GEOTECHNICAL CENTRIFUGE MODELLING
AT
THE UNIVERSITY OF WESTERN AUSTRALIA

[This article has been prepared jointly by all those involved in centrifuge model testing at The University of Western Australia. A list of research personnel, in alphabetical order, is given below.]

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1 INTRODUCTION

The main requirement for model testing in any area of Engineering is to ensure that key dimensionless groups are equivalent in model and prototype. In fluid mechanics, an area where dimensional analysis was pioneered, there are a number of such groups (Reynolds number, Froude number and so forth) which determine the performance of the prototype, and which need to be matched correctly in any small-scale modelling of the prototype. In solid mechanics, for problems where the self-weight of the material is important, the primary dimensionless group is the ratio of self-weight stress to the strength of the material. This principle needs to be taken even further in geotechnical research, where the response of soil and rock depends critically on the past and current stress state. Under these circumstances, it becomes necessary to simulate the full prototype stress field in any model experiment, distinguishing carefully between the ambient stress state prior to any perturbation, and the stress changes that take place subsequently during the experiment.

It is now widely accepted that centrifuge modelling provides the most versatile technique for obtaining stress conditions that are homologous in model and prototype. Other techniques – such as using a downward hydraulic gradient – may also be used, but none of these offers the same scope as centrifuge modelling. For element tests, or where the variation of stress through the event to be modelled is small (such as in modelling of a very deep tunnel, or the stress changes around an advancing cone), it is sufficient to use triaxial cells or larger so-called 'calibration chambers' where the boundary stresses are controlled. However, in problems where not just the ambient stress, but the *gradient* of ambient stress is important (such as an embankment on soft clay, or the performance of foundations on sand), centrifuge modelling becomes the optimum approach.

This paper describes the centrifuge facility that has been developed in the Department of Civil and Environmental Engineering at The University of Western Australia, and also presents brief descriptions of the current research projects being undertaken using the facility. The paper concludes with a summary of additional research areas where centrifuge modelling can play an important role both in fundamental research and in site-specific design studies.

2 CENTRIFUGE MODELLING

The primary aim of a centrifuge model test is to obtain similitude of stress and strain in model and prototype. This is achieved by accelerating a scale model, where all linear dimensions are reduced by a factor, N, to an acceleration of magnitude N gravities (g), effectively increasing the self-weight by a factor of N. Soil of density identical to the prototype is used in the model, so that the vertical overburden stress at a depth of z/N in the model is equal to that at a depth z in the prototype. Thus, for example, the stress distribution through a 0.5 m thick layer of soil in the centrifuge, at 200 g, is equivalent to the stress distribution in the same soil in the field over a depth of 100 m.

In general, model tests are carried out on soil which is similar in grain size to the prototype soil, in order to achieve similar stress-strain properties. Relative to the scale of the problem being modelled, the grain size of the model soil will therefore be a factor of N greater than in the prototype situation. Experiments have shown that this produces no measurable 'scale effect' provided that the ratio of grain size to the smallest significant dimension of the problem is less than about 3 - 5 %. For example, if a 1 m diameter pile were to be modelled at a scale of 100:1, the model pile would be 10 mm in diameter, and the grain size should be maintained below about 0.3 mm. In some cases, it may be necessary or appropriate to reduce the size of the soil grains in the centrifuge model tests, although it then becomes necessary to assess what difference such reduced grain size may make to the engineering properties of the soil.

2.1 Scaling Relationships

Centrifuge scaling relationships have been extensively described elsewhere, for example, Arulanandan et al (1988). The main principle is similarity of stress and strain, and the reduction of linear dimensions by a factor of N. The scaling factors for common quantities are summarised in Table 1.

Table 1

Scaling Factors for Centrifuge Modelling

Parameter	Dimensions	Scaling Factor
Acceleration	LT^{-2}	N
Seepage velocity	LT^{-1}	N
Length	L	1/N
Stress	$ML^{-1}T^{-2}$	1
Strain	-	1
Force	MLT^{-2}	$1/N^2$
Bending moment	ML^2T^{-2}	$1/N^3$
Time (diffusion)	T	$1/N^2$
Time (cyclic period)	T	1/N
Time (creep)	T	1

It is clear from Table 1 that correct scaling of time presents a problem - one that is common to any form of geotechnical modelling. Where consolidation is to be modelled, the time scale is reduced by a factor of N^2, which permits many years of prototype consolidation (or other form of diffusion) to be modelled in a few hours. However, if events such as liquefaction under cyclic or earthquake loading are to be modelled, then it becomes necessary to adjust the effective permeability of the soil (for example, by increasing the viscosity of the pore fluid) in order to match both cyclic period and diffusion time scale.

2.2 Centrifuge Facility at UWA

The centrifuge that has been installed at UWA was made in France by Acutronic, who were the manufacturers of the centrifuge at Nantes, one of the largest geotechnical centrifuges in Europe. The size of a centrifuge may be expressed as the product of maximum payload and maximum acceleration level, expressed in g-tonnes. The UWA centrifuge is a 40 g-tonne machine, with a maximum payload of 200 kg at an acceleration level of 200 g. Proportionally heavier packages, up to a maximum of 400 kg, may be tested at lower acceleration levels.

Acutronic make a range of geotechnical centrifuges, ranging from the Model 661 (as installed at UWA) up to the Model 680 (the Nantes centrifuge) which is a 220 g-tonne machine. A 600 g-tonne machine is currently being designed.

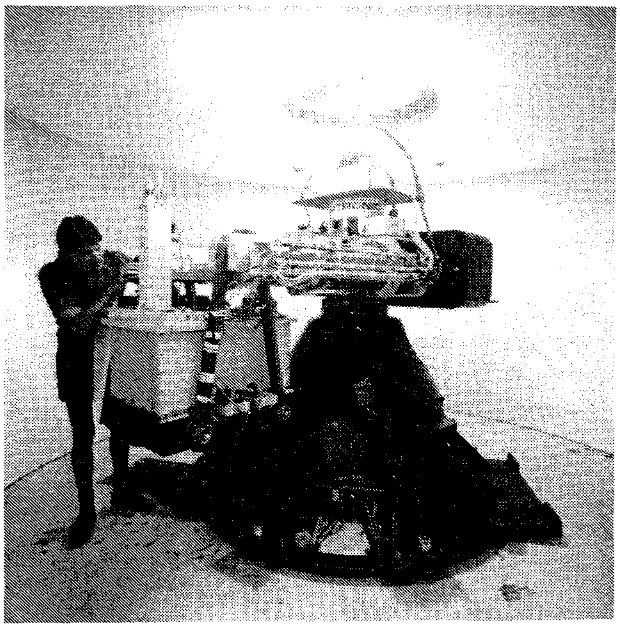


Fig. 1 Model 661 Acutronic Centrifuge

The Model 661 centrifuge, shown in Figure 1, has a swinging platform at a radius of 1.8 m, and a nominal working radius of 1.55 m. At maximum acceleration of 200 g, the rotational speed is 340 rpm, with a platform velocity of 64 m/s (230 km/h). The platform has a usable area of 500 mm by 700 mm, and can hold containers up to 500 mm high. Equipment mounted on the containers – such a cone penetrometer for 'in-flight' site investigation – is restricted to a height of 950 mm above the platform.

The centrifuge is housed at ground floor level in a specially-constructed circular reinforced concrete chamber. The chamber is located immediately outside an existing laboratory, and has direct access to that laboratory, which offers a spacious area for sample preparation. A novel feature of the housing is a 250 mm thick inner lining of high-density polystyrene, which has very good energy-absorbing characteristics, and also provides thermal and acoustic insulation. The chamber is completed by a curved fibreglass door, fitted with rubber seals to reduce air loss, and hung on a double pivot which allows sufficient access to remove the centrifuge if the need were to arise. At present, plans are being prepared to air-condition the chamber, in order to maintain a constant temperature throughout long tests, thus avoiding the large diurnal temperature variations which can cause significant zero-drift of instrumentation.

Communication with the centrifuge is via power and instrumentation slip-rings that are housed within the main axis, with the fixed cables exiting downwards, through the centre of the gearbox. This feature of the Acutronic design leaves the top of the central axis clear, thereby providing valuable additional space in the 'low-g' region. As may be seen in Figure 1, this space is used to house a 286 microcomputer, which will eventually handle all A/D data conversion and multiplexing, and also process-control of actuators on the package. The number of instrumentation slip-rings was

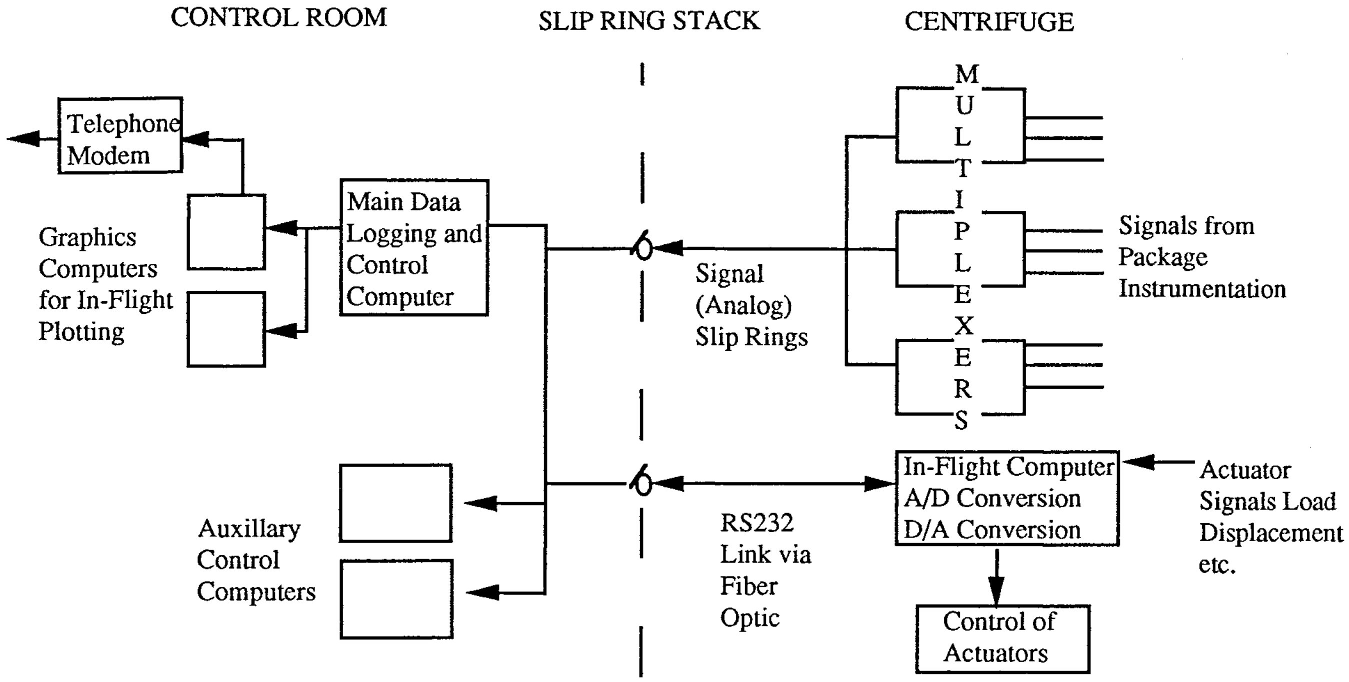


Fig. 2 Schematic representation of Centrifuge data logging and control system

deliberately limited to 23, since it was planned to multiplex signals on the arm. Thus, a total of 38 data channels are currently available, with plans to expand the system to over 100 as new multiplexing units are developed. In addition to the electrical slip-rings, there are two video slip-rings and a fibre optic slip-ring capable of transmitting data at up to 50 Mbps. The fibre optic link will eventually provide the primary mode of transmission for data digitised on the arm.

At present, a single hydraulic slip-ring has been added, with the hydraulic hose routed around the central computer (see upper part of Figure 1). This link will be replaced shortly by a 4-channel hydraulic slip-ring, to facilitate experiments on pollutant transport.

Two additional features that have proved most valuable are (a) miniature (20 gramme) CCD video cameras (Panasonic Model WV-CD1) that sit directly on the package, and (b) laser-operated remote sensing displacement transducers. The former devices permit close-up views of the test, with sufficient resolution to obtain quantitative measurements (using appropriate image processing software). The laser displacement transducer may be used to measure surface settlement of soft clay, or lateral movement of a pile, avoiding physical contact that may interfere with the measurement.

A number of packages and accessories have been developed since the centrifuge was installed. To date, most of the experiments have been performed in rectangular boxes, with internal dimensions 390 mm by 650 mm by 300 mm high. The boxes weigh about 70 kg, and permit models with up to 250 mm of saturated soil to be tested at the maximum acceleration level of 200 g. Electrical actuators have been developed for conducting cone penetrometer and foundation tests. Each actuator has two degrees of freedom, which allows relocation of the cone in-flight (between successive tests) and combined horizontal and vertical loading of foundations. The actuators are lightweight (10 - 12 kg), with a design specification of 10 kN at a maximum loading rate of 3 mm/s. Loading rates are controlled through software, and the above specification may be altered by changing either the motor, the reduction gear, or the recirculating-ball lead-screw.

2.3 Data Acquisition

The data acquisition system employed at the UWA centrifuge facility has been developed with the underlying philosophy of producing a fully automated, but versatile, control and data collection system. The principle of this system is shown schematically in Figure 2.

The system consists of a main data acquisition and control computer which is responsible for logging all data returning via the centrifuge slip-rings to a hard disk. This computer is also in communication with the computer mounted on the low-g central platform of the centrifuge, which provides control of actuators such as the cone penetrometer and foundation loading devices.

Rather than assigning all control, data-acquisition and graphing functions to a single computer, which would necessitate sophisticated and complex software development, these various tasks are distributed among auxiliary computers. The auxilary computers may each be programmed to perform specific tasks - such as operating solenoid valves for water level control, controlling hydraulic valves, or just graphing data.

The data logged by the main microcomputer are also passed to two graphics computers which can be programmed to display time records of selected channels, or to plot two or more channels against each other, during the test. One of the graphics computers also contains a modem, allowing the centrifuge user to monitor the test progress by telephone link, whilst the machine is running unattended - e.g. during long overnight consolidation periods.

The system outlined above requires a relatively large input from the centrifuge user - as each software package for the control and graphics computers must be set up for a particular test. However, each component is relatively simple to develop, and yet the whole system is extremely versatile.

2.4 Current Research Projects

The centrifuge at UWA has now been in operation for a year (since June, 1989). Use of the centrifuge has grown rapidly, and it is now heavily booked for the next six months. A list of major projects being undertaken are listed below:

- Shallow foundations on calcareous soil
- Embankment loading of piles.
- Response of rectangular box culverts.
- Studies of pollution migration through soil.
- Consolidation at low effective stresses.
- Modelling jointed rock.
- Mining induced subsidence.

These projects, which are supported through grants from industry and from the Australian Research Council, are described in more detail in the following sections.

3 SHALLOW FOUNDATIONS ON CALCAREOUS SOIL

3.1 Introduction

The geotechnical centrifuge at UWA is being used to explore the behaviour of shallow foundations in calcareous soil, with application to the design of offshore structures. Current design methods for shallow foundations on calcareous soil are based primarily on traditional bearing capacity calculations, which fail to take account of the high compressibility of calcareous soil. The study aims to examine various factors that affect foundation performance, namely: density (or void ratio), degree of cementation and layering of the soil, eccentricity and inclination of applied loading, and cyclic loading.

The project was one of the first to be carried out on the centrifuge, and necessitated considerable development of equipment and testing techniques. The main equipment consisted of actuators to permit 'in-flight' cone penetration testing and combined vertical and horizontal loading of the model foundations.

Calcareous soil recovered from the sea-bed on the North-West Shelf of Australia is being used for the model tests. The soil is uncemented, and is oven-dried and sieved (to remove the larger shell fragments) prior to use. Techniques are being developed to re-cement the soil, using calcium hydroxide, in order to simulate the cemented layers that are encountered in practice. Such cementation, and the intervening layers of calcareous muddy silt that exist in the field situation, are likely to be critical in determining punch-through and liquefaction failure of shallow foundations.

3.2 Equipment and Sample Preparation

The model tests have been carried out in a centrifuge 'package', that consists of a strong box upon which sit two actuators (see Figure 3). The taller of the two actuators comprises a cone penetrometer, which may be relocated across the width of the box between successive penetration tests. The cone is 10 mm in diameter, with a load cell at the tip and another load cell at the top of the shaft. The maximum penetration rate is 3 mm/s, with a maximum range of 30 MPa.

The shorter actuator provides loading for the shallow foundation, with independent control of vertical and horizontal displacement. Software allows particular loading paths to be followed, including maintaining a constant vertical load, during horizontal cyclic loading. In the early tests, cyclic loading was limited to slow, essentially drained, loading, with periods of 1 - 20 s. The system is currently being developed further, in order to achieve cyclic loading rates in the region of 10 Hz.

In the tests performed to date, a total of five cone penetrometer tests and two foundation tests have been carried out on each sample of soil. The number of tests is a compromise between maximising the amount of data from each sample, and yet avoiding too much interaction between tests. In each sample, tests were carried out at two acceleration levels (100g and 140g), in order to assess the validity of the model test results.

To date, a total of five soil samples have been prepared, as follows:

- A sample, (1), prepared by dry pluviation and densification by vibration. This produced a relatively dense sample.
- A sample,(2), prepared by dry pluviation leading to a less dense sample.
- Two identical samples, (3 & 4), prepared by mixing soil with silicon oil under vacuum, and placing the soil as a slurry. Silicon oil, with a viscosity one hundred times that of water, was used as the pore fluid in order to increase drainage times. Increasing the

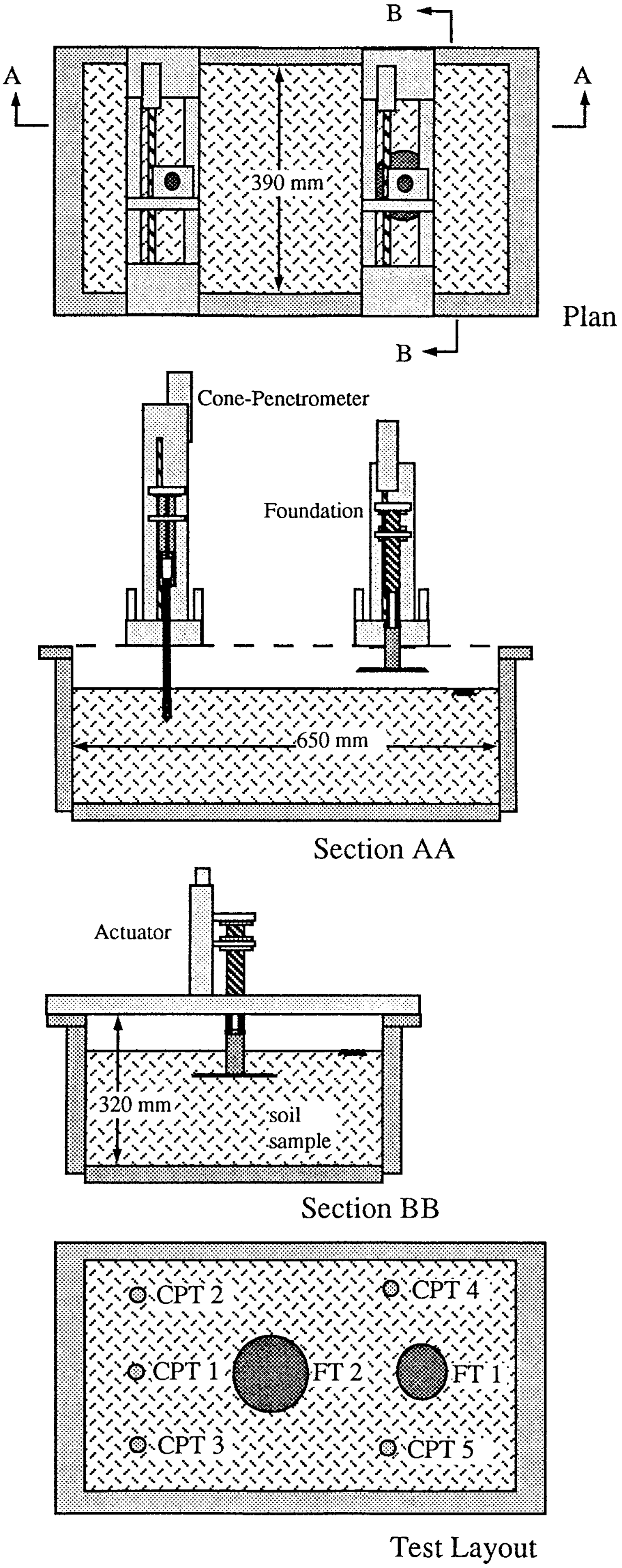


Fig. 3 Layout of Foundation Test Package.

loading rate by a factor of a hundred and reducing the effective permeability of the soil by the same factor allows correct simulation of excess pore pressures between model and prototype. (Note that, if water was used instead of silicon oil, the loading rate would have to be increased by N^2.) This technique, commonly used in modelling earthquake events at small scale, is particularly useful for modelling liquefaction under cyclic loading.

- A 'cemented' sample, (5), prepared by combining soil with calcium hydroxide and water, then flushing with carbon dioxide and saturating under vacuum. This produced a chemical reaction resulting in inter-particle bonds of calcium carbonate, thus producing a sample with a cemented micro-structure.

Using these samples, a total of ten foundation tests and twenty cone-penetration tests have been carried out.

3.3 Test Results

Differences in sample properties due to the different methods of preparation are reflected in the profiles of cone resistance, as shown in Figure 4(a). In general, the lateral variation in soil properties within each sample was minimal, as evidenced by the results of different cone tests in the same sample; Figure 4(b) for example shows the results of three such tests at different locations in sample 3.

Also shown in Figure 4(a) is an approximate envelope of cone resistance obtained from a typical site on the North-West Shelf. It is clear that, while the cone resistance of the upper 6 m may be matched reasonably well by the model soil, the layers of very low cone resistance (for example, in the range 7 - 14 m) are not reproduced. Inspection of the borehole logs shows that the low cone resistance is generally associated with a high fines content - calcareous muddy silt - compared with the silty sand that has been used in the model tests. The inclusion of layers of finer material in the model tests is an essential part of future work aimed at evaluating the potential for punch-through and liquefaction types of failure.

The model foundations consisted of flat circular footings, of diameters 70 and 100 mm. At acceleration levels of 140 and 100 g respectively, these represent a prototype foundation of diameter 10 m, which corresponds to a typical offshore foundation for jack-up rigs or small gravity-based platforms.

A typical response is shown in Figure 5(a) for a test on a 100 mm diameter footing (at 100 g) in the second soil sample. The bearing envelope shows no clear failure load, but rather a continuously increasing bearing capacity with increasing penetration. A bearing stress of just under 500 kPa is required for a settlement of 10 % of the footing diameter.

The test included three unload-reload loops, and also two stages of horizontal cyclic loading. Both stages of horizontal cyclic loading, at a shear stress amplitude of ±50 kPa, gave rise to significant vertical settlement of the footing. However, on subsequent vertical loading, the original bearing envelope was rejoined.

Foundation response from different sized models tested at different accelerations, but modelling an identical prototype, compared well, as shown in Figure 5(b). Thus the modelling technique is validated.

3.4 Future Tests

The actuator control is currently being developed further in order to increase the rate of cyclic loading to about 10 Hz. This, together with the silicon oil pore fluid, will allow simulation of pore pressure build-up during typical storm loading.

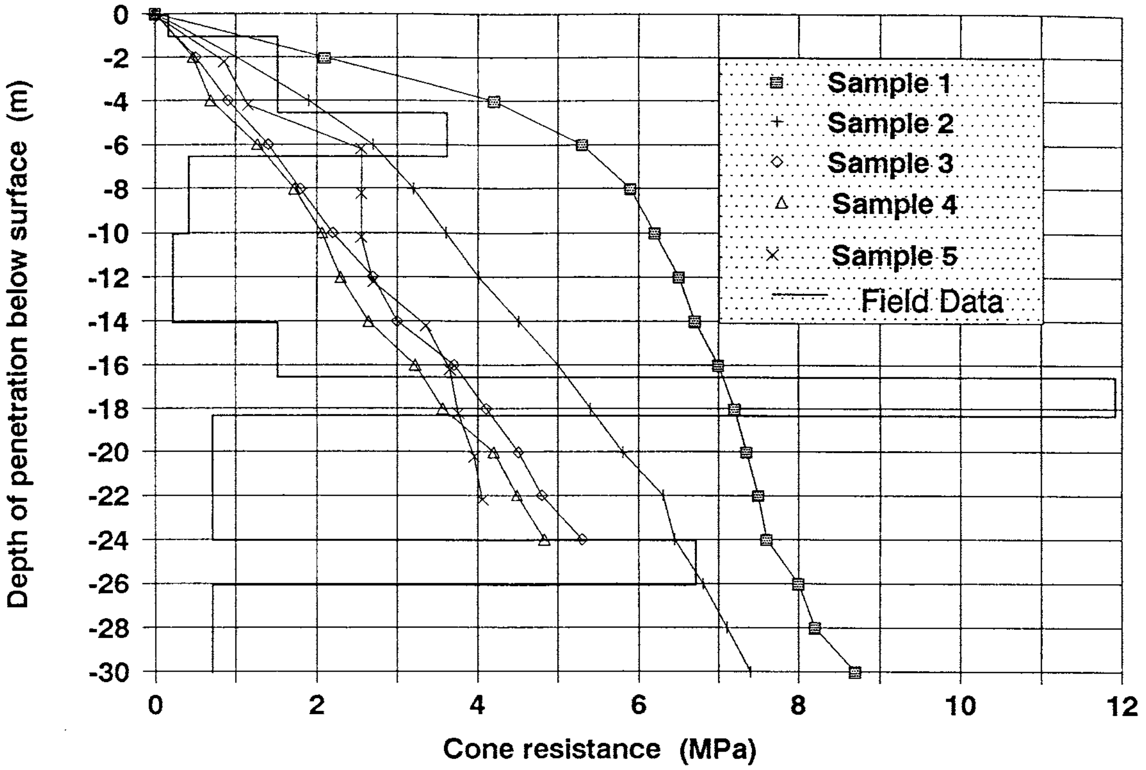
Comparison of the cone resistance profiles from the model and prototype situations indicates that the bearing response of the calcareous soil is significantly affected by the particle size distribution. In particular, a layer of finer material close to the surface may prove critical in the design of prototype shallow foundations. This aspect will be investigated in future testing.

It is also planned to include additional instrumentation in the soil in order to provide data on the transfer of stress. Miniature pore pressure transducers and earth pressure cells will be embedded beneath the model foundations, and the information used to develop analytical models of bearing capacity in calcareous soil.

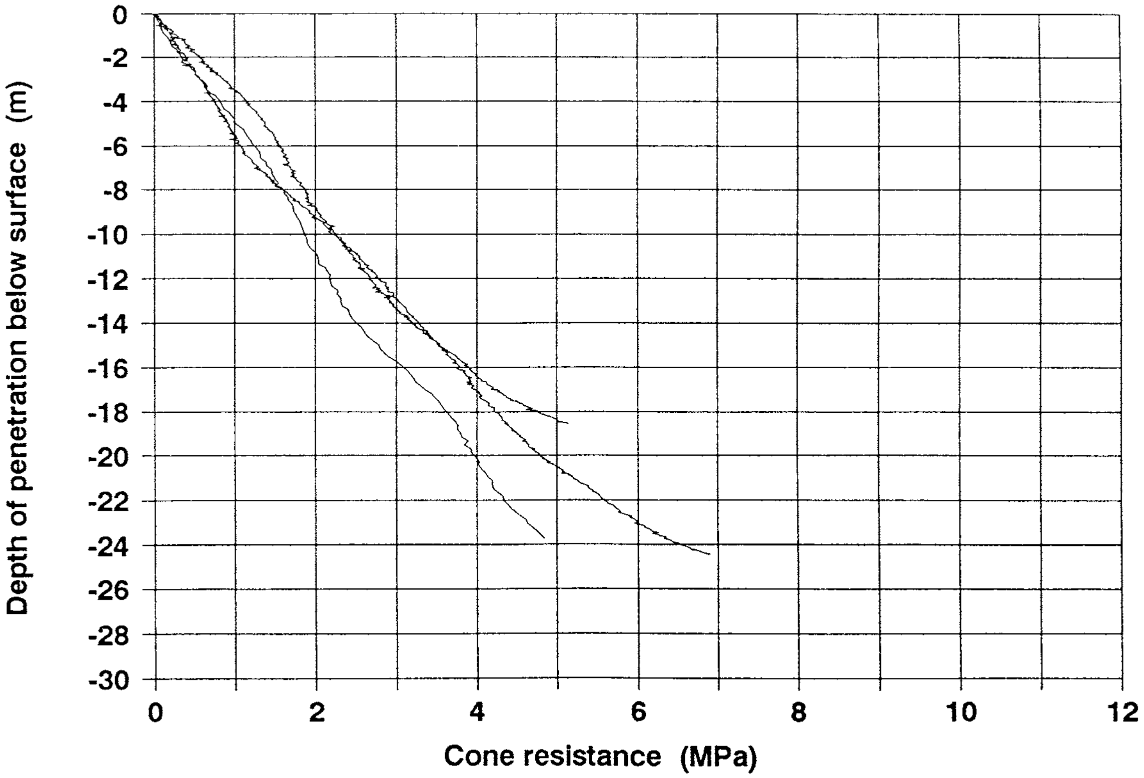
4 LATERAL LOADING OF PILES IN SOFT CLAY DUE TO NEARBY EMBANKMENT CONSTRUCTION

Construction of embankments on soft clay results in the development of significant time-dependent embankment settlements, and both horizontal and vertical movements within the soft clay. Where a bridge approach embankment is founded on soft clay, construction of the bridge itself is sometimes commenced before full settlement of the embankment has occurred. Piles supporting bridge abutments adjacent to such embankments may therefore experience significant lateral forces from horizontal soil movements. These lateral forces induce bending moments and deflections in the piles which may lead to structural distress or failure of the piles or bridge structure.

Design of piled bridge abutments subjected to such forces has in the past been based on both theoretical (Poulos, 1973) and empirical (DeBeer and Wallays, 1972) analyses. However, in a limited number of full scale field trials, the forces predicted by various approaches have in general been in poor agreement with measured values. Hence, prediction of the bending moments and deflections induced in abutment piles in this situation remains problematic. Because of this, a conservative design incorporating caissons to shield piles from lateral soil displacements may be adopted, or

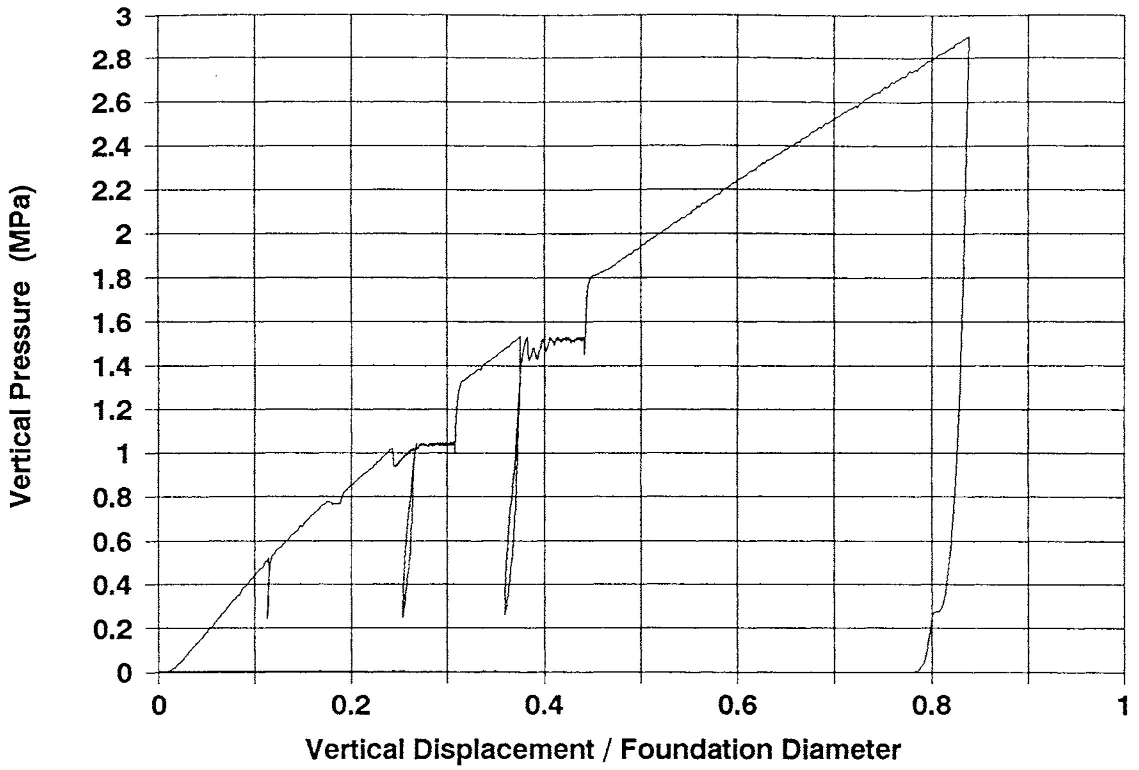


(a) Cone-Penetration Tests. Typical Profiles.

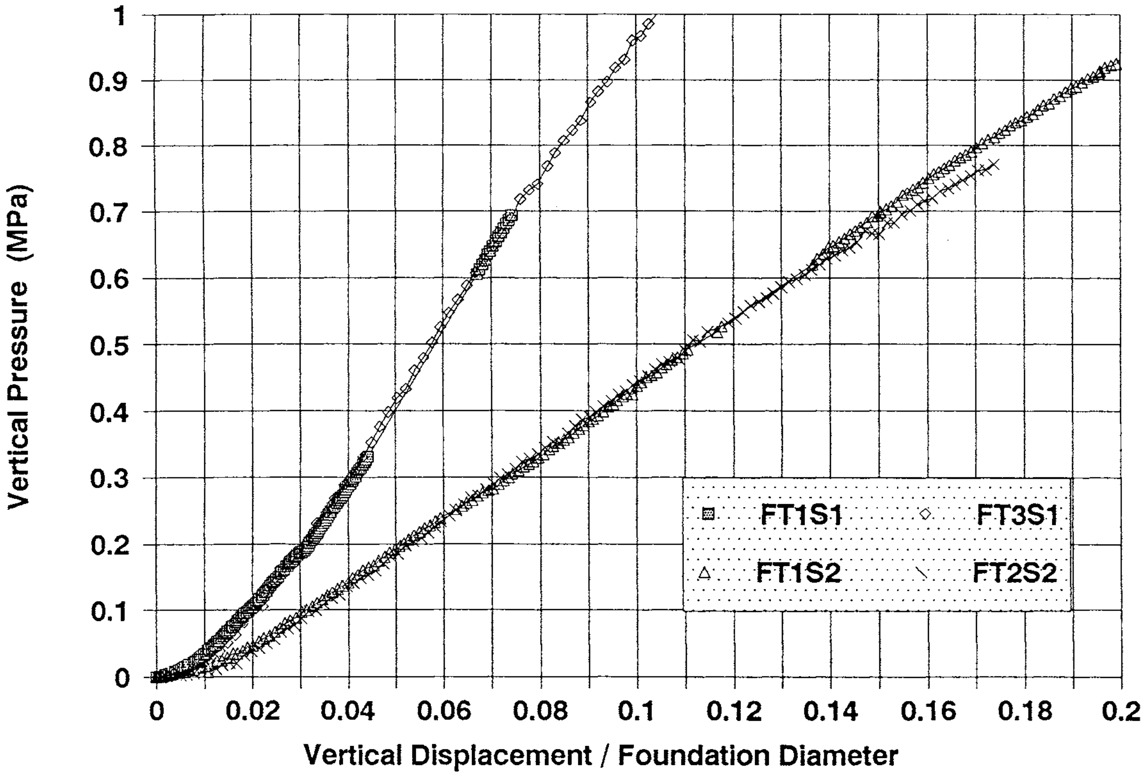


(b) Cone-Penetration Tests. Sample 3.

Fig 4. Cone-Penetration Data in Calcareous Soil.



(a) Bearing Pressure versus Penetration,
Foundation Test 2, Sample 2.



(b) Bearing Pressure versus Penetration, Samples 1 and 2.

Fig 5. Foundation Test Data in Calcareous Soil.

bridge construction may be delayed until full settlement of the approach embankment has occurred. If the bending moments and deflections induced in the piles can be estimated accurately, then more cost effective construction procedures may be implemented.

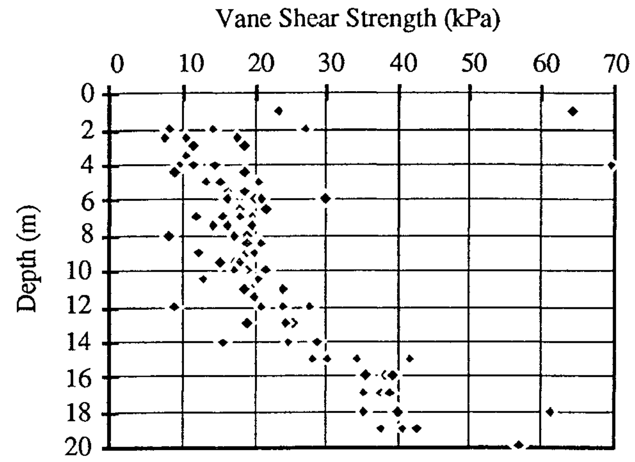


Fig. 6(a) Vane Shear Strength Test Results - Burswood Bridge Abutment

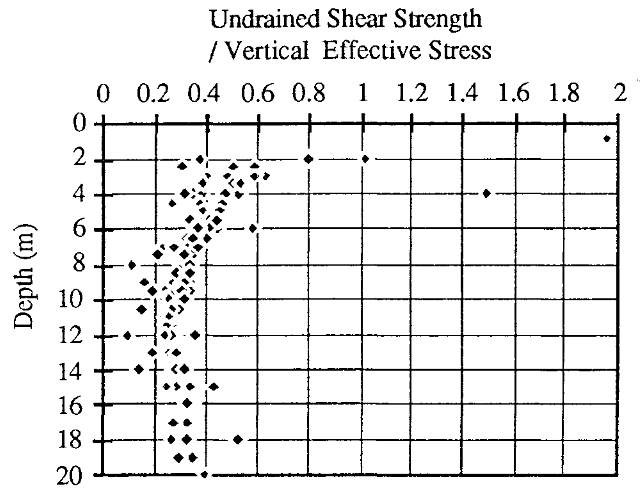


Fig. 6(b) Vane Shear Strength Test Results - Burswood Bridge Abutment

Centrifuge model tests are being conducted at UWA to obtain data on the interaction between an embankment on soft clay and piles driven nearby. This project is being sponsored by the Main Roads Department of Western Australia. It is directly relevant to the design of the proposed Burswood Bridge across the Swan River in Perth. The proposed abutment site on the Burswood Peninsular is underlain by an 18 m deep layer of soft to firm organic clay deposited in a meander of the Swan River (Geidans and Kilvington, 1984). Field vane shear test results from the proposed abutment location are shown on Figure 6(a) as shear strength versus depth, and on Figure 6(b) as the ratio S_u/σ'_v versus depth. The ratio S_u/σ'_v gives an approximate indication of the variation in OCR with depth, showing that the upper 10 to 12 m of the clay is overconsolidated.

Centrifuge models for this project are prepared by consolidating a slurry of kaolin under a surcharge of 60 kPa, before transferring the sample to the centrifuge for final self-weight consolidation at 110 g. The strength profile of the models, estimated from the results of CIU triaxial tests, is shown on Figure 7(a) with the field vane results superimposed for comparison. The stress history of the samples results in the overconsolidation profile indicated on Figure 7(b). These figures show that strength and overconsolidation profiles similar to the prototype may be achieved in the models by selection of an appropriate stress history.

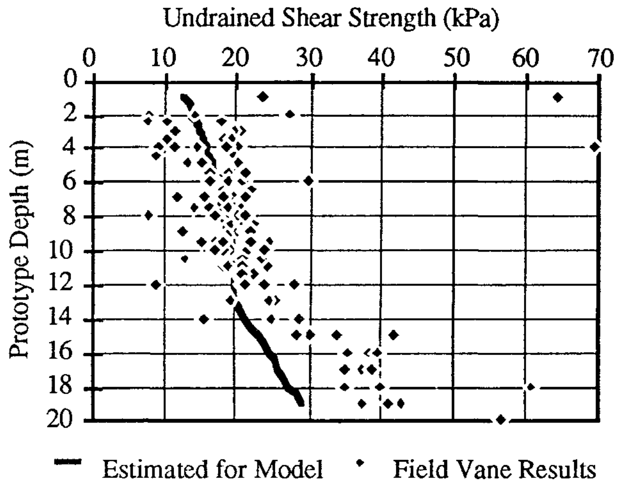


Fig. 7(a) Shear Strength and OCR profiles for Centrifuge Models

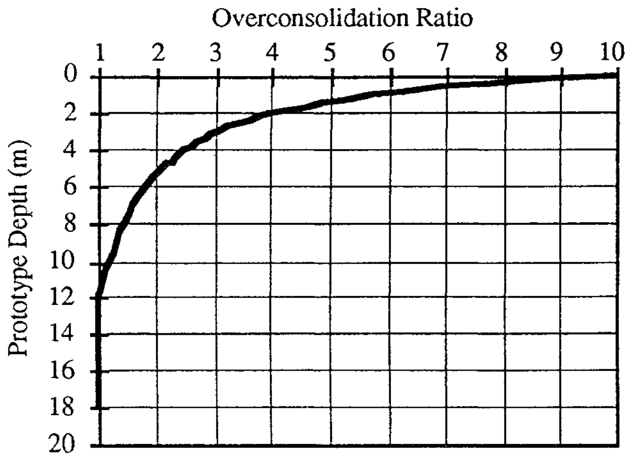


Fig. 7(b) Shear Strength and OCR profiles for Centrifuge models

The layout of the centrifuge models is illustrated on Figure 8. Model piles have been constructed from 3.2 mm square hollow brass sections to replicate the bending rigidity of the 310 UC 158 steel sections proposed for the prototype piles. The model piles are strain gauged externally to measure bending moment at ten levels, and their deflection above the soil surface is measured with a non-contact laser displacement sensor.

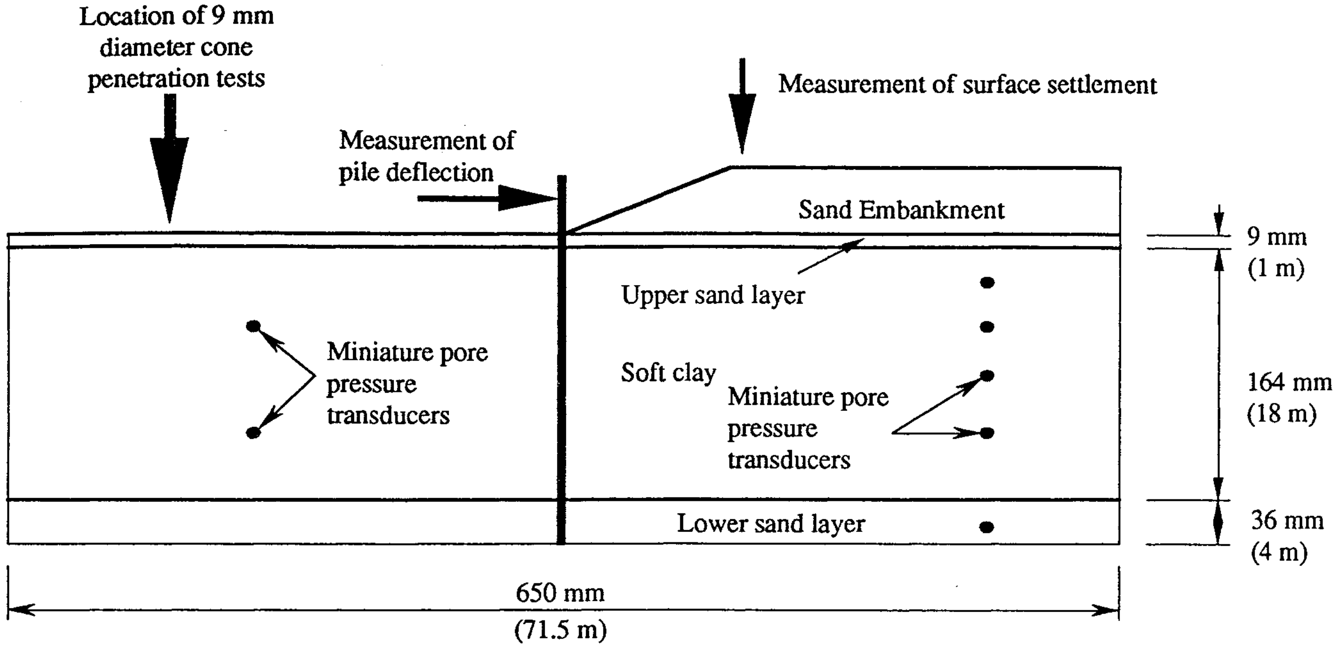


Fig. 8 Layout of Centrifuge Models

To date, the undrained shear strength of the soft clay has been assessed by performing cone penetration tests 'in-flight'. A sensitive 9 mm diameter cone penetrometer has been developed for this purpose. However, a major limitation of the cone penetrometer lies in the empirical factors used to correlated cone resistance with undrained shear strength.

A new device is currently being developed for the centrifuge, to enable shear strength to be measured more directly. The device comprises a cylindrical bar mounted at right-angles (to form a T) at the end of a vertical shaft. The T-bar is pushed into the soil and the penetration resistance measured by a load cell situated immediately behind the bar.

The results of the test are interpreted making use of the plasticity solution for flow of soil around a cylinder (Randolph and Houlsby, 1984), which enables the shear strength to be deduced directly from the measured penetration force.

The new device combines the advantages of the cone penetrometer (giving a continuous profile of 'strength') with the vane shear tests (which gives an 'exact' measure of shear strength). Experience so far has shown a significantly better correlation with shear strength than obtained with the cone penetrometer, independent of the overconsolidation ratio of the soil.

In preliminary testing, a sand embankment was constructed in several stages adjacent to a single pile by stopping the centrifuge, building the embankment by hand, and then restarting the centrifuge. Such an approach induced significant errors in the test results, as the pile was able to straighten when the centrifuge was stopped, but served to test the instrumentation systems and general modelling procedures.

The pile bending moments measured during one stage of embankment construction in a preliminary test are shown on Figure 9. Only seven levels of strain gauges on the pile were functional during this test. The bending moment data were fitted with a polynominal curve, from which lateral pressure and deflection profiles were derived using simple beam theory. These profiles are also shown on Figure 9.

To enable accurate modelling of embankment-pile interaction, it is imperative to construct the embankment 'in-flight" in the centrifuge, A sand hopper has been designed which will allow sand to be poured through more than 200 small valves onto the surface of the model during flight. Each individual valve takes sand from a separate compartment in the hopper, so that different amounts of sand may be poured through each valve. This will enable three dimensional embankments of virtually any shape to be constructed in-flight. Embankments of up to 12 m prototype height will be able to be constructed.

5 RECTANGULAR BOX CULVERTS

5.1 Introduction

In recent years, modelling of the soil-structure interaction of buried, flexible, circular culverts has been performed by numerous research groups. As a result, the soil-structure interaction problems of such culverts are better understood, and new design and analysis procedures are being proposed. In the meantime, research on rectangular box culverts has remained limited, and at present little information is available on the response of these structures to loading either by axle loads at low

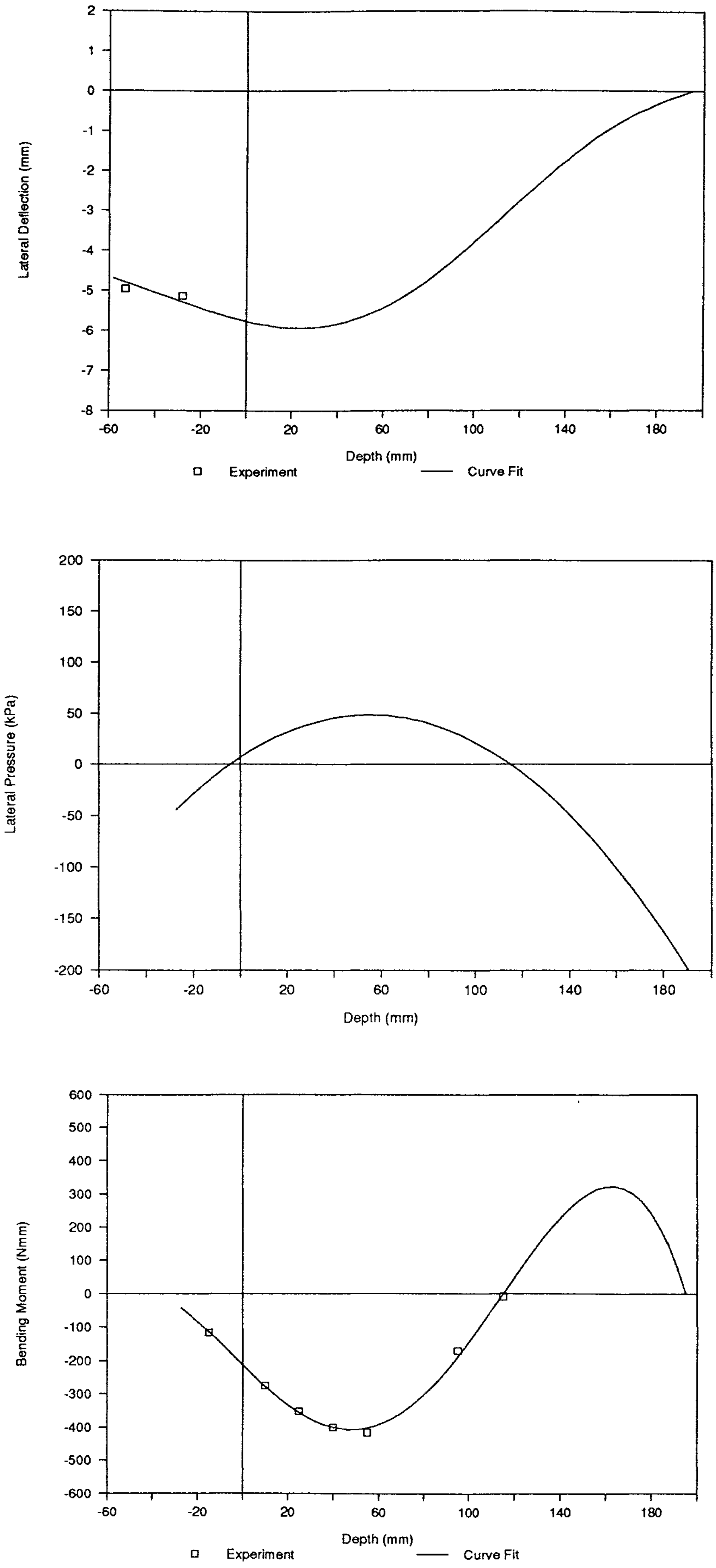


Fig. 9 **Preliminary Test Results - Pile Response at 2 m Embankment Height**

depths of cover, or by soil loads at high depths of cover. Such information is urgently required in order to assess present building code and safety standards, and to validate current methods in use for design of rectangular culverts.

The response of rectangular box culverts under different loading conditions is a problem which is difficult to solve theoretically or analytically, but may be examined conveniently using centrifuge testing techniques.

5.2 Current Research

The Geomechanics Group at UWA is presently embarking on a study of the pre-failure response of rectangular box culverts under two loading conditions. During the study it is planned to examine the relationship between the load carried by a buried rectangular culvert, and the relative soil structure stiffness.

Four model culverts will be manufactured from mild steel and instrumented at 12 points to measure bending or axial strain. Each steel culvert will have the same internal dimensions. However, wall thicknesses will be varied between the culverts, in order to produce a wide range in structural stiffness over the four models. All model culverts will be incorporated in homogeneous centrifuge samples constructed from dry silica sand.

The behaviour of each model culvert will be examined under two loading conditions, as shown in Figure 10. The first condition corresponds to a uniform soil load under a high depth of cover (Figure 10(a)), while the second condition corresponds to a live load, applied as a uniformly distributed strip load along the longitudinal axis of the culvert, under a low depth of cover (Figure 10(b)).

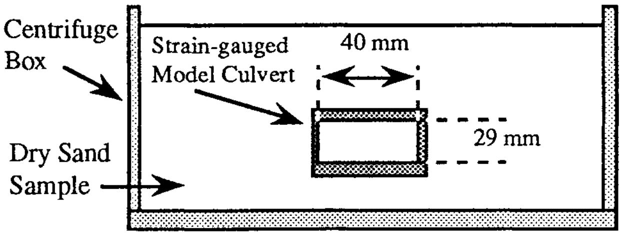


Fig. 10(a) Model Configuration for Soil Load at a High Depth of Cover

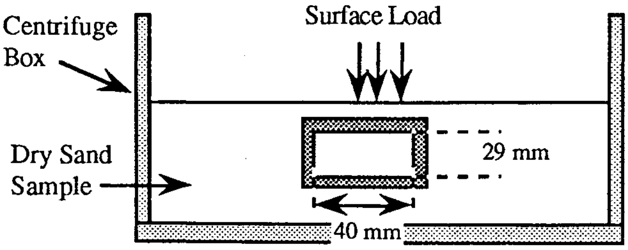


Fig. 10(b) Model Configuration for Surface Load at a Low Depth of Cover

Results from the test series will be used to establish a relationship between the load carried by a rectangular culvert and the soil-structure stiffness ratio. This will enable evaluation of current methods in use for rectangular box culvert design, and will provide valuable insight into the general behaviour of buried, flexible structures under different loading conditions.

6 MODELLING OF CONTAMINANT TRANSPORT PROCESSES IN SOIL

6.1 Introduction

During the past decade, much emphasis has been placed upon the importance of quantifying transport processes in the subsurface. A better understanding of the mechanisms which govern mass, heat and contaminant transport in soils is essential, if environmentally sound strategies are to be developed for controlling subsurface contamination.

At present, there exists a critical need for physical observations of pollutant behaviour in soils. Such observations are required both to validate existing mathematical transport models, and to aid in developing improved conceptual models of fundamental transport processes.

Controlled field experiments and laboratory column tests have traditionally provided the bulk of experimental data on pollutant behaviour in soils. However, researchers have recently come to recognise that a geotechnical centrifuge can provide a powerful testing tool for the physical modelling of transport phenomena in porous media.

Geotechnical centrifuge modelling supplies a means of carrying out small scale physical modelling of many transport problems, under repeatable and controlled laboratory conditions. It is a feature of centrifuge model tests that transient processes, such as groundwater contaminant migration, that occur in long prototype times, may be reproduced in a centrifuge model in short model test times. For example, a 1/100 scale model in a relative centrifugal field of 100g, is capable of reproducing almost 30 years of pollutant transport data, in only 25 hours of model test time.

Because the product of depth times acceleration is the same in centrifuge model and corresponding prototype, the stress distribution throughout the model will be identical to that throughout the prototype. This means that gravity dependent phenomena, such as free convection under non-isothermal conditions and physical migration due to density gradients, can be correctly replicated in a reduced scale centrifuge model: correct replication of these effects is not possible outside a centrifugal field, unless a full scale field test is carried out.

The Geomechanics Group at UWA is currently involved in two research projects entailing the centrifuge modelling of transport processes in porous media.

These projects are discussed under separate headings below.

6.2 Modelling of Absorption and Dispersion Processes

Although much progress has recently been made in the centrifuge modelling of transport processes, two fundamental areas of uncertainty remain associated with this field of research. The first concerns modelling the dispersivity and heterogeneity of a porous medium, in particular the observed dependence of field scale dispersion upon a 'length-scale' factor. The second concerns the modelling of sorption and retardation processes. Both factors must be addressed before modelling of site specific problems can be attempted on the centrifuge. The complexity of modelling sorption processes on the centrifuge demands the necessity of interdisciplinary co-operation, and the possibility of a collaborative research project with experts in this field is being investigated. A study of problems associated with the modelling of dispersion processes is already underway.

In order to replicate all dispersion processes correctly in a reduced scale centrifuge model, both macroscopic and microscopic prototype lengths must be scaled. This requires scaling of prototype particle sizes in the centrifuge model. In order to investigate prototype particle scaling on the centrifuge, a series of centrifuge tests is planned using models constructed of different gradings of silica sand. Three sands with particle diameters of 0.1 mm, 0.45 mm and 0.9 mm have been identified as suitable modelling materials. These sands will be incorporated in homogeneous centrifuge models of a pollutant transport problem, Figure 11, and tested at suitable g-levels. A comparison of scale will then be made between experiments. This will enable the feasibility of scaling lengths in a centrifuge model to be established, and will also provide valuable insight into the influence of particle size on microscopic dispersion processes.

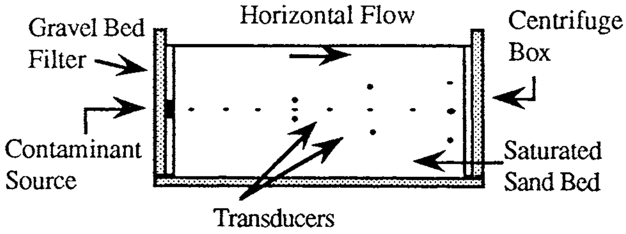


Fig. 11 Model Configuration for a Centrifuge Study of Dispersion Processes

At a later date, centrifuge models will be constructed which incorporate different layers of each modelling material in the same sample. This will enable the influence of macroscopic heterogeneities on mesoscopic (field-scale) dispersion processes to be assessed

It is proposed to use a standard sodium chloride solution as the model pollutant in all tests. The progress of the contaminant plume as it moves through the centrifuge model will be mapped by an array of buried resistivity probes, which are currently being developed at UWA.

All centrifuge model tests will be compared with theoretical predictions from a suitable numerical code. The work described above is being supported by funding from the Australian Research Council, and Alcoa Australia Ltd.

6.3 Coupled Physical Modelling of Heat and Contaminant Transport

To date, few experimental data exist on the subsurface migration of contaminants under non-isothermal conditions. Collaborative research between Cambridge University and The University of Western Australia has been initiated in this area, with small scale physical modelling of a coupled heat and contaminant transport problem.

A series of centrifuge model tests is to be performed in a rectangular strong box, using different gradings of fully saturated silica sand. High temperature sodium chloride solution will be introduced into each model during centrifuge flight, along a buried horizontal porous pipe, Figure 12. Contaminant transport and temperature rise in the soil surrounding the pipe will be monitored throughout each test by combined miniature resistivity and temperature probes, which are also being developed at UWA.

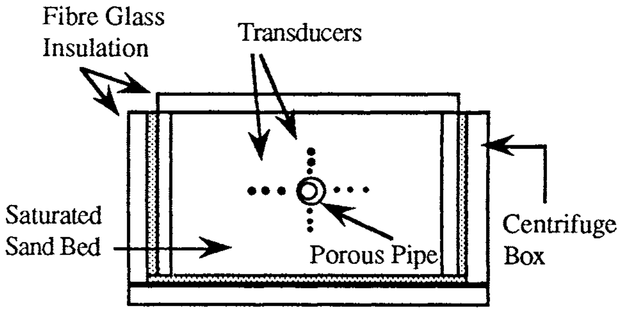


Fig. 12 Model Configuration for Coupled Heat and Contaminant Transport

During the centrifuge test series, the influence of both particle diameter (microscopic heterogeneity) and waste temperature on transport processes will be investigated. All centrifuge data will be compared with theoretical predictions from a suitable numerical code.

6.4 Future Research Projects

Funds are currently being sought for two further projects involving the centrifugal modelling of contaminant transport processes.

The first project will entail a study of dispersion in the presence of small vertical density gradients. Numerous field experiments performed in the presence of vertical density gradients have indicated that plumes in predominantly horizontal flow, tend to spread more in the lateral horizontal direction than the vertical direction. This seems to suggest that the dispersion tensor depends upon more than the two most commonly used terms: longitudinal dispersivity and lateral dispersivity. More experimental data are needed in order to quantify dispersion processes under such conditions. The Geomechanics Group at UWA have proposed a collaborative project in this area with the CSIRO Division of Groundwater Research.

Funds are also being sought to initiate a three year study into problems associated with the land disposal of waste effluents. During this project, the integrity of landfill liners under the action of real contaminants will be examined, and subsurface contaminant transport and recovery processes will be investigated in the presence of complicated flow and geological boundary conditions. Close collaboration with industry is anticipated at all stages of this project, with results from the study forming a much-needed bridge between fundamental research and waste management practice.

7 CONSOLIDATION OF SLURRIED TAILINGS

7.1 Introduction

The safe and economical disposal of mine tailings is one of the problems which confronts the mining industry, especially now with the increasing pressures being brought to bear on all aspects of mining by the environmental lobby. In many cases, mine tailings are deposited as dilute or thickened slurries in containment areas which may be natural topographical features or may be engineered specifically for the purpose. If the liquid entrained in the slurry either has the potential to pollute the underlying soil or groundwater, or has a commercial value, it may be desirable to contain the liquid completely in the disposal area and prevent any loss into the underlying formation, and/or to recover the liquid to feed back into the process stream.

For proper management of tailings disposal areas, both during the active life of the area and during any subsequent rehabilitation period, it is essential to understand the processes which control the movement of water in the tailings, the rate and final amount of settlement of the surface, and the changes in the strength profile through the depth of the tailings. This involves understanding the processes of initial sedimentation, self-weight consolidation under various drainage boundary conditions and formation of surface 'crusting' due to the combined effects of water table lowering in the tailings and surface dessication.

The current project in this area, funded by the ARC, is concentrating initially on understanding the process of self-weight consolidation. The approach which has been adopted is to develop numerical tools to model the processes, and to "calibrate" these tools with centrifuge modelling.

7.2 Numerical Modelling

The consolidation of slurried tailings is a classic example of large strain consolidation – that is, the changes in geometry and soil properties from the initial state to the final state are such that the original consolidation theory of Terzaghi, as traditionally applied, is not an appropriate means of analysing the problem. Thus, to deal with this problem, it is common to resorted to using the large strain consolidation model proposed by Gibson *et al.* (1967), which incorporates the features essential to deal with tailings consolidation: changing geometry of the layer and changing permeability and stiffness with reduction in voids ratio. An alternative approach has been adopted in the current project. Using numerical (finite element) techniques and fast modern computers, the traditional formulation of Terzaghi can be used for large strain consolidation problems provided the geometry and soil parameters are updated after each increment of consolidation; in effect, the small strain formulation is applied to small steps of consolidation, and the large strain aspect dealt with by updating the problem after each increment. In any practical application, this approach has the advantage that the updating phase after each consolidation increment can include addition of fresh tailings at the surface, which would occur in practice during the active life of the disposal area.

In the self-weight consolidation problem applied to tailings disposal, the drainage boundary conditions may be any of the following:

- surface drainage only
- surface and base drainage, but with the base water table being the same as the surface water table; this would correspond to the case of an impermeable disposal area with a filter layer at the base, but with no pumping from this layer.
- surface and base drainage, with the water table in the base being lower than the surface layer; this would include the case of complete underdrainage, with the water table in the underlying layer being kept below the base of the tailings
- combinations of the above, applying at different stages of the life of the area.

Numerical models, once formulated, require some means of verification or "calibration" if they are to be used with confidence in practice. It is possible to do this calibration using a combination of laboratory consolidation tests and observations of the performance of full-scale disposal areas. However, a much more satisfactory approach, at least in the early stages of development, is to use centrifuge modelling.

7.3 Centrifuge Modelling

Centrifuge modelling is the ideal method of investigating self-weight consolidation of soft soils. The scaling laws summarised in Table 1 indicate that consolidation takes place N^2 times faster than for the equivalent prototype. Thus, 1 day of consolidation on the centrifuge, at an acceleration of 100 g, is equivalent to 100^2 days (27 years) consolidation at prototype scale. The various drainage boundary conditions of interest, listed above, can easily be implemented on the centrifuge, and measurement of pore pressures and settlements throughout the layer is relatively straightforward on the centrifuge. After completion of consolidation, the strength profile can be determined using the in-flight site investigation tools already described. After the test, when the centrifuge stops, the layer can be sampled quickly to establish the final moisture content and dry density profiles.

An initial proving set of tests has already commenced using kaolin prepared at a water content equal to twice the liquid limit. Four drainage boundary conditions are being examined: top drainage only; top and bottom drainage with the bottom water table at the same level as the top water table; top and bottom drainage, but with both boundary water tables at the mid-height of the sample; and top and bottom drainage with both boundary water tables at the base of the container. Miniature 'Druck' pore pressure transducers are placed in the slurry to monitor the progress of consolidation, and surface settlements are measured using an LVDT resting on a small surface plate. Due to the increase in self weight with increasing acceleration, all transducers must be counterweighted using pulley systems to prevent them sinking through the slurry during the early stages of the test while the slurry is still soft. To date, tests of up to 36 hours have been run.

The results obtained from this testing indicate that the techniques adopted result in well-controlled tests which provide the quality of data necessary for calibration of the numerical model. A parallel programme of laboratory consolidation tests is now underway to determine independently consolidation parameters for the soil at all stages from a slurry to the maximum consolidation stress. The model will then be used to predict the performance in the centrifuge tests using these parameters.

Of primary interest in this programme is the 'crusting' effect of the low water table induced by complete or partial underdrainage. In theory, underdrainage induces suction in the pore water above the water table, with the final suction value determined by the height above the water table. If the soil remained fully saturated above the water table, these suctions would result in high effective stresses being induced in the soil right to the surface, giving much greater strength increase than would be achieved by self-weight alone. However, in practice, this effect is muted due to desaturation at some height above the water table. The centrifuge tests permit this whole process to be examined in a controlled way.

8 MODELLING OF JOINTED ROCK

The centrifuge facility is presently being used to study the response of reinforced and unreinforced blocky rock masses that are common to many mining, and some civil engineering, surface excavations.

The centrifuge study forms the physical modelling component of a research program aimed at defining a suitable design methodology for the reinforcement of unstable blocks of rock that form in the periphery of the excavation. The physical modelling is being conducted in conjunction with field work and analytical and numerical modelling.

Historically, the centrifuge has not been used widely in rock mechanics studies, partly due to limitations of even the largest machines to achieve sufficiently high stress levels in the rock. For surface excavations, where stresses are considerably lower than those encountered underground, the UWA centrifuge can model a maximum 'rock' slope height of about 50 m. Surcharging on the upper surface may be used to augment the stresses in the model material.

In a preliminary test, a model rock slope was built out of 14,000, 15 mm x 15 mm x 15 mm blocks. The blocks were assembled as a steep rock slope in a vertical, 'brick wall pattern' in both plan and section. The model arrangement is shown in Figure 13. The model blocks were lightweight (unit weight of 9.5 kN/m^3), and gave a Class 2 type uniaxial behaviour with a uniaxial compressive strength of around 0.75 MPa. The model was designed to simulate a rock mass with an inherent strength approaching that of a continuum.

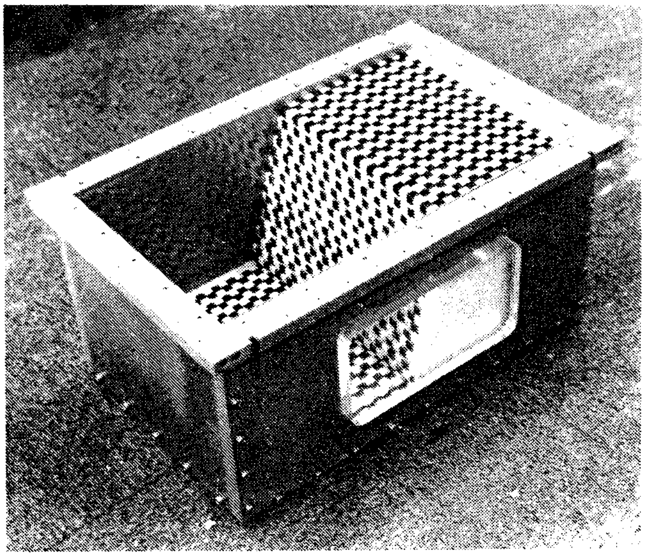


Fig. 13 Model arrangement of 'brick wall pattern'

The model rock slope had a free height of 275 mm, representing a prototype height of 55 m at 200 g. The stress level at the level of the toe of the slope was 0.52 MPa, with no surcharge, and 1.12 MPa with a surcharge of lead shot on the upper surface of the rock slope. These stress levels are probably insufficient to cause crushing of the model blocks near the toe, where the confining effect of adjacent blocks will increase the compressive strength beyond 0.75 MPa. No failure of the slope was observed, even with the full surcharge applied at an acceleration level of 200 g.

As predicted the initial model test did not lead to failure of the slope, mainly due to the high strength–to–weight ratio of the model blocks. However, variations in the geometry of the block assembly – for example from a vertical 'brick wall' assembly that is interlocked in two directions to, say, sloping stacks of blocks – will quickly convert the problem from one approaching a continuum to one approaching that of a simple sliding or toppling block on a plane. In these types of problems it is not the intact block strength that controls stability but rather the peculiar disposition of the mutually intersecting discontinuites. This is the type of problem that will be studied with the centrifuge. Here, the 'weights' of the blocks formed between the discontinuities may be increased by acceleration until a block type of failure mechanism results.

The possible failure mechanisms are in fact quite numerous and very complex, because each usually involves a multiple, and successive, block collapse, with each block capable of a distinct rigid body motion. To monitor these mechanisms, the centrifuge set-up allows video recording through a side window, laser scanning measurement and stereo-photogrammetric displacement profiling of the slope face during flight.

The types of problems to be studied are very difficult to simulate numerically and almost impossible to study in the field. This is especially true when the influence of model reinforcement is added. Also, in other physical modelling methods, it is very difficult to obtain correct similitude for the model reinforcement stiffness. It is hoped that this can be avoided at the high stress levels achieved by centrifugal modelling.

The analytical and numerical modelling methods include simple force-displacement style analytical procedures, finite difference, finite element, boundary element, discrete element and hybrid computational schemes. When these procedures are applied in rock mechanics, two fundamental problems exist in assessing their validity. The first concerns correctly describing the rock mass structural geometry of the field problem, the second concerns correctly describing the geometrical response of the rock mass to excavation. It is difficult, if not near impossible, to achieve an appropriate precision in these areas simultaneously. Thus, the validity of some discontinuum procedures is still to be verified for design purposes. The only rigourous way of checking the predictions of these methods is to carefully fabricate and construct a precise model, then subject that model to a uniform acceleration field and measure its response accurately. Verification of these numerical procedures in the area of slope design will be attempted in the centrifuge at UWA.

9 MINING-INDUCED SUBSIDENCE

9.1 Introduction

Ground subsidence can lead to expensive and potentially hazardous damage to surface and near surface structures: for example, the cracking of buildings and dams and rupturing of pipes and services. Furthermore, damage to lining systems employed in tailings ponds or landfill depositories may result in the escape of leachates which could pose a threat to ground water supplies.

Of particular interest to the resource development industry of Australia is the problem of mining-induced subsidence resulting from the extraction of minerals at depth. It is well known that the final surface disturbance resulting from mineral extraction will depend on the overlying strata and depth of soil cover. For example, expressions such as escarpments, plug settlement zones or areas of general subsidence may occur.

The aim of the proposed research is twofold and involves:

- a fundamental study of the propagation of discontinuities through a soil deposit, and
- the modelling of site specific cases for use in the calibration of numerical and predictive models.

9.2 Fundamental Study

In this study a series of centrifuge model tests will be performed to investigate the mechanisms involved in the propagation of induced boundary displacements through a soil deposit, and the resulting surface and near surface disturbances which result. In particular the following factors will be investigated:

- the effect of soil cover thickness
- the effect of stratified soil layers of differing properties
- the effect of different modes of induced displacement (i.e abrupt 'fault' type displacements which contain discontinuities of both slope and displacement, and displacements which contain discontinuities of slope only).

A versatile 'trap-door' displacement system will be mounted at the base of the centrifuge strong box such that a false floor containing an arrangement of rotating flaps and solid units will permit various modes of base deformation to be induced. The development of displacement and strain fields within the model will be obtained by image processing of the recorded movements of discrete markers placed in the model.

9.3 Site-Specific Modelling

An application in collaboration with the Geomechanics Division of the CSIRO has been made to NERDDC to fund a separate project where a series of centrifuge tests will be performed to model coal extraction techniques. During this study, specific mineral extraction processes, which allow for the controlled collapse of subterranean workings behind the advancing face, will be modelled. By modelling site specific cases in the centrifuge, it will be possible to calibrate numerical models formulated to predict surface disturbance in a controlled environment, and thus their application to field situations can be made with greater confidence. The Geomechanics Division of the CSIRO have a strong record of involvement in this area, and have access to surface subsidence records from coal mining areas which will permit comparisons with the centrifuge model tests to be made.

The two projects outlined above will be run in parallel, and it is anticipated that the data obtained from the fundamental study will be incorporated into the development of the numerical and predictive models used in the site specific study.

10 SUMMARY

This paper has described the new geotechnical centrifuge facility at The University of Western Australia, and summarised the various research projects that are currently being undertaken using the centrifuge.

In addition to the projects already described, there are many other areas where centrifuge modelling may prove useful. The centrifuge, by its nature, is ideal for any problems where self-weight loading is important. Such problems may involve static loading, as in retaining walls, reinforced soil, soil nailing, and the stability of slopes and excavations, or may involve dynamic loading where inertial and flow effects become important.

Centrifuge modelling has played a key role in research on earthquakes, and events such as blast loading, where inertial effects are critical. There is also a useful role to play for problems involving flow of granular materials, for example in the mining industry (transport, stockpiling and retrieval of ore and waste material) or in silo design.

The range of geotechnical problems where centrifuge modelling may prove useful is enormous, and it is likely that other geotechnical centrifuges will be established in Australia over the next few years. In the meantime, the centrifuge at UWA is seen as a national facility, and it is hoped that researchers and design engineers throughout Australia will make use of the facility.

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