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Evaluation of the parameters affecting the seismic response of underground cavities considering earthquakes in near and far fault fields

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ABSTRACT: The existence of underground cavities such as aqueducts and water supply pipelines causes changes in the estimated seismic response on the ground. Since the characteristics of an earthquake are different near and far from the seismogenic source and the corresponding regulations have not considered near- and far-field effects on loading, it is necessary to study and compare such effects. This study has used the finite element method and the two-dimensional Plaxis software to investigate seismic responses on the ground while there are underground circular cavities. To this end, a set of near- and far-field accelerograms belonging to Bam, Landers and Loma Prieta were selected. Those recordings were different in terms of frequency. To examine the effect of soil type, four types with different mechanical characteristics were selected, and the seismic responses on the surface of the ground were studied in the presence and absence of an underground cavity. The effect of the buried depth of the cavity was evaluated with regard to two different buried depths (H/R = 1, 3). The results showed that the presence of an underground cavity leads to an amplified response of the ground. For instance, the amplification index of the displacement on the ground with and without cavities in the most critical conditions (Landers earthquake) was found to be 4.8 and 6 as recorded in near-field and far-field accelerograms, respectively. Moreover, the farther from the cavity center (X/R > 4), the less amplification was clearly observed on the ground under different loadings. The selected parameters also proved to have significant effects on the acceleration and displacement on the surface of the ground. To gain more insight about these effects, further research is needed.

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1- Introduction

Considering the structural damages due to the 1994 Northridge Earthquake in Los Angeles, the 1995 Kobe Earthquake in Japan, and the 1999 Chi-Chi Earthquake in Taiwan, there are obvious differences among the responses of structures against near- and far-field earthquakes. The destructive earthquake in the city of Bam recalled the attention of engineers to the unique features of such earthquakes in our country [1]. Near-fault ground movements have unique characteristics that differ from the ground movements in areas far from a fault. The most prominent studies investigating the aspects of near- and far-field earthquakes were conducted by Hudson and Housner [2], Bolt [3], and Bertero et al. [4]. They used the recorded motions of the Port Hueneme earthquake.

The present study investigates the effects of various factors such as the parameters of near- and far-field earthquakes, the type of soil, and the depth of the cavity on the seismic response of underground cavities. To this end, numerical modeling and the validation of the numerical model are conducted. The results prove the significant impact of underground cavities on the seismic response of the ground.

2- Problem statement and verification

The current study has used the two-dimensional Plaxis finite element software for numerical modeling. This software can dynamically analyze geotechnical issues to model harmonic, earthquake, and explosion loads. The model dimensions were determined based on the results of the study estimated in the validation section. According to Figure 1, H and R indicate the maximum height of an underground cavity from the ground surface and its cavity, respectively. Two depth ratios of H/R = 1, 3 have also been used to check the burial depth of the cavity.

To investigate the effect of soil type on the seismic response of the construction, four types of soil with different values of shear wave velocity were selected, and the seismic response of the ground was evaluated in the presence of an underground cavity and free surface. Also, the data of some earthquakes with different frequencies were used as a basis to investigate the impacts of near- and far-field earthquakes.

The study conducted by Soltani [6] and the recorded results of the Gilroy region were used to verify the results of the software and validate the numerical model. To evaluate

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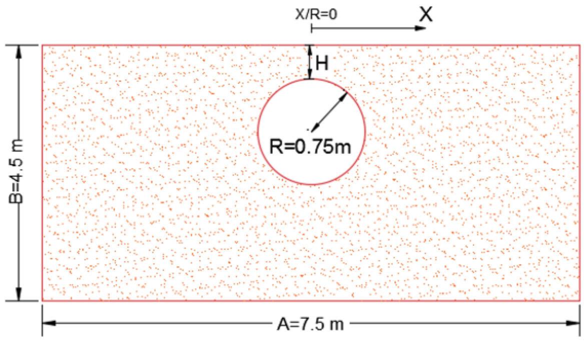

Fig. 1. Schematic view of the geometry and the primary dimensions of the numerical model

Table 1. The maximum rates of ground acceleration in far- and near-field earthquakes at distances of one and three times the cavity radius (X/R = 1, 3)

Earthquake	Earthquake field	The maximum ground surface acceleration (m/s^2)	Amplification factors of the maximum ground surface acceleration in the near- and far-field states	
		X/R=1	X/R=3	X/R=3 / X/R=1
Bam	Far-field	-1.24	1.27	1.02
	Near-field	-2.69	-2.71	1.07
Landers	Far-field	0.61	0.63	1.04
	Near-field	2.01	2.26	1.12
Loma Prieta	Far-field	0.95	1.22	1.3
	Near-field	2.63	3.45	1.31

the performance of the numerical model, the Gilroy area with two stations, namely Gilroy 1 (bedrock) and Gilroy 2 (ground surface), and the soil stratification characteristics of the area were simulated. Also, the acceleration time history of Coyote Lake earthquake (recorded in Gilroy 1) was applied as the input wave to the model.

3- Results and discussion

3- 1- Ground surface response in the presence of an underground cavity

A dynamic analysis was performed with various near- and far-field accelerograms of type III soil as a reference soil to compare the ground response in the presence and absence of a cavity.

The results suggested some amplification in the presence compared to the absence of the cavity, and the amplification reduction on the ground surface under different loading types was completely evident as the distance from the cavity center increased. At a distance of approximately four times the cavity radius (X/R = 4), the convergence of the ground surface displacement occurred in both cases. This distance, which was previously confirmed by other researchers such as Soltani and Bagheripour [7], is the distance where the effect of the cavity presence is significantly lost, and the response of the ground surface with the presence of the underground cavity is equal to the response of the free surface. It is noteworthy that the distance is very important in determining the size of the finite element model. On the other hand, the ground surface response was amplified in the presence of an underground cavity in all the investigated cases.

3- 2- Investigating the responses of the near- and far-field ground surfaces

Dynamic analyses were conducted to obtain acceleration time history graphs and acceleration response spectra on the ground surface by applying near- and far-field earthquakes. At this stage of the study, the height of the soil on the cavity was equal to the cavity radius (H/R = 1), and the studied area was modeled with type III soil according to the table provided in the full text of the article.

The results also showed that the maximum ground surface acceleration in both near- and far-field earthquakes was larger at a distance three times the cavity radius (X/R = 3) compared to the distance equal to the cavity radius (X/R = 1). This can clearly be observed in the displacement diagrams. Therefore, the maximum amplification in the ground surface acceleration in both near- and far-field accelerograms would not necessarily occur at distances close to the cavity, but there were significant amplifications at distances far from the cavity. Thus, the response taken on the ground surface was closely correlated to the distance, which is especially important in the design of linear structures. Table 1 shows the maximum acceleration of the ground surface under the accelerograms.

The study also addressed the seismic responses of the ground in different soil types and at various underground cavity depths.

4- Conclusion

The current study used the finite element method and the Plaxis software to investigate the ground surface seismic responses in the presence of an underground cavity under a set of near- and far-field accelerograms, different soil types, and various burial depths of the underground cavity. The analysis of parametric studies yielded the following results:

As the graphs of horizontal displacement and acceleration clearly showed, there was seismic amplification in the presence rather than absence of underground cavities, leading to ground surface displacements of more than 12 times of that in the conditions without cavities.

Based on the results, the maximum ground surface acceleration in both near- and far-field earthquakes was larger at a distance three times the cavity radius (X/R = 3) than at the distance equal to the cavity radius (X/R = 1), which is completely evident in the displacement diagrams. The largest ground surface amplification in both near- and far-field accelerograms did not necessarily occur at distances close to the cavity center; there was a significant amplification at far distances, which was completely influenced by the input loading and the geometric characteristics.

The investigations carried out on the burial depth of the cavity indicated that seismic amplification would not necessarily be observed at shallow depths. In other words, larger amplification was expected in the study area by getting closer to the source of the incoming wave, which was associated with the multiple scattering of waves in the environment. However, the amplification would change if the location of the load was changed.

In the study carried out on different soil types, the maximum displacement ratio decreased in both near- and far-field earthquakes with the increase of soil hardness. On the other hand, as the soil hardness decreased, larger amplification values were achieved. Therefore, amplification not only depends on the cavity size but also on different soil types.

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