Table of contents Search Author index

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Shallow foundation on geotextile-reinforced soil: a centrifuge model study

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ABSTRACT: A sand layer is often used as a substitution on clay soil in order to improve the bearing capacity of soil foundations. This layer can be reinforced by geosynthetics, yet the quantitative behaviour of such a structure still needs to be studied. In the LCPC[1] geotechnical centrifuge, reduced-scale shallow strip foundations are loaded under a 40-g gravity level. Three soil foundations are tested: clay, clay with a sand layer substitution-reinforced by a non-woven geosynthetic, and clay with a non-reinforced sand layer). In all instances, the clay remains in an undrained state. The soil foundation bearing capacity is mainly increased through the granular layer. The presence of a geosynthetic prevents against a sudden drop in bearing capacity once the critical load has been surpassed. A compromise solution may be found between the thickness of the substitution sand layer and the mobilised tensile strength of the geosynthetic as a means of providing satisfactory bearing capacity.

1 INTRODUCTION

Geosynthetic layers are widely used in landfill, embankment, railway and asphalt pavement, and retaining walls. In typical configurations, a sheet is either laid over weak soil, and then a thin layer of granular soil is added on top, or unrolled under the embankment. Geosynthetics were first used as a filter and separation between very distinct types of soils; they are now however expected to play a major reinforcement role as well. This technique remains to be developed for shallow foundations on soft soil. In the literature, many researchers have carried out laboratory experiments with vertically-loaded, reduced-scale models of shallow foundations lying on bi-layered soil (clay overlaid with sand to simulate soil substitution). A geosynthetic sheet is laid either at the clay/sand interface or in the sand layer to optimise foundation soil-bearing capacity and soil deformations (Milligan 1993, Milligan & Love 1994, Khing et al. 1994, Kenny 1998). Several parameters have been studied therein, such as thickness of the granular layer, number of reinforcement sheets, their geometrical distribution, and the nature and strength of synthetics. Other soil-related parameters are also important (e.g. soil characteristics, shear strength, saturation ratio, soil sample set-up) (Resl & Werner 1986, Abduljauwad et al. 1994). By means of X-ray radiography on laboratory tests, Bourdeau & Pardi (1989) focused on both the contribution of the geosynthetic sheet and the lateral confinement of the granular layer. A second geosynthetic sheet, placed in the granular layer, serves to improve vertical stiffness (Gourc et al. 1982). This last observation has since been confirmed by field-scale experiments (Delmas et al. 1986). Moreover, vertical stresses through the soil are more widely diffused as a result of the second sheet (Watn et al. 1996).

2 CENTRIFUGE MODELLING

In laboratory experiments on shallow foundations, fracture of the geosynthetic sheet is rarely encountered if field geosynthetics are employed. Since the applied loads in these models are small, no tearing is observed in the sheets, yet a loss of anchorage does occur. Failure therefore is obtained by means of sliding. According to the tests conducted, geosynthetic sheets with a very high length dimension are recommended. At failure however, the mobilised tensile stresses in the model are still lower than the intrinsic geosynthetic strength. The lack of similarity of stress values in geosynthetic sheets prevents them from behaving like they would under field conditions. This phenomenon represents the main drawback of reduced-scale models tested in the laboratory at a normal gravity level (called the "1-g gravity level", where $g = 9.81\ m/s^2$). Moreover, since stresses are less than those at the prototype scale, sand displays a greater tendency to dilate: its friction ratio rises, which is not a conservative finding.

One key feature of centrifuge modelling is that stresses and strains developed in reduced-scale models are consistent with data at the full scale (called the "prototype scale"). In addition, the relation between compressibility of the geosynthetic sheet and its thickness is respected during a centrifuge test. By virtue of an initial approximation, both J, the stiffness modulus, and T_f, the tensile strength of the geosynthetic, are still proportionate to the thickness as well (Dubreucq et al. 1995).

Let the model and prototype values of a specific parameter be designated X_p and X_m, respectively. The scale factor X^* is equal to the ratio X_m / X_p. In Table 1, 1/N denotes the ratio between lengths.

However, if the same soil and geosynthetic are used, the relative displacement U_p between soil and geosynthetic necessary to mobilise peak strength is the same in both model and prototype. The scaling factor on displacement 1/N is not satisfied by U_p, yet this discrepancy with respect to the theoretical similitude conditions seems to exert no significant impact on model behaviour (Dubreucq et al. 1995).

Table 1: Scale factors

	X^*
Acceleration	N
Unit weight	1
Length	1/N
Displacement	1/N
Strain	1
Strength	$1/N^2$
Stress	1

3 CENTRIFUGE TESTS

In the LCPC geotechnical centrifuge (Corte & Garnier 1986), a reduced-scale model of a shallow strip foundation is vertically loaded (Dubreucq 1999). The dimensions of the prototype structure are: L = 7.20 m and B = 1.20 m. The model scale is 1:40 (i.e. centrifuge tests are run at the 40-g level). Three kinds of soil foundation are tested: a) clay, b) clay overlaid by a sand layer 3 times the width of B with a depth H = B, and c) idem b) with a geosynthetic sheet placed at mid-height of the granular layer (Figure 1). This position of the geotextile has been chosen, as forwarded by Ismail and Raymonds (1995a,b), in order to improve efficiency.

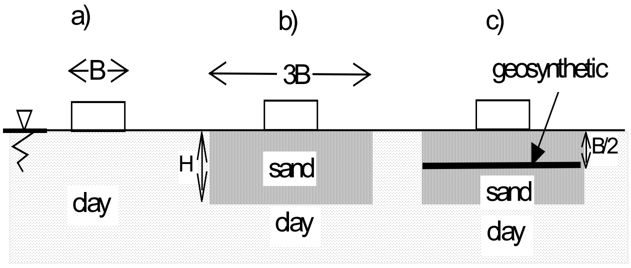

Figure 1: Centrifuge loading tests of a shallow strip footing on three different soil foundations

3.1 *Materials*

A common unwoven polypropylene geosynthetic with low tensile strength has been selected; its characteristics are calculated according to applicable French standards and have been listed in Table 2. Saturated Fontainebleau sand and Speswhite clay are used, with their characteristics being displayed in Tables 3 and Table 4, respectively.

Table 2: Characteristics of the model geosynthetic (and its equivalent prototype)

	Model	Prototype
Surface mass (g/m^2)	70	2800
Thickness (mm)	1.9	76
Critical tensile strength (kN/m)	2	80
Failure tensile strength (kN/m)	3.2	130
Critical strain (%)	15	15
Failure strain (%)	130	130
Secant stiffness (kN/m)	13	533

A cylindrical container, 90 cm in diameter and 31 cm in height, has been used to prepare the clay sample by means of consolidating a saturated clay slurry under jack.

Table 3: Characteristics of the Fontainebleau sand

Dry unit weight (kN/m^3)	15.6
Cohesion (kPa)	0
Friction ratio (°)	36.8
Density index (I_d, %)	65

Table 4: Characteristics of the Speswhite clay

Undrained cohesion (kPa)	20 to 28
Water content (%)	48
Void ratio	1.27

A fine coloured sand layer is placed at mid-height of the original sand layer in order to determine failure mechanisms. Soil remains saturated thanks to a lateral water pipe hooked up to the bottom of the container, and the groundwater table is maintained at the soil surface level.

3.2 *Experimental centrifuge device*

A rigid steel slab (18 cm long and 3 cm wide) is placed on the reconstituted sample (clay height of 125 mm, or 95 mm when overlaid by a 30 mm sand layer) at successively three distinct positions (Figure 2). Load is transmitted vertically on the top surface of the slab through a round cap, a transmission shaft and a servo-jack. The footing is thus free to rotate and move both vertically and horizontally. Loading is maintained at a speed of 6 mm/min, fast enough to consider the clay in an undrained state.

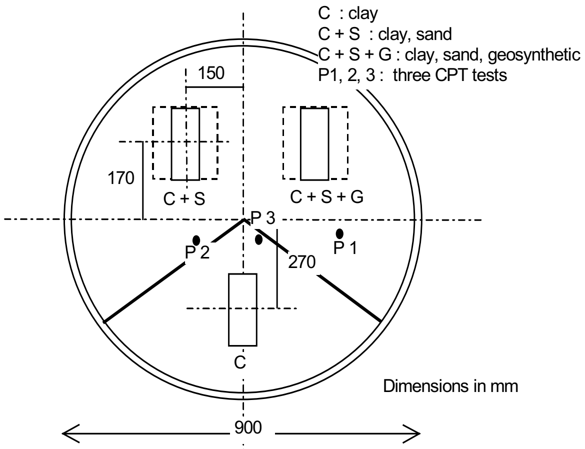

Figure 2: Centrifuge device

A very stiff beam sits on the container and carries the loading device. The applied load is measured by a load cell placed between the servo-jack and the transmission shaft. The FGP load cell features a 5000-N capacity accurate to within 10 N. Vertical displacements of the footing and of surface soil close to the transversal axis of the footing are measured by LVDT transducers (accurate to within 0.05 mm). Sensors are firmly attached to another transversal beam independent of the loading beam.

Tests are conducted at the 40-g gravity level. The footing on [clay] is loaded first, then the centrifuge is stopped to move and load it on [clay + sand] and lastly on [clay + reinforced sand]. Whenever sand layers are involved in the test measurement, the centrifuge is spun three times at 40 g for 5 minutes to ensure both a steady soil state and a fine soil/structure contact before starting the loading test. Moreover, in-flight CPT tests are carried out after each loading to control soil resistance.

3.3 *Loading test results*

Load/settlement curves are plotted in Figure 3 using model scale values. The critical load values Q_c have been added subsequently. The sand layers, both with and without reinforcement, produce a significant increase in critical load (from 690 N to 1120 N).

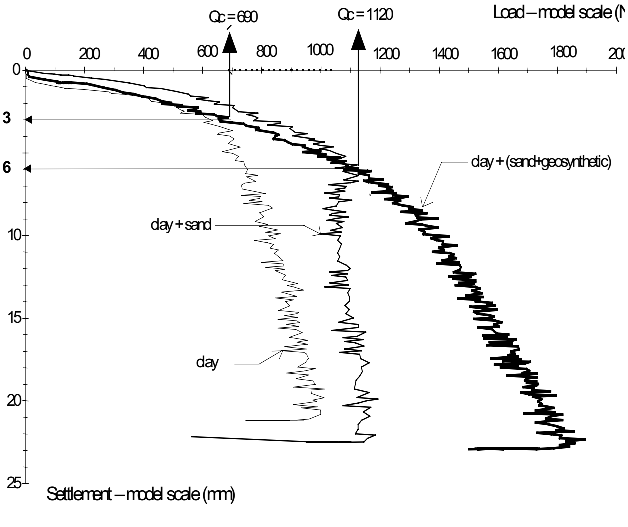

Figure 3: Load / settlement curves from the 40-g centrifuge tests

However, the initial vertical stiffness observed in the three tests is nearly identical. The presence of a geosynthetic sheet still allows reducing post-critical settlements for a given load, whereas the footing on [clay] or on [clay + sand] settles to a much greater extent. This behaviour has been observed in both Milligan (1983) and Milligan & Love (1984).

After testing, the container is meticulously disassembled in order to observe deformations to the soil and the geosynthetic. In Figure 4, post-failure vertical soil sections are drawn from displacement of the horizontal coloured sand layer. In the [clay] sample, an imprint of the slab has been perfectly traced.

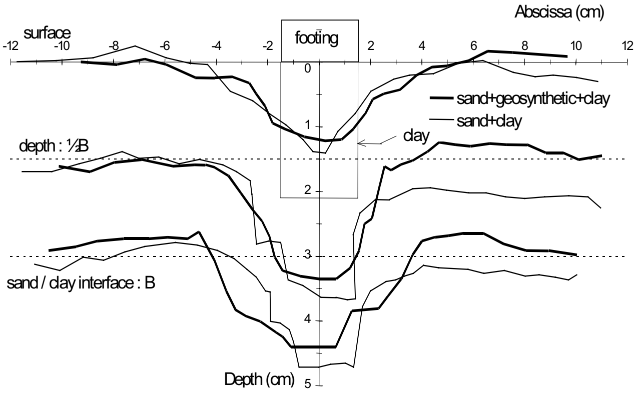

Figure 4: Vertical soil deformation at three different depths after failure

The geosynthetic sheet is neither torn nor unstuck after loading to result in less of a deformed shape. It has plastified at the intersection of two shearing planes, which begin on corners of the footing, to form a triangular wedge. Its presence induces a greater dispersion of the deformation field with respect to depth. Vertical loading stresses are typically assumed to disperse over depth at an angle α (Figure 5).

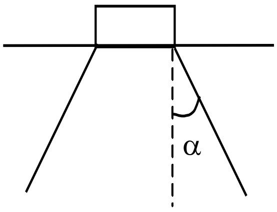

Figure 5: Typical diffusion of vertical stresses

Experimentally-observed bearing capacities lead to a $\tan \alpha = 0.3$ (whereas Therzaghi & Peck (1948) proposed 0.5 and Giroud & Noiray (1981) derived 0.6). Okumara et al. (1997) observed that α increases with H/B (at the 50-g centrifuge model test level, on non-reinforced bi-layered soil).

The geosynthetic sheet has provided no additional resistance in this case (critical loadings are in fact quite similar: 1.25 kN when the sand layer is reinforced vs. 1.12 kN when it is not).

4 CONCLUSION

The bearing capacity of a shallow strip foundation lying on reinforced soil has been measured in 40-g model tests carried out with the LCPC geotechnical centrifuge. Three soil foundation systems have been compared (clay, clay overlaid by a sand layer with geosynthetic reinforcement, and clay overlaid by a sand layer without reinforcement).

Results show that the initial vertical stiffness is not significantly modified by the presence of the sand layer (whether reinforced or not). On the contrary, bearing capacity is considerably improved and increases by 62% when including a sand layer without the geosynthetic sheet, and by 81% when the sand layer is reinforced. The addition of a geosynthetic does not significantly alter bearing capacity but does, on the other hand, prevent against a sudden increase in settlement once the applied load exceeds the critical value.

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