Centrifuge investigation of the load transfer mechanism above rigid inclusions

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Abstract: Reinforcing compressible soils by rigid inclusions is a method to reduce and homogenize settlements under many types of structures. A granular mattress, located between the structure and the group of piles, transfers part of the loads on the surface to the head of the piles anchored in rigid substrate. An experimental device, a mobile tray, has been especially designed in order to allow a better understanding of this reinforcement technique. This mobile tray simulates the settlement of the soft ground (not present here) located between the piles. With this device, a parametric study of the load-transfer mechanism in the mattress is conducted in centrifuge at 20g. Loads at the top of the piles and settlements at different places above the granular mattress are measured during the the mobile tray going down. A possible way to improve this reinforcement technique is to insert a geosynthetic layer between the head of the piles and the granular mattress. In centrifuge, due to scaling laws, the choice of the geosynthetic has to be taken very carefully. Tests with and without geosynthetic are performed for different thicknesses of granular mattress. Then the improvement of the load-transfer mechanism by the addition of a geosynthetic is studied in centrifuge.

Keywords: centrifuge, soil reinforcement, rigid inclusions, load transfer, geosynthetic.

1 INTRODUCTION

The soil reinforcement by vertical rigid piles (Figure 1) is becoming a widespread technique for both embankments and floor slabs (Simon and Schlosser, 2006). First, a rigid inclusions network is inserted in the soft soil. Then a granular mattress is installed at the top of the reinforced soil. “Arching” (Terzaghi, 1943) develops inside this platform in order to transfer the overloading directly to the caps of the inclusions. This mechanism is largely impacted by geometrical parameters (as the diameter *a* of an inclusion, the distance *s* between two inclusions, the thickness *H* of the granular mattress) and also by the granular mattress itself (geometry and size of the particles). Some experimental investigations of this reinforcement technique were already conducted in centrifuge on 2D models (Barchard, 2002; van Eekelen et al., 2003) and more recently on 3D models (Ellis and Aslam, 2009a, 2009b; Baudouin, 2010; Baudouin et al., 2010; Okyay, 2010).

A possible way to improve this reinforcement technique is to insert a geosynthetic layer between the caps inclusions and the granular mattress. By stretching, the geosynthetic transfers loads to the inclusions: it is called “membrane effect”. These two load transfer mechanisms are schematically represented in Figure 2.

This paper is focused on the role played by a geosynthetic layer installed within the load transfer platform, in terms of both efficiency of the load transfer and reduction of settlements. First is presented the centrifuge model based on the mobile tray device (Rault et al., 2010), then the experimental parametric campaign, that includes both tests with and without geosynthetic layer, is detailed. Finally, an analysis of the results is presented, showing the influence of the thickness of the granular mattress and of the geosynthetic layer on the load transfer mechanism.

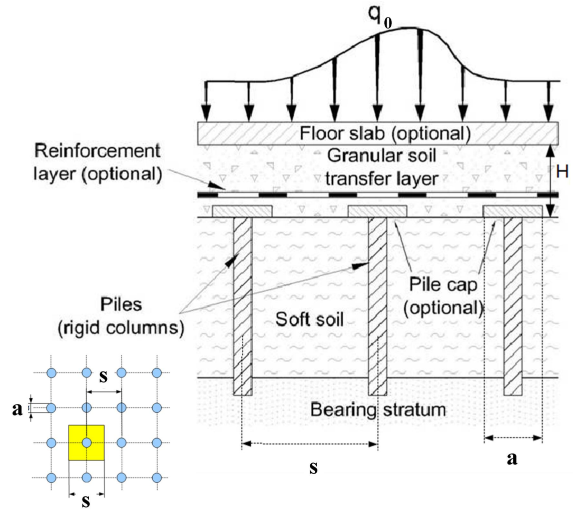

Figure 1. Components of the pile supported earth platform system (Simon and Schlosser, 2006) and definition of a unit cell in a pile mesh.

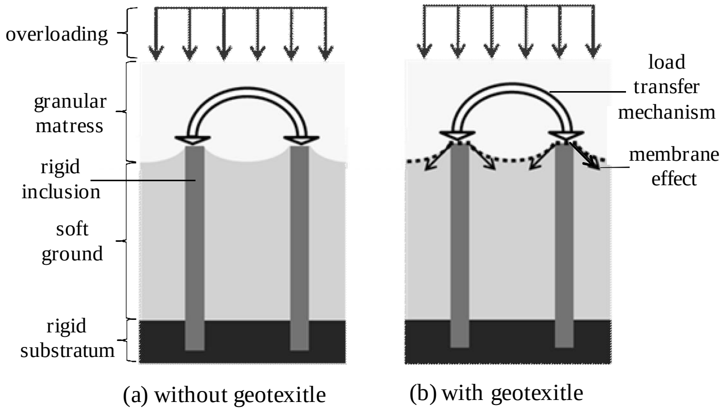

Figure 2. Schematic representations of the load transfer mechanisms in a granular - (a) without geotextile - (b) with a geotextile layer.

2 PHYSICAL MODELLING

2.1 Rigid inclusions technique

In centrifuge, the length is reduced by the acceleration (Table 1). The reinforcement technique by rigid inclusions is suitable to centrifuge modeling because the load transfer mechanisms mobilized by this technique depend mainly on geometrical parameters. A new device has been especially developed at the IFSTTAR to study this reinforcement technique and more precisely the behavior inside the granular mattress. The principle is to simulate the settlement of the soft soil by the going down of a mobile tray at a given controlled rate. This mobile tray is perforated to allow the crossing of the inclusions. To study the loads transfer mechanisms, load sensors have been located inside the pile caps and settlements have been measured at different locations above the granular mattress.

Table 1. Scale factors in centrifuge.

Quantity	Unites	Prototype	N*g* model
Classical dimensions :			
Length	m	1	1/N
Load	kN	1	$1/N^2$
Weight	kg	1	$1/N^3$
Time (diffusion)	s	1	$1/N^2$
Stress	kPa	1	1
Strain	%	1	1
Mobile tray design :			
Granular mattress density (γ)	kN/m^3	1	1
Granular mattress thickness (H) & Pile diameter (a)	m	1	1/N
Mesh density (α)	%	1	1
Geosynthetic parameters :			
Tensile load (T) & Secant stiffness (J)	kN/m	1	1/N
Strain (δ)	%	1	1

Table 2. Properties of the Hostun sand used in the model granular mattress.

d_{10} (mm)	d_{50} (mm)	d_{90} (mm)	Cu	Cc	ρ_{dmin} (g/cm^3)	ρ_{dmax} (g/cm^3)	e_{min}	e_{max}	ρ_s
0.125	0.320	0.880	3.52	0.88	1.40	1.73	0.532	0.893	2.65

2.2 Load transfer platform

2.2.1 Granular mattress

The granular mattress above the mobile tray simulates a load transfer platform where arching can occur. In order to obtain a better load transfer on the pile caps and to facilitate the development of shear strength in the mattress, unbound granular materials are commonly used. To respect scale issues and boundary conditions, a model granular mattress composed of a mix of five fractions of Hostun sand (HN38, HN34, HN31, HN04/08 and HN06/1) has been chosen (Baudouin et al., 2008). The Hostun sand is an angular sand currently used in laboratories and which physical properties are well established (Flavigny et al., 1990). The grading curve obtained is presented in Figure 3 and its properties are given in Table 2. It must be noted that the maximal diameter of the model sand is equal to 1 mm to respect similitude condition with the pile diameter.

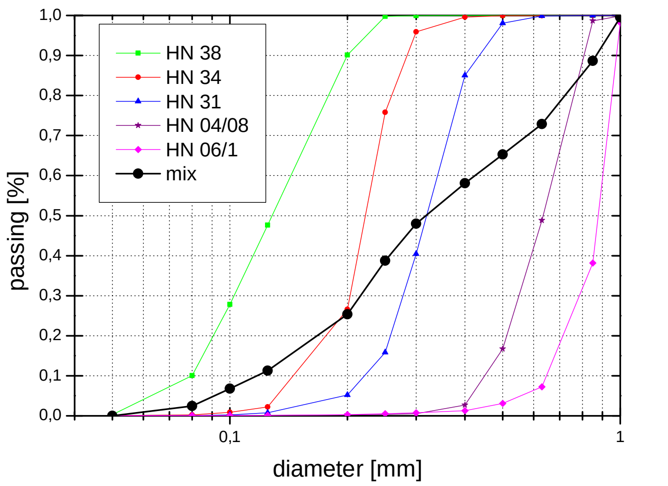

Figure 3. Grading curve of the model granular mattress made from five fractions of Hostun sand (HN38, HN34, HN31, HN04/08 and HN06/1).

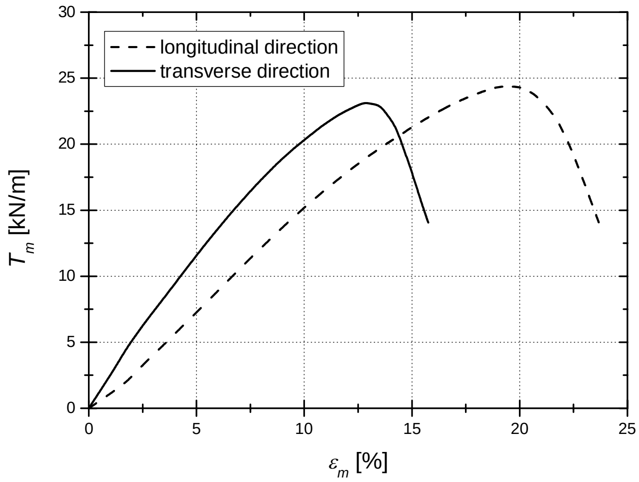

Figure 4. Tensile strength *versus* strain behaviour in longitudinal and transverse directions of the model synthetic.

2.2.2 Geosynthetic

Generally the geosynthetic layer is a geogrid (because of the use of unbound granular materials in the load transfer platform). However, the scale conditions applied to the granular mattress force the use of a sand which does not allow the use of a geogrid. The second main issue is the scale effect on the tensile strength of the geosynthetic. Many authors (Taniguchi et al., 1988; Springman et al., 1992; Viswanadham and König, 2004) have shown that the similitude condition on the tensile strength T and the secant stiffness J is N times smaller for a $N.g$ centrifuge acceleration (Table 1).

For these reasons, a woven fabric geosynthetic made of polypropylene and spilt fibre yarns it has been chosen to used. Tensile strength tests along longitudinal and transversal directions have been conducted on 100x200mm samples. Results are presented in Figure 4.

3 EXPERIMENTAL CAMPAIGN

3.1 Mobile tray device

In the initial configuration, the mobile tray (900mm internal diameter) presents the possibility to use up to 61 stiff piles on its whole surface (Figure 5). Three combinations of mesh densities are possible: α = 4.91%, 2.47% and 1.23%, where α is the ratio between the sum of cap piles areas and the total surface of the reinforced platform. These mesh densities correspond to a distance between two inclusions equal to s = 100, 141 and 200mm, respectively. A rough interface made of glued sand particles has been located above the tray (Figure 5). This interface simulates the actual contact soft soil-geosynthetic. The overloading applied on the load transfer platform is simulated by the filling of a water tank (Figure 6).

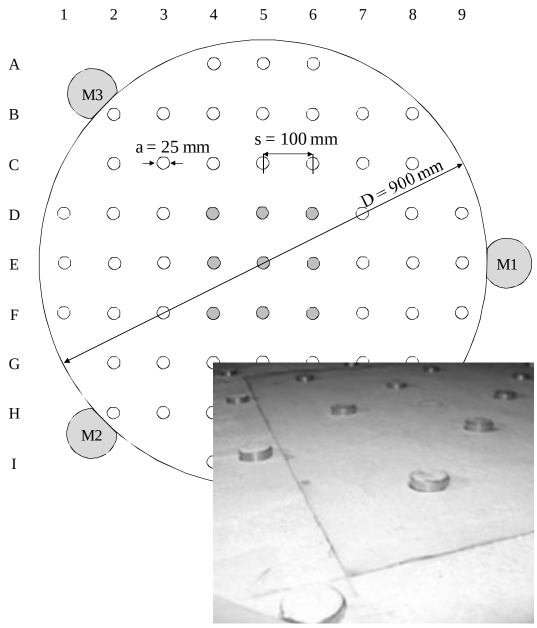

Figure 5. Schematic representation of the mobile tray and a close picture showing glued rough sandy interface.

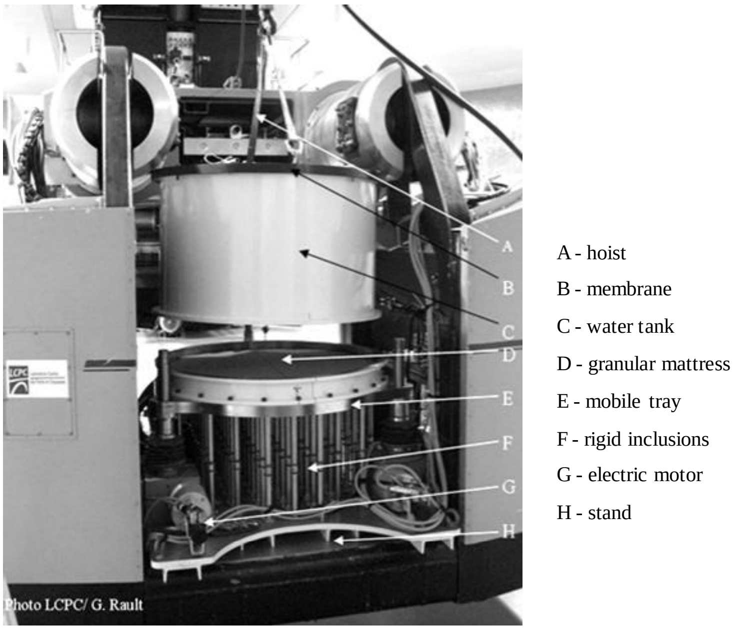

Figure 6. General view of the mobile tray device inside the basket of the centrifuge.

During the tests, all the transducers measurements have been recorded versus time:

- 9 force measurements would allow to evaluate the dispersion of the results (less than 10%), with the mean value of the force used in the calculation of the efficiency,
- 2 relatives settlements transducers; this information is duplicated by transducers located in the centre of the mesh and on a nearest stiff pile head,
- 1 relative settlement transducer located at the centre of a cell (diagonal of the mesh),
- 1 or 2 relatives settlement transducers located at the edge of a cell (according to the mesh),
- 2 absolute displacements for the mobile tray by laser transducers located at the centre and at peripheral position,
- a pressure transducer for the overloading located inside the tank,
- the mobile tray behaviour with parameters of the electrical control command, as torque and speed rotation of each electrical jack which complete the direct measurement of the laser.

3.2 Experimental program

The experimental campaign has been limited to the highest mesh density α=4.91%. Three granular mattress thicknesses have been tested: H=90, 50 and 35mm. For each thickness, two tests have performed: one reference test without geotextile (named “L0”) and another test with a geotextile without initial pretension (named “L1T0”). This series of six tests has been conducted in centrifuge at 20g. The adopted nomenclature can be easily understood. For example, the test named “H35S100L1T0” is a test performed with a granular mattress thickness H=35mm, a distance between two pile s=100mm (i.e. a mesh density α=4.91%), one geotextile layer “L1” without initial pretension “T0”.

3.3 Test chronology

3.3.1 Sample preparation

All the test preparations have been done without taking the mobile tray out of the centrifuge basket. First, the geotextile layer (when needed) is simply laid on the mobile tray. Then the granular mattress is installed as homogeneously as possible in relatively dense conditions up to the final height. Lack of working space did not allow any pluviation. The amount of sand used in the experiments is weighted before and after the tests in order to control their densities. The mean density for this campaign is equal to 16.0kN/m^3 with a standard deviation equal to 0.3. The empty water tank is screwed on the mobile tray and its rubber membrane lies on the granular mattress. Finally, inside the empty tank, the sample is instrumented with LVDTs to measure settlements at different locations on the membrane and a water pressure transducer is added to control the water level within the tank.

3.3.2 Centrifuge acceleration & overloading

The sample is pre-stressed by increasing the centrifuge acceleration step by step until 20g, and then decreasing back to zero. This incremental procedure is applied three times in order to achieve consistent pre-stressing of the granular load transfer platform. In Figure 7, during this pre-stressing period which corresponds to “phase I”, the mobile tray displacement under its center is controlled. It must be noted that, due to centrifuge acceleration, the center of the mobile tray went down around a half millimeter whereas its edges don’t move.

Then, in flight, the overloading is regularly applied on the load transfer platform by filling the reservoir with water. This overloading period corresponds to “phase II” in Figure 7. For this experimental campaign, a water pressure of 80kPa is reached in order to simulate a 5m height embankment in prototype scale. During this phase, the mobile tray continues to bend because of the overloading: the center goes down around 0.5mm. Bending is an experiment limitation very difficult to be avoided in centrifuge modeling.

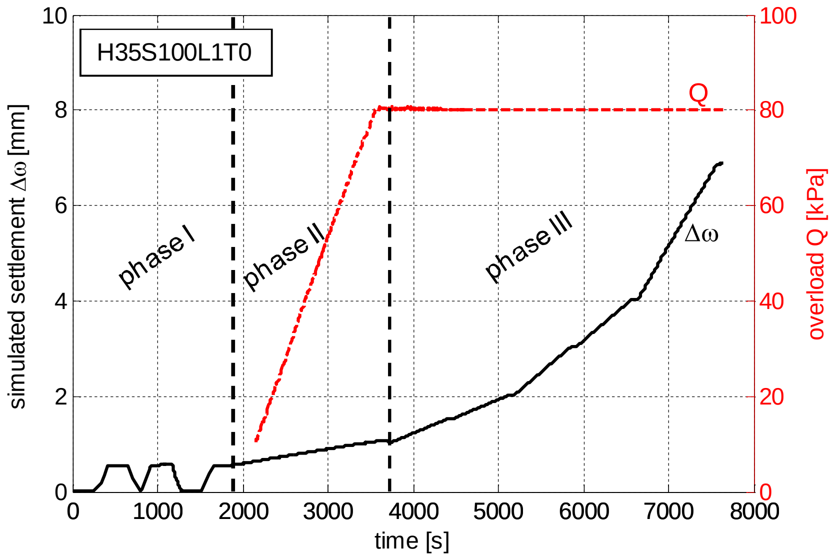

Figure 7. Mobile tray displacement $\Delta\omega$ under its center and overload Q applied to the granular mattress during the three phases of the test H35S100L1T0.

3.3.3 Settlement simulation

Soft soil settlement is simulated by the mobile tray down which corresponds to “phase III” in Figure 7. During the initial simulated settlement a low speed down is chosen (0.05mm/min) in order to understand the load transfer mechanisms. This speed is progressively increased (0.1, 0.2, and 1mm/min) to limit the overall duration of the tests. Between each step, a relaxation period is done in order to observe the time dependent behavior of the sample. This peculiar behavior is not treated in this paper. The mobile tray down is stopped when a 6 mm settlement in model scale is reached. It corresponds to around 25% of the diameter of a pile *a*=25mm. ASIRi project requirements (Simon, 2012) ask a maximum settlement of a soft soil under 10% of the pile diameter *a*. This range of deformation is widely covered.

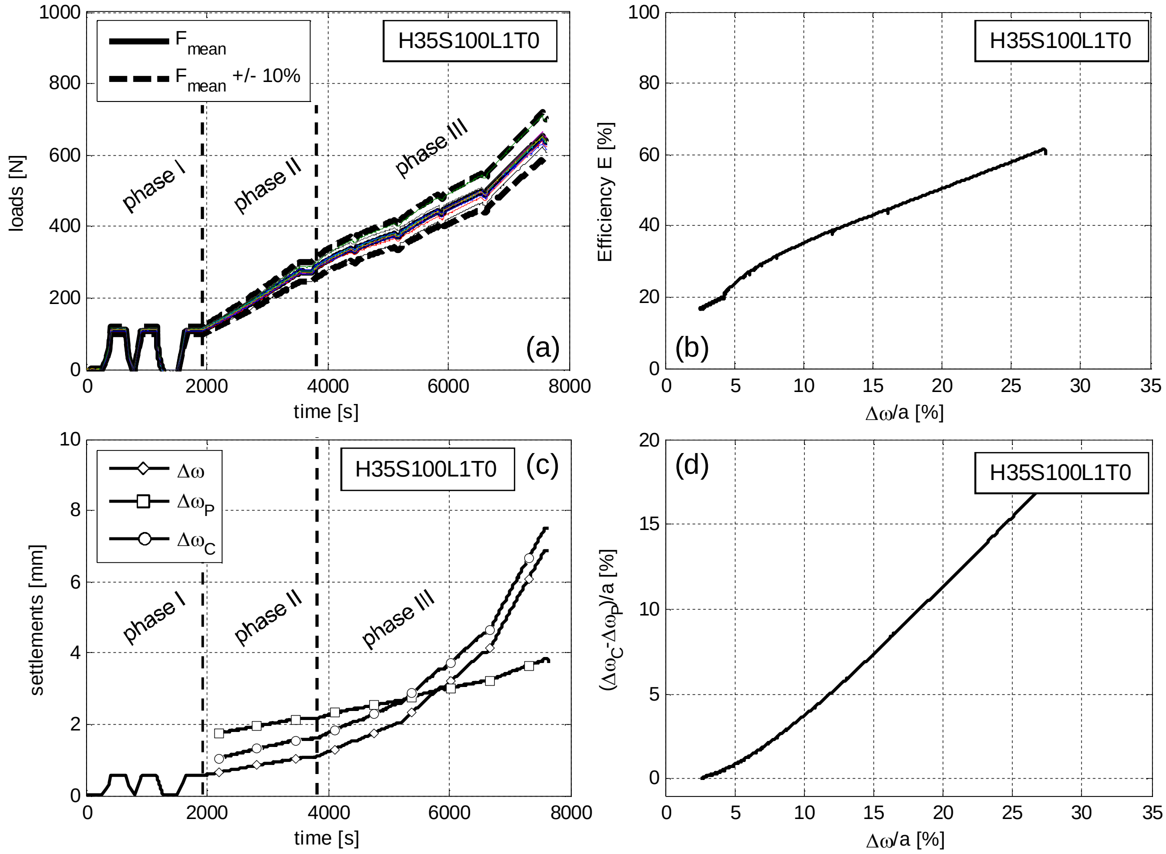

Figure 8. Evolutions of (a) loads *F* in the nine instrumented piles with the time - (b) the efficiency of the load transfer mechanism as a function of the ratio $\Delta\omega/a$ - (c) the settlements of the soft soil simulated by the tray $\Delta\omega$, above the central pile $\Delta\omega_P$ and the centre of an unit cell $\Delta\omega_C$ with the times - (d) the dimensionless differential settlement as a function of the ratio $\Delta\omega/a$ (test H35S100L1T0).

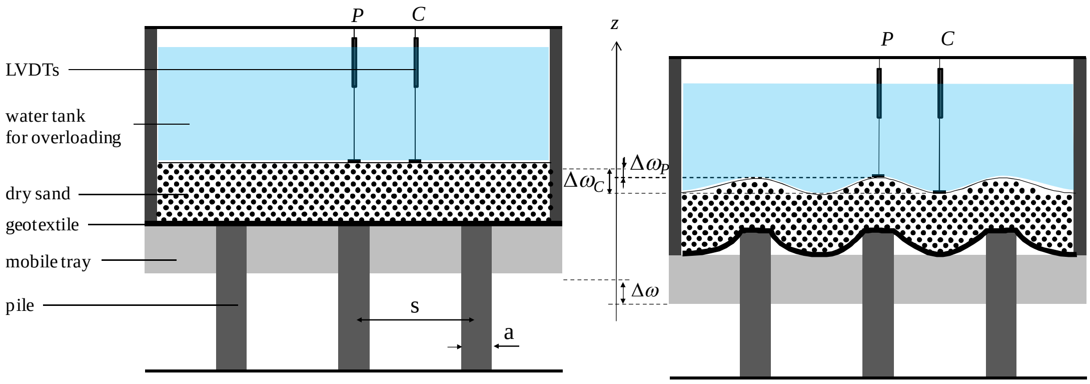

Figure 9. Schematic view of settlements measurements: above the central pile (point *P*, $\Delta\omega_P$) and at the middle of an unit cell (point *C*, $\Delta\omega_C$) - before (left) and during (right) the mobile tray down $\Delta\omega$.

3.4 Typical test results

Data from test H35S100L1T0 are presented and analyzed in this paragraph. This test has been performed on a 35mm height granular mattress with one geosynthetic. The test has been performed in three sequences (Figure 7): phase I) three centrifuge acceleration cycles (N=20g); phase II) overloading of the granular mattress (Q=80kPa) and; phase III) simulation of soft ground settlement by moving downwards the mobile tray ($\Delta\omega$).

Figure 8(a) presents the loads F on the nine instrumented piles *versus* time. During the cycles of centrifuge acceleration (phase I), loads on the piles increase due to a combination of two factors: the first, direct, is related to the weight of both the granular mattress and the load sensor itself (which is removed during the data analysis); the second, indirect, is due to the bending of the mobile tray caused by centrifuge acceleration. Then, the simulation of the soft soil settlement $\Delta\omega$ starts unintentionally. The load transfer mechanism begins with a possible load increase. From this stage, *F* continues to increase regularly during the overloading (phase II) also because of the combination of the overloading and the bending of the tray. Then, during phase III, the mobile tray goes down at different chosen speeds (Figure 7). The increase of *F* is now only due to the load transfer mechanisms.

Settlements at different locations above the granular mattress are presented in Figure 8(c): above the central pile $\Delta\omega_P$ and above the center of an unit cell $\Delta\omega_C$. These two LVDTs settlement measurements are schematically represented in Figure 9. During the overloading (phase II), $\Delta\omega_P$ and $\Delta\omega_C$ follow the mobile tray displacement $\Delta\omega$. Then, the settlement above the pile $\Delta\omega_P$ becomes less and less important while the settlement above the middle of a unit cell $\Delta\omega_C$ continues to follow approximately the tray $\Delta\omega$. This difference may be linked to differences in stress distributions in different zones of the mattress that may induce “arching”, particles rearrangements, strain localization and failure.

In order to study the improvement made by this reinforcement technique, two key parameters must be analyzed: the efficiency and the differential settlement. The efficiency *E* (Hewlett and Randolph, 1988) is defined as the ratio of the load on a pile *F* to the total load applied on a unit cell (the weight of the granular mattress *W* plus the overload *Q*). It represents the impact of the load transfer mechanism when the mobile tray is going down. The second key parameter is the differential settlement which has to be as low as possible so that the integrity of a structure is maintained. Recommendations of ASIRi project (Simon, 2012) requires a differential settlement lower than 20mm in prototype scale which corresponds to 1mm in centrifuge test at 20g. This limit represents 4% of the pile diameter (*a*=25mm) in this study. The efficiency *E* and the differential settlements $\Delta\omega_P$-$\Delta\omega_C$ are represented in Figure 8(b)&(d) versus $\Delta\omega$/a.

For this experiment, the soft ground settlement is simulated by the mobile tray going down movement, independently from *E*. However, load transfer towards the inclusion piles induces an unloading of the soft soil which leads to a reduction of its settlement. The non-linear “coupling” between the efficiency and the settlement is not reproduced by the mobile tray test procedure. This peculiar point has to be underlined in order to understand the analysis of the tests results in the next section.

4 ANALYSIS

4.1 Reference tests

First, the analysis is focused on the six reference tests (without geosynthetic). The evolutions of the efficiency *E* and of the dimensionless differential settlement $(\Delta\omega_C-\Delta\omega_P)/a$ at the surface of the granular mattress versus $\Delta\omega/a$ are presented on the left side of Figure 10. Following the thickness *H* of the granular mattress, three distinct behaviours may be observed : 1) for the more slender granular mattress, *H*=35mm, *E* increases, goes through a peak and then decreases; 2) for *H*=50mm, *E* increases all along the mobile tray before reaching an asymptotic value. The efficiency is twice more important than for the more slender mattress; 3) for *H*=90mm, *E* only increases. The load transfer mechanism is more pronounced for thicker granular mattress. This is easily understandable because the developments of “arching” effects are closely linked to geometrical parameters as the thickness of the mattress.

For all the cases, the differential settlements increase with the mobile tray “settlement”. But there is a large difference of amplitude between the three thicknesses of granular mattress. For *H*=90mm, there is nearly no differential settlement. Whereas, for *H*=35mm, the differential settlement increases quickly over 4% of the pile diameter *a* which is the limitation required by the ASIRi project (Simon, 2012). It is easily understandable that sand particles can rearrange in a more freely way inside a thicker mattress.

4.2 Tests with geosynthetic layer

The same process is followed for tests with a geosynthetic layer (Figure 10, right side). The behavior and the amplitude of the efficiency curves reveal some differences. Even for small granular mattress thickness (H=35mm), E always increase during the mobile tray downward movement. The amplitudes between the different thicknesses are closer. This difference remains under 20%. In addition to the load transfer mechanism by arching, the geotextile sheet induces a membrane effect by stretching. More the mobile tray goes down, more the deformation of the geotextile layer becomes large and more the tension of the geotextile induces additional loads on the pile. This membrane effect never stops (if we exclude the failure of the geotextile itself). These two mechanisms were schematically represented in Figure 2.

The differential settlement curves have similar trends than the ones of the reference tests. The amplitude of this phenomenon is largely impacted by the thickness of the granular mattress, not by the addition of a geosynthetic layer.

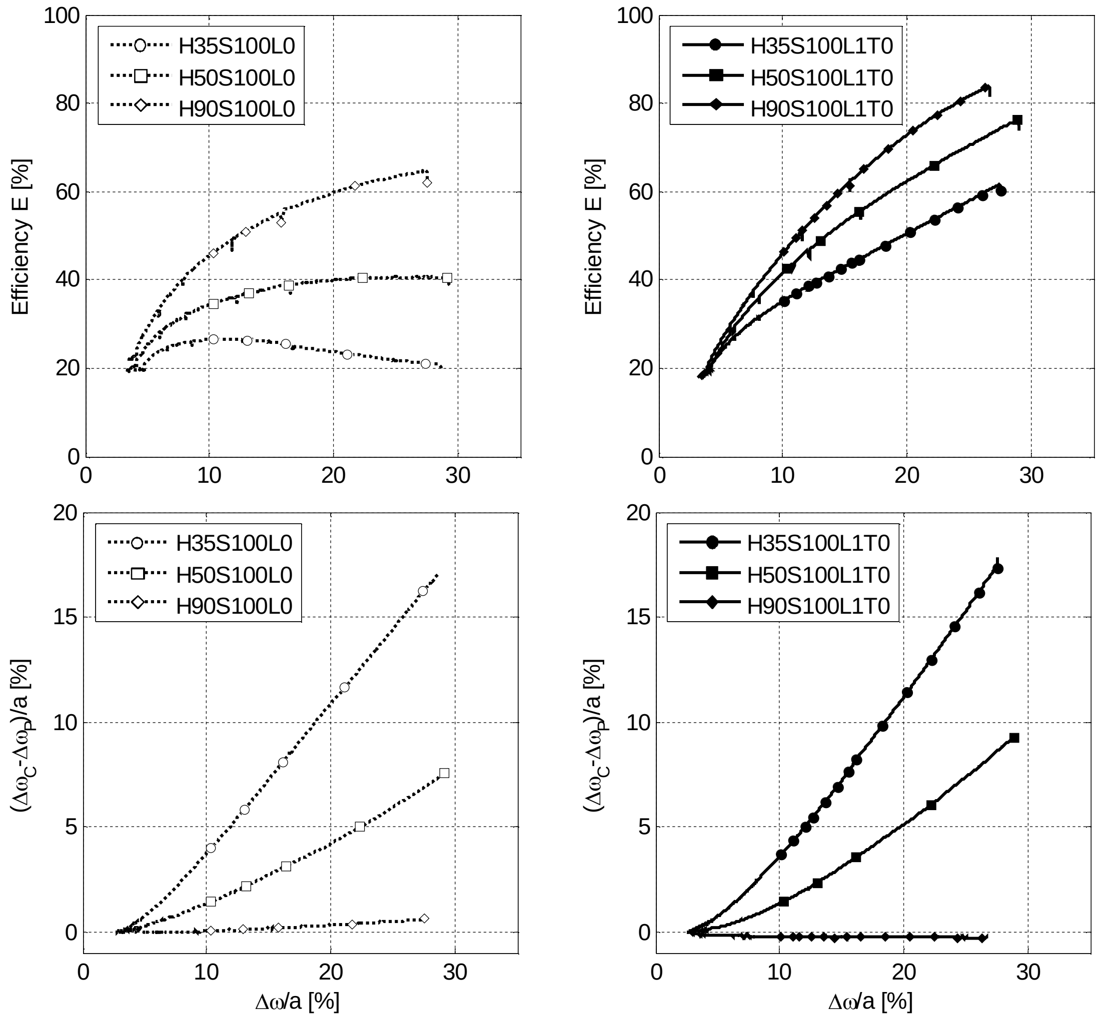

Figure 10. Evolutions of the efficiency E and of the dimensionless differential settlement $(\Delta\omega_C\text{-}\Delta\omega_P)/a$ versus $\Delta\omega/a$ for the three reference tests “L0” (left) and the three tests with a geosynthetic layer “L1T0” (right) for H = 35, 50 and 90 mm.

4.3 Improvements

Reference tests “L0” and tests with geosynthetic “L1T0” are compared in Figure 11. The efficiency E and the differential settlement ratio $(\Delta\omega_C\text{-}\Delta\omega_P)/a$ are represented versus $\Delta\omega/a$ (the mobile tray downward movement which simulates the soft ground settlement). It appears clearly that adding a geotextile layer improves significantly the efficiency. The difference with and without geosynthetic becomes more and more important with the mobile tray moving down. This improvement comes from the membrane effect. During the analysis of the reference tests, it has been seen that the efficiency seems to reach a maximum value if enough soft ground settlement is simulated. It shows the limitation of the load transfer mechanism by arching effects which does not exist with a geotextile layer. With geotextile reinforcement, the membrane effect does not stop increasing during the mobile tray downward movement.

The improvement of the differential settlement is too small to be analysed. But it must be compared to the improvement of the efficiency. This experiment does not simulate the real case in which soft soil settlement stops when it is enough unloaded by load transfer mechanisms. Due to the monitoring of the mobile tray by displacement, the simulated settlement of the soft ground never stops even if the efficiency improvement would permit the end the phenomenon in a real case. The geotextile layer does not reduce directly the differential settlement. But, at a same level of efficiency, the differential settlement is largely better. Thus, the addition of a geosynthetic layer results in an "indirect" reduction of the differential settlement.

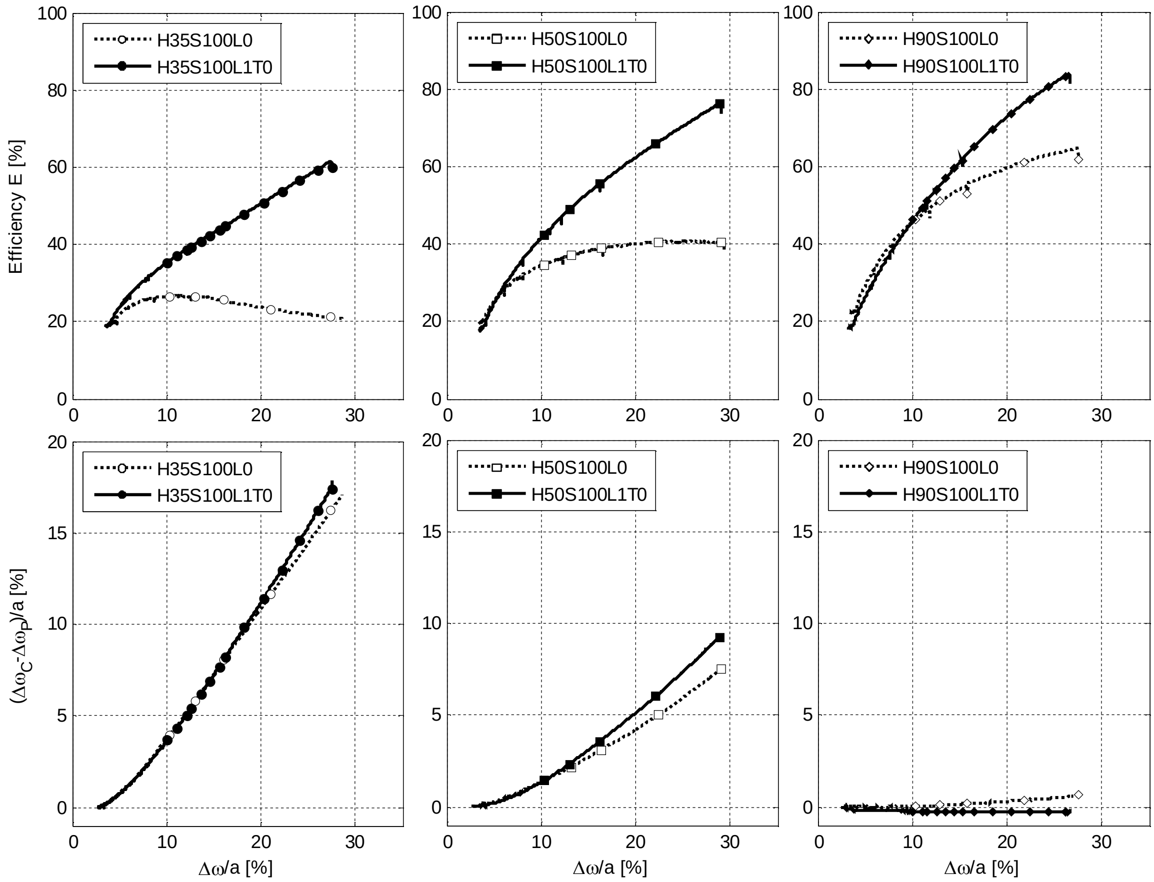

Figure 11. Comparison with and without geosynthetic reinforcement of the efficiency *E* and of the dimensionless differential settlement $(\Delta\omega_C - \Delta\omega_P)/a$ for the three granular mattress thickness: H = 35 mm (left) - H = 50 mm (middle) and H = 90 mm (right).

5 CONCLUSIONS

This paper studies the improvement achieved by the use of a geosynthetic layer on the load transfer mechanism in a granular mattress above a rigid inclusions mesh. A new experimental apparatus composed of a mobile tray has been especially designed to test in centrifuge at 20*g* this soil reinforcement technique. A granular mattress made of a mix of Hostun sand has been manually installed on the mobile tray. Then, this platform has been loaded to simulate an embankment. The idea consists of moving down the mobile tray to simulate the settlement of the soft soil located between the inclusions. The rigid inclusions mesh which perforates the granular mattress is instrumented to evaluate the load transfer on the pile caps. Settlements at the surface of the granular mattress are also studied because differential settlement is a key parameter in the design of this type of embankment. Three thicknesses of granular mattress (H=35, 50 and 90mm) have been tested on a mesh of rigid inclusions with a coverage area α=4.91%.

Without geosynthetic reinforcement, the load transfer mechanism gets more efficient as the thickness of the granular mattress increases. In this case, load transfer is mainly due to the developments of "arching" effects. Additionally, differential settlements decrease with increasing the thickness of the granular mattress. Efficiency in load transfer increases with the addition of a geosynthetic layer. This phenomenon becomes more obvious for smaller thickness of mattress. This improvement is due to the stretching of the geosynthetic sheet which induces a membrane effect. As the mobile tray goes down, the deformation in the geosynthetic becomes larger and more the stretching in it induces strong additional loads on the pile caps. No improvement of the differential settlement has been observed by adding a geosynthetic layer. However the monitoring of the mobile tray is done by displacement. So the simulated settlement of the soft ground and the differential settlement in surface of the granular mattress never stop. This is not the case on site where an equilibrium state is reached with the improvement of the efficiency. The geosynthetic does not reduce directly the differential settlement. But, at a same level of efficiency, the differential settlement is largely better: we can talk about an "indirect" improvement of the differential settlement.

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