Physical Modeling of Explosive Effects on Tunnels

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ABSTRACT

Physical modeling utilizing a geotechnical centrifuge was done to study the effects of explosions on underground tunnels. Centrifuge modeling allows the study of the effects of a large explosion on prototype scale, through experiments using smaller explosives, using scaled models of actual structures. Blasts scale to the third power of gravity (g). For example a one gram charge in a model subjected to 100 g’s is equal to a ton of prototype (full scale) explosives.

Scaled models of tunnels were tested in a geotechnical centrifuge under various conditions. The tunnels were tested at different burial depths, and tunnels were tested using protective coatings around the tunnels to attempt to mitigate the effects of blasts. Tests were also conducted in dry soil as well as underwater, for example a river bed. The effects of the explosions on the structures were recorded in the form of strain measurements taken at different locations on the underground structures at different times-before, during and after the explosions.

The results of the experiments provide valuable understanding of the effects of surface explosions on underground structures such as tunnels and pipelines. The results are useful for designing new underground structures as well as for developing protective retrofits for existing structures. The results can also be useful for developing, validating and calibrating numerical models.

KEYWORDS: explosions, centrifuge, physical modeling

INTRODUCTION

Terrorist explosions have the potential to cause significant damage to tunnels. The extent of damage depends on various factors, such as the size and type of explosives, the distance of the tunnel from the explosives, the nature of the intervening medium between tunnel and the explosives, and the properties of the tunnel. Explosives have the potential for causing maximum damage, when the explosives are in close contact with the target structure. However, the act of implanting explosives on the body of a tunnel is more likely to attract attention of alert surveillance units. On the other hand, it is more difficult to detect and deter the use of explosives on the ground surface (e.g., in a parked vehicle) immediately above a tunnel. The motivation of this study was to understand the impact of surface explosives in causing significant damage to underground tunnels.
GEOTECHNICAL CENTRIFUGE MODELING

Physical model tests using a geotechnical centrifuge were utilized in this study. Centrifuge modeling is used to study a wide range of geotechnical problems, such as those related to slope stability, foundations, retaining structures, underground structures, liquid migration through soil, and seismic effects. A geotechnical centrifuge allows small-scale model testing to simulate the same physical behavior in the soil as in full-scale prototype tests. This is possible when the model is constructed to 1/N scale and is subjected to an acceleration of N g (where g is the normal gravitation acceleration) and the mass density of the material in the prototype and the model are the same. Figure 1 compares the vertical stresses at different locations of a prototype and a 1/N scale centrifuge model. It can be seen that the stresses are equal at corresponding points in the prototype and the model.

Figure 1. Centrifuge Modeling Concept

The tests reported here were conducted on a 150 g-ton machine located at Rensselaer Polytechnic Institute (RPI) in Troy, New York. This machine is capable of testing soil models of up to 1.5 ton (3300 lb) weight at accelerations of up to 100 g. Figure 2 [1] shows a schematic view of the RPI centrifuge, which was used in the present study.

Figure 2. Schematic of Geotechnical Centrifuge (from [1])
Various parameters used in geotechnical engineering scale to different powers of $N$, depending on scaling relations, which can be derived from dimensional analyses. Table 1 from [2] presents the centrifuge scaling laws for common parameters.

**Table 1. Centrifuge Scaling laws (from [2])**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model Value where Prototype is 1.0</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$1/N$</td>
<td>m</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$N$</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>Velocity</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>Volume</td>
<td>$1/N^3$</td>
<td>m$^3$</td>
</tr>
<tr>
<td>Mass</td>
<td>$1/N^3$</td>
<td>kg</td>
</tr>
<tr>
<td>Force</td>
<td>$1/N^2$</td>
<td>N</td>
</tr>
<tr>
<td>Pressure</td>
<td>1</td>
<td>kPa</td>
</tr>
<tr>
<td>Dynamic Time</td>
<td>$1/N$</td>
<td>s</td>
</tr>
</tbody>
</table>

**CENTRIFUGE MODELING OF EXPLOSIONS**

**Background**

An explosion is fundamentally a volumetric phenomenon [3] and it has been established that the effects of a blast are related to the third power of the gravitational acceleration involved, i.e., related to effects of an explosion scale as $g^3$. Weight is the product of mass and gravity and a smaller mass of explosive in the model, subjected to a proportionately higher gravitational acceleration will have the same effects as a full-scale prototype explosive, detonated under the earth’s normal gravitational acceleration. Previous researchers have reported on the scale effects of blasting, utilizing dimensional analyses and centrifuge modelling in [4], [5], and [6].

This scaling relation indicates the applicability of using centrifuges for modeling blasting. A relatively small quantity of explosives can be used in centrifuge test, on relatively small-scale models (e.g., 1/100 scale) at high g levels (e.g., 100 g) and produce the effects of a significantly larger explosion. Physical tests using explosives on full-scale models are rare – due to safety concerns and financial reasons.

Numerical model analyses are sometimes used. However, they require sophisticated numerical tools and need to be validated and calibrated against physical test results, before such numerical methods can be used to give reliable results. Physical model tests using a geotechnical centrifuge provide opportunities to validate numerical results. In addition, they also allow designers to conduct parametric analyses and compare effects of alternative designs.

The dry centrifuge tests reported in this paper all utilized models constructed to 1:70 scale and were all conducted at 70 g, on board a 150 g-ton geotechnical centrifuge located at Rensselaer Polytechnic Institute, Troy, New York. In each test, charges with TNT equivalent of approximately 2.6 grams.
were utilized under 70 g acceleration. Following the centrifuge scaling relationship mentioned previously, this amount of charge created the same effects as 888 kg or 8.7 kN of TNT equivalent under normal gravity.

The submerged trials were constructed and tested on the RPI geotechnical centrifuge. The models were built at several scales and subjected to corresponding accelerations such that the prototype scale was preserved but the mass of the explosive differed. Coupled with several charge sizes, this allowed for an expanded experimental data set for TNT equivalents under normal gravity.

**Centrifuge Model Tests on Tunnels in Dry Soil**

The effects of a surface explosion on an underground structure were studied through centrifuge tests conducted at 70 g. Further details on this study were presented in [7]. According to the centrifuge scaling laws discussed previously, the model tested at 70 g represented a prototype structure with an outer diameter of approximately 5.5 m, which is representative of a relatively small underground road or transit tunnel. It may also represent a large diameter pipeline, such as is used for fuel and water conveyance over long distances.

The purpose of this study was to investigate the impact of surface explosions on underground structures. No specific prototype structure was modeled in this study; rather the model characteristics were selected to represent the behavior of an “average” structure.

The model structure was 0.6 m long and supported over a uniform layer of dry sand compacted to a unit weight of 15.7 kN/m³, which corresponds to a relative density of about 60%. The same sand was also backfilled around the structure and over the crown, to provide a soil cover extending to the ground surface. The entire setup was placed inside an aluminum model container with outside dimensions of 0.37m × 0.88m × 0.39m. Schematic views of the experimental setup are shown on Figure 3.

In each test two exploding bridgewire (EPW) RP-830 charges were exploded simultaneously. The TNT equivalent of explosives used in each test was 2.6 grams. Since the effects of an explosion scale in proportion to the third power of the acceleration level, 2.6 grams of explosives used in each test under a 70 g gravity field produced the same effects as 8.7 kN or 0.9 tons of explosives under 1 g gravity.
Centrifuge Model Tests on Submerged Tunnels

The effects of varying charge sizes on a submerged underground structure were studied through centrifuge tests. The prototype dimensions of the model were held constant throughout the study. The scale of the models, corresponding acceleration and actual explosive mass were varied in order to obtain data for several TNT equivalent masses. In accordance with the dry trials, the submerged structure was general and envisioned as an average representation of a field structure. Gravel was utilized as the soil medium in order to facilitate saturation of the models.

Instrumentation

In tests on dry and submerged soil, strain gages were used to measure the strains induced at different portions of the model structure due to the explosion. Strains were measured using up to 19 strain gages, installed at different locations along the circumferential and the axial directions at the mid span, as well as the two quarter spans of the structures. In addition, only circumferential strains were measured at the two ends.

The strain gage data were obtained at a frequency of 15,000 points per second (15 kHz) using an on-board data acquisition system. This relatively high rate ensured that the effects of the explosion were captured with sufficient resolution.

Centrifuge Modeling of Crater Formation

The crater formed on the ground surface due to an explosion has different definitions. A true crater is one that is formed by the initial detonation. Following the explosion, the material that is uplifted from the crater area, as well as from the surrounding ground, is deposited back into the newly-formed crater. These materials are termed ejecta and fallback. The final resultant crater, after ejecta and fallback has deposited in the crater, is termed the apparent crater. The dimensions of a crater measured after an explosion has occurred are those of the apparent crater. It is almost impossible to make a direct physical measurement of a true crater.

It is noted in [5] that an explosion causes damage to underground structures through two principal mechanisms. The first is through a direct loading by a shock wave created due to the explosion. The second mechanism of damage is large soil displacements in and surrounding the crater. The effects of these mechanisms were studied in this research through readings of strain gages installed at various locations of the underground structures that were monitored and acquired in real time, before, during and after each explosions and through measurements of apparent crater dimensions after each explosion.

At the end of each dry test, a symmetric, circular crater was formed as a result of the explosion. The size of the crater was measured in three-dimensional coordinates using a profilometer. It should be noted that the measurements were taken for the apparent crater, i.e., the crater that was observed at the end of the test. The crater initially formed during the explosion, the true crater, is deeper than the apparent crater. In the tests on dry soil, the average crater had a diameter of approximately 12 m and maximum depth of approximately 1.25 m, both in prototype scale.

In the submerged explosive trials, the blast energy caused the compact gravel to heave and produce a symmetrical mound at the point of detonation. Figure 4 illustrates the soil heave as a result of detonation. The white string in the photograph shows the contour of the ground surface.
Influence of Cover Thickness and Cover Material

The model tunnel was buried with a cover thickness of 1.8 m or 3.6 m (both in prototype scale) in the tests on dry soil. The intervening material placed between the ground surface and the tunnel was either soil, or a combination of soil and a compressible geofoam barrier. The compressible geofoam barrier was in the form of a spray-on polyurethane expanding polyurethane foam sealant. The geofoam was used to study the effectiveness of a compressible inclusion barrier layer between the source of explosion and the structure in reducing the impact of surface explosions.

RESULTS OF CENTRIFUGE TESTS

Strains Induced on Dry Tunnels

The distribution of strains within the underground structure was studied by comparing the strains measured at different locations due to the explosion. In different tests, the following parameters were varied, as follows:

- Thickness of soil cover above the structure: 1.8 m or 3.6 m (in prototype scale)
- Material around the structure: either soil, or soil along with a 0.9 m (in prototype scale) thick layer of geofoam

As expected, the results indicated that a thicker soil cover was more protective of the structure. The axial strain measured at the quarter span was reduced by approximately 40% when the thickness of the soil cover was increased from 1.8 m to 3.6 m (both in prototype scale). This is shown in Figure 5, where plots of axial strain measured on the top of the structure at quarter span are presented. The peak strains induced due to the explosions were found to be two to three orders of magnitudes greater than those under static overburden stress prior to the explosion.
The possible attenuating effects of a compressible inclusion material immediately around the underground structure were studied by placing a layer of polyurethane geofoam material around the model structure. The structure, coated with a 0.9-m thick (in prototype scale) of this geofoam was then placed in dry sand, compacted to the same relative density as in the other tests. A total cover thickness of 3.6 m (2.7 m of soil and 0.9 m of geofoam) was provided.

The results indicated that the presence of geofoam appeared to reduce the axial strain induced on the structure due to the explosion by approximately 64%. This can be seen Figure 6, where plots of axial strain measured on the top of the structure at quarter span are presented. It is noted that the same total thickness of material equal to 3.6 m (in prototype scale) was used in these two tests. Therefore, the reduced strain can be attributed to the presence of the compressible geofoam, in lieu of the less compressible soil of the same thickness.

Figure 6. Effects of cover materials on axial strains measured at quarter span, subjected to surface explosion
Strains Induced on Submerged Tunnels

The submerged testing was performed in order to measure the response of a buried structure to several explosive masses. The results of two trials are shown in Figure 7. The data is filtered and normalized to emphasize the non-linear relationship between charge size and strain. The time scale is modified to reflect the temporal aspects for a full-scale equivalent.

![Figure 7. Filtered axial strains measured at quarter span subjected to submerged surface charges](image)

**CONCLUSIONS**

Centrifuge testing provides a viable method to model the effects of explosions on underground structures. Centrifuge scaling relationships for explosion effects make it possible to model relatively large explosions, while using small quantities of explosives in the tests.

Results of tests reported here indicate that significant strains can be induced on underground structures due to explosions on the ground surface. Tunnel designers can compare the induced strains measured in the tests to the material properties of the underground structures to determine if structural damage is likely.

Results of centrifuge model tests can be used to verify and calibrate numerical models which are sometimes utilized to study the effects of explosions. The generally high costs and risks associated with full-scale field tests make centrifuge model tests attractive alternatives in this regard. The magnitudes of strains induced in the structure due to explosions depend on the nature and thickness of the intervening medium between the structure and the explosion. Tests on two different thicknesses of soil are reported here. As expected, induced strains reduce with increase in cover thickness.
Results of tests in which a polyurethane geofoam cover was installed around the structure indicate that the presence of a compressible inclusion barrier, such as geofoam, may have some beneficial effects in mitigating the impact of an explosion. This aspect may have practical significance in the design of underground structures which are made more resistant to explosions.

Testing of submerged structures yielded important considerations for the design of such systems. Blast energy is amplified and localized when compared to dry conditions. The gravel medium heaved in response to the explosions and produced a circular mound in the area of detonation.

REFERENCES


