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Mitigation of surface impact loading effects on the underground structures with geofoam barrier: Centrifuge modeling

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ABSTRACT

Studying the effect of dynamic loads on underground structures and applying mitigation strategies to reduce these effects are important for the safe design of these structures. In this paper, the effect of dynamic loading on an underground structure and the performance of geofoam as a barrier were investigated using centrifuge tests. Impact loading, created by blasting, was used as an example of dynamic loads. Two sets of centrifuge experiments were performed to study different mitigation systems. The first set of the experiments included two tests, one without a barrier and the other with a vertical geofoam barrier installed between the impact source and the underground structure. The second set of the experiments included the following three tests: a test with no barrier between the impact source and the underground structure; a test where a horizontal geofoam barrier existed near the source of the impact load; and another test where a horizontal geofoam barrier existed near the underground structure. The results of the tests confirmed the effectiveness of the geofoam barrier against dynamic loading effects and indicated that the barrier effect was more prominent when it was installed near the structure. This study also provided a better understanding about the effect of impact loading on underground structures and mitigation effects.

1. Introduction

Underground structures and utilities, including underground tunnels, subways, shelters, fuel supplies, silos, water supply and sanitation systems constitute the infrastructure and essential parts of modern cities. Operation of these structures and utilities during their service life and during emergency conditions is very important. Compared to surface structures, underground structures are considered to be less vulnerable during natural disasters like earthquakes, and low risk against seismic loads (Kusakabe et al., 2008). However, these structures may be vulnerable against dynamic loads, such as traffic loads (car, high speed train), machine foundations, pile driving and blast loading. These loads are exerted on underground structures in the form of vibrations. Characteristics of various vibration sources are illustrated in Fig. 1 (Itoh, 2003). Despite the differences observed in the vibrations caused by various dynamic loads, the energy that causes vibrations in the soil medium is due to a transmission of elastic waves. It can thus be said, ground vibration mitigation methods are the same for different vibration sources.

Traffic loads and machine foundations generate a mixture of body and surface waves, which are mainly composed of Rayleigh waves with an influence depth of approximately one wavelength (Miller and Pursey, 1955; Woods, 1968; Kim and Lee, 2000). These loads affect surface and shallow underground structures. In this regard, many researchers have investigated mitigation methods to decrease the effects of these types of dynamic loads. They have used mitigation procedures such as open trenches and in-filled trenches as barriers against vibrations.

To mitigate the vibrations induced by a machine foundation, Woods (1968) used an open trench in the vicinity of the applied load (active isolation) and near the structure (passive isolation), in the field tests. He concluded that a significant percentage of surface waves could be dampened by the trench system. Using a multiple ball dropping system and a vibration testing system in the centrifuge, Itoh et al. (2002, 2005) simulated wave generation and propagation from a surface ground vibration source to model high speed railway vibrations. They also studied the effects of various geometries and types of barriers on the vibration reduction and concluded that one, softer barriers were generally more effective than stiffer barriers and two, the geometry of the barrier significantly influenced the motion of the barrier. Murillo et al. (2009) used centrifuge modeling to study the effect of barrier parameters, such as geometry (i.e. depth and width of the barrier) and distance of the barrier from the loading source on the attenuation of traffic loadings (trains or heavy vehicles). Alzawi and El Naggar (2011)

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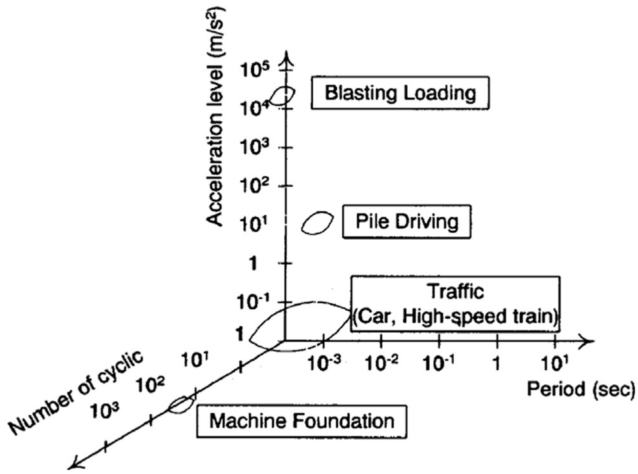

Fig. 1. Characteristics of various vibration sources (Itoh, 2003).

used open trenches and trenches filled with polyurethane foam in the field tests to reduce the effects of machine foundations. They investigated the barrier parameter effects, including the trench geometry and the trench distance from the dynamic load source.

Vibrations induced by blast loading propagate deeper than other dynamic loads and, hence, could affect even deep underground structures. Blast loading can generate significant body waves (P and S waves), and transmit the main energy of vibrations induced by blast loading through compression waves (Kim and Lee, 2000). Blast loading is commonly used to excavate rock and soil material in mining and tunneling projects. Soil improvement by blasting near dam foundations may also have some effects on underground utilities around these structures. Therefore, investigation into the effects of blast loading on underground structures is useful in their design. The methods used to investigate the effect of blast loading on underground structures are categorized as: field experiments, physical modeling by centrifuge tests, and numerical studies. Field experiments are costly, dangerous and can cause environmental problems. Wu et al. (2003), Ishikawa and Beppu (2007) and Lee et al. (2016) used field experiments to investigate the effects of blast loading. Wu et al. (2003) provided the results of in-situ tests conducted at a site in Sweden. In the tests, the blast was conducted in an underground structure, and the propagation of stress waves were recorded inside the rock, the rock-soil interface and the soil surface. Ishikawa and Beppu (2007) presented previous experimental works conducted by Professor A. Johoji. Among the issues investigated in the field research were the effects of blasts on straight, branch, and mesh type tunnel shelters. Lee et al. (2016) introduced a pre-cut discontinuity around a tunnel to investigate the possibility of vibration mitigation during blast tunneling.

Considering the significant improvements of numerical modeling in recent decades in geotechnical engineering, studying the effects of blast loadings on underground structures is now possible using numerical methods. Although numerical studies are cheaper and easier than field experiments, their results should be verified by experimental or field study results. Lu et al. (2005), Gui and Chien (2006), Wang et al. (2009), Shin et al. (2011), Feldgun et al. (2014) and De et al. (2016) numerically studied the effects of blast loadings on underground structures.

Centrifuge modeling is an appropriate method to investigate geotechnical phenomena such as blast loading and its effects on underground structures. Such tests are relatively safe, inexpensive and reliable. In centrifuge testing, the effect of a large amount of explosives can be modeled with only a small amount of explosives. Kutter et al. (1985, 1988), Tabatabai (1987), Davies (1994), De and Zimmie (2007) and De et al. (2016) used centrifuge modeling to investigate the effects of blast loading on underground structures. Among these studies, Davies (1994), De and Zimmie (2007) and De et al. (2016) studied different methods to reduce the blast effects on underground structures. They used a barrier between the loading source and the underground structures to reduce the blast effects, which is similar to a research on reducing vibrations induced by trains and machine foundations. Davies (1994) used both open and in-filled trenches (filled with polystyrene foam, reinforced concrete and a composite barrier composed of polystyrene foam and reinforced concrete) as a barrier against blast loading. He concluded that open trenches perform best in reducing blast-loading effects, but may not be an appropriate method to reduce blast loading effects due to stability and maintenance issues. De and Zimmie (2007) and De et al. (2016) used polyurethane geofoam as a barrier against blast loading. The underground structure used in their tests was an underground tunnel model. The surrounding of the tunnel was covered with polyurethane geofoam. These researches demonstrate the benefits of polyurethane geofoam as barrier against the surface explosion to reduce the effects of explosion on underground tunnels.

The previous studies confirm the effectiveness of a barrier in soils to reduce the vibrations caused by dynamic loads (blast loading, high speed railway, pile driving and machine foundations). In this paper, blast loading is modeled in centrifuge tests in order to study the effect of impact loads on underground structures. In order to mitigate the blast loading effect on underground structures, a barrier softer than soil media (geofoam barrier) is chosen. A geofoam barrier is located at different distances and arrangements toward the underground structure.

2. The centrifuge tests

The mechanical behavior of soil is nonlinear and stress-strain dependent. In order to accurately simulate a small-scale model in a centrifuge, the stress-strain behavior of the prototype should be reproduced appropriately in the model. For developing the same stress conditions both in the model and prototype, a model is constructed with dimensions N times smaller than the prototype's. The sample is then rotated with angular velocity (ω) in the centrifuge. Therefore, a radial acceleration ($r\omega^2$, r = radial of centrifuge) equal to Ng (g = acceleration of gravity) would be applied to the model, and the stress conditions produced in the centrifuge model are the same as the prototype stress regime. Considering the linear relation ($1/N$) between the model and the prototype dimensions, displacement would be scaled by the factor $1/N$. Therefore, the strain in the model and prototype would be the same. It can be concluded that the stress – strain curve, mobilized in the model, is exactly equivalent to the prototype curve. Various parameters used in the centrifuge modeling are scaled based on a dimensional analysis. Scaling laws for the related parameters of this research and for some main parameters of the centrifuge modeling are presented in Table 1.

In this research, five centrifuge tests were conducted using a centrifuge machine in the Geotechnical Engineering Research Center (GERC) of Iran University of Science and Technology (IUST). Two sets of experiments were performed in the centrifuge to study different

Table 1
Centrifuge Scaling law for related parameters of this research.

Parameter	Prototype	Model
Length	N	1
Stress	1	1
Strain	1	1
Force	N^2	1
Displacement	N	1
Velocity	1	1
Acceleration	1/N	1
Dynamic time	N	1
Energy	N^3	1
Mass	N^3	1
Flexural stiffness	N^4	1