CENTRIFUGE MODELING FOR BLAST STUDIES

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ABSTRACT: Scale testing is a common practice in many disciplines of civil engineering. However, in geotechnical engineering this technique is often inaccurate due to the non-linear material behavior of soils. As a result, corresponding stresses and strains of the reduced scale test will be quite small due to the incorrect stiffness of the soil. To correct the error, similarity of stress between model and prototype can be achieved by increasing the weight of each particle by an equivalent amount of gravities. This idea led to the development of model testing in a centrifuge. The principles of centrifuge modeling are now widely established and have been documented in detail. A set of scaling laws relates the observed behavior of the models to the prototype structures in the field. The scaling laws reveal some advantages of centrifuge modeling. For example, the scaling law for energy is $1/n^3$. This suggests that by testing a model sand layer with a buried charge of 1 gram at 100 g's represents a blast event that corresponds to 1 million kg in a field event.

INTRODUCTION

Terrorist attacks on the nation’s critical infrastructures have resulted in unfathomably devastating effects which amplified the need to assess the vulnerability of these structures to potential threats. Over the last 30 years, two new techniques have been developed which have proven to accurately simulate gravity-induced stress states in structures subjected to dynamic loadings. One of these techniques is the use of computer models, especially with the advancement of hydrocodes which can simulate blast loadings and material response in great detail. However, the accuracy and reliability of such calculations must be validated by experiments in which the gravity forces of concern are properly accounted for. The second technique is the use of large centrifuges to accurately simulate the stress states in the models that are experienced by the full-scale structures. Another major criterion is benefit of cube root scaling, only grams of explosive are needed for centrifuge modeling. Since it was not possible to construct and detonate ANFO, which requires at least 20 lbs to detonate, C4 (Detasheet) is commonly used in laboratory testing. For these series of test, C4 with an RP-83 EBW detonator containing 1.12 grams of RDX explosive was used. Comparisons of the equivalent mass factors show minor differences in impulse for ANFO (~0.87) and C4 (1.19) for burst in free air; and for displacements of buried explosives, C4 (10.95) and ANFO (0.93). Figure 1 show the US Army Centrifuge located in Vicksburg, MS, USA used to conduct these tests.

The experimental approach was to apply replica scaling to the problems. In replica scaling the small-scale model is built by reducing all the dimensions in the full-scale design by the scale factor. To preserve similitude with full-scale, all mechanics parameters should transform so that they have the same value at any scale, i.e. the governing equations should be identical at all scales. In replica scaling, most of the parameters of interest naturally scale to the required value. However, gravity is an exception, and in a 1/100-scale experiment it should be increased to 100 g. This is of particular interest in the problem of progressive collapse, dams, and subsurface structure because all of the loads in the problem are gravitationally induced loads. The
centrifuge should be able to simulate not only the internal state of stress in a modeled section and the hydrostatic load on the test section, but also the hydrostatic conditions that influence the bubble growth from an underwater explosion, and the peak pressure and impulse loads transmitted to the structure. This information can provide realistic indications of the dynamic loads and response of the structures subjected to underwater explosions that will, in turn, allow improvements to current empirically-based damage prediction tools. In addition, it provides data that can be used to validate the ability of advanced computer models now being used in attempts to calculate such loads and damage effects. This paper will describe three centrifuge studies relating to progressive collapse, vehicle and water borne attacks on dams and culvert IEDs. The U.S. Army Engineer Research and Development Center (ERDC) was tasked by the Department of Homeland Security (DHS), National Ground Intelligence Agency (NGIC), Joint Improvised Explosive Defeat Organization (JIEEDO) and the US Army Corps of Engineers Head Quarter to conduct laboratory experiments, using ERDC’s large geotechnical centrifuge, to evaluate factors that could influence the extent of damages that could result from a terrorist attacks.

![US Army Centrifuge](image)

**FIGURE 1. US ARMY CENTRIFUGE**

**RESEARCH OBJECTIVE**

The objectives of these studies were to investigate dynamic loading conditions on a multi-story, multi-bay building, earthen embankment and concrete gravity dams and culverts and the dynamic stress response of the structures subjected to loads from surface, underwater and sub-surface explosions under realistic hydrostatic and internal stress conditions. Data from these experiments were used to validate computer code calculations of potential damage to the structures from explosions and to improve current prediction methods.
CENTRIFUGE TESTING

Reduced scale centrifuge models are designed to replicate sufficient features of the prototype so that the test data can be extrapolated to the prototype scale. Test models are then placed on the centrifuge platform and subjected to an increased acceleration field to generate realistic stress distributions so that analysis can be made of the structural responses. The designed scale of the model is based on size of the centrifuge, the size of the prototype and the condition or event to be replicated.

Progressive Collapse Model

A 1/18-scale model of a 4-story reinforced concrete structure was tested at 18 g to support the development of computational modeling of progressive collapse of multi-story buildings. The model structure was 4 bays long and 3 bays wide with column spacing about 33 cm in each direction and story height of 20.3 cm. The columns and beams were nominally 2.54 cm x 2.54 cm and the floor slabs were about .85 cm thick, Figure 2. Threaded steel rods were used for the main reinforcing bars. The micro-concrete used masonry sand for aggregate. Bags of steel shot were placed on every slab to add a combination of dead and live load. Figure 3 shows a complete test model of the 1/18 scale reinforced 4-story structure on the left, and laser gages mounted on the concrete foundation on the right. High speed camera was also used to capture the failure during centrifuge testing, Figure 4.

Figure 2. First story formwork, rebar and column rebars.

Figure 3. 4-Story Reinforced Concrete Structure 1/18 Scale Model and laser gages.
Earthen Embankment and Concrete Gravity Dams

Dams have been targets of tactical and strategic military strikes since the early days of WWII. In most cases, these have been bombing attacks, although both surgical and massive demolition operations have been carried out. Attacks on dams could produce catastrophic effects resulting in casualties, flooding, loss of hydropower or river navigation, and damage to properties. A number of research studies have been performed to develop methods to relate the type and extent of damage to dams to the conditions of an explosive attack. Prior to the attack against the German dams, tests were carried out in England against small model gravity dams, and then against a small abandoned dam. While general rules of thumb were developed from these tests, they could not accurately model the damage because they did not reproduce the internal state of stress in the full scale structure that are created by the weight of earthen or concrete mass and the pressure in the reservoir. Embankment dams test series for vulnerability studies were built 1/100 scaled of a generic prototype, Figure 5. The impervious core is compacted upside down to ascertain the desired soil properties. The model container is then flipped over for the placement of the transition zones. Testing was conducted for both vehicle-borne (VBIED) and water side attacks (WSA) scenarios.

The concrete sections for the gravity dam were cast as a series of monoliths, with the base of each monolith anchored to a steel plate base. The alternate casting pattern allowed for sufficient curing for internal placement of sensors, Figure 6. A completed gravity dam test section is shown
in Figure 7. A 2-inch wide plate at the downstream toe of the model provided further restraint against sliding on the plate. The model sections were cast using a concrete mix in which aggregate size was scaled proportionally.

Figure 6. Casting of concrete gravity dam monoliths and strain gage placement.

Figure 7. Completed dam section with 8 monoliths.

Figure 8. Material and bending failures caused by submerged explosions.

Culverts
Improvised explosive devices (IEDs) in road culverts remain one of the most dangerous threats to our Soldiers, all branches and all ranks, on the battlefield. This asymmetric threat is an enduring and evolving threat in theater operations. Previous research of the physical/mechanical process of an underground detonation event indicates that the initial shock wave will expand outward. The shock wave from IEDs can loosen the surrounding mass; however, it is the gas pressure from the detonation in the culvert that pushes the overlying soil upward and outward. As the soil mass moves upward, the detonation gas volume expands. The expansion of the soil mass at detonation depends on the “ejection” velocity of the soil constituent after the gas pressure has dissipated. The total vertical displacement above the IED is controlled by the lifting blast pressure, overlying cover or mass and the dissipation rate of the detonation gas pressure. Since we have little control on the type or size of the explosives, the resolution for neutralizing culvert IEDs is contingent on the overlying mass and/or the rate for dispelling gas pressure. The design of the culvert test sections was based on the types of culverts currently being used at the USACE Afghanistan Engineers District (AED) in Kabul. Preliminary centrifuge tests were conducted to measure the vertical displacement of a specific class armored vehicle (MRAP). A culvert section was instrumented with strain gages and buried in a roadway compacted to standards received from AED. A scaled MRAP with multi-direction accelerometers mounted on top was placed over the culvert with the IED at center where it is lease visible from roadway inspection, Figure 9. Post test images are shown in Figure 10.

Figure 9. Buried culvert with strain gages cables with an IED at center.

Figure 10. Post test results of MRAP
An array of culvert blast hardening measures were also tested and evaluated for implementation to reduce the damaging impulse imparted to an MRAP vehicle from a certain amount of culvert-emplaced IED to a survivable level for vehicle occupants. A fully successful hardening measure must reduce crater fragmentation velocities to a point that MRAP hulls are not penetrated (i.e. breached) and crater upheaval velocities to a point that upward accelerations of the vehicle do not injure the occupants. An example of a slab mitigation test is shown in Figure 11. Various size and weight of slabs were tested for effectiveness as a restraining force of gravity against the lifting blast pressure. Another mitigation study was conducted to evaluate the effects of overburden mass inertia and the increase culvert volume for venting gas pressure by adding sacrificial culverts. The increased culvert volume should allow the gas pressure to “bleed off” at a rate controlled by the culvert cross section area and the culvert volume. The sacrificial culverts are closed ends and hidden from view. Figure 12 shows two different configurations with one sacrificial culvert stacked on top and two sacrificial culverts side by side arrangement. Other hardening methods were tested at full scale or reduce scale at earth’s gravity.

![Figure 10. Centrifuge culvert model with mitigation slab.](image1)

![Figure 11. Two configurations of model culverts, stacked (left) and side by side (right).](image2)
CONCLUSIONS

Centrifuge model tests of blast effects on structure provide realistic indications of the dynamic loads and response of the structures subjected to various types of surface and underwater explosions. The results of this study clearly show the different types of material and structural failure. This information will allow improvements to current empirically-based damage prediction tools for critical infrastructures subjected to explosion attacks. In addition, it provides data that can be used to validate the ability of advanced computer models now being used to calculate such loads and damage effects.

In a centrifuge test, stresses in the models can be made equal to those of the prototype and time dependent phenomena can be controlled. Centrifuge testing allows economical proof testing of designs, investigation of problem areas, and validation of numerical methods that have been cost prohibitive to study with prototype or large scale model testing. Centrifuge model testing is a technique of increasing relevance to engineering design and practice. Primary thrusts of research at the CRC are in the areas of blast effects, contaminant and groundwater migration, earthquake responses of earth structures, vehicle mobility and pavements, physics of frozen soils and water, hydraulic and coastal processes, and soil-structure interaction. The increasing wide variety of work carried out in this area has done much to establish a centrifuge as a worthwhile tool with enormous contribution towards solving challenging engineering and scientific problems worldwide. The CRC supports the Corps of Engineers and other Federal Agencies and collaborates with industrial, commercial, academic, and international organizations to address uncharted engineering and scientific problems worldwide.

References

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