Influence of a Tunnel on the Seismic Response of Adjacent Tall Building Considering Dynamic Building-Soil-Tunnel Interaction

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ABSTRACT

Excavating tunnels in urban areas could have a profound effect on the site characteristics and could change the free-field motion of the ground surface due to many different reasons. Although the previous earthquake events have ascertained that the response of the above-ground buildings close to the tunnel will also change, this effect is not well-addressed in the national and international design building codes. In this paper, considering a fully coupled system of building-soil-tunnel interaction, the presence of a tunnel on the seismic response of a two dimensional 15-story scaled benchmark building under two far- and two near-field benchmark earthquake records has been investigated. Additionally, non-linear dynamic analyses considering the material and geometric nonlinearity have been applied, and Mohr-Coulomb failure criterion and the equivalent linear method are implemented to obtain the nonlinear behavior of the soil. The interface between structural foundation and soil is simulated by normal, and shear springs, and the interaction between tunnel and soil is modeled using Coulomb Friction. As a parametric study, the effect of tunnel shape, cross-sectional area, the burial depth of the tunnel, and the effect of site soil material on the seismic response of the building is evaluated by evaluating the ratio of the structural responses with the presence of the tunnel to the structural responses without the presence of the tunnel. The results showed that the maximum relative displacements of the building for soils with 320 and 150 m/s in the presence of the tunnel decrease at most 10% under both far- and near-field earthquake records.

KEYWORDS

Building-Soil-Tunnel Interaction, Dynamic Analysis, Seismic Response

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1. **Introduction**

The analysis and design of buildings against earthquakes are accompanied by several simplifying assumptions that raise concerns about the realization of the expected seismic performance of the structure subjected to earthquake. One of the most important assumptions used in the seismic analysis and design of conventional residential buildings is their modeling and analysis independent of the site condition and assuming a fixed base at the base of the building columns [1]. In recent decades, with the development of the concept of soil-structure interaction and extensive research in this field, it has become possible to model and analyze structures on a flexible basis [2]. In addition to the concept of soil-structure interaction, to model and analyze the structure more accurately, it is necessary to consider the effect of local site effect on the amplitude, duration, and frequency content of strong ground motions. In the study of local site effect, the impact of different parameters such as bedrock depth, groundwater level, different soil types, reflection, scattering and refraction of waves in different soil layers, the sediment layers, soil dynamic characteristics such as shear wave velocity in different soil layers and surface and subsurface topography alone or with interaction on the seismic response of the structure has been extensively investigated in previous researches[3].

One of the site conditions that can affect the seismic response of buildings, especially in urban areas, and it has been less studied, is the presence of underground structures in the vicinity of existing above the ground buildings [4]. Excavating urban tunnels with different applications, sizes, geometries, and depths in urban areas can change the deformation pattern of the ground surfaces under seismic loads. It can simultaneously change the internal forces of the tunnel lining based on the distance of the tunnel axis from the adjacent structure. On the other hand, the tunnel's existence also changes the direction and intensity of the seismic waves entering the structures. Therefore, due to the construction of underground tunnels in the adjacency of residential buildings, a triple interaction is created between the building, soil, and tunnel system [5, 6]. In the technical literature, the effect of soil-structure interaction on the seismic behavior of the building, regardless of the presence of underground structures in its vicinity, has been extensively studied. Furthermore, the effect of earthquake on tunnel response without the presence of the building. and in fewer studies with the presence of the building has been investigated, However, there are limited studies on the tunnel presence on the seismic response of adjacent buildings [7, 8].

2. **Methodology**

In this research, a combination of two systems of soil-tunnel interaction and soil-building interaction have been studied using the concept of soil-structure interaction. Among the existing methods for soil-structure interaction, the substructure and the direct method are more common. In the substructure method, soil behavior is modeled using the dynamic stiffness, and the soil impedance matrix. In the direct method, part of the soil adjacent to the structure and additionally different soil layers are simulated. In this study, the finite element method has been applied to model soil environment and the building based on the direct method, and the foundation input motion has been calculated. Benefited from static and dynamic solvers and its ability to perform linear and nonlinear analysis, ABAQUS finite element software has been employed to model building-soil-tunnel system directly, according to Figure 1.

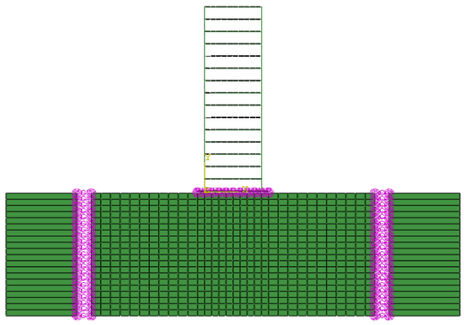

Figure 1. Soil-building interaction

The assumption of plane strain behavior and two-dimensional elements (CPE4) have been adopted to model the soil material, and the interface elements have been used to consider the interaction between soil and the foundation. also, two types of soft clay soil with two different shear velocities equal to 320 m/s (De type) and 150 m/s (Ee type) have been studied, respectively to investigate the effect of site soil type.

In numerical modeling, the element's dimensions must satisfy the accuracy and speed of the analysis, and the proper propagation of the wave in the medium.. To properly propagate the wave in the medium, the maximum element dimensions are limited by the following relation [9]:

$$\Delta L \leq \frac{\lambda}{10} \qquad (1)$$

Where λ is the wavelength propagated in the medium, which is related to the minimum shear wave velocity in the medium and the maximum input excitation frequency as follows:

$$\lambda_{min} = \frac{Vs_{min}}{f_{max}} \qquad (2)$$

According to the above two relations, the maximum dimensions of the elements in order to properly propagate the wave in the medium are determined as follows:

$$\Delta L \leq \frac{Vs_{min}}{10 \times f_{max}} \qquad (3)$$

where Vs_{min} is the minimum soil shear wave velocity (in m/s), and f_{max} is the maximum input excitation frequency (in HZ).

Solutions based on numerical, analytical and experimental methods have been proposed for seismic analysis of tunnels. In summary, common numerical methods in tunnel seismic design are direct methods of soil-tunnel interaction analysis. Coulomb friction model has been used to consider the interaction between soil and tunnel. This model determines the friction behavior between the contact surfaces using a friction coefficient μ and is determined according to Equation (4):

$$\tau_{crit} = \mu\rho \;\; ; \mu = \tan(\delta) + \frac{c}{\sigma} \qquad (4)$$

Where μ and ρ are the friction coefficient and the contact pressure between the two surfaces (in Pa) respectively, δ is the angle of friction between the tunnel concrete and the soil (in ^{o}), c is the cohesion (in Pa), and σ is the vertical stress (in Pa) on the axis of the tunnel.

3. **Results and Discussion**

In this study, the effect of an underground tunnel on the seismic response of the above-ground building is considered, and the following results can be expressed:

The soil-building interaction increases the first period of the building, and its effect on the seismic response of the roof displacement in soft soil is more than the hard soil and increases the roof displacement. The first story drift of the building with a flexible base is increased 42% for De soil type and 53% for Ee soil type. The building-soil-tunnel interaction also affects the maximum displacement of the building floors. In general, it shows a decrease in the maximum displacement of the floors compared to the system without a tunnel. The maximum reduction for H/D =1.5 is equal to 10%. With the increasing cross-sectional area of the tunnel (station compared to circular tunnels), the reduction in displacement reaches about 20%. This reduction is significant in seismic calculations. In this study, the tunnel effect on the maximum displacement response decreases with increasing depth, and its effects can be generally ignored for the ratio of depth to diameter of the tunnel greater than 3 (H/D> 3). The maximum stress ratio created in the members increases by 22% for near-field earthquakes in De and Ee soil type for Kobe earthquake and by 9% for De soil type for El-Centro earthquake.

4. **Conclusions**

As a general result, an increase in lateral displacement was observed considering the soil-building interaction, and the performance level of the building may decrease, which is a safety threat. Considering the building-soil-tunnel interaction, by increasing the tunnel cross-sectional area and decreasing the tunnel depth, the maximum displacement of the building floors decreases and can also increase the seismic stress of the structural members of the building, which should be considered in the design of the building. According to the highlighted results, to have a building with expected performance, it is advised to consider the building-soil-tunnel interaction in the analysis and design process.

5. **References**

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