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Numerical and physical modeling of geofoam barriers as protection against effects of surface blast on underground tunnels

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ABSTRACT

An explosion on the ground surface may cause significant damage to an underground structure, such as a tunnel or a pipeline. The extent of damage would depend on the intensity of blast, the material and configuration of the structure, as well as the nature and geometry of the intervening material.

An underground structure may be protected by means of a protective barrier, installed directly above the structure. The effectiveness of using a compressible barrier, made of polyurethane geofoam, to mitigate the effects of surface explosion was investigated.

The effects of a surface explosion were studied through a combination of physical model tests and numerical modeling. Reduced-scale (1:70 scale) physical model tests were conducted using a geotechnical centrifuge, where the scaling law for explosions was utilized to model the effects of a large explosion using a relatively small mass of explosives under a high gravitational field (70 *g*, in this case). The results of the physical model tests were used to calibrate a three-dimensional numerical model in which a fully-coupled Euler–Lagrange solver was utilized to model the explosions.

Tunnel configurations with and without protective barriers were studied to assess the mitigation provided by protective barriers. Material properties for polyurethane geofoam barriers were evaluated from laboratory tests. The influence of barrier thickness in reducing the strains, stresses, and pressures on the tunnel induced by an explosion was studied. The beneficial effects of a protective geofoam barrier were found to increase with increasing barrier thickness only up to a certain thickness, beyond which, further increase in thickness did not result in additional reductions. The results will help in design optimization, while planning protection systems for new tunnels, as well as for retrofitting existing tunnels.

1. Introduction

Anthropogenic explosions pose a threat to many components of the transportation infrastructure. Underground structures, such as tunnels and pipelines are vulnerable to explosions that may occur both above and below the ground. The extent of damage depends on the characteristics of the structure and those of the intervening subsurface deposit, as well as the nature of the explosion.

While the threat of underground explosions can generally be mitigated through carefully controlled access into tunnels, it is more difficult to prevent explosions that are set off on the ground surface. Therefore, it is important to evaluate the damage potential of various sizes of explosive devices set off on the ground surface with the intention to cause harm to underground structures, such as transit tunnels and pipelines.

The effects of explosions on geotechnical media and structures may be studied through physical model testing as well as through numerical modeling. Full-scale physical tests provide the most direct assessment of the effects, but are also the most difficult to conduct due to logistical and safety concerns. For these reasons, full-scale tests using explosives are typically not conducted in the civilian sector. In contrast, numerical modeling of explosions must rely on careful calibration with physical tests before the results are considered acceptable in design.

In this paper, the effects of surface blasts are studied through a combination of numerical modeling and reduced-scale physical model tests conducted on a geotechnical centrifuge. First, the

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concept of centrifuge scaling related to the effects of an explosion is explained, followed by a description of the physical models and instrumentation. Next, the basic components of the numerical model are presented and material properties selected for use in the model are discussed. Lastly, results from the physical model tests and numerical models are analyzed and compared. An essential component of the model, which is of key interest to this paper, is the use of a protective geofoam barrier to mitigate the effects of a surface explosion.

2. Principle of centrifuge modeling of explosions

The effects of an explosion under high gravity, such as those experienced on board a geotechnical centrifuge, follow the Hopkinson (or cube-root) scaling law (Baker et al., 1973). Thus, the shock waves created at two different scaled distances by two explosive charges, having the same geometry and type of explosive but different quantities of charge, would scale as the cube-root of the weight of explosives. Conversely, if two explosions produce similar shock waves, their weights will vary by the cube of the distance.

This relationship makes geotechnical centrifuge modeling a viable method for conducting experiments to study the effects of explosions on geosystems. A relatively small amount of charge may be used in a reduced-scale (1:N scale) centrifuge model, which is tested at a high gravity: N times *g*, where *g* is the normal gravitational acceleration (9.8 m/s^2). The effects of the explosion, in terms of cratering and damage caused by shock wave, will be proportional to those caused by a much larger quantity of explosive under earth's normal 1 *g* gravity. In fact, according to the cube-root relation, the effects of the explosion on the centrifuge model will be proportional to the full-scale effects due to a quantity of explosives that is N^3 (N raised to the third power) times the weight of explosives used in the experiment (Goodings et al., 1988; Kutter et al., 1988).

For example, the tests described in this paper were conducted on a 1:70 scale model, subjected to a centrifuge acceleration of 70 *g*. Thus, for the purpose of these tests, N = 70. Therefore, the effects of explosion, such as cratering and shock waves, were the same as those created at normal gravity by an amount of explosives that is $(70)^3$ times, i.e., 343,000 times greater. Taking advantage of this scaling law makes handling and testing of centrifuge explosion tests logistically less challenging than full-scale tests.

Several researchers have demonstrated the advantage of utilizing a geotechnical centrifuge to model explosions and have shown that centrifuge scaling of characteristics, such as soil grain size, etc. do not affect the results related to explosions (Goodings et al., 1988; Kutter et al., 1988). Based on results of over 100 tests, conducted at *g* levels between 1 *g* and 100 *g*, Goodings et al. (1988) concluded that centrifuge tests provided a valid method of modeling the effects of explosion on soil. Kutter et al. (1988) and Davies (1991) studied the effects of explosions on underground structures through centrifuge model tests. Liu and Nezili (2015) reported results of centrifuge tests where a tunnel buried in saturated soil was subjected to internal explosion. Jayasinghe et al. (2013) reported on comparison between centrifuge test results and numerical simulation to study the effects of an underground blast on piles in saturated soil.

3. Description of centrifuge model

The centrifuge tests were conducted on a 150 *g*-ton geotechnical centrifuge at Rensselaer Polytechnic Institute, located in Troy, New York. The model consisted of a cylindrical tunnel located inside a dry sand subsurface. The sand used in the tests was Nevada #120 sand, characterized extensively during prior geotechnical research programs and published by Arulmoli et al. (1992). The sand was placed dry at a uniform unit weight of 15.7 kN/m^3, which corresponds to a relative density of approximately 60%.

The model underground structure consisted of a 760-mm long copper pipe with an outer diameter of 76 mm and a wall thickness of 2.5 mm. Linear dimensions, such as diameter and thickness, scale directly in proportion with acceleration level. At 70 *g* acceleration, the model represented a prototype with an outside diameter of 5.5 m, wall thickness of 0.133 m, and flexural stiffness (EI) of 13×10^6 kN m^2. The length of the prototype structure was 53 m, based on a 760-mm long model tested at 70 *g*. In the numerical model, a 54-m long structure was simulated.

No specific prototype condition was modeled in the analyses reported here; rather, the characteristics of a wide range of prototype structures were studied and a model was selected such that it represents the behavior of a generic prototype structure. Further discussions on this are provided in De and Zimmie (2007). Fig. 1 shows the typical model configuration used in these tests.

Each model structure was instrumented with up to 19 strain gages to measure axial and circumferential strains at different locations. Strain gage measurements were acquired in real time during the tests and saved at a rate of 15,000 data points per second (15 kHz) for each strain gage. The high rate of data acquisition ensured that the relatively short peak, reached instantaneously after the explosion, was captured with sufficient resolution.

In each explosion, 2.6 g of TNT equivalent of explosive was used. According to the centrifuge scaling relations, this corresponded to approximately 900 kg of TNT equivalent under a normal 1 *g* environment. The charge was located on the ground surface along the mid-section of the model structure, as shown in Fig. 1. The inner surfaces of the aluminum sample container were lined with corrugated cardboard in order to dampen the shock waves and minimize reflected energy returning to the structure. Strain gage measurements (presented later in the paper) indicate that there was no measurable indication of reflection from the container.

Further details of the centrifuge model are described by De and Zimmie (2007).

4. Protective geofoam barrier

The object of the study described in this paper was to assess the effectiveness of a protective geofoam barrier in mitigating the effects of an explosion. A compressible barrier consisting of a layer of polyurethane foam was utilized. The geofoam barrier was in the form of a semi-circular, cylindrical shield, placed directly in contact with the top half of the tunnel, as shown in the transverse section in Fig. 1.

Fig. 2 shows a photograph of the model tunnel with a compressible protective geofoam barrier. In this particular model, the geofoam barrier has a thickness of 19 mm (0.75 inch) in model scale, which corresponds to a thickness of 1.33 m in prototype scale at 70 *g*.

Results from tests with a compressible geofoam protective barrier configurations are compared later in this paper with tests where no barrier was used, to evaluate the relative effectiveness of this kind of geofoam barrier. Comparisons between a compressible and rigid barrier were presented by De et al. (2013).

4.1. Compressible barriers

Compressible porous inclusions, such as geofoams, are widely utilized in geotechnical engineering in applications where a reduction of pressure under static condition is required. Such inclusions, when placed behind earth retaining structures, beneath foundations, and above pipelines and tunnels, compress readily