Soil Dynamics and Earthquake Engineering 83 (2016) 1–17

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Evaluation of underground tunnel response to reverse fault rupture using numerical approach

Mohammad Hassan Baziar [a,*], Ali Nabizadeh [b], Ronak Mehrabi [c], Chung Jung Lee [d], Wen Yi Hung [d]

[a] Center of Excellence for Fundamental Studies in Structural Engineering, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[b] School of Civil Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran
[c] School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[d] Department of Civil Engineering, National Central University, Taoyuan, Chungli, Taiwan

ARTICLE INFO

Article history:
Received 25 February 2015
Received in revised form
12 November 2015
Accepted 14 November 2015

Keywords:
Earthquake fault rupture
Tunnel
Numerical modeling
Centrifuge modeling

ABSTRACT

The present paper implemented a finite-element methodology to simulate the interaction behavior between tunnel and sandy soil deposit when a reverse fault rupture propagated from the base rock to the ground surface. The location of shear zones and propagation of subsurface rupture traces through overlying sand were discussed with the changes in the tunnel location, tunnel rigidity and soil relative density. The results indicated that the presence of a tunnel could have a significant influence on the fault rupture path. It was further shown that different factors affected the rotation and displacement of the tunnel. This study also investigated the evolution of a surface deformation profile using both centrifuge experiments and the finite element simulation. The results of finite element studies were verified using centrifuge experiments. Reasonable agreement between numerical and experimental results indicated the credibility of the numerical approach. Verified numerical methodology was then used to present a parametric study, offering further insight into the effect of different parameters on the soil-tunnel interaction phenomenon.

1. Introduction

Population growth and scarcity of land have led to frequent exploitation of underground spaces. Tunnels are therefore becoming increasingly useful structures in transportation and utility networks. For the serviceability of underground structures like tunnels, earthquakes are the most serious threats among various kinds of natural hazards.

Earthquakes cause both ground shaking and permanent ground deformation. A review of literature indicates that most of the researches have focused on the seismic response of soils and structures under earthquakes and dynamic loading. However, most strong earthquakes are associated with large displacement of a faults which is a significant hazard to serviceability of infrastructures. Observation after recent earthquakes in Turkey (Kocaeli and Duzce) and Taiwan (Chi-Chi) revealed that the majority of damages, occurring to the infrastructures such as tunnels, were caused by permanent ground deformations induced by fault movements [1–7].

In depth studies on consideration of earthquake-induced fault ruptures such as; the way they propagate through the overburden soil, their interaction with surface and underground structures and methods for incorporating these information into engineering designs, have been the subject of distinct research so far and can be mostly classified in 3 categories including:

- Field studies of case histories,
- Experimental analysis and controlled centrifuge model tests and
- Numerical approaches calibrated against the field or experimental data.

Since 1970s, the interaction of faults with buried pipelines has attracted the attention of the researchers (e.g. [8–11]). In addition, the interaction of fault ruptures with shallow and deep foundations have been studied by several researchers through comprehensive studies using significant amount of field evidence, experimental modeling and analytical analyses (e.g. [12,5–7,13–21]).

General findings showed the importance of the interplay that took place between the propagating fault rupture, the soil, the foundation and the supported structure. One of the most important general conclusions of these studies was that, depending on the rigidity, continuity, and surcharge loading, foundations could

* Corresponding author. Tel.: +98 912 12515 20; fax: +98 21 77240398.
E-mail addresses: Baziar@iust.ac.ir (M.H. Baziar), Nabizadeh@iust.ac.ir (A. Nabizadeh), Ronak_mehrabi@civileng.iust.ac.ir (R. Mehrabi), Cjleeciv@ncu.edu.tw (C.J. Lee), Wyhung@ncu.edu.tw (W.Y. Hung).

http://dx.doi.org/10.1016/j.soildyn.2015.11.005
0267-7261/

often force the fault rupture to deviate and thus they protected the structure from the imposed fault deformation [22]. The foundation position, relative to the fault outcrop, also appeared to be one of the crucial factors affecting the response. Thus, it is feasible to design structures able to survive fault rupture that reaches the ground surface. There are several research efforts that have culminated in the development of practical recommendations and validated analysis methodologies for the design of structures against surface fault rupture. Gazetas et al. [23] has reported a set of practical design recommendations for fault–foundation interaction.

Most of the available literature about tunnel damage due to faulting are from a number of earlier case histories (e.g. [24–26]). Severe damage occurred to different types of tunnels during the 1999 Chi-Chi Earthquake in Taiwan [24]. The Wrights tunnel, a railroad tunnel was subjected to an offset of about 1.8 m of the strike-slip San Andreas fault during the 1906 San Francisco earthquake [27]. Comprehensive study of field observations showed an attractive interaction between the faulting phenomena and tunnels.

Seismic codes such as Eurocode EC8 1994 [28] ban constructing structures adjacent to active faults. However, in some situations it can not be avoided for a long structure such as tunnel to cross geological faults. Moreover, attempting to predict the exact location of a fault breakout at the surface is almost meaningless [29]. The location of tunnel is one of the most important parameters affecting the fault rupture path. A key to develope a rational design and mitigation framework for this hazard is to investigate the factors affecting the response of tunnel against large tectonic dislocations. To date, very little laboratory and numerical research have been reported to investigate the behavior of tunnels located in the zone of faulting [30,31] and the questions about appropriate methods to design tunnels in this area still remain unanswered.

To this end, this paper tries to examine the tunnel feature and seismic fault rupture propagation theory in dry sand, using physical and numerical modeling. It is hopeful that the new findings help to reduce hazard relating to the deformation induced by thrust faulting.

Numerical simulation allows to conduct parametric studies in less time and with lower cost than laboratory experiments and hence numerical modeling can be one of the most effective methods to investigate the effects of faulting on tunnels. For this purpose, a simple elastoplastic constitutive soil model, with Mohr-Coulomb failure criterion in combination with an isotropic strain softening behavior were added in a two-dimensional plane strain finite element modeling. This elastoplastic model was quite successful to simulate fault propagation through sandy soils [5,6].

Experimental model tests were used to verify the numerical models to ensure that they could reveal reasonable predictions. Baziar et al. [21] reported the results of 80-g centrifuge tests to investigate the performance of tunnels embedded in sandy soil and subjected to reverse fault rupture. Centrifuge modeling was used to allow detailed examination of the factors affecting the tunnel-fault rupture interaction in a controlled environment.

2. Problem definition

Geometrical properties of the studied problem are depicted in Fig. 1. The prototype dimensions were chosen 80 times greater than the physical model tests. A 52.9 m-long and 16 m-thick soil profile was assumed. For the interacting analyses, a model tunnel with outer diameter of D and thickness of t was placed at different coordinates (X, Y) measured from the fault tip. The fault dipped at the selected angle of 60° measured from the horizontal line to produce the vertical offset of h at bedrock.

3. Centrifuge model configuration

Baziar et al. [21] conducted a series of centrifuge tests to investigate the influence of various factors on the behavior of buried tunnels subjected to reverse faulting. A total of seven model tests were reported in their study. Two of tests were modeled with the absence of tunnel with two different soil relative densities to find where the free field fault would emerge at the ground surface for the soil layer depth of $H=16$ m. The other five tests, with the presence of a tunnel, designed to investigate the behavior of soil-tunnel system subjected to reverse faulting, gave specific attention to the influence of soil relative density, tunnel position based on the fault tip and tunnel rigidity on the fault rupture paths. Table 1 summarizes the soil properties used in the experiments.

4. Numerical modeling methodology

The ABAQUS [32] software, based on the finite element approach, was used to conduct the numerical analysis. The analysis was performed in two-dimensional plane strain condition and the model dimensions were chosen the same as the prototype scale. Numerical analysis was performed in two steps:

1. Gravity loading was first applied to the soil strata and the tunnel structure.
2. Fault movement was then initiated by applying specific boundary conditions in which the left part of the model base and the corresponding boundary side (hanging wall) moved according to the assumed fault angle (60°) while the rest of the model remained immovable.

In order to simulate the fault movement, the hanging wall side of the model was detached from the foot wall side by creating a 0.5 cm discontinuity in the model base and then applying an upward pressure equal to soil weight above the created discontinuity. This innovative method, employed here, would obviate the necessity for bedrock modeling.

The soil body and the tunnel structure were both modeled using structured quad-dominated continuum finite elements. The choice of a very refined mesh (element size of the order of 1 m or less) in the probable region of soil rupture is a prerequisite for a successful numerical simulation [23]. Therefore, meshing had dense formation in the central part of the model with elements

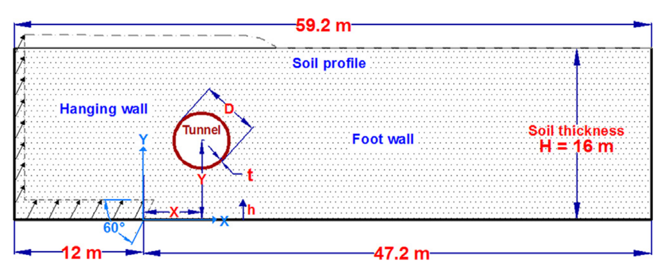

Fig. 1. Schematic diagram of the studied problem, indicating basic parameters and dimensions at the prototype scale.

Table 1
Summary of soil properties used in the experiments.

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