



Centrifuge investigation of load transfer mechanisms in a granular mattress above a rigid inclusions network

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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, set between the structure and the group of inclusions, transfers by arching effects a part of loadings to the piles embedded in rigid substrate. A geosynthetic can be added between the heads of the rigid inclusions and the granular mattress. In addition to the arching effect, a membrane effect happens caused by the stretching of the geosynthetic sheet. An experimental mobile tray device, especially designed to test this reinforcement technique in centrifuge at 20g, consists in simulating the settlement of the soft soil located between the inclusions. An initial pretension can be applied to the geosynthetic. A parametric study of the load transfer mechanisms in the mattress is conducted with three different thicknesses of granular mattress, two different rigid inclusions networks and different initial pretensions in the geosynthetic.

The efficacy of the load transfer and the settlements at the surface of the granular mattress are studied and discussed. With and without geosynthetic reinforcement, load transfer mechanisms are better for thicker load transfer mattresses and for higher mesh densities. The improvement made by a geosynthetic reinforcement is clearly shown through both load transfer and differential settlement reduction.

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1. Introduction

Reinforcement of soft soil with vertical rigid piles is now a widespread technique for both embankments and floor slabs (Simon and Schlosser, 2006) (Fig. 1). A famous example is the Rion–Antirion bridge in Greece, with its piers put on a granular platform, installed on a network of vertical steel piles that reinforces the soft soil on the sea bed (Garnier and Pecker, 1999; Rault et al., 2006). In the granular mattress, installed above the reinforced soil, “arches” develop and transfer the load through the piles (Fig. 2(a)). However, the understanding of the *arching effect* (Terzaghi, 1943) is not complete, as many parameters play a role, such as the height of the mattress H , the pile spacing s or the area ratio α which is the proportion of pile area in an unit cell: $\alpha = (\pi a^2/4)/s^2$ with a the pile diameter (or the cap diameter if there is one). The improvement due to the presence of a geosynthetic reinforcement between the piles and the granular mattress needs to be clarified. The geosynthetic transfers, directly to the piles, a part of the weight of

the embankment which is not already transferred by arching. This mechanism, called *membrane effect* (Le Hello and Villard, 2009), translates the ability of a geosynthetic to adapt itself to support by tension the force acting initially perpendicularly to its plane (Fig. 2(b)). More the subsoil settles under the geosynthetic, more the membrane effect will be efficient (because of the large deformation inside the geosynthetic sheet).

The physical modelling approach has been used in the past for piled embankments using 1g models in axisymmetrical tests (Dinh, 2009; Thorel et al., 2010), a 2D geometry (Hewlett and Randolph, 1988; Low et al., 1994; Horgan and Sarsby, 2002; Jenck, 2005; Jenck et al., 2005, 2007; Chen et al., 2008) or a 3D configuration (Bergdahl et al., 1979; Demerdash, 1996; Kempfert et al., 1999). Rigid inclusions reinforced with geosynthetic have also been studied with 2D (Eskişar et al., 2012) and 3D (van Eekelen et al., 2012a, 2012b) models.

In centrifuge, some studies about piled embankments without geosynthetic reinforcement have been conducted: with 2D models (Barchard, 2002) and more recently with 3D models (Ellis and Aslam, 2009a, 2009b; Baudouin, 2010; Baudouin et al., 2010; Okyay, 2010). And, on the other hand, numerous of centrifuge tests have studied the improvement due to geosynthetic most of the

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Notations

α	(%) area ratio	Q	(N) load applied by the water tank on an unit cell
a	(mm) pile diameter	ρ	(g/cm ³) mean density of the load transfer platform
$d_{\max}$	(mm) maximum grain size	s	(mm) pile spacing
E	(%) efficacy of the load transfer mechanism	σ_{ss}	(kPa) vertical stress on the soft soil (the mobile tray)
ε	(%) deformation of the geosynthetic	σ_{tot}	(kPa) total vertical stress (mobile tray and piles)
F	(N) vertical pile load	T	(kN/m) tensile strength of the geosynthetic
ϕ	(°) friction angle of the load transfer platform	W	(N) weight of the load transfer platform on a unit cell
g	(m/s ²) earth gravity	ψ	(°) dilatancy angle of the load transfer platform
H	(mm) thickness of the load transfer platform (granular mattress)	$\Delta\omega$	(mm) simulated settlement of the subsoil by the mobile tray
J	(kN/m) secant stiffness of the geosynthetic	$\Delta\omega_C$	(mm) settlement on the load transfer platform above the centre of a unit cell
N	(–) g-level	$\Delta\omega_P$	(mm) settlement on the load transfer platform above a pile
q_0	(kPa) stress applied by the water tank on the load transfer platform		

time in slope stability problems (Porbaha and Goodings, 1996; Sharma and Bolton, 1996, 2001; Viswanadham and König, 2004, 2009; Raisinghani and Viswanadham, 2011; Rajabian et al., 2012). However the use of a geosynthetic layer in the granular mattress above a rigid inclusions has never been studied in centrifuge.

In the framework of the French national project ASIRI (“Amélioration des Sols par Inclusions Rigides” in French) (IREX, 2012), several experimental approaches have been investigated including geosynthetics: full-scale tests with the CNAM (“Conservatoire National des Arts et Métiers”) (Briançon et al., 2009), 2D Schneebeli models at INSA Lyon (Jenck, 2005; Jenck et al., 2005, 2007), and recently centrifuge tests at IFSTTAR (detailed in this paper). Analytical methods and numerical simulations of rigid inclusions reinforced by geosynthetic have also been conducted in the scope of this project (Briançon and Villard, 2008; Jenck et al., 2009; Le Hello and Villard, 2009; Chevalier et al., 2011) and also by other authors (van Eekelen et al., 2003, 2011; Kempfert et al., 2004).

This paper is focused on the role played by a geosynthetic layer installed within the load transfer platform, in terms of both efficacy 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: i) the geosynthetic, ii) the height of the mattress, iii) the area ratio and iv) the pretension of the geosynthetic layer.

2. Centrifuge modelling

2.1. Physical modelling

Centrifuge modelling is a powerful tool for the study of geotechnical structures using reduced scale physical models. It is particularly relevant when stress gradient or free surface is important, like in arching phenomenon. In centrifuge modeling, the similarity of the conditions between the model (reduced scale) and the prototype (full scale) is guaranteed by the scaling factors. These scaling laws are presented in Table 1 (Phillips, 1869; Corté, 1989; Garnier et al., 2007). In the IFSTTAR centrifuge, the model size that may be installed in the swinging basket is 1.40 m in length $\times$ 1.15 m in width $\times$ 1.50 m in height. The maximum weight is 2000 kg for experiments performed at 100 g. The g level N of the test series is 20 corresponding to a reduce scale of 1/20; this choice is issued from an optimisation between the instrumented pile diameter a , the granular mattress thickness H , the maximum grain size $d_{\max}$, the geotextile performance and its recommended scaling law (Viswanadham and König, 2004; Garnier et al., 2007).

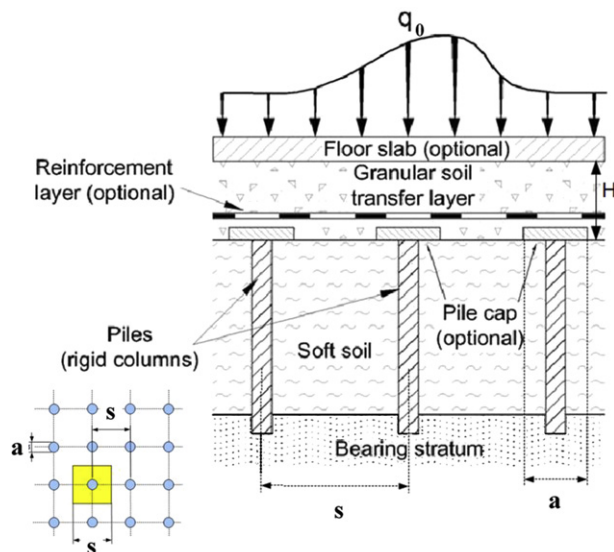


Fig. 1. Constituents of the pile supported earth platform system (Simon and Schlosser, 2006) and definition of a unit cell in a network of piles.

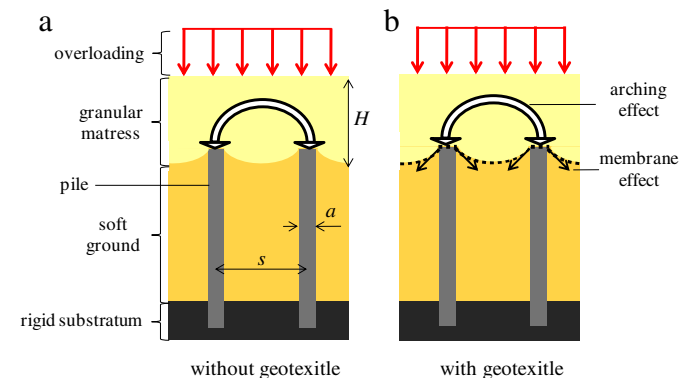


Fig. 2. Schematic representations of the load transfer mechanisms in a granular mattress - (a) without geotextile - (b) with a geotextile layer.

Table 1
Scaling factors for centrifuge modeling.

Quantity	Unites	Prototype	Ng 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			
Mesh density (α)	%	1	1
Granular mattress height (H)	m	1	1/N
Granular mattress density (ρ)	kg/m ³	1	1
Pile diameter (a)	m	1	1/N
Settlement (ω)	m	1	1/N
Efficacy (E)	%	1	1
Geosynthetic parameters			
Tensile load (T)	kN/m	1	1/N
Secant stiffness (J)	kN/m	1	1/N
Strain (δ)	%	1	1

2.2. Mobile tray

2.2.1. Principle

The device (Fig. 3) already used to study arching effects inside a granular mattress supported by piles embedded in a simulated soft ground (Okay, 2010; Rault et al., 2010) is equipped with a special device to study the effects of a horizontal reinforcement. The centrifuge tests are performed with a geosynthetic layer located at the interface below the granular mattress. In addition to the classical rigid inclusions reinforcement parameters such as α and H , several initial pretensions of the geotextile were studied.

The particularity of this device is that the soft soil settlement is simulated by a rigid mobile tray which can move downward. The tray is attached to three electric jacks which control its downward displacement. Fixed to the substratum, the pile heads go through holes perforated in the tray and punch both the geosynthetic layer and the granular mattress. The mobile tray (900 mm in internal diameter) is perforated by 61 holes, in order to use a maximum of 61 stiff piles ($a = 25$ mm) on its whole surface. Two area ratios (Fig. 4) are available for this present study: $\alpha = 4.91\%$ and 2.47% (resp. $s = 100$ mm and 141 mm). A square frame ($640 \times 640 \times 10$ mm³) is designed to control the initial pretension (§2.3.3) of the geosynthetic layer and its placement during the tests (Fig. 4).

Above the mobile tray (Fig. 3), a steel ring is screwed in order lay down the granular mattress. Three thicknesses are tested: $H = 35$, 50 and 90 mm. Then, a water tank is screwed on this steel ring in order to apply overloading on the load transfer platform by filling it with water in flight.

2.2.2. Instrumentation

The main parameters measured during the tests, are the pile loads with cells inserted in the stiff piles heads and the settlements with transducers located straight above the pile heads and in the middle of a cell versus the displacement of the tray. The combination of all the parameters allows quantifying the efficacy of the composite foundation in several configurations.

The mobile tray is instrumented as follow:

- 9 pile loads F from 9 rigid inclusions instrumented with a load cell located in the vicinity of the centre of the tray to study the load transfer mechanisms (Fig. 4). They allow to appreciate the dispersion of the results (less than 10%), the mean value of the force is used in the calculation of the efficacy,
- 2 LVDTs located inside the water tank which measure the settlement in surface of the granular mattress above pile $\Delta\omega_p$ (Figs. 4 and 5),
- 1 LVDT located inside the water tank which measure the settlement in surface of the granular mattress above the centre of a cell $\Delta\omega_c$ (Figs. 4 and 5),
- 1 LVDT located inside the water tank which measure the settlement of the granular mattress above the middle of the edge of a cell (Fig. 4),
- 2 LASER displacement transducers which measure the simulated settlement of the subsoil by the tray in the centre $\Delta\omega$ (Figs. 4 and 5) and in peripheral position (Fig. 4),
- 1 water pressure transducer inside the tank (Druck PDCR81) to measure the overloading q_0 .

Those sensors are connected to on board Spider8 data acquisition modules from HBM coupled with visualization and recording software (Thorel et al., 2008).

2.3. Materials properties

2.3.1. Model granular mattress

The granular mattress located above the mobile tray simulates a load transfer platform where arching mechanisms can occur.

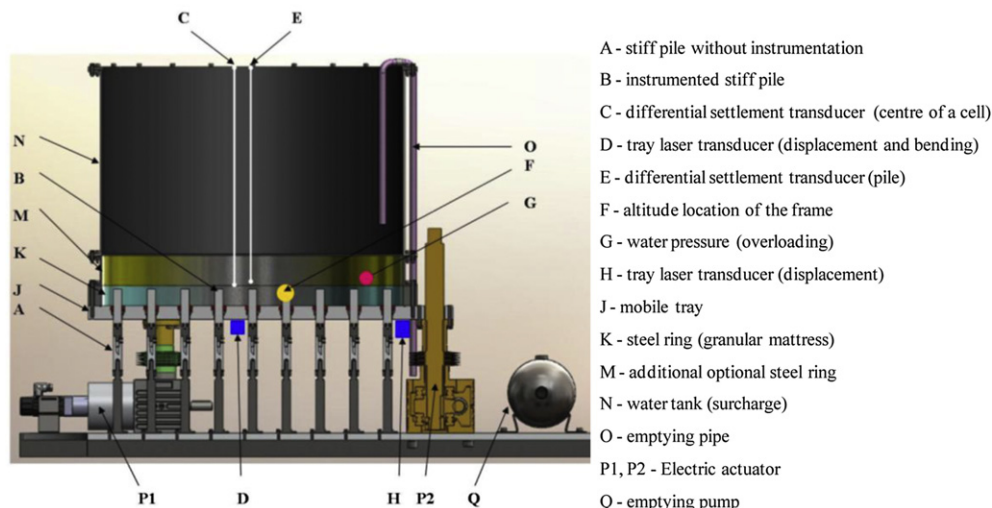


Fig. 3. Schematic view of the mobile tray with functional components and location of the instrumentation.

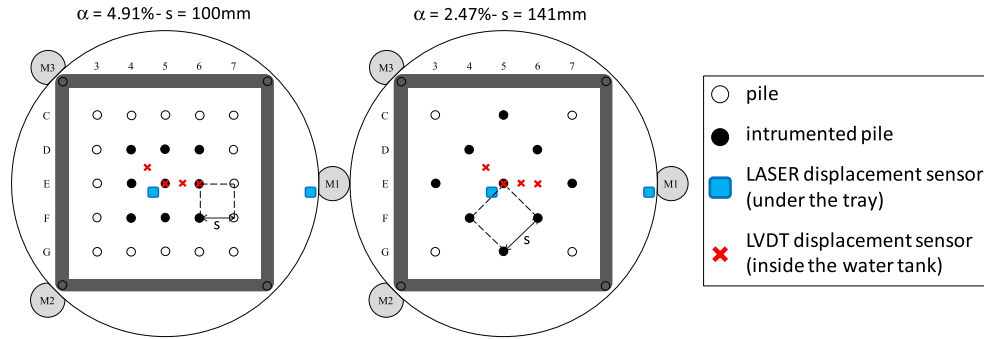


Fig. 4. Schematic top view of the mobile tray with location of the instrumentation for the two area ratios: $\alpha = 4.91\%$ and 2.47% (resp. $s = 100\text{ mm}$ and 141 mm).

In order to obtain an important load transfer in the piles and then to facilitate the development of shear strength in the mattress, unbound gravel materials with very angular grains are used. To respect scaling relations mentioned in Table 1, the prototype material has to be used in the model test. However, unbound gravel cannot be used in small scale model because the characteristic dimension of the pile (in our case the pile diameter $a = 25\text{ mm}$) is too small compared to the grain size. Thus, the grain size distribution has to be scaled down: at least, 20 particles are needed above the head pile (i.e. $20 \cdot d_{\max} < a$). In the time, the model material has to keep the same stress-strain behaviour as the prototype one. The choice (Baudouin et al., 2008) has been made to use a mix of five fractions of Hostun sand (HN38, HN34, HN31, HN04/08 and HN06/1). 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 exposed on Fig. 6 and its properties are given in Table 2.

One must be note that $d_{\max} = 1\text{ mm}$ in order to verify the scale condition of the characteristic dimension of the structure to grain size ($d_{\max}/a < 20$). The mean density wished for this campaign is $\rho = 1.63\text{ g/cm}^3$ which is relatively dense. At this density, triaxial tests in compression at different confining pressures $P_c = 25, 50, 100$ and 200 kPa are presented in Fig. 7. The physical properties of the model sand at this density are summarized in Table 3.

2.3.2. Geosynthetic modelling

As unbound gravel is mainly used in situ for the load transfer platform, the geosynthetic, located over the soft ground and the piles, is classically a geogrid. In the centrifuge model, the gravel is replaced by sand. Nevertheless, the scaling of geosynthetics focuses mainly on its tensile strength. Several authors (Taniguchi et al., 1988; Springman et al., 1992; Viswanadham and König, 2004)

have shown that the similitude condition on the tensile strength T is N times smaller for a $N \cdot g$ centrifuge acceleration:

$$T^m = \frac{1}{N} T^p \quad (1)$$

where m and p indicate respectively model and prototype. Then, because the acceleration has no effect on deformation, the secant stiffness J^m of the model geosynthetic has to be $1/N$ times the prototype geogrid:

$$J^m = \frac{1}{N} J^p \quad (2)$$

For these reasons, the choice has been made to use a woven biaxial geotextile composed of high modulus polypropylene fibres, the Geolon® PP25 (110 g/m^2), provided by Tencate. The thickness of this geosynthetic is 0.54 mm (ISO 9863-1, 2005). Tensile strength tests in longitudinal and transverse directions have been conducted on $100 \times 200\text{ mm}^2$ samples following the ISO Standard (ISO 10319, 2008). Results are exposed in Fig. 8. Model and prototype main characteristics of the geosynthetic are summarized in Table 4.

2.3.3. Geosynthetic pretension

In a preliminary phase at $1g$, the geotextile layer is prepared, always with the same procedure to warrant the repeatability. The geotextile layer is cut following a cross shape along its fabric directions. Then it is placed on a pretension device to apply the controlled tension according to its fabric directions. Identical suspended masses apply the same pretension in both fabric directions to keep the isotropic characteristic of the behaviour during the test. The geotextile layer is clamped between the upper and lower parts of the frame by screws. The final stage of the preparation consists in

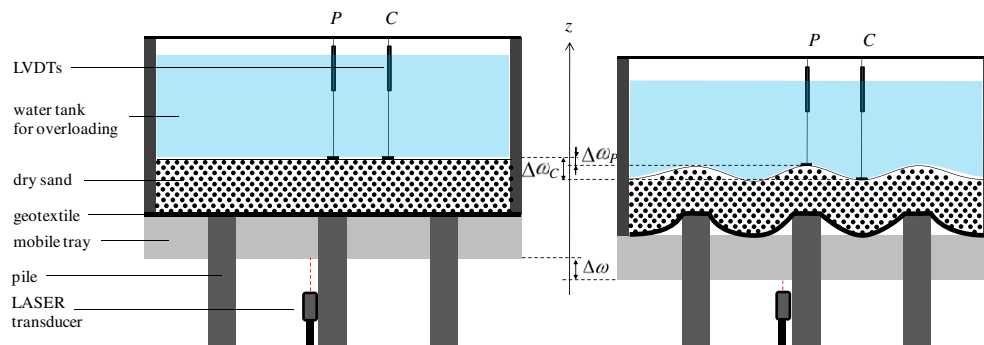


Fig. 5. Schematic view of the LVDT sensors and the measurements of the different settlements above the central pile (point P, $\Delta\omega_P$) and above the middle of a cell (point C, $\Delta\omega_C$): before the test (left) and after the mobile tray down simulated by the settlement $\Delta\omega$ (right).

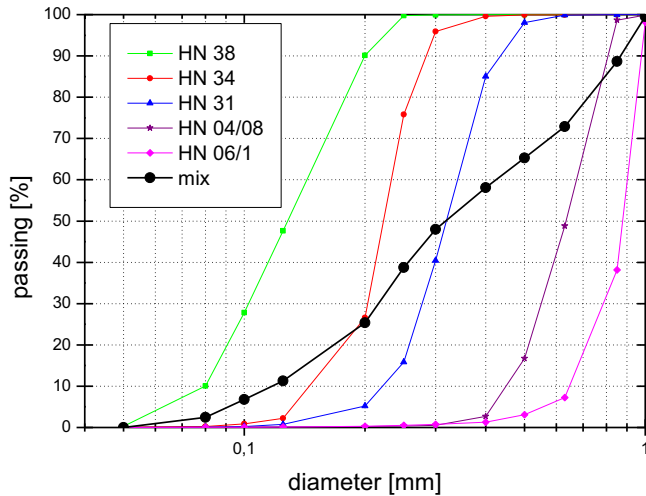


Fig. 6. Grading curve of the model granular mattress made from five fractions of Hostun sand (HN38, HN34, HN31, HN04/08 and HN06/1).

cutting the excess of geotextile layer and to install the frame on the tray. Three pretension values have been decided to cover the program: T2 (250 N/m eq. 1% of the tensile strength), T1 (50 N/m eq. 0.2% of the tensile strength) and T0 (no tension). The principle of the pretension method and a view of the different elements of the device used to apply this process are presented in Fig. 9 and Fig. 10.

3. Experimental campaign

3.1. Experimental program

The experimental campaign includes the two area ratios, $\alpha = 4.91\%$ and 2.47% , that can be tested with the frame to control the initial pretension of the geotextile. For each mesh density, three granular mattress thicknesses are tested: $H = 90, 50$ and 35 mm. There are six different geometrical combinations in which at least two tests are performed: one reference test without geotextile (named “L0”) and one test with a geotextile without initial pretension (named “L1T0”). For some families, all the tests at two different initial pretensions are performed. To conclude, a series of 20 tests is conducted with this mobile tray device in centrifuge at 20g.

The identification of each test follows a logical nomenclature. For example, the test name “H50S141L1T0” is a test performed with a granular mattress thickness $H = 50$ mm, a distance between two pile $s = 141$ mm ($\alpha = 2.47\%$), one geotextile layer “L1” without initial pretension “T0”.

3.2. Test procedure

3.2.1. Sample preparation, centrifuge acceleration and overloading

All the test preparation is performed with the mobile tray installed inside the centrifuge basket (Fig. 11). For this whole series of tests, the roughness of the tray is obtained by gluing on it the same sand used for the tests. The stiff piles are capped with the same

Table 2
Properties of the Hostun model sand (Baudouin et al., 2008).

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

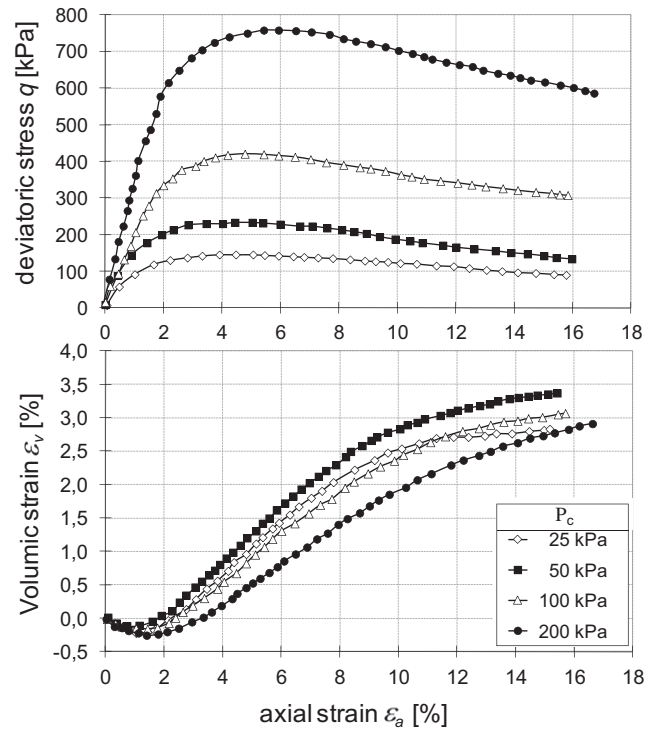


Fig. 7. Triaxial compression tests at $P_c = 25, 50, 100$ and 200 kPa of the model sand at $\rho = 1.63$ g/cm³ – deviatoric stress q versus axial strain ϵ_a (top) and volumetric strain ϵ_v versus axial strain ϵ_a (bottom).

process. If required, the frame which holds the geotextile layer at the expected pretension is screwed on the mobile tray.

Then the dense sandy mattress is manually installed as homogeneously as possible up to the final height. The amount of sand is weighted before and after the test to control the density of each test. The mean density for this campaign is equal to 1.63 g/cm³ with a standard deviation equal to 0.03 and a coefficient of variation of 1.87% .

The surcharge applied on the mattress simulates the construction of an embankment (without the possibility of arching inside it). The loading will be generated by filling with water a tank that has a deformable membrane at the bottom. The empty water tank is screwed on the mobile tray, its rubber membrane lying on the granular mattress. Inside the tank, four LVDTs are installed to measure the mattress settlement at different locations over the membrane. A water pressure transducer is used to control the water level in the tank.

The mattress is pre-stressed by increasing the centrifuge acceleration step by step until 20g, and then decreasing back to zero. This procedure is applied three times in order to achieve consistent pre-stressing of the granular mattress. Because of the centrifuge acceleration, the mobile tray displacement under its centre (Fig. 12 and Fig. 13) reaches a half millimetre due to self-weight bending whereas its edges do not move.

By filling the reservoir in flight in order to simulate a 5 m high embankment in prototype scale, a stress is regularly applied on the load transfer platform up to 80 kPa (“phase II” on Fig. 12). During this phase, the mobile tray continues to bend because of the

Table 3
Physical properties of the model sand.

Density ρ (g/cm ³)	Friction angle ϕ (°)	Dilatancy angle ψ (°)
1.63	43	9

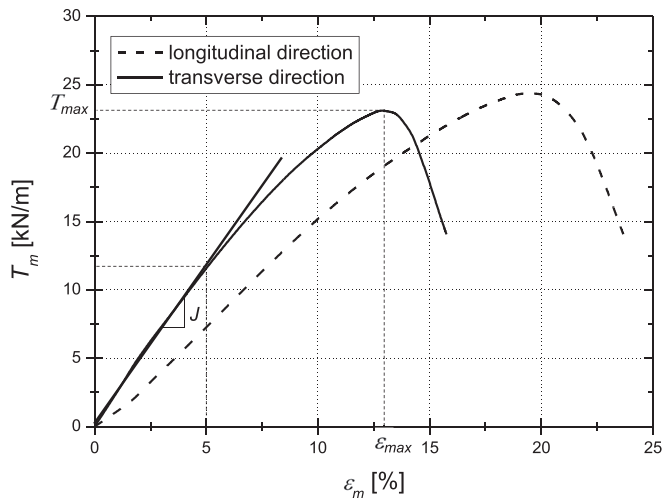


Fig. 8. Tensile strength – strain behaviour in longitudinal and transverse directions of the model geotextile.

overloading: the centre goes downward around 0.5 mm. The mobile tray is constructed accepting a certain amount of bending or deflection of the rigid plate in order to limit the weight of the equipment. This is a compromise between reduction of the deflection and limiting the weight of the equipment inside the basket of the centrifuge.

3.2.2. Mobile tray chronology – simulation of the settlement

The soft soil settlement is simulated by the mobile tray moving down (“phase III” on Fig. 12). To observe the load transfer mechanisms, a low speed is applied during the initial simulated settlement (0.05 mm/min). This speed is progressively increased (0.1, 0.2, and 1 mm/min) to limit the overall duration of a test. Between each step, a relaxation period is done in order to observe time dependent behaviour of the sample. This peculiar behaviour is not detailed in this paper. The mobile tray is stopped when a 12 mm settlement in model scale is reached. If the bending of the tray is added, the mobile simulate a settlement of the soft soil $\Delta\omega$ around 13 mm. It corresponds to around 52% of the diameter of a pile ($a = 25$ mm) which gives a value of 26 cm for the prototype.

3.3. Typical test results

In this paragraph, data from test H50S141L1T0 are presented and analysed. All the following test characteristics are given in model scale. This test is done on a 141×141 mm² mesh ($\alpha = 2.47\%$) with a 50 mm height granular mattress and a no-pre-tensioned geosynthetic. The chronology of this test (Fig. 12) includes three phases: I) centrifuge acceleration cycles ($N = 20g$), II) overloading of the granular layer ($q_0 = 80$ kPa) and III) simulation of soft soil settlement by moving downwards the mobile tray ($\Delta\omega$).

Table 4
Model and prototype main characteristics of the geosynthetic.

	Model		Prototype	
	Longitudinal	Transverse	Longitudinal	Transverse
Maximum tensile strength T_{max} (kN/m)	24.5	23.9	490	478
Strain at T_{max} ϵ_{max} (%)	19.3	12.9	19.3	12.9
Secant stiffness at 5% J (kN/m)	148	238	2960	4760

Table 5
Tests properties of the experimental campaign.

α (%)	s (mm)	H (mm)	Geotextile	Initial pretension	Name
4.91	100	90	0		H90S100L0
		90	1	T0 ^a	H90S100L1T0
		90	1	T2 ^c	H90S100L1T2
		50	0		H50S100L1T0
		50	1	T0	H50S100L1T0
		50	1	T1 ^b	H50S100L1T1
		35	0		H35S100L0
		35	1	T0	H35S100L1T0
		35	1	T1	H35S100L1T1
		35	1	T2	H35S100L1T2
		90	0		H90S141L0
		90	1	T0	H90S141L1T0
		90	1	T1	H90S141L1T1
		50	0		H50S141L0
2.47	141	50	1	T0	H50S141L1T0
		50	1	T1	H50S141L1T1
		50	1	T2	H50S141L1T2
		35	0		H35S141L0
		35	1	T0	H35S141L1T0
		35	1	T1	H35S141L1T1

^a T0: no tension.

^b T1: 50 N/m eq. 0.2% of the tensile strength.

^c T2: 250 N/m eq. 1% of the tensile strength.

In Fig. 13(a), the loads F on the nine instrumented piles are followed versus the time. During the cycles of centrifuge acceleration (phase I), F increase is due to the combination of two factors. One, direct, is the weight of the granular mattress and the one of the load sensor itself (which is removed during the data analysis). The second, indirect, is due to the bending of the mobile tray with centrifuge acceleration. Then, a simulation of soft soil settlement $\Delta\omega$ happens and load transfer mechanisms start which induces increase of F . From this state, during the overloading (phase II), F continues to increase regularly also because of the combination of these two previous factors: overloading and bending of the tray. Then, phase III starts with the mobile tray downward displacement at the different chosen speeds (Fig. 12). During this phase III, F only increase because of load transfer mechanisms.

The settlements on the surface of the granular mattress are represented (Fig. 13(c)): above the central pile $\Delta\omega_p$ and in the centre of a cell $\Delta\omega_c$, and compared to the simulated settlement $\Delta\omega$ of the soft soil by the mobile tray. During the overloading (phase II) and the beginning of soft soil settlement simulation (phase III), the settlements in surface of the load transfer platform $\Delta\omega_p$ and $\Delta\omega_c$ follow the soft soil settlement $\Delta\omega$. It means that the entire granular mattress seems to follow the mobile tray. In surface of the load transfer platform, the punching of the load transfer platform by the piles is not observable. Then, with the simulated settlement $\Delta\omega$ increase, the settlement above the pile $\Delta\omega_p$ becomes less and less important while the settlement above the middle of a cell $\Delta\omega_c$ continues to follow approximately $\Delta\omega$. Differences between $\Delta\omega_p$ and $\Delta\omega_c$ for the higher values of $\Delta\omega$ may be linked to different stress distributions in the different zones of the mattress that may be induced by “arching”, particles rearrangements, strain localisation and failure.

Two parameters are firstly used to analyse the influence of a geosynthetic layer installed at the bottom of the mattress: the efficacy (Fig. 13(b)) and the differential settlement (Fig. 13(d)). The first parameter, the efficacy E (Hewlett and Randolph, 1988), represents the impact of load transfer mechanisms (by arching and by membrane effect in the case of geosynthetic reinforcement) when the mobile tray is moving down. The efficacy E is defined in Eq. (3) as the ratio of the load on a pile F to the total load applied

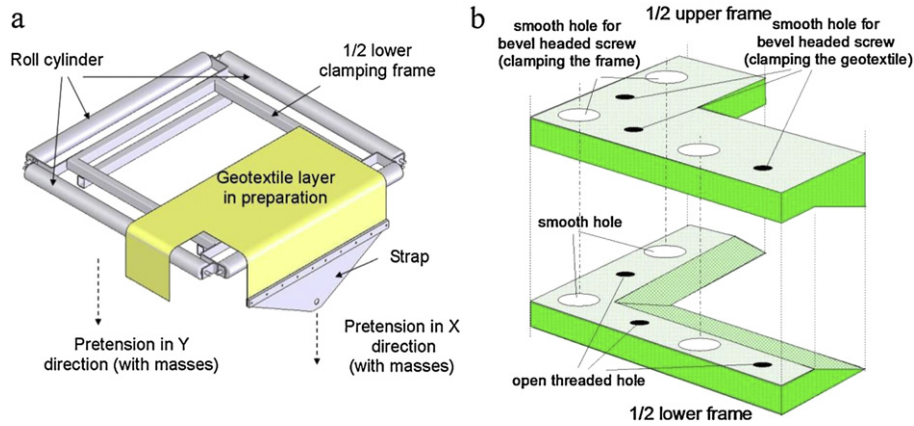


Fig. 9. (a) Principle to warrant an isotropic pretension before clamping with the double frames - (b) Detail of the 2 half pretension frames for altitude positioning of the geotextile layer.

on an unit cell (the weight of the granular mattress W plus the overload Q).

$$E = \frac{F}{W + Q} \quad (3)$$

The second parameter, the differential settlement at the surface of the load transfer platform, is the difference between the settlement above the centre of a unit cell and above a pile ($\Delta\omega_C - \Delta\omega_P$). In this way, the differential settlement takes the higher possible value. This differential settlement has to be as low as possible to maintain the integrity of a structure. Indeed it is the worst phenomenon to avoid. A differential settlement of 20 mm at the prototype scale corresponds to $(\Delta\omega_C - \Delta\omega_P)/a = 4\%$.

The efficacy and the differential settlements are represented in Fig. 13(b) and (d) versus $\Delta\omega/a$. The efficacy E increases with $\Delta\omega/a$ as a direct consequence of the increase of the pile load F . It should be noted that the efficacy doesn't start from the area ratio value α (in this case 2.47%) as it theoretically should be. It is due to the

bending of the tray during the centrifuge acceleration which induces the beginning of the soft soil settlement and so the load transfer mechanisms. The role of the geosynthetic layer in the load transfer mechanisms will be discussed later. In the same time, the differential settlement increases more and more quickly.

4. Analysis

The analysis of the experimental campaign must combine two points: a study of the efficacy of the load transfer mechanism and a verification of the acceptability of the differential settlement at the surface of the granular mattress. The soft soil settlement, simulated by the mobile tray downward movement, is independent from the efficacy in our experiment. It has been observed on field (IREX, 2012) that load transfers towards the inclusions through the mattress induce an increase of the efficacy and then an unloading of the soft soil which conducts to a reduction of its settlement. The non-linear "coupling" between the efficacy and the settlement is

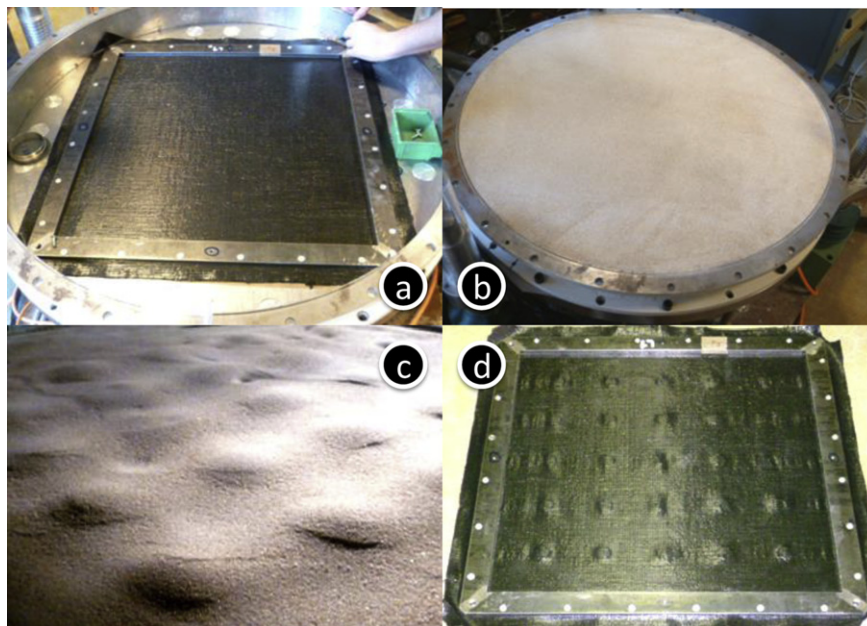


Fig. 10. (a) View of the double frame screwed on its testing location to keep constant the pretension of the geotextile layer - (b) The sample is ready for centrifuge testing before the placement of the water tank above the mobile tray - (c) View of the soil after test - (d) Observations of the geosynthetic after test.

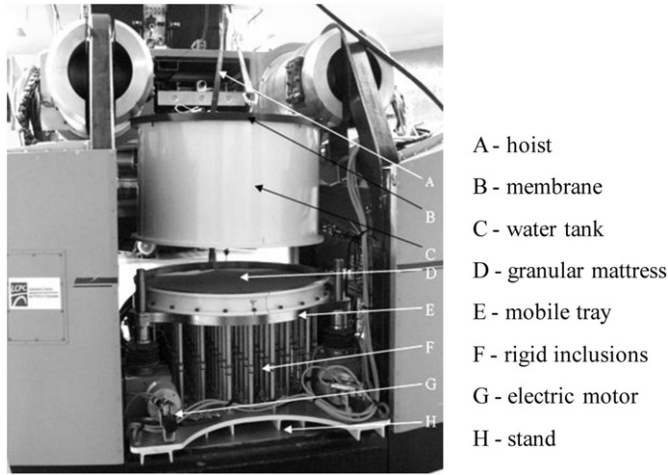


Fig. 11. Preparation phase of the on board experimental device in the swinging basket (the upper part of the equipment is risen with a crane to free the access to the mattress).

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 next section. Then it is interesting to cross the analysis of the efficacy E and the differential settlement with the stress σ_{ss} which remains on the soft soil. σ_{ss} is calculated from E and α :

$$\sigma_{ss} = \frac{1 - E}{1 - \alpha} \sigma_{tot} \quad (4)$$

with σ_{tot} the total stress applied on a unit cell $\sigma_{tot} = (W + Q)/s^2$. By analysing the stress on the soft soil σ_{ss} which has a real physical and practical meaning, different geometries of the problem (H and α) can easily be compared to each other.

4.1. Tests without geotextile

The analysis is firstly focused on the six reference tests (without geotextile reinforcement). In Fig. 14, the efficacy E , the stress on the soft soil σ_{ss} and the dimensionless differential settlement $(\Delta\omega_C - \Delta\omega_p)/a$ are plotted as a function of the ratio $\Delta\omega/a$. For the three granular mattress thickness $H = 35, 50$ and 90 mm, results of the tests with $\alpha = 4.91\%$ (or $s = 100$ mm) are presented

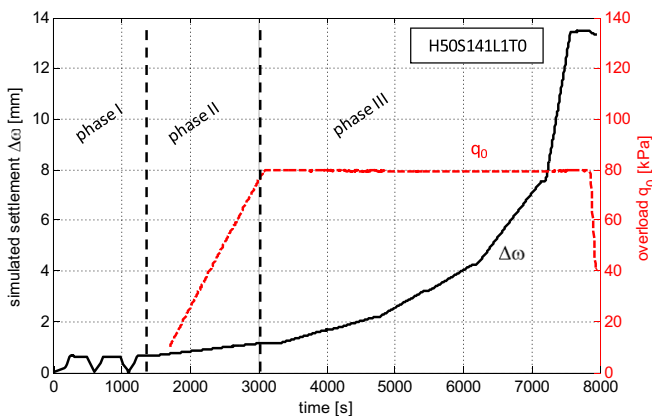


Fig. 12. Mobile tray displacement under its centre $\Delta\omega$ and overload q_0 on the granular load transfer platform during the three phases (test H50S141L1T0).

on the left side of Fig. 14 and results of the tests with $\alpha = 2.47\%$ (or $s = 141$ mm) on the right side.

For $\alpha = 4.91\%$ (or $s = 100$ mm), following the thickness of the granular mattress, the efficacy curves have distinct behaviours. For tests without geotextile, the efficacy of the load transfer mechanisms is only due to the arching effect. The efficacies all start from the same value which is linked to α , but not equal to α due to the bending of the tray (§3.3). Then, for the two thinner platforms, $H = 35$ and 50 mm, E increases, goes through a peak and then decreases. For $H = 50$ mm, the peak is higher than the one for $H = 35$ mm. It translates a better load transfer mechanism. But it happens for deeper settlement of the soft soil. For $H = 90$ mm, E only increases but seems to reach a maximum value which could be the peak. Finally, the efficacy is always higher for thicker mattresses. However, the peak of efficacy happens for deeper settlements of the soft soil. Inside thick mattresses, it takes more space to develop their full potential of arching. The same remarks can be done about the other mesh density $\alpha = 2.47\%$ (or $s = 141$ mm). Between these two mesh densities, the efficacy is twice more important for the denser mesh $\alpha = 4.91\%$. All these remarks are easily understandable because the development of “arching” effects is closely linked to geometrical parameters as the thickness H of the mattress and the distance between piles.

The other parameter to study is the stress which remains on the soft soil σ_{ss} . Its behaviour is slightly different than the one observed for the efficacy. Contrary to E , the initial value of σ_{ss} depends on the thickness of the mattress but not on α . So, for low settlements of the soft soil, the stress which remains on it is higher for thicker mattress. A thicker mattress itself applies a more important stress on the soft soil due to its weight. After this first phase, the σ_{ss} behaviour corresponds to the one observed about E : σ_{ss} is lower for thicker H and/or for higher α .

For all the cases, the differential settlements increase with the mobile tray going down. But there is a large difference of amplitude between the three thicknesses of the granular mattress. For $H = 90$ mm, there is nearly no differential settlement. Whereas, for $H = 35$ and 50 mm, the differential settlements increase quickly. The punching of the mattress by the head pile has more space to be absorbed in a thicker mattress which conducts to a lower differential settlement. For the same reason, the differential settlement is a little lower for a lower mesh density ($\alpha = 2.47\%$). There is more space between the piles. So the punching of the mattress by the piles has more space to be absorbed. However, as it has been mentioned in the introduction of the analysis, the mobile tray test procedure doesn't reproduce the “coupling” between the efficacy and the settlement which is observed in situ. The unloading of the soft soil by load transfer mechanism is largely better for the higher area ratio $\alpha = 4.91\%$. So the soft soil settlement stop should induce a lower differential settlement in surface contrary to $\alpha = 2.47\%$.

In Fig. 15, the efficacy E is also represented as a function of the ratio $(\Delta\omega_C - \Delta\omega_p)/H$. This ratio of the differential settlement on the mattress thickness corresponds to the shearing strain in the granular mattress. In this axis, the efficacy curves have a similar shape for the two thinner mattresses $H = 35$ and 50 mm. First, E curves increase, then reach a maximum value around 4% of the shear strain of the mattress and finally decrease. For the thicker mattress, $H = 90$ mm, it is more difficult to conclude because not enough shearing is observable. However, the initial trend seems to confirm the remark done about the thinner mattresses. To conclude, the arching mechanism is well correlated with the shearing strain of the mattress. Then thicker is the mattress, deeper the settlement of the soft soil has to be, in order to fully develop the arching inside the granular mattress.

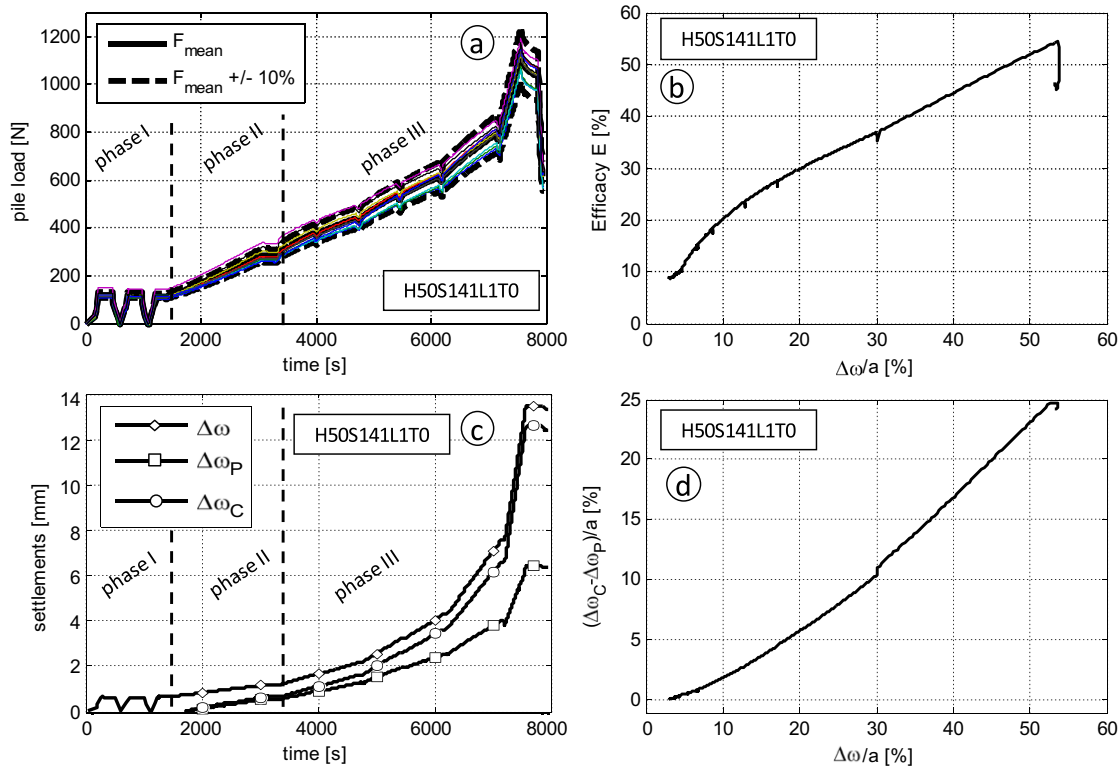


Fig. 13. (a) Pile loads F in the nine instrumented piles versus time - (b) efficacy E of the load transfer mechanisms versus $\Delta\omega/a$ - (c) settlement of the soft soil simulated by the tray $\Delta\omega$, settlements at the mattress surface above the central pile $\Delta\omega_p$ and on the middle of a cell $\Delta\omega_c$ versus time - (d) the dimensionless differential settlement versus $\Delta\omega/a$ (test H50S141L1T0).

4.2. Tests with geotextile layer without initial pretension

The same test procedure is followed for the tests with a geotextile layer without initial pretension "L1T0". In the same way as the reference tests in Fig. 14, the "L1T0" tests results are exposed in Fig. 16. In addition to the arching effect, the membrane effect plays an important role in the load transfer mechanisms when the mattress is reinforced by a geosynthetic. The geosynthetic transfers directly to the piles, a part of weight of the embankment which is not already transferred by arching. 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 ends before the loose of contact between the tray and the geosynthetic. At this point, if we exclude a possible failure of the geotextile itself, the entire load applied on the mobile tray is transferred to the piles. These two mechanisms were schematically represented in Fig. 2.

The behaviour and the amplitude of the efficacy E reveal some differences with the reference tests without geosynthetic. As it has been mentioned earlier, with the geosynthetic, E increase never ends before the loose of contact with the tray. At this point, the entire load is transferred to the piles: $E = 100\%$. This point is nearly reached at the end of the tests for $\alpha = 4.91\%$ (Fig. 16) whereas, for $\alpha = 2.47\%$, the efficacy E is between 40% and 60%. The membrane effect is governed by the deformation of the geosynthetic which is higher when the piles are closer: for $s = 100$ mm ($\alpha = 4.91\%$). Between the three thicknesses of mattress, $H = 35, 50$ and 90 mm, E is always higher when the mattress is thicker. But efficacies are closer each other than they were for reference tests.

About the stress σ_{ss} which remains on the soft soil, when the efficacy reaches its maximum value $E = 100\%$, σ_{ss} becomes nil (no more contact with the tray). As tests without geosynthetic, for

low soft soil settlement, σ_{ss} behaviour is slightly different than the one observed for E because its initial value depends on H . After this phase, σ_{ss} is lower for thicker H and/or for higher α . For $\alpha = 4.91\%$ tests, it is interesting to observe that, for thicker mattress, the loss of contact between the tray and the geosynthetic ($\sigma_{ss} = 0$ kPa) happens for lower soft soil settlement. This observation goes in the good direction: the arching effects are strong in thicker mattress, so it remains less stress on the geosynthetic which finally decollates for lower displacement of the mobile tray.

The differential settlement curves have similar trends than the ones observed for the reference tests. The amplitude of this phenomenon is largely impacted by the thickness of the granular mattress. On field, the differential settlement must be as low as possible. Then to compare the global efficacy of different reinforcement geometries, these differential settlements must be compared. But the mobile tray procedure is controlled by displacement and not by stress on soft soil as it is the case on field. So, differential settlements should be compared for a same stress remaining on the soft soil σ_{ss} .

4.3. Improvements made by a geotextile layer

Reference tests "L0" and tests with geotextile without initial pretension "L1T0" are compared in Fig. 17. In this figure, the evolutions of the efficacy E , the stress on the soft soil σ_{ss} and the differential settlement on the simulated settlement $(\Delta\omega_c - \Delta\omega_p)/\Delta\omega$ are represented as a function of the ratio $\Delta\omega/(s - a)$. The distance $(s - a)$ corresponds to the closest distance between two edges of different piles. This distance represents the thickness of the mattress to obtain a full arching mechanism if the hypothesis of semi-cylindrical arches is taken (Low et al., 1994). It is also the initial distance to calculate the deformation of the geotextile (Abusharar et al., 2009). These tests

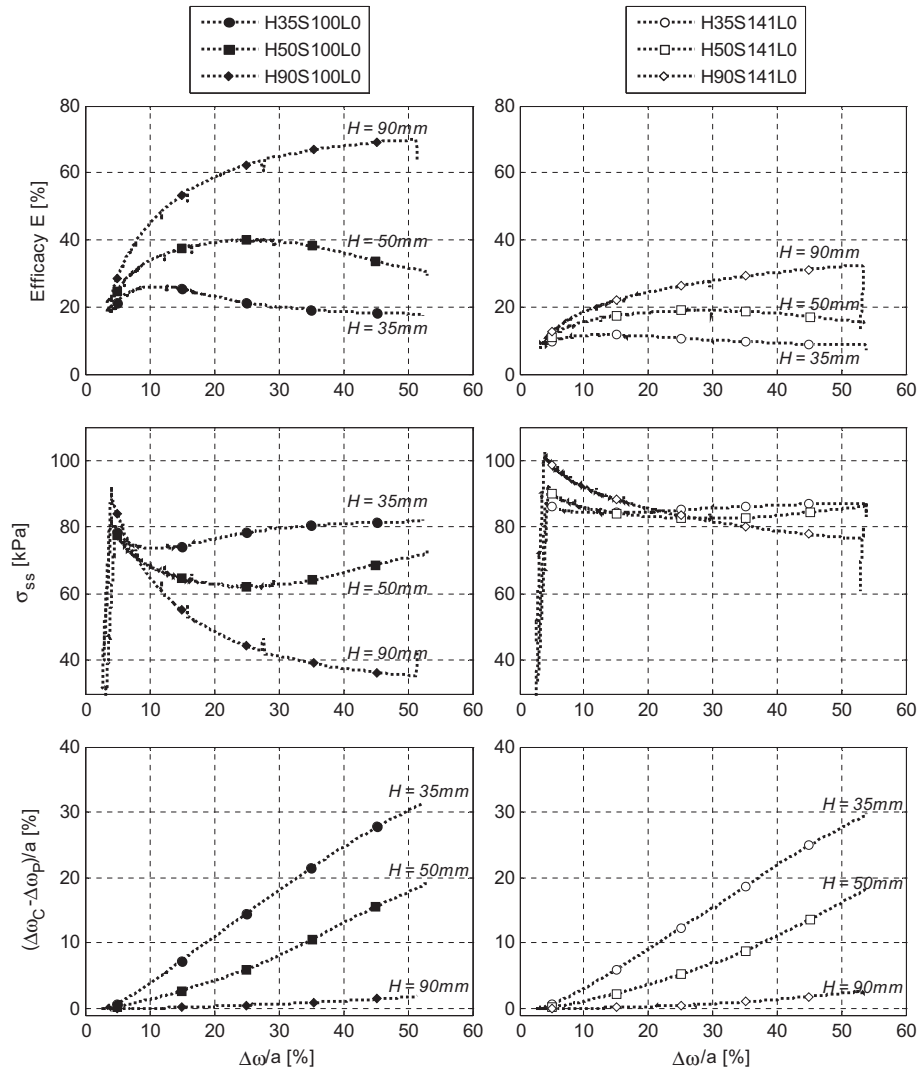


Fig. 14. Efficacy E (top), soft soil stress σ_{ss} (middle) and dimensionless differential settlement $(\Delta\omega_C - \Delta\omega_P)/a$ (bottom) versus $\Delta\omega/a$ for the six reference tests without geotextile for $H = 35, 50$ and 90 mm and for $s = 100$ mm - $\alpha = 4.91\%$ (left) and 141 mm - $\alpha = 2.47\%$ (right).

are classified by the thickness of their granular mattress ($H = 90, 50$ and 35 mm) then same area ratio α or pile spacing s can be compared.

In the beginning of the soft soil settlement, there is nearly no improvement of the efficacy E or the stress on the soft soil σ_{ss} between tests with and without geosynthetic. Then, tests with

geosynthetic have a better efficacy. It happens sooner for the thinner mattresses because the arching effect is low compared to the membrane effect. This efficacy increase becomes more and more important when the mobile is moving downwards. Deformation inside the geosynthetic becomes larger and induces a better load transfer. The difference of the load transfer between tests with

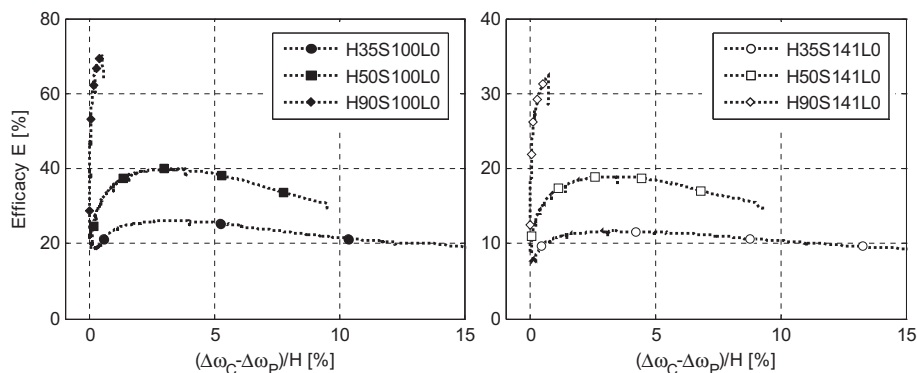


Fig. 15. Efficacy E versus $(\Delta\omega_C - \Delta\omega_P)/H$ for the six reference tests without geotextile for $H = 35, 50$ and 90 mm and for $s = 100$ mm - $\alpha = 4.91\%$ (left) and 141 mm - $\alpha = 2.47\%$ (right).

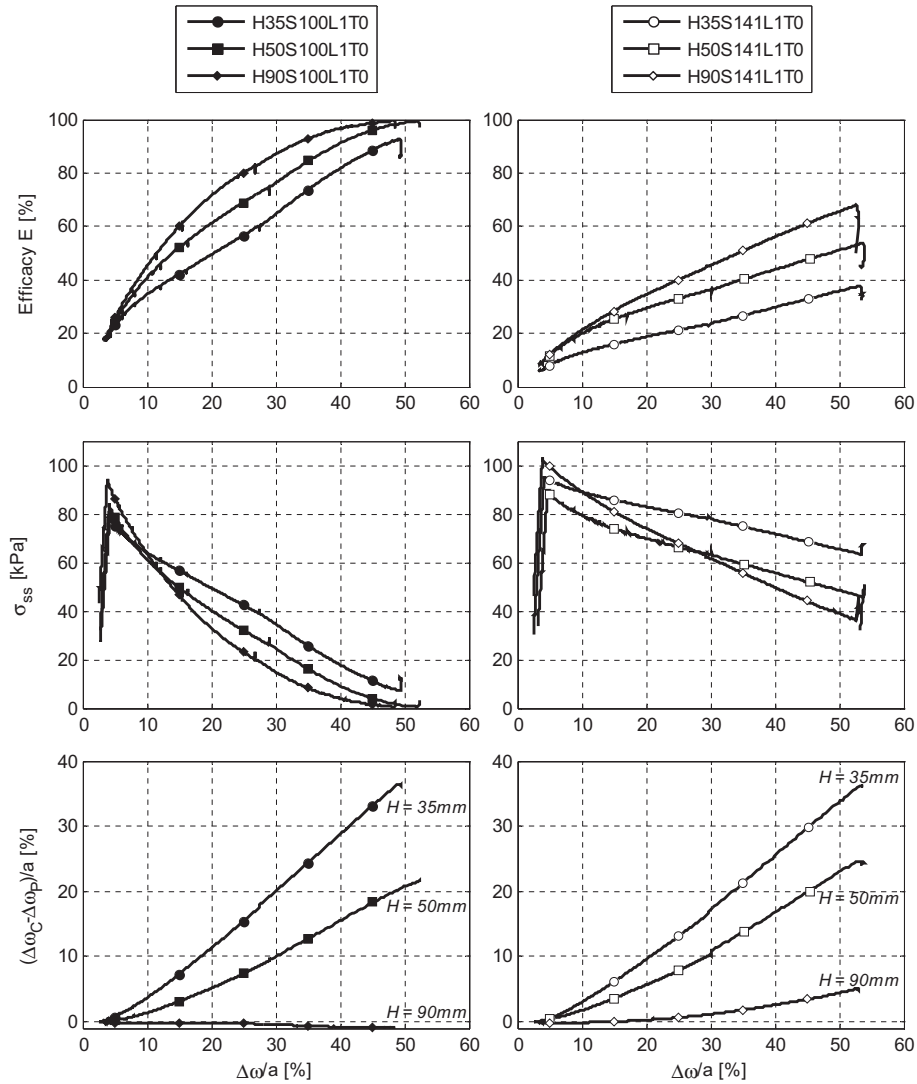


Fig. 16. Efficacy E (top), soft soil stress σ_{ss} (middle) and dimensionless differential settlement $(\Delta\omega_C - \Delta\omega_P)/a$ (bottom) versus $\Delta\omega/a$ for the tests with a layer of geotextile without an initial pretension (“L1T0” tests) for $H = 35, 50$ and 90 mm and $s = 100$ mm - $\alpha = 4.91\%$ (left) and 141 mm - $\alpha = 2.47\%$ (right).

and without geosynthetic is not only due to the membrane effect. The insertion of a geosynthetic improves the arching mechanism too. It has been experimentally proved by van Eekelen et al. (2012a).

The differential settlement in surface is presented in Fig. 17 as a percentage of the soft soil settlement $(\Delta\omega_C - \Delta\omega_P)/\Delta\omega$. When it reaches 100%, it means that the entire differential settlement at the base of the mattress is transmitted to its surface. The classification by the thickness of the granular mattress obviously shows the impact of this parameter on the differential settlement. For $H = 90$ mm, the improvement of the differential settlement is too small to be analysed. The comparison is only possible for $H = 35$ and 50 mm with two different ranges. For $H = 35$ mm, $(\Delta\omega_C - \Delta\omega_P)/\Delta\omega$ is between 35% and 45% and, for $H = 50$ mm, $(\Delta\omega_C - \Delta\omega_P)/\Delta\omega$ is between 60% and 70%. For each category, these curves have similar trends. The distance $(s - a)$ seems to be relevant in order to compare different area ratios (Table 5).

By comparing tests with and without geotextile, the differential settlement is a little higher with geotextile for high displacement of tray. It is an artefact of the experimental procedure which doesn't reflect the reality in situ. Due to the monitoring of the mobile tray

by displacement, the simulated settlement of the soft soil never stops even if the soft soil unloading would permit the end the phenomenon in a real case. In the mobile tray experiment, the geotextile does not reduce directly the differential settlement. But, if two tests with and without geotextile are compared at a same stress remaining on the soft soil σ_{ss} , the differential settlement in surface is clearly lower for the mattress reinforced by the geotextile. For example, if tests H50S100L0 without geosynthetic (Fig. 14) and H50S100L1T0 with geosynthetic (Fig. 16) are compared at $\sigma_{ss} = 65$ kPa, the differential settlement obtained is divided by two with a geosynthetic (Table 6). That is why we talk about an “indirect” improvement of the differential settlement by geotextile in the case of our experiment.

4.4. Pre-tension effects

With the frame device, described in Section 2.3.3, it is possible to apply an initial pretension to the geotextile layer. The results and the analysis of the tests without initial pretension “T0” were already developed in the previous sections. Now, the effects of the initial pretensions “T1” and “T2” are studied. “T1” (resp. “T2”)

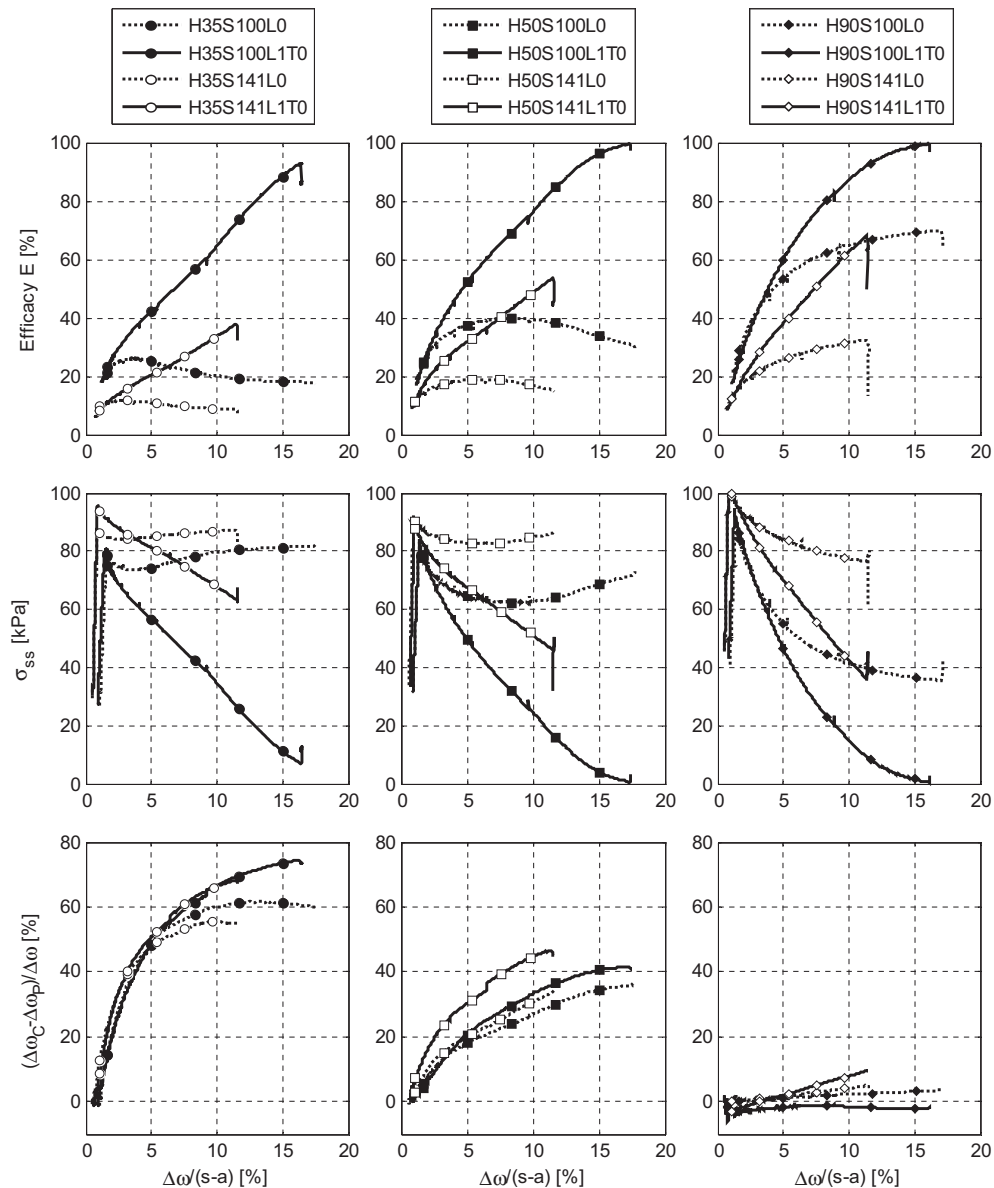


Fig. 17. Evolutions as a function of the ratio $\Delta\omega/(s-a)$ of the efficacy E , the soft soil stress σ_{ss} and the differential settlement ratio $(\Delta\omega_C - \Delta\omega_P)/\Delta\omega$ for the reference tests “L0” and the tests with geotextile without initial pretension “L1T0” – tests classified by the thickness of the granular mattress: $H = 90$ mm on the left - $H = 50$ mm in the middle - $H = 35$ mm on the right.

corresponds to an initial pretension equal to 50 N/m i.e. 0.2% tensile strength (resp. 250 N/m i.e. 1% tensile strength). On Fig. 18 are exposed the results of two tests families: “H35S100” and “H50S141”. From the tests results with “T0”, “T1” and “T2”, no difference can be clearly highlighted about the efficacy and the differential settlement. The initial pretensions put in these two tests series do not seem to act upon the membrane effect and more generally on the load transfer. Theoretically, applying an initial pretension to the geotextile changes its behaviour. It increases its

secant stiffness initially but also all along its use. The strength–strain relation is translated to lower deformation. The pretension increases the secant stiffness performance of the geotextile, not its tensile maximum strength. In our case, the two chosen pretensions should be too small to see some improvement in the reinforcement. In situ, the pretension goal is to insure the setting up of the geotextile layer on the soft soil. This practical point cannot be investigated by the developed device.

5. Conclusions

The improvement of the load transfer mechanisms due to the reinforcement by a geosynthetic layer in a granular mattress above rigid inclusions has been investigated. Three thicknesses of granular mattress ($H = 35, 50$ and 90 mm) and two networks of rigid inclusions ($\alpha = 4.91$ and 2.47%) have been tested in the IFSTTAR geo-centrifuge, using the mobile tray device.

Table 6

Comparison of the normalized differential settlement $(\Delta\omega_C - \Delta\omega_P)/a$ at a same stress remaining on the soft soil $\sigma_{ss} = 65$ kPa for tests $H = 50$ mm and $s = 100$ mm without (H50S100L0) and with (H50S100L1T0) geosynthetic.

Test H50S100	σ_{ss} [kPa]	$\Delta\omega/a$ [%]	$(\Delta\omega_C - \Delta\omega_P)/a$ [%]
L0 (Fig. 14)	65	20	4
L1 (Fig. 16)		10	2

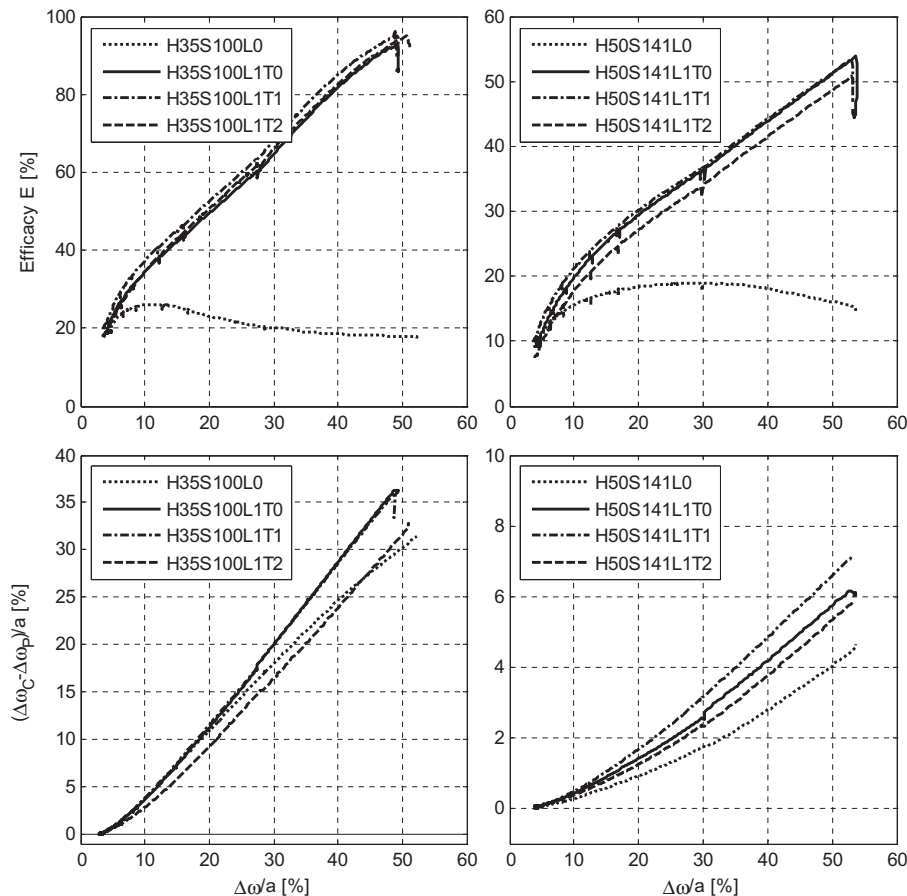


Fig. 18. Evolutions of the efficacy E and of the dimensionless differential settlement $(\Delta\omega_C - \Delta\omega_P)/a$ as a function of the ratio $\Delta\omega/a$ – Effects of the initial pretension “T0”, “T1” and “T2” for the series of tests “H35S100” (left) and “H50S141” (right).

Without geosynthetic reinforcement, the load transfer mechanism is only due to the development of arching effects inside the mattress. The differential settlement at the surface of the load transfer platform is lower for thick mattress but also for smaller α because the punching of the mattress by the piles has more space to be absorbed. The differential settlement is correlated to distance $s - a$ which represents the thickness of the mattress to obtain a full arching mechanism with the hypothesis of semi-cylindrical arches. The arching effects mainly depend on geometrical parameters: they are greater for thicker granular mattress and for higher mesh density. The peak of efficacy is obtained for deeper soft soil settlements in the case of thick mattress and low mesh density. However the efficacy should be compared to the shear strain of the mattress which is the ratio of the differential settlement on the thickness of the mattress. The efficacy - shear strain relation exhibits a same behaviour for all the mattress thickness. The arching mechanism needs great shear strain to be fully developed.

When a geosynthetic layer is inserted directly at the surface of the mobile tray, the geosynthetic transfers directly a part of the weight of the embankment which is not already transferred by arching. This mechanism, called membrane effect, translates the ability of a geosynthetic to adapt itself to support by tension the force acting initially perpendicularly to its plane. More the subsoil settles under the geosynthetic, more the membrane effect will be efficient. For this reason, improvements of the efficacy and the stress which remains on the soft soil take some soft soil settlement to clearly appear. The improvement of the load transfer mechanism is not only due to a better membrane but also to an improvement of the arching effect by the geosynthetic.

In the mobile tray device case, no improvement of the differential settlement has been observed by adding a geosynthetic layer. It is a consequence of the monitoring of the mobile tray by displacement. As a soft soil settlement is applied, so the differential settlement in surface of the granular mattress never stops. However, in situ, the load transfers induce an increase of the efficacy and then an unloading of the soft soil which conducts to a reduction of its settlement. The non-linear “coupling” between the efficacy and the settlement is not reproduced by the mobile tray test procedure. However, for a same level of stress on the soft soil, the differential settlement is largely smaller with the reinforcement by a geosynthetic.

The addition of an initial pretension does not bring any clear improvement. The membrane effect is governed by the deformation of the geosynthetic. So it largely depends on its secant stiffness. However, not enough pretension has been initially applied to improve significantly the secant stiffness of the geosynthetic.

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