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Centrifuge Modelling of an Embankment on Soft Clay Reinforced with a Geogrid

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ABSTRACT

The behaviour of reinforced embankments on soft clay has been explored using the technique of centrifuge modelling. Controlled in-flight construction of the embankment was carried out in a geotechnical centrifuge over a soft clay layer reinforced with scaled-down and instrumented geogrid reinforcement and the behaviour of the subsoil and the response of the geogrid were observed. These observations are compared with those from another centrifuge test in which a scaled-down woven geotextile was used instead of the geogrid. A new technique for measuring the tension induced in the reinforcement was developed and used in the centrifuge tests. It was found that a geogrid reinforcement that is placed directly on top of the clay layer may not contribute significantly towards the stability of the embankment because of poor adhesion at the clay–reinforcement interface. Copyright © 1996 Elsevier Science Ltd

1 INTRODUCTION

Embankments on soft clays are often unavoidable when building roads, railways or flood control barriers. The lowest safety margin for such embankments is at the end of their construction when the loading is at its maximum, but the strength of the subsoil is at its minimum due to the development of excess pore pressures. The long-term stability of such embankments is usually satisfactory because of the gain in the strength of the subsoil due to consolidation under the embankment loading. Therefore, short-term instability controls the design of these embankments.

Several techniques, such as staged construction, preloading and instal-

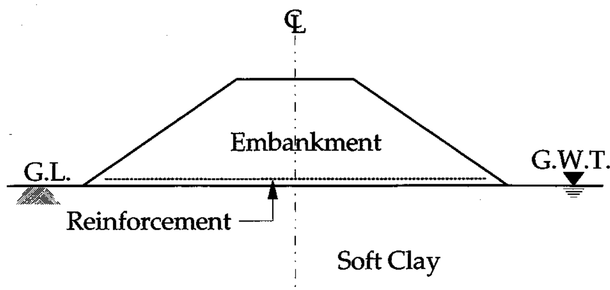

Fig. 1. Reinforced embankment on soft clay.

lation of wick drains, are available for improving the stability of the embankment. However, in recent years, the trend in the design of embankments on soft clay is to specify base reinforcement as the solution for the short-term instability (Fig. 1). The idea behind this technique is to make use of the tensile strength of the reinforcement to limit the spreading of the embankment and the lateral displacement of the clay foundation. The spreading of the embankment and the lateral movement of the clay foundation impose shear stresses on the embankment–reinforcement and clay–reinforcement interfaces which are resisted by the tension mobilized in the reinforcement, as shown in Fig. 2.

Steel meshes and tie rods used in earlier applications of base reinforcement have now been replaced by modern geosynthetics such as polyester woven geotextiles or polypropylene geogrids. A geotextile relies on the adhesion between itself and the adjacent soil to mobilize the tension, whereas a geogrid is able to mobilize tension mainly by generating passive resistance from the column of the soil confined between its large apertures. The adhesion between a geogrid and the adjacent soil is usually poor because of small surface area.

In this paper, the behaviour of reinforced embankments is explored using the technique of centrifuge modelling. In particular, the effectiveness of a geogrid reinforcement placed directly on top of the clay surface is

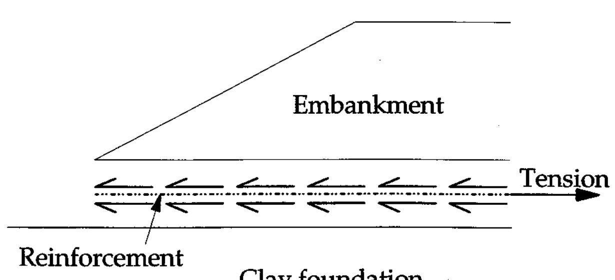

Fig. 2. Basic mechanism of tension mobilization in the reinforcement.

examined by comparing its behaviour with the behaviour of a geotextile reinforcement also placed directly on top of the clay surface. A new technique for the measurement of tension induced in the reinforcement during the embankment construction is also described.

2 CENTRIFUGE MODELLING

Centrifuge modelling, because of its ability to reproduce the same stress levels in a small-scale model as those present in a full-scale prototype, is a useful tool for the investigation of geotechnical problems. Idealized conditions may be created in centrifuge models to facilitate the validation of analytical or numerical solutions. Furthermore, centrifuge modelling offers the advantage of ease of management, greater control over the entire event, shorter consolidation time-scale and the option to continue the test up to failure. In the past, centrifuge modelling has contributed significantly towards improving the understanding of the behaviour of geotechnical structures leading to better design methods (Sun, 1990).

2.1 Equipment for centrifuge model testing

In the present study, three 1:40 scale centrifuge model tests were performed on reinforced embankments on soft clay using the Cambridge University 10 m balanced beam centrifuge (Schofield, 1980). Figure 3 shows the details of a typical centrifuge model. Table 1 gives brief specifications of each of the three tests. Due to inherent symmetry about the centreline, only the left half of the structure was modelled. Such an arrangement helped in constructing a model of reasonable size within a relatively small strongbox. A special clamp was built to anchor the model reinforcement to the right side of the liner. This clamp, while preventing the horizontal movement of the reinforcement, allowed for its downward vertical movement following the settlement of the clay foundation.

Two types of model reinforcements — a multifilament polyester woven geotextile and a polypropylene geogrid, were used in the present study. The model geotextile (Fig. 4) was supplied by Akzo Industrial Corporation b.v., The Netherlands, and the model geogrid (Fig. 5) was supplied by Netlon Corporation, UK. The process of scaling-down the prototype reinforcement to obtain the model reinforcement has been discussed in detail by Springman *et al.* (1992). Figure 6 shows the load–elongation curves for the two model reinforcements obtained by testing 200 mm wide strips in an Instron tensile testing machine. Table 2 gives the properties of the prototypes represented by these model reinforcements at 40 g.

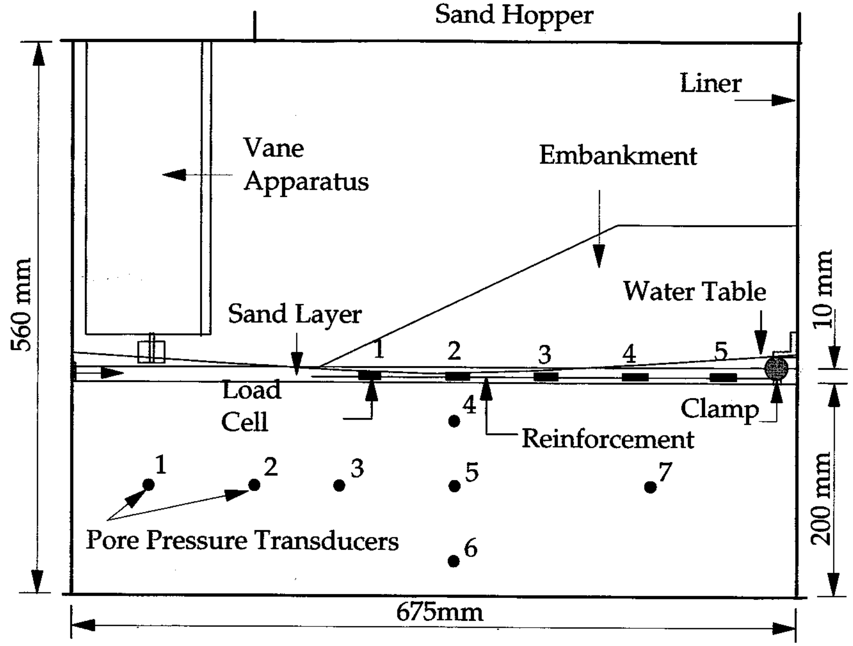

Fig. 3. Arrangement of a typical centrifuge model.

Figure 7 shows the position of load cells constructed on the model reinforcement for measuring tension induced in it during embankment construction. A typical load cell consisted of an approximately 12·5 mm wide and 0·7–1·5 mm thick strip of epoxy resin cast across the entire width

TABLE 1
Details of the Centrifuge Tests

Test code	*Depth of clay*	*Reinforcement*
JSS7	200 mm	Geotextile
JSS8	200 mm	Unreinforced
JSS9	200 mm	Geogrid

TABLE 2
Strength Characteristics of Model Reinforcements

Reinforcement	*Secant modulus (kN/m)*	*At extension (%)*
Geotextile	5000	1
Geogrid	6000	1

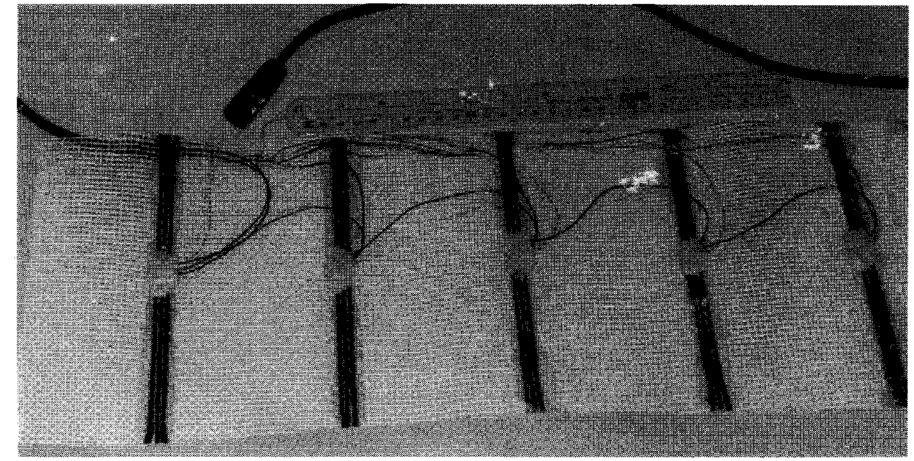

Fig. 4. Model geotextile.

of the reinforcement. The epoxy strip was reinforced with a combination of insulated copper wires and strips of carbon fibres before casting. The method of construction of load cells was different for each of the two model reinforcements, as seen from Fig. 8 showing details of the load cells. For the model geotextile, insulated copper wires and strips of carbon fibre were woven in between its filaments across its width. For the model geogrid, the two adjacent transverse ribs were brought closer to each other before weaving insulated copper wires and strips of carbon fibre through the longitudinal strands in such a way that the adjacent transverse ribs

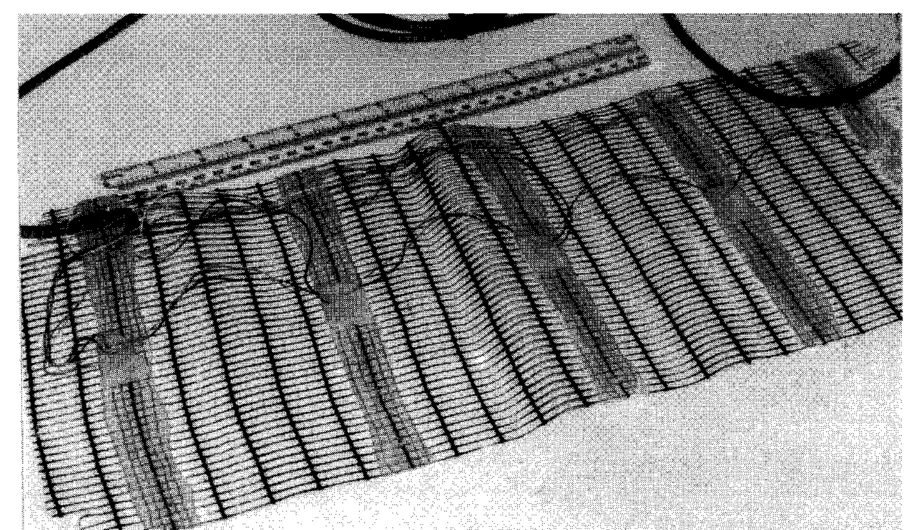

Fig. 5. Model geogrid.

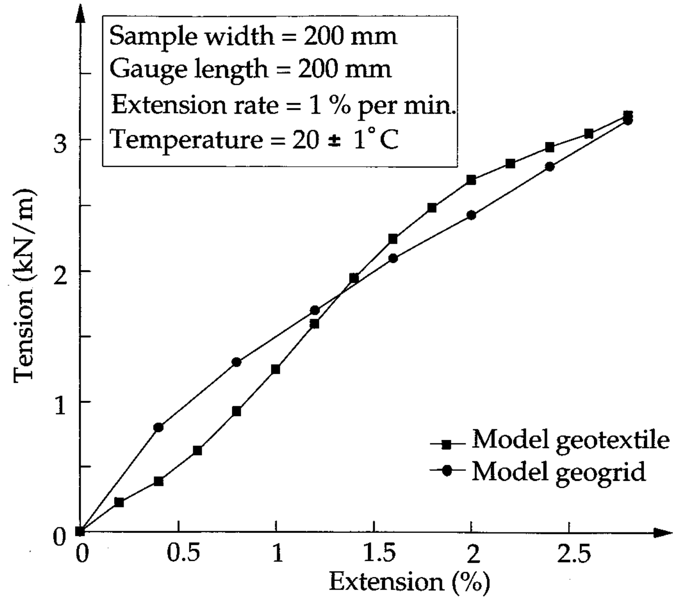

Fig. 6. Load–extension curves for model reinforcements.

remained close to each other after the weaving was complete. The function of the insulated copper wires and strips of carbon fibre was to provide stiffness to the load cell section facilitating the construction of thinner load cells. In addition, they also provided a key to the epoxy for better

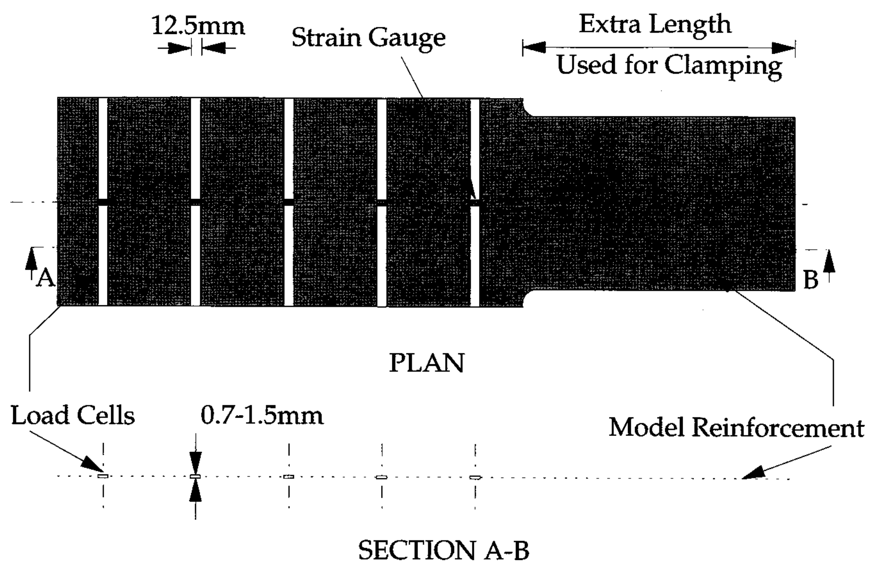

Fig. 7. Spacing of load cells on model reinforcement.

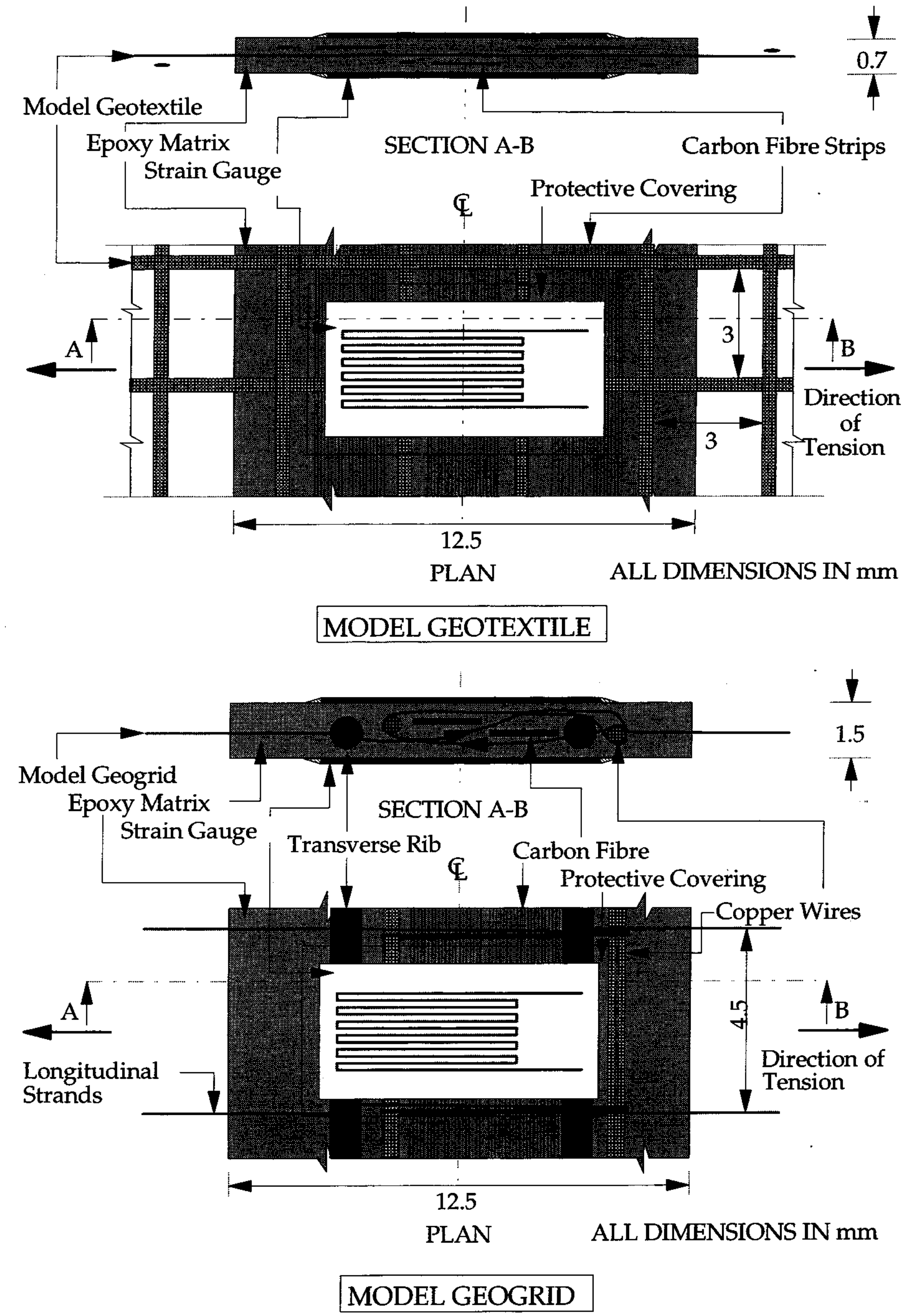

Fig. 8. Details of load cells on model reinforcement.

transfer of strains from the reinforcement to the epoxy. The epoxy resin was squeezed in a thin thread from a glue gun along the entire width of the reinforcement. The section was then sandwiched between two layers of cling film and clamped between a pair of parallel glass plates while the epoxy cured at room temperature. Great care was necessary to obtain a uniform hardened deposit of epoxy. Constantan strain gauges (350 Ω self temperature compensating) were glued centrally to the upper and lower surfaces of the epoxy strip using a cyanoacrylate adhesive and were wired as two opposite arms of a Wheatstone bridge circuit. Two variable resistance dummy gauges formed the other two arms of the bridge circuit. These dummy gauges were located in a small junction box which was mounted close to the cell sections. It is worth noting that the errors due to thermal effects may be reduced by keeping all the gauges in a bridge circuit at the same temperature. The bridge circuit was wired to give tensile strains in the epoxy as the reinforcement was pulled and to eliminate strains due to bending of the load cells. The model reinforcement with load cells was calibrated by subjecting it to known magnitudes of tension in an Instron tensile testing machine. The calibration curves (tension vs voltage output) for the load cells on the model geotextile were fairly linear, whereas those for the load cells on a model geogrid showed slight non-linearity (Fig. 9). The calibration procedure was repeated several times before and after centrifuge model testing and the calibration curves were found to be repeatable.

2.2 Procedure for centrifuge model testing

The spewhite kaolin clay was mixed with deionized water (120% by weight) under partial vacuum. The resulting slurry was consolidated to a maximum vertical pressure of 100 kPa in a consolidometer. Two days before the day of the centrifuge test, it was unloaded and trimmed to the dimensions of the model. Miniature pore pressure transducers were installed at various locations in the clay block to monitor excess pore pressures generated during the embankment construction. The clay block and the liner were then placed in a strongbox. A matrix of small black plastic markers was installed on the front of the clay block. These markers were used for the measurement of clay displacements from the photographs taken in-flight through the front perspex window. The model reinforcement with calibrated load cells was then attached to the end clamp and was placed directly on top of the clay surface. A 10 mm thick layer of sand was then deposited on top of the reinforcement in order to prevent it from moving before the embankment construction. A typical centrifuge test consisted of first bringing the clay foundation to a state of

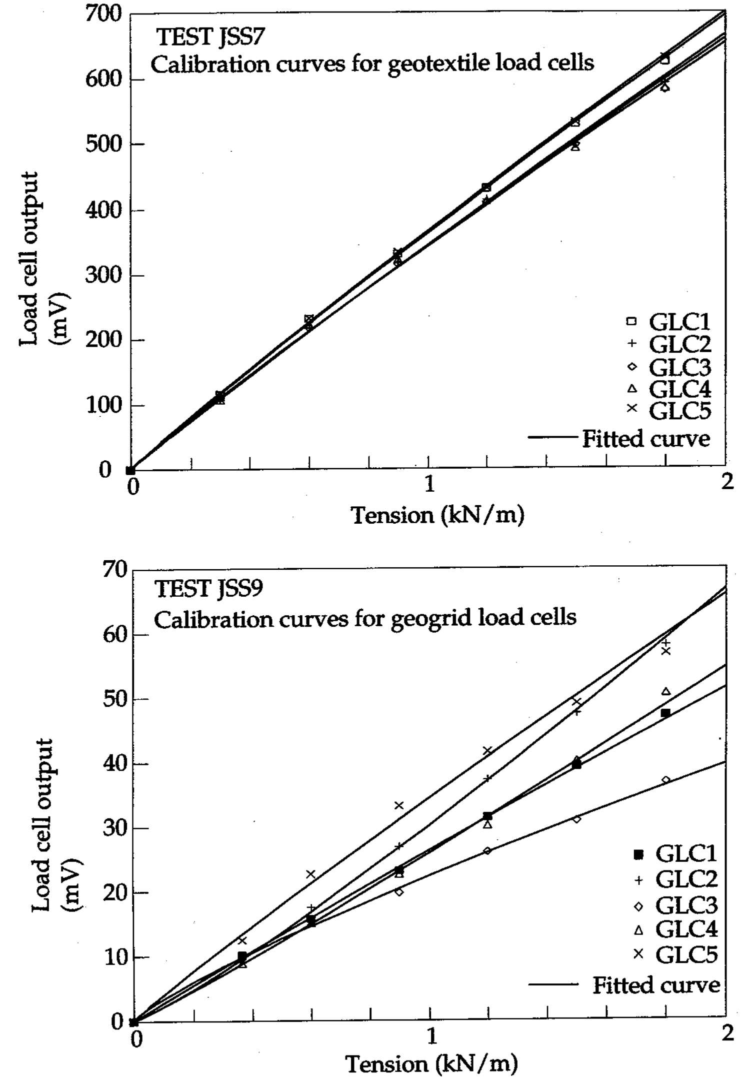

Fig. 9. Calibration curves for load cells on model reinforcement.

hydrostatic equilibrium with a steady water table at 10 mm above the top of the clay foundation. In-flight vane shear tests were then carried out at different depths (deepest test at 135 mm), using a miniature vane shear apparatus to check the consistency of the clay foundation. The rate of rotation of the vane was 1°/s. The average undrained shear strength of the clay foundation obtained from in-flight vane shear tests was approximately 9 kPa at 45 mm (1·8 m prototype) depth to approximately 13 kPa at 135 mm (5·4 m prototype) depth. After the completion of the vane shear

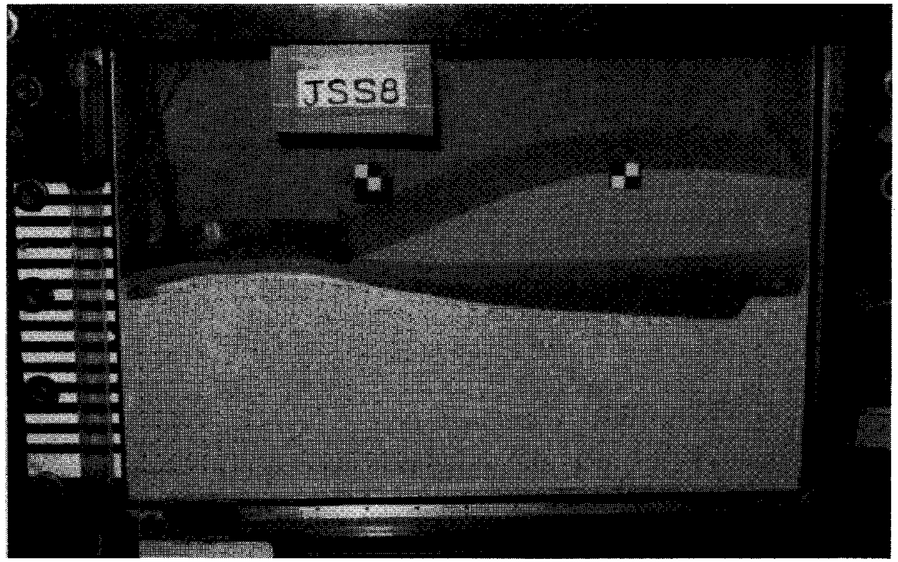

Fig. 10. Failure of an unreinforced embankment (test JSS8).

testing, an embankment was constructed in-flight in 20 stages (15 s interval between successive stages) by pouring sand from a hopper mounted on the top of the strongbox. The tension in the reinforcement and the displacement and excess pore pressures in the clay foundation were constantly monitored during the embankment construction. If no failure was observed, the clay foundation was allowed to consolidate under the embankment loading. The centrifuge was stopped when there was no applicable change of pore pressure in the clay foundation.

3 RESULTS

Rapid construction of the embankment caused significant deformation of the clay foundation. Excess pore pressures in the clay and the tension in the reinforcement both increased as the embankment construction progressed. The clay foundation for test JSS8 (unreinforced) failed when about 85% of the embankment as constructed, resulting in a classic circular failure surface as shown in Fig. 10. The clay foundation for test JSS9 (geogrid reinforced) also failed a few seconds before the completion of the embankment construction (95% of the embankment constructed). However, the failure surface in this case was not fully developed, as seen from Fig. 11. The geogrid reinforcement was found intact after the removal of the sand embankment during post-test investigations. Up to 4 mm (160 mm on prototype

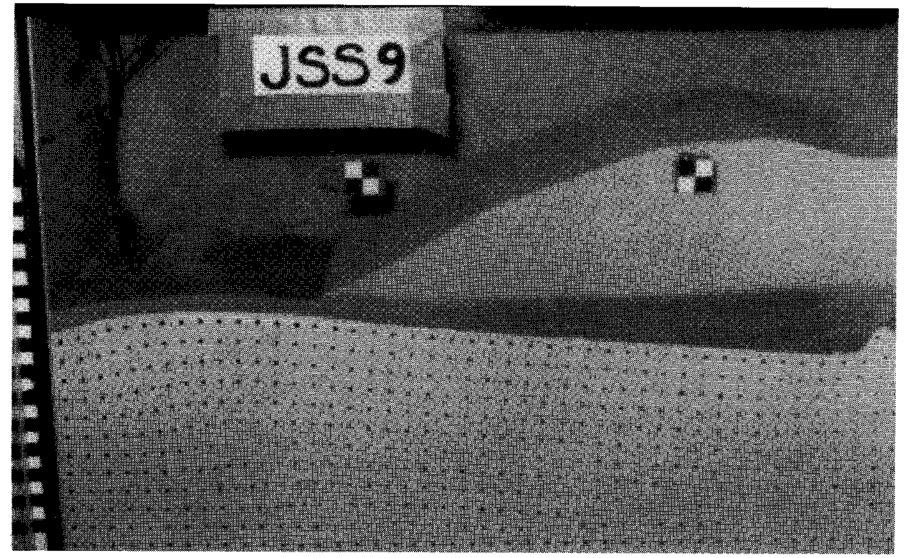

Fig. 11. Failure of a geogrid-reinforced embankment (test JSS9).

scale) of lateral movements were observed for test JSS7 (geotextile reinforced), but the embankment remained serviceable at the end of its construction, as seen from Fig. 12 depicting the displacement pattern for the clay foundation obtained by measuring the in-flight photographs taken before and immediately after the embankment construction. The magnitude of excess pore pressure in the clay foundation

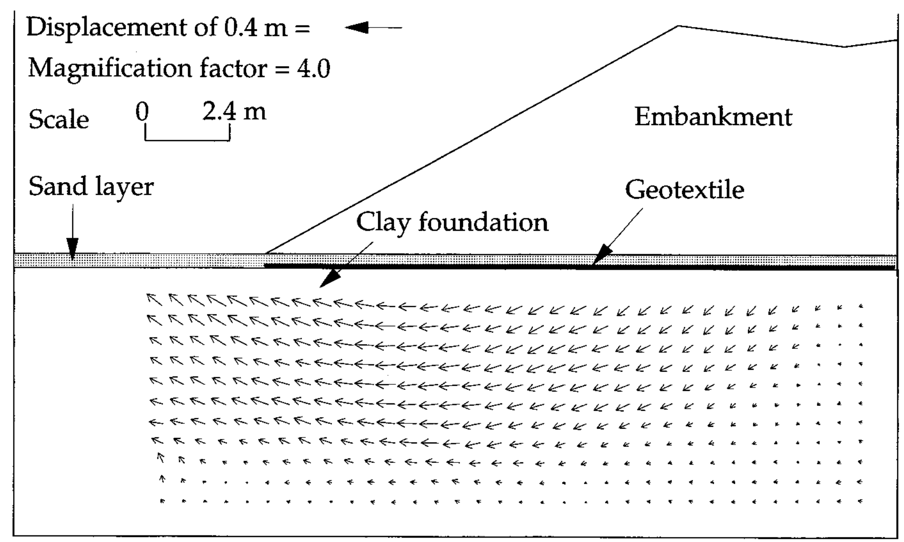

Fig. 12. Displacement pattern for a geotextile-reinforced embankment (test JSS7).

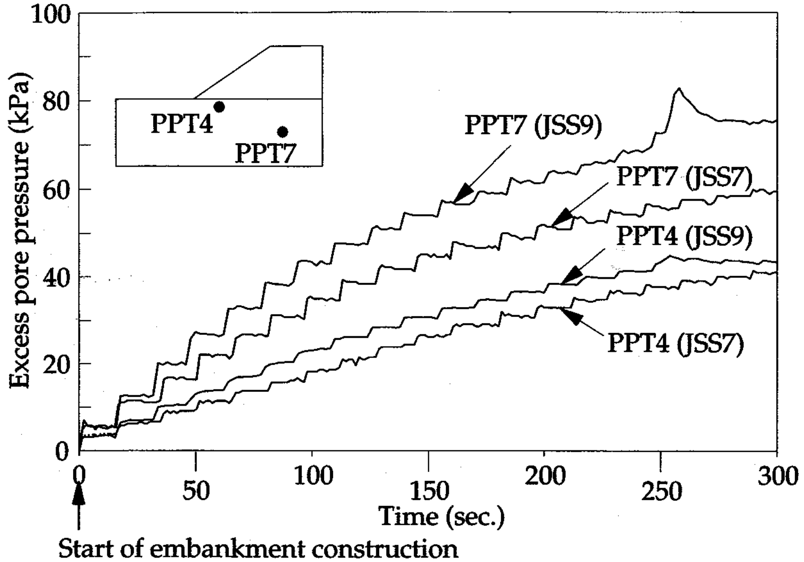

Fig. 13. Excess pore pressures in the clay foundation during embankment construction.

was higher for test JSS9 as compared to that for test JSS7 from the beginning of the embankment construction, as shown in Fig. 13. Figure 14 shows the tension induced in the reinforcement during embankment construction for tests JSS7 and JSS9. The plot for the test JSS9 clearly shows the failure of the clay foundation indicated by a sudden increase in the tension as the clay foundation squeezed past the geogrid, imposing significant drag on it. The magnitude of maximum tension induced in the reinforcement was almost the same for tests JSS7 and JSS9, as seen from Fig. 15 showing the tension profile across the width of the reinforcement. However, compared to test JSS7, less tension was induced in the section of the reinforcement underneath the slope of the embankment for test JSS9.

4 DISCUSSION

Figure 16 shows the distribution of horizontal displacement at the top surface of the clay foundation superimposed on the distribution of axial displacement in the reinforcement for tests JSS7 and JSS9. The distribution of horizontal displacement at the top surface of the clay was obtained from the in-flight photographic measurements taken before the start and immediately after the completion of embankment construction. For test JSS9, the distribution of horizontal displacement was obtained just before

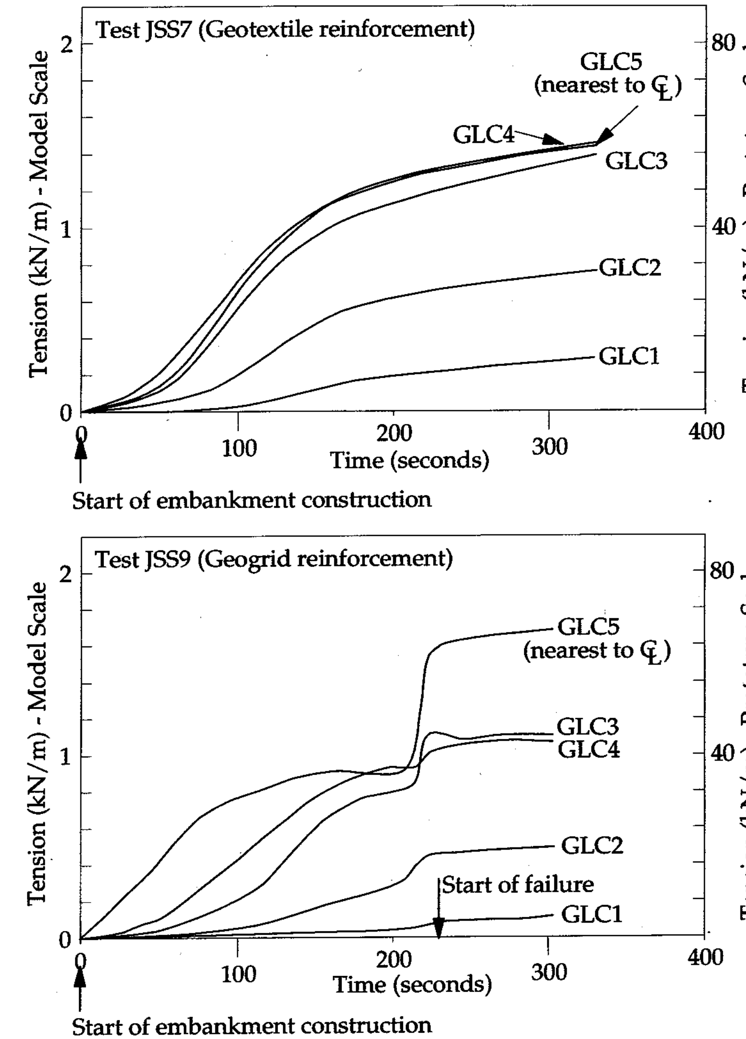

Fig. 14. Tension induced in the reinforcement during embankment construction.

the onset of the failure of the clay foundation. The axial displacement distribution in the reinforcement was obtained by numerically integrating the distribution of axial strain, which in turn was derived from the tension profiles obtained at the end of embankment construction. It can be seen from Fig. 16 that the axial displacements of the geogrid are much less than the horizontal displacements at the top surface of the clay for test JSS9, which implies that slip occurred at the clay–geogrid interface for test JSS9, even before the onset of failure in the clay foundation. In comparison, for test JSS7, the extension of the geotextile and the lateral displacement at

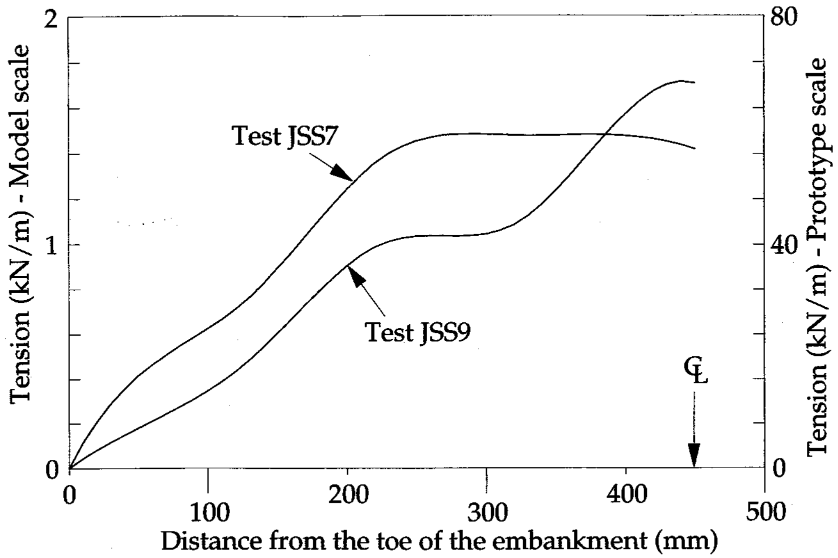

Fig. 15. Tension profile along the width of the embankment at the end of construction.

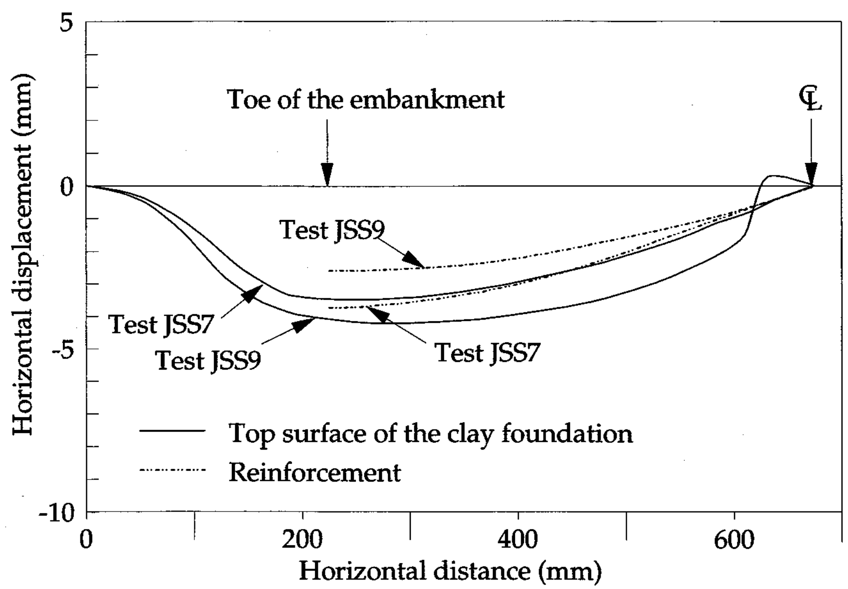

Fig. 16. Lateral displacement of the reinforcement and the top surface of the clay foundation.

the top surface of the clay foundation are consistent, indicating no slip at the clay–geotextile interface. The slip at the clay–geogrid reinforcement may be attributed to the following reasons:

(a) the geogrid was unable to mobilize enough passive resistance because it was installed at the interface with no continuous columns of soil confined between its apertures;
(b) there was a lack of adherence at the clay–geogrid interface due to the unusually large apertures of the geogrid resulting in a very small surface area.

An examination of the excess pore pressures induced in the clay foundation for tests JSS7 and JSS9 reveals that the magnitudes of excess pore pressures were higher for test JSS9 from the beginning of the embankment construction. This observation also implies that the geogrid reinforcement was not as effective as the geotextile reinforcement in reducing the lateral displacement of the clay foundation. In other words, a greater extent of clay reached the yielding point for test JSS9 as compared to test JSS7, which resulted in higher excess pore pressures in the clay foundation.

It is worth noting that although the clay foundation for test JSS7 did not fail, it nevertheless deformed considerably, indicating significant yielding of the clay foundation. This has been confirmed by the results of finite element back analyses of the centrifuge tests carried out by Sharma (1994) using a non-linear elasto-plastic model to represent the clay foundation. Numerical results obtained by Sharma (1994) indicate that almost the entire clay foundation was at critical state at the end of embankment construction. Yet, it managed to avoid failure in the case of test JSS7, but failed in the case of test JSS9. The only component that prevented the failure in the case of test JSS7 was the availability of sufficient adherence at the clay–reinforcement interface.

5 CONCLUSIONS

The behaviour of reinforced embankments on soft clay was investigated using the technique of centrifuge modelling. Particular attention was given to the effectiveness of a geogrid reinforcement placed directly on top of the clay foundation. A new technique for measuring tension in the reinforcement was developed and used successfully in the centrifuge model tests. Controlled in-flight embankment construction was carried out successfully in the centrifuge over a soft clay layer, and the behaviour of the subsoil and the response of the reinforcement were observed.

A geogrid reinforcement placed directly on top of the clay foundation may not be very effective in preventing lateral deformation of the clay foundation and, therefore, may not contribute significantly towards the stability of the embankment. This may be due to the fact that such an installation inhibits the confinement of soil between the large apertures of the geogrid and as a result, hampers the geogrid from developing any passive resistance. In the absence of passive resistance, the geogrid has to rely on its adherence with clay in order to resist the lateral deformation of the foundation which can be fairly insignificant, because of the small surface area of the geogrid. A woven geotextile, on the other hand, performed satisfactorily when placed directly on top of the clay foundation. The magnitude of tension induced in the reinforcement was only of the order of lateral thrust in the embankment, but was enough to prevent the failure of the embankment. On the basis of the slip observed at the clay–reinforcement interface and small tensions recorded in the reinforcement, it can be inferred that the stiffness and the surface characteristics of the reinforcement are more important than its ultimate strength.

In situations where the reinforcement has to be rolled directly on top of the clay foundation (e.g. marshy land which can not support any earth moving equipment), it is better from the point of view of stability of the embankment to use geotextiles instead of geogrids. Although substantial savings can be made by using geogrids in place of geotextiles, the use of a geogrid would invariably require the placement of a granular fill over the clay foundation before the geogrid can be installed. The cost of placing a granular fill would significantly reduce the savings and in some situations may render the geogrid option more expensive.

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