MODELING DYNAMIC FIELD PHENOMENA WITH THE ARMY CENTRIFUGE

by

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ABSTRACT

The U.S. Army Engineer Waterways Experiment Station (WES), located in Vicksburg, Mississippi, has recently installed a uniquely powerful and large centrifuge. Although much of the recent world-wide interest in centrifuge modeling has concentrated on geotechnical problems, the new WES centrifuge facility will address research needs in physical modeling across the full range of engineering applications. The purpose of this paper is to describe the WES centrifuge, to discuss current research being conducted in the centrifuge facility and our vision for the future. The research described here will focus on field problems involving dynamics particularly earthquake work and blast loading. However, the WES centrifuge is uniquely broad-based in its research applications; many types of field problems, involving fluid-flow, heat transfer, and cyclic and static loading are being addressed in a wide range of fields: geotechnical, structural, environmental, hydraulics, coastal engineering, and engineering for cold regions. Some initiatives in these areas are also described.

KEYWORDS: centrifuge; physical modeling; dynamic loading; earthquake engineering; blast phenomena; groundwater; cold regions; dredge material; contaminant migration

1. INTRODUCTION

The WES has a long history of physical modeling. Its pioneering research in the early 1930s in areas of hydraulics engineering and flood control used scaled physical models carved in the loess soil. Hydraulic physical modeling experiments which replicated such historic locations as the Los Angeles Harbor, the New York Harbor, Niagara Falls, and the Old River Control Structure on the Mississippi River have been conducted throughout its 65 years of service to the Army and the Nation.

During the past several decades, with the advent of analog and digital computers, WES moved into the numerical modeling arena. With the rapid advance in computer technology leading to PCS and supercomputers, research is now being conducted using numerical modeling techniques including finite difference, finite element, discrete element, and discontinuous deformation analysis. Recent accomplishments include the development of a three-dimensional water quality model for the entire Chesapeake Bay, the use of complex three-dimensional codes to investigate cratering and air-blast effects from explosive events, and the use of two-dimensional effective stress finite element analysis for predicting large deformations occurring in embankment dams as the result of earthquake induced liquefaction in the dam and/or its foundation material.

The WES centrifuge is capable of spinning a payload of up to 8 tonnes and achieving accelerations of up to 350 gravities (g). This centrifuge provides a physical modeling capability which greatly enhances research techniques. Case histories and/or physical model experiments are required to validate numerical computer codes. Physical models have the advantages of being controllable, relatively inexpensive, and provide better known conditions than field cases.

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Researchers can better control the material properties and boundary conditions of physical models. The cost of centrifuge experiments is far less than full-scale field experiments which may involve hundreds of thousands or millions of dollars.

2. MODELING FIELD PROBLEMS IN A CENTRIFUGE

Physical modeling of field problems generally involves the construction and experimentation with scale models of a prototype or field structure. The response of the model to a physical perturbation such as cyclic loading, earthquake, ocean waves, explosion or even freezing or groundwater changes can be measured and interpreted in terms of the field problem under consideration. Realistic model behavior data can provide valuable information for designers about failure mechanisms and long term performance.

In many engineering fields, particularly geotechnical engineering, gravitational effects dominate performance. Where the behavior of a material is stress dependent, such as with the engineering properties of soil, then simple scaling of a field problem and experimental investigations on the laboratory floor will give erroneous results. For example, in a slope failure it is common to observe cracking near the ground surface where the confining stresses are low but the shear stresses are high, rupture along a slip surface at greater depth and finally flow at depth as the confining pressure increases still further and the shear stress ratio reduces to a value below the critical state or characteristic threshold value, (Figure 1).

If one were to attempt to model the slope failure in Figure 1 on the laboratory floor at 1/50 scale without the benefit of a centrifuge, the effective confining stresses in the soil would be 50 times less than those same stresses in the field and hence could bring the full depth of soil in the model into a region where tensile fracture (or cracking) dominates.

The use of a centrifuge however, overcomes this modeling error by increasing the weight of each particle in the model by an equivalent number of gravities. Generally the linear scale of the model and the number of gravities are chosen to be identical. Therefore, a 1/50 scale model of a 20 m high earth slope would be 400 mm high. Under a steady acceleration of 50 gravities (approximately 500 m/s^2), it would have identical self-weight stresses at equivalent points in the model and in the prototype. The behavior of the miniature slope will then mimic the behavior of the prototype. Each soil 'element' in the centrifuge model is subject to the same stress path as its equivalent 'element' in the full scale prototype.

Figure 2 shows a silt slope failure in remolded Vicksburg loess, carried out on the WES centrifuge. Details of the failure can be seen, including the cracking near the top of the slope, and rupture along the slip surfaces which run nearly parallel to the slope. The response shown is typical of loess behavior with no deep seated flow movement.

Scaling relationships can be derived from physical principles which interpret the centrifuge model experimental investigation data in prototype terms (Schofield 1980 and 1981, Schofield and Steedman 1988). These are summarised in Table 1.

As a technique for solving engineering problems, the use of the centrifuge was first pioneered in the Soviet Union and in the United States (US) during the 1930s (some references claim the concept of a centrifuge model can be traced to the 19th century or earlier). Although the idea did not fully develop in the US at that time, the Soviets recognized its potential in the area of weapons effects and developed a major program of centrifuge modeling. It is understood that this continued until the recent political changes.

In the west, the development of centrifuges for study of geotechnical problems was led by academic researchers in the United Kingdom (UK) committed to the study of soil as a plastic material. A number of centrifuge centers developed in the UK, US and in Europe during the 1970s and 1980s, primarily attached to universities or research institutions.

Miniature instrumentation and, recently, the development of affordable advanced data acquisition systems has revolutionized the potential for centrifuge models. Model experiments can now provide detailed quantitative information on the response of a model at many different points for comparison with numerical models or analytical solutions. Miniature instrumentation has already been developed which can measure displacements, pore fluid pressures, accelerations, resistivity, wave height, shear wave velocity, and so on. 'In-flight' site investigation tools can perform cone penetration probes, vane shear experiments or other explorations of the 'site'. Miniature cameras can observe the behavior of the structure in close up. Systems can load the soil and structures, trigger earthquakes, generate water waves, freeze ice sheets, carry out staged construction, release contaminants or detonate explosives.

The wide range of physical phenomena that may be created in a centrifuge and the quality and detail of the data that may be captured from a model in-flight clearly provides substantial opportunities for engineering research studies. The Corps of Engineers has been involved with centrifuge modeling since the 1970s, and the recent development of the WES Centrifuge Research Center in Vicksburg demonstrates the Army's full commitment towards the use of physical modeling as an integral part of engineering analysis.

3. THE WES CENTRIFUGE

The design specification of the centrifuge followed a review of available academic facilities which had shown that none were able to routinely conduct experimental models of the large field structures and problems with which the Corps is principally concerned (Ledbetter, 1991). The facility was therefore designed with a unique operating envelope. It was required that model containers should be easily placed on and off the centrifuge and these requirements led to the design of a beam centrifuge with a swinging platform based on the French designed Acutronic 661, 665, and 680 series of geotechnical centrifuges. Other centrifuges in this Acutronic family include one at Rensselaer Polytechnic Institute, Troy, New York, at the Centre for Cold Oceans Resources Engineering, St. Johns, Newfoundland, and several in Japan and Europe. Figure 3 shows the WES Centrifuge in its containment structure; key parameters are listed in Table 2 and Figure 4 shows the performance envelope relating payload capability to centrifugal acceleration. Prototypes of the order of 300 m in breadth and 300 m deep can be simulated in models subjected to up to 350 gravities (around 3500 m/s^2).

A wide range of modeling capabilities was required and actuators and appurtenances have been designed to fulfill these requirements. Models can be constructed in a range of containers that depend on the geometry of the problem under investigation (plane strain, axi-symmetric, three dimensional, etc.) and the type of phenomenon to be recreated.

Recent world-wide interest in centrifuge modeling has concentrated on geotechnical applications; however, the WES centrifuge facility has a much broader mission. The WES centrifuge will address research needs in physical modeling across the full range of engineering applications. Investigations are possible under climatic conditions ranging from desert to polar to ocean regions. Key capabilities include: (1) force and displacement controlled load systems, (2) earthquake simulation, dynamic vibration loading and water wave generation, (3) blast loading, (4) model package environmental control, (5) in flight manipulation of the model materials and fluids, (6) miniature instrumentation, cameras and in flight site interrogation, and (7) high speed data acquisition and control systems.

The new capabilities that will flow from the centrifuge will depend on the ingenuity of its users and the design of its appurtenances. In this respect the design of the centrifuge itself is merely one component of the development of new capabilities in physical modeling.

4. CENTRIFUGE MODELING OF DYNAMIC PROBLEMS

The use of centrifuges to address field problems involving dynamics dates back many years. As noted above, the Soviets made use of centrifuges as early as the 1930s and 1940s for the study of weapons effects. WES, which first used centrifuge modeling for cratering studies in the 1970s, has now developed the capability for carrying out such explosive investigations on its new centrifuge (as discussed further below).

In the field of earthquake modeling, Professor Mikasa at the University of Osaka pioneered the development of the first centrifuge 'earthquake' actuator by using a tilting mechanism to create a pseudo-static lateral acceleration field on a soil model in flight, (Mikasa et al. 1969). Steedman (1991) provides a review of the application of the centrifuge to dynamic geotechnical studies which highlights some of the important achievements of Japanese researchers in earthquake centrifuge modeling.

Since the 1980s, a variety of actuators have been developed around the world for the simulation of earthquake-like base shaking on centrifuge models. These have ranged from sophisticated units using servo-hydraulic systems to provide broad band shaking input to less mechanically complex systems that can apply a broadly sinusoidal base shaking motion of a given duration and frequency. In general, limitations posed by the high gravitational field in which the equipment must work and the high development cost has restricted the use of servo-hydraulic systems to low g centrifuge applications and small models. At WES, the requirement to conduct experimental models of large field problems has led to the development of a robust mechanical shaker designed to operate at over 200 gravities, significantly higher than any earthquake centrifuge modeling on other beam centrifuges carried out to date. Early indications, using a prototype version of the system developed together with Cambridge University, have provided encouraging results, as seen in Figure 5.

The WES earthquake shaker (Figure 6) uses the angular momentum stored in high speed rotating flywheels to provide the energy source for the shaking motion. Power is transferred from the flywheels to the base plate beneath the model via a continuously oscillating shaft which is briefly 'grabbed' by a high speed clutch for the desired duration of excitation. Figure 7 shows the equivalent-shear-beam laminar model container which is 900 mm in length, 650 mm in height and 355 mm in width. This container incorporates shear sheets on each of the end walls to transfer the complementary shear stresses generated on vertical planes in the specimen by base shaking in the horizontal direction. This improves the uniformity of shear.

From Table 1 it is seen that as the g level is increased it is necessary to increase the frequency of shaking and simultaneously to reduce the amplitude of motion. At high g levels these small displacements may become comparable to the manufacturing tolerances of the moving parts; particular attention has been paid to this issue in the design of the WES shaker. The resulting system is robust and economic, and will provide a pre-programmed duration and frequency of shaking.

In fields such as the seismic design of retaining walls, centrifuge model studies have provided valuable insights into the mechanisms underlying the onset of permanent movement and the ultimate failure of different forms of wall. Conventional approaches to the prediction of permanent movement of monolithic walls have been investigated and refined using centrifuge model behavior data (Steedman and Zeng 1996). Other studies have investigated the point of application of the dynamic force increment and the consequences of the development of excess pore pressures and liquefaction in the backfill behind anchored walls (Steedman and Zeng 1990).

A key area of interest to WES has been the study of liquefaction and the dynamic response of embankments and dams. WES has made extensive use of centrifuge modeling in this field to provide realistic data for the validation of numerical codes and other analyses and a substantial program of research is planned for the new facility (described further below).

The WES involvement and interest in centrifuge earthquake engineering experiments and studies dates back about twenty years to collaboration with the University of Cambridge (Morris 1979). WES conducted experiments in the 1980s of models including dry and saturated embankments with and without surface supported and embedded structures. Figure 8 shows one of these experiments for investigating a nonlinear dynamic effective stress method of analysis.

Shown in Figure 8 is a schematic view of a saturated embankment with an embedded structure for simulating strong soil-structure interaction during earthquake shaking. The foundation sand was Leighton Buzzard Sand with a mean grain size of 0.225 mm at an average relative density of 52%, and the structure was a solid piece of aluminum alloy. Centrifuge experiments were at a nominal centrifugal acceleration of 80 g. Therefore, the model simulated a structure 8.6 m high by 12 m wide embedded 2 m in the foundation sand. Peak acceleration of the input horizontal shaking at the base of the model was 0.13 g.

Accelerometers (ACC), pore pressure transducers (PPT) and a linear variable differential transformers (LVDT) were used to monitor the response of the model as shown in Figure 9. As can be seen, a significant amount of instrumentation was used to obtain good and reliable data. An important advantage of centrifuge earthquake experiments is the wealth of data and information that can be acquired, as evidenced in this figure.

Figure 10 shows computed and measured horizontal accelerations at the top of the structure at the location of ACC 1938 (Figure 9). Vertical accelerations due to rocking of the structure occurred and are shown in Figure 11 along with computed motion. The frequency content is higher than seen in Figure 10 because the foundation soils are stiffer under the compressive stresses due to rocking than under the induced shear stresses from the horizontal acceleration.

Contours of computed residual porewater pressures in the foundation are shown in Figure 12 along with the measured maximum values (indicated by the triangles). Very symmetrical distributions of the residual porewater pressures are seen for the model investigations. The measured responses shown in Figures 10 through 12 cannot be obtained by any other means under the equivalent prototype stress states and provide valuable insight to behavior under earthquake excitation and for numerical model development and verification.

Other fields involving dynamic loading that have been addressed using the centrifuge include dynamic loading of foundations ('machine vibration'), (see Laue and Jessberger 1994), and wave loading on coastal defences and sea bed deposits (Sekiguchi et al. 1994).

The modeling of instability of sand beds caused by water waves at g has been hampered by the need for very large or deep wave tanks. At high g it becomes practical to adopt viscous scaling of the pore fluid because of the small size of the wave tank, and researchers at Kyoto University have shown that using this technique, wave induced liquefaction can be reproduced in a sand bed deposit, (Sekiguchi et al. 1994). This class of problem will also be addressed in future at WES.

5. CURRENT RESEARCH AT WES

A number of research projects using the centrifuge are currently underway at WES. In the following paragraphs, a few of these investigations are described which demonstrate the Corps' interest in a wide range of applications. Some of these fields are entirely new to centrifuge modeling.

In the field of earthquake engineering, a large study has commenced to investigate aspects of the prediction of liquefaction. This has the potential for a major impact on the design of remedial measures for earth dams in seismic areas in the US. To date, the factors which strongly influence the prediction of a soil to liquefy and its residual strength as used for design purposes have been evaluated only on laboratory element test data and fortuitous field performance data. The new research approach is to use the new large earthquake shaker mounted on the WES centrifuge to conduct a series of models experiments, monitoring the development of excess pore fluid pressure in the foundation soils directly as a function of the density, amplitude of shaking and number of load cycles. This approach will not need to extrapolate design factors from small laboratory samples and may lead to significant improvements in design and analysis techniques.

A second research program is concerned with the gravity driven mixing and flow of immiscible fluids as oils seep into the natural groundwater environment. The purpose of the models is to acquire data suitable for the validation of numerical models of DNAPL (denser than water non-aqueous phase liquid) movement in groundwater, the development of which have been hampered by the lack of realistic experimental or field data. In a centrifuge model under high gravity, the time taken for a diffusion event is reduced by the square of the model scale over the equivalent time in the field. This occurs because of the small physical size of the model and the higher hydraulic gradients. This is a strong advantage for any experiments investigating long term diffusion type problems as the centrifuge can achieve in a few hours what would take many years to tens of years of monitoring in the field.

The first centrifuge experiments undertaken by the Corps in the 1970s were in the field of blast crater modeling. More recent work has studied the effects of blast and blast induced liquefaction on structures. Figure 13 shows a crater formed in dry sand in the blast chamber on the WES centrifuge, with a buried charge equivalent to 500 lb of high explosive (PETN). The model, at 45 gravities, has a crater diameter of 300 mm, equivalent to 13.5 m in the field. The WES centrifuge has a substantial capability for modeling the effects of explosions on a wide range of structures, again benefiting from the capability to operate at up to 350 gravities. In the scaling of blast phenomena, energy scales with N^3, Table 1, and hence 1 gm of high explosive at 100 gravities will generate an event equivalent to a 1 tonne explosion in the field. At 350 gravities, large explosions can be replicated. The program of work in blast modeling includes the simulation of field events to demonstrate the internal consistency of the models and the effects of explosions on a range of structures and facilities in different ground conditions.

Engineering for cold regions is another field of interest to the Corps and in this area studies have commenced concerning the effects of ice forces on structures with the growing of an ice sheet under increased gravity in a specially designed insulated container. Earlier studies at Cambridge University have shown that ice grown under increased gravity in the laboratory has an internal structure like that of a multi-year ice sheet in the Arctic, with a profile of snow on the surface, random crystals at shallow depth and vertically oriented crystals below that. If ice sheets of similar form to those found at sea can be formed in a centrifuge model then this pioneering research may provide a new route altogether for the development of engineering solutions for cold regions engineering.

Finally, in the environmental area, a research program has been initiated to investigate the consolidation of dredged material and the consequential damage to capping layers. Initial experiments have addressed the long term settlement of the material. Continuing experiments will investigate the movement of contaminants. As was noted earlier, small volumes of material in a centrifuge can replicate large volumes in the field. For contaminant migration investigations, this means that even small samples, which can be readily managed in the laboratory, can provide a basis for realistic modeling and simulation of the behavior of the full scale prototype. Samples can be used this way rather than simply used to acquire parameters in a laboratory element test.

6. VISION

The development of the WES Centrifuge Research Center marks the transition of centrifuge modeling from a pure geotechnical engineering research tool to a modeling technique of wide application in engineering work. The Centrifuge Research Center aims to become the world's leading centrifuge modeling facility supporting the Corps of Engineers, the Army, the Department of Defense, other federal agencies and other nations, collaborating with academic and industrial organizations and addressing novel and demanding engineering problems world-wide.

7. CONCLUSIONS

The WES is continuing its tradition of 65 years of physical modeling with the acquisition of the most powerful centrifuge known to date and the development of unique applications and appurtenances for conducting research. Centrifuge investigations are possible across a wide range of engineering fields. Research is being conducted in earthquake engineering, environmental problems concerning groundwater flow, geotechnical engineering, blast phenomena, cold regions and ice formation, dredge material disposal behavior, and contaminant migration. Research is planned in the engineering areas of soil-structure interaction (behavior of large lock structures), hydraulics and coastal (wave loading on beaches and sea beds), and airfield pavements. The Corps is convinced that numerical and physical modeling must progress together to solve today's and future engineering problems. The centrifuge will allow us to investigate phenomena not previously feasible including the performance of large civil engineering structures up to and beyond their design limits and long term prediction of environmental problems.

The WES centrifuge modeling capability marks the transition in centrifuge development from academic research to broad application in engineering research and problem solving. The increase of gravity in a centrifuge and its influences on physical processes provides great benefit for modeling field phenomena. The opportunities for application to physical processes are limited only by imagination.

8. ACKNOWLEDGMENTS

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Table 1. Scaling Relations

PARAMETER	FIELD	CENTRIFUGE MODEL (Ng)
Stress	σ	σ
Strain	ε	ε
Length, displacement	L	L/N
Area	A	A/N^2
Force	F	F/N^2
Volume	V	V/N^3
Mass	M	M/N^3
Energy	E	E/N^3
Frequency	f	Nf
Velocity	v	v
Acceleration	a	a/N
Time (for inertial events)	t	t/N
Time (for diffusion events)	t	t/N^2

Table 2. Key Characteristics of the Army Centrifuge

Army Centrifuge	
Radius to platform	6.5 m
Payload at 143 g	8000 kg
Payload at 350 g	2000 kg
Capacity	1144 g-tonne

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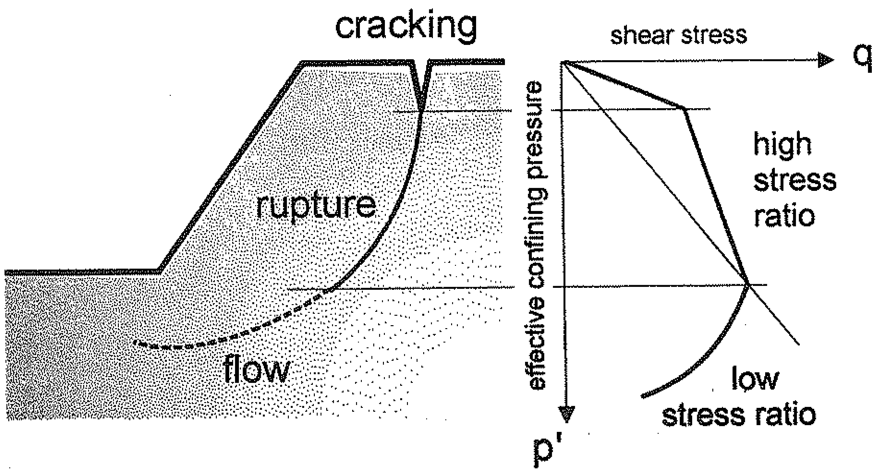

Figure 1: Ratio of shear stress to confining pressure governs soil behavior

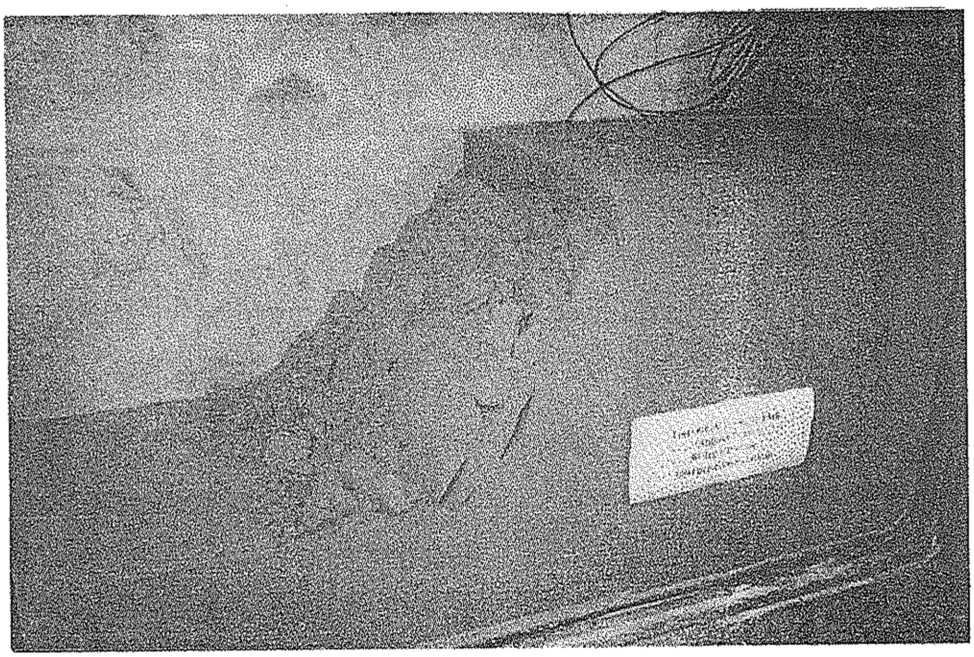

Figure 2: Failure of a silt slope in Vicksburg loess

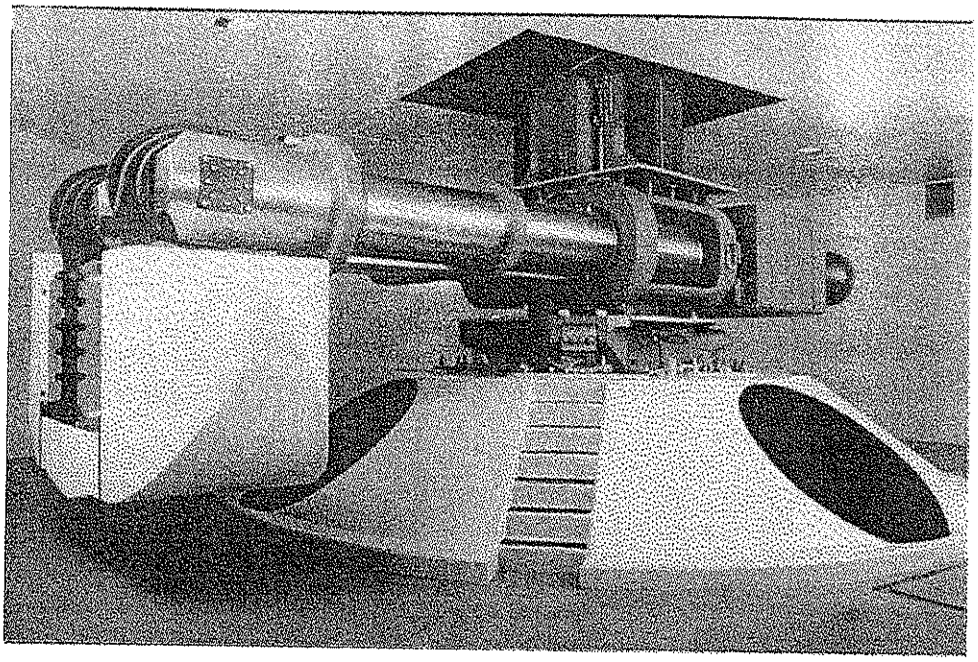

Figure 3: The Army centrifuge at the Waterways Experiment Station

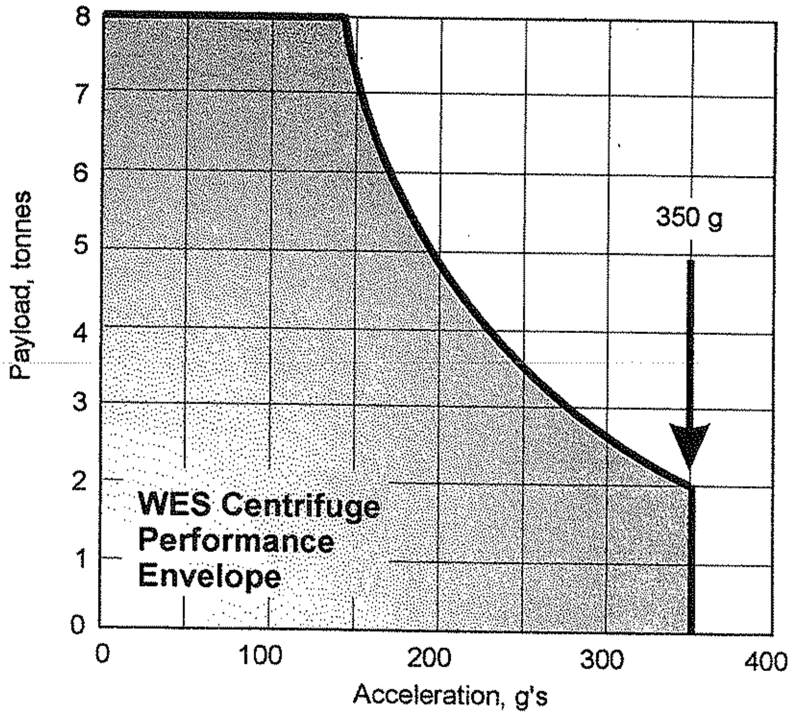

Figure 4: WES Centrifuge performance envelope

CONTROLLED EARTHQUAKE EXPERIMENT
RAW ACCELERATION DATA; UNIFORM DENSE DRY SAND
1 Hz, 25 Cycles, 25 Seconds

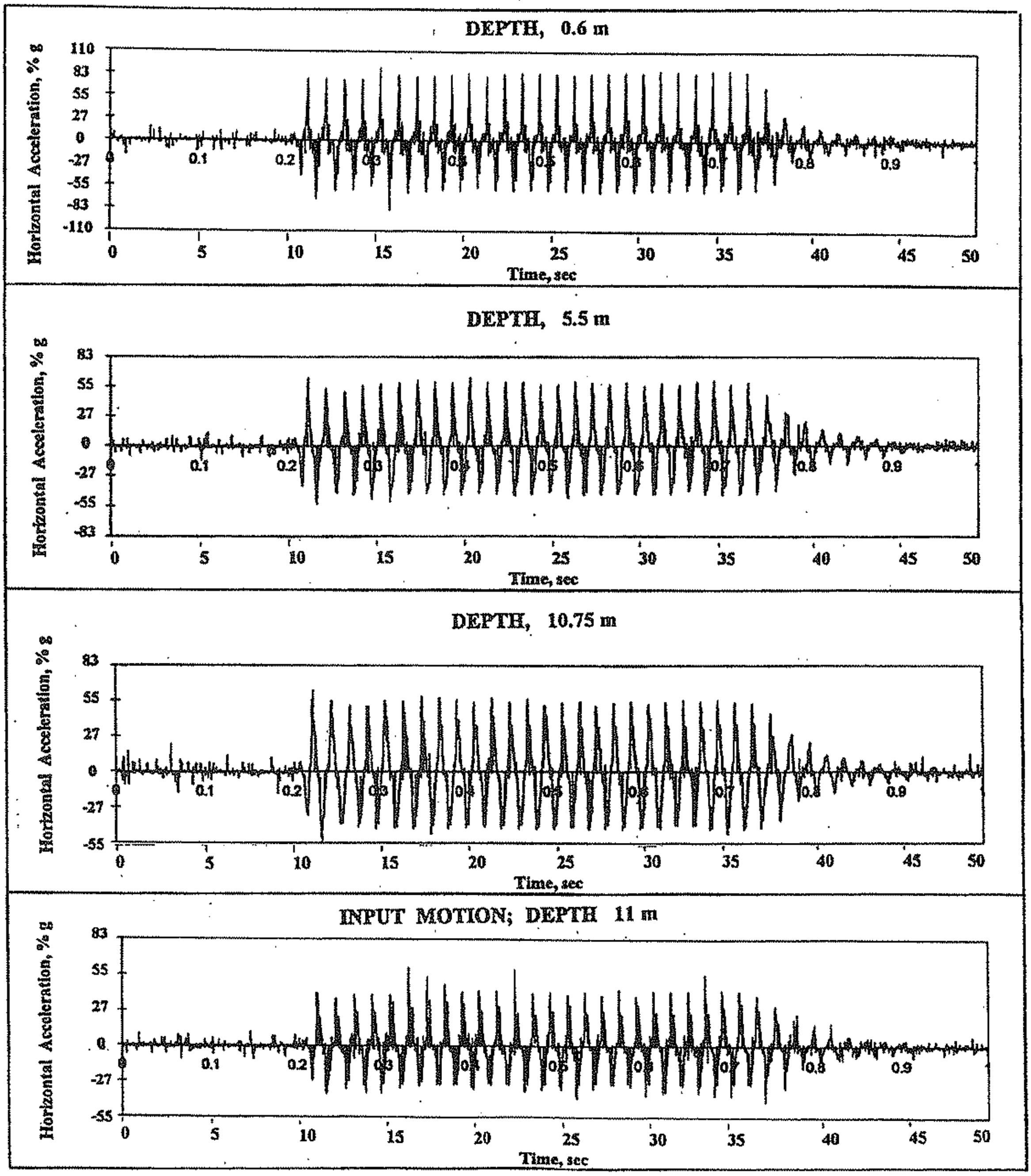

Figure 5: Accelerations recorded at different depths in a dry sand bed
(prototype units)

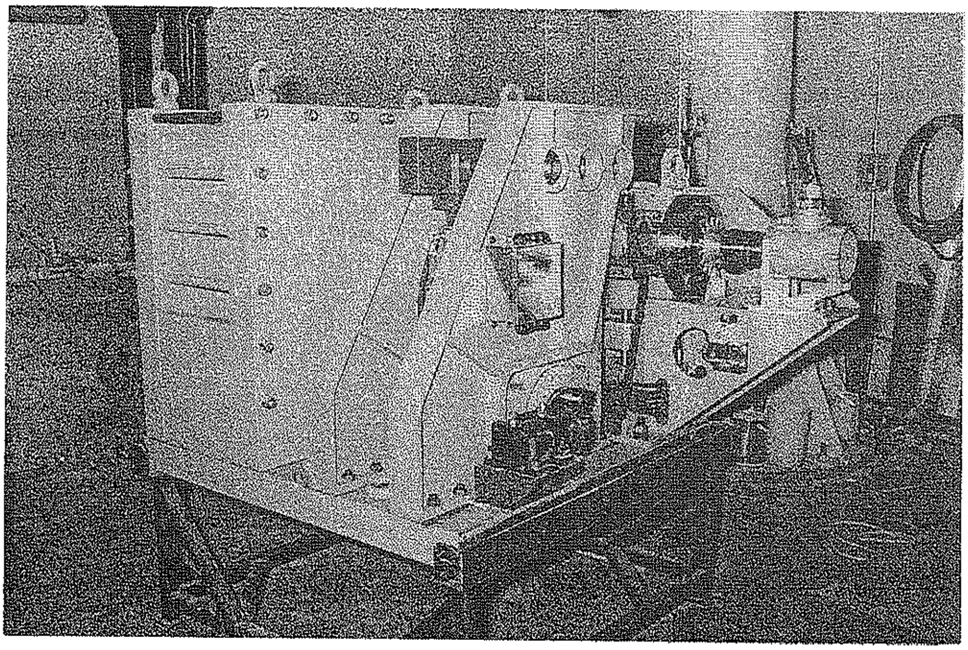

Figure 6: The WES earthquake shaker

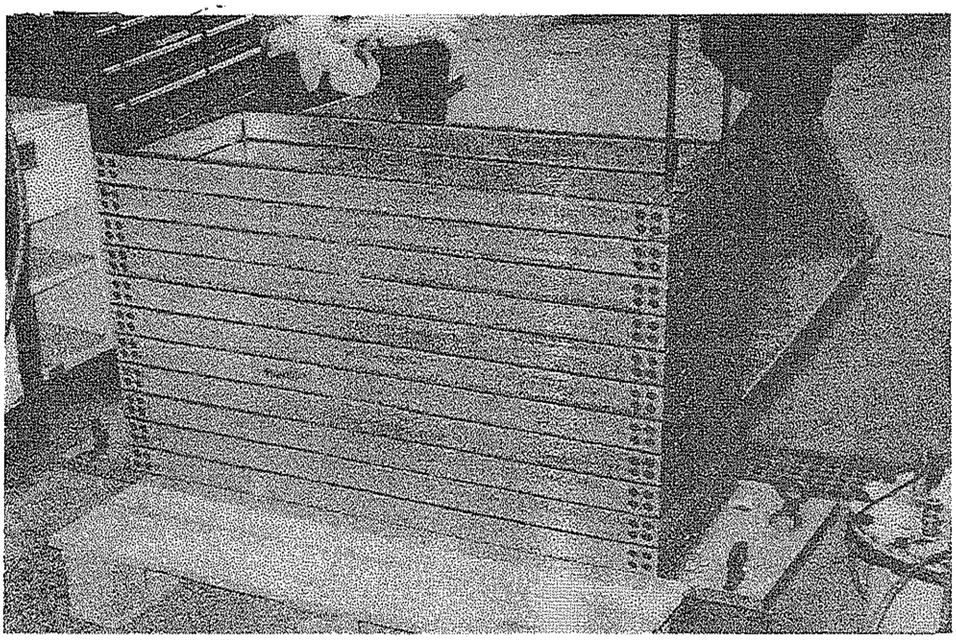

Figure 7: Equivalent-Shear-Beam model container

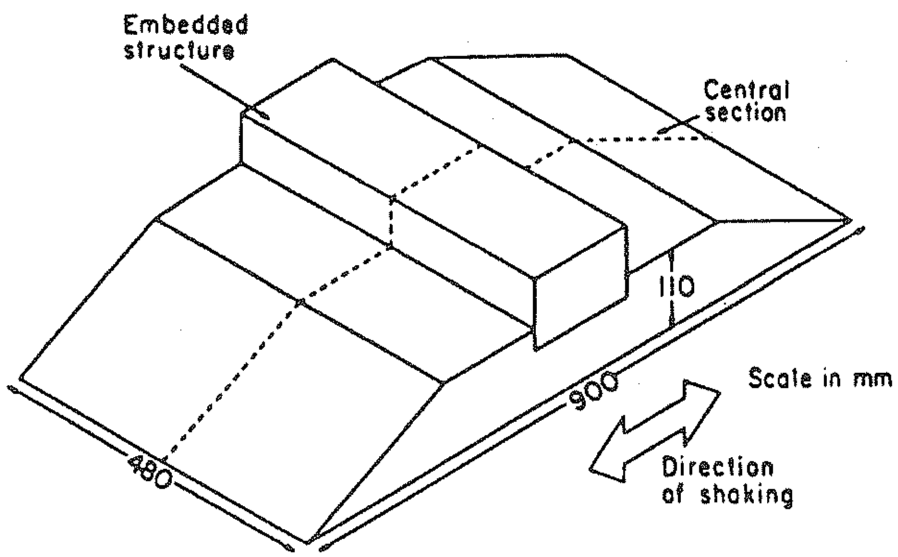

Figure 8: Model of large embedded structure in saturated sand embankment experiments at 80 g

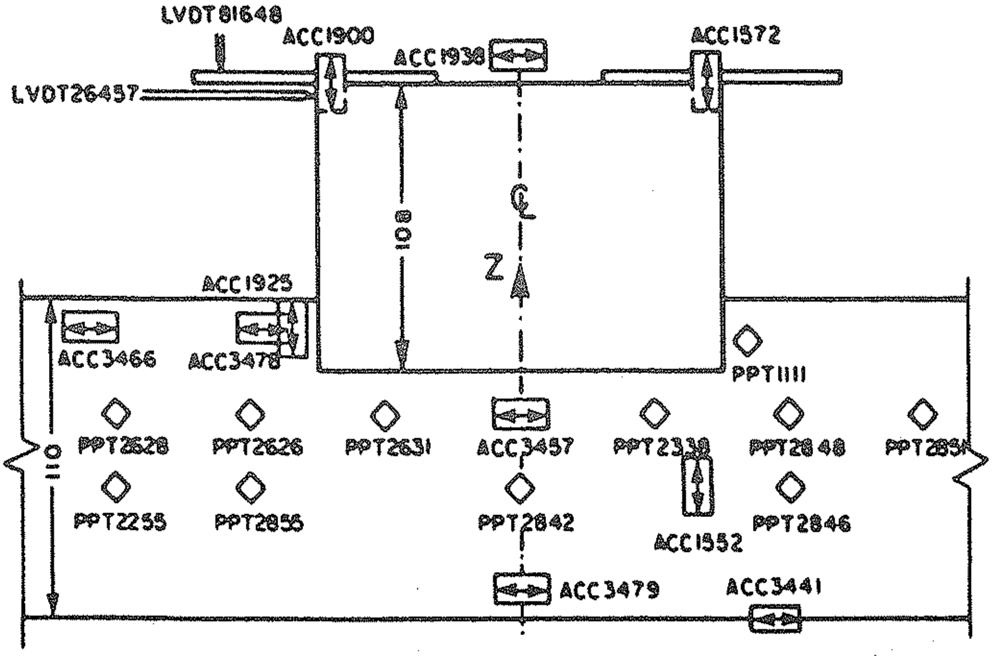

Figure 9: Location of instrumentation in central section of the embedded structure model

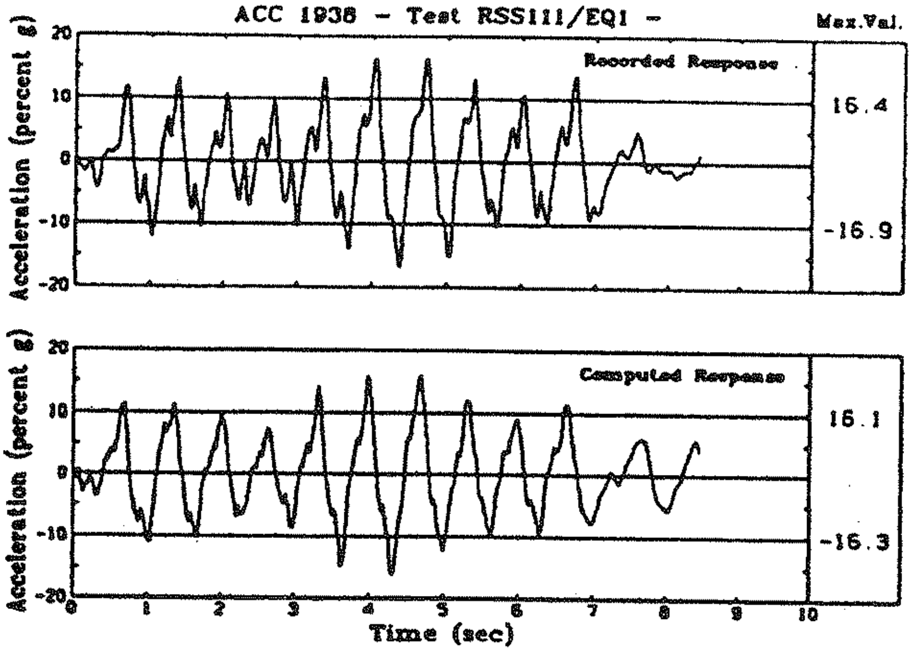

Figure 10: Recorded and computed horizontal accelerations at ACC 1938 (prototype units)

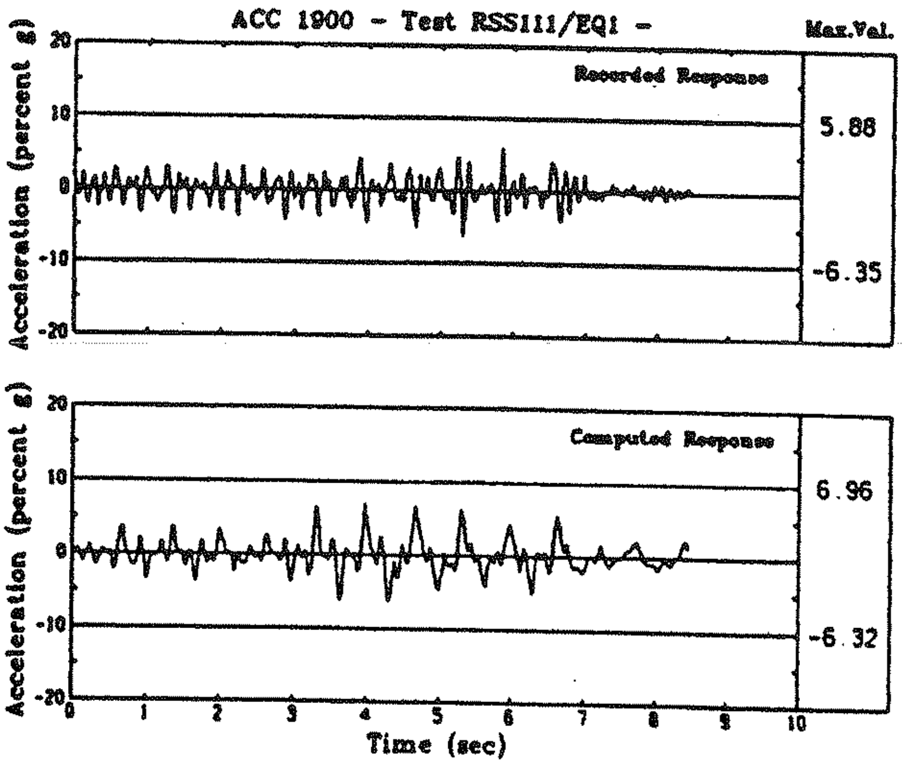

Figure 11: Recorded and computed vertical accelerations at ACC 1900 (prototype units)

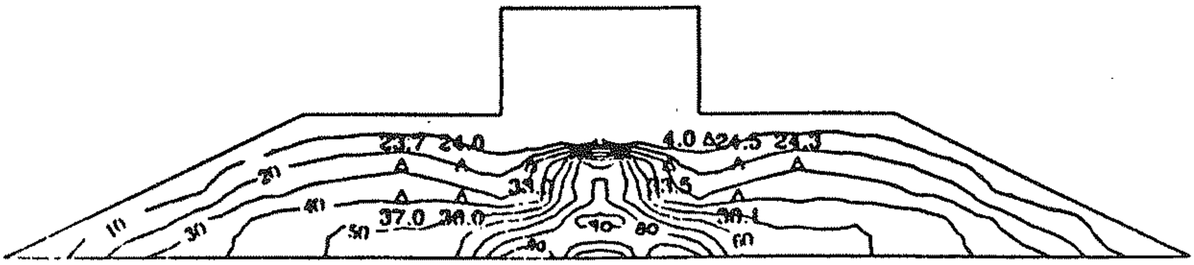

Figure 12: Residual pore water pressures in a saturated embankment model

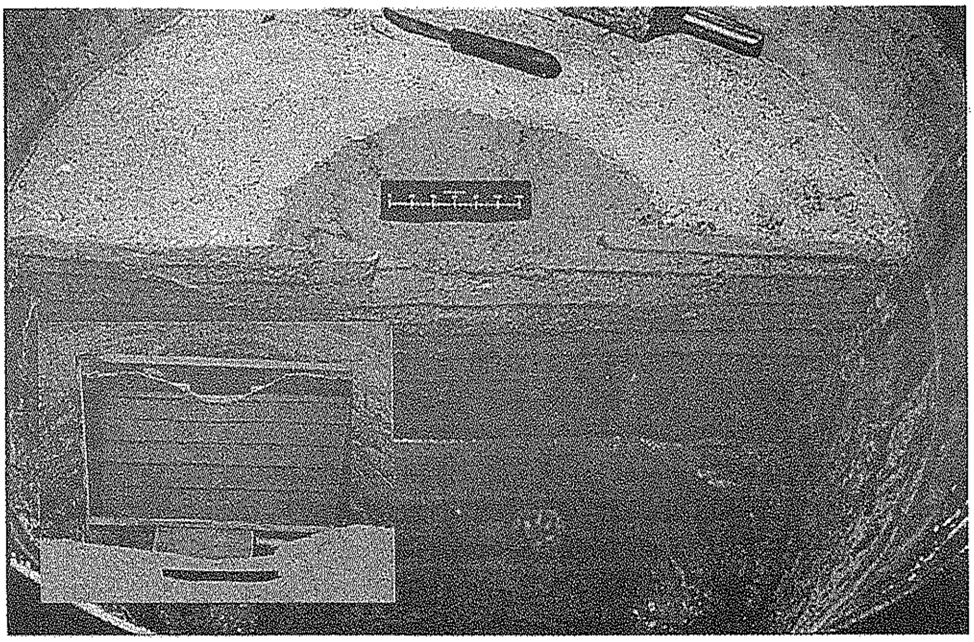

Figure 13: Crater formed in dry sand with buried charge