Proceedings of the

SYMPOSIUM ON RECENT ADVANCES IN GEOTECHNICAL CENTRIFUGE MODELING

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.

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AMERICAN LITERATURE
ON GEOTECHNICAL CENTRIFUGE MODELING
1931 - 1984

The earliest references in the American literature to centrifuge modeling were by Philip Bucky and his students at Columbia University from 1931 to 1949. The topics addressed were associated with mining engineering relating to mine roof design. Photo-elastic techniques were also introduced to the centrifuge technique at this time (Sinclair and Bucky, 1940). This work was followed by Louis Panek at the U.S. Bureau of Mines in College Park, Maryland, from 1949 to 1962. Panek was concerned with bolting systems for mine roof reinforcement.

Clark indicated awareness of the centrifuge technique in 1955 (Caudle and Clark, 1955) and developed a centrifuge at Missouri School of Mines, Rolla. A number of masters theses resulted between 1962 and 1970 that never reached technical journals or symposia (Chan, 1960 (MS); Esser, 1962 (MS); Haycocks, 1962 (MS); Gomah, 1963 (MS); Haas and Clark, 1970). Their work concerned stresses in mine openings, rock bolts, voussoir arches, photo-elastic study of slope stability, and lined and unlined cylindrical cavities. Wang et al. (1968) carried out tests utilizing photo-elastic models of rock beams.

The centrifuge technique was mentioned by Hubbert (Hubbert, 1937) in 1937. Also, mention was made of the technique by others (Caudle and Clark, 1955; Schuring and Emeri, 1964; Rambosek, 1964; Anderson and Reichenback, 1966; Shuring, 1966, U.S. Army, 1968), but actual research results were limited to the few indicated above, prior to 1970.

In 1969 Schofield introduced centrifuge modeling to the soil mechanics and foundation engineering literature in the English publication Advance (Schofield, 1969). This and activities at Cambridge University, Manchester University, and the Manchester Institute of Science and Technology (UMIST) influenced the growth of the technique in Europe. Later through funded research for the U.S. Army Corps of Engineers in Vicksburg, and a steady stream of sabbatical appointments at Cambridge University from 1975 and on Schofield influenced the growth of the technique in the U.S.

Another influence on the growth of centrifuge modeling in the soil mechanics field was the work of Oveson while on sabbatical leave at the University of Florida in 1971 and 1972. He tested the behavior of scaled models of cellular coffer dams over a range of scales and demonstrated the need for centrifuge modeling. Also, he obtained a small surplus centrifuge which he modified for geotechnical use that still remains at the University of Florida under the direction of Townsend. Oveson used the centrifuge to study the bearing capacity of footings in sand that culminated later in his classic paper in Geotechnique in 1975.

In the decade of 1970-80 several developments occurred on the American scene. The use of centrifuge for modeling geophysical events and processes was carried to North America following the work of Ramberg in Swedan. Ramberg began his work in Chicago and later at the University of Connecticut where he proposed a high-g centrifuge for tectonic modeling. Lacking funding Ramberg returned to Swedan to carry out his work. However, Dixon in Canada using plastecine clay models studied the deformation in diapiric structures. (Dixon, 1974,1975). This was followed in 1980 and 1981 by research reports on modeling of tectonic development of Archean Greenstone Belts (Dixon and Summers, 1980,1981).

Several European scientists published centrifuge modeling results in the North American literature. Notable are Habib (1974) on shallow footings Waterways Experiment Station reports on River Bank Stability (1976), Atkinson and Potts (1977) on subsidence above shallow tunnels, Schofield (1978) on slope stability using the basket centrifuge, and, recently, Morris (1981) and Dickin and Leung (1983) on dynamic soil structure interaction and anchor plate pull-out respectively.

In 1976 Schmidt reported the first of a long series of results of explosive cratering data. The work of Schmidt and Holsapple has revolutionized the science of crater prediction at nuclear explosive levels and was accomplished by scale tests in the centrifuge at Boeing Company in Seattle, Washington, using small chemical explosives and impact of small projectiles at high velocities. (Schmidt, 1976,1978-1981; Holsapple, 1978-1984).

The results dramatically reduced the size estimates for craters formed by near-surface large-yield nuclear explosions and by planetary impact of large bodies. Because neither phenomenon can be tested at full scale, centrifuge simulation is the only alternative for obtaining an experimental data base. Estimates of crater sizes were reduced owing to the onset of a strength-gravity transition above which cratering efficiency decreases with size. Existing field data were too sparse and were conducted in far too diverse media to observe the phenomenon.

The application of these findings to Lunar and Planetary Science were pointed out by Gaffney (1978), Gaffney and Cheney (1983), and Gaffney, Brown, and Cheney (1983).

Scott (1977) entered the centrifuge literature in 1977 with cyclic and dynamic test on piles. This was followed in 1978 and on by work on modeling earthquake (Liu, Hagman, and Scott, 1978) and a general summary (Scott, 1978). Scott participated in a special preprint volume on Centrifuge Modeling of Geotechnical Problems at the ASCE National Convention in Atlanta, GA, in 1979 on pile tests and continued work reported in the XI Offshore Conference (Scott, 1979a,1979b). Scott's work on pile testing in the centrifuge was reported at the Stockholm Conference (Scott, 1981) and elsewhere (Scott, Ting, and Lee, 1982; Scott, Tsai, Steussy, and Ting, 1982).

The Scott-Morgan (1977) report on the "Feasibility and Desirability of Constructing a Very Large Centrifuge for Geotechnical Studies" was an outcome of a workshop on Geotechnical Centrifuge Modeling sponsored by the National Science Foundation at the California Institute of Technology in December 1975. This report has become a standard reference for many U.S. research proposals and results.

Scott has delved into many other projects on the centrifuge, some of which have been reported by his colleagues and students (Ortiz, Scott, and Lee, 1981) on forces on retaining walls, and (Prevost, Cuny, and Scott, 1981; Prevost, Cuny, Hughes, and Scott, 1981) on offshore gravity structures.

The special preprint volume on Centrifuge Modeling of Geotechnical Problems (1979) indicated the development of a geotechnical centrifuge research center at UC Davis with two small centrifuges in operation. Papers on modeling of lateral earth support (Shen, Kim, Bang, and Mitchell, 1979), overconsolidated clay slopes using a drum centrifuge (Fragaszy and Cheney, 1979), and simulation of earthquake motion (Arulanandan, Canclini, and Anandarajah, 1979), all coming from the UC Davis geotechnical group.

In the same specialty session Ko (1979) gave results he obtained on buried pipes and Townsend, Goodings, Schofield, and Al-Hussaini (1978) gave results of mine waste embankments utilizing in both cases the Cambridge University centrifuge.

Since that time Ko has developed a facility at UC Boulder and has produced a steady flow of results with his graduate students and colleagues

(Ferguson and Ko, 1981; Goble, Ko, and Houghnon, 1981; Kim and Ko, 1982; Ko, Azevedo, and Sture, 1982; Leung, Schiffman, Ko, and Pane, 1984; Gemperline and Ko, 1984; Ko, Dunn, and Simantob, 1984). The range of interest included cone penetrometers, piles, slopes, excavations in sand, footings on steep slopes, and effects of overtopping earth dams. These topics are addressed also in the following M.S. theses: Cargill, 1980; Ferguson, 1980; Houghnon, 1980; Kim, 1980 (Ph.D.); Croce, 1982; DePonati, 1982; Harrison, 1983; Manzoori, 1983; and Scully, 1983.

Townsend has developed the centrifuge at the University of Florida, Gainesville, that Oveson started, and is in the process at this date in building a second slightly more powerful centrifuge. His work has included bearing capacity of footings in sand, evaluation of the collapse of cavities (sink holes), and evaluation of sedimentation and consolidation characteristics of phosphatic waste clays. The latter is addressed by Bloomquist (1982 Ph.D. dissertation), Bertin (1978 M.S. thesis), McClimans (1984 M.S. report), Townsend and Bloomquist (1983), and Townsend and Israel (1983) reports.

The UC Davis group has also continued to produce research publications utilizing the two small centrifuges: swing bucket and drum (Cheney and Fragaszy, 1980; Cheney, 1981; Fragaszy and Cheney, 1981; Shen et al., 1981; Cheney and Oskoorouchi, 1982; Cheney and Brown, 1982; Shen et al., 1982; Arulanandan et al., 1981; Arulanandan and Anandarajah, 1983; Arulanandan et al., 1983; Bang and Shen, 1983; Cheney, Shen, and Ghorayeb, 1984).

During this same period the large man-rated centrifuge at NASA Ames Research Center was obtained for modification for geotechnical engineering research. This machine is designed to carry 6,000 lbs of soil payload (8,000 lbs with container) at 300 g's and at a radius of 30 feet. Details of this machine were presented by Cheney (1980). It will be the largest facility of its kind in the western world.

Early in 1984 the drive motor of the modified facility suffered a collapse of the thrust bearing of the motor rotor that caused extensive, although minor, damage to commutator bars and drive train.

Still other centers of geotechnical modeling have been developed. Sutherland et al. (1979) utilized the 25-foot radius Sandia Centrifuge at Albuquerque, New Mexico. Sutherland and his colleagues have carried out a number of tests for government agencies involving subsidence over coal mines and stability of tailings dams (Sutherland, 1982; Sutherland et al., 1983,1983a; Sutherland et al., 1984).

Prevost at Princeton University has a small centrifuge and with his colleagues, has investigated the dynamic response of laterally loaded piles, buckling of a spherical dome, dynamic soil structure interaction, and subsurface wave reflections. (Prevost and Abdel-Ghaffar, 1982; Prevost et al., 1983; Prevost and Scanlan, 1983a,b; Cole, Scanlon, and Prevost, 1983a,b,).

In 1982 Goodings at the University of Maryland reported the work relating to the flow problem through and over waste embankments that was involved in her Ph.D. thesis at Cambridge and the Corps of Engineers, Waterways Experiment Station, Vicksburg. She has gained access to a small centrifuge at Goddard Space Flight Center near College Station and has produced several publications (Goodings, 1984a,b,c; Goodings and Schofield, 1984a,b). Her interest has progressed to boundary problems in reinforced soil structures (Santamarina and Goodings, 1984).

Whitman from MIT utilized the Cambridge Geotechnical Centrifuge to carry out basic tests in liquefaction. The first results were given by Whitman, Lambe, and Kutter (1981). Subsequently results were given by Whitman and Lambe (1982); Whitman, Lambe, and Akiyaina (1982); and Lambe and Whitman (1982).

Kutter accepted the position as Managing Director of the large centrifuge at NASA Ames Research Center after receiving his Ph.D. at Cambridge University and is now part of the UC Davis group. His M.S. thesis (1980) and his Ph.D. dissertation (1982) utilized the 'bumpy road' earthquake simulator that he developed at Cambridge. This work was presented in England (1982) and later in the U.S. (1983,1984a). A review of the costs of centrifuge construction was presented by Kutter in 1984a.

In 1982 Clark called together a workshop on "High Gravity Simulation for Research in Rock Mechanics" in hopes of raising interest in a large high-g machine for research in mining problems. Lade et al. (1981) published results at ISSMFE, Stockholm conference with Jessberger, Kabowske, and Jordan on modeling deep shafts, but rock mechanics centrifuge application is sparse to date.

The U.S. Air Force has shown increasing interest in centrifuge modeling of blast induced behavior (Nielson, 1983; Schmidt, Fragaszy, and Holsapple, 1981).

In the last few years there has been a blossoming of U.S. centrifuge activity. New centrifuges are being discovered and brought into play for example at Kirtland Air Force Base under the operation of the New Mexico Research Institute. Sterling at the University of Kentucky has built a 6,000 g-lb centrifuge for model landfill subsidence (Sterling and Ronayne, 1984). Ko at the University of Colorado, Boulder, has obtained funds for building an intermediate size centrifuge. At this writing there is high probability that there are some centrifuges that are being used that have been overlooked and papers presented that are not reported here. For this, apologies are extended.

The growth of the centrifuge as a research tool in the U.S. is phenomenal. The day will come when every well-equipped geotechnical research laboratory will include a centrifuge for model testing, and at that stage comprehensive reference lists such as this will be unfeasible.

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