FINAL REPORT

WORKSHOP ON CENTRIFUGAL TESTING OF GEOTECHNICAL MODELS

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December 16 and 17, 1975

WORKSHOP ON CENTRIFUGAL TESTING

OF

GEOTECHNICAL MODELS

California Institute of Technology
December 16 and 17, 1975

ATTACHMENTS

(1) Pre-conference material,
List of attendees

(2) Program

(3) Complete bibliography

(4) December 18 report

(5) Dr. Charles C. Ladd's letter

(6) Mr. Gordon W. Dukleth's paper

ATTACHMENT #1

Pre-conference material

and

List of attendees

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Dr. Charles A. Babendreir
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Dear Dr. Babendreir:

When scaling relations are established for certain materials, including soil, it is found that satisfactory model tests can only be performed if an increased gravitational acceleration is employed in the model. For this reason, in the past 40 years in the USSR and 10 years in Europe, centrifugal testing of soil and rock models has been intensively pursued.

The method has been applied to a wide and increasing variety of problems in the earth sciences. Problems studied have included soil, rock, and photo-elastic materials, and have concerned concrete dams, structural stability, and transient water flow in soils. In certain cases, where it has been applied to situations which have later been studied in field tests, or in computer simulations, it has been reported to give satisfactory prediction of performance. On the other hand, questions have been raised about the correctness of centrifugal modeling, and some of these are still to be answered. A brief history of the technique and a short bibliography accompany this letter.

It is possible that the absence of centrifuge developments for geotechnical purposes in the United States has been due to the lack of ready availability, until recently, of papers and discussion on the technique. The suggestion has been made also that the progress in and accessibility of large computers in the U.S. as compared to the USSR has diverted attention from alternative geotechnical approaches. For example, at a September 1973 workshop, "Simulation of Earthquake Effects in Structures", the possibility of centrifugal modeling was not even mentioned.*

Whichever is the case, this seems an opportune occasion to open a general discussion on centrifuges, centrifugal testing of geotechnical models, and the advantages and drawbacks of the method. To this end, a Workshop on Centrifugal Testing is being held at the California Institute of Technology, on 16 and 17 December, 1975, under the sponsorship of the National Science Foundation.

I hope this brief historical background will excite your interest if you are not already aware of developments in the technique. As part of the preparation for the meeting, I am duplicating a number of what I consider the more important references for incorporation in a booklet on the centrifuge technique. This will be mailed out to indicated participants a month before the Workshop, to give some of the basic information prior to the meeting. I invite your participation in the Workshop and hope you can arrange to attend. A card for your response is enclosed.

Yours sincerely,

RONALD F. SCOTT
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* National Academy of Engineering, "Earthquake Environment Simulation", Washington, D.C. 1974

RFS/nh
Enclosures/3

BRIEF HISTORICAL BACKGROUND

OF GEOTECHNICAL TESTING BY CENTRIFUGE

The technique of centrifugal testing of model soil and rock structures was initiated at about the same time in the early 1930's in both the United States, by P. B. Bucky, and the Soviet Union, by G. I. Pokrovksy. Bucky performed tests on the stability of mine openings, by using extremely small models in a centrifuge with a radius of about 0.2 meters; the tests were conducted at centrifugal accelerations up to 2000g. Bucky postulated tests at up to 15,000g on an apparatus with a radius of 3 meters! The technique did not apparently meet wide acceptance in geotechnical work in the U.S. and only a few experiments have been carried out. In contrast, the work begun by Pokrovsky and his colleague, I. S. Fyodorov, in the USSR led to widespread use of centrifuges for soil engineering purposes in the Soviet Union. The method is actively being pursued there at present. Pokrovsky started out with soil models and used larger centrifuges, up to 1.5 meter radius, at lower accelerations, less than 100g, in his early work than Bucky.

In the early 1960's H. Ramberg, a Swedish geologist and a number of his students began an extensive series of tests in model geological structures, in studies of the stability of various tectonic processes. In the middle 1960's, A. N. Schofield in England, after some preliminary investigations of the stability of clay slopes under rapid drawdown conditions in a small centrifuge, undertook the construction of a large centrifuge (1.5 meters radius, 750 kg package, acceleration to 130g) for geotechnical tests, at the University of Manchester Institute of Science and Technology (UMIST). This machine was followed by the installation of an even larger machine at the University of Manchester under the supervision of P. W. Rowe. Experience has now been accumulated on a large number of model tests of soil structures, carried out on these centrifuges. At Cambridge University, where Schofield began his centrifuge studies, work by students of K. H. Roscoe and C. P. Wroth continued on a centrifuge facility rented from a British aerospace company while design and construction proceeded on a much larger facility (5 meters radius, acceleration to 300g). This centrifuge has been completed and preliminary studies are now underway. Geotechnical work has also been done on centrifuges in Japan, Denmark, and France.

From these efforts in Europe, a number of theses, reports, papers, and at least four books have emerged. A partial bibliography accompanies this letter.

There are at least three, and possibly four areas where centrifugal modeling appears of value in the geotechnical sciences: (1) Reduced scale testing of actual or proposed structures. In this application the real soils or real rocks are employed in the model in corresponding scaled model layers. The usual difficulties and questions regarding sampling techniques, and the representative nature of samples are encountered. However, model results of mechanisms, displacements, pressures, times, and forces are scaled directly to predict the prototype performance.

(2) Testing of soil models at real stress levels but with idealized geometrical or boundary conditions. The model, for example, an earth dam, may be constructed of one soil type, whose deposition is arrranged so that it will be homogeneous as nearly as can be achieved. In this case, on comparison with analytical or numerical analyses, the performance of the model upon loading can be used to identify those aspects of behavior which depart from the idealized relations used in analysis. Suitable arrangements of testing of type (2) may, in addition,elucidate the constitutive relations of material behavior.
(3) Testing for educational purposes. By means of the centrifuge, deformations and failures can be induced in structures under effectively full-scale load and stress conditions. Still, motion-picture, or video tape records of structural behavior can illustrate classroom precepts under circumstances which could not be attained in a prototype structure.

When testing in a centrifuge, it is possible, particularly in cases of geological and mining problems, to use a material whose properties are also reduced, to enhance the scale effect. This will always cause questions to be raised about the correspondence of model and prototype material relations.

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October 20, 1975

BRIEF BIBLIOGRAPHY ON CENTRIFUGAL TESTING OF GEOTECHNICAL MODELS

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The bibliography is intended to be a short illustrative list of papers from diverse areas of geotechnical testing. Bucky wrote one of the earliest papers in 1931 on the stability of the roofs of tunnels in mines. He used the technique of stroboscopic light flashes, new at that time, to get some of his data. Mining studies have been continued by Hoek and by Russian investigators as reported in the second volume of the book by Pokrovsky and Fyodorov. This is one of only three books on the topic; of the other two, the one by Ramberg describes his centrifugal studies of geological stability problems caused by material density differences in a gravitational field. The other, a recent book by Malushitsky is concerned with the stability of soil and rock embankments in a wide variety of conditions.

The theory behind model and centrifugal testing is discussed by Roscoe, as well as in Pokrovsky and Fyodorov's book. Roscoe was interested in soil model tests of which a number of examples are given in the other references. The earliest readily-available Russian paper is the very short one by Pokrovsky and Fyodorov in the first international soils conference. Preliminary work in England is described by Avgherinos and Schofield in a paper on slope stability, a topic which is further examined by Bassett, and Smith and Hobbs, who carried out some numerical analyses.

Other aspects of soil mechanics have been studied by Ovesen, and Mikasa and Takada, who were interested in the behavior of footings on sand. Ovesen points out a problem in centrifugal testing, the change of friction angle, with acceleration. The general application of centrifugal methods to field studies was discussed by Rowe in a paper of wider range. Laut has concerned himself with seepage problems, especially those of polluted liquids in a paper of environmental interest.

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ATTACHMENT #2

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December 16 - 17, 1975

sponsored by
California Institute of Technology
and
National Science Foundation

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ATTACHMENT #3

Complete bibliography

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ATTACHMENT #4

December 18 Report

CALIFORNIA INSTITUTE OF TECHNOLOGY

PASADENA, CALIFORNIA 91125

DIVISION OF ENGINEERING
AND APPLIED SCIENCE

CENTRIFUGAL TESTING OF GEOTECHNICAL MODELS

REPORT ON DISCUSSION, 18 DECEMBER 1975

1. Introduction

Following the workshop meeting on December 16 and 17, R. F. Scott convened a meeting of a smaller group on December 18 to consider the material presented from the point of view of the future of centrifugal testing in the United States. He wanted to develop some conclusions and recommendations as to whether or not and how the technique might be brought forward. If it was felt to be a promising approach, he felt the group should consider size, number and distribution of centrifuges that might be required.

When the meeting started, Scott began by saying that he had organized the meeting with National Science Foundation (NSF) support for the purpose of bringing centrifuge technology to the attention of people in the geotechnical area in the United States since it had received widespread application in Europe. The people in this selected group were all knowledgeable in various areas of geotechnical work ranging from soil mechanics through rock mechanics to geology and geophysics. He wanted to get their feelings on what they had heard in the previous two days and how they thought the technique might be useful in their specialized fields of interest. With an outline of his thoughts from each person, Scott would attempt to summarize the overall situation in a report which would be forwarded to NSF. Negative or critical, and positive attitudes were equally welcome, since the report should fairly represent informed opinion. He recognized that it would not be completely representative since people who felt the technique had little usefulness had presumably not come to the meeting. Each of the members was then asked to give a brief rundown of the kind of problems in his field which he thought might be susceptible to centrifugal testing and his opinions as to the use of the method. The discussion began in the soil mechanics area and ended in geophysical applications. Only brief summaries of discussions are presented here in the order in which they were given.

2. Soil Mechanics and Engineering

J. Wool:*
His interest lay in the problems of dam owners, both public and private. Of particular concern was the performance of earth dams during strong earthquake ground motion. The 1971 San Fernando earthquake had caused many changes in views of the safety of dams in California. Following the earthquake, the Division of Safety of Dams, State Department of Water Resources, required 29 hydraulic fill dams under their jurisdiction throughout California to be checked for safety during future estimated strong ground motions. This review of hydraulic fill dams has been completed, and many of the dam strucutures were found to be potentially unsafe.

The second phase of the program, the dynamic stability evaluation of certain other dams, is now in progress in the State. Since not all of the structures could be rebuilt, the consequence of these investigations has been that many reservoirs must be operated either at reduced water levels or, in extreme cases, maintained empty in order to meet safety requirements. Some dams have been strengthened or rebuilt and plans have been made to reconstruct or alter others. The nature of the problem requires description.

Two very destructive earthquakes which affected modern structures, occurred in Japan, at Niigata, and in Alaska in 1964. Investigation indicated that soil liquefaction played a substantial part in the damage that developed. This phenomenon had been extensively studied since that time with the result that questions had arisen about the ability of earth dams in particular to survive earthquakes without liquefaction. Then the San Fernando earthquake happened and caused almost catastrophic damage to the Lower San Fernando dam through liquefaction of a portion of the fill.

A method of analysis had been developed, largely by the engineering school at Berkeley, to evaluate the liquefaction potential of an earth dam shaken by selected ground motions under a given design earthquake. The method utilizes a combination of field investigations, laboratory test results, and finite element computer analysis in order to arrive at its conclusions. A number of empirical constants are employed at various stages. These are arrived at partly by judgment and partly by making the results of the analysis fit the observed outcome in a number of cases of observed liquefaction behavior. It is the use of this method which has resulted in the necessity for redesign, reconstruction, or the imposition of operating restrictions on many dams. No practical tests of the applicability of the method have been made so far except in calculations that confirm the behavior of the San Fernando Dam (Upper and Lower) during assumed 1971 earthquake shaking levels at the site, plus the general behavior of the Sheffield dam in Santa Barbara during an earthquake in 1925. As a consequence, he feels

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* For affiliation, see list of participants in appendix.

that the analysis, considering the assumptions made in its derivation, is ultraconservative, especially in the cases of well-compacted dams on materials not subject to liquefaction. Some other method of analysis or test is needed as confirmation. Since full-scale tests are impractical he feels, from what he has heard, that the centrifugal method of testing could well be such an alternative method. This is contingent upon the development of the ability to correctly duplicate the appropriate shaking in the model that would produce essentially the same effects on the model as the design earthquake would on the full-sized dam. If this can be done, it appears that good indications of the three-dimensional deformations of dams could be obtained--something that is greatly needed at this time. It would not be necessary to check every dam, but several typical configurations could be tested in model form in centrifuges for comparison with parallel analyses. It would be desirable to make the models as large as practical. This would involve utilizing a large centrifuge.

In response to a question by A. N. Schofield, Wool discussed the current cost of a typical dynamic finite element stability analysis. In the case of Stone Canyon Dam, for which a study is now being performed, the total cost of field drilling, sampling and testing plus laboratory testing, design earthquake criteria from consultants, the computer work, and preparation of the report is estimated to be $170,000. This dam has a maximum height from bedrock to crest of 235 feet. For Los Angeles Dam, which is the dam now under construction that will replace the Upper and Lower San Fernando dams severely damaged by the February 9, 1971 earthquake, the bill for earthquake evaluation and stability analysis was approximately $230,000, not including the cost of field testing and sampling. E. L. Dodson of the Corps of Engineers commented that a dynamic analysis of Fort Peck Dam, the largest earth fill dam (by volume) in the United States, was recently undertaken. The total study cost $400,000 of which one half was spent on the field investigation. A question was asked on the present status of the dam analysis process of the Department of Water and Power. Wool said that the second phase of the State program includes the analysis of 10 additional Department dams. Two studies have been completed, and the present schedule calls for the completion of approximately one analysis per year for the next several years.

Wool also indicated that they had, of course, other dynamic problems which were principally in the area of pipe and culvert design for earthquake resistance. These structures were mostly sensitive to geological and faulting problems which would be brought up later in the discussion. Wool was also asked about the position of the Department with respect to nuclear power plants. He said that responsibilities in DWP were distinctly divided between the water and power areas and he had little involvement with the latter. Scott said he might make a few remarks on this subject.

R. F. Scott:
Because of their large cooling-water requirements which necessitated construction close to the sea or large rivers, nuclear power plants are frequently founded on deep alluvial deposits of saturated soil. Therefore, in his experience it had frequently turned out that the controlling foundation design requirement for a nuclear power plant hinged on the possibility of liquefaction of the underlying soil during a design earthquake. This was true whether a plant was established on the West coast, normally thought of as seismic area, or whether it was built on the East coast or in central U.S.A., neither of which are considered seismically very active. Current liquefaction analysis almost always indicated for all earthquake motions considered in nuclear plant design that the natural soil would liquefy. In these circumstances the same general approach to the analysis of liquefaction potential was employed as was used in the case of design of earth dams.

Frequently extreme and costly construction measures had to be undertaken in order to prepare or condition the foundations of these plants to make sure that such postulated liquefaction would not take place. Although it was not possible to say in the absence of full-scale tests whether or not the method was truly indicative of the liquefaction potential, it was true that the design requirements imposed by liquefaction protection procedures frequently appeared extremely conservative compared to current foundation design practice. Nuclear power plants also represent a situation in which soil-structure interaction is more important than in the case of earth dams. In either event an alternative method, such as centrifugal testing, of assessing or evaluating the analysis procedure would be extremely useful.

Discussion continued with the following comments by the Corps of Engineers representatives present; they were concerned with a variety of soil mechanics problems.

E. L. Dodson:
He pointed out the wide involvement of the Corps of Engineers with both static and dynamic soil mechanics problems. In regard to Mississippi River banks and levees and the potential for soil liquefaction under static conditions, they had already talked with Schofield concerning the possibility of studying these problems using the Cambridge University centrifuge.

In addition, they have been engaged in a study of a variety of procedures, such as the Berkeley approach and the University of Michigan characteristic methods, to analyze the dynamic liquefaction potential. In each case, however, rather similar assumptions were required and he also would like to see an alternative procedure developed for either analysis or the testing of analyses. Many of their problems were concerned with soil-structure interaction in particular and this would be an important area where the centrifuge might make a useful contribution.

W. Sherman

As an illustration of their concern, he said that the Corps of Engineers, in their search for alternative analysis procedures, had even given consideration to building a dam at the Nevada test site where it could be shaken by nuclear blast ground motions. Although of short duration, these might give effects similar to an earthquake.

In addition to conventional civil analysis and design procedures, the Corps of Engineers was also heavily involved in the design of structures to protect against the effects of nuclear weapons. To this end, they were interested in the results of projectile penetration distances in soil, cratering effects, and wave propagation. Naturally, they were also concerned with the protection of dams from the effects of nuclear or conventional weapons and were interested in the behavior of dams under the dynamic loading imposed by such weapons.

He mentioned that he had recently been in the Soviet Union where he had examined a centrifuge at the Institute of Bases and Foundations. This machine had a radius of 2 meters and a capability of 200 g. While he was there they had discussed another centrifuge in Baku which was primarily used for earthquake engineering studies. The Corps of Engineers for some time had been considering the use of centrifuges in geotechnical model testing, but felt that they would probably be unable to afford the construction and maintenance of a large facility on their own. For this reason, they had been considering approaching other agencies with the purpose of possibly establishing an inter-agency large centrifuge facility. A report on centrifuge testing techniques had been prepared and would be available in the near future.

C. C. Ladd:

Said that his particular area of interest involved construction on soft ground, especially clays. In many cases of practical interest, it is not possible to measure what goes on in the field since the processes are too long. Settlements may well not be substantially complete for many tens of years. As a consequence, little experience exists to enable evaluation of methods of predicting rates and amounts of settlements. At present, largely empirical methods of prediction are used and he felt that the centrifuge may well give insights into the mechanics implied by such methods. There is a wide variety of structures for which predictions of stability and settlement are required. All of these cannot be examined, but the centrifuge may be useful in studying one or two typical problems such as oil tanks on soft ground, for example. He thought it could be employed in pursuing fundamental research with varying soil types into a number of problems in which the boundary conditions could be matched. He gave the following summary of his conclusions.

1. The U.S. should support centrifugal testing as applied to geotechnical engineering.

2. The initial support should emphasize the development of one very versatile and well-staffed facility for the purpose of:

   a. Performing research on selected topics.
   b. Serving as a training center to develop the expertise needed to open other facilities if the research proved beneficial (and, if so, to investigate new areas).

3. The research areas should be of three types:

   a. Typical topics currently being studied by centrifugal methods in Europe so as to facilitate a transfer of technology, say two on soil-structure interaction and one on soft ground construction.
   b. Two or three topics of importance, but having a relatively low degree of risk (these may include one or more of the above items).
   c. One or two topics of importance, but with an admittedly high degree of risk, such as probably applies to earthquake engineering.

M. E. Harr:
He was glad to see interest developing in centrifuges. He had submitted a proposal for centrifuge research to NSF in 1961-62 but it had been rejected. Eventually he got some funds from Highway authorities to study the effect of repetitive acceleration loadings on soil properties. A small centrifuge was obtained and triaxial tests run in it at different levels of acceleration to study possible changes. This work was described in a thesis by H. D. Sharma. Some property changes were found but were not sufficient to justify a continuation in the research.

(Some general discussion ensued at this point with the general conclusion that the changes which had been obtained probably were not the result of accelerations.)

Harr also is in possession of Dr. L. A. Panek's U.S. Bureau of Mines centrifuge but it is currently in storage and he has not used it. He also mentioned a growing interest in the study of probabilities of failure in soil mechanic situations. He thought that centrifugal studies could play some part in examining such questions.

3. Rock Mechanics and Engineering

During his talk at the centrifuge meeting of the previous day, Dr. Hoek* said he thought centrifuges had considerable potential in the study of both relatively small-scale soil problems and large-scale problems of

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* Golder Brawner and Associates, Vancouver, B.C., Canada; unable to be present at this discussion.

crustal deformation. On the other hand, he felt on the basis of his experience that centrifuges were of less value for studying intermediate-scale rock mechanics problems at small to intermediate depths. These were, he felt, unsuitable for centrifuge study because the behavior of rock masses in these zones was principally dictated by the joint, fault, and fracture patterns in the rock. Since one could not reasonably expect to model these features at the scales employed in the centrifuge, he thought that the mechanisms that would appear in centrifuge model tests would not correctly represent those of full-scale materials and tests.

S. Green
He did not think that Hoek's lack of enthusiasm for the use of a centrifuge in such intermediate-scale rock problems meant that it was of no use whatsoever. He could visualize a number of rock mechanics situations in which the centrifuge could be very useful. He cited its application to "long wall" mining and to mine caving problems.

In addition, he felt that the technique might have a considerable amount of use in petroleum engineering in the study of changing subsurface oil and gas pressures and their effects on subsidence or consolidation. As an example of the latter, he referred to the problems that existed with very high pressure gas fields on the Gulf coast. It is not known whether these gas pressures will substantially decline following production. The conditions attendant upon such field behavior might lend themselves to study by centrifugal models. Another possibility was the investigation of the potential for subsidence in geothermal areas where large quantities of hot water or steam might be pumped out of the ground. Such subsidence could cause damage to the casing and piping needed to develop such areas.

Finally, a further area of interest to him was that of nuclear bomb blast test effects. He felt that it might be worthwhile to study wave propagation in typical terrestrial materials in order to assist in the analysis of wave effects from nuclear tests. Another possibility was the investigation of block and joint movements by appropriate selection of centrifugal models.

Scott pointed out that there would be some scaling difficulties in some of the problems mentioned by Green. Typically such rock mechanics problems might involve in the prototype scale dimensions of hundreds or thousands of meters which could not be reproduced properly on the centrifuge at a few hundred g. Therefore, it would be necessary to scale the model material as well as the acceleration in order to meet the scaling laws requirements. This always, of course, raised questions regarding the identification of model and real material behavior.

D. Gault
His interests lay in the field of planetary science, in particular, the influence of impact craters and cratering history on planetary surfaces. He had a number of concerns which might find application in centrifugal

testing. One of these is the effect of the gravitational field on the size and shape of the crater excavated. He referred to the spectrum of crater morphologies exhibited on a planetary surface. The small craters are essentially bowl-shaped whereas very large craters have much smaller depth to diameter ratios since they are gravitationally unstable when formed. At about the 10 to 15 kilometer diameter size on the moon, for example, crevices appear on the crater walls, presumably as a result of slumping. At larger sizes, central peaks appear until, at very large dimensions, complex central structures make their appearance. As the crater grows extremely large (for example, Mare Orientale on the moon), concentric rings of mountain ranges are formed surrounding the central zone.

Experiments have been performed at Ames Research Center on craters formed in granular materials by the impact of hypervelocity objects. Craters up to 1 meter diameter have been created. In addition, they have tried a number of experiments in which craters have been formed in targets while the target was decelerating at a high level of g. This would correspond to centrifugal studies at high g levels. He considered that the centrifuge might be useful in extending the model studies to values of g very much greater than 1 in order to study the development of terraces, central peaks, and other phenomena associated with large craters.

A current interest relates to the problem of firing penetrometers from a Martian orbiter in order to land instruments on the Martian surface for the purpose of remotely carrying out seismological, meteorological, or chemistry experiments. He would certainly like to review the applicability of centrifugal testing to such studies.

R. Bjork:
He was also concerned with cratering studies but in a more quantitative way in association with Department of Defense work. In his studies he had encountered problems with the scaling laws which affect the size of craters. As Gault had pointed out, it is observed that large craters are relatively shallower than small ones on the earth's surface. How was it possible to extend high explosive cratering data to, for example, the results of nuclear tests? Much of the experience of the nuclear tests was based on the craters formed in Pacific nuclear cratering sites. These, he felt, were probably not applicable to other rock or alluvial sites. He thought that liquefaction may well have played a considerable part in the final shape of craters formed in the Pacific.

Another area of his interest coincided with that of the Corps of Engineers personnel in that he was concerned with the vulnerability of earth dams to bombs. It is known that the soil behavior in small model tests is not correct in such studies, and he felt that centrifugal tests could well be useful.

A further possibility would be the study of the generation of either surface or internal (density differences) gravity waves induced at sea by explosions.

He noted that the Naval Ordnance Laboratory at Whiteoak, Maryland, had a large centrifuge which had been employed in bubble collapse studies. Other centrifuges are also available in various defense or NASA-related centers.

In discussion, Schofield pointed out that in cratering studies the effect of Coriolis forces would have to be taken into account since, otherwise, distorted crater shapes or particle trajectories would be deduced from the experiment. Sections of Pokrovsky's book applied to this problem. Pokrovsky indicated that for Coriolis effects not to influence the test results, the particle velocities should lie below about 1½ meters per second or considerably above 60 meters per second. Velocities in the region (1.5 to 60) within these limits would result in distortions. Bjork commented that it could be arranged for particle trajectories to lie in a preferred direction to minimize Coriolis effects.

At this stage in the meeting, attention was turned to problems on a still larger scale, those of rock deformation and flow in the earth's crust and mantle.

4. Geology and Geophysics

J. Dixon

He was interested in quantitative geology to the extent that he would like to understand the amounts of strain and the mechanisms of displacement in problems of crustal gravitational instability. He already possessed a small centrifuge with which he was pursuing studies similar to those he had undertaken with Ramberg. His centrifuge had a radius of 25 centimeters and a capability of 1000 g. He was using it to compare rock fabric as obtained in the centrifuge with that indicated by field studies as a function of strain in the material elements.

Some discussion ensued between Dixon, Ramberg, and other members of the group regarding the desirable upper limit for a centrifuge to be applied in these studies. Ramberg felt that with workable specimen sizes, mechanical and other considerations would limit the maximum g's usefully attainable to about 10,000.

H. Ramberg:

Said that there are a number of problems of stability in geology which remain to be investigated. He felt that there was considerable promise in looking in the areas of chemical and thermal equilibrium as applied to geological problems. Thermal equilibrium investigations would require running geological problems in a centrifuge with the capability of simulating the appropriate thermal environment. For this purpose, he would think that an extreme value of acceleration which could prove useful to both geological and geophysical problems would be about 5,000 g.

H.-P. Liu:
Remarked that centrifuge modeling techniques could be applied to the study of earthquakes, particularly to premonitory effects which might be used for earthquake prediction. Because of the long recurrence time between major earthquakes (on the order of 50 to 100 years), centrifuge modeling could be a useful method to study the surface tilts, changes in wave velocities, etc., in models of the earth's crust before fracture. If a realistic crustal model of a fault could be built on a large centrifuge, the results of the model study would serve to guide the locations of field instrumentation. Theories of earthquake focal mechanisms could also be tested on the centrifuge. Because of the size of the problem, it would be necessary to model the material as well as the scale as controlled by the centrifugal acceleration available. However, the kind of material that he was interested in modeling would be one with elastic-brittle characteristics rather than the viscous or plastic behavior associated with Ramberg's or Dixon's experiments. In an appropriate fluid-filled porous model material, he felt that it would be possible to study the behavior of a dilating medium and the effects of the pore fluid in relation to earthquakes.

Further, it might be possible to examine the question of the occurrence of earthquakes which appear to have developed as a consequence of dam construction and reservoir filling. It is not known at present if the weight of water in the reservoir or resulting pore pressures in the underlying rocks has played the important part in the generation of earthquakes.

5. General Discussion.

C. A. Babendrier:
He suggested that environmental controls be retained if centrifuges were to be adapted from aerospace to geotechnical problems. If this were done, it would be possible to simulate certain extreme environments in geotechnical problems such as were encountered in arctic areas or in connection with the ocean floor. It might also be useful to apply centrifuges to studies of biomechanical problems and possibly gravitational effects on plant growth. (It had been pointed out previously by A. Giovannetti of Ames that a centrifuge was in use at Ames for raising rats at levels of a few g in order to see what was the continued effects of high g on growth and development of mammals.)

There were a number of other areas in which Babendrier felt centrifugal investigations might be of interest. Some were of a structural nature, including the collapse of cooling towers for nuclear and thermal generating stations, and possibly studies of concrete creep such as had developed in the ~~John Hancock~~ Water Tower Plaza building in Chicago.

Some comments ensued upon the size, operating conditions, and cost of centrifuges for geotechnical purposes. Green considered that the purchase and operation of a centrifuge machine would involve about the same level of sophistication as that involved in an MTS testing machine. He thought that approximately $150,000 to $200,000 would be adequate to construct a machine equivalent to the one employed at Cambridge University. The nature of operational management would require further study.

Scott addressed a question to Schofield: "What did he consider would be a 'big' machine and what would be the upper size that might be feasible to operate?" Schofield said that to him 'big' but still feasible would be a 2,000 g-tonne machine of which he would like to see one in the United Kingdom, professionally operated, maintained, and run as a national facility. He went on to discuss the redesign of the machine at Ames and indicated that he would prefer to see a bigger package on a shorter radius arm than had been proposed. The object would be to subject a larger specimen to a lower level of g, say perhaps a maximum of 100 g. The arm would preferably incorporate a swinging specimen container so that the test would align itself with the acceleration field. Scott pointed out that there might be a question of the ability of the Ames centrifuge DC motor to perform satisfactorily with these requirements.

R. F. Scott:
He summarized the discussion so far in terms of the particular needs for centrifuge machines. It appeared to be clear that some level of expertise must be developed in the country first before attempts could be made to build and operate very large machines. It would seem to be desirable to encourage the use of a number of machines at something like a 2 meter radius and perhaps 20 to 50-g tonne level. At the same time there would appear to be a considerable need in the intermediate period for a few machines capable of sustaining payloads in the range of 200 to 300 g tonnes; these would be about the same size of device as is currently operated in England at Manchester and Cambridge. Considering the range of problems that had been presented, it would also appear that the presence of one very large facility at about the 2,000 g-tonne level mentioned by Schofield could also prove of considerable advantage. Such a facility would have capabilities in excess of even what was proposed to be developed at Ames and would require a detailed study in its own right. If such a machine were to be considered, it would be desirable to examine the possibilities of introducing new design concepts for it such as the incorporation of the payload in a vehicle in a tracked circular tunnel.

In summary, since the apparent consensus of opinion at this meeting was that useful advances could be made in geotechnical work by the use of centrifuges, a spectrum of machines would yield the best mix for the range of problems to be studied. This would consist of some small machines at the university or individual corporation level, a few large machines perhaps at the inter-agency level (for instance, Corps of Engineers, NSF, Bureau of Mines, Bureau of Reclamation), and possibly one very large machine operated preferably as a national facility. The development time scales associated with these would range from months to a year for the small machines, up to one or two years required for design and construction of a very large machine.

Finally, it had been apparent from comments by a number of people during the conference that many centrifuges existed, particularly at the various NASA centers and government contractors throughout the country. Many of these saw little current use. A very suitable first step would be to take an inventory of all these machines and their capabilities and to assess which of them might be available for geotechnical testing.

Appendix: List of Participants in

CENTRIFUGE DISCUSSION

18 December 1975

C. A. Babendreier, National Science Foundation, Washington, D.C.

R. Bjork, Pacifica Technology, Inc., Del Mar, California.

J. Dixon, Queen's University, Kingston, Ontario, Canada.

E. L. Dodson, Chief, Geotechnical Branch, Engineering Division, Directorate of Civil Works, Office of the Chief of Engineers, Department of the Army, Washington, D.C.

D. E. Gault, Ames Research Center, Mt. View, California.

S. Green, President, Terratek, Inc., Salt Lake City, Utah.

M. E. Harr, Professor of Soil Mechanics, Purdue University, Lafayette, Indiana.

C. C. Ladd, Professor of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

H.-P. Liu, Research Fellow, Engineering and Geophysics, California Institute of Technology, Pasadena, California.

H. Ramberg, Professor of Petrology and Mineralogy, Uppsala University, Sweden.

A. N. Schofield, Professor of Soil Mechanics, Cambridge University, England.

W. Sherman, Soils and Pavements Lab., WES, Corps of Engineers, Dept. of the Army, Vicksburg, Mississippi.

J. Wool, Los Angeles Department of Water and Power, Los Angeles, California.

R. F. Scott, Professor of Civil Engineering, California Institute of Technology, Pasadena, California (Chairman).

ATTACHMENT #5

Dr. Charles C. Ladd's letter

CENTRIFUGAL TESTING FOR RESEARCH ON PROBLEMS RELATED TO SOFT GROUND CONSTRUCTION

C.C. Ladd

December 1975

I INTRODUCTION

Centrifugal testing is used for several reasons (as a teaching aid, for fundamental research, and as a design tool) and has been applied to a variety of geotechnical problems (embankments on soft ground, stability of excavations, earth pressures on walls and buried structures, behavior of reinforced earth, etc.). Based on the comments made at the International Seminar on Centrifugal Modelling held at Cambridge University last September, I conclude that there is little consensus among those involved in centrifugal testing regarding either the most appropriate role for the device or those classes of geotechnical problems for which it is best suited (but the same probably applies to most new developments).

My interests are mainly related to soft ground construction and NSF is charged with supporting "basic research." Thus my comments and opinions will be restricted to centrifugal testing as applied to this topic.

II ADVANTAGES OF CENTRIFUGAL TESTING

Centrifugal testing requires that the stress-strain properties of the soil be independent of time (i.e. the effects of creep cannot be modelled) and the behavior of the model must be governed by strains (i.e. not displacements per se). If these conditions are met, the advantages of the centrifugal test compared to ordinary model tests and full scale field tests are:

1. It can employ real soils with well defined properties and boundary conditions which have the correct stresses due to self weight.
2. The small scale greatly reduces the time required to simulate consolidation behavior (proportional to the inverse of the square of the scale factor).
3. The model can be fully instrumented, especially regarding detailed deformations and hence strains.

III SUGGESTED AREAS FOR RESEARCH WITH CENTRIFUGAL TESTING

The following are examples of areas of research in soft ground construction that I consider worthy of study.

A. Consolidation Settlement of 2 and 3D Loads on Saturated Clays

There is very little evaluated experience in this area. Most model tests have used remolded clays and well documented field cases are extremely rare. Tests with representative soil types are needed to determine the amount of settlement (especially for cases with significant local yielding) and the results compared with various predictive techniques (one-dimensional, Skempton-Bjerrum, stress path, elastic theory, etc.). Rates of consolidation can be compared to recently developed numerical procedures based on Biot, diffusion, etc. theories

B. Undrained Stability and Deformation of Loads on Saturated Clay

If it can be shown that the primary model behavior is controlled by strains rather than displacements, the following topics are of interest:

1. Applicability of the "$\phi = 0$" method of analysis to relatively isotropic non-strain softening clays. What are the modes of failure, what is the location of circular arc failures, what is the proper definition of strength?

2. The behavior of lean sensitive clays, which are both highly anisotropic and strain softening.

3. The effects of a layered foundation, especially one having a stiff upper crust, and the relative importance of embankment strength and rigidity.

4. The influence of repeated loads on deformation behavior and possible changes in undrained strength due to cyclic loading.

C. Settlement of Loads on Sand

This is a very common problem with surprisingly little definitive information. Methods of ascertaining in situ compressibility will require field testing, but centrifugal tests should be very advantageous in studying the effects of repeated loads and they may be useful in developing much needed information regarding the influence of geometry, i.e. width of loaded area and depth of foundation sand.

IV ANTICIPATED PROBLEMS WITH CENTRIFUGAL TESTING

Centrifugal testing requires a very high level of technical expertise and experience, even given a fully operational device. Examples include instrumentation, methods for applying loads and controlling water conditions, design of the experiment, preparation of the model, means for recording and interpreting data. Development of these broad capabilities will either require extensive training abroad or the importation of foreign talent. Any large scale device will need substantial support staff. There will also be severe logistical problems (especially transportation of soil models) if the facility is widely used by different organizations. This problem will undoubtedly restrict its utilization.

The art of centrifugal testing is really still in its infancy with many unresolved issues regarding its general applicability and usefulness. Thus it is possible to expend considerable funds and end up with highly questionable results. My list of research areas involves a fair degree of risk with most of the topics. Examples are the relative importance of creep versus Terzaghi type consolidation and strain versus displacement phenomena for problems of limiting equilibrium.

V CONCLUSIONS (Included at the Request of Dr. Scott)

1. The U.S. should support centrifugal testing as applied to geotechnical engineering.

2. The initial support should emphasize the development of one very versatile and well staffed facility for the purpose of:

   a. Performing research on selected topics.
   b. Serving as a training center to develop the expertise needed to open other facilities if the research proved beneficial (and, if so, to investigate new areas).

3. The research areas should be of three types:

   a. Typical topics currently being studied in Europe so as to facilitate a transfer of technology, say two on soil-structure interaction and one on soft ground construction.
   b. Two or three topics of importance, but having a relatively low degree of risk (these may include one or more of the above items).
   c. One or two topics of importance, but with an admittedly high degree of risk, such as probably applies to earthquake engineering.

ATTACHMENT #6

Mr. Gordon W. Dukleth's paper

SEISMIC SAFETY EVALUATION STUDIES*

By
Gordon W. Dukleth
Division Engineer
Division of Safety of Dams
Department of Water Resources
The Resources Agency
State of California

I don't suppose that all of you are aware that California administers a dam safety program for all non-federal dams located within the state. The act has been in existence since 1929. It provides for state supervision of dams exceeding 25 feet in height with reservoirs containing in excess of 50 acre-feet of water. The act is administered by the State Department of Water Resources under the powers and authorities of the state.

California has always been concerned about the safety of its works be they buildings, dams, or other structures because of its experiences with earthquakes. Intense population concentrations accentuate the hazards. The consequences of dam failure are generally viewed as potentially calamitous events. We view the responsibility of assuring the safety of life and property from the operation of dams and reservoirs seriously.

We have traditionally applied earthquake analysis by pseudo-static methods using some percentage of gravitational forces to simulate earthquake accelerations. Usually these were in the range of 0.05g to a maximum of 0.20g to represent different intensities of earthquake shaking. For many years these were considered satisfactory and had acceptance in

*Presented at the Conference, "Recent Developments in Design, Construction, and Performance of Embankment Dams, University of California, Berkeley, California, June 17, 1975.

engineering circles as an adequate design technique. It was the best approach available although its shortcomings were realized. It has been concluded that the method can yield erroneous results. We were not always that safe. The proof of the deficiency came about in the San Fernando earthquake of 1971.

Since 1971 the Department of Water Resources has had greater preoccupation with earthquake engineering. This should not be considered an obsession but a great commitment to seismic safety particularly as represented by the security of hydraulic structures. Created in San Fernando's aftermath was the Governor's Earthquake Council which came to grips with virtually every facet of seismic safety. The activities of the Legislative Joint Committee on Seismic Safety were stimulated greatly. The Governor's Earthquake Council and the Joint Committee have gone out of existence but the Legislature has created a Seismic Safety Commission whose membership is now being determined. There continues to be much official legislative and executive interest in seismic safety and it has a large impact on our state program in the Division of Safety of Dams.

Dr. Seed and his colleagues investigated the actual behavior and failure of Lower San Fernando Dam which proved the applicability of dynamic analysis where liquefaction of the embankment occurred. When the theory had been sufficiently tested to warrant its application more widely, our office required that all hydraulic fill dams in the state be analyzed using similar dynamic analysis and modern state-of-the-art techniques. Including the two San Fernando Dams in the Van Norman Complex, there were 36 hydraulic fill dams in the state. Only a few of these were exempted from the requirement of the investigation because of peculiarities surrounding each. In December 1971 the owners of 29 hydraulic fill dams were requested to have dynamic analyses made of their dams.

Findings of these investigations have been varied. Not all of the hydraulic fill dams are subject to liquefaction as was the fate of Lower San Fernando Dam. This is because of the nature of the construction performed, the types of materials that went into the construction, and the potential for ground shaking that can be expected at any particular site. A few of these dams are located on the western slope of the Sierra Nevada roughly north of the latitude of San Francisco in a relatively quiet seismic area in which the maximum peaks of ground acceleration can be expected not to exceed 0.2g. These dams have been determined to respond satisfactorily under the maximum credible earthquake. We know that they have been performing capably for many years although this does not prove that they possess a sufficient margin of static safety. These analyses, however, indicate to us an assurance of their overall capability to withstand static and dynamic forces.

Population concentrations principally in the San Francisco Bay area and in the Los Angeles Metropolitan area also are in the most active seismic areas in the state. Obviously, this is where the water supply is immensely important and dams were built in the early era when hydraulic fill techniques were most in vogue. Most of these dams have been found to need substantial work. This has involved total reconstruction on new sites adjacent to old as is being done at Upper San Leandro and Arrowhead, removal and replacement on substantially the original sites as is being done at Silver Lake, and rehabilitation as has been done at Calaveras. Where analysis predicted liquefaction to be obvious, reconstruction appears to be the only solution to ensure safe dams.

In other cases reinforcement to control the effects of possible crest subsidence and loss of freeboard from induced excess strain may be appropriate rehabilitation without the expense of total reconstruction. These cases present the more difficult problems of evaluation to determine the configuration of remedial construction to know how much of the old dam can be incorporated into the new without removal and replacement of its parts. We have maintained that any proposal for rehabilitation must be subject to rigorous and rational analysis so that there will be assurance the end result will be a safe dam when acted upon by the maximum credible earthquake.

Operating restrictions have been adopted pending completion of whatever remedial work there is to be done. In no case have we required a restriction on reservoir operations without a report of findings to justify such action. Imposed restrictions run the gamut of complete draining of the reservoir to operational curtailment limited by the absolute necessity to provide municipal or other services essential to the public health and welfare.

Only at Lake Arrowhead have we not had a restriction on the reservoir level and that only because of the catastrophic economic circumstances if this were done. There has been a diligent effort finally culminating in a construction contract to build a new dam. This work is now under way. We were prepared to invoke a severe restriction to achieve proper safety if nothing were done to ameliorate the situation.

It will be several years before all of the hydraulic fill dams have been remedied so their reservoirs can be operated safely and restrictions can be lifted. Some owners are still engaged in preparing engineering reports on their dams to enable decisions to be made.

A summary of the status of investigation of the hydraulic fill dams, as of May 1, 1975, is attached.

We are proceeding to have evaluations performed on other dams on a systematic priority basis in a program phase succeeding the hydraulic fills. We have spent considerable time and effort to determine the proper priority on a rational and defensible basis. Our procedure is to weigh the factors of location of these dams with respect to populated areas, the seismic environment, the condition of the dam, and the existence of problem materials within it. Some owners have taken the initiative in this work and are well advanced in it. We will be discussing the continuing program with owners to develop a satisfactory reevaluation approach for each specific case.

We are endeavoring to determine trends for application on older dams which may shortcut the exhaustive analytical procedures of dynamic analysis, save some cost, and result in more expeditious findings than are available at the present. This requires some research but our ability to support this kind of applied research is limited. There are many dams for which we do not have a satisfactory analysis of seismic safety. This deficiency will not be overcome in a short period of time. It will take several years to achieve our objectives within a proper order of priorities. Not only do we have the responsibility to see that this work proceeds but the public also demands it be pursued in those situations whereby local issues are generated around the safety of dams located in their communities.

It has been attributed to us to require dynamic analysis of all new dams for which applications are pending before us. That is not our policy. Where the determination of dynamic response appears to be justified, we will require use of these sophisticated methods. However, the owner may elect to employ these techniques even if we do not request their application. Dynamic analysis using time histories of seismic events, dynamic soil testing techniques, and computer finite element analysis is a greatly improved method to evaluate embankment dam stability. But it is not always necessary to apply these complex analyses, especially for dams of moderate height which are built on competent foundations, with conventional sections, for which there is good compaction, and overall proper construction supervision is exercised.

It seems to me that something needs to be done in the form of developing guidelines for dynamic analysis so that greater uniformity and reproducibility will result without jeopardizing freedom of thought and initiative among professional people in dam engineering. It implies a precision in practices governing technical details of obtaining and processing data. This is a venture to which our office shall give consideration. Furthermore, it would be extremely helpful to have analytical procedures to derive the magnitude of permanent structural deformation from dam embankment strain determinations.

Attachment

Hydraulic Fill Dams
Under Investigation for Earthquake Stability

Dam Name	Location by County	Status of Investigation May 1, 1975	Comments
Blakely	El Dorado	Report shows adequate stability - under review by DWR	Additional drilling and testing needed
Buell	Santa Barbara	Completed - dam unstable	Altered to nonjurisdictiona size
Butt Valley	Plumas	Report shows adequate stability - under review by DWR	Additional data received April 30, 1975
Calaveras	Alameda	Completed - dam unstable	Storage restricted 30'. Ballast fill construction complete
Chabot	Alameda	Completed	Reinforcement scheduled for 1976-77
Chatsworth	Los Angeles	Completed - dam unstable	Reservoir drained, owner revaluating reconstruction
Crane Valley	Madera	Report states dam is stable - under review by DWR	-
El Capitan	San Diego	Report shows dam stable at reduced level of 30'	Storage restricted 30'
Fairmont	Los Angeles	Report shows dam unstable	Storage restricted 14' - owner will remove dam after acceptable alternate is built
Finnon Lake	El Dorado	Report shows dam stable - DWR concurs	No remedial work necessary
Haiwee	Inyo	Report shows dam unstable	Storage restricted 10' - Remedial construction under consideration

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Dam Name	Location by County	Status of Investigation May 1, 1975	Comments
Hawkins	San Benito	Investigation proceeding under "Stipulation for Judgment"	It is indicated that dam has some strength and stipulation amended to raise storage restriction from 50 AF to 300 AF until November 1, 1975
Henshaw	San Diego	Report shows dam unstable	Storage restricted 57' - Alterations planned which reduc storage capacity to 50,000 AF
Lake Almanor	Plumas	Report shows dam is stable - DWR concurs	-
Lake Arrowhead	San Bernardino	Report shows dam is unstable	No restriction on storage - New dam under construction by San Bernardino County
Lake Chabot	Solano	Completed - dam is satisfactory DWR concurs	-
Lake Francis	Yuba	Report states dam is stable - DWR concurs	-
Lake Wohlford	San Diego	Investigation proceeding - One year extension granted for completion	Storage restricted 15'
Lower Franklin	Los Angeles	Investigation completed - Dam unstable	Storage restricted 22' - Reconstruction planned
Magalia	Butte	Report states dam stable	No restriction on storage - Ballast fill to be added.
Misselbeck	Shasta	Dropped	Storage restricted 46' - Contains only 20 AF
Mockingbird Canyon	Riverside	Report shows dam unstable - under review by DWR	Storage restricted 16'

Dam Name	Location by County	Status of Investigation May 1, 1975	Comments
Morning Star	Placer	Investigation under way - Preliminary report due	-
Ridgewood	Mendocino	Investigation under way	Alternative actions under consideration by owner in lieu of full analysis
San Pablo	Contra Costa	Report shows dam unstable	Storage restricted 19' - Owner is determining scope of remedial construction
Shasta River	Siskiyou	Investigation under way - Report overdue	Encouraging owner to complete analysis or restrictions will be necessary
Silver Lake	Los Angeles	Report shows dam unstable	Reservoir drained - Reconstruction contract imminent
Upper San Leandro	Alameda	Report shows dam unstable	Storage restricted 30' - New dam being constructed
Woodward	Stanislaus	Report concludes dam safe - DWR concurs	A toe drain and ballast fill will be constructed because of seepage problems which improve dynamic stability