

INVESTIGATION OF PHYSICAL MODEL ON SOFT SOIL REINFORCED BY RIGID INCLUSIONS UNDER CYCLIC LOADING

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ABSTRACT: Soft soil reinforced by rigid inclusions is one of the techniques to homogenize and to reduce the settlement of earth structures. Various cases of structures under cyclic loading are inevitably encountered in the practice. Therefore, the understanding of this technique under cyclic and/or dynamic loading is required. This paper is aimed to present a series of experimental studies performed at 1-g laboratory scale to simulate the soft soil reinforced by rigid inclusions subjected to cyclic loading. Tests were performed with two kinds of embankment or Load Transfer Platform (LTP), i.e., sand and gravel. The cycles were applied in terms of surface pressure on the top of embankment. The experimental results highlighted the efficiency of load transfer and the accumulation of the settlement during the cyclic loading. The evolution of average efficiency as a function of number of cycles at low level of surface pressure ($P_m = 5$ and 15 kPa) showed the insignificant variation on both embankments.

Keywords: Rigid inclusions, soft soil reinforcement, efficiency, cyclic loading

1. INTRODUCTION

Constructions of roads, railways and other engineering structures in areas, where loose or soft cohesive deposits are found, usually involve with problems such as excessive settlements, deformations and stability problems. These problems have been one of the major challenge for infrastructure planning and implementation.

An interesting–alternative construction technique on soft soil reinforced by rigid inclusions involving granular platforms is widely implemented across the world due to rapid construction, low cost and small total/differential settlements [1-7]. This technique consists in driving a rigid pile network through the soft soil layer, in order to transmit the loads towards a more competent stratum (in general, the substratum is situated at a depth of a few meters up to 15-20m). The rigid piles can also have pile caps or enlarged heads, in order to increase the surface covered by the piles. This technique is different from those of classical deep foundations, because the piles are not directly connected to the superstructure: a Load Transfer Platform (LTP) or an embankment is built over the improved soil layer, where shearing mechanisms termed as “arching effects” take place. This arching effect partially transmits the load from the surface to the piles, thus permitting to reduce and homogenize the surface settlements. An additional geosynthetic layer can also be placed at the platform base. This layer takes

part to the load transfer due to the membrane effect.

The French project ASIRI (Amélioration des Sols par Inclusions Rigides) has brought responses concerning the behaviour of soft soil reinforced by vertical rigid inclusions. The recommendations for the design and installation were then published [8]. However, these studies were only focused on the case of monotonic loading. In case of cyclic loading, a principal citation work in laboratory scale, carried out by Heitz et al. [9], is relevant to the case of dynamic cyclic loading with high frequencies (1-5 Hz). Special investigations have also been performed to describe the cyclic mechanism of a granular earth-platform with rigid pile reinforcement by centrifuge modeling [1,10], but only few number of cycles have been prescribed. Houda et al. [11-12] also investigated the physical evidence of the effect of vertical cyclic loading ($N < 50$) on soil improvement by rigid piles with a small-scale laboratory experiment. Many such mechanisms, e.g., the use of granular layer, geosynthetic reinforcement, are sophisticated and their description by means of analytical design scheme remains problematic.

This paper describes some of experimental results carried out from a series of experimental observations on soft soil reinforcement by rigid inclusions subjected to cyclic loading using a 3D small-scale physical model. The effects of two kinds of embankment over the soft soil, preloading and boundary conditions are described.

2. PHYSICAL MODELLING

2.1 Test Set-up

In order to study the behavior of soft soil reinforcement by rigid inclusions, a 3D laboratory physical model has been developed. Fig. 1 shows the model test in this study. In fact, a major disadvantage of this reduced model still exists. The similarity of geotechnical problems is very complicated because of the complexity of the material behavior. The results of the reduced models can predict the behavior of the actual structure quantitatively, while being aware of the limits of the application and the type of physical modeling. The model makes it possible to represent certain aspects of the prototype behavior, without being a true reduced model respecting the rules of similarity. In addition, the parametric experimental studies obtained from this model can be used as a database for calibrating and verifying the numerical models [11-12].

According to the experimental observations performed by Houda et al. [11-12] and Da Silva Pinto et al. [13], this model is under normal gravity at 1/10th scale on the lengths. The device consists of a rigid steel tank of 1x1 m². It contains 16 steel pipes with a diameter of 40 mm and a height of 600 mm. In this approach, the modeled inclusions have to be sufficiently rigid and experienced insignificant deformation. Then, the steel pipes were filled with a concrete mix at compressive strength of 23.5 MPa (cube at 28 day). The inclusions were spaced in a square mesh of 200 mm, center to center. In plane surface covered by the inclusions (or pile caps), a recovery ratio (α) can be expressed as;

$$\alpha = \frac{A_p}{A} \quad (1)$$

where A_p is the inclusion section and A is the unit cell surface. Therefore, this spacing provides a recovery ratio equal to 3.14 %. In addition, 4 half-inclusions were arranged along an edge of the work, behind a window made of acrylic which allows the observation of deformation.

The device is instrumented with force sensors at the top of the four-central inclusions and settlement sensors at the base of the granular platform (Fig.1b). The Load Transfer Platform (LTP) has a thickness of 300 mm in this part of the study. The monotonic and cyclic loadings were applied to the surface of the embankment via a cushion under air pressure (P_m), allowing the application of a uniform vertical load over the entire section of the device.

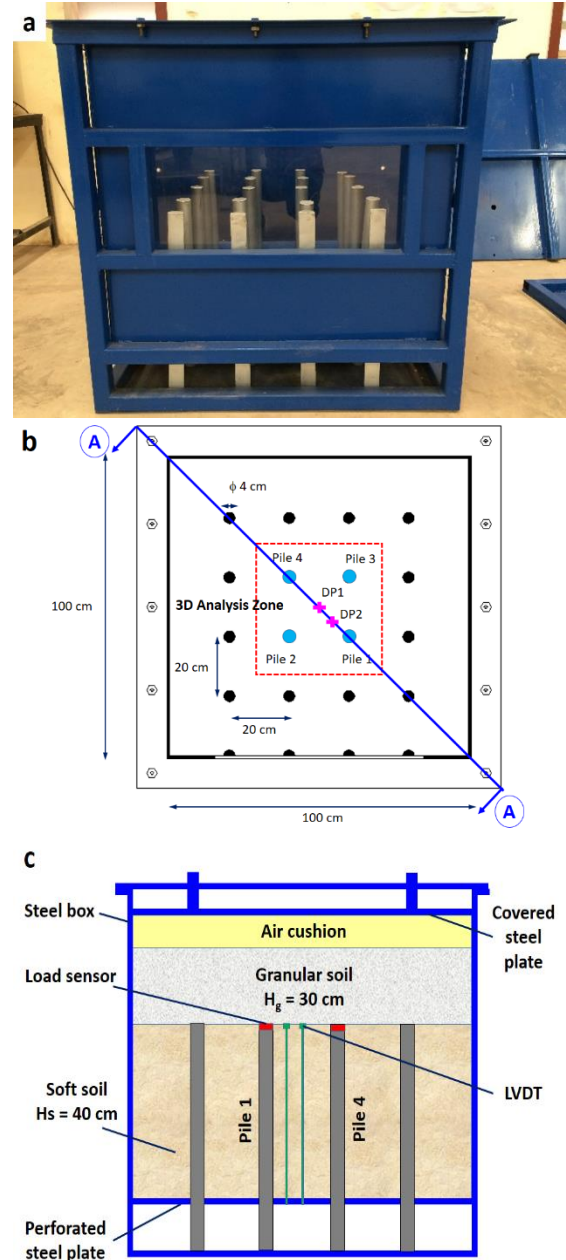


Fig.1 (a) Photograph of the model; (b) schematic plane view of test set-up; (c) cross section of test set-up with instrumentation

The complex analysis of soil-structure interactions developing in this model requires appropriate instrumentation. For this study, the following parameters were measured in the central zone, far from the boundaries:

- Forces transmitted to the top of the four central inclusions are measured by 5 kN force sensors; F_1 , F_2 , F_3 and F_4
- Settlement of soft soil was measured at two points (DP_1 and DP_2) by 50 mm – displacement transducers.

2.2 Materials

The soft soil used in this study was simulated by a mixture of polystyrene balls, sand and water (Fig.2a). This mixture can represent the compressibility characteristics similar to the real soft soil. The analogue soil also provides an advantage of being easy to set-up and of having a homogeneous density [11-14]. In addition, a satisfying repeatability from one experiment to another can be achieved by using the analogue soil. Fig.2b shows the grain size of the materials in this study.

A mixture representing a soft soil was prepared with the ratio of sand: water: polystyrene balls at 40: 4: 1 by weight. It is worth noting that the presence of the water contributed to the homogenization of the sand with polystyrene. The average density of the mixture in this study was 5.5 kN/m³.

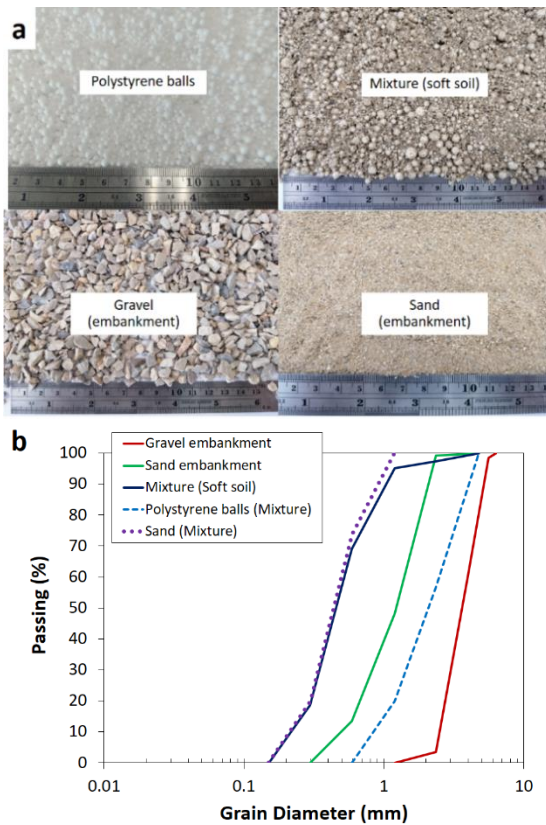


Fig.2 Materials and Grain size distribution of materials used in this study.

An embankment of 0.3 m height as a LTP was constructed over the soft soil layer reinforced by the inclusions. Two kinds of embankment or load transfer platform, i.e., sand and gravel, with grain size D_{50} of 1.2 mm and 3.4 mm, respectively, were used. The sand was prepared by the pluviation and tamping methods providing the average unit weight of 16.67 kN/m³. The friction angle of 43° was

examined from triaxial test. While gravel was prepared by tamping method which gave the average unit weight of 15.4 kN/m³. With this unit weight, the friction angle of 37° could be achieved.

2.3 Test Program

Table 1 summarizes the preliminary test campaign with different loading conditions in this study. The test set-up was first performed by:

- Filling the model with soft soil
- Construction of the embankment layer
- Placing the air cushion on the top of the embankment
- Closing the tank with the covered steel plate
- Consolidation as a result of the weight of embankment for 12 hours.
- Application of loading, P_m .

Prior to filling with soft soil, the friction between the soft soil and the steel tank was minimized by smearing silicone grease and then placing a layer of plastic sheet on the walls of steel tank. In this study, three levels of loading $P_m = 5, 15$ and 25 kPa, for 3 hours each, followed by an unloading to $P_m = 0$ kPa for monotonic test series were performed. In case of cyclic loading, the cycles (N) were applied in terms of surface pressure (maximum and minimum values). Two patterns of ΔP_m (between 5-15 and 15-25 kPa) with a period of 8 min were applied.

Table 1 Program of experimental tests

Test	Type of embankment	P_m (kPa)	Number of cycles (N)
M_s	Sand	5-15-25	-
M_g	Gravel	5-15-25	-
Cy_s1	Sand	5-15	500
Cy_s2	Sand	15-25	500
Cy_g1	Gravel	5-15	500
Cy_g2	Gravel	15-25	500

3. TEST RESULTS

In this study, after finishing the construction of embankment, the consolidation period of 12 hours was performed. At this stage an inclusion only supported the weight of embankment for a unit cell of $A = 0.04$ m²). Then, the application of surface pressure (P_m) was performed.

Fig. 3 shows typical results under monotonic loading of the test M_s. After a consolidation period of 12 hours, three steps of loading ($P_m = 5, 15$ and

25 kPa) were applied. The forces on the four central inclusions and the displacements were measured. The values of F_i (in this study, i from 1-4, Fig.3b) were not different and indicated that the distribution of the load in the system was homogeneous. The settlements measured beneath the embankment showed a prominent value at mid-span between Pile1 and Pile4 (DP_1 , Fig.3c). It was found that the difference between DP_1 and DP_2 for each loading was almost constant. A small increase in settlements (0.3-0.4 mm) was observed when P_m was kept constant for 3 hours.

Fig. 3d shows the average efficiency of the four central inclusions as a function of time. The efficiency of the system (E) can be defined as the ratio of the load acting on the inclusion (F) to the total load applied on a unit cell (weight of embankment (W) and surface pressure, P_m):

$$E = \frac{F}{W + P_m} \quad (2)$$

It can be seen that, at the beginning of applying the surface pressure ($P_m = 0$ to 5 kPa), while the surface pressure was applied the force on the inclusion did not increased coincidently. The increase rate of force on the inclusion was slower than that of the surface pressure. After that the mobilization of the force took place.

The increase in surface pressure at $P_m = 5$ kPa provided an increase in the average efficiency of 68%. When $P_m = 15$ kPa was applied, the average efficiency could reach 80%. However, the average efficiency decreased to 75% when applying $P_m = 25$ kPa.

The cyclic tests of two kinds of embankment were performed with the same geometrical configuration. Two patterns of load sequence (monotonic and cyclic) were performed. The effect of stress level, at which the cycles of $N = 500$ were performed, was highlighted. Before applying the cyclic loading, each test experienced the static loading for three hours.

Fig.4 typically shows the forces on the inclusions of the test Cy_s1 consisting of applying two stages of static loading $P_m = 5$ kPa and then $P_m = 15$ kPa followed by an application of cyclic loading by means of $\Delta P_m = 10$ kPa ($P_m = 5$ and 15 kPa). During cyclic loading, the variation of the forces measured on each inclusion could be found. However, the force repartition on the four inclusions could be satisfactory. The maximum difference of 12 % between the average value (F_{av}) and the value of F_i on each inclusion was found (the maximum difference of 10% [11-12] was reported).

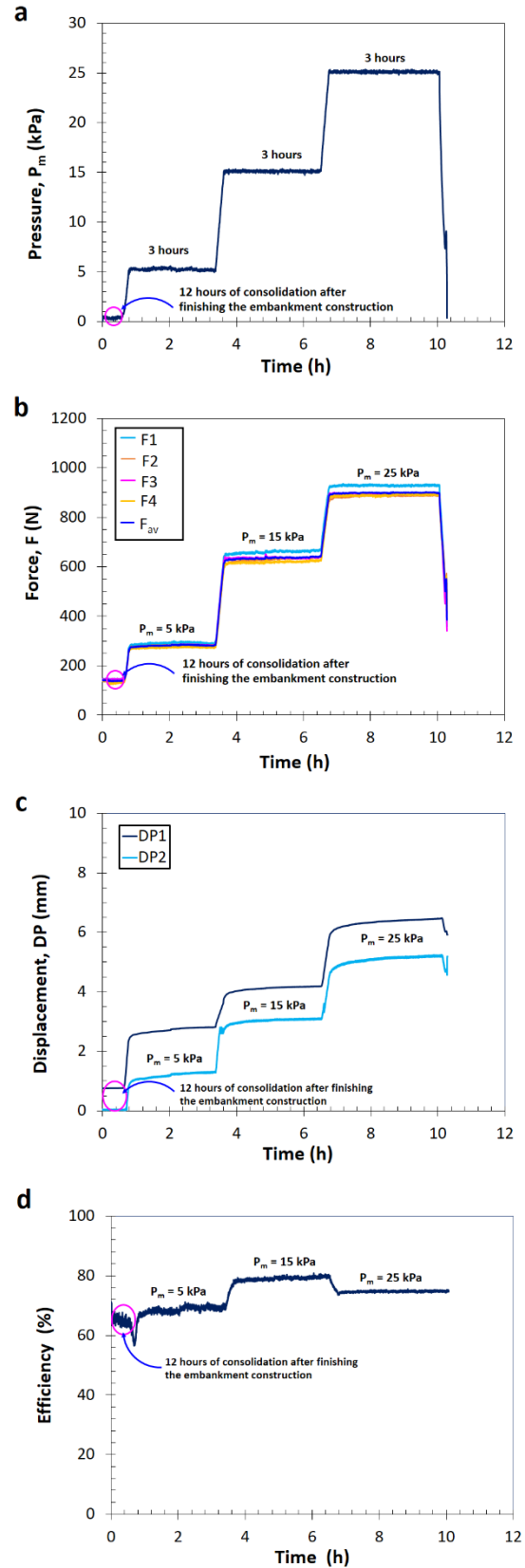


Fig.3 Monotonic test, M_s, on sand embankment.

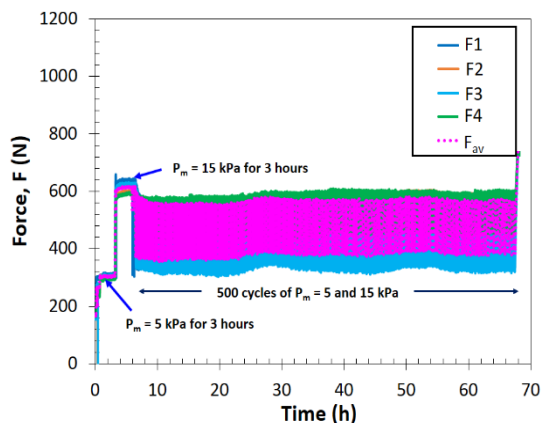


Fig.4 Evolution of force on the head of four central inclusion with sand embankment (test Cy_s1)

Fig.5 shows the evolution of average efficiency of four central inclusions as a function of number of cycles (N) for two kinds of embankment. These average values were computed by taking into account the center of cycle. It can be seen that the initial values of efficiency of gravel embankment were lower than those of sand embankment due to the friction angel. Starting with the low level of cyclic loading ($P_m = 5$ and 15 kPa), the efficiency of 79% and 70% could respectively be found for sand (Cy_s1) and gravel (Cy_g1) embankments.

During cyclic loading, there was no significant variation in efficiency for both kinds of embankment. Okkay et al. [10] performed a centrifuge model and reported that the loading-unloading cycles did not influence the behavior of pile group on soft soil. Their results also showed the similar efficiency values for monotonic and cyclic loading tests. When starting with the higher level of cyclic loading ($P_m = 15$ and 25 kPa), the average efficiency decreased slightly as a function of number of cycles. In comparison between two embankments, a higher reduction rate in efficiency was observed on gravel embankment (Fig.5b). The efficiency started at 64% after the consolidation period of 12 hours and then decreased until reaching 58% .

When considering the settlement of the system, the settlement at mid-span (DP_I) was then considered. Fig.6 shows the satisfactory repeatability of the monotonic loadings before applying the cyclic loadings on both kinds of embankment. The application of cyclic loading induced an accumulation of settlement. The accumulation settlement due to cyclic loading on gravel embankment (Fig.6b) was obviously found to be greater than that on sand embankment as a result of low efficiency.

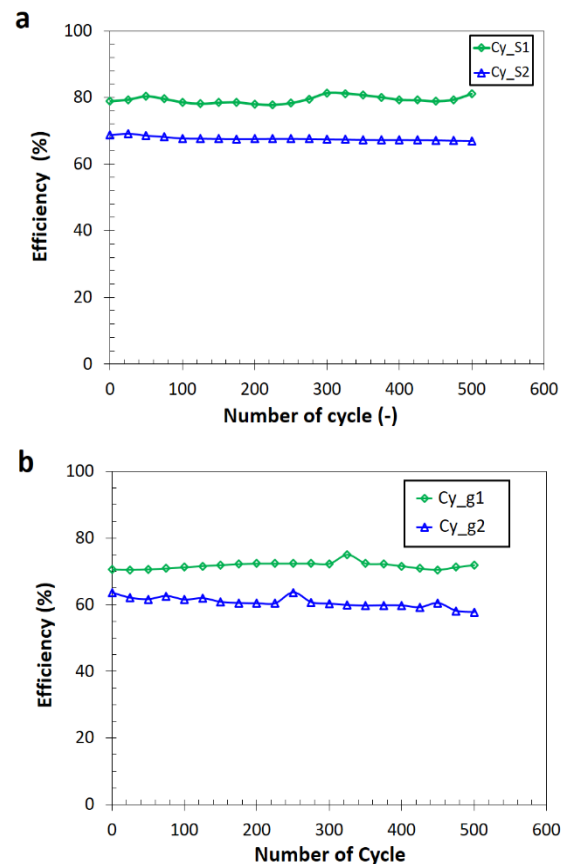


Fig.5 evolution of the average efficiency at the head of four central inclusions as a function of number of cycles: (a) sand embankment; (b) gravel embankment.

4. CONCLUSION

Based on experimental investigation on soft soil reinforced by rigid inclusions in laboratory scale, the preliminary results for two kinds of embankment were presented and analyzed. With $1-g$ scale model, a drawback still exists because of the scaling law. However, a parametric study obtained from this model allows access to a better understanding of the mechanical behavior of soft soil reinforced by rigid inclusions. This includes the constitution of a large experimental studies to develop and validate numerical approaches.

Monotonic test results serving as the reference tests consisted of applying three levels of surface pressure ($P_m = 5, 15$ and 25 kPa) and each loading level was kept constant for 3 hours. On both kinds of embankment, the efficiency increased as a function of applied surface pressure for a certain values. When $P_m = 25$ kPa was applied, a reduction in efficiency could be observed. The average efficiency of gravel embankment was less than that of sand embankment as a result of unit weight and friction angle.

Under cyclic loading, at low level of surface pressure ($P_m = 5$ and 15 kPa) the evolution of average efficiency as a function of number of cycles had no significant variation on both embankments. This is in accordance with the results carried out by centrifuge tests [10]. Comparing the basal settlement between two kinds of embankment, low density and low friction angle could induce more settlement accumulation.

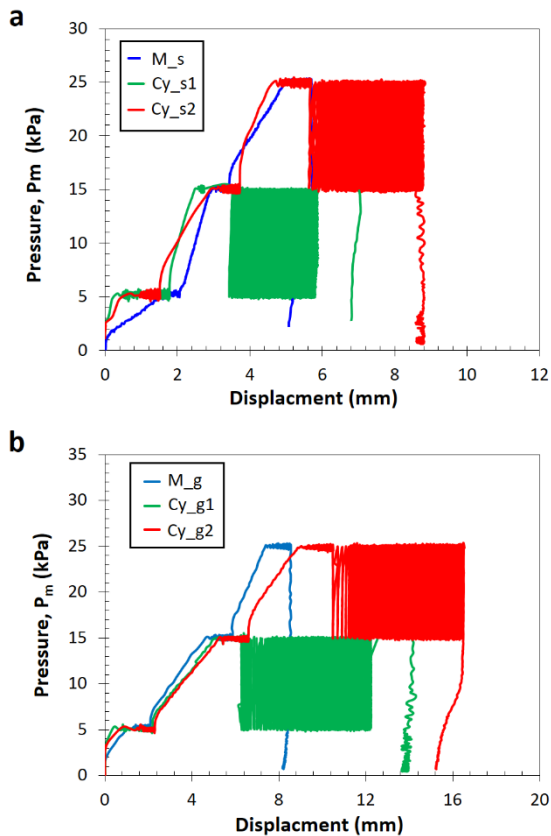


Fig.6 Settlement (DP_i) evolution with the applied surface pressure: (a) sand embankment; (b) gravel embankment.

5. ACKNOWLEDGMENTS

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