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Obtaining Cyclic Load-Transfer Curves

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Summary: Load-transfer curves are commonly used in the design of piled foundations subjected to substantial lateral loads. There currently exists a need to develop a database of this information for the calcareous sediments present on the North West Shelf of Australia. In particular, the behavior of piles subjected to cyclic loading in these soils needs to be understood and quantified.

A geotechnical centrifuge can be used to experimentally determine load-transfer curves. Instrumented model piles have been tested at high acceleration levels to simulate prototype conditions. In order to model cyclic conditions accurately, the pile has to be loaded at high frequencies. This necessitates a suite of pile loading hardware as well as an automated load control system.

The necessary rate of pile lateral loading creates a requirement for data acquisition at frequencies higher than 10 kHz. In order to accommodate this, and other data logging requirements, a 32 channel data acquisition system has been developed and installed in the geotechnical centrifuge facility at the University of Western Australia.

Post processing of the experimental data involves curve fitting bending moment data followed by numerical differentiation and integration to obtain profiles of deflected shape and pile force per unit length. These results can be combined to form load-transfer curves for piles subjected to monotonic and cyclic loading conditions.

1 NOTATION

CPT = Cone Penetrometer Test
d = pile diameter
g = acceleration due to gravity = 9.81 ms^{-2}
H = shear force
ℓ = Pile length
M = pile internal moment
N = number of equivalent earth gravities
P = force per unit length
p = lateral pressure
r = radius
t = pile wall thickness
ω = angular velocity
y = pile lateral deflection
z = depth
z_o = unit depth

2 INTRODUCTION

In recent years there has been substantial development of the hydrocarbon fields present in the North West Shelf of Australia. The weather conditions in this region are considered to be extreme due to the prevalence of cyclones in the summer months. Consequently, the design of offshore structures needs to consider the effects of cyclic loading due to wave action.

Piled foundations are commonly used for offshore structures to provide the necessary vertical and horizontal resistance. Although extensive studies have been carried out to determine the axial capacity of piles in calcareous soils, there is a paucity of data covering the lateral response. Due to the unique nature of these soils and the problems which have been associated with platform installation in the past, it is necessary to develop a more complete understanding of the soil behaviour.

The most popular approach for the design of piled foundation systems subjected to lateral loading utilises load-transfer curves. Load-transfer or "P-y" curves idealise the soil as a set of non-linear independent springs which describe the relationship between force per unit length and lateral displacement at a prescribed depth. Once the nature of these curves is known it is relatively easy to implement them in a beam-column style analysis to determine the response to applied loads.

P-y curves can be obtained experimentally using small models in a geotechnical centrifuge. In order to determine these curves for monotonic and cyclic loading conditions, it is necessary to develop a range of software and hardware to control the experiments and convert the results to a usable form.

This paper describes how cyclic P-y curves can be obtained using the geotechnical centrifuge at the University of Western Australia. The hardware, software and analytical methods, which have application in other fields of research, will also be described.

3 CENTRIFUGE TESTING

The Geomechanics Group at the University of Western Australia currently operate two centrifuges, a "Fixed Beam" and a "Drum". A fixed beam centrifuge operates by rotating a package which contains soil, model equipment and instrumentation about an axis (Figure 1). A drum centrifuge rotates a ring of soil about an axis. The fixed beam centrifuge was used for the pile lateral loading and further details regarding this facility can be found in Randolph *et. al.* (1).

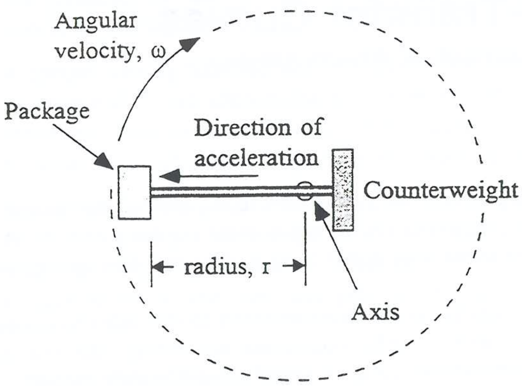

Figure 1. A basic fixed beam centrifuge.

The rationale behind testing small models in a centrifuge to represent full scale conditions has been explained by Schofield (2). The fundamental advantage is that it is possible to use small manageable models to represent prototype events in a cheaper, quicker and simpler manner than would be required for full scale tests.

The scaling effects associated with using a centrifuge are a function of the radial acceleration generated by the rotation of a package about a fixed axis. This rotation results in an acceleration (Ng) being applied to the package, the magnitude being dependent on the radius (r) and angular velocity (ω) as described in (1) below.

$$Ng = \omega^2 r \qquad (1)$$

The effect of this acceleration is for the stress gradient in the package to be the same as that of a prototype with length dimensions N greater. Further scaling relationships also exist as outlined by Schofield (2).

3.1 Model Pile Testing

For this research, a closed-ended model pile of dimensions d = 13 mm, and ℓ = 340 mm is being used. This pile is tested at an acceleration of 160 g to represent a prototype with dimensions d = 2.08 m and ℓ = 54.4 m.

The model pile is made of 12 mm diameter by 1 mm thick aluminium alloy tube to which thirteen levels of strain gauges calibrated for bending moment are attached. A 0.5 mm thick coating of epoxy is also applied in order to protect the gauges. This model pile has a bending stiffness of 3×10^8 Nmm^2 based on the combined EI of the aluminum wall and epoxy coating. The corresponding prototype stiffness for this model is 26.7×10^3 MNm^2. A typical steel pile used in offshore conditions has a d/t ratio of approximately 30 with a corresponding stiffness of 44.5×10^3 MNm^2. It is assumed that differences in pile stiffness would have little
load-transfer curves.

The model pile used in this testing was closed-ende
to protect the internal wiring of the bending momen
Offshore piles are typically open-ended but recent
(Dyson & Randolph (3)) has shown that, for calcare
at least, pile tip conditions have very little effect o
lateral behaviour.

The model pile is installed by either jacking or dri
strongbox with internal dimensions of 650 long × 3
325 deep (mm). The soil depth is typically 270 mm
in a prototype pile embedment depth of 43.2 m.

During a monotonic test, the pile is loaded later
constant rate until a prescribed load limit is achieve
testing involves displacing the pile laterally betw
load limits at a specified frequency for a defined n
cycles.

4 PILE LATERAL LOADING

When designing offshore foundation systems th
design case relates to storm loading. Consequen
foundation systems need to be designed to
considerable cycling due to wind and wave action.

Whilst axial and lateral loads are often combin
prototype conditions it is assumed that the late
transfer characteristics of soil are virtually independ
axial behaviour. For this reason, pile model testing
restricted to purely lateral loading. In order to unde
testing, considerable specialist equipment and s
required.

4.1 Pile Lateral Loading Hardware

Experimental P - y curves can be generated by i
the results of laterally displaced model piles. Th
moment profile, as obtained from the gauges duri
can be used to determine pile lateral force per unit
and lateral deflection (3).

$$\frac{d^2M}{dz^2} = P$$

$$\int\left(\int \frac{M}{EI}\,dz\right)dz = y$$

The pile is loaded laterally using a combination o
purpose loading leg and a general purpose act
author has designed two loading legs: the first whic
pile head rotation and the second which allows
rotation. Each load leg is instrumented with strain
measure lateral load and, in the case of the restrain
loading leg, pile head moment. The two loadin
illustrated in Figure 2.

There are two general purpose actuators use
centrifuge. The "Cone" actuator, typically used f
soil characterisation tests, can drive laterally at

ranging from 0.0025 mm/s to 3.14 mm/s. This actuator has been used for slow, drained, monotonic testing. The "Footing" actuator is more powerful in the lateral direction and has the capacity to load at rates ranging from 0.4 mm/s up to 80 mm/s. This actuator is used for fast cyclic work.

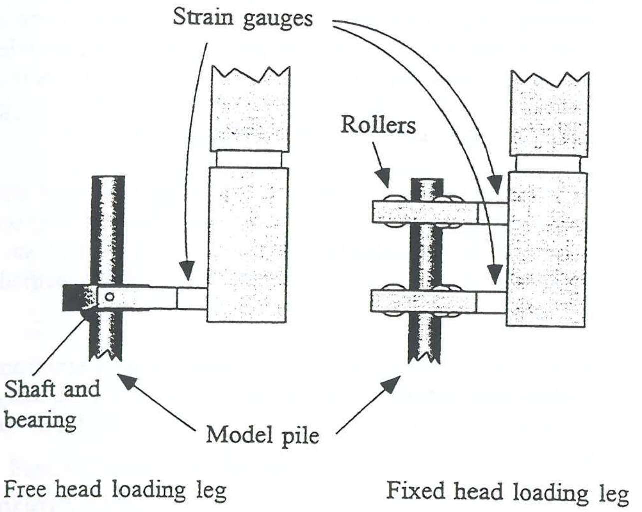

Figure 2. Pile head loading apparatus

Typical prototype wave loading conditions correspond to a loading frequency of approximately 0.1 Hz. The degree of drainage during loading strongly affects the lateral behaviour of a pile. Consequently, the pile needs to be loaded at a rate which replicates the prototype drainage conditions. Consolidation events in the centrifuge scale with N^2 so at a test g level of N = 160 the model loading rate would need to be 160^2 x 0.1 = 2560 Hz. This is unachievable with the existing equipment over the desired load limits. This frequency can be lowered however, by modifying the viscosity of the pore fluid. In this instance, silicon oil with a viscosity 100 times greater than water is used, reducing the required loading frequency by a factor of 100 to 25.6 Hz.

The footing actuator, using the software which has been developed by the author, is capable of cycling at 25 Hz for small displacements and at rates up to 9 Hz for displacements of +/- 3 mm. This corresponds to a pile lateral displacement of +/-25 % of the diameter. A typical cycle, at this rate, is over in nearly 0.1 s. As a consequence of the time scale in which these events occur, it is necessary to control the actuator with an automated system.

4.2 Automated Load Control System

The actuator control system is a combination of a series of computers and interface systems which are located within the centrifuge and in an external control room.

Whilst the centrifuge is in operation, all changes made to the package and equipment are controlled or triggered externally via slip rings. These changes are made in the control room where the test is monitored. The control computer "CPU2" is linked to the centrifuge via the COMS port and then through a slip ring to the "Flight1" computer. On CPU2 there resides a number of programs designed for controlling various actuators and other equipment.

The programs, which the author has developed specifically for laterally loading piles, contain a number of routines. It is possible to maneuver the pile head through 2 dimensions in real time or cycle the pile head between load or displacement limits. Cycling can be either frequency controlled or velocity controlled for a specified number of cycles.

Once the desired mode of pile head loading has been selected, the data is sent via the COMS port to the Flight1 computer situated on the centrifuge turret. This computer has a program which accepts the data from the control room and interprets the desired mode of loading. The Flight1 program then sends commands to the actuator controlling the rate, direction and duration of loading. For the manual movement modes, the Flight1 program sends a constant stream of data via the COMS port back to CPU2 so that the status of critical instrumentation is known. For the cyclic modes of operation, the Flight1 program is self contained and does not send any information back to the control room until the loading package is complete. This is designed to maximise the responsiveness of the load and displacement control.

The cyclic loading routine is designed to achieve the desired velocity of loading without exceeding the target loads or displacements. This is achieved using an algorithm that ensures that the speed of the actuator is proportional to the square root of the difference between the target load limit and the current load (Equation (4)).

$$\text{Velocity} = \frac{\text{Maximum velocity.}\sqrt{\text{load} - \text{limit load}}}{\sqrt{\text{Soil stiffness constant}}} \tag{4}$$

In theory the actuator would never reach the load limit as the velocity would be zero. In reality, the momentum developed by the entire system ensures that the actuator reaches the limits.

Figure (3) shows the effect of this algorithm on the relationship between pile head displacement and load with time.

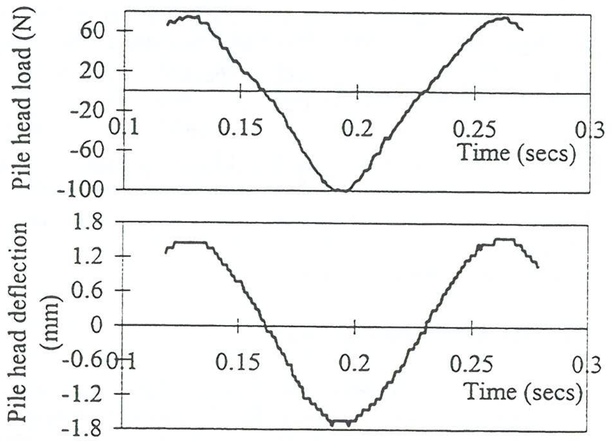

Figure 3. Relationship between displacement and pile head load with time for cyclic loading.

It can be seen that there is a sinusoidal response of the pile head during cycling as the actuator accelerates and decelerates about the load limits.

During a typical cyclic package, in calcareous sediments, the stiffness of the soil changes quite dramatically. The cyclic loading routine has been designed to maintain a constant frequency by modifying the soil stiffness constant after each loading cycle. If the previous cycle was too slow, corresponding to a softening of the soil and increased lateral displacement, the soil stiffness constant is decreased. If the previous cycle is too fast, corresponding to a stiffer sample, the constant is increased.

5 HIGH SPEED DATA ACQUISITION

Cyclic events in the centrifuge occur over a very short space of time. As a consequence of this, it is necessary to record a large amount of data very rapidly. For this case of cyclic loading of a pile, there are 19 channels of data which need to be recorded: 13 bending moment gauges, 2 laser displacement transducers, 2 load cells and 2 actuator displacement transducers.

Within a typical cycle of loading it is desirable to have at least 100 sets of data points for analysis. Cycling at 9 Hz means 900 sets of data or 900 x 19 = 17100 data points are required per second, corresponding to a data acquisition rate of 17.1 kHz. Cycling at higher frequencies or sampling a larger number of instruments would obviously increase the demands on a data acquisition system.

In order to satisfy these and other fast data acquisition requirements on the centrifuge, a high speed data acquisition system was developed by the author. This system has the ability to log 32 channels of information at a frequency of 6.25 kHz, 2 channels at 100 kHz or, for the lateral loading instance, 19 channels at 20 kHz.

5.1 Data Acquisition Hardware

The core components of the fast data acquisition system are two new computers situated on the centrifuge turret; "Flight2" and "Flight3". These machines are dedicated to data acquisition and contain ComputerBoards DAS16Jr cards. Each of these cards can log one channel at up to 100 kHz or 16 channels at 6.25 kHz. The two computers are connected with the Flight1 computer and a separate computer "Control" in the control room via an Ethernet connection through a slip ring. Data acquisition is triggered manually from the control room or independently via the Flight1 computer. Data is streamed directly to RAM disks, then to the hard disks on the Flight2 and Flight3 computers and finally, after the test is complete, through the Ethernet connection out to the hard disk on the Control computer.

5.2 Data Acquisition Software

A number of different programs, and components of programs are used to control the acquisition of data. In the centrifuge there is the "Streamer" program from Keithley Metrabyte which controls the DAS16Jr cards. This program is triggered either manually from the Control computer via the Ethernet or via a rising digital trigger from the DAS8 Flight1 computer.

The Flight1 computer has the data acquisition triggerin incorporated in the load control routines. The last step program prior to commencing lateral loading in sending a digital trigger to the Flight2 and Flight3 com This remote triggering ensures that all data from the r test is recorded, regardless of how quickly an event The two data acquisition computers are tri simultaneously and stream data independently.

From the control room, the two data acquisition compu the centrifuge can be accessed via the Ethernet conn This enables characteristics of the data acquisition s number of channels and rate of acquisition to be specif changed whilst the centrifuge is in flight.

After a cyclic loading test is completed, the data sent f centrifuge is converted from binary to ASCII format us Streamer software so that it can be analysed preconstructed spreadsheet templates.

6 CONSTRUCTION OF LOAD-TRANSFER CU

Once a test is complete it is necessary to convert experimental data into P - y curves. The first stage process is to separate the data into individual cycles. each cycle it is then possible to develop a set of P - y c

Once a cycle has been isolated, discrete events dur cycle need to be separated. This results in a se "snapshots" of the bending moments, pile head displacements and rotations at a particular instant.

Each of the sets of bending moment data need to be co into a polynomial form in order to facilitate differe and integration using equations (2) and (3). This is a using a spreadsheet which splices three curves tog linear function and two 4th order polynomials) as illust Figure 4. These curves are spliced together using b conditions of continuity of the first and second der (shear force and pile force per unit length) as well as tip moment.

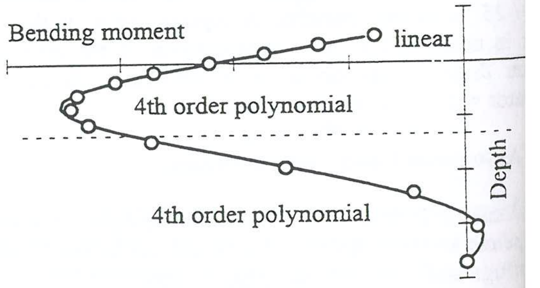

Figure 4. Curve fitting of bending moment dat

Once the polynomial forms of the bending momen are quantified, they are differentiated and integrated give the pile force per unit length and the lateral de Boundary conditions of pile head rotation and defle measured during the test, are used in the integr determine the pile shape.

The shape and pile lateral force per unit length relationships for each selected cycle are then combined to form load-transfer curves at specific depths. Figure 5 shows typical drained monotonic load-transfer curves for a sample of calcareous sand (Dyson & Randolph (4)).

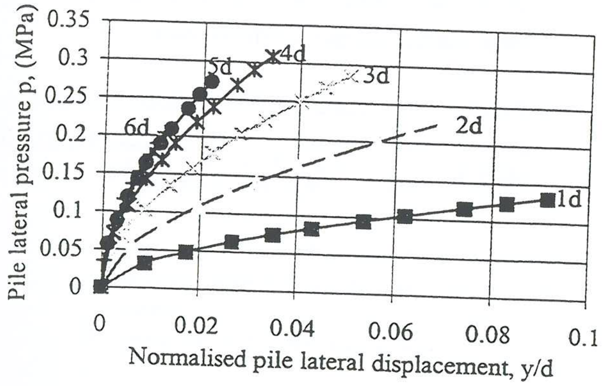

Figure 5. Monotonic drained P - y curves for calcareous sand

This drained behaviour can be compared to Figure 6 which shows an example of undrained load-transfer curves for a calcareous sand after 11 cycles at 9 Hz.

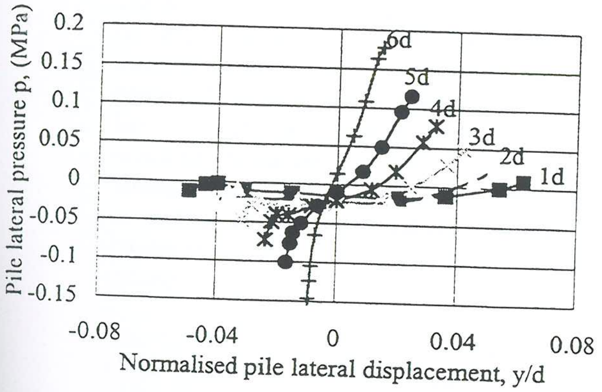

Figure 6. P - y curves for calcareous sand after 11 cycles

It is immediately obvious that there is a significant difference in behaviour. The cyclic curves display far less strength at all deflections and have a different shape in general.

It can be seen that after only 11 cycles the near surface soils have virtually zero strength. This indicates that gapping or fluidisation of the soil is occurring at these depths. It is only at the extremes of the lateral displacements that the pressures start to increase.

This transition in soil strength with progressive cycling can be seen in Figure 7. This shows, at a depth of 2 diameters, the change in lateral load-transfer behaviour. The soil stiffness reduces steadily with cumulative cycles and appears to exhibit gapping or very low strength behaviour after 6 cycles tending, to equilibrium after 9 cycles. The load-transfer relationships tend to be exhibit a substantial change in gradient towards the end of each curve, suggesting a sharp increase in soil stiffness either side of the gap.

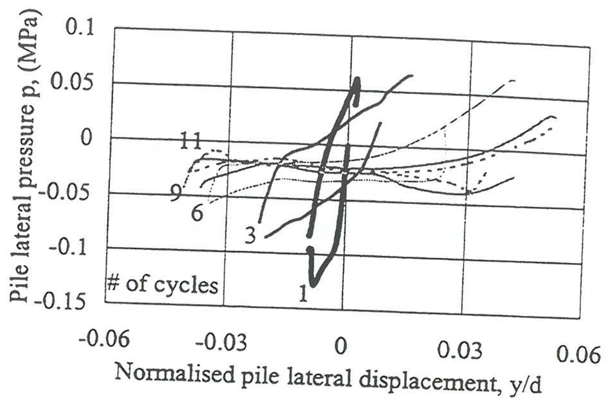

Figure 7. Cyclic P - y curves for calcareous sand at 2 d

Whilst these are only preliminary results, the consequences for design are numerous. Further testing is required to expand this database of load-transfer data.

7 CONCLUSION

Geotechnical centrifuges are a very useful tool for experimental research in designing offshore foundation systems, and many other areas related to soil mechanics.

The centrifuge and associated equipment and software at the UWA Geomechanics Group is capable of applying cyclic loads to a variety of different foundation types. The data acquisition system has the capacity to either manually or automatically record data at rates of up to 100 kHz, and record information from as many as 32 channels.

A framework has been developed, using the data obtained from experimental testing, to determine P - y curves for laterally loaded piles in any soil. This methodology has been shown to provide accurate results in previous studies investigating monotonic drained loading conditions (Dyson and Randolph (4)) and also in preliminary tests undertaken for this research.

As expected, initial results indicate that the cyclic undrained behaviour of calcareous sand is far different from the drained monotonic results obtained previously. Further testing using the equipment and software developed should provide an extended database of cyclic load-transfer curves for calcareous sand and silt.

8 ACKNOWLEDGEMENTS

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development and experimental research would not have been possible.

9 REFERENCES

1. Randolph M. F., Jewell R. J., Stone K. J. L. and Brown T. A., “Establishing a new centrifuge facility”, (1991), Proc. Int. Conf. on Centrifuge Modelling - Centrifuge 91, 3 - 9.
2. Schofield A. N., “Cambridge University geotech centrifuge operations”, (1980), Geotechnique **30**(3), - 268.
3. Dyson G.J. and Randolph M.F., “Installation effec lateral load-transfer curves in calcareous sand”, Proc Conf. Centrifuge 98, (submitted Nov. 1997).
4. Dyson G.J. and Randolph M.F., “Load transfer curve piles in calcareous sand”, (1997), Proc. 8th Int. Co the Behaviour of Offshore Structures, 245 - 258.