

SEISMIC ANALYSIS OF UTILITY TUNNEL CONSIDERING WAVE PASSAGE EFFECT

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ABSTRACT

The dynamic interaction between underground structure and soil has long been a hot topic in current researches. However, there is still limited available research on the seismic response of the utility tunnel. In this paper, the response of the utility tunnel under seismic loading is investigated by using finite element method (FEM), with a commercial FEM software package, ABAQUS. To investigate the seismic soil-structure interaction, a three dimensional nonlinear finite element model has been developed and the nonlinear plasticity is incorporated in the model so that the interaction performance of the soil-structure system can be evaluated more precisely. Finally, the wave passage effect is considered in the numerical simulation and computation results reveal that the internal forces are magnified by the wave passage effect.

Keywords: utility tunnel, 3-D model, seismic response, wave passage effect

INTRODUCTION

Underground structures are becoming more and more prevalent in the modern world because of the decreasing availability of aboveground space and resources due to fast growing population. As an integral part of the infrastructure of modern society, underground structures are used for a wide range of applications, including transportation systems, such as subways and railways, highways, and sewage and water transport. This investigation concentrates on one kind of the underground structures named utility tunnel which can hold many kinds of lifelines, such as water pipelines, gas pipelines, and communication lines. The first utility tunnel may be originated from Paris. Now Japan is the leading country in the construction of the utility tunnel. In China, The first utility tunnel was built at 1994 and there are two utility tunnels in Shanghai now.

For underground structures such as utility tunnels, the seismic design approach differs from that of the surface structures (e.g., bridges and buildings). For aboveground structures, the seismic loads are largely expressed in terms of inertial forces. The traditional methods generally involve the application of equivalent or pseudo-static forces in the analysis. However, the design and analysis for underground structures should be based on an approach that focuses on the displacement/deformation aspects of the ground and the structures, because the seismic response of underground structures is more sensitive toward such earthquake induced deformations.

There are two fundamental approaches in present seismic design of underground structures. One approach assumes that the seismic ground motions induce a pseudo-static loading condition on the

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structure (Wang, 1993; Penzien and Wu, 1998; Penzien, 2000; Huo, 2005). The second approach is to carry out dynamic, non-linear soil-structure interaction analysis using finite element methods, with which large numbers of researches have been carried out. For example, Matsui etc. (2001) conducted a research concerning the performance of RC duct-type underground structures subjected to strong earthquakes. Balakrishnan etc. (2006) presents the results of a seismic soil-structure interaction study performed to develop racking curves for the BART Warm Spring project. After the collapse of the Daikai subway station during the 1995 Kobe earthquake, many researchers (Huo, 2005; Montesinos etc., 2006) investigated its seismic response and the failure mechanisms. But most of the researches were based on the 2-D model and focused on the racking deformation of the rectangular underground structures. The real three dimensional analysis, which considers the dynamic soil-structure interaction effect, is scarce. Usually, the utility tunnels are box shaped shallow buried concrete structures. The earthquake damage data of underground structures shows that shallow tunnels are at greater risk during an earthquake than deeper tunnels; roughly 60% of the total cases with overburden depths less than 50m suffered certain damages (Wang, 1993). It is concluded that the utility tunnel may be damaged more severely than deep ones during the earthquake. To the author's knowledge, however, there is still limited available research on the seismic response of the utility tunnel.

In view of foregoing picture, a three dimensional nonlinear finite element model has been developed in this paper to investigate seismic soil-structure interaction for utility tunnels. The nonlinear plasticity is incorporated in the model so that the interaction mechanism of the soil-structure system can be evaluated more precisely. The wave passage effects have also been studied. Computation results reveal that the internal forces are magnified by the wave passage effect so that they cannot be ignored under certain condition. Furthermore, relatively deeper buried utility tunnel is also examined in this research.

THE BACKGROUND OF ANALYSIS METHOD

In the dynamic analysis of underground structures, there are two primary questions that have to be taken into consideration: 1) artificial boundary conditions, 2) soil/structure interface.

The most common analytical soil-structure interaction models are based on the assumptions that the soil domain could be represented by a semi-infinite space. The simulation of the unbounded domains in numerical methods is a very important topic in dynamic soil-structure interaction (SSI). In order to simulate soil medium in a simple yet realistic manner, numerous researches are/were conducted since Alterman (Alterman, 1968) first put forward the concept of placing the artificial truncated boundary far away from the domain that interest in. Here, only a few of those in the literatures are cited. The most widely used is the viscous boundary (Lysmer and Kuhmeyer, 1969), which replaces the far field with viscous damping. The viscous-spring boundary, which adds spring at the boundary simultaneously, in order to simulate the elastic resilience of the soil, is also used widely at present. Clayton and Engquist (1977) deduced the Paraxial Approximation boundary based on the elastic wave propagation equation, which is the remarkable artificial boundary condition in the 1970s. Liao got the more general used multi-transmitting boundary condition also from the wave propagation equation (Liao, 1984).

In ABAQUS, first- and second-order infinite elements was provided that are based on the work of [Zienkiewicz et al. \(1983\)](#) for static response and of [Lysmer and Kuhlemeyer \(1969\)](#) for dynamic response. The elements are used in conjunction with traditional finite elements, which model the area around the region of interest, with the infinite elements modeling the far-field region. The dynamic response of the infinite elements is based on consideration of plane body waves traveling orthogonally to the boundary. By choosing the proper damping constants d_p and d_s to eliminate reflection of longitudinal and shear wave energy back into the medium. These values of boundary damping are built into the infinite elements in ABAQUS. It has been testified that the infinite elements transmit all normally impinging plane body waves exactly (provided that the material behavior close to the boundary is linear elastic).

General problems involve non plane body waves that do not impinge on the boundary from an orthogonal direction and may also involve Rayleigh surface waves and Love waves. Nevertheless, these “quiet” boundaries work quite well even for such general cases, provided that they are arranged so that the dominant direction of wave propagation is orthogonal to the boundary or, at free surfaces and interfaces where Rayleigh or Love waves are of concern, they are orthogonal to the surface. As the boundaries are “quiet” rather than silent (perfect transmitters of all waveforms), and because the boundaries rely on the solution adjacent to them being linear elastic, they should be placed some reasonable distance from the region of main interest. Ismail & Mullen (2000) and Yue et.al (2006) made some comparisons in the dashpots boundary and the infinite element in ABAQUS. The results showed that the infinite element in ABAQUS have many advantages over the dashpots/viscous boundary.

Another question is the contact simulation during the seismic analysis. In ABAQUS, the interface behavior between the ground and the structure can be modeled as tied (typically) or frictional. The friction coefficient is $\mu = \tan \phi$, where ϕ is the frictional angle between ground and structure. The magnitude of the friction coefficient depends on the type of the materials at the interface and on the surface characteristics of the contact area. For a concrete liner embedded in soft ground (clay or sand), ϕ ranges between 20° and 40° .

On the other side, the constitutive law of soil is also a crucial issues especially in the numerical simulation. Huo (2005) compare the structural response difference between the Drucker-Prager model and the Pyke’s model, which consider the dependence of dynamic shear modulus and damping on the magnitude of the cyclic shear strain. The results showed that the peak response was almost the same and there was tiny difference after the peak motion, because the Drucker-Prager model is elastic before yielding. So in this paper, Drucker-Prager model is adopted.

THE ANALYSIS AND EXPLANATIONS

Example analysis

In order to study the wave passage effect in seismic response of utility tunnels, an example analysis has been carried out with the following parameters. The model cross section is $15\text{m} \times 15\text{m}$, and the length is 100m. Figure 1 is the cross section of the structure. Figure 2 is the finite element model, which including the infinite elements. The total number of elements is 3864, including 252 contact elements which produce automatically.

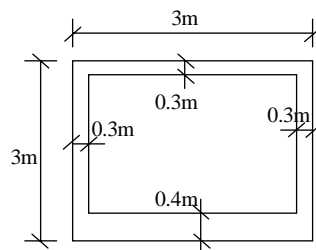


Figure 1. The section of structure

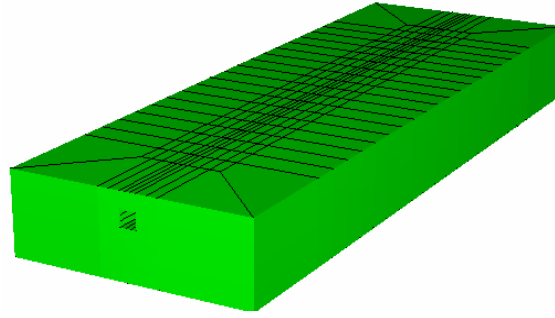


Figure 2. The finite element model

The material parameters of the soil, structure and the contact pair are listed in the table 1.

Tabel 1. material parameters of the soil, structure and the contact pair

	soil	structure	Contact pair
Unit weight(KN/m ³)	19.6	25	_____
Poisson's ratio	0.35	0.15	_____
Yong modulus(MPa)	300	24,000	_____
friction angel(degree)	30	_____	_____
dilation angel(degree)	3	_____	_____
k^*	0.8	_____	_____
yielding stress(KPa)	500	_____	_____
Coefficient of friction, μ^{**}	_____	_____	0.4

* k is the ratio of the flow stress in tri-axial tension to the flow stress in tri-axial compression.

** μ is the coefficient of friction, which describes the frictional contact between the ground and the structure, i.e., the shear force acting on the interface is equal to the normal force times 0.4. The friction coefficient of 0.4 corresponds to an interface friction angle of 22°, which is representative of a soil-concrete interface.

The infinite elements in ABAQUS are adopted to eliminate wave reflections back into the calculation domain from the artificially introduced truncated boundary due to the semi-infinite domain. Horizontal motion of the actual earthquake (figure 3) imposed at the base of the mesh.

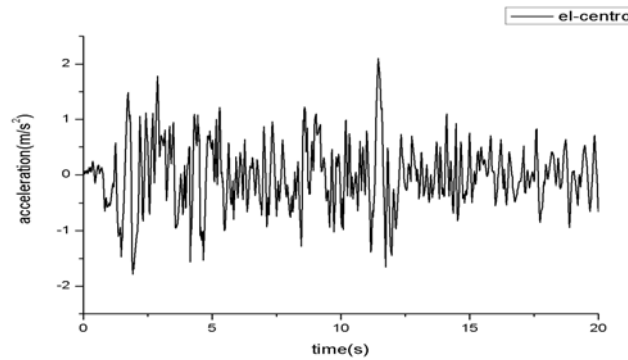


Figure 3. The input acceleration time history

In order to verify the accuracy of the finite element mesh, the model is refined as figure 4. The number of the elements is 10116, which the number of contact elements is 756. Figure 5 is the time acceleration histories of top center point of two models. There is almost no difference between the two meshes from figure 5. The calculation time of the finer mesh is, however, almost 8 times over the coarse mesh. So the coarse mesh is used in the following investigations.

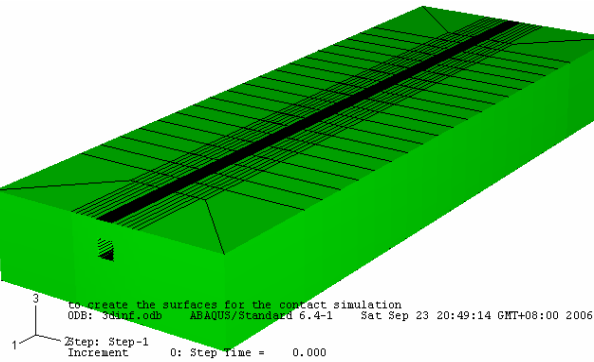


Figure 4. The refined finite element model

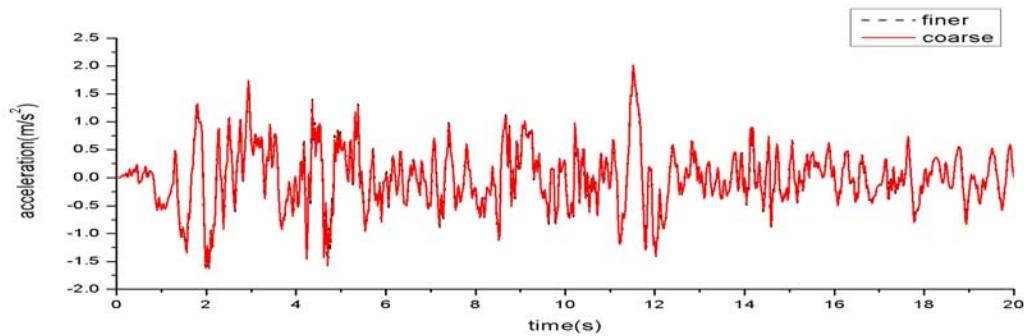


Figure 5. The acceleration history of top center point for the finer and coarse mesh

The consistent input

The input motion is parallel to the axis of the structure, and imposed at the base of the mesh. Figure 6 and figure 7 are the time histories of axial strain of the center element on the top and the left surfaces of the structure. It is observed that although the two element lies on the same cross section, they have different amplitudes. It indicates that the structure's deformations are composed of axial and bending deformations. Figure 8 and 9 are the contact pressure on the interface and the friction stress respectively. It is obviously that slip/stick occur during the analysis.

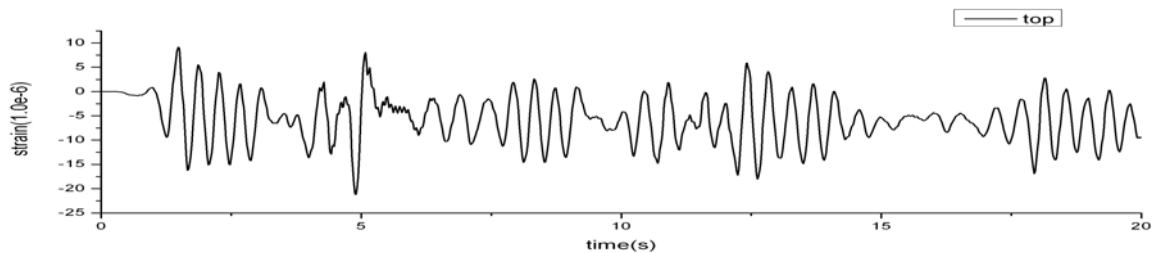


Figure 6. Axial strain of center element on top surface of the structure

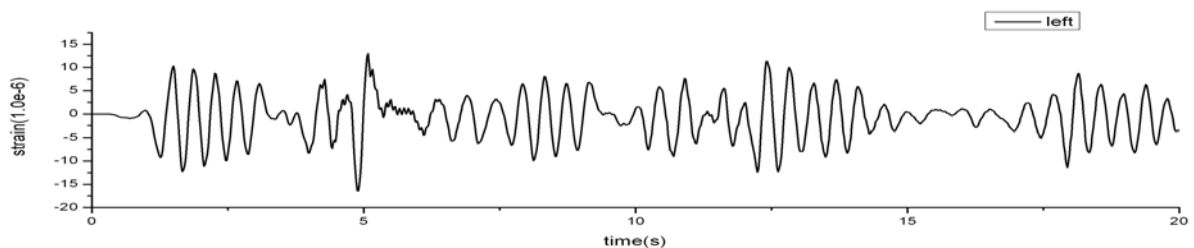


Figure 7. Axial strain of center element on left surface of the structure

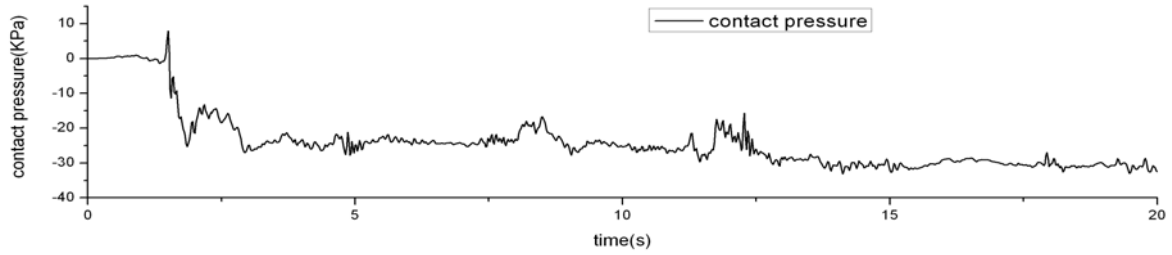


Figure 8. Contact pressure on the interface between soil and structure

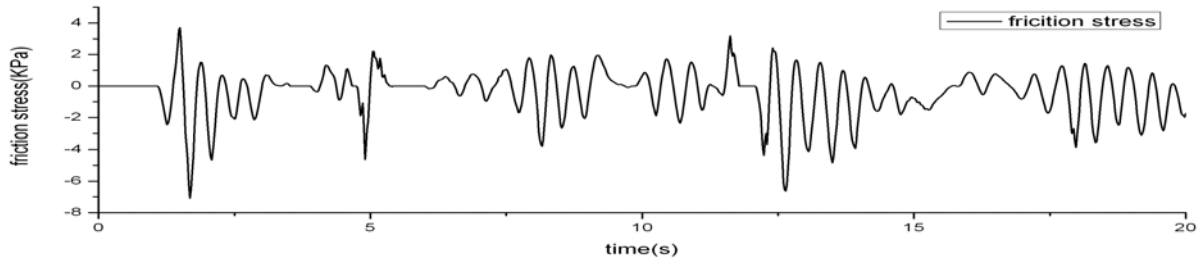
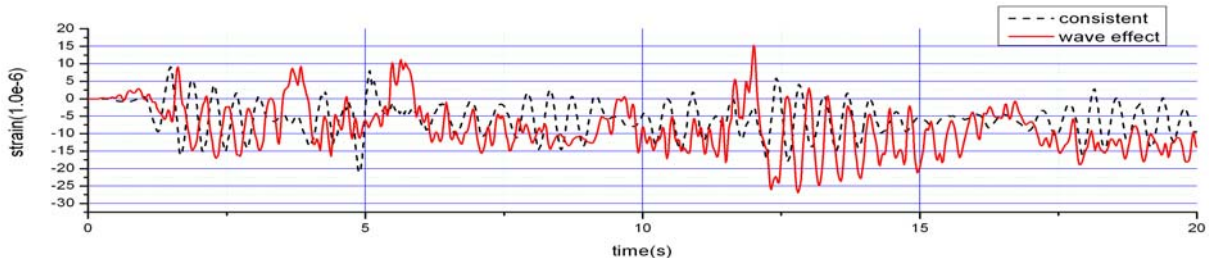


Figure 9. Friction stress on the interface between soil and structure

Wave passage effects

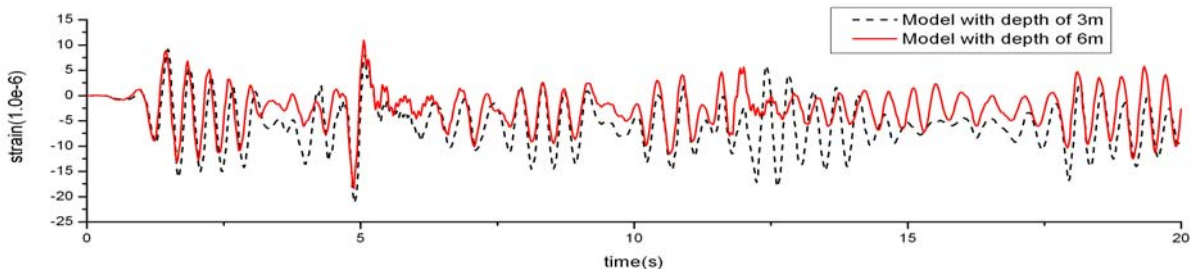
The utility tunnel is long line underground structure, so that the wave passage effect should be considered during the analysis. As a matter of fact, this effect may cause different responses of the structure. Figure 10 is the time history of structural strain, in which the structural strain is magnified because of the wave passage effect. Under the consistent excitation, the nodes excited at the same time. The time delay will exist, however, when considering the wave passage effect. The response of the structure at different nodes will be excited with time delay, so the axial response of the structure will be magnified.



**Figure 10. Axial strain of the center element on top surface of the structure
Effect of wave passage**

Effect of model depth

This time the buried depth changed to 6m, and other conditions are the same as before. From figure 11, it can be seen that the depth has little effect on the structural response. This may mainly be attributed to the fact that the effect of self-gravity of soil is small under the horizontal wave.



**Figure 11. Axial strain of the center element on top surface of the structure
Effect of model depth**

CONCLUDING REMARKS

As a modern infrastructure, the utility tunnel has many advantages over traditional method of laying lifelines. This paper established a three dimensional finite element model with the software package, ABAQUS, and the seismic response of the utility tunnel is studied. In the analysis, the elastic plasticity model, Drucker-Prager model is incorporated to simulate the soil response. And infinite elements in ABAQUS are adopted in conjunction with traditional finite elements to simulate the infinite domain of soil. During the analysis, it is observed that the variety of contact pressure is complex and slippage and/or sticking on the interface between soil and structure occurs. The wave passage effect is then studied in the paper. Results show that the response of structure is magnified by the wave passage effect. It is found out that the burying depth has little effect under the horizontal input motion.

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