Dynamic Excitation for Geotechnical Centrifuge Modelling

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ABSTRACT: The method of physical modeling in the centrifuge is growing in acceptance in the U.S.A. following many years of use in U.S.S.R., Denmark, England, Norway, France and Japan. Simulation of dynamic events (machine vibration, wave forces, earthquake) in modeling in the centrifuge has important applications, especially on the large national Geotechical Centrifuge being constructed at NASA-ARC. The most difficult problem is that of earthquake simulation. Several schemes for light weight shakers have been proposed in a Workshop on Dynamic Excitation for Geotechnical Centrifuge Model Testing held in August, 1979. More recently, a scheme has been presented which utilizes traveling waves generated through a diaphragm at the side of the container which has many promising advantages and does not negate the work done in shaker development, but improves their utilization.

INTRODUCTION - THE PRINCIPLE OF CENTRIFUGE MODELING

The use of scaled models of large objects to study physical phenomena is quite common in many fields of engineering. Wind tunnels for aerodynamics and water channels for hydraulics are examples. Scaled models of geotechnical stuctures under normal gravity have a serious lack of similitude because the stress levels in the model do not match those in the full scale prototype. This defect in modeling is removed by placing the model in an increased gravitational field, making the model material appear heavier. The centrifuge is a convenient way for providing an artificial gravity owing to centripetal acceleration.

If a model of the prototype structure is built whose dimensions are reduced by a factor 1/n, then an acceleration field of n times g, the acceleration due to gravity, is required for the stresses in the model due to self weight to be the same as those in the prototype structure. If the only scaling relationship needed were to establish equivalent states of stress in model and prototype, the method would be perfect. Unfortunately, there are other characteristics of response that depend upon conditions other than stress alone.

For example, elastic stress waves in soils are governed by the wave equation, while transient flow of pore water fluid is governed by the diffusion equation. These two governing equations lead to different scaling relations for time, if all other physical properties are made the same.

In order to establish a complete set of scaling relations for a given problem, the experimenter must either utilize the method of dimensional analysis or, if the physics of the behavior is thoroughly known, analyze the differential equations governing the behavior. If similarity requirements are not completely satisfied in a particular problem, the experimenter must justify these deparatures from similarity by means of experimental evidence.

If, for example, an experimenter can show that for a wide range of scale (n = 10 to 100) the results of centrifuge model tests are unaffected by using a constant grain size of the sand used to make the models, one can conclude that similitude of grain size is not important in that particular case. Some other factors to be considered are the finite size of the experimental package, variation in g-level across the model and the methods of construction of the models.

There are two reasons why a large capacity centrifuge is needed. One is to supplement the tests performed on smaller capacity machines in verifying the range of validity of model tests in the low g range (large models). The other is to permit more extensive instrumentation made possible by larger size models and thus obtain more detailed data on deformation and stress distribution.

Problems that can be addressed by centrifuge modeling include static, dynamic, thermodynamic and fluid dynamic processes coupled with body force loading. A few examples are: explosive cratering blast induced liquefaction, earthquake response of earth structures and soil-structure interation, rubble-bed behavior during in situ coal gasification or in oil shale in situ retorts, frozen soil behavior, frost heave, off-shore structures behavior, and wave-seabed interations.

CYCLIC LOADING IN THE CENTRIFUGE

The area of cyclic loading in the centrifuge may be divided into two classes of problems, (1) wherein the cyclic loading is applied to a structure founded in soil such as in wave forces on wharves and off shore drilling platforms, and machine vibration of foundations; and (2) wherein the cyclic loading is applied to the structure from the base rock such as earthquakes.

(1) Foundation Vibration

The analytical approach in foundation vibration commonly used (Richard et al., 1970) is to modify elastic half space theory to determine the foundation response. These equations can be used to obtain scaling relationships. It remains to be seen if such relations hold in a non-elastic soil. Two dimensionless parameters appearing in the theory are:

(1) Dimensionless frequency factor

$$a_o = \omega r_o \sqrt{\frac{\rho}{G}}$$

wherein ω = circular frequency of input vibration, r_o = radius of footing, ρ = mass density of the half-space material and G = shear modulus.

(2) Mass Ratio

$$b_o = \frac{m_o}{\rho r_o^3}$$

for the translational modes of vibration, m_o = mass of footing.

The above non dimensional parameters must remain the same in the model as in the prototype in order to scale accurately a model that is reduced in size by 1/n in all dimensions, with a_o = constant, ω must increase by a factor of n. Similarly, the mass of the footing must be decreased by $1/n^3$ (with b_o = constant). This latter requirement is automatically satisfied by the scaling of the dimensions if the model footing is made of the same material as the prototype footing.

If the walls of the box containing the model foundation soil are far enough away from the model footing, the distortion of free field behavior caused by reflection or echoes from the walls can be negligible.

(2) Earthquake Response

To simulate an earthquake in a model foundation soil, two schemes have been suggested: (1) Having a box within a box and providing an actuater (shacker) that produces lateral relative motion between them. If the mass of model box is equal to or smaller than its counterpart, the motion of the model box will be the equal to or larger than its counterpart. (2) An impulsive force is applied to the side of the container which produces a traveling wave across the model foundation soil. By staging the impulsive load when produced by explosives or by controlling the amplitude and frequency of a shaker, the desired ground motion is obtained at the foundation or building site in the model.

Both of these approaches are plagued by the box effect, i.e., reflections or echoes from the side walls and the bottom which can distort the desired ground motion. However, the second approach, that of an induced traveling waves, has been shown by Zelikson, Devaure and Badel to overcome this problem. See their paper presented in this session. This may be partly due to the fact that reflections off the walls may be made part of the induced reproduceable ground motion that matches the scaled earthquake amplitudes of acceleration, frequency and psuedo-velocity spectra.

WORKSHOP ON DYNAMIC EXCITATION FOR GEOTECHNICAL CENTRIFUGE MODEL TESTING

On August 21, 1979, a workshop was held at NASA Ames Research Center (ARC) in Mt. View, California to address the problems involved with dynamic excitation in the centrifuge applied to geotechnical physical modeling. This meeting was timely because the design of the large geotechnical centrifuge at ARC was progressing and the knowledge of future extension of the facility to modeling of dynamic events was needed in order to assure that such an extension be feasible.

The design at this point is complete and is shown in Figure 1. The capability is initially 6000 lbs. of model weight at 300 g, with a future extension of 40,000 lbs. of model weight at 100 g (2,000 g-tons). When completed (early 1982) this facility will provide a valuable resource to the geotechnical community.

The general problem of dynamic excitation in geotechnical engineering involves more than earthquake excitation. The

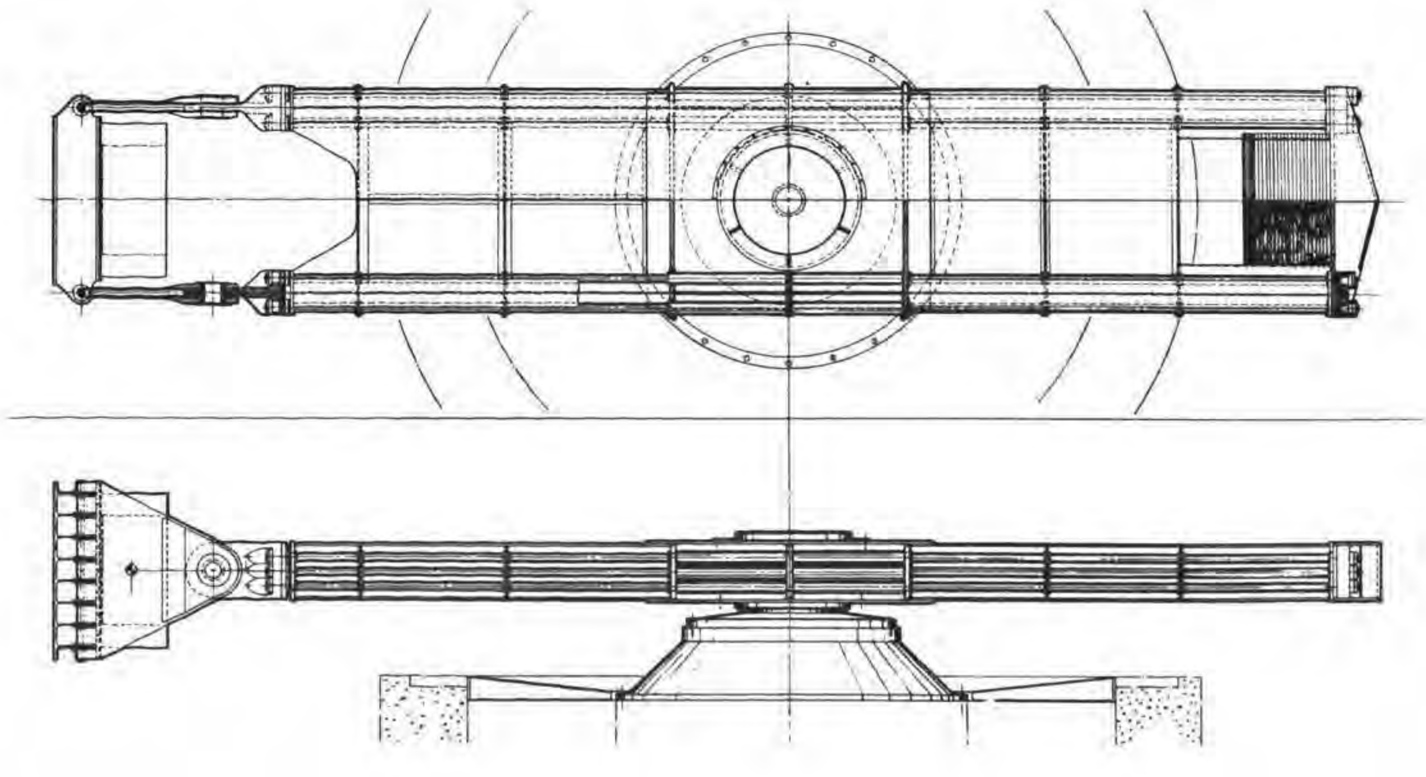

Fig. 1 NASA-Ames Research Center - Geotechnical Centrifuge

dynamic response of machine foundations, off-shore structures, piles during driving, buried structures and tunnels to impulsive loading must be included. However, the problem of simulating earthquake motion in the centrifuge is the most challenging problem that we face.

The discussion centered upon the formation of Table 1, which seeks to list the several problem areas in which centrifuge modeling with dynamic excitation is useful. It can be observed that earthquake simulation is one of many problem areas, but is singularly the most difficult in both application and theory of modeling. Serious objections are:

1. The "box effect" - traveling waves bouncing off the sides and distortion of the payload support structure violates similitude.

2. In saturated systems, the scaling law for time in ordinary dynamic events is at odds with time scaling in hydrodynamic events such as seepage and consolidation. Proposed solutions to this problem (artificial soil with finer gradation or artificial pore fluids) need to be verified.

These latter objections lead some to the conclusion that, at present, only undrained tests should be run, and that a programmable transient excitation is not really needed. Fine details need not be modeled yet. Another reason given why programmable transient excitation is not required results from the view that the principal use in geotechnical earthquake engineering should be to test theories as well as single and complex performance prediction methods. In this mode, the theory or the prediction scheme can be applied for several single harmonic modes of given amplitudes, frequencies and durations, and its performance against centrifuge data for the same cases can be evaluated. If a prediction method works well for several of these cases, it is highly probable it will also work for the programmable transient as well. However, programmable transient excitation capability is needed in true replica modeling for design or safety evaluation purposes.

Another aspect of a shaker design is the importance of payload support and guidance. Many shaker systems have been developed without consideration of the load paths and stiffness requirements necessary to transmit very large forces in a very short time.

The centrifuge itself may give rise to extraneous vibration, especially if any component is in resonance with the dynamic excitation.

The most promising areas of dynamic excitation, (i.e., having a high probability of useful results with an acceptable dynamic excitation) are those where loads are applied to the structure and fed into the soil. These include lateral loads on piles, offshore structures, and machine foundations. Interferences between piles in pile groups or multiple dynamically loaded footings and changes in the "group effect" at larger levels of strain may be a subject of study, but the interferences with the payload bucket itself must be avoided.

CONCLUSION AND RECOMMENDATION OF THE WORKSHOP

The presentations of various methods of simulating earthquakes in the centrifuge indicated that the feasibility of accurate simulation is low and will be expensive. The feasibility of modeling soil-structure interaction problems such as off-shore structure, marine structures, machine foundations, and interaction effects is high, requiring little development beyond the state of the art in dynamic shakers. The problems of blast effects and underground excavation appear to be promising, as well as water wave propagation studies and Tsunami-shore model studies.

Of all the on board shakers proposed, the simplest and most straightforward method is the cocked-spring approach of Derek Morris and the Cambridge group. Such an arrangement should be built and used on early tests. The available parameters are amplitude and frequency of the spring mass system. The next step in generating more realistic motions could be to simply add an explosive pulser to the same spring set used for the cocked-spring arrangement. Since this offers the opportunity for several additions of energy during a test, dampers could be added in order to add complexity to the acceleration histories. The parameters available for tailoring accelerograms are then:

ω = spring-mass frequency

β = damping

A_{pn} = peak acceleration from the n pulse where n = 1,2 . . . 6 HE chambers

t_{pn} = time at which the n pulse is applied n = 1,2,3, . . . 6.

The next more complex system is the hydraulic arrangement described by Klaus Cappel of Wylie Laboratories. The motions produced by this system appear to be very similar to those produced by the explosive pulser-spring arrangement, but produced by different means. The rotary valve is analogous to the spring-mass system, in that it produces a fixed frequency.

Uneven spacing of valve ports and change port wave shapes are analogous to changing HE detonation times and tailoring pulse pressure-time histories. The added feature of Cappel's proposal is the potential for easy extension to motion in two planes. However, it appears that some basic development work would be needed to demonstrate feasibility and system operation. Thus, if this system looks promising, a small breadboard version might be developed while the spring-mass systems are being used in initial centrifuge testing.

The electrodynamic system is quite distinct from the above shakers in that, in spite of the weight reductions obtained by cryogenic cooling, the electromagnetic shaker consumes a large portion of the payload weight of the centrifuge. This system appears to be useful only for a dedicated test series with extremely exacting simulation requirements as a very small model (a few hundred pounds).

The piezoceramic shaker, taken at face value, seems to be by far the best system because it offers complete electrical control over acceleration vs. time, including acoustic reproduction of an arbitrary earthquake-time history. However, the technology of extrapolation to the UC Davis NASA-NSF Geotechnical Centrifuge should be placed on a firm basis, and the resolution of items 1 and 2 in the discussion (box effect and scale distortion) should be made before proceeding. If this can be done and the cost is reasonable (=$250 K), the system should be developed quickly and the development of intermediate explosive or hydraulic shaker systems avoided.

The above conclusions were reached without consideration of the "Bumpy Road" actuator. This novel proposal was not presented at the workshop, but has come to our attention through Professor A. N. Schofield of Cambridge University, England. The first results of this scheme are seen today. The method requires a rigid stationary structure surrounding the centrifuge in close proximity and a centrifuge structure that can carry the additional forces in the radial and tangential directions owing to the tracking loads on the "bumpy road". These forces cannot be balanced on the arm and, therefore, must produce unbalanced forces and moments on the rotor

TABLE I.

PROBLEM	SPECIAL EQUIPMENT NEEDS	RANGE OF INPUT	SIZE	RANGE OF OUTPUT
Earthquake Simulation	Shaker, Control System, Structural Guides, Instrumentation	Frequency 30-1000 Hz. Force 100g Max. Stiffness of Buckets	100 Lb. Small Cent. to 10000 Lb. Medium Cent. to 10,000 Lb. Large Cent.	Stress to Failure Large Strain Large Cumulative Strain 3-D Specimens
Machine Foundations		Frequency 1000 - Up		Vibration Amplification Attenuation
Marine Structures & (Soil and Piers)	Special Bucket	Frequency 5 - 10 Hz.	Deep	Settlement, Liquefaction
Impulsive Loading on Buried Structures	Methods for Achieving Large Impulsive Load	Single Pulse		Pressure Transmission Fracture, Buckling
Pile Driving	Miniaturized Pile Driver	Repetitive Blows		SPT Correlations
Subsurface Excavation & Bin Action		Quasi-static		Block Caving Criteria
Transient Water Waves		Impact or Deterioration Periods .03 to .15 Sec. at 100g.	Shallow but Wide Large Bucket	Transient Response Near Source
Cratering (Contributed by L. K. Davis of WES)	Mounting for Projectile Firing Device, Facility Capability to Take 0.1 psi Airblast Inside (No Conventional Windows)	N/A	No Special Requirement Beyond Those Presently Planned for the System	Crater & Soil Flow Measurements, High Speed Photography of the Specimen

bearings. These concerns are not insurmountable and further, the Cambridge University centrifuge is now being modified to include the "Bumpy Road" mechanism, and data on its performance should be available before the end of 1980. This method of dynamic excitation for the centrifuge merits serious consideration.

The development of an earthquake simulator for the centrifuge will be costly and subject to serious questions of similitude, especially in saturated media. Nevertheless, the importance of earthquake problems in the national interest may justify the effort required to resolve these objections and to obtain the physical data needed.

TRAVELING WAVE SCHEME

All the excitation schemes presented at the workshop involved shaking the whole model container. The presentation of the alternative scheme, that of producing a traveling wave through the soil model described by Zelikson, Davaure and Badel, is equivalent to the field tests being developed at SRI International by Bruceand Lindberg (1981) and Higgins (1981), wherein earthquake motion is simulated by staged explosions in the ground.The scheme has several advantages.

1. The force required to actuate the motion is smaller than that required to shake the whole model container.
2. The problem of wall reflections or echoes can be treated successfully.
3. The force input can be made self equilibrating, thereby eliminating the need for a large reaction mass or a large imbalance transferred through the centrifuge supports.
4. The scheme is not limited to explosive excitation. All the methods of excitation proposed could be modified to provide an impulsive loading through a diaphragm to the model soil with a self equilibrating reaction to the container.

CONCLUSION

The present session on cyclic loading in the centrifuge serves to add to the ongoing dialogue on methods of dynamic excitations for centrifuge modeling. The French proposal offers an intriguing possibility, worthy of further development and study.

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