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Centrifuge Modelling of the Ground Reaction Curve of Fibre Reinforced Soil

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ABSTRACT: The phenomenon known as the 'arching effect' occurs when a portion of granular mass yields relative to an adjacent stationary region. The movement is resisted by shearing stresses which act to reduce the pressure on the yielding support and increase the pressure on the adjacent stationary supporting zones. Arching is widely observed in both natural and man-made structures such as piled embankments, tunnels, and above mine works and sinkholes. One method of increasing soil shear strength and its resistance to deformation is through the use of randomly distributed discrete fibres. The degree of improvement has been shown to be directly related to the fibre content in the soil, the fibre aspect ratio, orientation and mechanical properties. In this research the arching effect is recreated in a geotechnical centrifuge model using a 'trapdoor' apparatus within a plane strain container and the effect of fibre reinforcement on results is examined. Both the trapdoor and an adjacent support were instrumented to measure the force (and derived pressure) distribution. Soil and trapdoor displacements were determined using digital image analysis. The influence of fibre content is examined whilst maintaining constant fibre length, applied compactive effort, and soil height.

1 INTRODUCTION

It is important for civil engineers to assess the effect that changes in local stress conditions and consequent ground movements may have on the stability of nearby structures. In geotechnics, this generally applies to the problems of tunnelling, piled embankments and mine works. In granular soils, these activities can result in the formation of well-defined zones of displacing (yielding) and stationary (stable) soil. This phenomenon, commonly known as arching, results in a significant decrease in pressure beneath the yielding portion of soil compared to the geostatic pressure. The pressure is redistributed such that the majority of the force is transferred from the yielding area to the rigid surrounding areas. A trapdoor is a device commonly used to experimentally investigate the arching phenomenon (Terzaghi, 1943). The general mechanism and apparatus used for this research is illustrated in Figure 1. Displacement of a trapdoor causes a prism of overlying soil to yield as shown. The resulting displacement is transferred through the soil to the surface to form a subsidence trough. The curved dashed lines represent the vertical shear planes along which sliding occurs. The depth and shape of the subsidence trough is a function of the mechanical properties of the soil, the soil height to trapdoor width ratio and the displacement of the trapdoor.

One ground improvement technique finding increasing popularity with geotechnical engineers is soil reinforcement by inclusion of randomly mixed discrete fibres. Several studies (Maher and Gray 1990; Zornberg 2002; Michalowski and Cermak 2003) have been done to determine the extent of improvement in shear strength offered by fibre reinforced soils (FRS) and to provide an analytical framework for studying FRS. The purpose of this research is to investigate the effect of fibre inclusion on the standard trapdoor test in terms of both pressure distributions across the trapdoor and adjacent supports as well as mechanisms of soil displacement. In these tests the content of the fibre concentration, as a percentage of dry soil mass, was varied whilst fibre type and dimension (fibre aspect ratio) was kept constant. In order to replicate the stresses experienced in realistic geotechnical structures using a reduced scale model, the Nottingham Centre for Geomechanics (NCG) geotechnical centrifuge was used (Ellis et al. 2006).

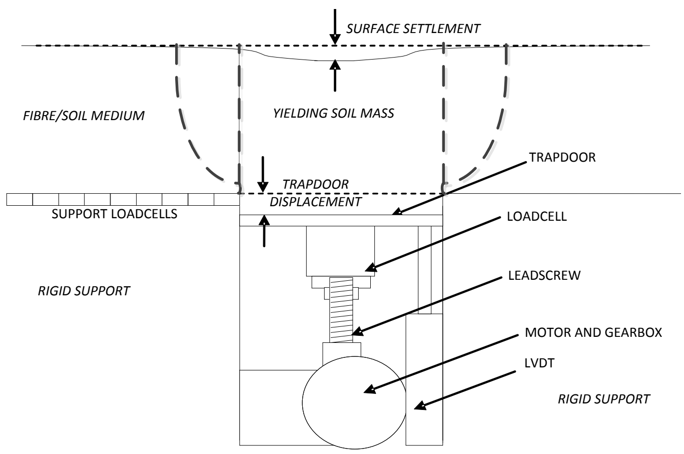

Figure 1. Schematic of trapdoor apparatus.

2 EXPERIMENTAL SETUP

2.1 Apparatus

Tests were carried out using a rectangular plane strain container with plan dimensions of 0.7 m × 0.2 m and useable height of 0.4 m. A schematic of the trapdoor apparatus used is shown in Figure 1. Displacement of a 60 mm wide trapdoor is achieved by means of a geared DC motor and leadscrew arrangement. A load-cell is incorporated into the mechanism in order to measure trapdoor load. A linear variable differential transformer (LVDT) records trapdoor displacement. The motor is housed inside one of two timber blocks which form the rigid supports either side of the trapdoor. Nine thin small aluminium plates, instrumented with strain gauges, are mounted on the surface of the left support to measure loading across the support to a horizontal distance of 135 mm from the trapdoor edge (each plate is 15 mm in the model horizontal direction). A digital camera was used to record images through the Perspex front of the container from which soil displacements were obtained by application of PIV techniques (GeoPIV by White et al., 2003).

2.2 Materials and model preparation

The sand used in all tests described herein was a silica sand supplied by David Ball Group plc known as Fraction C. The sand has an average grain size, d_{50}, of 500 µm and a maximum/minimum void ratio of 0.81/0.55. The fibre used in all tests was of polypropylene type with a diameter of 0.5 mm, giving an aspect ratio, L_f/d_f, of 24. The fibre was supplied by Pinnacle Brushes ltd and was found to have a Young's modulus of approximately 3 GPa. The sand was mixed thoroughly with the fibres in three stages to make up the total height of the fibre-soil composite. Each sand layer (~1/3 of the total soil height) was then poured carefully by hand onto the assembled trapdoor apparatus before being levelled and compacted using a timber board to ensure uniformity of compaction across the sand layer. A vibrating hammer was then used to compact the sand across each layer. The same compaction effort and method was used in each test preparation. The resulting average densities for the fibre-soil composite are given in Table 1.

Table 1. Centrifuge experiment details.

Test	Fibre Content, F_c	Relative Density, I_d
FC0	0%	90%
FC0.25	0.25%	108%
FC0.5	0.5%	100%
FC1	1%	99%

The centrifuge was run at an angular velocity of 160 rpm corresponding to a centrifuge acceleration of 50 g at a point 1.7 m from the axis of rotation (corresponding approximately to the depth of the trapdoor). A centrifuge scaling factor of N = 50 was adopted for analysis of results in prototype scale. The height of the sand layer was kept very close to 100 mm for all tests; representing a 5 m layer at prototype scale. The trapdoor width is 3 m prototype scale giving a height to width ratio, H/B, of 1.66.

3 RESULTS

3.1 Ground Reaction Curves

Figure 2 (a) shows plots of trapdoor displacement, δ, normalised by trapdoor width, B, versus trapdoor load normalised by the theoretical load from the soil at 50 g, F_{50}, for all tests. This characteristic response has been referred to in many texts and is known as the ground reaction curve (GRC) amongst other names. The derivation of the curve for a range of soil grain sizes and H/B ratios is described in detail in Iglesia et al. (1999). The GRC predicted by Iglesia's approximation for an H/B ratio of 1.66 and d_{50} of 500 µm is also plotted for comparison. Iglesia et al. (1999) conducted many centrifuge tests to determine the shape of the curve and defined three distinct phases; the initial arching phase, the maximum arching (minimum loading) phase and the load recovery phase. Several parameters can be determined from the ground reaction curve principally: the secant modulus of initial arching, M_B, which is the initial gradient of the GRC; the minimum load; and the load recovery index, λ, which is the gradient of the transition from the minimum loading stage to the ultimate state. The plot shows that fibre inclusion has an effect on the loading response compared to the no fibre case and predictions from Iglesia's method. The main difference between the fibre test data and the no fibre/Iglesia method is that the initial gradient is slightly higher (implying a stiffer response), the minimum loading is slightly lower, and the recovery index is higher. Details of these parameters are given in Table 2.

Table 2. GRC Parameters from data plotted in Figure 2 (a).

Test	M_B	Min	λ
Iglesia et al (1999)	63	0.26	0.85
FC0	79	0.24	1.05
FC0.25	86	0.18	1.16
FC0.5	106	0.16	1.35
FC1	88	0.19	1.37

It can be seen from Figure 2 (a) for all tests that there were some minor variations in load with trapdoor displacement (typically less than 0.1 of the normalised load). This was due to the fact that the measured load was influenced by residual frictional forces acting on the trapdoor which could not be fully compensated for.

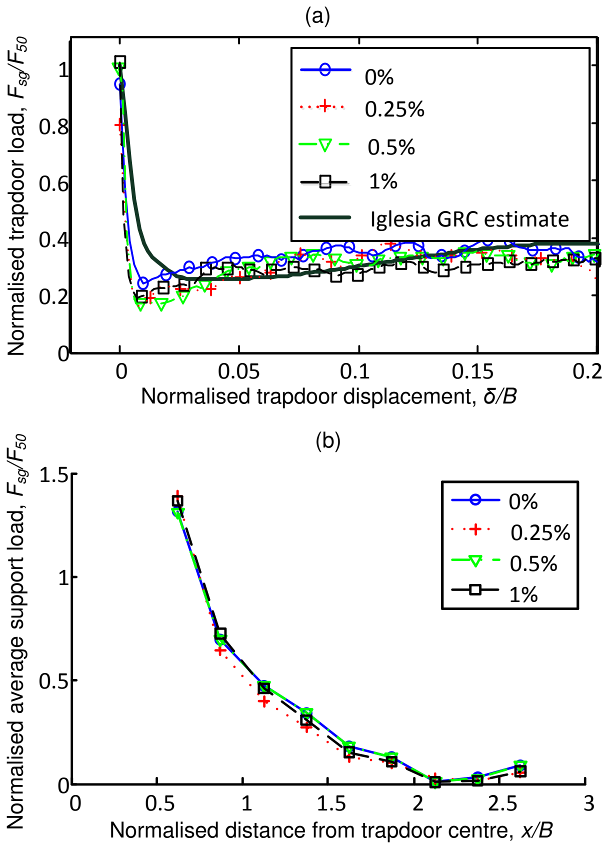

Figure 2 (a) Ground reaction curves for all tests;
(b) Loading distribution on support for all tests

Figure 2 (b) shows the loading increase across the support, F_{sg}, at the end of each test (where the trapdoor was displaced by 12 mm, or 20% when normalised by B). The load increase, calculated as: $F_{sg}=F_{sgm}—F_{50m}$ where; F_{50m} is the measured load at 50 g and F_{sgm} the measured load, is normalised by the calculated theoretical loading at 50 g, F_{50}. The x-axis shows horizontal distance from the trapdoor centre normalised by B. All responses show that the majority of the load from the displaced soil is transferred to the first 0.5 m of support, the increase in load decays approximately exponentially with distance from the trapdoor. In general, Figure 2 (b) shows that fibre inclusion has no significant effect on the load distribution on the adjacent support. This is as expected since the trapdoor loading is also invariant with fibre content.

3.2 Displacement analysis

Figure 3 (a) to (d) show maximum settlement, S_{max}/B, versus trapdoor displacement, δ/B. The figure shows the displacement at four normalised depth to trapdoor depth ratios, z/z_{td}, of 0.05, 0.3, 0.6 and 0.95. The plots close to the surface (z/z_{td} = 0.05) show that in all tests the magnitude of maximum settlement increases at roughly the same initial gradient with trapdoor displacement, with surface displacement being much less than those occurring at the trapdoor. For the 0% fibre case the gradient then increases and tends towards the 1:1 line after a trapdoor displacement of around δ/B = 0.1. This indicates that subsequent surface displacements are thereafter equivalent to trapdoor displacements and the zone of soil above the trapdoor effectively displaces downwards as a rigid body. The plots for the same test case at greater depths show that soil displacements tend towards the 1:1 line at lower values of δ/B compared to the surface, with displacements nearest the trapdoor effectively matching those of the trapdoor throughout the test. As no gap was formed between the soil and the trapdoor, the difference between surface displacements and trapdoor displacements must be accounted for by expansion of the volume of the soil (dilation). The surface displacement results for FRS soils generally show reduced settlement with trapdoor displacement implying that the FRS either exhibits a greater dilative capacity or mobilises a larger volume of soil during the test.

Figure 4 (a) to (d) show displacement magnitude normalised by the maximum settlement, S_{max}, against x/B, where x is horizontal distance from the trapdoor centre, for a trapdoor displacement of δ/B = 0.2. This plot compares the shape of the subsidence curve between tests. The results show a very general pattern at the surface and at shallow depths, where the effect of fibre inclusion is shown to extend the width of the settlement trough. This result indicates that the high fibre content tests do indeed mobilise a larger volume of soil compared to the baseline test with no fibre. At higher depth ratios, the curves exhibit very similar characteristics to the baseline case.

Figure 5 (a) to (d) show plots of soil volume loss, V_{ls}, which was calculated as the integral of vertical soil displacements at a given depth in model scale versus trapdoor volume loss, V_{td}, calculated as $\delta\times B$. The figure shows the displacement at four normalised depths. Marshall et al. (2012) used a similar plot of soil volume loss versus tunnel volume loss to explain the cumulative dilative behaviour of the soil. The 1:1 line indicates equality between the two volume losses. The comparison between the 1:1 line and the soil volume loss, at all depths, describes the general behaviour of the material. As all the volume loss in the material is significantly less than the 1:1 line the implication is that both the soil and fibre-soil composite behaviour is dilative. At relatively small displacements, the soil and the trapdoor volume losses are approximately equal but as the magnitude of shear displacements within the soil increase and dilation increases, the difference between the two volume losses increases. The trapdoor volume loss then increases faster than the soil volume loss at a gradient proportional to fibre content. As with maximum subsidence, the soil volume loss tends towards equality at higher depth ratios. The soil volume loss is significantly reduced for cases with high fibre content compared to the baseline test with no fibres.

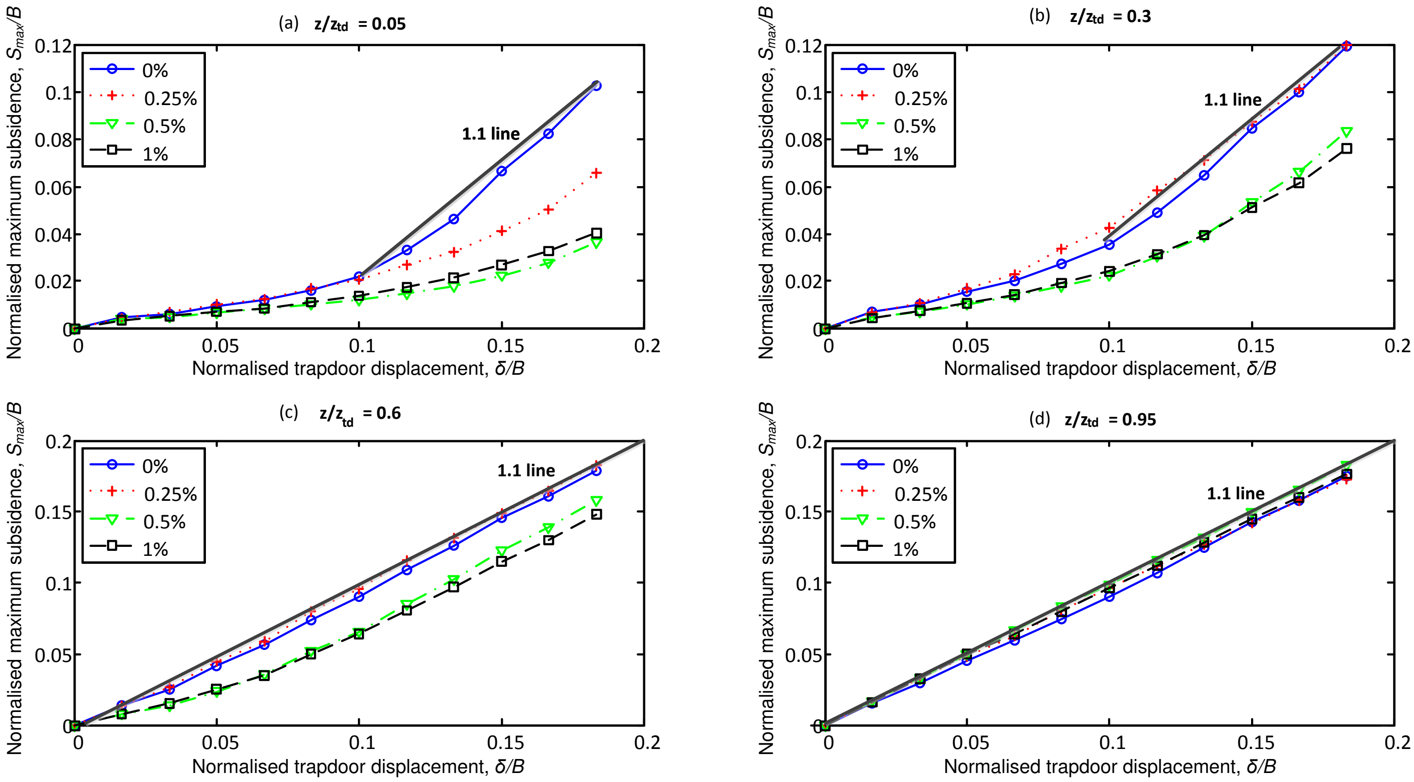

Figure 3 Maximum settlement, S_{max}/B versus trapdoor displacement, δ/B

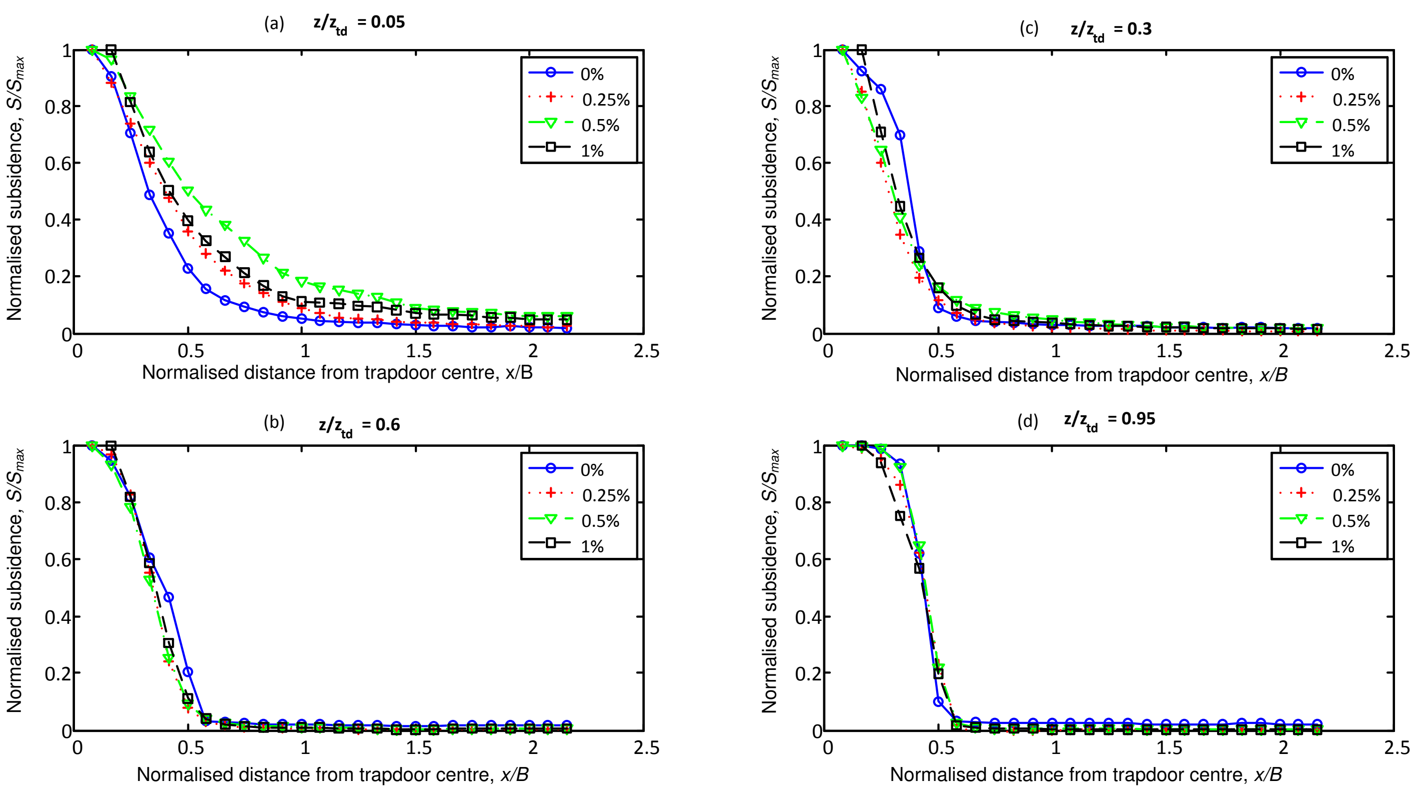

Figure 4 Settlement troughs, S/S_{max} versus distance from trapdoor centreline, x/B

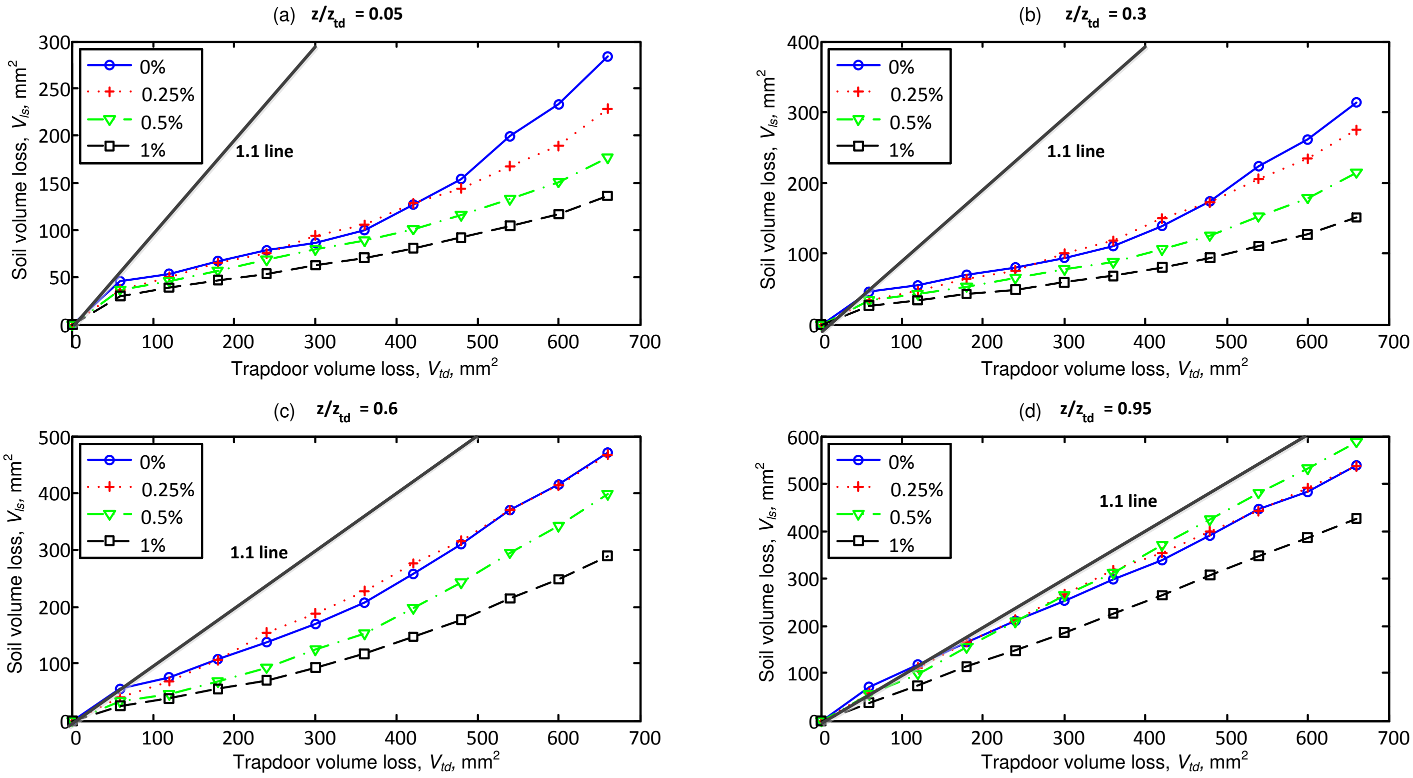

Figure 5 Soil volume loss, V_{ls}, versus trapdoor volume loss, V_{td}

There is some uncertainty concerning the scaling of fibres used in reduced scale centrifuge tests, particularly the fibre to structure ratio (L_f/B). The scaling approach outlined by Visvanadam et al. (2009) considered the fibres as discrete elemental inclusions within the soil, implying that identical fibres, with similar mechanical properties, to those used in the field should be used in centrifuge tests. An objective of this research is to explore the validity of this assumption by carrying out a modelling-of-models exercise where L_f, B and N are varied and the H/B ratio is kept constant to create equal prototype conditions.

4 CONCLUSIONS

A trapdoor apparatus has been developed to model the arching in sands and sand-fibre composites resulting from loss of support. Fibre-soil composites were tested with a fixed fibre aspect ratio and fibre content by dry soil mass of 0.25%, 0.5% and 1% and compared to a baseline 0% fibre case. The relative density of the material for each test was above 90%, sand cover height, scale factor and trapdoor width were kept constant. The following conclusions can be drawn from the results presented:

- The loading response shows some agreement with theoretical ground reaction curves (GRCs), however the fibre content tends to increase the initial gradient of the GRC, lower the minimum load, and increase the recovery gradient.
- Loading on the adjacent supporting structure exponentially reduces with distance from the trapdoor edge. The support loading profile appears to be invariant to fibre content.
- Maximum observed settlement is significantly reduced with fibre inclusion at the surface and at shallow depths for trapdoor displacements greater than 10% of its width.
- The width and depth of the surface subsidence trough tends to increase with fibre content.
- Soil volume loss, compared to trapdoor volume loss, is significantly reduced with fibre inclusion at trapdoor displacements greater than 1% of its width, particularly at shallow depths indicating that the soil behaviour is dilative. The reduction in soil volume loss is proportional to fibre content.

Further work will investigate the effects of variation of fibre aspect ratio and fibre to trapdoor width scaling effects.

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