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3D liquefaction assessment of soils surrounding circular tunnels

Berna Unutmaz *

Civil Engineering Department, Kocaeli University, 41380 Kocaeli, Turkey

A R T I C L E I N F O

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A B S T R A C T

The aim of this paper is to investigate the effect of underground circular tunnels on cyclic behavior and liquefaction potential of soils surrounding them. For this purpose, an intensive numerical analyses scheme which includes three-dimensional, finite difference based total stress analyses on generic soil, tunnel and earthquake combinations has been performed. The effect of tunnel diameters, depth of tunnel center, support thickness of tunnels and the strength of soils have been discussed in detail. It is concluded that changing the diameter and support thickness of the tunnels does not make a remarkable change on surface acceleration. Similarly, the liquefaction potential of the soils considered does not depend on the diameter and support thickness. However, it was shown that the most important parameter defining the liquefaction potential is the depth of the tunnel from the ground surface. If the tunnels are deeper, they are less vulnerable to liquefaction compared to shallow tunnels.

1. Introduction

The underground structures have been used beginning from ancient times. The first tunnel on the world is thought to be built around 4000 BC. At that times they were using the tunnels for mining, water supply and even as a war tactic. The increasing values of surface land and also increase in both domestic and municipal necessities gave rise to use of underground tunnels even more in the recent century. Today, the tunnels are not only used for water transmission but also they are a good alternative of transportation systems, especially in cities to avoid traffic jam. They are also used for sewage, storage and so on. For this reason, the safety of tunnels shows an increasing importance for human lives and maintaining a standard of living. The seismic safety of these structures also requires a special attention. During the recent earthquakes such as 1995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake, the 1999 Kocaeli and Duzce, Turkey earthquakes, some underground structures experienced some damage. Although not as destructive as superstructures, the damages in these structures were also of concern (Hashash et al., 2001).

In some studies (Hashash et al., 2001; Pakbaz and Yareevand, 2005; Dowding and Rozen, 1978; Sharma and Judd, 1991; Chen et al., 2012 and etc.), the authors indicate that the response of the tunnel type of structures depend on tunnel properties such as depth, shape, support thickness, method of excavation, the properties of the surrounding soil (stiffness, water table elevation, and etc.) and the seismic loading (frequency content, duration of excitation, peak ground acceleration and so on).

The aim of this study includes determining the behavior of tunnels under cyclic loading and the liquefaction potential of surrounding soils. Within this scope, three dimensional, numerical, finite difference analyses were performed to simulate both static and seismic stress states and performances. These models include combinations of different diameters, support thicknesses and depths of tunnels in addition to different soil profiles and different earthquake loadings. The tunnels are excavated as a full circle as done in TBM method. Also a preliminary examination of the construction stage was carried out.

2. Finite difference modeling

In the scope of this study, 3-D finite difference-based simulations were performed for the purpose of assessing the behavior of tunnels under dynamic loading. 1-D equivalent linear soil site response analyses were also conducted by SHAKE91 (1972) software to verify the response of free field (i.e. no structures are included). The numerical assessment scheme included (i) 3-D static assessment of soil + tunnel system, (ii) 3-D seismic assessment of soil + tunnel system for the purpose of estimating both structure and soil inertia-induced cyclic shear stresses acting on the horizontal plane and (iii) 3-D seismic assessment of the free field soil sites (without the tunnel system) for the purpose of enabling direct comparisons with 1-D SHAKE91 simulations, useful for the calibration of the 3-D model. The reason for this calibration is the fact that, SHAKE91 is a widely accepted program all over the world in modeling 1-D propagation of seismic waves. It has been used for

* Tel.: +90 2623033290.
E-mail address: berna.unutmaz@kocaeli.edu.tr

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years for site response analysis and the results obtained from SHAKE91 analysis are assumed to be validated among these years. However, 3-D analyses are neither as common nor as validated as the 1-D analyses. For this reason, a comparison, thus calibration of 3-D mesh with 1-D model is thought to increase the reliability of the 3-D model. The boundary conditions at the sides of the model are selected as "free field", which accounts for the free field motion that would exist in the absence of any structure.

Fig. 1 presents the reasonable agreement for an example site of clean sand having a shear wave velocity and internal friction angle of 100 m/s and 32° respectively and shaken by Sakarya record of 1999 Kocaeli earthquake. As equivalent linear soil parameters, modulus degradation and damping, Vucetic and Dobry (1991) curves have been adopted in 1-D SHAKE analysis. The mesh dimensions for 3-D analysis is 30 m's in all x, y and z directions whereas a 30 m height column is used in 1-D SHAKE analysis. The acceleration time history is applied as an outcrop rock motion in the SHAKE analyses and the resulting acceleration values at the within bedrock are applied at the base of 3-D model. This reasonably well agreement as presented in Fig. 1 confirmed the validity of the mesh adopted for 3-D site response analysis scheme. The variation of acceleration and shear stress values with depth for the case having shear wave velocity 100 m/s is presented in this figure, comparing the results obtained from both SHAKE91 and FLAC-3D (2005) software. It should be noted that due to differences in the adopted analysis schemes in SHAKE and FLAC softwares (e.g.: frequency domain vs. time domain, equivalent linear vs. nonlinear, or wave mechanics vs. finite difference-based analyses), a perfect match has never been the ultimate goal. The main reason in these differences is that, SHAKE analysis are 1-D whereas FLAC analysis are in 3-D. In 1-D analysis, the waves are assumed to propagate upwards vertically whereas in 3-D analysis, the waves scatter in all three dimensions. The boundary conditions also affect the response of the soil mass in 3-D. Although, a wide mesh as possible is modeled and free field boundaries are used, it does not guarantee to wipe off the reflections from the boundaries. In 1-D analysis, equivalent linear soil parameters are used whereas in 3-D, the nonlinear models are adopted which also changes the result.

Fig. 2 presents typical meshes adopted for the numerical simulations. The separate parts at the edges of the meshes are the schematic representation of free field boundary conditions in FLAC-3D. Such boundaries allow the motion at the far ends of the mesh to be same as the free field conditions, i.e. no structures (tunnels in this case) exist. In this way, upward propagating waves suffer no distortion as the mesh behaves as if it is an infinite model. As explained in FLAC-3D User's Manual (2005), the lateral boundaries of the main grid are coupled to the free-field grid by viscous dashpots to simulate a quiet boundary and the unbalanced forces from the free-field grid are applied to the main grid. A more detailed explanation of this boundary condition can be found in FLAC-3D User's Manual (2005).

The total stress analysis, have been used in this study as it is easier and more convenient to use. Details about total stress versus pore pressure analyses can be found in Unutmaz (2012). Different homogeneous soil profiles with shear wave velocity values $V_s = 100$ m/s, $V_s = 200$ m/s and $V_s = 300$ m/s were selected as case studies. The other important soil parameters are tabulated in Table 1.

These four soil profiles were shaken by four different real strong motion data: (i) 1995 Kobe Earthquake, $M_w = 6.9$, Chihaya Station (CHY), (ii) 1979 Imperial Valley Earthquake, $M_w = 6.4$, Cerro Prieta (IMP), (iii) 1989 Loma Prieta Earthquake, $M_w = 7.0$ Santa Cruz USCS Lick Observatory Station (LP), and iv) 1999 Kocaeli Earthquake, $M_w = 7.4$, Sakarya (SKR) records. The strong ground motions were obtained from PEER database, and the larger horizontal components have been used in the analyses. The other properties of the earthquake records are tabulated in Table 2.

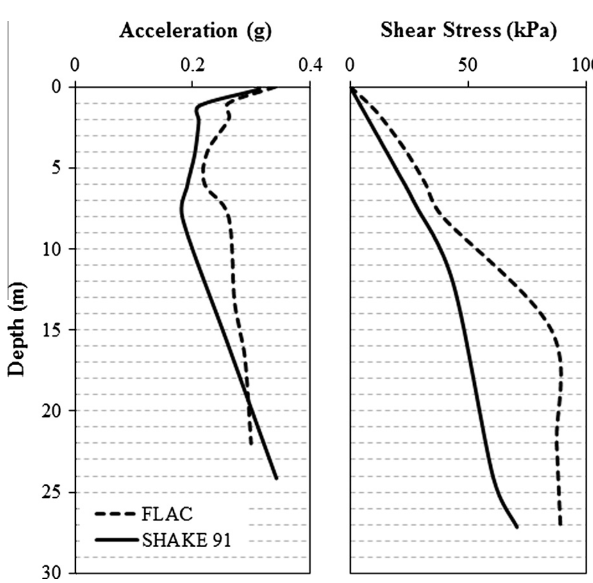

Fig. 1. Comparison of SHAKE91 vs. FLAC-3D.

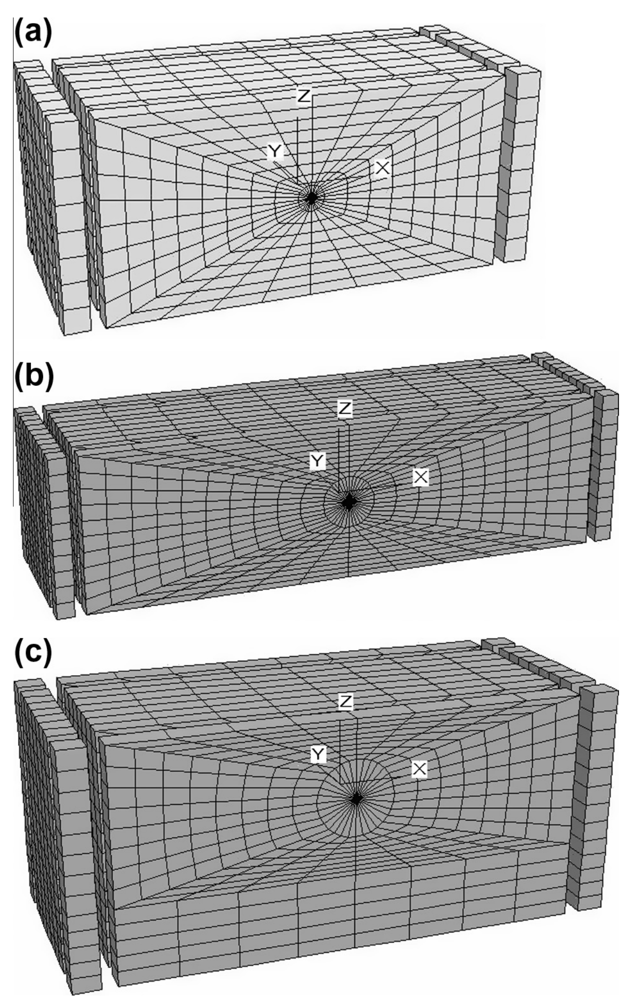

Fig. 2. Typical finite difference meshes: (a) $D = 4$ m, $z = 15$ m, (b) $D = 10$ m, $z = 15$ m and (c) $D = 10$ m, $z = 10$ m.