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Centrifuge modeling of interaction between reverse faulting and tunnel

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ABSTRACT

In this study, a series of centrifuge tests, modeling reverse fault rupture with 60° dip angle, were conducted in a dry sandy soil with a tunnel embedded in the soil layer. The test results showed that the tunnel and soil responses depended on the tunnel position, soil relative density and tunnel rigidity. Tunnels appeared be able to deviate the fault rupture path, while this deviation may be associated with significant rotation and displacement of the tunnel. However, a deeper tunnel was able to diffuse the shear deformation to a wider zone with an unsmooth surface displacement which may cause severe damage to the surface structures. Finally, the tunnel rotation, the location of the fault outcropping, the vertical displacement of the ground surface, the effect of tunnel rigidity on fault rupture path and surface displacement and the effect of soil relative density on fault–tunnel interaction were reported and discussed in this study.

1. Introduction

Three large magnitude earthquakes, Kocaeli and Duzce [1–7] and Chi-Chi [7–12], have revealed that fault ruptures could cause severe damages to structures especially tunnels embedded within the zone of faulting. Earthquake fault rupture might cause severe damage even to the underground structures designed to be safe against dynamic excitations. However, the earthquake engineering researchers in the past four decades have focused more on the dynamic reaction of soils and structures rather than the ground displacement due to rupture of the earth's crust.

Tunnels, being underground structures, have long been assumed to have the ability to sustain earthquake with little damage. Investigations of mountain tunnels after the Chi-Chi Earthquake in central Taiwan [10] revealed that many tunnels suffered significant damage to various extents. The results also showed that the tunnels, passing through displaced fault zone, suffered more damage by the fault throw than by the seismic loading waves.

Usually the damages induced by earthquake fault rupture can be recognized with discontinuous deformations of soil overlying fault rupture which results in vertical or lateral offset at the ground surface.

Research on the topic of the fault rupture in free field condition and its interaction with structures can be generally categorized in the following four groups:

(1) Case histories of surface fault rupture.
(2) Accurate and controlled geotechnical laboratory studies, including 1-g conditions and centrifuge model tests.
(3) Numerical modeling of fault rupture.
(4) Analytical studies.

A series of field studies were conducted after several earthquakes in the last decade [7,9,10,13–17]. Fault movements of the 1999 Kocaeli and Duzce Earthquakes in Turkey were responsible for extensive damage to the tunnel lines [13,14]. Landslides caused by the 1930 North Izu and the 1978 Izu Oshima Island Japan earthquakes were responsible for severe damage of Tanna and Inatori Tunnels, respectively [15]. Comprehensive study of field observations from the Chi-Chi earthquake showed a marvelous interaction between the faulting phenomena and tunnel [10]. The location of tunnel appeared to be one of the most important parameters affecting the fault rupture path.

While the interaction of fault ruptures with shallow and deep foundations have been studied by a few researchers using analytical [18–21], numerical [22–30] and experimental [29,30–36] methods, very little research have been reported to investigate

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the behavior of tunnels located in the zone of faulting [37]. The current study presents the results of experimental studies to gain insights of the tunnels interaction with reverse fault rupture. It is hopeful, the new findings help engineers to design safer tunnels where located in the fault zone.

Unlike the surface structures such as buildings for human dwelling which occupy just a limited area, the lifeline facilities such as water supply tunnels, gas tunnels, transportation tunnels and utility tunnels, due to their extensive length, have larger probability to pass a fault rupture and therefore are very crucial to understand their interaction with rupture shear zone. In order to construct such structures close to active faults, the shape and the magnitude of fault rupture as well as the location of surface fault rupture with the presence of tunnel should be estimated, especially for the sandy soil layers. This kind of soil layers tend to develop an inclined ground surface and simultaneously scarps on the ground surface prior to reaching the shear rupture planes to the ground surface.

In this study several centrifuge tests under 80-*g* centrifugal acceleration have been carried out to examine the interaction of reverse fault rupture propagation in the dry sand layer with the presence of a tunnel. The effects of tunnel depth, tunnel location, soil relative density and tunnel rigidity on the fault tunnel interaction have been presented in this research. The results of these tests revealed that the location of the rupture planes in the ground can be affected by the position of tunnel and its rigidity.

Typical prototype geometry of a tunnel embedded in a dry sandy soil layer under the reverse fault rupture, studied in this research, is shown in Fig. 1. For modeling the reverse faulting, an upward displacement of the hanging wall at the bedrock was applied causing the propagation of the fault rupture through the soil layer towards the surface. With such bedrock displacement, discontinuity emerges at the ground surface and provides a boundary between the lifted hanging wall with the dip angle of 60° and the static footwall on the right side of the tunnel. The tunnel is located in the zone of faulting and hanging wall.

Based on the rupture patterns observed from the testing results, the key sketch for observation of surface rupture and distorted surface is depicted as Fig. 1. In Fig. 1, W indicates the distance from the bedrock fault to the location of the right side surface outcropping, α indicates the dip angle of the fault plane, H indicates the thickness of the ground model and h indicates the vertical offset of the fault to induce the surface rupture.

2. Material properties

2.1. Soil type

Quartz sand was used for all centrifuge model tests with the unit weight of 15–16 kN/m^3 and the relative density of D_r=50 and 70%. The tested soil is classified as poorly graded sand (SP) according to the Unified Soil Classification System (Fig. 2). The

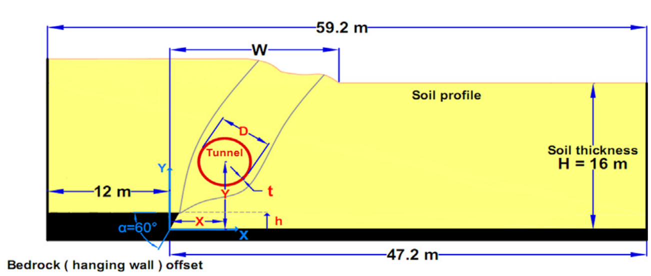

Fig. 1. Sketch of the problem and its geometry in the presented study, interaction of reverse fault rupture and tunnel.

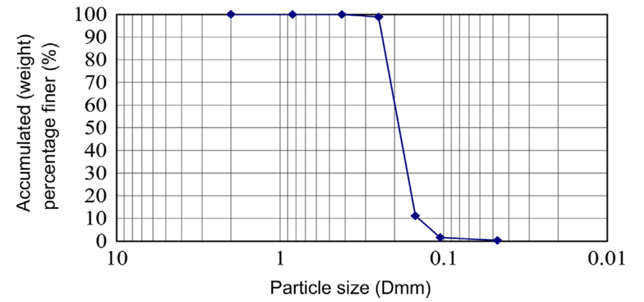

Fig. 2. Particle size distribution curve for quartz sand.

Table 1
Physical properties of quartz sand.

Soil type	G_s	ρ_{max}(g/cm^3)	ρ_{min}(g/cm^3)	d_{50}(mm)	d_{10}(mm)	φ (D_r = 70%)
SP	2.65	1.66	1.38	0.193	0.147	38°

Table 2
Mechanical properties of the aluminum alloy (6061-T6).

Unit weight (kN/m^3)	Young's modulus E(GPa)	Poisson's ratio ϑ	Tensile yield stress f_{yk}(MPa)	Tensile strength f_{bk}(MPa)
27	**70**	**0.33**	**500**	**600**

properties of crushed quartz sand were reported by Lee et al. [38]. The sand had a specific gravity (G_s) of 2.65, and maximum and minimum dry unit weight of 16.6 kN/m^3 and 13.8 kN/m^3, respectively with D_{50}=0.193 mm and D_{10}=0.147 mm. The quartz dry sand had a friction angle of 38° obtained from direct shear tests at a relative density of 70%, and a secant shear modulus G of 0.5 MPa obtained from simple shear tests at a relative density of 55% [37]. The tested sand under various stress levels had an almost linear failure envelope, with cohesion close to the zero. The dilation angle of sand was measured to be 10°–11°. Table 1 reports the properties of soil as used in this research.

2.2. Tunnel material type

The tunnel lining was modeled by an aluminum alloy (6061-T6) frames having an external diameter of D=49.4 and 49.8 mm with a thickness of t=1.2 and 1.4 mm, respectively, corresponding to D=4.24 and 4.32 m with the thickness of t=0.24 and 0.28 m concrete tunnel type at the prototype scale.

The tunnel thickness was selected such that the tunnel lining can resist against existed axial force and bending moment, caused by fault movement, without occurrence of large distortion or failure of lining.

The tunnels were tested using epoxy coatings with the thickness of 0.5 mm around the tunnels to model the effects of friction on the soil–tunnel interaction. The friction between the soil and the epoxy coating was about 22° according to the direct shear test for the specimen with half epoxy and half sand. The resistance of epoxy coating is much smaller than the aluminum tube and hence did not affect the rigidity of the tested tunnels.

Table 2 reports the mechanical properties of the aluminum alloy (6061-T6) used in the tests. The above properties imply that the model tube corresponds to medium flexible lining at prototype scale.