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Investigating the Behavior of Underground Structures in the Event of an Earthquake

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***Abstract*—**The progress of technology and producing new machinery have made a big change in excavation operations and construction of underground structures. The limitations of space and some other economic, politic and military considerations gained the attention of most developed and developing countries towards the construction of these structures for mine, military, and development objectives. Underground highways, tunnels, subways, oil reservoir resources, fuels, nuclear wastes burying reservoir and underground stores are increasingly developing and being used in these countries. The existence and habitability of the cities depend on these underground installations or in other words these vital arteries. Stopping the flow of water, gas leakage and explosion, collapsing of sewage paths, etc., resulting from the earthquake are among the factors that can severely harm the environment and increase the casualty. Lack of sewage network and complete stoppage of the flow of water in Bam (Iran) is a good example of this kind. In this paper, we investigate the effect of wave orientation on structures and deformation of them and the effect of faulting on underground structures, and then, we study resistance of reinforced concrete against earthquake, simulate two different samples, analyze the result and point out the importance of paying attention to underground installations.

***Keywords*—**Earthquake, underground structures, underground installations.

I. Introduction

DURING the last few decades, a lot of studies were carried out to know the behavior of underground structures against earthquake. Generally, underground structures have more resistance than ground structures, so they experience less changes and destructions. So, many of developed countries insist on building and using these structures. These types of structures are designed and built in a way that they will have good resistance and strength against heavy static loads and side loads resulting from earthquake. That is why analysis of structure's behavior against earthquake has an important role in its design [6].

II. Studying the Effects of Earthquake on Underground Structures

A. Underground Structures

Underground structures are human-made structures which are built in the depth of the ground and surrounded by soil and stones. Considerable resistance and strength against earthquake is one of the characteristics of these structures. Lengthiness and full establishment in one or more layers of soil and stone have important role in design and resistance of underground structures against earthquake. Underground structures include tunnels, metro stations, warehouses, fuel & material reservoirs, harbors and canals and most people believe that underground structures are safe against earthquake. In some countries, harbors and strategic warehouses are built underground, in tunnels or metro stations. Japan, as a country where earthquakes occur frequently, is one of the pioneers in building and establishing underground tunnels. So, we can find a lot of reports and researches in this field prepared by Japanese engineers and researchers. One of the earthquakes, which attracted the attention of most experts because of great destructions, was Baotou earthquake (6.4 Richter) and Kobe-Japan in 1995, when underground installations and tunnels of this city were damaged and about 30 tunnels was destroyed [1]. The most important parameters that are taken into account in study of underground structures' destruction are as follows [6]:

- Shape, dimensions and depth of the structure
- Specifications and type of soil or stones surrounding the structure
- Specifications of structure
- Intensity of Earthquake

B. Case Study

In this section we will have a case study regarding the effects of earthquake on underground structures.

Bolus Tunnel- Turkey 2016

Bolo tunnel with the length of 3.2 km and width of 6 m is located in some part of Ankara-Istanbul highway and crosses North Anatolian Fault Zone. About 200-300 m of this region is covered with a kind of coarse clay and this layer of the soil surrounds the tunnel. All these cases and more than 720 mm deformation and density of clay around the tunnel were considered in design and execution of the tunnel. In the earthquake occurred in 1999 in Turkey with the intensity of 7.2 Richter as a result of displacement in the said fault, the mouth of this tunnel collapsed despite special strategies used in it.

Railway Tunnel- San Francisco, 1906

This tunnel was built between 1876 and 1880 and turned to a ruined tunnel in 1940. Its length is 1920 m and one of its mouths crosses San Andres fault for about 120 m. After San Francisco earthquake (7.7 Richter), this tunnel disjointed in two sides of the fault and the tunnel was closed for more than one year. After some studies in 1907, the engineers found that the tunnel should be reconstructed with displacement of 1.5 m.

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The fault displacement was between 2.5 to 4.5 m.

C. The Effect of Earthquake

The waves of earthquake have special parameters like frequency, center of earthquake, intensity and so on, the study of each is effective in determining the behavior of structure against earthquake. The effects of earthquake on underground structures are categorized in two general groups [5]:

a. Effects resulting from vibrations of earthquake
b. Effects resulting from faulting

1. Effects Resulting from Vibrations of Earthquake

The waves of earthquake are categorized in several groups, each has unique properties and has special effects on underground structures. The responses of underground structures to the waves of earthquake are deformations categorized in three groups: axial deformations, bending deformation, and hoop deformations.

a) Axial Deformations

Axial deformations, which occur as a result of impact of pressure waves with underground structure, cause deformations in the structure by creating pressure stresses and tensile stress. Stresses resulting from pressure waves of earthquake, when being large enough to go beyond the tolerance of designed concrete, can cause crazing and shelling in the walls of underground structures, and stresses resulting from tension can cause fractures and collapsing of structure's external layers into its internal layers. Studying pressure waves helps better understanding of this process.

Pressure wave (PW) is the speediest waves among earthquake waves. So, it is the first wave of the earthquake that influences the structure. As the vibrations of earthquake are elastic ones, so they produce tension and pressure when they strike the structures. In order to better understand this case, consider a spring that a wave has been produced in it. While going ahead in the length of the spring, it shrinks some part of the spring and this causes the part adjacent to the shrunk area to be elongated. This time cycle will continue until the wave completely passes the spring. Pressure is produced in spring as a result of compaction and tension is produced as a result of shrinkage which is observed as pressure stresses and tension stresses in structure. In case that these stresses will be more than the tolerance of the structure, they may have destructive and bad effects.

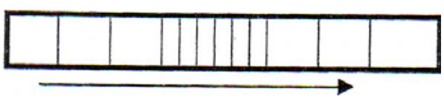

Fig. 1 Impact of pressure wave and axial deformation

These waves (pressure waves) cause axial deformations in underground structures and are categorizes in body waves group [2]. As we can see, the more the length of the wave striking the structure, the more the displacement occurring in the structure.

We can use the following formula in order to calculate the maximum axial stress, where ρ is the density, v is the initial velocity of wave (pressure wave), and Vw indicates the maximum velocity of a particle along diffusion of wave.

$$\delta= \rho\ v\ |VW| \quad (1)$$

b) Bending

Bending results from shear waves (S) along a structure. In case that these waves are diffused along longitudinal direction of the structure, shear stresses will cause great damages to the structures. These waves which are vertically applied on the length of the structure and, unlike P waves, they are diffused vertically. Even if they are diffused on the structure, diagonally or vertically, they still can cause deformation and destruction. Bending resulting from these waves in the structures is divided into two groups: positive bending, where concave direction is upward and negative bending, where the concave direction is downward. On the basis of these bindings, structures experience tension and compaction in upper and lower parts. For example, in a negative bending, the upper part is tensioned, and the lower part is compacted and if these stresses are higher than the tolerance of the structures they will cause serious damages in the structure. In designing tunnels and lengthy underground structures, the analysis of deformations resulting from two above-mentioned waves depends on extension of x-axis of the structure. What is obvious is that the wavelength of earthquake has an important role in the effects of these waves on underground structures. The maximum shear tension in an underground structure (as it was described above) is calculated from the formula below, with the difference that Vw is the velocity of wave's diffusion in vertical direction on x-axis of the structure and V is the velocity and S is wave velocity [6]:

$$\delta= \rho\ v\ |VW| \quad (2)$$

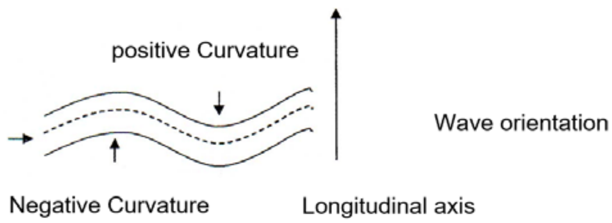

Fig. 2 Deformation because of wave orientation

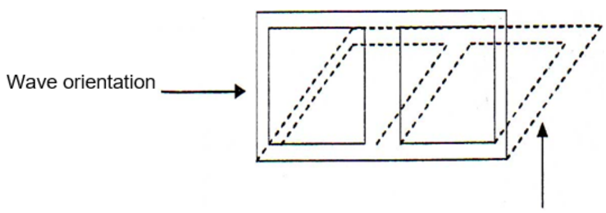

Fig. 3 Hoop deformation

c) Hoop Deformations

Hoop deformations occur when the waves of earthquake strike, vertically or approximately perpendicular with x-axis of the structure. This case occurs only when the wavelength of earthquake is less than the radius of underground space [3].

These waves produce shear stress when they strike structures. Fig. 3 shows the behavior of a structure against hoop deformations.

2. The Effect of Faulting on Underground Structures

Faulting is the main factor, which causes earthquake. Faults are lengthy areas where the layers of the earth are fractured and produced a zone. These fractures are often slant and are not vertical. So, in terms of weight, a plate is on another plate. Location and direction of these faults can be specified by looking at tectonic maps of the region [5].

Earthquake occurs as a result of geodynamic movements of the earth and its layers. Earthquakes occurs when a plate goes under another plate and the energy resulting from this displacement is released as the waves of earthquake. As some of underground structures are linear, so they may cross these faults and even in some cases it is inevitable. As displacement resulting from faulting is very destructive and the design of the structure should be such that they can resist against earthquake otherwise it will not be economical. It is not recommended to consider the direction of faults when designing and executing lengthy underground structures (like tunnels and metros) and underground structures should not cross the faults. On the other hand, studying the movements and displacement of faults can provide valuable information for engineers to help them to determine the amount of movement of faults (vertical or horizontal). For example, Bolu tunnel in Turkey in the earthquake of 2016 (7.2 Richter) was completely destroyed and in an earthquake in Kobe-Japan in 1995 (with the same intensity of Turkey's earthquake) Nujima fault moved 1.3 m in vertical direction and 1.8m in horizontal direction. Displacement of fault differs by increasing the depth of the fault and it is not the same throughout the fault.

Determining the amount of displacement and application of underground structure in structure design facing the fault is very important, such that a displacement, even a small one, has a very destructive role on some structures. While these displacements are of less importance in some other structures with different application, like canals. Displacements of some faults during earthquake are presented in the table below:

TABLE I
INVESTIGATION OF DISPLACEMENTS OF SOME FAULTS DURING EARTHQUAKES [1]

Place of Earthquake	Date	Intensity	Horizontal Displacement	Vertical Displacement
Kobe-Japan	1995	7.2	1.3	1.8
Kuli-Binabad	1979	7.1	2.25	3.8
Karizan-Khavaf	1979	6.6	-	0.6
Tabas	1978	7.7	-	0.7

When it is not possible to prevent the crossing of structure with fault, it is recommended to consider the following cases in structure design:

- Using flexible joints in crossing place
- Using intentional weak points to concentrate the damages resulting from earthquake
- Increasing the cross-section area at the amount of expectable displacement resulting from earthquake

D. Studying Resistance of Reinforced Concrete Against Earthquake [4]

Considering irrefutable role of reinforced concretes on construction of underground structures, in this section we will study deformations of reinforced concrete resulting from earthquakes.

After the earthquake on 1995 in Japan, Civil Engineers Association of this country carried out very extensive studies to analyze the behavior of reinforced concretes against earthquake. In these studies, earthquake was simulated on a piece of a concrete which was being examined.

Two samples of concretes, which were designed to tolerate the loading of 5000 kN, were considered in these experiments. One of these samples (a) with the dimensions of 3.0×1.75 was fixed on base plate of earthquake simulator machine and its surroundings were filled with a certain dry soil with the thickness of 4.75 m and the second sample (b) with the same dimensions and without fixing, between the same sample of soil and 1.5 m below the level of the system were studied (Fig. 4). The dimensions considered for the system are 4.75×11.6 m and the same around the concrete samples had a density of about 87% and minimum porosity of 1.091 and maximum porosity was 2.688.

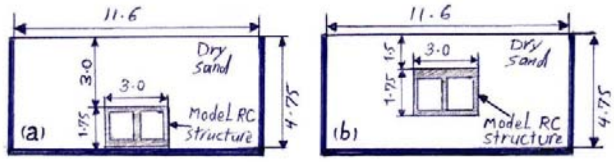

Fig. 4 Free Sample (b)- Fixed Sample (a)

The simulated wave on the sample in the middle of the depth of system being studied had the velocity of 180 m/s while it increased by increasing the depth from surface to the ground (0-200 m/s).

This experiment was planned from several simulations with different maximum accelerations, the description is offered in Table II.

TABLE II
RESULTING FROM SEVERAL SIMULATIONS WITH DIFFERENT MAXIMUM (cm/s^2)

Item	Fixed Sample	Free Sample
1	60	105
2	109	223
3	225	1041
4	1127	1044
5	477	596
6	531	1033
7	1126	-

The properties of samples being studied were such that they would be destroyed as a result of earthquakes simulation.

The thickness of side walls and upper surface was 10 cm and that of the lower surface was 30 cm and in order to put the steel used in concrete in yield position we used a kind of round bar with lowest elastic resistance (about 280 kPa). It should be mentioned that the designed concrete has the rigidity of 20% around the soil sample.

III. Conclusion

A. Results of Experiment

Plastic Deformations in Samples

The highest displacement in lower and upper parts of reinforced concrete samples was observed in strong vibrations. The usual displacement in the samples depends directly on displacement of soil surrounding them. Inside and outside of side reinforcements and bottom of side parts of free and fixed samples in earthquake simulation were measured at the accelerations of 1127 and 1041 m/s². A considerable amount of slope reductions which is called load proportion, is observable when the proportional displacement reaches at 4 mm. In this case, yielding of reinforcement was observed. It is necessary to refer to the method of determining the amount of background displacement (1). In order to determine the amount of background displacement in each experiment, two plates with certain distance are places in top and bottom of the mold. Displacement of these plates has a close relationship with displacement of background such that, by determining the displacement of these two plates, we can find the displacement of the background. The results of the experiment show that the proportion of displacement completely depends on deformations of the background between elastic and plastic states. Although in free sample, the phase between the order of displacement of sample and background was satisfactory, the reaction of background was relatively high.

With all these descriptions, common plastic deformations in non-fixed samples were the same. On the whole, there was no fracture in samples being studied, and the fractures resulting from bending were clearly observed in the top and bottom corners of the samples. Some fractures with deflections were observed in internal wall of the samples.

Studying the fractures showed that these fractures result from tensile stresses, which are probably as a result of dynamic pressures of the ground. One of the important results of these experiments is the direct effect of shear stress in upper plates and changing the shape of the structures.

B. Analyze of Experimental Data

The results obtained from the statistics of past destructions and experiments carried out in this regard showed that, despite what people assume, underground structures are susceptible against earthquake and can cause big damages in case of destruction. In this paper, we pointed out the importance of paying attention to underground installations during earthquake and analysis of earthquake waves and their effects on structures. We also described some experiments and their results and discussed about the importance of paying attention to the behavior of underground structures against earthquake.

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