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Modelling Of High Pressure Grouted Compaction Anchors

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INTRODUCTION

Pressure grouting of anchors deployed in granular soils is a widely used construction technique in which a grout bulb is created by expanding the diameter of the borehole cavity in the region of the fixed length. A compaction anchor, as discussed in this paper, is created by fixed length expansion only and not by the injection or permeation of grout into the surrounding soil. The expansion process compacts the soil adjacent to the fixed anchor length altering the stress regime and increasing the strength and stiffness of the soil.

A detailed investigation of the effect of the compaction process on the load capacity of model anchors, tested at field scale stresses in a geotechnical centrifuge, has been undertaken at the University of Manchester. The design, development and use of the test equipment is discussed and test results showing the effectiveness of the system are presented.

ANCHOR TEST EQUIPMENT - SPECIFICATION, DESIGN AND PREPARATION

A centrifuge test package was built to investigate the relationship between anchor fixed length expansion and the load-displacement characteristics of a 1:50 scale model compaction anchor. The equipment was designed to satisfy the following criteria:

- To model the expansion and subsequent loading of a deep vertically installed compaction anchor at field scale stresses, in a 50g gravitational field, in the Peter W Rowe geotechnical centrifuge.
- To enable the model anchor to simulate controlled fixed anchor length radial expansion to 125% initial diameter.
- To allow the work done in expanding the fixed length against the confining soil to be measured.
- To enable controlled loading of the model anchor to failure, with accurate measurement of anchor load and fixed length displacement.
- To allow measurement of changes in the soil stresses around the anchor during both the expansion and loading phases of the tests.
- To be robust enough to withstand soil stresses of the same order as those acting on field scale anchors.

The test package was designed for use in the 6.4m diameter beam centrifuge in the Peter W Rowe Laboratory at the University of Manchester. A full description of the operation of the centrifuge is given by Craig and Rowe (1981).

Model Preparation

The model anchor was installed and tested in air dry Mersey River sand, with properties shown in Table 1. The model anchor was firmly held in position in a steel test cell with dimensions 0.56m x 0.56m x 0.69m deep. One of two procedures was then used to fill the test cell with sand depending on the relative density required. Medium dense sand beds (Rd ≈75%) were prepared by uniformly pluviating the sand into the test cell, at a controlled rate, from a sand spreader. For loose sand beds (Rd ≈50%) a fine metal grid was first placed in the bottom of the test cell over which a 50mm layer of sand was carefully poured. The grid was then pulled up through the sand layer to give a bed of very loose sand. This procedure was repeated to completely fill the test cell. The soil density was then calculated by weighing the model. This technique consistently produced sand with a relative density of 40-45%. If required the soil could be densified on a vibrating table to reduce the voids ratio.

Mersey River Sand

Effective size, $d_{10} = 0.16$mm
Average particle size, $d_{50} = 0.2$mm
Uniformity coefficient $d_{60}/d_{10} = 1.8$
Particle specific gravity $G = 2.655$

Maximum dry density	1726 kg/m^3	$n = 0.35$	$\phi'_{peak} = 38.5^\circ$
Minimum dry density	1407 kg/m^3	$n = 0.47$	$\phi'_{cv} = 29.0^\circ$

Table 1: Properties of Mersey River sand.

Vertical Loading Rig

A 20kN capacity stepper motor driven loading rig, shown in Figure 1, was used to load the anchors to failure. The loading rig incorporated a load cell to measure directly the mobilised anchor load and was fitted with an array of LVDTs to measure anchor head displacement.

Miniature Total Earth Pressure Cells

One of the advantages of geotechnical centrifuge modelling is that the soil bed around models of deep structures is easily accessible both before a test, when the soil bed is being built up, and by post test excavation. This accessibility enabled total earth pressure cells to be placed in the soil surrounding the model anchors during model preparation.

The earth pressure cells were dimensioned and manufactured to ensure optimum performance when used with the centrifuge instrumentation system and with due consideration of the factors outlined by Krizezk et al (1974) and Weiler and Kulhawy (1982). The best compromise between a cell small enough to minmise inclusion effects in the soil bed while achieving a large enough diameter to ensure a balanced action of the soil grains over the area of the diaphragm was met in a cell 32mm in diameter, 5mm thick housing a 20mm diameter strain gauged diaphragm on the active face. The earth pressure cells were carefully calibrated before each test in a 508mm diameter Rowe cell filled with Mersey River sand of the appropriate density.

To ensure minimum system compliance, all mechanical and hydraulic systems for generating fixed length expansion and loading the model anchor were designed to be located at the end of the centrifuge arm and adjacent to the model test cell. The tests were controlled remotely using a

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PC in the centrifuge control room to read, process and store the data gathered by the array of sensing instruments placed on the model test package. A custom written interactive icon driven program was used to present information on the conditions within the model, in real time and in graphical format, to the test operator.

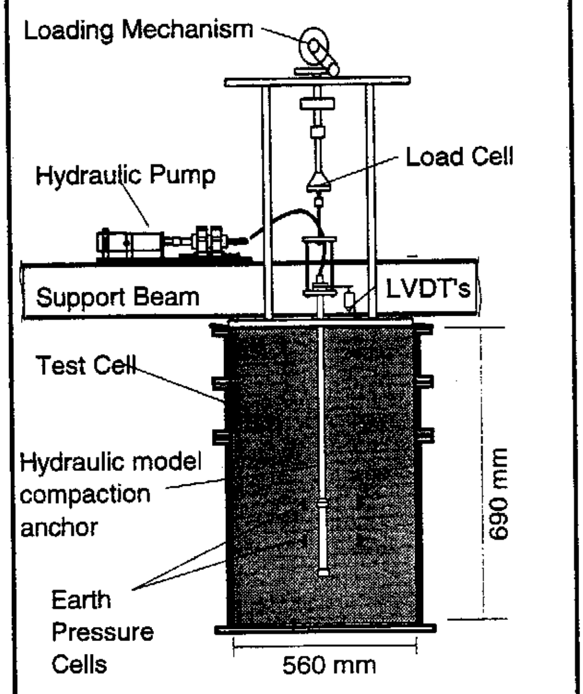

Fig 1. Section through hydraulic model anchor and test package.

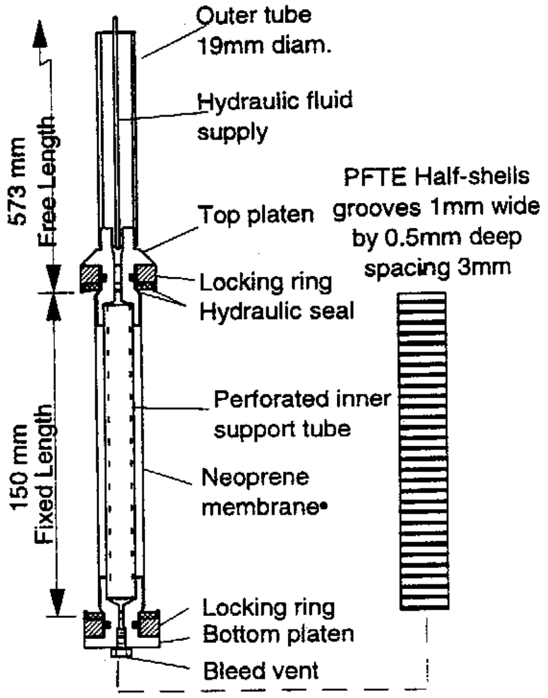

Fig 2. Section through hydraulic model expanding anchor.

DEVELOPMENT OF THE VERTICAL EXPANDING MODEL ANCHOR

Design Options

Since the model anchor fixed lengths were typically 150mm long by 25mm diameter unexpanded, the mechanics of expansion presented a dilemma. Three feasible design approaches were identified:

- A mechanically expanded anchor.
- A hydraulically expanded anchor using water.
- A hydraulically expanded anchor using a cementitious grout or resin anchor which hardened within a short period.

The design of a mechanically expanded anchor using a system of sliding wedges to push out the surface of the anchor fixed length against the confining soil, was briefly considered based on a concept similar to that reported by Lee (1991) and used for models of shallow anchors. However the components housed inside the fixed length would, through necessity, have been small and therefore insufficiently robust to withstand the forces generated during the expansion of deep anchors.

A hydraulic anchor was designed and manufactured, based on the principle adopted by Mohamed and Hanna (1985) of expanding the fixed anchor length with a water filled bag. The disadvantage of this approach was in the inevitable dimensional instability during the loading phase. The correct simulation of grout body expansion and subsequent resistance to pull-out required a fixed anchor length which remained rigid after expansion. This was achieved by using a low viscosity resin in place of water to generate the fixed length expansion.

Hydraulic Model Anchor

The design of the hydraulic anchor is shown in Figure 2. The outer surface of the anchor fixed length was formed by two closely fitting, thin walled, PTFE cylinders, each split longitudinally along one side. These overlapping cylinders, or half-shells, formed a fixed length of 150mm with a diameter of 25mm. The half-shells were expanded, up to a maximum diameter of 31mm, by pressurising, via a small bore tube passing down the inside of the free anchor length, an internal water filled neoprene membrane. The dimensions of the anchor were chosen such that under test conditions the model anchor simulated a field anchor with free a length of 28.7m and fixed length of 7.5m and giving a h/D ratio of 17.

Hydraulic Pump

The expansion pressure was generated by a hydraulic pump with a rated capacity of 3.5MPa, shown in Figure 1, designed to operate in gravitational fields up to 100g. To achieve flexible and accurate control of the anchor expansion process a stepper motor driven capstan pump was used. The stepper motor rotated the threaded piston rod which reacted against a thrust block forming part of the pump body causing it to be drawn along a low friction linear guide. This relative motion displaced water from the pump thus pressurising the system. The volume of fluid displaced was calculated, with an accuracy of ± 0.05cc, by measuring the movement of the pump body. A pressure transducer, mounted on the pump body, measured the hydraulic pressure.

HYDRAULIC ANCHOR PERFORMANCE

The inadequacy of a water filled fixed length hydraulic anchor was clearly demonstrated when an expanded anchor was tensioned monotonically at a uniform displacement rate to a fixed length displacement exceeding that which was believed to be achieved at failure. The anchor was expanded to 110% its initial diameter under a pressure of 2340kPa and subsequently loaded to failure. The load and pressure response is shown in Figure 3. A rapid reduction in anchor pressure is evident with increasing displacement. The load response was typical of that expected from a compaction anchor up to a displacement of 6mm, where a sharp increase in load of 30% occurred. Post-test excavation of the anchor revealed that gross deformation had taken place over the fixed anchor length leading to buckling of the PTFE half-shells, shown in Figure 4.

DESIGN OF A RESIN FILLED ANCHOR

Expansion System

As the option of manufacturing a mechanically expanded anchor had been shown to be unworkable the development of a resin or grout anchor offered the only way forward. Three key areas of development were identified:

- Identifying a suitable resin.
- Developing a reusable resin handling system.
- Designing and manufacturing a model resin anchor.

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Centrifuge operational constraints necessitated the use of a resin which displayed low viscosity in small bore tubing for at least 40 minutes after mixing but hardened completely within 90 minutes. Comprehensive trials of cementitious grouts, epoxy and polyester resins led to the adoption of a polyester resin (Crystic 471 PA LV (Resin A) manufactured by Scott Bader Ltd) with suitable rheological and curing properties.

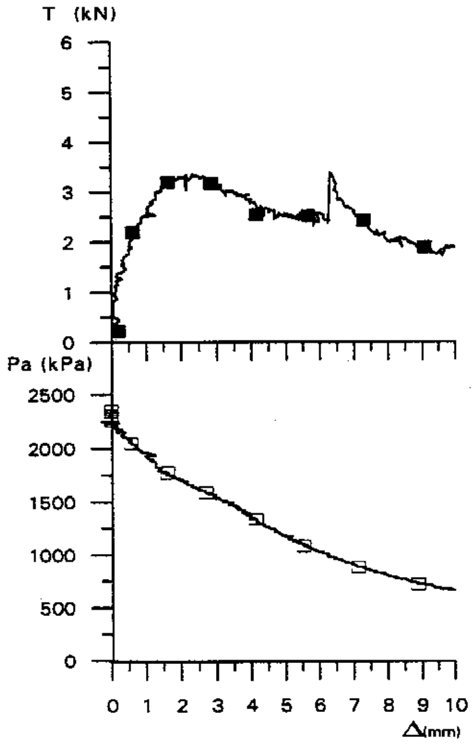

Fig 3. Hydraulic anchor load (Tf) and pressure (Pa) response during anchor displacement (Δ)

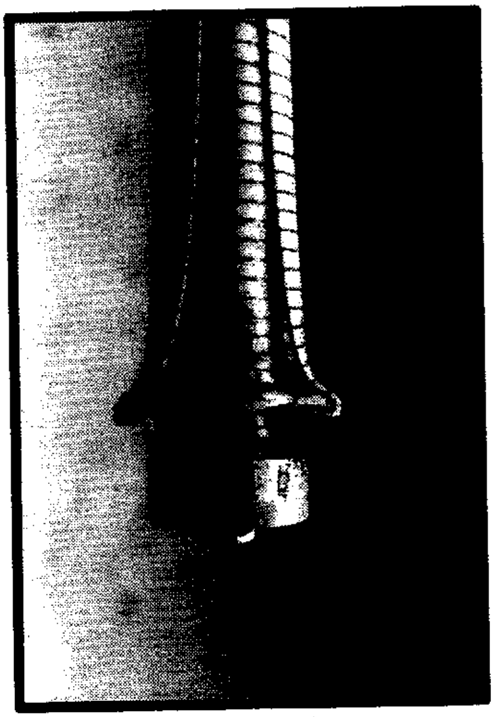

Fig 4. Condition of hydraulic anchor after expansion and loading.

Resin Handling System

A specially designed grout exchanger was placed between the hydraulic pump and the resin anchor to provide an interface between the water from the pump and the resin. The design of the grout exchanger allowed the hardened resin to be easily removed after a test making the system economically viable.

Resin Anchor Design

Detail of the model resin anchor is shown in Figure 5. The resin was contained in a latex membrane sock, sealed at the top and stretched over a perforated steel tube. This component was designed and manufactured for one-off use and was discarded after each test. Thin strips of steel formed an outer covering to the membrane, presenting a roughened shearing surface to the confining soil. The strips were attached to the anchor free length to transfer the anchor load to the soil. The dimensions of the resin anchor differed from the hydraulic anchor, simulating, under test conditions, a field anchor with a free length of 23m, fixed length of 8.5m and a h/D ratio of 15.

The model resin anchor tests were carried out in sets of two. In the first test the anchor was expanded, with associated modification of soil stress regime adjacent to the fixed anchor length, and loaded to failure. After the test the anchor was exhumed and the dimensions of the expanded resin bulb carefully measured. The same anchor was then reinstalled in a new bed of sand and subjected to a second pull-out test. In the secon test the stress system in the soil adjacent to the fixed length was not modified by in-situ fixed length expansion.

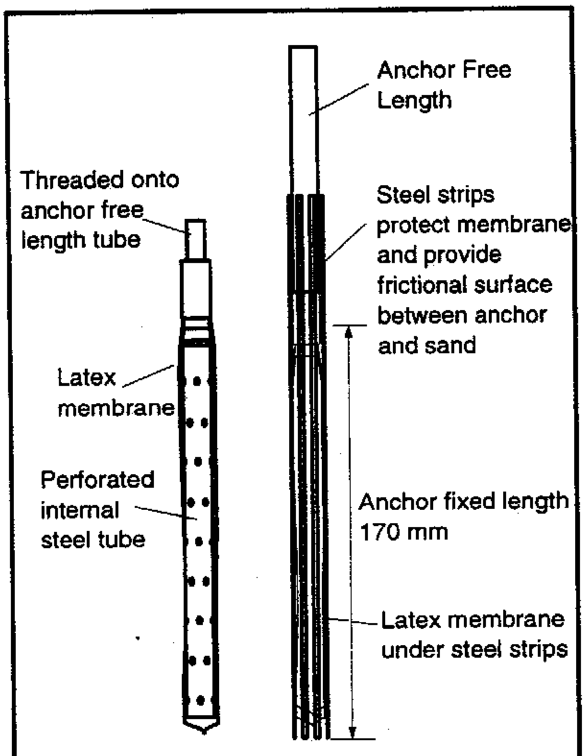

Fig 5. Detail of model resin anchor.

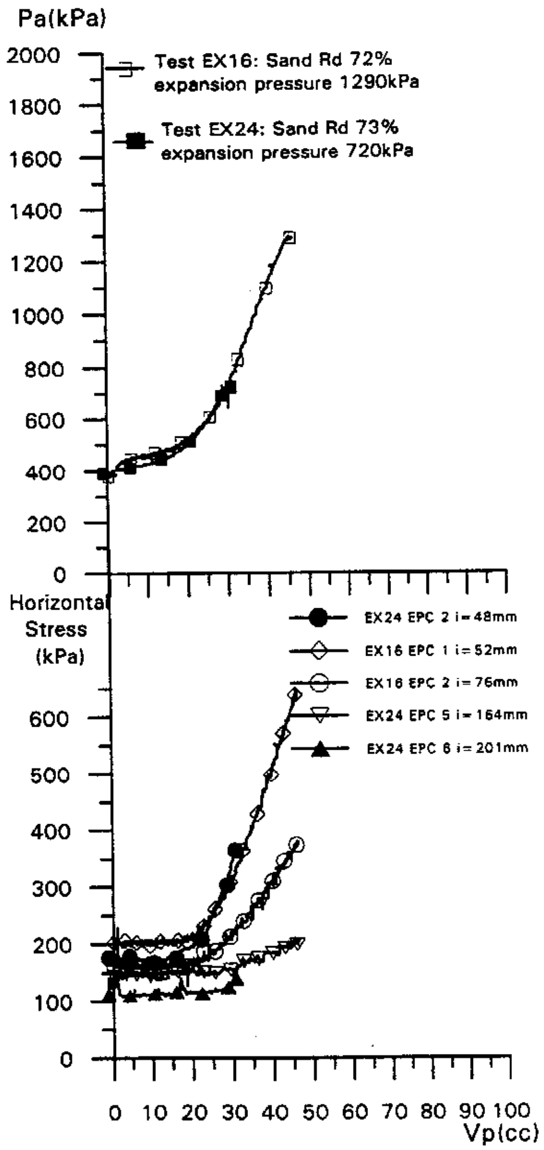

Fig 6. Measured soil stress response to anchor pressure increase (Pa) during expansion.

RESIN ANCHOR PERFORMANCE

Anchor Expansion

The expansion of the anchor, in terms of the volume of resin pumped into the fixed anchor length (Vp), due to the applied anchor pressure (Pa) was recorded in each test. The high quality of the data acquisition and the good reproducibility achieved between tests is demonstrated by the data presented in Figure 6. Data from two tests in medium dense sand where the ultimate anchor expansion pressures (Pa) were 1290kPa and 720kPa are presented. The anchor pressure (Pa) and the lateral stress, measured by earth pressure cells located at different distances (i) from the anchor surface, are plotted against the pumped volume (Vp).

Data from a number of tests are plotted in Figure 7 to show the development of the zone of increased lateral stress with distance from the expanding anchor surface. This data provides information for evaluation against cavity expansion theory and indicates that for expansion pressures less than 1500kPa the rigid boundary of the test cell did not influence the anchor expansion process.

The relationship between expansion pressure (Pa) required to generate a given increase in anchor fixed length diameter ($\varepsilon_\theta\%$) for the model resin anchors is shown in Figure 8, where:

$\varepsilon_\theta\% = (D2-D1)/D1 \times 100\%$ D1 = initial fixed length diameter
D2 = fixed length diameter after expansion

The degree of fixed length expansion ($\varepsilon_\theta\%$), was calculated from post test measurement of the fixed anchor length.

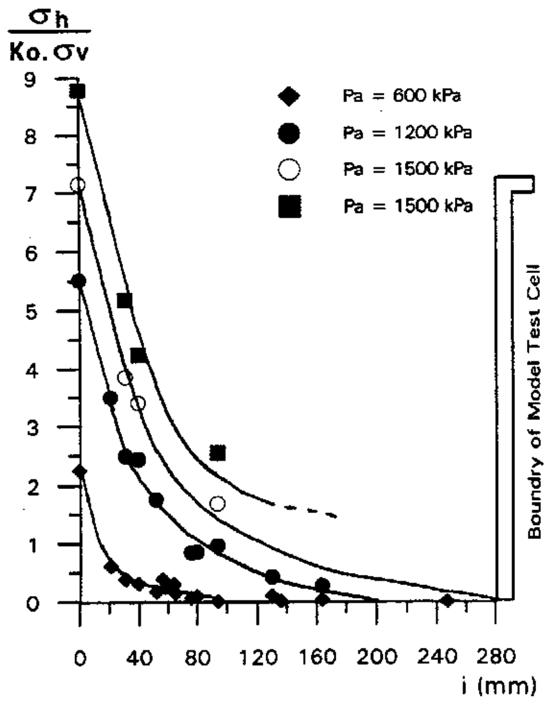

Fig 7. Measured change in total lateral stress (σh/Ko.σv) with distance (i) from anchor during expansion.

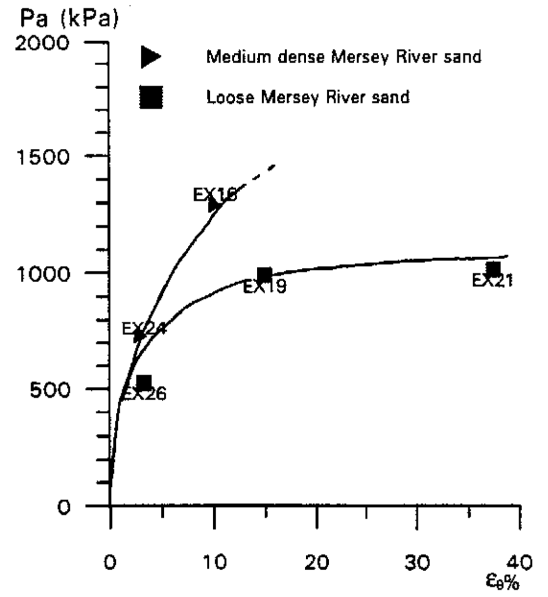

Fig 8. Relationship between anchor pressure (Pa) and degree of fixed anchor length expansion (ε_θ).

Since the stiffness and strength of the soil increases with relative density, the pressure required to achieve a given degree of expansion also increases with relative density. However the limit pressure (that is the pressure that will cause infinite expansion of the cavity without an increase in pressure) is lower for a loose sand than for a dense sand. This suggests that there is no practical benefit to be gained in attempting to increase the lateral soil stresses by trying to expand the anchor with pressures greater than the limit pressure.

Loading

Examples of the typical effect of in situ expansion on the load displacement characteristics of the resin anchors in medium dense sands (Rd ≈ 75%) is shown in Figure 9 and for loose sands (Rd ≈ 50%) in Figure 10.

It can be seen that the ultimate load capacity (Tf) of an anchor benefiting from in-situ expansion was significantly higher than that for the same anchor tested without in-situ expansion. Furthermore the initial load-displacement response of anchors expanded in-situ was stiffer than that of the same anchor not benefiting from in-situ expansion. It appears that most of the performance enhancement comes from greater skin friction developed as a result of the increase in normal stress acting on the anchor surface.

In Figure 11 the ultimate load generated by the anchor fixed length (Tf_{Lfixed}) mobilised at a fixed length displacement of 1.2mm is plotted against the anchor expansion pressure (Pa). It appears that the ultimate load resistance of the anchors increases linearly with increasing anchor expansion pressure (Pa) irrespective of the initial sand density.

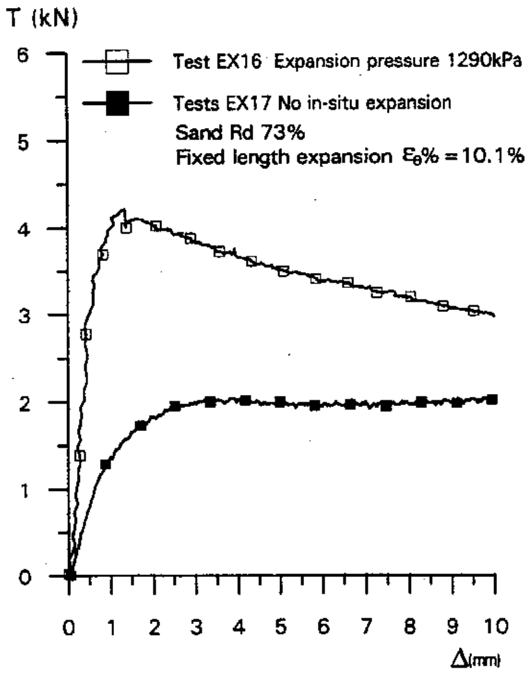

Fig 9. Comparison of load (T) - displacement (Δ) response for anchors with and without in-situ expansion in medium dense Mersey River sand.

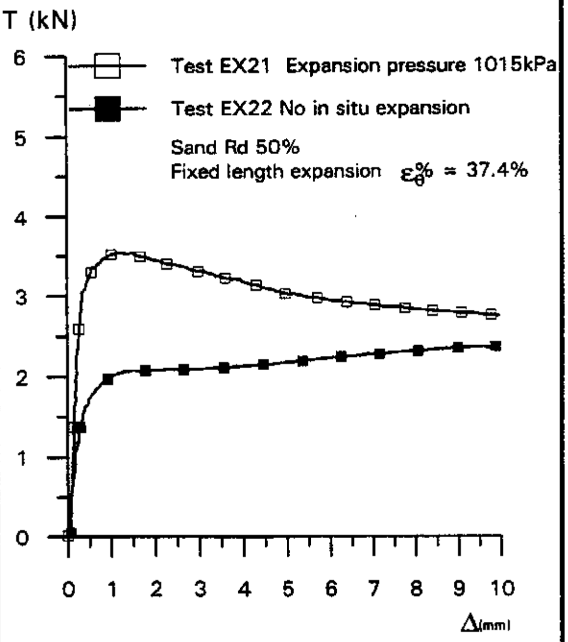

Fig 10. Comparison of load (T) - displacement (Δ) response for anchors with and without in-situ expansion in loose Mersey River sand.

CONCLUSIONS

The results from the expansion and loading tests on the model resin anchors demonstrate the effectiveness of the equipment and instrumentation system developed for the investigation of model compaction anchor performance.

A series of geotechnical centrifuge tests were carried out to investigate the influence of fixed length expansion on the load displacement behaviour of a model compaction ground anchor. A model anchor, where the fixed length expansion was generated by pressurising a water filled membrane, was found to deform under loading in a manner that greatly influenced the load displacement characteristics. To circumvent this problem an innovative centrifuge resin handling system was developed and used to test a model anchor with expanding, resin filled, fixed length.

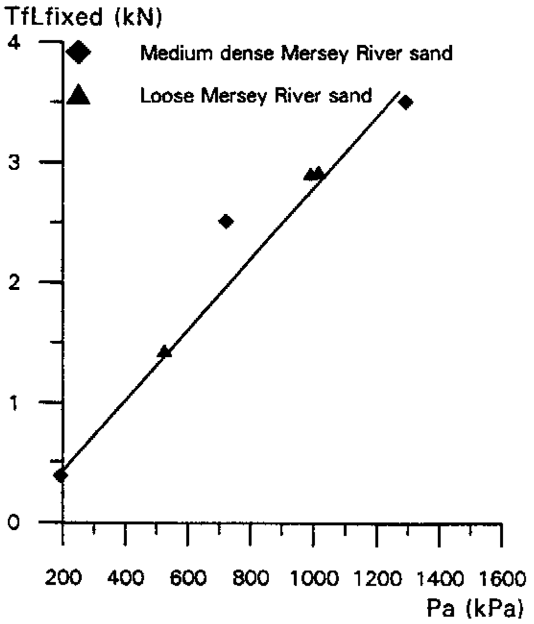

Fig 11. Relationship between ultimate fixed length anchor load (Tf_{Lfixed}) mobilised by anchors subject to varying in-situ expansion pressures (Pa).

For a deeply embedded model anchor (h/D=15) the ultimate load capacity increased as a function of fixed length expansion pressure. The in situ expansion effectively compacts the surrounding soil to improve the grout body soil interaction, significantly enhancing the ultimate load capacity of the anchor. In loose sands this enhancement may be of the order of 180% while in medium dense sands an increase of 200% may be expected. The maximum feasible anchor expansion pressure, however, is a function of the relative density of the soil.

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