., 2008); b) the tunnel and fault rupture model (after Nabizadeh et al., 2014)

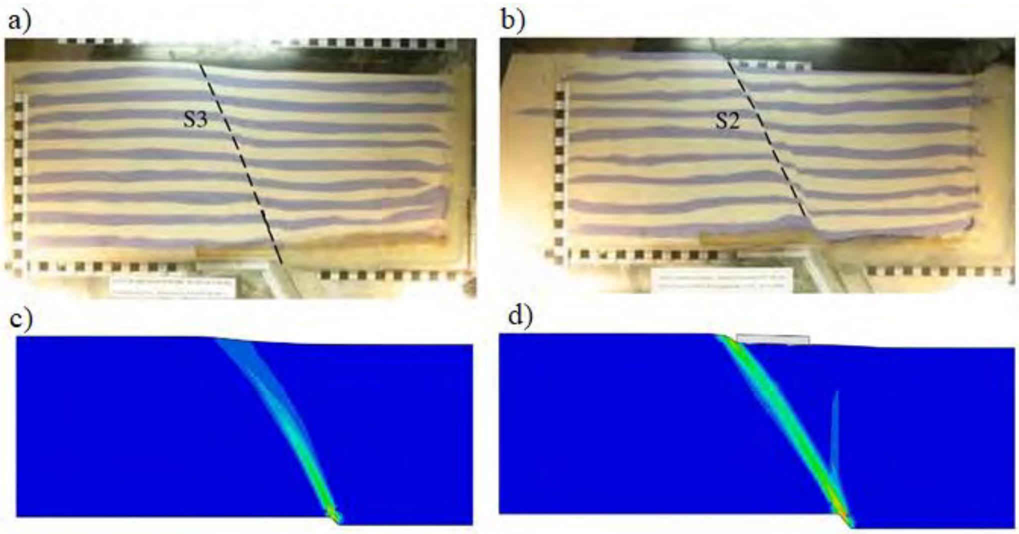

Figure 4. Comparison between experimental results (Bransby et al., 2008) and numerical simulation: a) Deformed soil for the free-field centrifuge test; b) Centrifuge model for the test with foundation (S/B=0.3, q=91kPa); c, d) Deformed mesh with plain strain contours in finite element analysis

Nabizadeh et al. (2014) conducted a series of centrifuge tests under 80-g centrifugal acceleration to model normal faulting interaction with the tunnel. Schematic of test conditions in this research is shown in Figure 3(b). A tunnel with internal diameter of 4 m and lining thickness of 0.24 m in prototype scale was placed in the position shown in Figure 3(b). The tunnel lining was modeled using aluminum alloy (6061-T6) frames. The fault dip angle was 60° to produce the vertical offset of 50 mm (4 m in prototype). Values of mechanical soil parameters were reported as, γ=15.65kN/m3, φ=38° and ψ=10°.

As it can be seen in free-field condition, the numerical results obtained from the finite element analysis are in good agreement with the experimental data (Figure 5(a) and (c). Based on the experiment performed with the presence of the tunnel and numerical study, it is found that results from numerical analysis are almost in agreement with the centrifuge model test with regard to growths of the shear zones within the soil and displacement of the tunnel (Figure 5(b) and (d)). However, the difference between the numerical and experimental results can be due to the assumption of the soil as a continuous media in the finite element analysis, while in reality it is a particular media. Soil surface disturbance is highly variable, and the finite element continuum model may not fully reflect the soil disturbance behavior (Baziar et al., 2016; Saeedi Azizkandi et al., 2019).

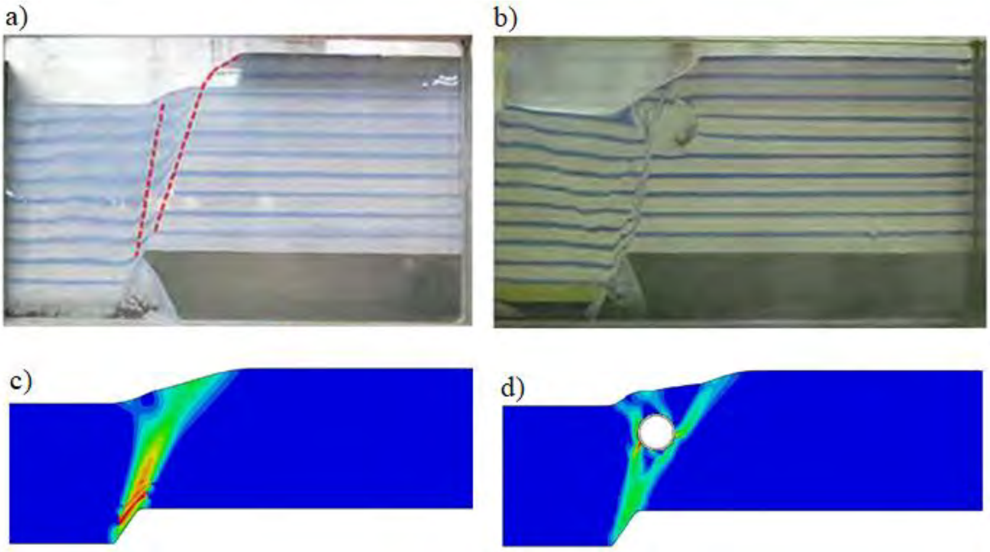

Figure 5. Comparison between experimental results (Nabizadeh et al., 2014) and numerical simulation: a) Deformed soil for the free-field centrifuge test; b) Centrifuge model for the test with tunnel; c, d) Deformed mesh with plain strain contours in finite element analysis

RESULTS AND DISCUSSION

The finite element simulation in free field condition were conducted to determine the fault rupture path, and select positions (S) of the foundation and tunnel location (x) in other models (Figure 1). To compare the value of foundation rotation for both with/without tunnel presence conditions, the foundation rotation without the tunnel was first evaluated, as shown in Figure 6. For 0.25≤S/B≤1.25, the foundation rotations are more than 5° and therefore threatening stability occurs according to Table 1.

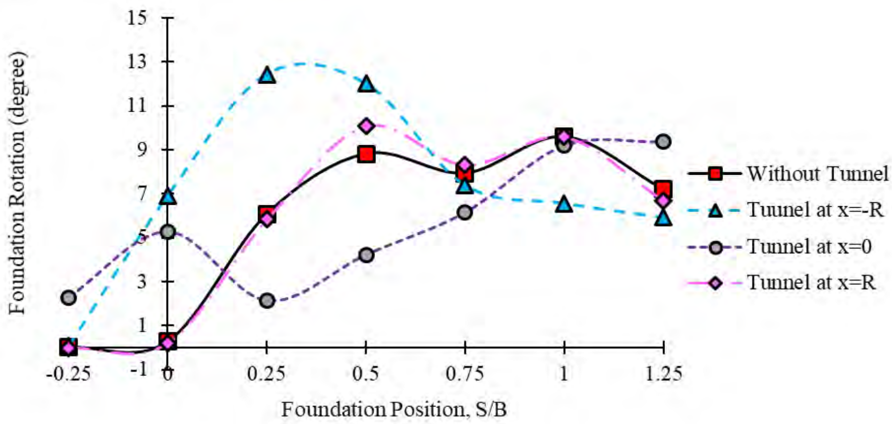

Figure 6. Foundation rotation due to fault rupture.

A tunnel with an internal diameter of 4m and thickness of 0.24m was embedded in the depth of 8m in different horizontal distances (x) from the rupture path (in free-field condition). The results show that the existence of a tunnel, in some cases, can increase the foundation rotation. Figure 7 shows the results of the numerical analysis for the position of the tunnel, which has been the most rotation of foundation at h=4 m. It illustrates the existence of a tunnel changes the fault rupture path. In some positions (S/B=-0.25, 0.25, 0.5 and 1.25), the width of shear zone was wider in the soil profile and on the ground surface, compared to the cases without a tunnel. For S/B=-0.25 and 0, the tunnel causes to change the level of damage, based on the foundation rotation, from negligible (0≤θ<1°) to sever and threatening stability, respectively (Figure 6). The foundation experiences the most rotation (θ=12.4°) when it is positioned at S/B=0.25 and tunnel is located at x=-R.

The results indicated that one of the most important parameters affecting the amount of foundation rotation and development of shear planes through the soil layer is position of tunnel relative to the fault rupture (x). Therefore, it is necessary to not only evaluate the effects of permanent ground deformation on tunnels but also consider the effect of tunnel presence on the fault rupture path and surface structures.

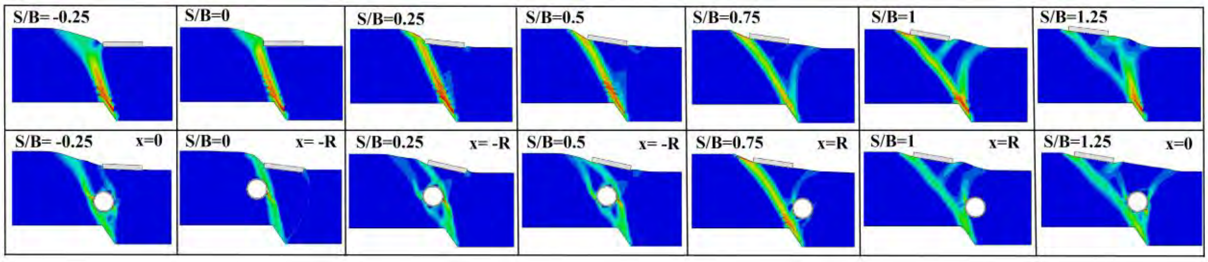

Figure 7. The effect of the presence of a tunnel with internal diameter of D=4m, embedded in depth of y=8 m, on normal fault–foundation interaction (FE computed plastic strain contours) at h=4 m.

CONCLUSIONS

A numerical analysis was conducted to survey the effect of the tunnel presence on the interaction between the normal fault and shallow foundation. The results show that the existence of a underground tunnel, in some cases, can increase the foundation rotation and causes to change the level of damage, based on the foundation rotation, from negligible (0≤θ<1°) to sever and threatening stability. The foundation experienced the most rotation (θ=12.4°) when it is positioned at S/B=0.25 and tunnel is located at x=-R. In other words, the presence of a tunnel has doubled the amount of foundation rotation. Numerical results confirmed that the development of a shear zone through the soil layer was influenced by the existence and the location of the tunnel. Therefore, it is necessary to not only evaluate the effects of permanent ground deformation on tunnels but also consider the effect of tunnel presence on the fault rupture path and surface structures.

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