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An Investigation of the Seismic Interaction of Surface Foundations and Underground Cavities Using Finite Element Method

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ABSTRACT

In this study, the seismic interaction of surface foundations and underground cavities was investigated. For this purpose, a parametric study of geometric dimensions of the foundation and cavity, their location, and the effect of the interaction between surface foundations and underground cavities was evaluated. The variable parameters include the ratio of the overburden height to the foundation width (H/B = 0.5, 1 and 2), the location ratio of the cavity to the foundation width (X/B=0, 2 and 8) and the ratio of the cavity diameter to the foundation width (d/B=0.5, 1 and 2), respectively. The accuracy of the finite element method was evaluated using a laboratory study and it was found that the used method provides an accurate prediction of tunnel behavior. The results indicated that by increasing the overburden height, the stress on the tunnel surfaces was increased for all values of X/B (the horizontal tunnel distance to the foundation width). Therfore, in the case where the tunnel is located exactly along the center at the bottom of the foundation (X/B=0, d/B=2), the maximum stress generated is approximately 2.13 times greater than its corresponding value in the ratio of the depth to width of 0.5 (X/B=0, d/B=0.5). It can be concluded that the higher overburden height, the greater stresses caused by the dynamic loads of the earthquake on the tunnel wall.

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1. INTRODUCTION

In recent years, tunneling has been focused on creating spaces suitable for transportation and utilities in urban environments. In fact, development of technology in machinery and drilling equipment makes it relatively easy to build such underground structures. Moreover, the limitations of surface spaces for implementation of construction projects as well as security issues have attracted the attention in construction of underground structures for civilian, military, and mining applications [1-6].

On the other hand, according to the seismicity of Iran and the dominant of seismic lateral forces arising from the earthquake in the design of structures, in most cases, it is necessary to have an adequate understanding of the behavior of the foundations when applying seismic forces in addition to static forces [7]. Many complex analysis and dynamic problems in earthquake engineering level are being carried out by various researchers around the world. The soil environment or the stone surrounding the structure and the foundation behavior has a significant impact on the structure's behavior against earthquake [8-13].

The site conditions, the structure geometric, the mechanical properties of the soil and the foundation behavior can be effective on the dynamic response of the structures. Therefore, given the increasing importance of using underground structures such as tunnels as well as the need for the foundations to be built around tunnels and the dynamic load caused by seismic load and the effect of the waves generated by the dynamic load on underground tunnels. Also, given the destructive effects that dynamic forces can have, an investigation on seismic interaction of surface foundations and underground tunnels required due to limited studies conducted in this area. Considering the increasing development of underground structures and high cost of construction for

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any of these structures as well as their importance in the intercity and inland transportation network, it is necessary to study their sustainability against the dangers of the earthquake and their resulting vibrations.

Various studies have been conducted on interaction of tunnels and the soil surroundings. Asakereh et al. [14] examined the behavior of the reinforced strip foundations on the reinforced sand with cavity under cyclic loading. To this end, several experiments were carried out on strip foundation located in reinforced or non-reinforced sand with geogrid with a cavity inside it. The number of reinforced layers and cyclic load range were evaluated. The presence of the cavity causes an increase in failure in the areas where foundations are under successive loading [14]. Asheghabadi and Matinmanesh [15] studied the seismic behavior of tunnel considering the interaction of soil-tunnel. The seismic analysis was conducted using the finite element method. This analysis was performed by considering three real history of ground movements. The results indicated that the existence of a tunnel exacerbates the seismic waves at the surface of the soil and the maximum amount of exacerbation occurs at the surface of the tunnel and soil contact [15]. Sabouni [16] studied variations of the displacement and effective stresses of the strip foundation in the presence of single and double cavities. For this purpose, the Plaxis 2D finite element software was used and the parameters such as size, location of the cavity, number of cavity and placement position (single cavity, two adjacent cavities and two cavities on each other) were investigated [16]. Lee et al. [17]studied the resistance of strip foundations in clay in the presence of underground cavities using the finite element method. Tsinidis et al. [18] studied tunels seismic response in soft soil. In the aforementioned study, several experiments were conducted to examine the response of box tunnels, which were under sinus and seismic stimulation in dry sand and soil to investigate the relative flexibility of the soil and tunnel as well as the interaction of soil and structure. The system was investigated using full-time history analysis with the exact implementation of the finite element models. The results indicate a vibrational deformation state along with known racking rocking for tunnels with box cross-section under seismic stimulation [18]. In a numerical parametric study, Tsinidis et al. [19] examined different rectangular soil-tunnel systems with the aim of identifying characteristics of the critical response of rectangular tunnels under transverse vibration. Numerical results showed that when the soil around the tunnel was unstable, a hybrid deformation pattern of vibrational and racking shape was developed for tunnels exposed to vibration, as well as internal deformations in the floor and lateral walls of the flexible tunnels [19]. Alielahi et al. [20] studied the seismic behavior of the ground in the presence of unlined tunnels exposed to the vertical waves of S and P using the boundary element method. Several simple and practical relationships presented for estimating the seismic zoning of environments in which unlined tunnels were used [20].

Most underground structures in urban areas, such as subway tunnels, are buried in shallow soil, and there are countless buildings on them. The presence of buildings around the tunnel in urban areas makes the seismic behavior of the tunnel different from the tunnel located in the suburban areas. When a tunnel is affected by dynamic loads, it vibrates and the vibration propagates in the soil in a wave motion. When a wave reaches the earth surface, it causes vibrations in buildings. In contrast, the vibration of buildings under dynamic loads also causes the tunnel to vibrate. If the tunnel or building is subjected to a critical force such as an earthquake or the distance between them is small, the interaction between the tunnel and the building foundation can cause serious damage to them. In order to investigate the problem, the dynamic interaction between the tunnel and the adjacent building should be examined and all the parameters that can be effective should be discussed so that if there is a building near the tunnel, its effect on the tunnel's internal forces should be determined. According to the explanations, the seismic interaction of surface foundations and underground cavities is investigated in this study. For this purpose, a parametric study of geometric dimensions of the foundation and cavity and their location and the effect that they can have on the interaction between surface foundations and underground cavities is evaluated using the finite element method. ABAQUS software [21] is used for simulation. One of the most important aspects of innovation and novelty in this study is considering the study of seismic interactions between surface foundations and underground cavities along with applying the effect of the earthquake on these structures.

2. THE PROCEDURE

The variable parameters in this study include the ratio of the overburden height to the foundation width (H/B: 0.5, 1 and 2), the location ratio of the cavity to the foundation width (X/B: 0, 2 and 8) and the ratio of the cavity diameter to the foundation width (d/B: 0.5, 1 and 2), respectively. These cases are shown in Table 1. According to the study conducted by Pais [22] at MIT (U.S.A.), the width and height of the foundation under investigation were considered 12 and 1.00 meters, respectively. So, due to the mentioned variables, 27 finite element models were simulated. The applied loads on the model of this study are dynamically considered.

3. FINITE ELEMENTS SIMULATION

The details of modeling in ABAQUS were presented in this part. These details include the definition of element type, material characteristics, boundary conditions,

TABLE 1. Introducing the cases in the present study

Number	Symbol	H/B	X/B	d/B
1	d/B: 0.5, X/B:0, H/B:0.5	0.5	0	0.5
2	d/B:1, X/B:0, H/B:0.5	0.5	0	1
3	d/B: 2, X/B:0, H/B:0.5	0.5	0	2
4	d/B: 0.5, X/B:2, H/B:0.5	0.5	2	0.5
5	d/B:1, X/B:2, H/B:0.5	0.5	2	1
6	d/B:2, X/B:2, H/B:0.5	0.5	2	2
7	d/B:0.5, X/B:8, H/B:0.5	0.5	8	0.5
8	d/B: 1, X/B:8, H/B: 0.5	0.5	8	1
9	d/B: 2, X/B:8, H/B: 0.5	0.5	8	2
10	d/B:0.5, X/B:0, H/B:1	1	0	0.5
11	d/B:1, X/B:0, H/B:1	1	0	1
12	d/B:2, X/B:0, H/B:1	1	0	2
13	d/B:0.5, X/B:2, H/B:1	1	2	0.5
14	d/B:1, X/B:2, H/B:1	1	2	1
15	d/B:2, X/B:2, H/B:1	1	2	2
16	d/B:0.5, X/B:8, H/B:1	1	8	0.5
17	d/B:1, X/B:8, H/B:1	1	8	1
18	d/B:2, X/B:8, H/B:1	1	8	2
19	d/B:0.5, X/B:0, H/B:2	2	0	0.5
20	d/B:1, X/B:0, H/B:2	2	0	1
21	d/B:2, X/B:0, H/B:2	2	0	2
22	d/B:0.5, X/B:2, H/B:2	2	2	0.5
23	d/B:1, X/B:2, H/B:2	2	2	1
24	d/B:2, X/B:2, H/B:2	2	2	2
25	d/B:0.5, X/B:8, H/B:2	2	8	0.5
26	d/B:1, X/B:8, H/B:2	2	8	1
27	d/B:2, X/B:8, H/B:2	2	8	2

loads, analysis type, interaction between surfaces, mesh, and the element used for mesh.

The geometric properties of the model are shown in Figure 1. The solid technique was used to simulate all the sections (Figure 2).

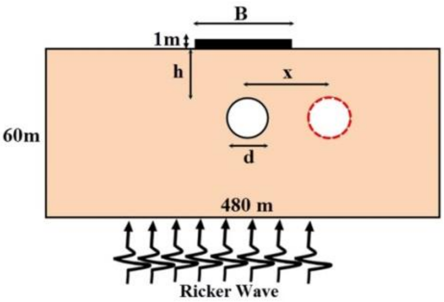


Figure 1. The geometric properties of the models

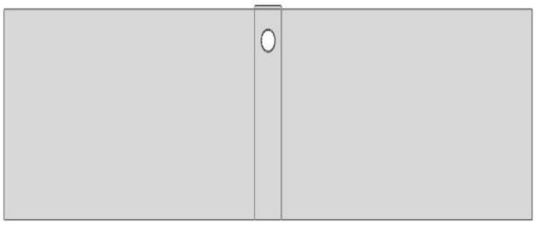


Figure 2. A sample of the defined geometric model

The behavior of sections is also three-dimensional and deformable. The deformable section is one of the five sections used in this software to model the deformable sections in two and three-dimensional spaces [21]. The characteristics of the soils are presented in Table 2. These parameters were selected based on the study of Jafari et al. [23].

The damping of materials in the soil generally results in from viscosity, friction, and plasticity development. A soil damping matrix is required for soil and structural analysis. The coefficients α and β of the damping matrix are calculated according to Riley's method (Equations (1) and (2)) [15].

$$[c]= \alpha\,[m]+ \beta\,[k] \tag{1}$$

$$\frac{1}{2}\begin{bmatrix} \frac{1}{\omega i} & \omega i \\ \frac{1}{\omega j} & \omega j \end{bmatrix}\begin{Bmatrix} \frac{\alpha}{\beta} \end{Bmatrix} = \begin{Bmatrix} \frac{\xi i}{\xi j} \end{Bmatrix} \tag{2}$$

Given the half-infinity of the real model, the seismic energy applied into the model must be exited through the boundaries (geometric damping). There are several methods to apply the energy-absorbing boundary. One of these methods is the viscose boundary. In this method, the damper elements are placed on the boundaries. The coefficiency of these damper elements is obtained from Equations (3) and (4) [15] in which ρ is the soil density, Cse is the shear wave velocity and A is the lining surface.

$$Fd=Cd.\dot{u} \tag{3}$$

$$Cd=\rho.Cse.A \tag{4}$$

There are two types of spring and damper elements in ABAQUS software [21]. In ABAQUS/Standard, there is just one node element. A dual-mode element can only be used in ABAQUS/Explicit. ABAQUS/Explicit has been used to perform nonlinear dynamic analysis. The spring and damper elements are defined in the interaction module using the Springs/Dashpots menu. Explicit

TABLE 2. Parameters of the used materials

β	α	n	E (kPa)	ρ (kg/m3)	Material name
0.08	0.001	0.30	40000	1900	Soil layer
---	---	0.20	20560000	2400	Concrete

dynamic analysis was used to analyze the models. Ricker type with a PGA scale of 0.3g and a central frequency of 4.3 Hz was used to apply the vertical invasive wave, and a shear wave velocity of 400 m/s was considered at the bottom of the soil block (Figure 3).

Also, in order to reduce the effect of the reflection coefficient applied to the model boundaries, the dimensions of the model were considered to be large enough.

For the regularity of the meshing or more simplicity in some parts of the modeling, there is a need for different parts of the model to be built and interconnected separately. In places where two parts of a model are to be connected, the degrees of freedom of the connected surfaces should be conjuncted to each other. The interaction tool is used for this purpose. By fixing the nodes on the two surfaces, this tool keeps their positions relative to each other by analyzing the displacements of the two nodes in a problem-orientation

In areas where a collision occurs during nonlinear analysis between two separated elements, the collision characteristics must be defined on two levels. Otherwise, the collision is not considered, and the two elements collapse into each other. In order to define the property of the collision, the nature of the collision of the elements should be defined in the software in terms of the nature of the collision. In normal collisions, the surface of the collision has tangential and frictional behavior. The use of contact behavior in modeling has the capability of simulating the collision and separating two levels from each other [21].

Since the materials used in the models include the soil and concrete of the tunnel, the interaction and contacts between the surfaces should be properly simulated. To this end, through the interaction module which is commonly used to define contacts and interactions between surfaces, using the Tie interaction, the interaction between the soil and concrete of the tunnel is applied to the models.

Tie interaction is one of the practical interactions in civil engineering which can be used to integrate the soil interaction and the concrete tunnel in which both are modeled with solid elements [21, 24].

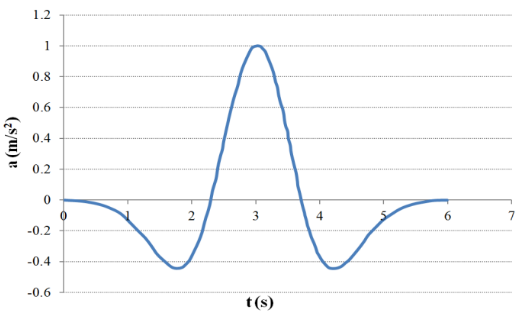


Figure 3. History of the Ricker wave

One of the most important parts of ABAQUS [21] software is defining or attributing mesh attribution. This part can be called the most important part of the software. In the finite element analysis of this study, models with large elements analyze at first (few numbers of elements) and one of the output quantities such as the maximum stress value generated at a desired point in the model is noted. Then the elements become finer and the problem is analyzed again. The process of subtracting the elements continues until the difference between the results becomes very low. Meshing or gridding which is representative of the model is sufficiently good enough to ensure that the applied forces are exactly calculated (Figure 4).

C3D8R soil elements were selected in which linear fragile eight nodes cube elements are reduced by an integral method. In each node, these elements have three degrees of freedom in three directions which in total constitute 24 degrees of freedom for each element and they are practical and reliable in terms of efficiency and accuracy.

4. VALIDATION OF THE NUMERICAL MODEL

Validation of the finite element method was carried out according to study conducted by Jiang et al. [24]. In Jiang's study, the seismic response of underground tunnels was studied using a laboratory study and the finite element. The laboratory study was conducted by the shaking table. The length, width, and height of the shear box of the soil were 3, 1.80, and 1.91 m, respectively. It consists of 16 steel frames which are placed on each other (Figure 5).

Each frame is made up of a square steel tube with dimensions of 2×100×100 mm. The tunnel laboratory model was selected based on Shanghai tunnel. The cross-section of this tunnel is 3000×3000 mm and the thickness of the walls is 300 mm. According to the laboratory facilities, the laboratory model was constructed on a scale of 1:5 as shown in Figure 6.

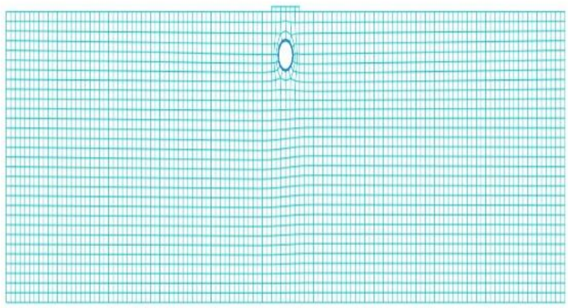


Figure 4. Cross-section meshing of one of the models understudy

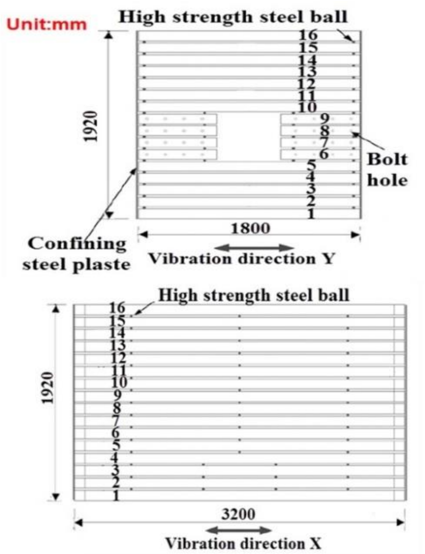


Figure 5. The shear box of the soil used in Jiang et al. study [25]

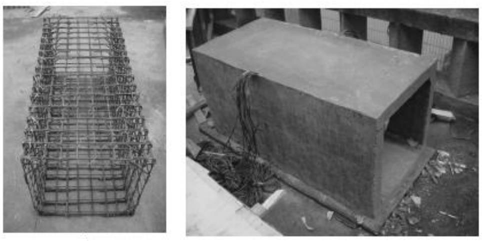


Figure 6. The tunnel modeling of Jiang et.al study [25]

Saturated clay was used in the experiment. Soils were poured into 20 cm layers in a box. Each layer was knocked into a specific density. Table 3 summarized the soil specifications used by Jiang et al. [25].

To measure the response of the structure, the soil, the shear box, accelerometers, pressure measurement devices, and sensors for measuring displacement at different points inside and outside the soil were embedded (Figure 7). El Centro earthquake characteristics were used for seismic stimulation. Figure 8 shows the history of the stimulus applied. Loading was applied from the bottom of the model and the outputs related to the center of the foundation and the tunnel were extracted. The outputs related to the two points A6 and A12 are shown in Figures 9 and 10.

TABLE 3. The physical characteristics of the soil in Jiang et.al study [24]

Special Dry Weight (g/cm^3)	Porosity Coefficient (e)	Adhesion Resistance (kPa)	Internal Friction Angle (°)
1.53	0.943	24.40	**27.9**

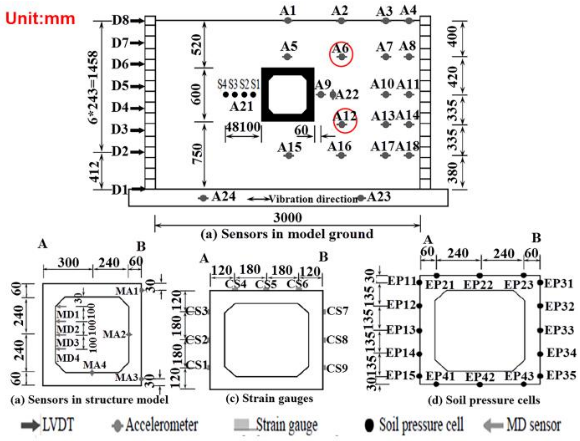


Figure 7. Shear box of the soil used in Jiang et al. study [25]

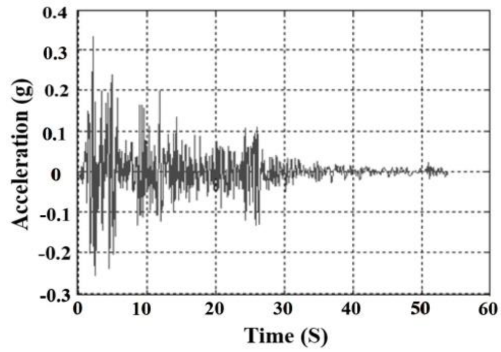


Figure 8. El Centro Earthquake record [25]

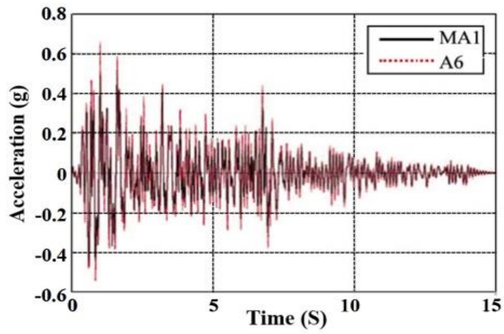


Figure 9. The soil acceleration at A6 in Jiang et al. study [25]

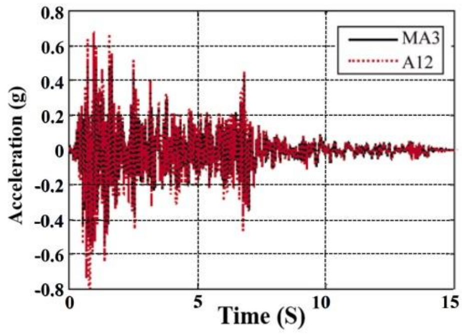


Figure 10. The soil acceleration at A12 in Jiang et al. study [25]

The model introduced in Jiang et al. [25] study was simulated according to the specifications mentioned using the finite element method used in the present study (Figures 11 and 12). The outputs which include the acceleration generated at points A6 and A12 are extracted (Figures 13 and 14). The details of the used method were presented in the previous part.

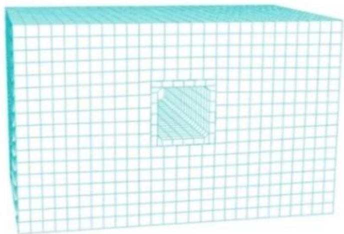


Figure 11. The meshing of Jiang et al model using the finite element method in the present study

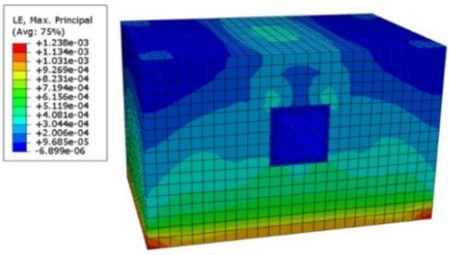


Figure 12. The strain distribution in the simulated model using the finite element method in the present study

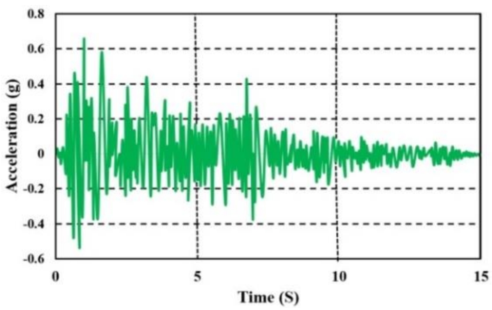


Figure 13. The acceleration generated at point A6 in the ABAQUS software

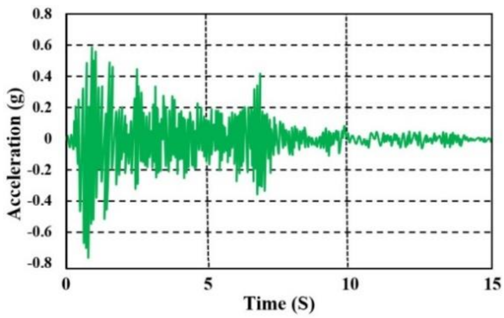


Figure 14. The acceleration generated at point A12 in the ABAQUS software

Figures 15 and 16 compare the results of the study conducted by Jiang et al. [25] and the simulated model using the finite element method used in this study. Given the obtained values, it is seen that the results are very close to each other. Therefore, the use of finite element simulation is accurate.

5. RESULTS OF THE PARAMETRIC STUDIES

The outputs are stress, displacement, and acceleration, respectively. The performance of simulated cases is compared using various diagrams, so that the parameters in the present study which include the tunnel diameter, the depth of tunnel location, the tunnel distance, and the foundation depth can be evaluated. For this purpose, each output of acceleration, stress, and displacement are interpreted separately according to the variables which are H/B, X/B, and d/B ratios, respectively.

5. 1. Evaluating the Maximum Acceleration of the Tunnel

Acceleration response of tunnels for different values of X/B (0, 2, and 8) is illustrated in Figures 17a to 17c. The studied parameters are shown on each of the figures for better understanding the diagrams. Also in Figure 18d, the acceleration responses of all the tunnels (27 models) are presented to evaluate their

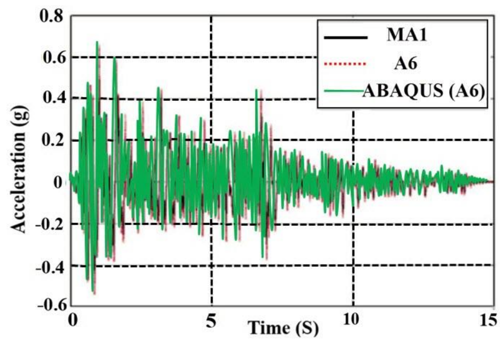


Figure 15. The acceleration generated at point A6 in ABAQUS software

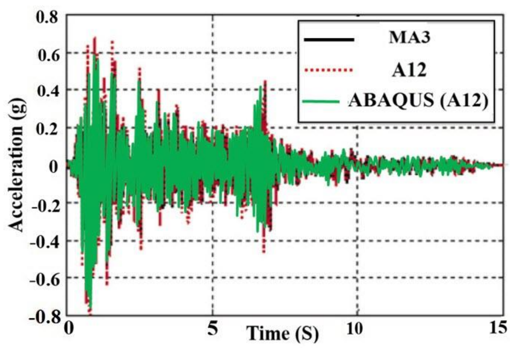
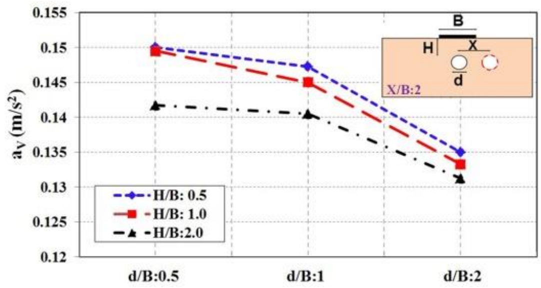


Figure 16. The acceleration generated at point A12 in ABAQUS software

overall behavior. According to these diagrams, when the ratio of tunnel location depth to the foundation width is equal to 2 (H/B=2.0), the generated acceleration value in all cases is less than other cases (H/B=0.5 and H/B=1.0). The reason for this is that whatever the overburden height is lower, (the depth of tunnel location), the soil becomes more vibrational under the influence of an earthquake, and its characteristics and parameters change. Thereby the acceleration applied to the tunnel lining is increased.

Another issue that can be seen from the illustrations in Figure 17 is that the acceleration created in the tunnel lining for different location depths (H/B=0.5, H/B=1, H/B=2) is very close when the ratio of horizontal distance of the tunnel from the center of the foundation is 2 and the diameter-to-width ratio is 2. In other words, the difference between the acceleration in the tunnel lining is very close to each other. Another parameter that can influence the acceleration in the tunnel lining is the horizontal distance of the tunnel relative to the center of the foundation which can be seen according to Figure 17. The acceleration generated in the tunnel lining is reduced in most cases by increasing the horizontal distance of the tunnel to the center of the foundation. According to the results, it can be stated that the horizontal distance of the tunnel relative to the center of the foundation has an effective role on the acceleration generated on the tunnel lining and this should be considered when designing tunnels near urban areas.

Another variable parameter which is also considered in this study is the diameter variation ratio of the tunnel diameter. As can be seen in Figure 17, any changes in the diameter parameter when the horizontal distance of the tunnel to the width of the foundation is equal to 2 (X/B = 2), the changes in the diameter parameter results in more changes in the generated acceleration. In other words, the slope of acceleration in this case is higher than other cases.



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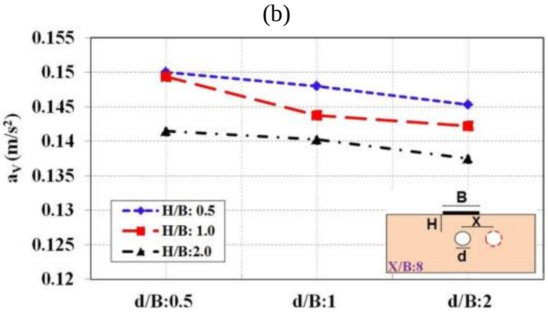

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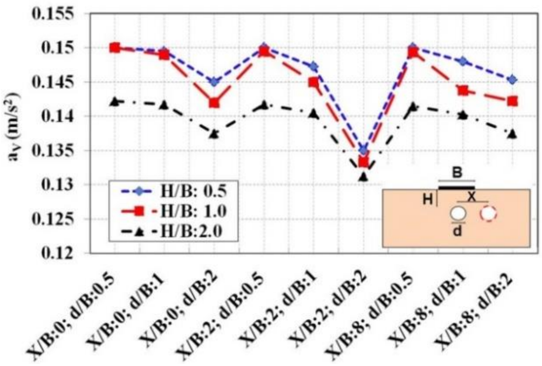


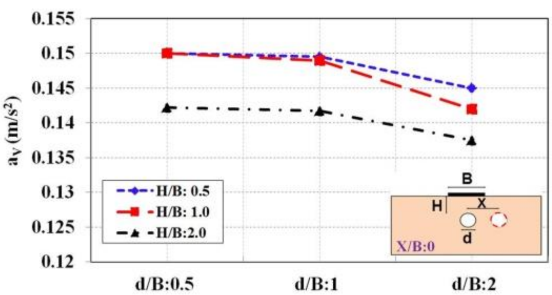
(d)

Figure 17. Comparison of the generated acceleration values in simulated tunnels a: X/B:0 b: X/B:2 c: X/B:8 d: total comparison

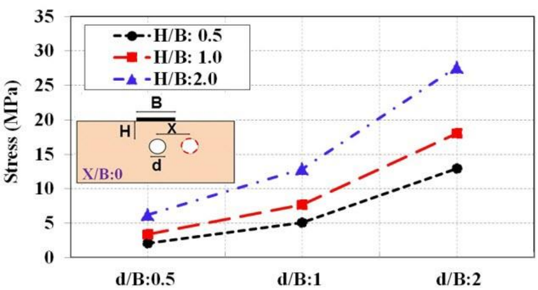
5. 2. Comparison of Maximum Stress Values in the Tunnel

Figure 18 compares the stress values generated in simulated tunnels with the aim of examining H/B ratios for various horizontal distances (X/B). As can be seen, by increasing the overburden height, the stress on the tunnel surfaces is increased for all X/B values.

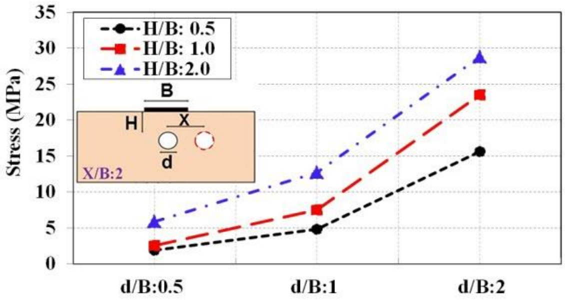
For example in the case where the tunnel is located exactly along the center and at the bottom of the foundation (X/B=0) and the diameter to width ratio of the foundation is equal to 2, the maximum stress generated in the depth to width ratio of the foundation is 2 and this is approximately 2.13 times greater than its corresponding value in the ratio of depth to width of 0.5.



(a)



(a)



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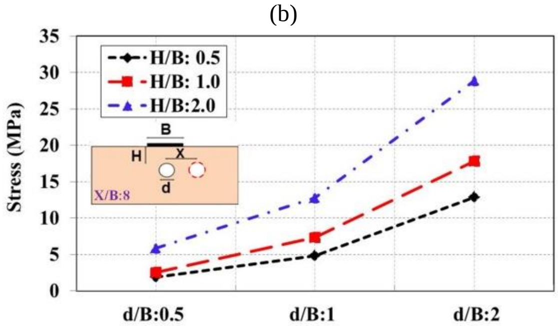
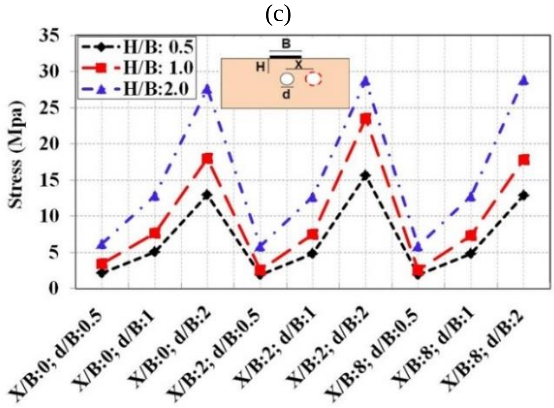


(c)



(d)

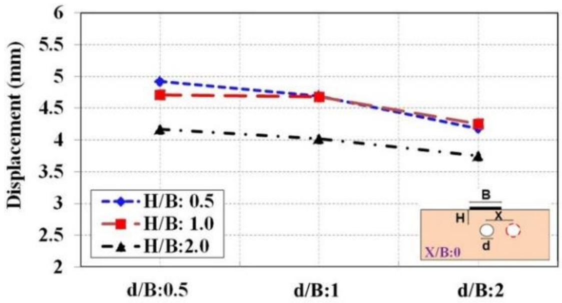
Figure 18. Comparison of the generated stress values in simulated tunnels **a:** X/B:0 **b:** X/B:2 **c:** X/B:8 **d:** total Comparison

So it can be concluded that the higher the overburden height, the greater the stresses caused by the dynamic loads of the earthquake on the tunnel wall. When the effect of the dynamic loading of earthquake forces is applied to the models, the depth of tunnel location is directly related to the overburden weight on the tunnel, and whatever this depth increases, the tunnel is placed under less stress.

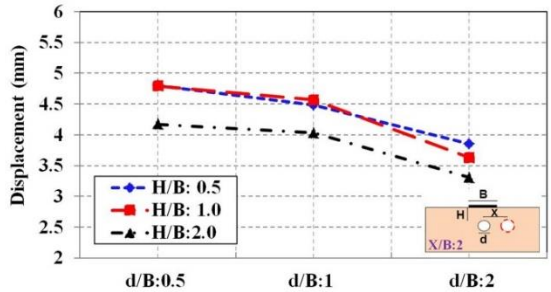
5. 3. Comparison of the Maximum Displacement Values in the Tunnel

The tunnel walls displacement values are compared in Figure 19. As shown in these diagrams, the tunnel lining displacement has been reduced by increasing the depth of the tunnel at all the different horizontal distances of the tunnels. For the case that the tunnel is located exactly along the center and at the bottom part of the foundation (X/B=0) and the diameter to width ratio of the foundation is equal to 0.5, the maximum displacement in the depth to width ratio of the foundation is approximately 5% lower than its corresponding value in the depth ratio to width of the foundation 0.5. On the other hand, according to Figure 19, it can be seen that by increasing the horizontal distance of the tunnel to the central axis of the foundation, the tunnels which have the same diameter to width ratio of foundation (X/B=1) carry lower displacements by increasing depth of location. Therefore, it can be concluded that when underground tunnels are exposed to dynamic earthquake loading, selecting the diameter of the tunnels can affect the displacement of the tunnel lining.

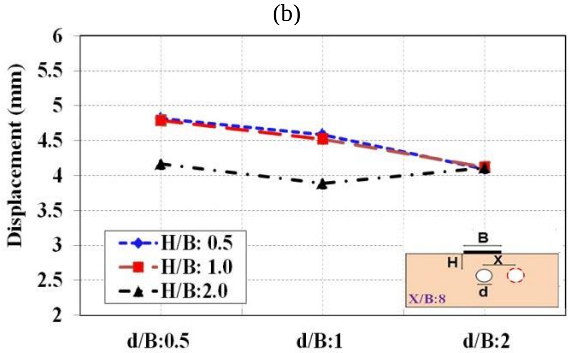
When the tunnel is located exactly along the center and at the bottom of the foundation (X/B=0) and the diameter to width ratio of the foundation is equal to 0.5, the maximum displacement generated in the depth-to-width ratio of the foundation 2 is 5 percent lower than its corresponding value in the depth to width ratio of 0.5. On



(a)



(b)



(c)

Figure 19. Comparison of the generated displacement values in simulated tunnels **a:** X/B:0 **b:** X/B:2 **c:** X/B:8

the other hand, according to Figure 19, it can be seen that by increasing the horizontal distance of the tunnel to the central axis of the foundation, the tunnels which have the same diameter to width ratio of foundation (X/B=1) carry lower displacements by increasing depth of location. This can be deduced when the underground tunnels are exposed to dynamic earthquake loading, selecting the diameter of the tunnels can affect the displacement of the tunnel lining.

5. CONCLUSION

In the present study, the seismic interaction between the surface foundation and underground cavities was investigated. For this purpose, a parametric study of the geometric dimensions of the foundation and cavity and their location and the effect that they can have on the interaction between surface foundations and underground cavities is evaluated using a finite element method. ABAQUS software was used for simulation. Variable parameters include the ratio of the overburden height to the foundation width (0.5, 1 and 2), the ratio of the cavity location to the foundation width (0, 2 and 8) and the ratio of the cavity diameter to the foundation width (0.5, 1 and 2). The most important results are presented below:

- Whatever the overburden height (depth of tunnel deployment) is lowered, the soil will become more vibrational under the influence of an earthquake, and its characteristics and parameters change, thereby increasing the acceleration applied to the tunnel lining.
- The horizontal distance of the tunnel towards the center of the foundation plays a significant role in the acceleration generated on the tunnel lining and when designing tunnels near urban areas, this should be taken into consideration.
- When the dynamic loading effect of seismic forces is applied to the models under investigation, the depth of the tunnel has a direct relationship with the weight of the overburden on the tunnel, and whatever this depth increases, the tunnel will be under less stress.
- Comparison of the displacement values generated in the tunnel walls shows that when the tunnel is located exactly below the central axis of the foundation (X/B = 0), the displacement of tunnel lining is increased by increasing depth of tunnel location. For the case where the tunnel is located exactly along the center and at the bottom of the foundation (X/B=0) and the diameter to width ratio of the foundation is equal to 0.5, the maximum stress generated in the depth to width ratio of the foundation 2 is approximately 2.13 times greater than its corresponding value in the ratio of depth to width of 0.5.
- By increasing the horizontal distance of the tunnel to the central axis of the foundation, the tunnels which have the same diameter to width ratio of foundation (X/B=1), carry lower displacements by increasing depth of location. So it can be concluded that when the underground tunnels are exposed to dynamic earthquake loading, selecting the diameter of the tunnels can affect the displacement of the tunnel lining.

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Persian Abstract

چکیده

در مطالعه ی حاضر به بررسی اندرکنش لرزه‌ای پی های سطحی و حفره های زیرزمینی پرداخته شد. برای این منظور با استفاده از مطالعه پارامتریک ابعاد هندسی پی و حفره و موقعیت قرار گیری آن‌ها و تاثیری که می توانند بر اندرکنش بین پی های سطحی و حفره های زیرزمینی داشته باشند، ارزیابی شد. متغیرها به ترتیب شامل نسبت ارتفاع روباره به عرض پی H/B (۰.۵، ۱ و ۲)، نسبت موقعیت قرارگیری حفره به عرض پی X/B (۲،۰ و ۸) و نسبت قطر حفره به عرض پی d/B (۰.۵، ۱ و ۲) می باشند. بارهای اعمال شده به صورت بار لرزه ای به کف مدل به صورت دینامیکی در نظر گرفته شدند. اعتبارسنجی روش اجزاء محدود به کار رفته، با استفاده از شبیه سازی یک مطالعه‌ی آزمایشگاهی مورد بررسی قرار گرفت و نشان داده شد که تحلیل عددی صورت گرفته، از تطابق خوبی نسبت به واقعیت برخوردار می باشد. مقایسه مقادیر تنش ایجاد شده در تونل های شبیه سازی شده نشان می دهد با افزایش ارتفاع روباره، تنش ایجاد شده برروی سطوح تونل به ازای تمامی مقادیر X/B (فاصله ی افقی تونل نسبت به پی) افزایش یافته است. بطوریکه به عنوان مثال در حالتی که تونل دقیقاً در امتداد مرکزی و در قسمت تحتانی پی قرار گرفته (X/B=۰) و نسبت قطر به عرض پی برابر ۲ می باشد، بیشینه تنش ایجاد شده در نسبت عمق به عرض پیِ ۲، حدوداً ۲.۱۳ برابر از مقدار متناظرش در نسبت عمق به عرض ۰/۵۰ بیشتر شده است. از این موضوع می توان به این نتیجه دست یافت که هر چقدر ارتفاع روباره بیشتر باشد، تنش های ناشی از بارهای دینامیکی زلزله بر جداره ی تونل ها بیشتر می شود. به عبارتی می توان بیان نمود هنگامی که اثر بارگذاری دینامیکی ناشی از نیروی زلزله بر روی مدل های مورد بررسی اعمال شود، عمق قرار گیری تونل رابطه ای مستقیم با وزن سربار وارده بر روی تونل دارد و هر چقدر این عمق بیشتر شود، تونل تحت تنش‌های کمتری قرار می گیرد.