Geosynthetics, J. Kuwano & J. Koseki (eds)
© 2006 Millpress, Rotterdam, ISBN 90 5966 044 7

Soft ground improvement by vertical rigid piles and basal geosynthetic reinforcement – physical modelling

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Keywords: soil improvement, pile, geosynthetic reinforcement, membrane effect, physical modelling

ABSTRACT: The soft soil improvement technique concerned by this study consists of a pile grid and a granular earth platform including basal geosynthetic reinforcement. A two-dimensional physical model is developed to study the load transfer mechanisms occurring in this composite platform. The granular platform material is simulated by a mix of steel rods which constitutes a two-dimensional analogical soil; the soft soil is simulated by foam and the pile by fixed rigid elements. A basal geosynthetic layer is embedded with a movable jaw system. Results are obtained in terms of loads at platform base using load cell instrumentation and in terms of displacement field in the whole model using image processing method. Parametric studies are performed on the geosynthetic stiffness influence in combination with the foam compressibility by using four different geosynthetic stiffness and two different foam materials.

1 INTRODUCTION

The technique of soft soil improvement by vertical rigid piles and basal geosynthetic reinforcement is more and more used to develop road and railway networks as well as industrial areas. However, no guidelines exist in France to design this type of structure. Analytical methods exist to determine the load transfer onto the pile but they lead to dissimilar results (Horgan and Sarsby 2002). A project entitled "ASIRI" for "Amélioration des Sols par Inclusions RIgides" which means "Soil Improvement by Rigid Piles" begins in 2005 to solve this problem. Our contribution to the "laboratory test" theme of this project consists in a two-dimensional physical modelling which allows precise analysis of the load transfer mechanisms occurring in the platform, as well as the settlement reduction and homogenization observation.

2 IMPROVEMENT PRINCIPLE

The soft soil improvement is obtained by the combination of a rigid pile grid driven trough the compressible soil layer until the rigid stratum and a granular earth platform situated between the improved ground and the surface structure in which basal geosynthetic reinforcement is embedded. The improvement principle is illustrated by Figure 1.

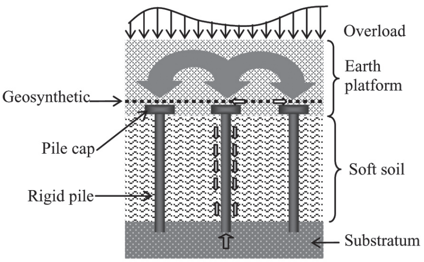

Figure 1. Schematic of geosynthetic reinforced piled foundation.

This granular platform is made of gravel, ballast or coarse soil. Differential settlements occur at the platform base between the piles and the soft soil. These differential settlements induce two types of mechanism. (1) The shear stresses induced in the granular dense material lead to arching. The arch formation depends on the platform height (Rathmayer 1975). (2) The deflection of the basal geosynthetic reinforcement induces membrane effect. Both mechanisms lead to partial load transfer onto the piles. Both mechanisms are treated separately in most of the design methods (BS 8006 1995, Kempfert et al. 2004): the load transfer by arching is first determined as if no basal reinforcement were present and the geosynthetic is then designed for carrying the rest of the load. The presence of the soft soil is not always taken into account in the design methods, whereas it can contribute to the improvement system behaviour.

Pile caps can be added to increase the covered area. Friction along the piles is also implicated in this soil/structure phenomenon.

Piles are preformed or manufactured in-situ. A list of pile types and installation techniques is described by Briançon et al. (2004). This technique differs from those of classical piles, because the piles are not rigidly connected to the surface structure.

The soil-structure interaction phenomena are complex and their understanding needs to be ameliorated. A two-dimensional model test is therefore proposed. It is a simplification of the reality and it constitutes a first approach.

3 SMALL SCALE MODEL

3.1 *Test apparatus*

The developed small scale model is two-dimensional and uses analogical materials. Figure 2 shows the test apparatus. The granular platform material is simulated by a mix of 60 mm long steel rods; the soft soil is simulated by foam and the pile by fixed rigid elements. A basal geosynthetic layer can be inserted at platform base. The vertical boundaries are covered by Teflon sheet in order to simulate symmetry planes. As far as two piles are represented, the system behaviour can be studied more precisely in the model centre between both piles were the boundary effects are avoided. The pile width is $a = 0.1$ m and the pile spacing is $s = 0.65$ m. The capping ratio is the proportion of the treated area covered by piles. It is here equal to $a/s = 15\%$. Parametric analyses were already performed on the influence of these geometrical parameters (Jenck et al. 2005).

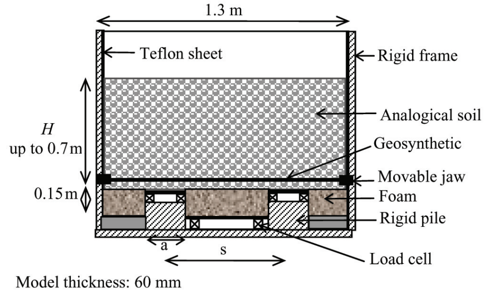

Figure 2. Two-dimensional test apparatus.

Figure 3 shows the ideal basal geosynthetic deflection in the model test. Point A, B and C should have equal vertical displacement and no horizontal displacement. A movable jaw system to incorporate the geosynthetic reinforcement was designed to respect these conditions. Figure 4 is a photograph of the system. A jaw fixes the geosynthetic band at each model boundary. It can freely move in the vertical direction and is designed to support the horizontal force. In the experiment, the tension membrane in the geosynthetic does not exceed 200N.

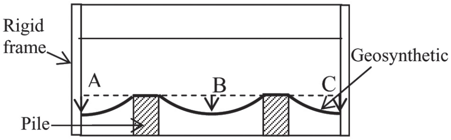

Figure 3. Basal geosynthetic deflection.

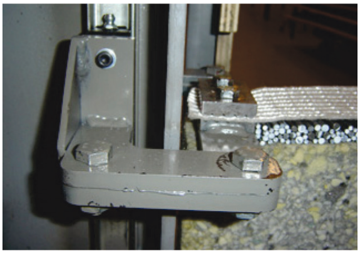

Figure 4. Jaw fixing the geosynthetic layer.

The model is instrumented by load cells to determine the load distribution at platform base between the piles and the foam.

The granular platform is built in several 0.1 m-thick layers until a maximum height of 0.7 m. Photographs are taken at each stage and the displacement fields in the whole model is obtained by an image processing method.

The results given by this model test are precise and reproducible; several parametric studies can thus be performed.

3.2 *Schneebeli soil*

The granular platform material is simulated by a mix of 3, 4 and 5 mm-diameter steel rods, 60 mm long: the Schneebeli soil.

Dolzhenko (2002) performed biaxial tests on analogical soil samples, confined at pressures between 20 and 50 kPa, which correspond to the stress level encountered in the presented physical model. Figure 5 presents the obtained results. The friction angle is 24°, the cohesion is null and the modulus depends on the stress level. This soil is dilative from the loading beginning and the dilation angle is 4°. Its behaviour is analogue to dense sand behaviour.

This soil was used because it presents many advantages. The properties are close to those of dense granular soil, no facial support is needed because of rod piling, the unit weight (62 kN/m^3) is larger than for sand, leading to similitude distortion reduction and it is particularly well adapted to the image processing method because faces are coloured to have grey contrast. However, the friction angle is smaller

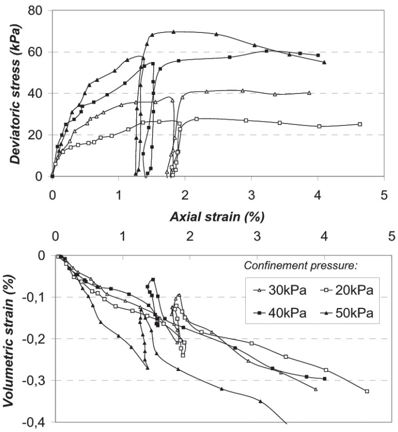

Figure 5. Biaxial test results on Schneebeli soil.

than for granular materials that usually constitute the platform and no extension to the third direction is possible.

3.3 *Compressible foam*

Two different foam materials are used to simulate the soft soil layer. Loading tests are performed on foam elements placed in the test apparatus rigid frame and vertically loaded in order to determine their compressibility. For a limited foam deformation, the behaviour is almost elastic linear in compression. A "modulus" is determined by the ratio between the vertical applied stress to the vertical displacement of the foam. The obtained values for F1 and F2 foams are given in Table 1. These values are directly related to the foam element thickness equal to 0.15 m (Fig. 2).

Table 1. Modulus for a 0.15 m thick foam element.

F1	59 kPa
F2	277 kPa

3.4 *Geosynthetic reinforcement*

60 mm-wide geotextile bands are used as basal reinforcement. High resistance geotextiles (RP) and "Typar" bands are used. Loading tests are performed on the geosynthetic bands in order to determine their actual stiffness. Table 2 summarizes the obtained results. The case 4 RP 200 was not tested but the stiffness is supposed to be higher than for RP 200.

Table 2. Geosynthetic reinforcement stiffness.

S1	S2	S3	S4
4 Typar 20 kN/m	RP 75 130 kN/m	RP 200 200 kN/m	4 RP 200 Not tested

4 EXPERIMENTAL RESULTS

4.1 *Load transfer onto the piles*

The efficacy is the proportion of the platform weight carried by the piles (Hewlett and Randolph 1988), namely the ratio of the vertical load applied on the piles to the total platform weight. When no basal geosynthetic is incorporated the load transfer is only due to arching in the granular fill. When no arching occurs the efficacy is equal to the capping ratio value (here equal to 15%).

Figure 6 depicts the efficacy according to the platform height *H* for the case without geosynthetic reinforcement and for the four different geosynthetic stiffness values. The soft soil is simulated by the more compressible foam (F1). The efficacy increases with *H* for every case. The efficacy is increased due to tension membrane effect when geosynthetic reinforcement is incorporated. This figure shows that the more the stiffness, the more the efficacy. The efficacy reaches 0.43 for the case without geosynthetic and reaches 0.78 for the reinforcement using S4 geosynthetic. This corresponds to an efficacy increase of 80%.

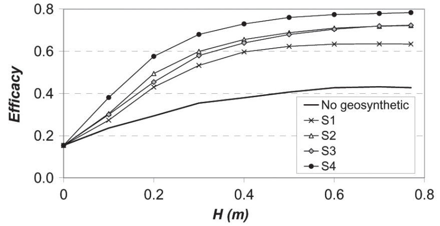

Figure 6. Efficacy according to platform height *H*, for foam F1.

The efficacy obtained without geosynthetic reinforcement is almost the same for the soft soil simulation using F2 or F1 foam: no foam compressibility influence is noted. However, the efficacy increase brought by the basal geosynthetic reinforcement is less with F2 than with F1: the maximum efficacy is only increased by 20% when using F2 and no geosynthetic stiffness influence is noted (same results whatever the stiffness). In other words the foam compressibility has an influence on the load transfer mechanism when basal geosynthetic reinforcement is incorporated. These conclusions are valid for the range of geosynthetic stiffness and foam compressibility investigated.

4.2 *Settlement reduction*

The settlements in the platform are reduced compared to the non-reinforced-by-pile case (Jenck et al. 2005) even without basal geosynthetic reinforcement. This is due to arching effect in the granular material. The maximum platform settlements are reached at platform base mid-span between both piles. Figure 7 depicts the settlement reduction at this location obtained with the several stiffness values compared to the case without geosynthetic reinforcement, for the more compressible foam. This figure shows that the more the stiffness, the more is the basal settlement reduction.

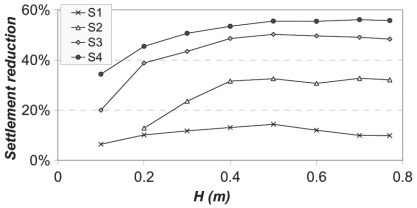

Figure 7. Basal settlement reduction compared to the case without geosynthetic for F1 foam.

For F2, it is found that the foam settlements are smaller than for F1 because of higher rigidity and the settlement reduction brought by the geosynthetic reinforcement reaches 35% whatever the geosynthetic stiffness.

4.3 *Geosynthetic deflection*

Figure 8 presents the S3 geosynthetic deflection for $H = 0.7$ m obtained with F1 or F2 foam. The deflected shape can be approximated by a parabola for F1, whereas the geosynthetic deflection is restrained by the foam F2 which is not compressible enough. This can explain why the efficacy increase and the settlement reduction are less when simulating the soft soil with F2 foam.

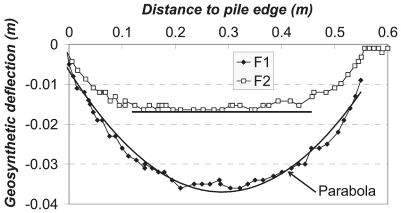

Figure 8. Geosynthetic (S3) deflection for $H = 0.7$ m corresponding to F1 and F2 foams.

5 CONCLUSIONS

A two-dimensional physical small scale model was developed to study the load transfer mechanisms onto the piles occurring in the granular earth platform and in the basal geosynthetic reinforcement. This model uses the Schneebeli analogical soil to simulate the granular platform material. The results are obtained in terms of both loads and displacements. The results given by this model test are precise and reproducible, permitting several parametric studies.

This paper focuses on the geosynthetic stiffness influence in combination with the foam compressibility simulating the soft soil. When the foam is compressible enough the more the geosynthetic stiffness, the more is the load transfer onto the pile and the settlement reduction. For a less compressible foam the geosynthetic deflection is restrained which limits the tension in the membrane and thus the reinforcement effect brought by the geosynthetic.

Nevertheless, these conclusions are limited to the range of the parameters investigated, more particularly concerning the geosynthetic stiffness and foam compressibility values.

ACKNOWLEDGEMENTS

The authors thank Alain Nancey, from Bidim Geosynthetics SA, for furnishing the geosynthetic reinforcement material.

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