Influence of Underground Opening with Stiff Lining on Seismic Response of Buildings

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Abstract

In this study, the influence of an underground opening at different depths on seismic performance of a 15-storey moment resisting building subjected to the 1995 Kobe earthquake is investigated. The numerical model consists of a superstructure, soil medium, and an underground opening, all simulated using finite element method in time domain considering soil nonlinearity and soil-structure interaction. The results are presented in terms of foundation rocking angle, distribution of maximum shear force developed in the structure, maximum lateral deflection as well as inter-storey drifts of the building. The results indicate that the underground opening has a notable influence on seismic response of the building. Particularly, the maximum foundation rocking angle is reduced with the presence of the underground opening with stiff concrete lining and the reduction is more significant when the underground opening is constructed at a lower depth. In addition, for a shallower underground opening, as the foundation rocking decreases, seismic energy dissipation is reduced, which in turn, causes more seismic energy transmitted to the structure and consequently larger shear forces are developed in the structure, which reveals the importance of consideration of underground structure in the seismic design of superstructures. Moreover, according to the results, the building constructed above a shallow underground opening experiences relatively smaller lateral displacement and inter-storey drifts subjected to earthquake excitation.

Keywords: Underground opening, soil-structure interaction, seismic response

1. INTRODUCTION

A growing need for underground structures such as tunnels and pipes as a result of urbanisation has drawn great attention to the related safety issues. Particularly, it is critical to estimate the potential hazards induced by the earthquake to the underground structures as well as the superstructures. For commonly employed seismic design methods using design spectra based on national standards, the interaction between underground opening, soil and the superstructure is typically neglected or simplified due to the complexity of the problem. However, some researchers have highlighted the importance of underground structure-soil-superstructure interaction, which should be taken into account to ensure the safety and the cost (Lou et al. 2011). There have been extensive studies related to either underground opening-soil interaction (Anastasopoulos and Gazetas 2010), soil-superstructure interaction (Tabatabaiefar and Fatahi 2014; Hokmabadi and Fatahi 2016; Nguyen et al. 2016), or soil-pile-structure interaction (Hokmabadi et al. 2014; Nguyen et al. 2017), while studies on coupled underground opening-soil-superstructure interaction is still quite limited (Wang et al. 2013).

In this study, seismic response of a building sitting on soil with an underground opening constructed below is studied adopting the finite element method (FEM) in time domain employing PLAXIS 3D-Version 2016 software. The direct method which is found to be more favourable than the sub-structuring method in the nonlinear analysis is adopted to study the fully coupled response of the system. The results presented in terms of the foundation rocking angle, the shear forces developed in the building, the maximum lateral deflections, and the inter-storey drifts indicate the important role of the underground opening-soil-structure interaction in the seismic design and the effects should therefore be carefully assessed by engineers to ensure the accuracy of the design.

2. ADOPTED NUMERICAL MODEL

Fig. 1 shows the general layout of the numerical model adopted in this study. The superstructure, modeled in this study, is a 15-storey moment resisting building. The 15 ×15 × 1 m shallow foundation, which satisfies both criteria of the maximum allowable settlement and the bearing capacity, is adopted for the structure. Additionally, Table 1 presents the properties of columns utilised in this study. Furthermore, the behaviour of the structural elements is simulated using a linear elastic model, while accounting for Rayleigh damping with 5% damping ratio nominated at the first mode natural frequency (f_1= 0.83 Hz) and the second mode natural frequency (f_2= 2.34 Hz) of the building to simulate structural damping during the dynamic analysis.

Table 1. Properties of columns adopted in this study

Columns	Properties	
Storey Levels	EI (MPa·m^4)	EA (MPa·m^2)
1~3	152.72	8580
4~7	104.39	7150
8~11	68.35	5720
12~15	42.61	4576

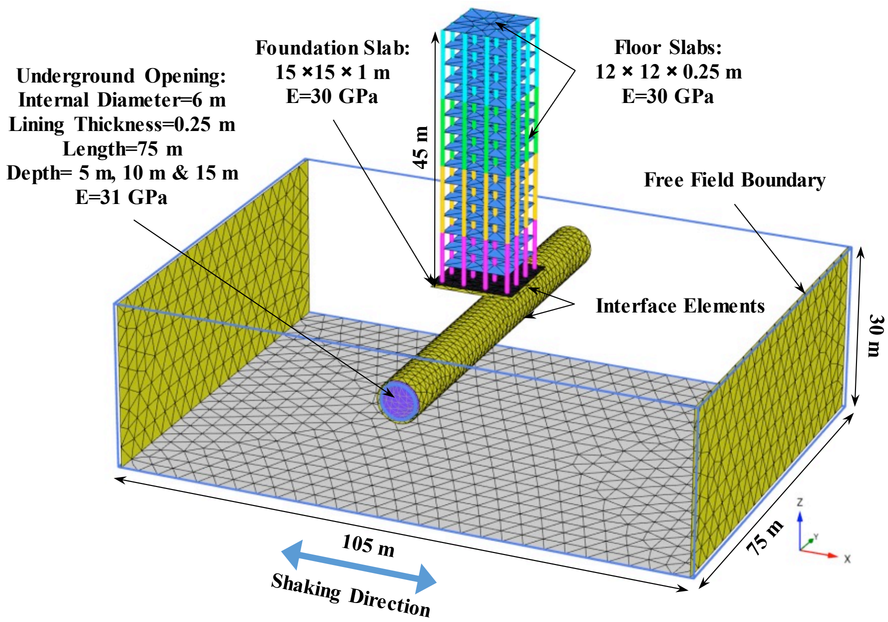

Figure 1. Established model with general information provided

As shown in Fig. 1, the circular underground opening is situated right below the superstructure. In addition, 4 different arrangements of the underground opening are considered in this study to assess the impact of underground opening on seismic performance of the surface building. The arrangements are: (1) the building constructed without the presence of the underground opening, (2) the building with a 15 m deep underground opening present in the model, (3) the building constructed above an underground opening buried 10 m below, and (4) the building constructed above an underground

opening buried 5 m below.
In the numerical model, the superstructure sits on a 30-m thick soil deposit with a unit weight of 14.42 kN/m^3 and an average shear wave velocity of 428 m/s. As the nonlinearity and plasticity are major concerns in simulating soil behaviour in the analysis related to the interaction between soil and structure, the Hardening Soil model with small-strain stiffness (HSsmall Model) offered in PLAXIS 3D is adopted in this study due to its ability to reproduce hysteretic damping and modulus decay at small strains. Specifically, the reference secant stiffness E_{50}^{ref}, the reference tangent stiffness E_{oed}^{ref}, and the reference unloading/reloading stiffness E_{ur}^{ref} are 19.54 MPa, 25.03 MPa, and 92.68 MPa, respectively, with the reference maximum shear modulus G_0^{ref} and the threshold shear strain $\gamma_{0.7}$ at which G_{secant}= 0.722 G_0^{ref} being 264 MPa and 1.23 × 10^{-4}, respectively. In addition, cohesion c = 50 kPa and friction angle φ = 18 ° are adopted in this study. Moreover, a set of interface elements is added between soil and structure to capture possible slipping and gapping. The value of strength reduction factor R_{inter} for the interfaces is set to be 0.7.

Two different sets of boundary conditions are employed for static analysis and dynamic analysis separately. Fully fixed base with horizontally fixed side boundaries are adopted during static analysis where only the gravity loads are applied. For dynamic analysis, free-field boundary conditions are applied to all the four sides of the model to eliminate the influence of wave reflection due to artificial boundaries. Moreover, the model size is chosen to be large enough so that the wave reflection at boundaries can be neglected. Furthermore, the bedrock is modeled as a rigid base in seismic analysis. In addition, as shown in Fig. 2, seismic acceleration time-history recorded during the 1995 Kobe earthquake with peak ground acceleration of 0.62 g and predominant frequency of 0.83 Hz is applied to the bedrock to simulate the earthquake excitation.

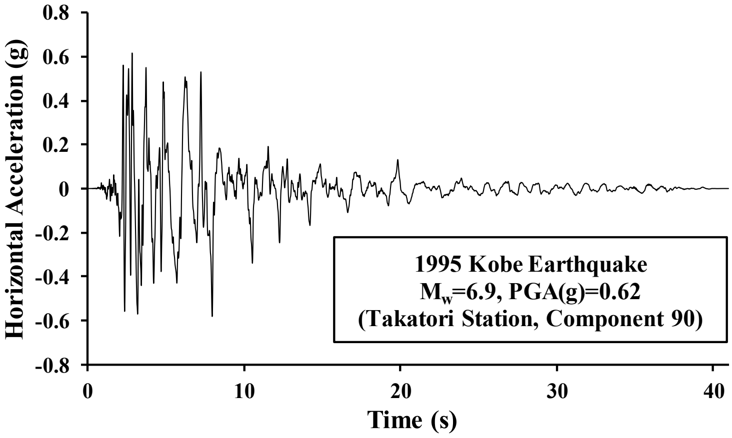

Figure 2. Input acceleration time-history of the 1995 Kobe earthquake

3. RESULTS AND DISCUSSION

Fig. 3 shows the maximum foundation rocking angles of the building subjected to the 1995 Kobe earthquake considering different underground opening arrangements. It can be observed that the presence of underground opening with stiff concrete lining decreases the maximum foundation rocking angle, while the reduction becomes less pronounced with increasing depth of the underground opening. For instance, the maximum foundation rocking angle of the structure with an underground opening buried 10 m below is 6% less than that without underground opening, while the corresponding value decreases for the structure with a 15 m deep underground opening. As excavated soil is replaced by underground opening with reinforced concrete lining, the compressibility of the ground decreases as a result of introducing strong concrete lining. Furthermore, it is evident that with a shallower underground opening with stiff concrete lining, the effective compressibility of the ground decreases, reducing the foundation rocking.

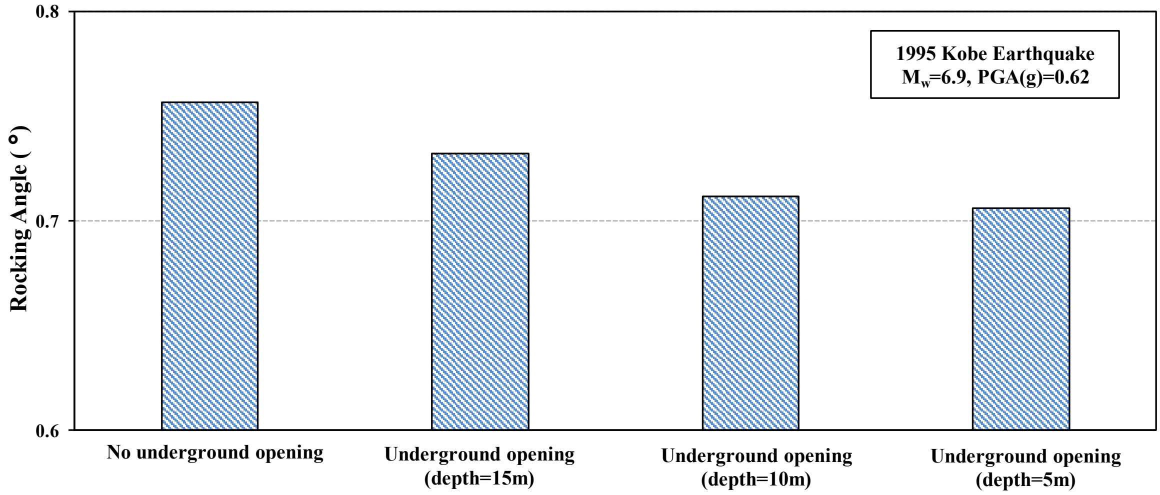

Figure 3. Maximum foundation rocking angle subjected to the 1995 Kobe earthquake considering different underground opening arrangements

Figs. 4 and 5 depict the distribution of maximum shear force and maximum base shear in the superstructure under the influence of 1995 Kobe earthquake, respectively. According to Fig. 4, the distribution of shear force developed in each level varies, which indicates that the soil-structure interaction has altered dynamic characteristics of the system such that the input motion results in different portions of the structure's higher mode responses, as explained by Hokmabadi and Fatahi (2016). Furthermore, as observed in Fig. 5, the maximum base shear increases with the presence of the underground opening and the value becomes larger when the underground opening is shallower. These observations are strongly related to the interaction between the soil and the structure. As mentioned earlier, stronger ground as result of the presence of the underground opening with stiff concrete lining reduces the foundation rocking, which in turn causes less seismic energy dissipation and consequently, more seismic energy is transmitted to the structure, producing larger base shear as observed in Fig. 5.

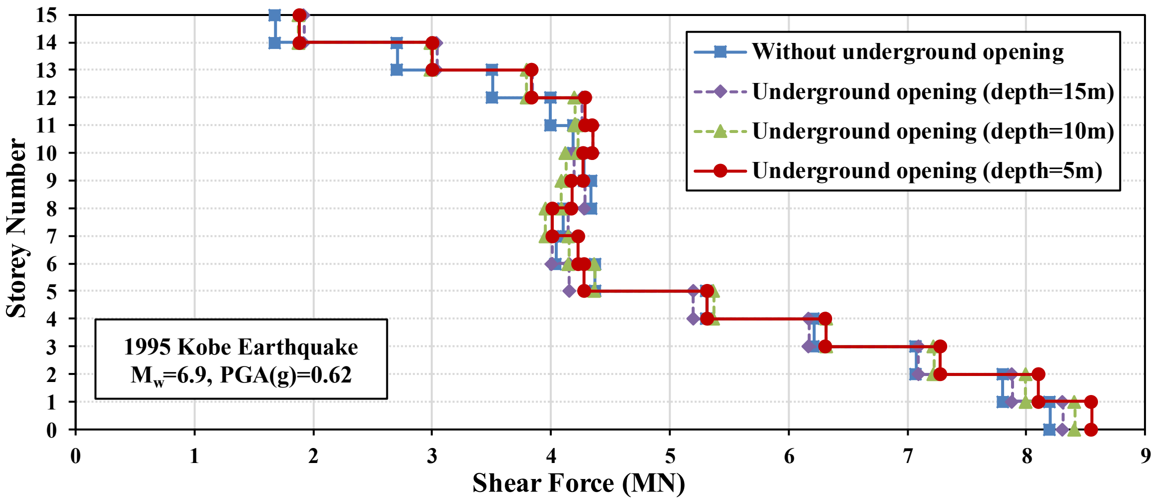

Figure 4. The distribution of maximum shear force in the building subjected to the 1995 Kobe earthquake considering different underground opening arrangements

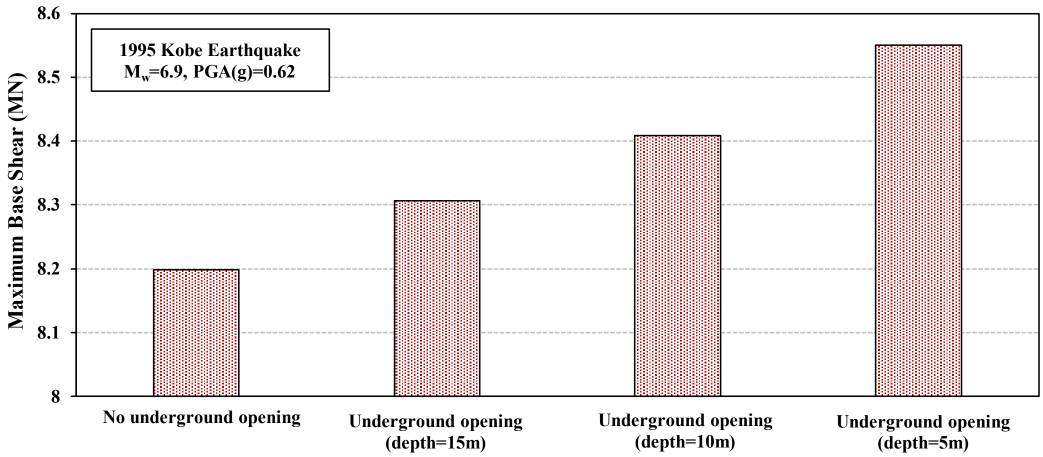

Figure 5. Maximum base shear in the building subjected to the 1995 Kobe earthquake considering different underground opening arrangements

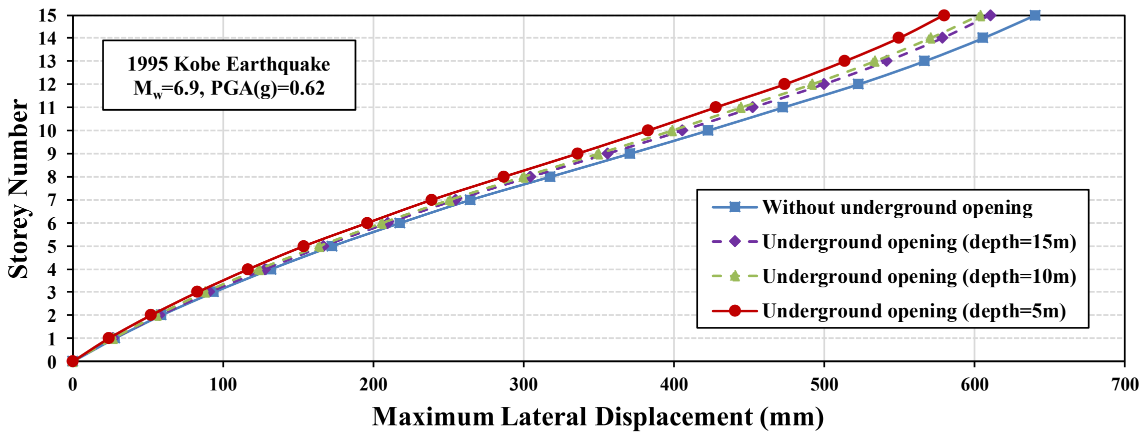

Figure 6. Maximum lateral displacement of the building subjected to the 1995 Kobe earthquake considering different underground opening arrangements

Fig. 6 presents the maximum lateral deformation of the building under the influence of the 1995 Kobe earthquake considering different underground opening configurations. The maximum lateral deflection for each level is recorded when the top level of the structure undergoes the maximum lateral displacement. Both foundation rocking and structural distortion (which is directly associated with shear force) contribute to the lateral displacement of the building. Particularly in this case, where the shallow foundation is adopted, a significant portion of lateral displacement is attributed to the rocking component. Hence, the trend of the maximum lateral deformation (Fig. 6) is in good agreement with that of the maximum foundation rocking angle reported in Fig. 3. For example, the building constructed on the ground excluding the underground opening, experiences the most significant foundation rocking and lateral deformation on the top level (i.e. 0.756° and 641 mm, respectively), while the building with a 5 m deep underground opening experiences the least foundation rocking and lateral displacement on the top level (i.e. 0.706° and 580 mm, respectively). It is noted that seismic response of the building is altered notably by the underground opening.

Fig. 7 shows the inter-storey drifts of the building, which are defined as the ratio of lateral deflection variation between two adjacent levels to the story height (i.e. 3 m). As the inter-storey drift is correlated to the lateral deformation, similar to the results reported in Fig. 6, the drift decreases when the underground opening is present. For instance, the maximum inter-storey drift for building without underground opening is 1.77 % while the corresponding value for building with a 5 m deep underground opening is reduced to 1.63 %.

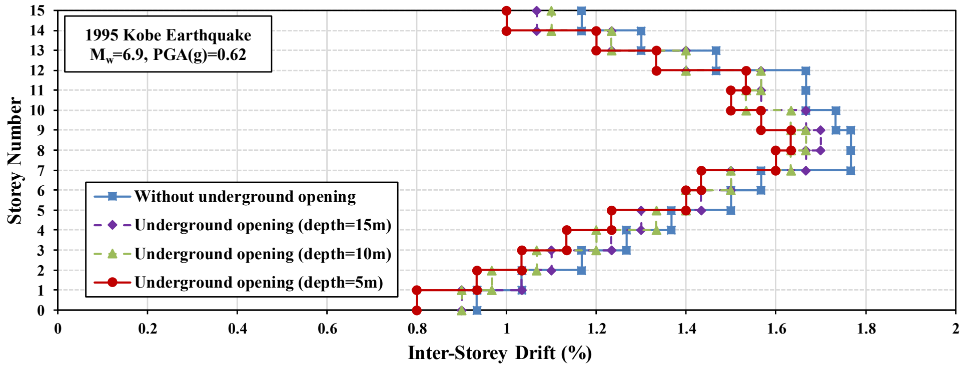

Figure 7. Maximum inter-storey drifts of the building subjected to the 1995 Kobe earthquake considering different underground opening arrangements

4. CONCLUSIONS

In the present study, the effect of the underground opening on seismic performance of a 15-storey building subjected to the 1995 Kobe earthquake has been investigated. The coupled soil-structure system has been simulated using the finite element method in time domain, considering the underground opening-soil-structure interaction. The results indicate that the seismic response of the building is impacted by the underground opening. In particular, the maximum foundation rocking angle decreases with the presence of the underground opening with the stiff concrete lining and the reduction is more significant for shallower underground opening, attributed to the presence of stiff concrete lining. Moreover, as the foundation rocking decreases, the seismic energy dissipation is reduced, which in turn results in more seismic energy transmitted to the structure and consequently larger shear forces are developed in the structure. Furthermore, it is found that the presence of shallower underground opening can reduce the maximum lateral deformation and inter-storey drift of the superstructure. In general, ignoring the presence of underground opening for the sake of simplicity may result in under-prediction of the structural forces, which can be safety threatening.

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