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The influence of dimensional analysis on the interpretation of model loading tests of reinforced ground

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ABSTRACT: Geotechnical models can be prone to significant errors which arise usually from two main sources, boundary and scale effects. The presence of reinforcements in the model amplifies the traditional scale effect and in many model tests full scale reinforcing materials have to be used. To estimate the effects of inclusions in a model, it is necessary: (1) to reduce the mechanical properties of the relevant materials by dimensional analysis and/or (2) to interpret the results in the light of dimensional analysis. The objective of the paper is to show how the results of model tests using full-scale reinforcements should be interpreted in the light of dimensional analysis. A dimensional analysis is reported covering the results of a series of axi-symmetric model loading tests. The tests were undertaken to investigate an established construction method in which geosynthetic reinforcement is used in the support of structures built on super soft clay. Super soft clay is defined as a cohesive soil having a water content *much higher* than its liquid limit.

1 INTRODUCTION

A large number of 1-g model loading tests have been conducted to study the bearing capacity and load-displacement characteristics of reinforced soil. The models usually consist of a tank filled with soil, reinforcement, a loading plate and a loading device. Shallow footings or unpaved roads are frequently the focus of these studies.

A potential disadvantage of using models is the uncertainly in respect of how closely the model represents the behaviour of a full-scale prototype under field condition. The errors arise from two main sources, boundary and scale effects. The side-boundary effects can be avoided by arranging for the boundaries of the model to be remote from the loading plates.

Elimination of scale effects is not so simple as it is not sufficient simply to reduce the geometrical dimensions in the model. In addition, it is necessary to reduce the mechanical properties of the materials in the system. The amount of this reduction can be derived by dimensional analysis.

Dimensional analysis, described in detail by Langhaar (1951), provides the basis for establishing scaling laws which can be used to convert data from a small model into design information for a large prototype. Dimensional analysis also reduces parametric variables leading to easier interpretation of the model tests.

Dimensionless parameters in geotechnical modelling can be formed by choosing two independent variables embracing fundamental dimensions, often length and force, and combining them with the remaining variables in dimensionless terms. If the design conditions are satisfied, dimensionless parameters will not vary with scale. Accordingly, the dimensionless response of the model, for example the dimensionless bearing capacity, remains constant when the scale changes.

2 SCALE EFFECT DUE TO REINFORCEMENT

It is frequently difficult to model soil reinforcements, in particular those which are formed from geosynthetic materials. It is recognised that the presence of full-scale reinforcements amplifies the traditional scale effect and Gottardi and Simonini (1995) have reported the results of some loading model tests modelled at different scales. The results show that the relative influence of geosynthetic reinforcements on the bearing capacity becomes greater in a smaller scale model.

To minimise the scale effects, the physical properties of the reinforcement should be reduced when used in a model. The properties which need to be considered include strength, tensile stiffness, in-plane rigidity and geometry. However, the relative importance of the reduction of the various properties of a reinforcement is not always apparent. In addition, manufacturing the proper material for model tests is difficult. Love (1984) has reported the difficulties in obtaining an ideal geosynthetic reinforcement to model unpaved roads. Love identified the mechanical properties of the reinforcement required in the model using dimensional analysis.

Interpretation of the results of the model tests without taking account of scale effects will result in overestimating the effect of the reinforcement (Fakher and Jones 1995). The object of this paper is to show how the results of model tests using full scale reinforcement may be interpreted in the light of dimensional analysis.

3 MODEL LOADING TESTS ON "SAND-GEOSYNTHETIC-SUPER SOFT CLAY"

3.1 *Experimental study*

A series of axi-symmetric model loading tests have been conducted to investigate the bearing capacity of a three-layer construction system, formed from sand, geosynthetic reinforcement and super soft clay, Fig. 1 (Zakaria, 1994). Super soft clay exhibits *no effective bearing capacity* and these soils have a very high water content (Jones and Zakaria 1994).

In order to permit construction on super soft clay a primary construction stage can be used. In this technique a layer of fill is placed on the soil supported on a geosynthetic reinforcement layer. On this layer of fill, the main construction can be constructed. Placing the initial layer of fill and the reinforcement is not simple and a number of different methods have been used in practice (Broms 1987; Fischer et al. 1995; Tan et al. 1994; Toh et al. 1994; Yano et al. 1985).

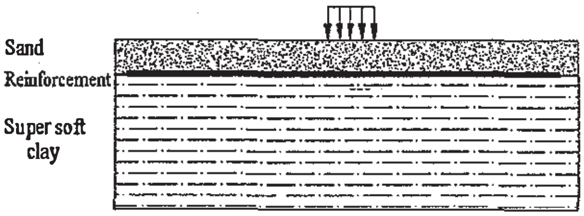

Figure 1: Using geosynthetics and sand layer to improve bearing capacity

Although demonstrably successful, there is no comprehensive explanation of the improvement mechanism associated with the technique of using a primary construction stage. This is the subject of current study.

The scale models used in the study to date have used a wide range of geogrids and geotextiles supporting three different sizes of footing on a *super soft* soil formed as a clay slurry with a water content of 140 per cent (Zakaria 1994). The lateral restraint of the geosynthetic in the models was developed by the interface resistance friction between the geosynthetic reinforcement and the soil alone. In some previous experiments associated with the construction on *soft* soils using geosynthetic reinforcement mechanical restraint of the reinforcement is provided by a system of counterweights (Hirao et al, 1992). This technique can be criticised because the vertical position of the pulleys does not change with the settlement of the loading plate. This influences the deformed shape of the reinforcements at high settlements and results in the development of an additional component of the tension force in the reinforcements.

A rotational viscometer was used to measure the shear strength and viscosity of the super soft clay. This device is used in the drilling industry to measure rheological properties of drilling mud (Rabia 1989). The shear strength, identified as the shear stress at zero strain rate, was obtained by extrapolation based on the Bingham model. A value of 60 N/m^2 was obtained.

3.2 *Dimensional analysis of model tests*

For the case of a single very wide layer of reinforcement, a simple analysis can be undertaken by assuming that the controlling factors in the system are;

$$f(q,B,D,a,S,R,c) = 0 \quad (1)$$

Where:

f = a function which governs the system.
q = bearing capacity (kN/m^2).
B = diameter of the circular footings (m).
D = the thickness of sand layer (m).
a = grid aperture size (m).
S = stiffness of the reinforcement in tension (kN/m).
R = in-plane bending stiffness (rigidity) of the reinforcement (kN.m).
c = shear strength of the clay (kN/m^2).

The bearing capacity, q, is derived based on (δ/B)=0.5, where δ is the settlement of the footing under the load. The stiffness of the reinforcement, S, is determined as the initial portion of the stress-strain curve. The in-plane bending stiffness, R, refers to the flexural rigidity defined by test method (ASTM D 1388 1975).

In practice, the cohesionless fill on top of the geosynthetic reinforcement is placed hydraulically so it is expected that this material is in a loose state. In view of the placement method and the range of fill used in practice, it can be assumed that the bearing capacity is not sensitive to the change of the shear strength and deformation properties of the cohesionless material. In addition, the length of the geosynthetic reinforcement has been shown not to be a dominant factor, as the study indicated that if more than 75% of the surface area of the model was covered by the reinforcing material, the reinforcement was fully effective.

A number of writers on dimensional analysis have stated the rule that the number of independent dimensionless parameters in a complete set is equal to the total number of variables minus the number of fundamental dimensions in the parameters, (Langhaar 1951). Since there are 7 factors in equation (1) and the model involves only two dimensions, force and length, the system can be studied by any complete set of 5 independent dimensionless parameters. In this study, the following parameters were considered:

$$g[(\frac{D}{B}),(\frac{a}{B}),(\frac{q.B^3}{R}),(\frac{R}{S.B^2}),(\frac{q}{c})]=0 \qquad (2)$$

Where g is a function which governs the system.

The dimensionless parameters in equation (2) can be identified as (π_1, π_2, ..., and π_5) respectively. Application of a model test for a real life project requires that the model and the prototype should be similar, that is (π_i) relating to the model and the prototype should be same. However, it is not feasible to impose complete similarity in a model test; consequently, some of the independent dimensionless variables may deviate from their correct values resulting in *scale effects*.

Consider a model footing which has dimensions n times smaller than the prototype:

$$\frac{B_p}{B_m}=\frac{D_p}{D_m}=\frac{a_p}{a_m}=n \qquad (3)$$

Where $_p$ and $_m$ refer to the *prototype* and the *model* respectively and the soils in the model and the prototype have the same density. (In most cases, the aspect of particle size is of no practical significance and it is necessary only to ensure that there are sufficient particle contacts on all boundaries or inclusions (Mitchell 1991).

In order to satisfy similarity, all the (π_i) values should be the same for the prototype and the model.

Thus: $(\pi_5)_m=(\pi_5)_p$

and

$$\frac{R_p}{R_m}=\frac{q_pB_p^{\ 3}}{q_m.B_m^{\ 3}} \quad \text{and} \quad \frac{R_p}{R_m}=n^3 \qquad (4)$$

It can be concluded that the geogrid in the tests requires a rigidity ($1/n^3$) times that of the reinforcement used in practice. In respect of (π_4) it can be concluded that the required stiffness of the geosynthetic reinforcements in the model needs to be ($1/n^2$) times that used in practice.

3.3 *Dimensionless Results*

In order to present the results of the study, the trend of the data was first considered. The dimensionless parameters in Equation (2) were changed several times to identify the controlling parameters in the equation.

In the main model study it was found that the geogrids reinforcements generally offered a higher bearing capacity than the geotextile reinforcements. The main contributing property from the reinforcement proved to be the in-plane rigidity, R, not the tensile stiffness, S. In addition, the size of the grid aperture was shown to be a minor contributing factor to the improvement of the bearing capacity. A linear relationship between q/c and D/B for each geosynthetic reinforcement was established; however, the trend from one type of geosynthetic to another was not clear. A similar relationship was observed between $(q.B^3)/R$ and D/B.

It was found that a classification system for the bearing capacity of the soil could be formed by plotting the results of q/c versus D/B and a third dimensionless parameter. A classification system in which the third parameter included S but not R was not clear. However, third dimensionless parameters which included R, such as $(q.B^3)/R$, were observed to be promising and the parameter $R/(S.B^2)$ was found to provide the best fit, Fig. 2. Three separate zones are identifiable in Fig. 2.

In theory, S and R might be considered as independent parameters in the term $R/(S.B^2)$, however they are linked through the manufacturing process of the geosynthetic material.

4 CONCLUSIONS

The following general conclusion can be made in respect of the study of the primary construction system used to build on super soft soil:

1) In order to accurately model a reinforced soil, the mechanical properties of a full-scale reinforcement should be reduced.

2) Where a full-scale reinforcement is used in a model, the overestimation of the effects of the reinforcement can be avoided using dimensional analysis.

3) The in-plane bending stiffness (flexural rigidity) of soil reinforcement is an important (dominant) factor in construction over super soft clay. This has not been always apparent and current analytical procedures used in the design of reinforcement geosynthetics on super soft clay ignore this parameter.

4) A graphical expression has been identified which could form the basis for a method to estimate the bearing capacity of super soft clay overlaid by a layer of geosynthetic reinforcement and a cohesionless fill layer.

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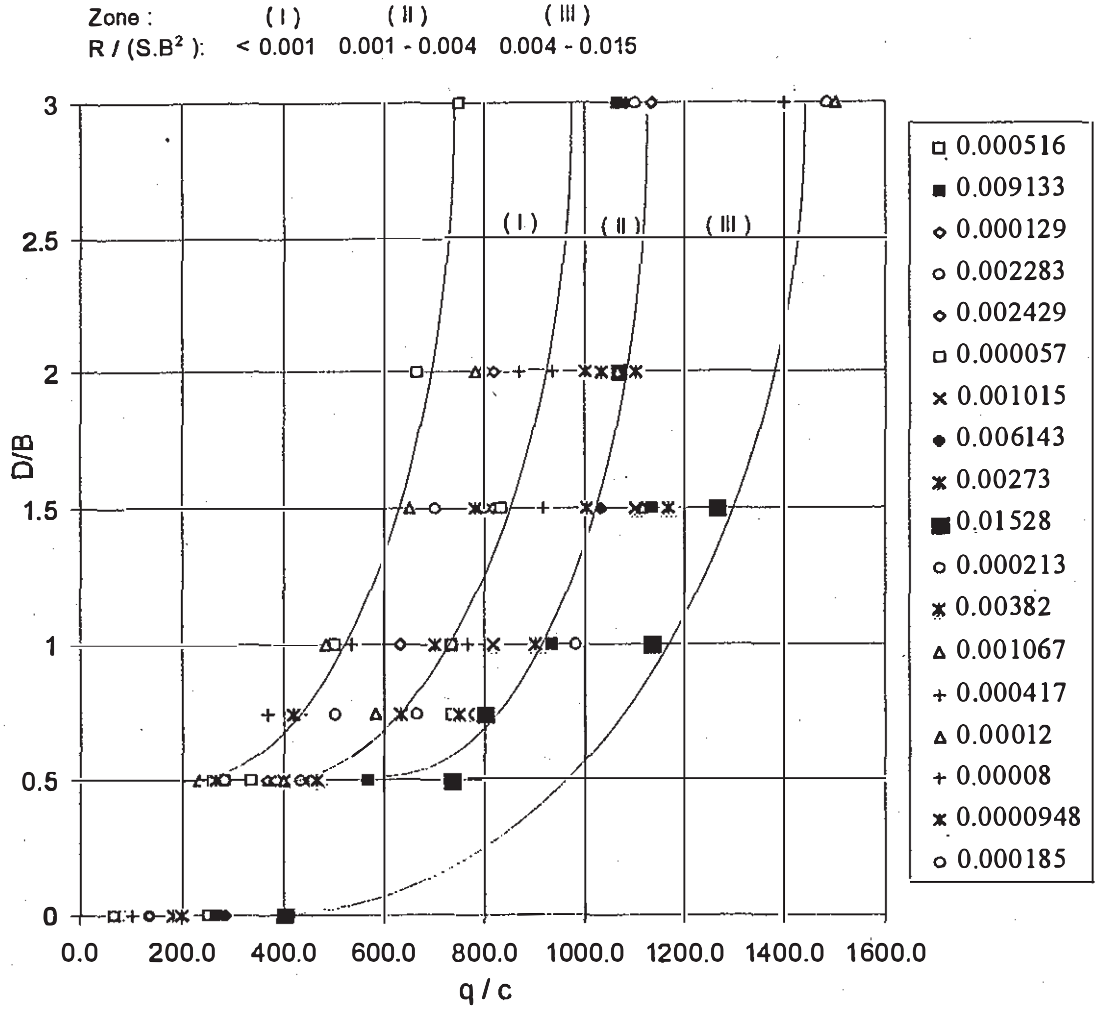

Figure 2: The dimensionless results of the bearing capacity tests on a small size axisymmetric footing on super soft clay (the legend shows the amount of $R/ S.B^2$ in each test)

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