

Centrifuge modelling of plate bearing tests

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Current guidance given on plate bearing testing of granular soils suggests that the plate be at least five times the nominal size of the coarsest material. However this limiting ratio can have a huge influence on the reaction load required from plant and resources when conducted to confirm strength parameters used in the design of the sub grade and platform materials of working piling platforms. The aim of the research presented in this paper was to investigate the effect of particle to plate size to establish, if any correlation which would allow the use of a smaller plate size and plant on site to allow more economical plate testing of the platform for design purposes. Different sized model plate bearing tests were carried out in a centrifuge on a large, coarse grained Devonian Limestone. The results from the test series reported show a good similarity in the bearing stress against displacement behaviour between the different sized plate sizes.

Keywords: Plate bearing test, centrifuge modelling, scale effects

1 BACKGROUND

Prior to 2004 several piling rig incidents resulting from improper design and maintenance of the working platforms led to the Federation of Piling Specialists (FPS) instigating the preparation of a design guide in collaboration with the Building Research Establishment (BRE). The BRE Report 470, “Working Platforms for Tracked Plant” provides guidance on the design, installation and maintenance of piling platforms.

The BRE report gives guidance on the determination of the shear strength parameters from the granular fill required for the design of the platform. It is recommended that the characteristic value of ϕ_{cs}' (critical state angle of friction) be established through the testing of the granular fill under conditions close to those experienced in the field, BRE 470 (2004).

One of the testing methods available for determining the strength parameters is plate loading tests as described in BS1377: Part 9 (1990). The strength parameter can then be back calculated using the traditional bearing capacity equation (1) (e.g. Terzaghi (1943); Hansen (1970); Vesic (1973); etc) below.

$$q_{ult} = 0.5 \cdot \gamma \cdot B \cdot N_{\gamma} \cdot S_{\gamma} \quad (1)$$

Where:

γ =platform material density (kN/m³), B=plate diameter, N_γ =bearing capacity factor, S_γ = shape factor.

For plate bearing tests of known geometry the remaining unknowns in the equation are N_γ and S_γ . Both these parameters following Lyamin *et al.* (2007) are shown to be dependent on ϕ_{cs} . Several authors have published equations for N_γ (e.g. Hansen (1970) and Lyamin *et al.* (2007)). The bearing capacity and shape factor can be found using equations (2) and (3) below, after Lyamin *et al.* (2007),

$$N_\gamma = \tan(1.32\phi_{cs}) \cdot (N_q - 1) \quad (2)$$

Where:

$$N_q = \frac{1 + \sin \phi_{cs}}{1 - \sin \phi_{cs}}$$

$$S_\gamma = 0.0336\phi_{cs} + 0.0000672\phi_{cs}^2 \quad (3)$$

Data collated by De Beer (1965) and highlighted by Loukidis and Salgado (2010) suggest that the actual shape factor for circular footings lies between 0.7-0.82.

Owing to the limits placed on the recommended plate size that can be used by BS1377: Part 9 (1990), carrying out tests at prototype scale can often prove impractical and uneconomical. For plate bearing tests the British Standard requires the plate to be five times the size of the ‘nominal particle of the coarsest material, BS1377:Part 9 (1990). However the understanding of the definition of nominal particle size in plate bearing tests for determining the plate size is very vague within industry. A common misconception is that the size to which the standard refers to concerns the maximum particle present in the material, Corke (2010a). The aim of the research presented was to investigate the effect of maximum particle on different plate sizes to improve the understanding and possibly allow small scale tests on the material to validate the strength parameters used in design and hence construct a more economical platform as highlighted by Corke (2010b).

However a concern with small scale testing that has been investigated in the past is the scale effect associated with the bearing capacity of shallow foundations on sands and granular material. This topic has been extensively explored through centrifuge tests, finite element modelling and 1g testing by researchers e.g. Bolton and Lau (1988); Cerato and Lutenegeger (2007); Ovesen (1979); Kusakabe *et al* (1991). For a coarse grained material an inherent absolute scale exists between the foundation dimension and soil particle size. This may lead to greater scale dependence for footings or plates on coarser granular material than that which is also present for finer grained material existing at a micron scale, Cerato and Lutenegeger (2007). Current design techniques for the bearing capacity of shallow foundations do not account for the scale effects present between soil and foundation.

2 INTRODUCTION

A series of tests involving the centrifuge modelling of plate bearing tests on sharp, angular granular soil using a variety of plate sizes and soil gradings was carried out at the Geotechnical Engineering Research Centre at City University London. The aim was to investigate the effect of the plate to maximum particle size ratio on bearing capacity of the plate.

In order to achieve some similarity between model and prototype it was necessary to select a granular soil which closely resembled the crushed stone aggregate or crushed demolition waste typically used in the construction of working piling platforms. The typical material used for construction of working platforms is a well graded, angular particle soil with sizes ranging from a maximum of 75mm down to 0.063mm and is required to be free of any organic matter or clay, BRE 470 (2004), such as 6F2 or MOT Type 1. The material selected for testing was a grey Devonian limestone sourced from a quarry in Ashburton, Newton Abbot, UK. It was selected from a crushed aggregate stock pile having being passed through the crushing, washing and sorting plant and contained sharp, angular grains from 3.35mm down in size and was free of any clay particles. The maximum size available from this material determined the limits of the scaling factors available for testing with regards to maximum particle and plate size.

The test series presented in this paper represents one of the gradings, grading 0, chosen for examining the effect of plate to maximum particle size. The grading was effectively a single size grading with particles ranging from 2.411-3.350mm as seen in Figure 1. The particles in the grading consisted of all that were collected on a 2.411mm aperture sieve following a 3.35mm sieve. Table 1 describes the index properties of the grading used. The tests were carried out at the same acceleration level of 22.4g such that the maximum particle size in the model was equivalent to a 75mm sized particle in the prototype.

Properties	Grading 0
Minimum voids ratio, e_{min}	0.71
Maximum voids ratio, e_{max}	1.12
Specific gravity, G_s	2.73
D_{50} (mm)	2.88
D_{max} , (mm)	3.350
D_{min} (mm)	2.411
γ (kN/m ²)	14.78

Table 1. Index and sample properties of the limestone single sized grading 0 used in the testing series.

Three different diameter plate sizes (B) were chosen; 10, 20, 24mm. These model plate sizes represented prototype plate diameters of 224, 448 and 538mm respectively when accelerated at 22.4g (N, scale factor=22.4) in the centrifuge. The combination of these plates with the grading described previously allowed the B/D_{max} ratio to be varied between 2.9 to 7.2.

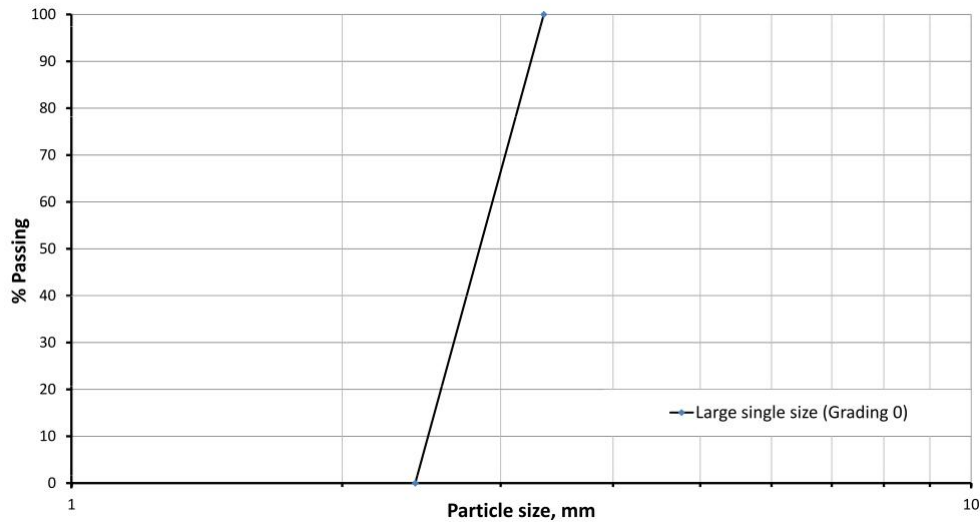


Figure 1. Grading curve for the limestone grading used in presented test series

2.1 Soil testing and preparation

In order to prepare the test gradings required in the test series the limestone crushed aggregate was dry sieved using the method described in BS1377: Part 2 (1990). Sieve apertures described in both BS1377: Part 1 (1990) and ASTM-D422 (2007) were used to allow better control of the final sample grading in order to match the required grading curves. In order to determine the specific gravity five samples were tested according to the Small Pyknometer test described in BS1377: Part 2 (1990). A specific gravity of 2.73 was obtained for the limestone from the particle density tests.

Prior to any test sample preparation it was necessary to establish the maximum and minimum voids ratios of the individual grading, e_{\min} and e_{\max} respectively in order to control the relative density used in the centrifuge tests. The limiting voids ratios presented in Table 1 were established using the ASTM D4253 (2006) and D4254 (2006) methods for determining the maximum and minimum index densities of the gradings. The minimum voids ratio was established as average of at least two samples to ensure repeatability of the result.

3 APPARATUS AND TESTING

3.1 Instrumentation

The model plates were driven into the prepared soil samples using the motor and screw jack assembly shown in Figure 3. A loading beam attached to the bottom of the screw jack allowed the force plate and model plate to be attached. The plates were driven into the soil at a constant rate of penetration of 1mm per minute until a settlement of at least 0.1B was achieved.

Figure 2 shows the force plate used to measure the reaction force of the model plates when being driven into the soil samples. The force plate consists of three load cells sandwiched between two 6mm thick stiff aluminium plates. The load cells are set on a 60mm pitch circle diameter and the load is applied at the centre between the three load cells. The force plate enabled bending moments to be removed that may have been present in the un-level seating of the plate on the test sample. The reaction force from the loading of the plate was taken as the sum of the three load cells.

The tests were carried out in a uPVC test tub, Figure 4 with an internal diameter of 152.4mm (D_{model}) and an aspect ratio of 1. The tub was placed within an aluminium strong box, see Figure 3, and its size maximised to the internal width of the strongbox. It was necessary to select the tub and plate sizes so as to minimise the boundary effects. Ovesen (1979) carried out several tests on the bearing capacity of circular footings on dry sand, to investigate the scaling law relationships. He found a constricting influence when the container diameter (D_{model}) was less than five times the model diameter. Adopting container to model diameters less than this ratio resulted in high peak values, often between 10-20%. The minimum ratio used for the tests presented was achieved with the largest model plate diameter, 24mm which gave a B/D_{model} ratio of 6.35.

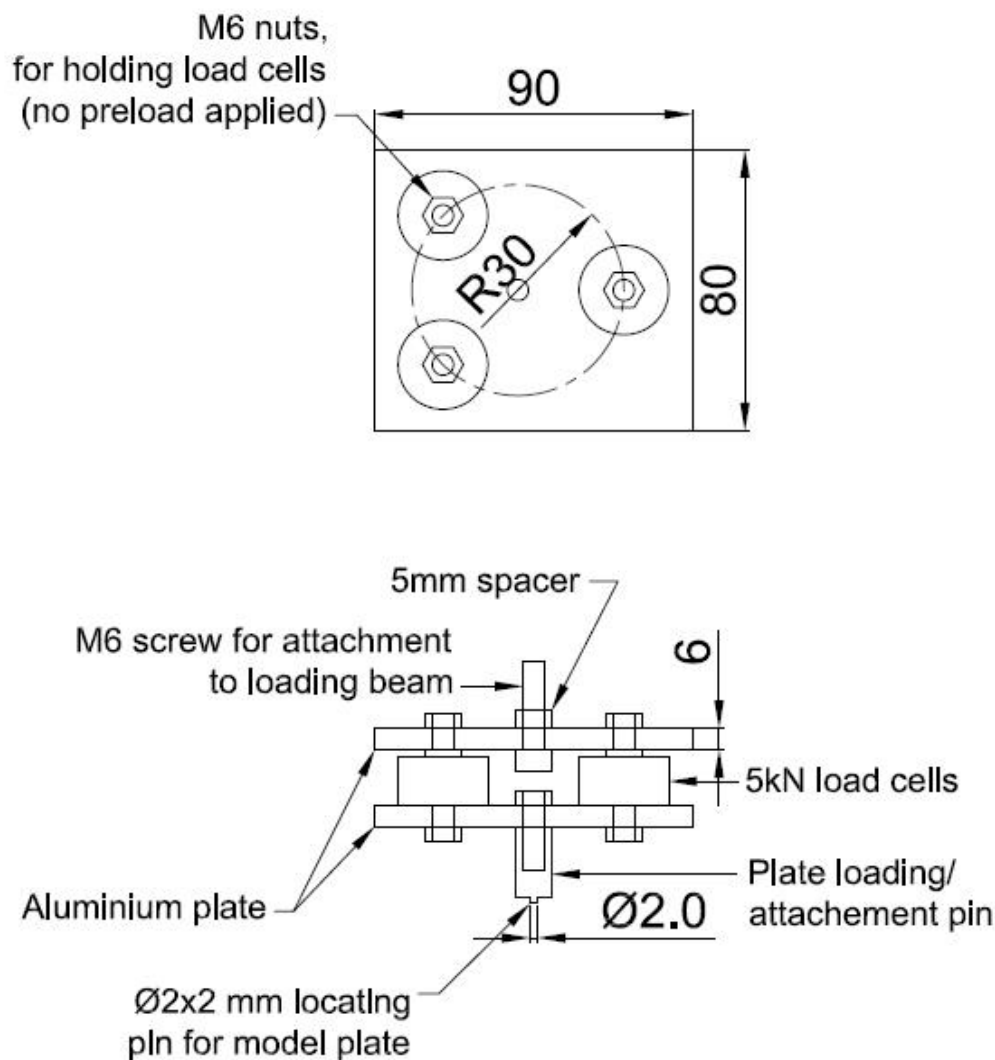


Figure 2. Force plate used for measuring axial reaction load from the model plate driving.

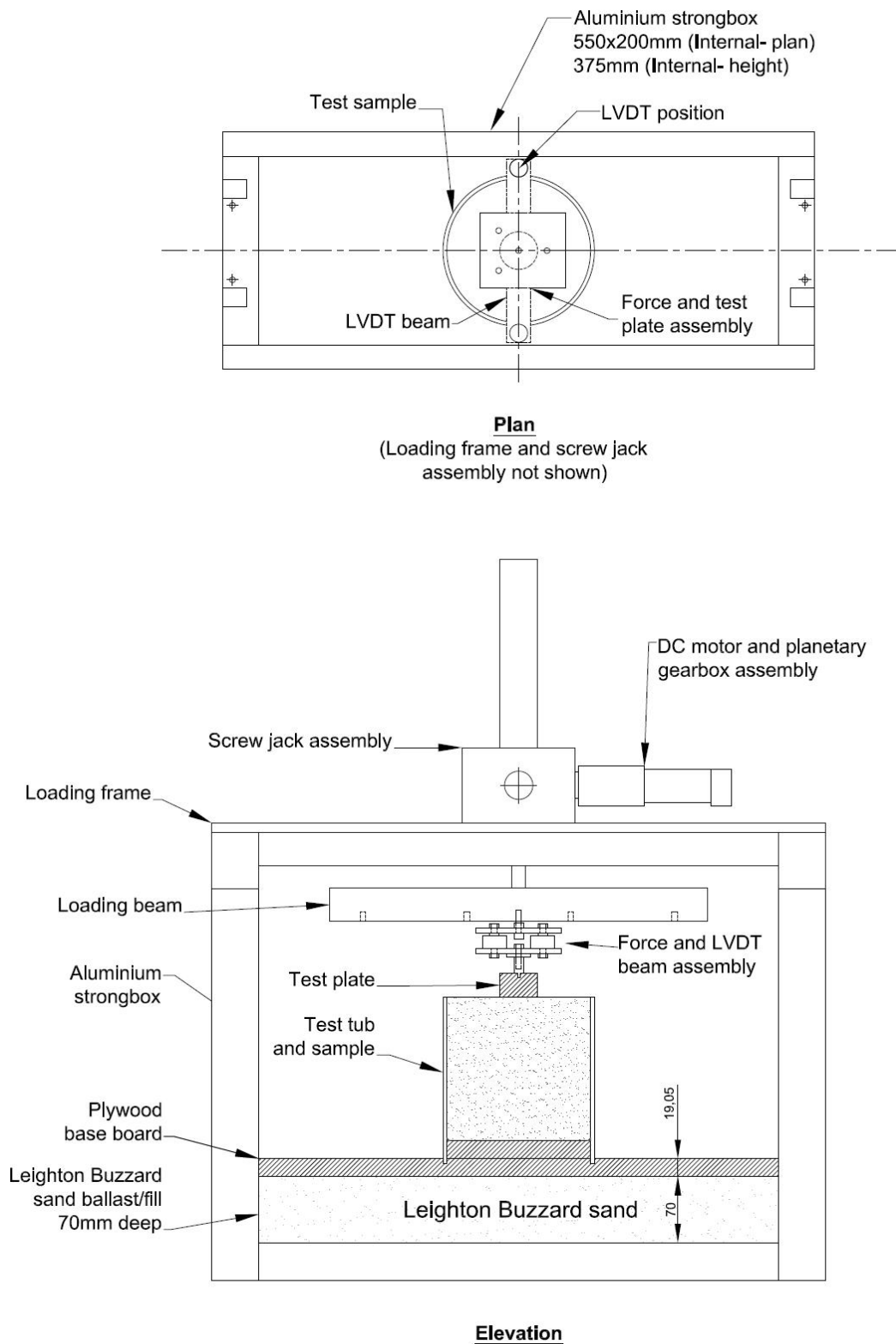


Figure 3. Assembled testing equipment and instrumentation.

Two linear variable differential transformers (LVDTs) were positioned either side of the loading beam (in plan), Figure 3, in order to measure the vertical displacement of the plate as it was driven. The final displacement of the plates was taken as the average of the two LVDT readings. The LVDTs measured the displacement of the LVDT beam shown in Figure 3.

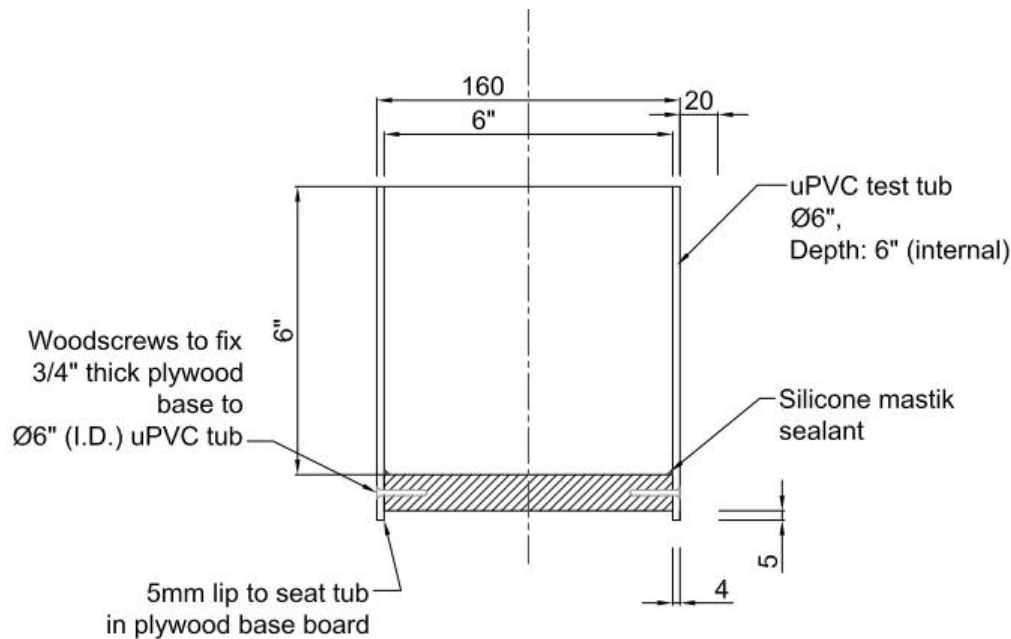


Figure 4. Testing tubs used to contain testing sample.

3.2 Test sample preparation

All tests were carried out at a relative density (D_r) of 75%. Working piling platform material for construction use requires a high level of compaction to subsequently mobilise a high angle of friction to generate a substantial bearing capacity for the tracked piling plant.

The test samples were prepared by filling the test tubs shown in Figure 4 in three equal layers and tamping down each layer with a circular wooden plate as so to avoid any crushing of the particles directly beneath. The fixed volumes of the tubs were filled to the calculated mass values representing 75% relative density. This method was used to attempt to keep the voids ratio consistent through the depth of the sample.

A sample once prepared was seated on the plywood base board (Figure 3) within the strongbox. The loading and instrumentation was then mounted onto the box before the model plate was positioned. The model plates were located in the centre of the sample by aligning a recess located on the top of plate to the locating pin shown in Figure 2.

The assembled test equipment was then spun up on the centrifuge to 22.4g. This was in order to achieve a maximum prototype soil particle size of 75mm. The motor and lead screw was initiated to take up any slack between the model plate and locating pin before carrying out the test. The load cells were monitored at this time to ensure the plate was not loaded prematurely.

4 TEST RESULTS

The results of the test series on the different plate sizes tested on the same 'single size' grading and relative density are reported. The data is presented as the load normalised over the area of each individual plate against the settlement recorded.

Figure 5 shows the bearing stress, q , plotted against the settlement, w . The failure modes exhibited for each of the model plates are consistent with that expected for local shear failure for moderate density granular soils ($36\% < D_r < 75\%$). The tests show a gradual increase in the bearing capacity of the plates with increasing embedment. Test T2 was carried out by a different researcher at a slightly larger scale factor of $N=25$, thus representing a maximum particle size of 83.75mm and a prototype plate diameter of 250mm for the 10mm diameter model plate. The oscillations present in all of the tests results in Figure 5 are probably a result of the interaction and re-arranging of the large sized particles as they were sheared.

It is clear from Figure 5 that for settlements less than 4mm, there appears very little difference in the observed load displacement of the different plate sizes. This clear pattern of behaviour possibly indicates that over small displacements the scale dependence between foundation and soil which has been highlighted by other researchers in the testing and modelling of shallow foundations on coarse grained material is not as predominate as it may be over larger displacements.

For larger settlements exceeding 4mm there is a clear influence observed between plate and maximum particle size which shows increasing bearing capacity with increasing plate size. However it is common practice in shallow foundation design and the analysis of plate bearing tests to define the ultimate bearing capacity achieved at a settlement corresponding to 10-15% of the plate diameter, Corke (2010a). By applying this ultimate capacity criterion to the results shown in Figure 5 it is apparent that the settlements corresponding to 10-15% of the plate diameters is achieved within the zone showing little influence between particle and plate size.

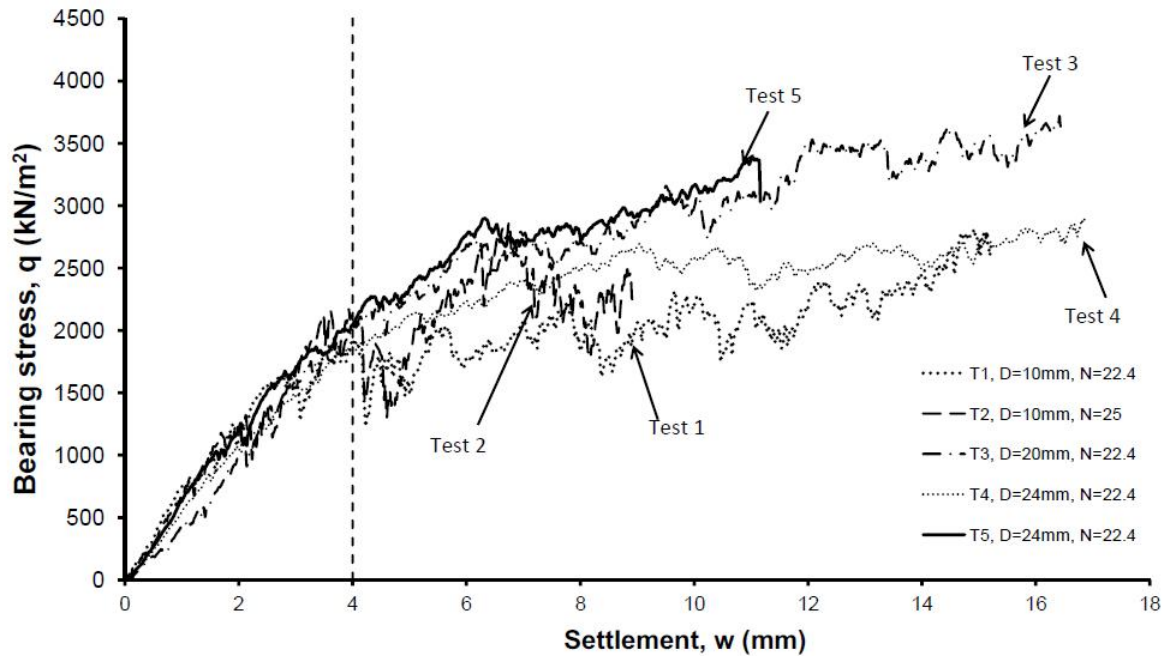


Figure 5. Bearing stress-settlement graph of the test carried out using different plate sizes on the same soil with constant relative density.

5 CONCLUSION AND FURTHER WORK

It is possible to conclude from the short series of plate bearing test carried out on a coarse grained single size material that over small strains/displacements there is very little influence of the scale effects between soil and foundation.

There is currently a larger series of tests being carried out at City University London aimed at further investigation of the effect between maximum particle size and plate diameter. These tests will be conducted on a variety of different gradings including smaller single size gradings, a set of three identical gradings with each being scaled up or down from the other and also on a scaled down grading which closely resembles that of a MOT Type 1 or 6F2 materials which is typically used in platform construction.

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