A laboratory device to analyze the behavior of pile-supported embankment reinforced by geosynthetics

Laurent Briançon[1]
Université de Lyon, INSA-Lyon, GEOMAS, France

Abdelkader Abdelouhab
Texinov, France

ABSTRACT: Pile-supported embankment on soft soil are currently reinforced by geosynthetics. Many analytical methods have been developed to design the geosynthetic but they are simplistic and do not take into account all the complexity of the developed mechanisms. Despite all the difficulties met when simulating the behavior of pile-supported embankments in the laboratory, it is shown that 1g physical modeling tests can help one to understand the behavior. A new small-scale model, which has been developed to reproduce the behavior of pile-supported embankment at the scale 1/10. A specific study have been made to find and qualify a foam simulating the behavior of the soft soil. The first tests have validated the ability of the device to correctly simulate the behavior of pile-supported embankment.

Keywords: Geosynthetic, pile-supported embankment, laboratory device

1 INTRODUCTION

Construction of roadways and railways often represents a challenge for ground improvement techniques for constructing embankments on soft soil areas. A geosynthetic reinforced and pile-supported embankment system could be an interesting solution to comply with the strict requirements regarding settlement and stability for roadway and railway embankments. This technique also allows for reduction of the construction time in comparison to other soft soil improvement methods. Although this improvement technique is commonly used, its design is complex due to the interactions between all of the reinforcement components, such as piles, geosynthetic reinforcement, pile heads and working platform.

To improve the knowledge in this field, in the frame of a laboratory PITAGOR (Platform of Technological Innovations Applied to the Geosynthetics of the Reinforced Structures) founded by the French National Research Agency, a new small scale model has been developed to reproduce the behavior of pile-supported embankment. Many cares have been taken to ensure that the small-scale model is close to the real behavior of pile-supported embankment. In particular, the soft soil has been simulated with a foam presenting the same behavior. The monitoring of all piles allowed controlling the loading. The first results highlight that this new device is able to well simulate the pile-supported embankment and will allow investigating the interaction between all components constituting this soil improvement method.

2 BACKGROUD

Many laboratory tests in the field of pile-supported earth platforms were carried out on reduced scale models in 2D conditions (Jenck et al., 2005; Chen et al., 2008), in 3D conditions (Hewlett and Randolph, 1988,

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[1]Bâtiment J.C.A. Coulomb, 34 Avenue des Arts
INSA de Lyon - Domaine Scientifique de la Doua
69621 VILLEURBANNE Cedex, France

Demerdash, 1996, Kempfert et al., 1999, Hironaka et al., 2006) or more recently (Mc Guire, 2011, Van Eekelen et al., 2013, Houda, 2016). They mainly focused on the load transfer in the earth platform without taking into account systematically the behavior of the soft soil.

The results of the models in 2D conditions highlighted that it was not able to reproduce the behavior of a 3D problem. Many studies in 3D conditions have been performed on only four piles (Kempfert et al., 1999; Hironaka et al., 2006; Van Eekelen et al., 2013), their results can be affected by the boundary effect. Such authors modelled the behavior of the soft soil by a settlement plate (Demerdash, 1996; Hironaka et al., 2006); but recent full-scale experimentations (Briançon and Simon, 2012, 2017) highlighted that the major of load transfer occurs during the embankment setting up and thus the presence of a rigid base during the construction step is not able to reproduce the cinematic of the mechanisms.

Both studies used more than four piles in their experimental device (Mc Guire, 2011, Houda, 2016). Mc Guire (2011) studied the influence of the geometrical parameters on surface deformation and critical height of samples of sand. The base and lateral boundaries of the sample are held fixed and the columns are displaced upwards into the sample. The author found valuable results on the critical height but did not focus his study on the soft soil, which plays however, a significant role on the load transfer mechanisms. The apparatus of Houda (2016) contains 16 piles; the soft soil is modelled by a mixture of sand and polystyrene balls. This artificial soil presents a compressibility close to real soft soil but the setting up was difficult and it has not been proved that the initial conditions were always the same. Another problem of this small-scale device is that even if 16 piles were used, the load has not been measured on the pile located near the wall of the tank and the monitoring of this experimental device was not able to check if the load apply was the same on the central grid and on the other grids. Without knowing the initial conditions applied on the central grid, it is difficult to conclude on the load transfer mechanisms.

Even if such laboratory small scale devices allowed proposing design methods (Hewlett and Randolph, 1988; Kempfert et al., 1999; Van Eekelen et al., 2015), this short background shows the difficulty to model pile-supported embankment with them. To simulate correctly the real behavior of pile-supported embankment, the small-scale device must be designed such as:

- the load applied is the same on all the grids,
- the central grid is not affected by the boundary effect,
- the behavior of the soft soil and the geosynthetic are well modelled.

We have not found in the literature a small-scale model taking into account all these key points.

3 LABORATORY DEVICE

A new small-scale model has been developed to reproduce the behavior of pile-supported embankment at the scale 1/10 (Figure 1). The device consists in a rigid tank of inner square section 1.2 meter x 1.2 meter made of three stacked frames, a base and a top: the lower frame, 0.5 meter high, contains the monitoring at the pile toe, the middle frame, 0.5 meter high, contains the piles and the soft soil, the upper frame, 0.5 meter high, contains the granular load transfer platform (with or without a geosynthetic), the soil modelling the base of the embankment and an air pressure membrane to simulate the load of the embankment. The top is fixed on the upper frame. This model is made of 36 metallic piles, 30 mm in diameter, installed in 200 mm square grid. It has been chosen to set up 36 piles to get two lines of piles between the central grid and the wall of the tank. The behavior of reinforced load transfer platform and the piles will be observed on the central grid without boundary effects. The piles cross the middle and the lower frame and are directly set on the rigid base. The geosynthetic could be fixed between the middle and the upper frame or fixed inside the upper frame for the case where the geosynthetic is not directly laid on the pile heads.

The soft soil has been simulated by two types of foam; their compressibility have been characterized by odometer tests. To simplify the drilling for the 36 piles inside the foam, the 0.5 meter of soft soil is modelled by five 0.1 meter thick carpets of foam. Such tests could be performed without foam to measure the shape of the geosynthetic. The load transfer platform is simulated by granular materials and reinforced on not by geosynthetic, the embankment materials is simulated by sand.

Figure 1. Small-scale device

4 MONITORING

To simplify the understanding of the sensors location, piles are called by their columns (letters A to F) and their row (numbers 1 to 6), also the four piles of the central grid are called C3, D3, C4 and D4 (Figure 2). Piles of the central grid are particularly monitored with:

- Force sensors located at the toe of the pile (FS1 to FS4),
- Pressure cell located on the head of the pile (PC1),
- Force sensor located on the head of the pile (FSR1).

The four force sensors are the same (R10X of Scaime) with a range of 10 tons. The toe of the monitored pile has been specifically adjusted to be connected to the force sensor (Figures 2 and 3). The pressure cell PC1 (BED-A-200KP of Kyowa) has the same section than the pile and a range of 200 kPa. The head of the pile has been specifically adapted to insert the transductor of the sensor inside the pile (Figures 2 and 3).

The sensor FSR1 has also the same section than the pile and it is very thin. This sensor is a Force Sensing Resistor ® (Interlink Electronics). It consists of two membranes separated by a thin air gap. The air gap is maintained by a spacer around the edges and by the rigidity of the two membranes. One of the membranes has two sets of interdigitated fingers that are electrically distinct, with each set connecting to one trace on a tail. The other membrane is coated with FSR ink. When pressed, the FSR ink shorts the two traces together with a resistance that depends on applied force. Both membranes are typically formed on flexible polymer sheets. The top substrate could be made with a slightly less flexible material, sufficiently deformable to allow a reasonable force to push the top substrate against the bottom substrate to activate the sensor. The inside surface of one substrate is coated with carbon-based ink. When the two substrates are pressed together, the microscopic protrusions on the FSR ink surface short across the interdigitated fingers of the facing surface. At low forces, only the tallest protrusions make contact. At higher forces, more and more points make contact. The result is that the resistance between the conducting fingers is inversely proportional to the applied force. This force sensor is cheaper than the Pressure Cell but it is not linear and requires a specific calibration. The tests without soft soil will allow calibrating this sensor from the force sensor located at the toe of the same pile. If the first tests validate the relative accuracy of this sensor, all the piles will be monitored by them.

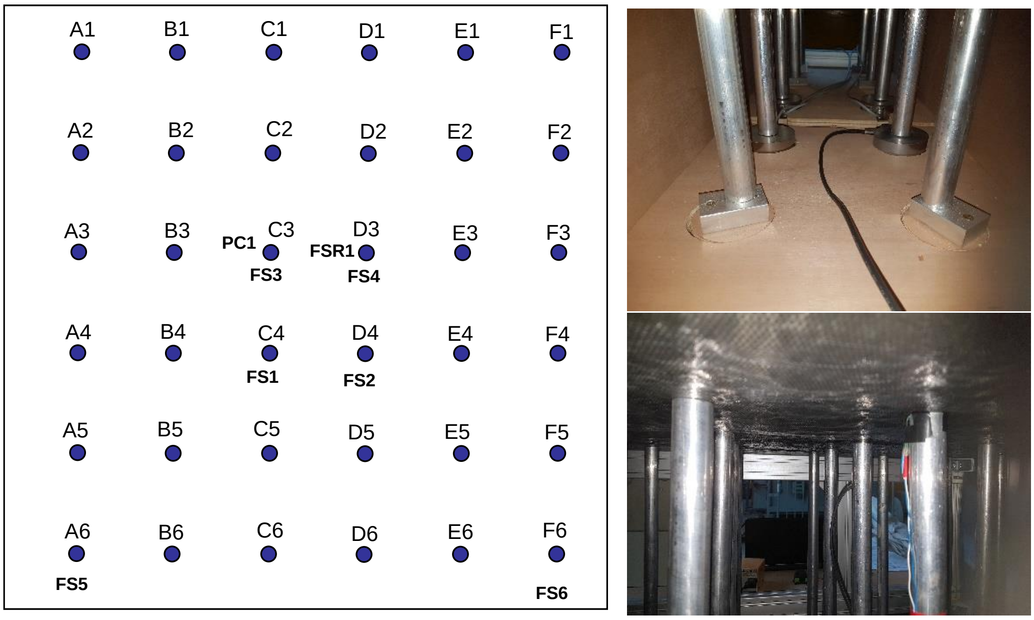

Figure 2.

To control the homogenous distribution of load on the piles, two other force sensors have been set up at the toe of the pile A6 and F6. Like for the pressure cell, the sensor FS5 is cheaper than the others. If the results of the first tests validate its accuracy, all the piles (except those of the central grid) will be monitored by them.

After the tests of qualification, all the piles would be monitored by a force sensor at their toe and a pressure cell at their head.

To record all the measures sent by the sensors, a logger DT85 from Datataker with four channel expansion modules is used to obtain 94 channels to connect the sensors.

The geosynthetic deflection and the settlement at the soil surface (below the air pressure membrane) are also monitored. The deflection is only measured in the case of tests without soft soil and the settlement at the soil surface can only be measured at the end of the test after removing the air pressure membrane. For the geosynthetic deflection, a rail is fixed in the lower frame between the two central lines of piles (row 3 and row 4). A laser sensor can move on the rail and it is connected to a wire displacement sensor. With this device, the wire displacement sensor gives the location of the laser sensor and the laser sensor gives the deflection of the geosynthetic (Figure 3). The same device can be fixed on the upper frame after removing the air pressure membrane to measure the settlement of the soil.

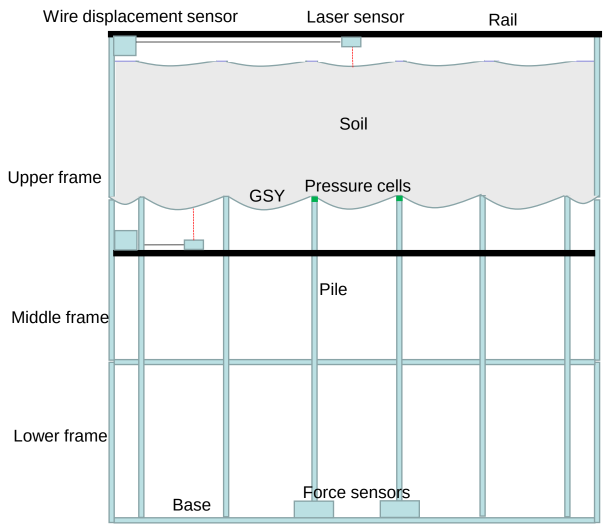

Figure 3. Monitoring for the test without soft soil

5 SOFT SOIL MODELLING

To model the soft soil, eight types of foam have been tested to find those that are more homogenous and with a compressibility, characteristics close to the real soft soil (Figure 4). To check the homogeneity, the density of five sample of each foam have been calculated from their sizes and their mass (Table 1). The void ratio of the one sample of each foam has also been calculated. To determine it, each sample has been put inside a water tightness cylinder of the same diameter and the same height. The mass of the cylinder is measured without foam, with dry foam and with saturated foam. From these masses, the void ratio is calculated (Table 1).

Figure 4. Foam samples

Table 1. Characteristics of foam samples.

Foam	Parameters		
	Density		Void ratio e_0
Type A	Mean value	0.024	2.58
	Coefficient of variation (%)	**2.0**	
Type B	Mean value	0.077	6.02
	Coefficient of variation (%)	**1.7**	
Type C	Mean value	0.022	
	Coefficient of variation (%)	2.7	
Type D	Mean value	0.035	
	Coefficient of variation (%)	3.2	
Type E	Mean value	0.022	
	Coefficient of variation (%)	5.0	
Type F	Mean value	0.04	2.00
	Coefficient of variation (%)	**2.4**	
Type G	Mean value	0.021	3.97
	Coefficient of variation (%)	**1.7**	
Type H	Mean value	0.025	
	Coefficient of variation (%)	**3.4**	

Finally, each type of foam has been tested in an odometer to characterize its compressibility. The loads applied for the test have been chosen from the load which will be applied on the foam for the test of pile supported-embankment small scale apparatus assuming that the efficiency of the reinforcement solution is upper than 60 %.

The criteria for the selection of foam for the pile supported-embankment tests are:

- The homogeneity of samples determined by the density,
- The compressibility,
- A linear behavior in the range of the applied stress.

The coefficient of variation has been calculated. It is defined as the ratio of the standard deviation to the mean of the five samples of each type of foam. It shows the extent of variability in relation to the mean of the density. It is chosen to compare the homogeneity because the mean value of the eight types of foam varies between 0.022 and 0.077 and in this case, the standard deviation is not a good indicator for the comparison. Four foams (A, B, F and G) present a coefficient of variation lower than 2.5 %, the four others (C, D, E and H) have been considered like too heterogeneous and have not been qualified to modelled the soft soil.

The results of the compressibility tests (Figure 5) show that it is not possible to simulate the real compressibility of a soft soil with the five foam samples with a virgin consolidation line and an over consolidated line. In addition, the choice of the foam type is done from the linear behavior of the foam for the range of stress applied on soil in the rigid inclusions device. Considering a thickness of soil of 0.5 m on the rigid inclusion and an efficiency upper than 60 % (ie 40 % of the load apply on a grid is transfer to the soil), the stress applied on the soil does not exceed 5 kPa. The samples A and H have a linear behavior between 0 and 5 kPa. These foams have been qualified to perform the tests to simulate the soft soil.

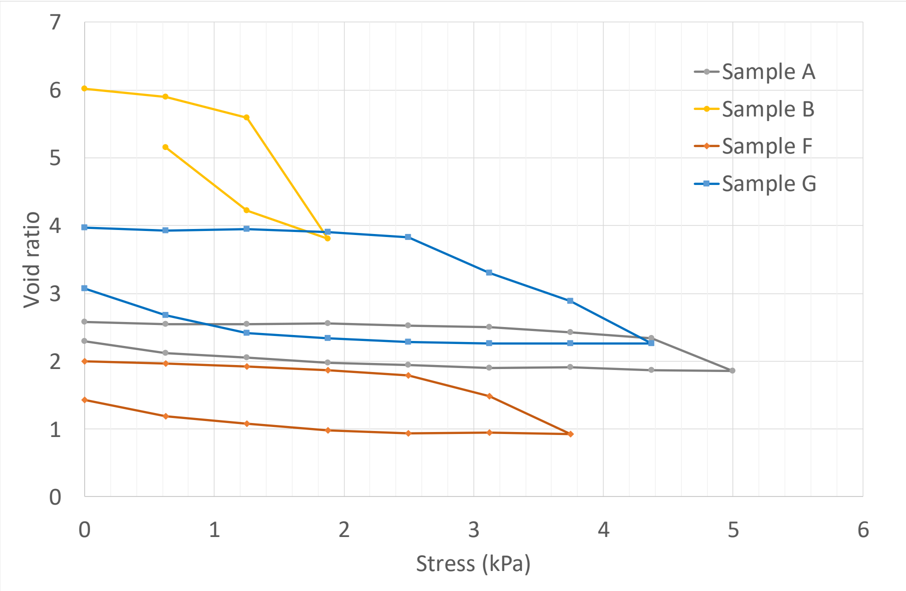

Figure 5. Compressibility tests

6 PROCEDURE OF SETTING UP

The same procedure is applied for all tests to limit the influence of the setting up on the results. The verticality of piles is controlled before each test. When all sensors are installed and connected to the data logger, the geosynthetic is laid out directly on the piles for the tests without soft soil and on a thin layer of sand when the foam carpets are used to simulate the soft soil. The geosynthetic is fixed to the clamp located on the four sides of the middle box. The upper box is filled by soil; it is possible to use a first soil to simulate the load transfer platform and a second soil to simulate the base of the embankment. To well simulate the real condition of the setting up, the soil is systematically put on the piles of the row 1 and pushed to the direction of the other piles by layers of 10 cm. The mass of the soil of each layer is measured to control its density. After that, the air pressure membrane is laid on the soil and the top is fixed on the upper box. The air pressure membrane is inflated to apply a pressure simulating the height of the embankment.

At the end of the test, the top and the air pressure are removed and the deformation of surface of the soil could be measured.

7 FIRST TESTS RESULTS

A first test has been performed without foam, with a woven geotextile laid out directly on the piles and with two layers of fine sand (10 cm in thickness). After the setting up of each layer of sand, the deflection of the geosynthetic has been measured between the rows 3 and 4 with the laser sensor moving on a rail and for 5 locations of the rail (X1 to X5). Figure 6 shows the deflection of the geosynthetic for the central grid between the piles C3 and D3. This Figure shows the ability of the device to measure with a good accuracy the deflection of the geosynthetic, the first observations are:

- The deflection measured on two symmetrical lines X4 and X5 are similar,
- The deflection of the geosynthetic decreases from the line X4 to the line X1.

Figure 7 shows the deflection of the geosynthetic under a layer of 20 cm of sand along the line located between the rows 3 and 4. The deflection is not perfectly symmetrical for all the grids due to the procedure of the setting up: from column A to F and from row 1 to 6. The shape of the geosynthetic deflection shows that it will be necessary to monitor the piles in the central grid and in the others, to be sure that there is not boundary effects.

From these measures, it will be possible to draw a 3D deflection shape of the geosynthetic for each loading step for tests without foam to simulate the soft soil.

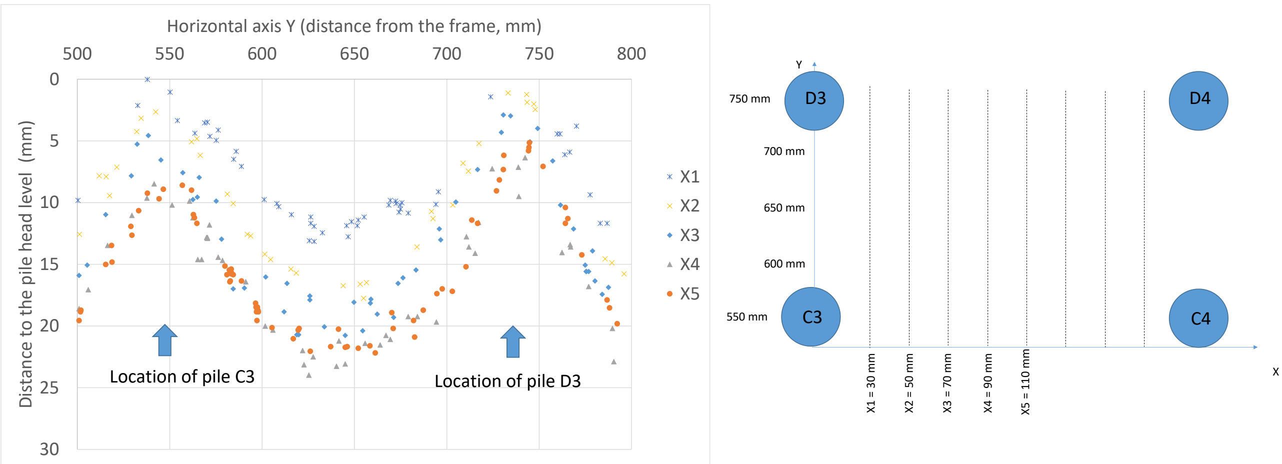

Figure 6. Deflection of the geosynthetic in the central grid under a layer of 20 cm of sand

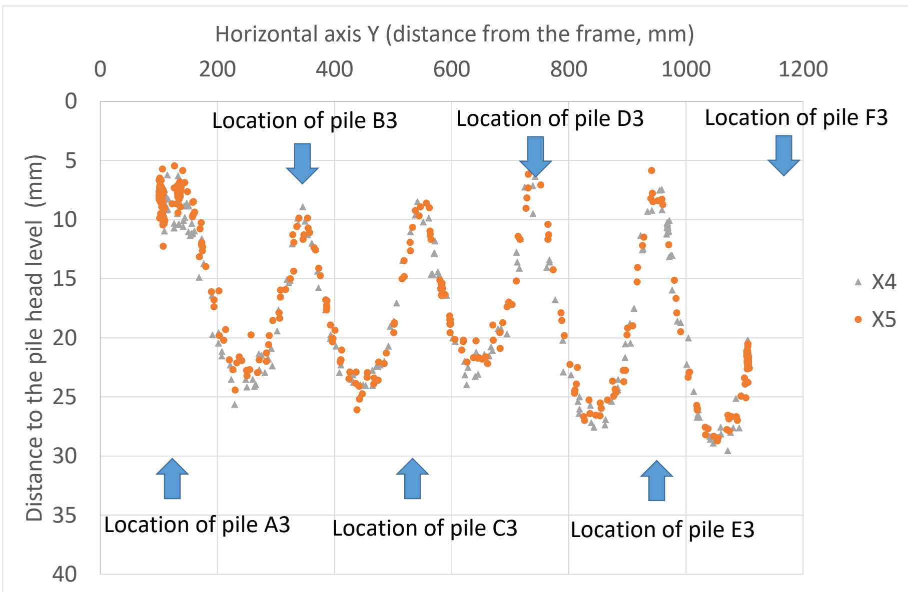

Figure 7. Deflection of the geosynthetic under a layer of 20 cm of sand

8 CONCLUSION

A new laboratory device has been developed to reproduce the behavior of pile-supported embankment at the scale 1/10. Two types of foam have been selected to simulate the behavior of the soft soil from laboratory tests. A specific monitoring allows measuring the stress applied on the pile head, the load at the pile toe, the deflection of the geosynthetic, the stress on the foam simulating the soft soil and the geosynthetic strain. The first tests validated the ability of this device to reproduce the behavior of the granular layer reinforced by geosynthetic on rigid inclusions. They also show the importance to check the stress distribution between the central grid and the others. To ensure a good control of the stress distribution, it is necessary to monitor with force sensors the piles of the central grid but also the other piles adjacent to the wall.

An experimental study will be performed to test many configurations to analyze the load transfer, to determine the role of each component and to optimize the design of the geosynthetic.

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