MODELING THE GEO-HAZARD EFFECTS OF SURFACE EXPLOSIONS ON EMBANKMENTS AND UNDERGROUND STRUCTURES EMPLOYING THE GEOTECHNICAL CENTRIFUGE

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Abstract: Explosions on the ground surface, produced by terrorist activities, represent a critical source of geo-hazard. Such events can cause significant damage to structures located on or close to the ground surface. The extremely transient nature of such blast loads, together with the mechanism of crater formation and transfer of a blast excitation through soil, makes it a challenging task to model such events.

Centrifuge model testing offers a unique opportunity to study soil-structure interaction phenomena using reduced scale physical models, subjected to high gravity. Thus, a relatively small mass of explosives can be used under a high gravity, to model the same effects as produced under normal gravity when a much larger quantity of explosives is used.

The paper studies the geo-hazards due to surface explosions on earth embankment dams and underground structures. The tests on the model earth dams investigated the effectiveness of a surface blast located on the crest of a dam in causing a breach. The results indicated that larger craters were produced when the soil in the dam was under saturated conditions, as opposed to dry conditions. The craters produced were sufficiently large to breach the dam when the upstream water level was high.

The tests on underground structures investigated the levels of strain that a surface blast could induce on an underground structure (such as a tunnel or a pipeline) located at some depth underground. Strain measurements recorded during the tests indicate that significant strains (both axial and circumferential) may be generated on the body of an underground structure due to surface explosions. The presence of a compressible inclusion barrier immediately outside the structure can reduce the strains induced by an explosion.

The tests reported in this paper were not intended to model conditions on any specific structure; rather the properties selected for the models were “generic” in nature, meant to provide a general understanding of the phenomena.

I INTRODUCTION

Explosions produced by terrorist activities have the potential of causing significant damage to many components of civil infrastructure. The extent of damage to the structures depends on the distance as well as the properties of the material through which shock waves, produced by the explosion, travel. Explosions have the maximum potential for causing significant damage when the explosives are either embedded within or have intimate contact with the target structure.

The process of implanting explosives in the ground by terrorists and detonating an underground explosion require elaborate preparation. The potential for such explosions can be reduced through
vigilant security surveillance around sensitive structures. However, the potential for a surface explosion, such as one caused by a mobile container (e.g., a truck or a bus laden with explosives) is more difficult to deter. Such explosions require shorter preparation time and can avoid scrutiny by using vehicles commonly used in everyday transportation.

This paper discusses the geo-hazard effects of surface explosions on two types of structures, namely earth embankments (such as dams and levees) and underground structures (such as tunnels and pipelines). In the case of an earth dam or levee, detonation of explosives located at the crest of the structure can produce a crater which can breach the earth embankment and cause flooding in low-lying downstream areas. An explosion on the ground surface near the location of an underground tunnel or pipeline can induce substantial strains on the structure, which may significantly damage or fail the structure.

Study of the geotechnical effects of surface explosions poses special challenges. Full-scale field tests provide the most reliable results, but are also expensive and risky to undertake. Numerical simulation provides a safe means of modeling different configurations. However, numerical modeling of blast effects is extremely complex and requires sophisticated techniques and calibration with physical measurements before they may be utilized in practice.

Physical model tests, utilizing a geotechnical centrifuge, provide an opportunity to study the effects of explosions using relatively small quantities of explosives, taking advantage of centrifuge scaling laws, discussed in the next section.

II GEOTECHNICAL CENTRIFUGE MODELING

A. Background

Centrifuge modeling is widely used to study geotechnical problems 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. As illustrated in Figure 1, the stresses at corresponding locations of the model and prototype are similar. Table 1 (from Sausville et al., 2005) presents the centrifuge scaling laws for common parameters.

A geotechnical centrifuge allows one to conduct experiments on small-scale models under high gravitational accelerations. 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.

The physical behavior of soil materials is generally dependent on overburden body stresses in a non-linear manner. Therefore, it is necessary to induce in the test the same body stresses as in the real-life prototype. A geotechnical centrifuge provides a means of doing this, by inducing a high gravity acceleration on the model by spinning it in a bucket about a vertical axis. Figure 2 (from Elgamal, 1991) shows a schematic view of the RPI centrifuge, which was used in the present study.
B. Centrifuge Scaling Laws

An explosion is fundamentally a volumetric phenomenon (Taylor, 1995) and it has been established that the effects of a blast are related to the third power of the gravitational acceleration involved. 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. Researchers like Schmidt (1980), Schmidt and Holsapple (1980), Cheney and Fragaszy (1984), Kutter et al. (1988), and Goodings et al. (1988) reported on the scale effects of blasting, utilizing dimensional analyses and centrifuge modeling.
III CRATER FORMATION DUE TO EXPLOSIONS

As shown in Table 1, lengths scale as N or the g level. For example, a 1 unit high dam tested at 100 g is equivalent to a 100 unit high prototype dam. Thus shear forces would scale as g² and blasting, a volumetric phenomenon, scales as g³. This indicates the applicability of using centrifuges for modeling blasting. For example, a one gram charge (a typical charge for this project) detonated in a 100 g test is equivalent to one million grams of explosive (100 x 100 x 100 grams = 1000 kg), or one metric ton (2200 lbs).

Table 1. Centrifuge Scaling laws (Sausville et al., 2005)

<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/s²</td>
</tr>
<tr>
<td>Velocity</td>
<td>1</td>
<td>m/s</td>
</tr>
<tr>
<td>Volume</td>
<td>1/N³</td>
<td>m³</td>
</tr>
<tr>
<td>Mass</td>
<td>1/N³</td>
<td>kg</td>
</tr>
<tr>
<td>Force</td>
<td>1/N²</td>
<td>N</td>
</tr>
<tr>
<td>Pressure</td>
<td>1</td>
<td>kpa</td>
</tr>
<tr>
<td>Time</td>
<td>1</td>
<td>s</td>
</tr>
</tbody>
</table>

The five main components of the soil to be determined when experimenting with explosives are soil density, composition, water content, homogeneity and shear strength. With respect to particle size, Schmidt and Holsapple (1980) found no detectable effects of grain size on explosive cratering. Further, Brownell (1992) found that particle size effects can be considered negligible, provided the soil behaves the same in the model as it would in the prototype.

There are two common definitions of craters that form during an explosion, a true crater and an apparent crater (Figure 3). The true crater is caused by the initial detonation. The apparent crater is the final resulting crater or the crater that is visible after the explosion. In general, the apparent or final crater is smaller in volume than the true crater due to ejecta and fallback. The ejecta are soil, rock, and debris that are ejected from the ground by the explosion. Fallback is the material that falls or settles back into the true crater thus creating the apparent crater (Rubin, 2005). Fallback can be an important consideration when dealing with water, that is, saturated soils and soils below the water table. Such soils usually liquefy due to explosive effects, and the fallback (or perhaps flow-back or wash-in are better terms) can be considerable, thus resulting in a much larger true crater relative to the apparent crater.
In the case of dams and embankments with water upstream, it is usually the depth of the true crater that will determine whether or not the dam is breached. Relying on apparent crater data (universally the most common) can be misleading. In this project, a high speed camera capable of 50,000 frames per second was used to film the blasts. This assisted in the determination of differences in dimensions of the true versus apparent craters, at least in a qualitative sense. All craters measured in this research were apparent craters only.

**IV CENTRIFUGE TESTS ON EARTH EMBANKMENTS**

Five major crater dimensions were analyzed in this research: length, depth, breach width, breach depth and the volume of the crater. The main focus of concern for this research and on an earth embankment dam is the breach depth. This is the depth of the crater at the crest of the dam. Crater depth is the maximum depth of a crater and, in general, will be greater than the breach depth. These dimensions are shown more clearly in Figures 4 and 5 (Sausville, 2005). If the embankment is breached and water passes over the dam, catastrophic failure of the embankment will occur.

For each test the charges were placed horizontally on the surface of the dam and then wired to the firing module mounted on the centrifuge. Wires from the firing module were connected to a control unit in the control room. When the centrifuge reached the desired g level the charges were detonated, the centrifuge shut down, and the sample box was removed for crater measurements using a profilometer. Details regarding the measurement technique are provided by Pena (2003).
A total of 15 tests were conducted during this research. Results were compared with a test conducted on a dry embankment from Pena (2003). Plots of breach depth versus quantity of explosives for both dry and saturated embankment are presented in Figure 6. Craters discussed in this paper were much larger because the soil was saturated. However, the saturated trend line begins to approach the trend line of the dry embankment when the water level was lowered 0.5 meters (prototype scale) below the crest.

Water was placed on both sides of the dam in the saturated tests. The effective stress in the soil decreased as the water level was raised and the dam was almost 100% saturated when the water level was flushed with the surface. The drop in effective stress caused a reduction in shear strength of the soil, which caused increased damage to the dam as a result of the explosion. Also, the impact of the explosion was directly transferred from the water to the soil, unlike in the dry or partially saturated soils, where compressible air voids absorbed some of the impact. Further, saturated soils tend to liquefy and lose shear strength due to the explosions. Sausville (2005) reported that larger craters were produced in saturated soils compared with dry and partially saturated soils.
The partially saturated tests utilized water on only one side of the dam. A geomembrane/kaolin clay core was used to prevent water from flowing to the other side. Upon detonation, water immediately breached the crest of the dam and produced massive erosion down the dry side of the embankment. This produced large breach depths on both sides (Sausville et al. 2005).

V CENTRIFUGE TESTS ON UNDERGROUND STRUCTURES

A. Experimental Model

The effects of a surface explosion on an underground structure were studied through centrifuge tests conducted at 70 g. 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/m$^3$, which corresponds to a relative density of roughly 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 7.
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.

B. Instrumentation

Strain gages were used to measure the strains induced at different portions of the model structure due to the explosion. Strains were measured 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.

C. Results

1. Craters

The surface explosion immediately above the underground structure created a crater, which was measured using a profilometer at the end of each test. Since the measurements were made at the end of each test, only the apparent crater, which included the fallback of material ejected due to the explosion, was measured. The average crater had a diameter of approximately 12 m (in prototype scale) and a maximum depth of approximately 1.25 m (also in prototype scale). The same quantity of explosives was used in each test and the soil conditions were also very similar. Therefore, the crater dimensions were not found to vary appreciably between different tests on the underground structures.

2. Strains on Underground Structures

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 8, 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 9, 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.

![Figure 8. Effects of thickness of soil covers on axial strains measured at quarter span of underground structure, subjected to surface explosion](image-url)
VI CONCLUSIONS

Explosions detonated on the ground surface present a serious potential threat. Apart from the obvious and critical harm to lives and properties in the immediate vicinity, such explosions also have the potential for causing damage to nearby structures as the impact of the explosions travel through the subsurface. Centrifuge scaling relationships for explosion effects make it possible to model relatively large explosions, while using small quantities of explosives in the tests.

It is noted that the tests reported in this paper were not intended to model conditions on any specific structure; rather the properties selected for the models were “generic” in nature, meant to provide a general understanding of the phenomena.

Results of centrifuge model tests on saturated earth embankment dams showed that clay cores caused deeper cuts compared to the research of others reported in the literature. Obviously, craters experienced no wash-in for dry tests. However, there was measurable fallback subsequent to the explosion in dry tests. Saturated and partially saturated tests represent more realistic conditions than dry tests because of the presence of water on either or both sides of the embankment. Larger craters were formed as a result of the explosion with high water levels due to reduced effective stress caused by pore pressure in the saturated or partially saturated embankment. This same pore pressure in the saturated dams produced larger craters than dry dams which did not experience the same reduction of effective stress. Logically it follows that larger craters were created when water was flush to the dam crest as was demonstrated by the experiments. It is very important to note that the experiments also demonstrated that if water is higher than breach depth, a dam will fail. That is, once water starts flowing over the dam, catastrophic failure will occur.

The tests on underground structures indicate that explosions on the ground surface can induce significant strains on underground structures. The measured strains can be utilized to evaluate the
extent of damage for given material properties of the structures. The results from limited experiments involving geofoam indicate that it is possible to mitigate the impacts of an explosion on an underground structure when a layer of compressible inclusion barrier is placed immediately outside the structure. Additional studies are warranted in this area to further investigate this effect and determine appropriate dimensions and material properties.

Centrifuge modeling is a viable tool to study geo-hazards related to surface explosions, which is generally very difficult to model in full-scale tests. Results of centrifuge model tests can be used to verify and calibrate numerical models which are frequently 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.

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VIII REFERENCES


