Title

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A symposium on Recent Advances in Geotechnical Centrifuge Modeling was held on July 18-20, 1984 at the University of California at Davis. The symposium was sponsored by the National Science Foundation's Geotechnical Engineering Program and the Center for Geotechnical Modeling at the University of California at Davis.

The symposium offered an opportunity for a meeting of the International Committee on Centrifuges of the International Society for Soil Mechanics and Foundation Engineering. The U.S. participants also met to discuss the advancement of the centrifuge modeling technique in the U.S. A request is being transmitted to the American Society of Civil Engineers to establish a subcommittee on centrifuges within the Geotechnical Engineering Division.

PART II

QUASI-STATIC APPLICATIONS

EVALUATION OF A CONSTITUTIVE MODEL FOR SOFT CLAY USING THE CENTRIFUGE

BY

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ABSTRACT: A general constitutive model has been formulated which may provide a rational method for prediction of the time-dependent performance of embankments on soft clay foundations, with due consideration for creep effects during the undrained, consolidation, and fully drained stages. Tests on embankment type soil structures are being performed on the U.C. Davis Schaevitz Centrifuge to measure the time-dependent pore pressure and deformation behavior for comparison with predictions made using the constitutive model. This paper inlcudes descriptions of the building, testing, and monitoring of the centrifuge models. The results of the centrifuge tests are compared with predictions made using a simplified form of the constitutive model.

Centrifuge testing is valuable for investigating the accuracy and usefulness of new soil behavior models, particularly in the absence of or as a supplement to detailed field records. The unique conditions imposed by the centrifugal environment, such as stress history, stress path, geometry, and curved "gravity" field can be properly accounted for in numerical analyses. Further, careful model preparation minimizes the uncertainty concerning the value and spatial variation of soil properties.

INTRODUCTION

A general time-dependent constitutive model considering the combined effects of creep and hydro-dynamic consolidation of soft clays was formulated by Kavazanjian and Mitchell (1977, 1980). Later, Bonaparte (1981) extended the model to acount for plane strain conditions and other important factors including anisotropy and creep pore pressure response. The model has been shown to predict well the results of triaxial and plane strain tests, using various stress paths, on both remoulded and undisturbed San Francisco Bay mud. Moreover, the model was successfully used to make blind predictions as a part of the NSF/NSERC workshop held in Montreal (Kavazanjian et al., 1980). The true capability of the model for use in more complicated field problems has yet to be evaluated, however. Field loading situations represent much more complex geometric and stress conditions than are the case for laboratory specimens subjected to uniform boundary loadings. Thus, to evaluate more fully the usefulness of the model, centrifuge model testing and well-documented field case studies are helpful. This paper describes a centrifuge test program, still in progress, that is designed for this purpose.

The centrifuge provides a controlled environment in which prototype structures can be studied as scaled-down models, while preserving the stress states required to develop the appropriate soil properties. Table 1 lists some advantages and limitations of centrifuge testing for geotechnical studies. Although the modelling of actual structures may be uncertain, the conditions imposed by the centrifugal environment, such as stress history, stress path, curved gravity field, and boundary constraints, can be readily accounted for by treating the test as a real event and incorporating these conditions in analysis procedure. Thus, centrifuge testing is well suited for the study of deformation and failure phenomena and for the evaluation of constitutive models.

CONSTITUTIVE MODEL

The time-dependent constitutive model proposed by Kavazanjian and Mitchell (1977) has been updated over a period of several years to account for various factors affecting the behavior of clays. A current version of the model which has been coded into a finite element computer program SPIN2D was developed by Borja (1984). Only the principles of this formulation are described herein; details can be found in Borja (1984).

The constitutive model is applicable for "wet" clays (i.e. normally consolidated to lightly overconsolidated) of low to medium sensitivity. Deformation is separated into two components: time-independent (or immediate) and time-dependent (or delayed) as suggested by Bjerrum (1973). The time-independent, immediate component assumes an elasto-plastic, strain-hardening material that follows the Modified Cam Clay yield surface and the associative flow rule developed by Roscoe and Burland (1968). The time-independent deviatoric behavior is modeled by projecting the Modified Cam Clay model into the deviatoric stress-strain (q-γ) plane and assuming it to take on a hyperbolic shape.

For the time-dependent delayed component, the model assumes that both the Modified Cam Clay yield surface and the associative flow rule can be used to generate the delayed strain rate tensor. The validity of this assumption has been shown by laboratory test results obtained by Bonaparte (1981). Two approaches for generating the creep strain rate tensor are used. The first is to use the conventional volumetric creep equation for secondary compression and to scale it using the Modified Cam Clay yield surface and the associative flow rule. The second is to use the deviatoric creep function of Singh and Mitchell (1968) and similarly to scale it as above. For brevity, the first approaches is called "C_α scaling" and the second "SM scaling".

Consideration of time-dependency requires that the yield surface expand not only as a result of increase in stress (as in conventional strain-hardening plasticity) but also due to increase in time, i.e. quasi-preconsolidation or aging. The time-state relationship is described by two age variables. The volumetric age t_v is evaluated by determining how far in the void ratio e direction a state point is from the immediate state boundary surface in e-p'-q space. On the other hand, the deviatoric age t_{dev} is obtained by determining the distance of a state point in the shear strain γ direction from the immediate deviatoric stress-strain curve in the q-γ plane.

A total of 11 soil parameters, as listed in Table 2, is required. The parameters can be determined from conventional triaxial laboratory tests as shown in the table and, in principle, only two triaxial tests are needed to generate them. An isotropically consolidated undrained triaxial compression (ICU) test with pore pressure measurement can be used to determine all parameters except the Singh-Mitchell creep parameters. The Singh-Mitchell parameters can be obtained from a single-multiple increment creep test using the superposition procedure outlined by Singh and Mitchell (1968). In practice, however, additional test results would be desired to improve confidence in the values obtained.

CENTRIFUGE EXPERIMENTS

Several models of a sand embankment on a clay foundation were tested using the U.C. Davis Schaevitz centrifuge. This centrifuge has a radius of approximately 3 ft and an allowable payload of 10,000 LB-G, as described by Houston (1978). During the centrifuge tests, both deformations and pore pressures were measured to provide data for comparison with numerical predictions.

Materials - A kaolinite clay of low plasticity was chosen as the foundation material because of its relatively high permeability and the consequent shorter time required for consolidation. Classification properties of the material are: specific gravity, 2.61, liquid limit 34%, platic limit 12%, plasticity index, 22%. It contains 25% sand size, 40% silt size and 35% clay size particles by weight and is classified as (CL) in the Unified System.

Series of triaxial tests (ICU) and undrained creep tests (ICUC) were performed to determine the required model parameters. The values of the parameters obtained from the results of these tests are listed in Table 2.

Monterey 0 sand was used to construct the embankment and a drainage blanket. The properties of this sand have been well documented by Lade (1971) and are summarized in Table 2.

Model Geometry - The models consisted of a drainage boundary at the bottom, a layer of soft clay foundation overlain by a saturated sand blanket, and the sand embankment,as shown in Fig. 1. Because of space limitations, only half of a symmetrical embankment and foundation system was modelled.

Apparatus - A strong box with inside dimensions of 16-1/2 in. x 8 in. in plan x 12 in. in height was built to contain the model. A transparant plexiglas plate was used as one of the side walls of the box to enable side viewing of the sample container during testing. The other walls were aluminum plates lined with teflon to minimize side friction and adhesion. Similarly, a thin layer of silicon grease was spread on the plexiglas for the same purpose. The box was sufficiently rigid to maintain plane strain conditions in the model.

Model Construction - The model's clay foundation was prepared by press consolidation of a thoroughly mixed slurry (initial water content w_i = 90%) in the model container. A 4 psi consolidation pressure was used to produce a clay cake that was sufficiently strong for later installation of measurement sensors. The top sand blanket was constructed by deposition of sand under water followed by static densification to a specified void ratio. The sand embankment was built inside a template in layers.

Instrumentation - Pore pressures developed in the foundations were measured with five miniature semiconductor pressure transducers (manufactured by Entran, EPB-125 Series). The stainless filters were secured by heat shrinkable plastic tubing on top of the transducer diaphragm to filter soil particles. Care was exercised to properly de-air the transducer before inserting it into the clay foundation.

The transducers were installed as follows. First, horizontal holes in the foundation clay were drilled by a auger. The holes were then backfilled with thin slurry that was injected using a long syringe. This was followed by insertion of a de-aired transducer. Each transducer was oriented with its pressure sensitive area parallel to the direction of acceleration forces to minimize any effects the centrifugal forces might have on its response. In a calibration test using only water in the model box, transducer sensitivity proved constant over the test G range.

Deformations in the foundation clay were determined by a photographic method. Through an angled mirror arrangement, a remote-control camera mounted on the centrifuge arm recorded movements of plastic marker beads implanted on clay surface in a 1 in x 1 in grid pattern. The coordinates of markers on each photo negative were digitized and stored using a comparator. Deformations that occurred between any two frames could then be calculated using a data reduction program (Britto, 1980).

Test Procedure - After construction of the model and installation of instruments, the model container was placed in the swing-up basket. Both static and dynamic balance were established before activating the centrifuge.

The centrifuge test consists of two stages, as schematically shown in Fig. 2. The first stage, called the re-initialization stage, was intended to re-establish the past maximum consolidation pressure on the foundation material. The second stage was used to further load the clay. The length of Stage I was purposesly chosen to be long enough to ensure full dissipation of all excess pore pressure before commencing the loading stage.

TEST PROGRAM AND RESULTS

At the time of writing, two series of centrifuge model tests have been performed: (I) a series of tests on models having the same geometry and loading conditions, and (II) a series of modeling of model tests. Detailed descriptions of the test program are given by Mitchell and Liang (1984). The results from these tests were evaluated using a simplified version of the constitutive model and a computer program, CON2D, originally developed by Chang and Duncan (1977). As the analysis using the SPIN2D computer program to evaluate Series II tests has not yet been completed, only the results of Series I tests are presented herein for comparisons with predictions using the complete constitutive formulation.

The measured pore pressures of two transducers during Stage II are shown in Fig. 3; Stage II began 84 minutes after the start of Stage I. The observed vertical settlements at two representative locations in the foundation clay are plotted against time and shown in Fig. 4.

ANALYSIS AND COMPARISONS

Fig. 1 shows the mesh and boundary conditions used to represent the model for finite element analysis. The acceleration-time history of the centrifuge test was reproduced in the FEM computations. The clay soil was represented in the finite element mesh by quadrilateral elements, each with nine displacement nodes and four pore pressure nodes (Q9P4 elements); whereas, the sand blanket and embankment were represented with nine displacement node quadrilateral elements (Q9P0 elements). The sand embankment and drainage layer were modeled in progress to explore other possible causes of the observed discrepencies. Nevertheless, the model accurately described the time-dependent deformations. It is also apparent that creep does play a significant role in the magnitude of these deformations, as may be seen by comparing the curves for analyses with and without creep in Fig. 4. The differences between the analysis that did not account for creep deformation and the analysis that included creep by C_α scaling can be as high as 25% to 30%.

CONCLUSION

A time-dependent constitutive model which considers the combined effects of creep and hydro-dynamic consolidation is being evaluated by comparing centrifuge test results with numerical FEM predictions. Three sets of analysis have been performed: two of them considered creep strains (SM scaling and C_α scaling) and one in which the creep strain effect was neglected. The results of the comparisons suggest that:

1) For relatively permeable and low plasticity clay materials, creep does not play a significant role in pore pressure response. Analyses that either used SM scaling or neglected creep altogether, provided very satisfactory predictions.
2) Creep strains are significant contributions to the total time-dependent deformations. For the kaolinite tested, C_α scaling analysis provided a better prediction of consolidation deformations; whereas, SM scaling analysis seemed to underpredict the rate of creep strains and thus the total deformations.
3) The constitutive model underestimates immediate deformations but predicts long-term delayed deformations well.

4) Overall, the agreement between the predicted and observed behavior was good, thus adding further support to the concept of summed immediate and delayed deviatoric and volumetric components that are computed using readily determined soil properties.
5) Centrifuge testing proved to be a viable tool for studying predictive models of soil behavior.

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TABLE 1

ADVANTAGES AND LIMITATIONS OF CENTRIFUGE TEST

Advantages:

* Boundary conditions (both deformation and drainage) are well defined.
* Spatial variations and uncertainties of material properties can be minimized by careful model preparation.
* The effects of various stress histories, stress paths, and geometry conditions can be easily studied.
* Time-dependent problems such as consolidation can be studied in a short period of time.
* Measurement of responses such as deformation and pore pressure variations are easy and accurate.

Limitations:

* Careful model construction procedure are required to simulate the prototype structure.
* The gravity field in the centrifuge is radial and the vertical stress distribution deviates from a straight line stress distribution.
* Boundary restraints may distort the actual behavior of the model.

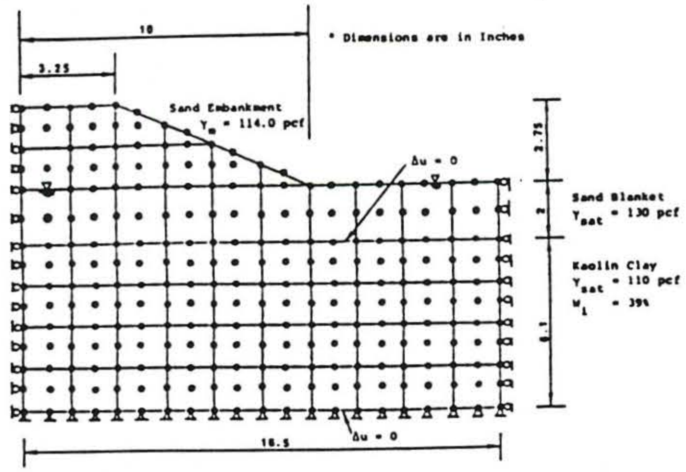

Fig. 1 Model Configurations

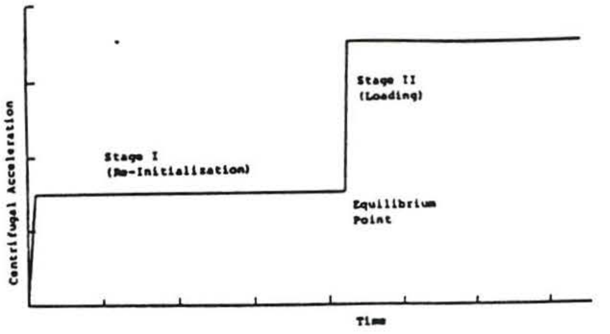

Fig. 2 Centrifuge Testing Procedure

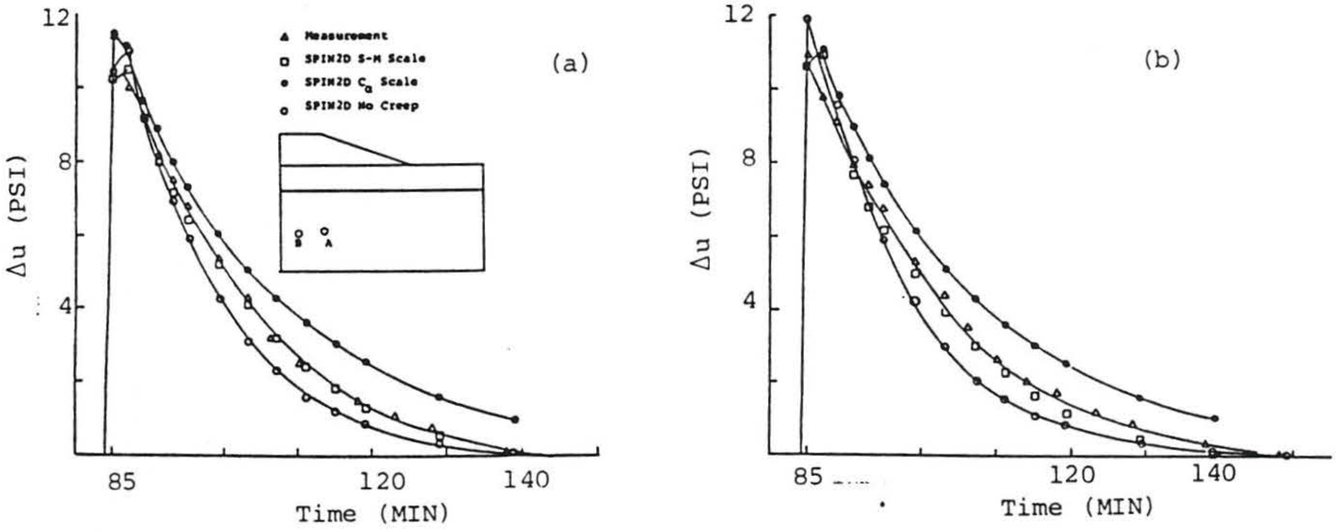

Fig. 3 Comparisons of Pore Pressure Response

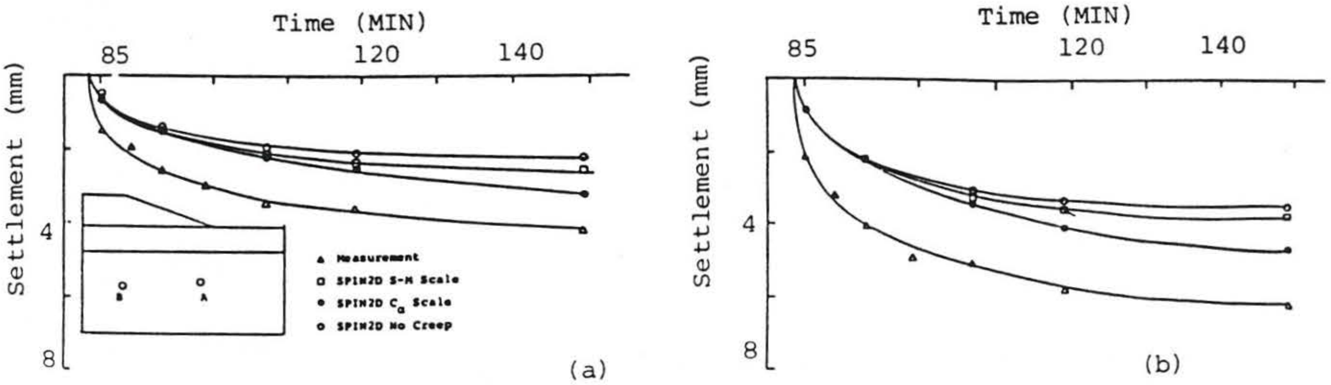

Fig. 4 Comparisons of Vertical Settlement