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Modelling the inflight construction of sand compaction piles in the centrifuge

Modélisation de la construction de colonnes ballastées "en vol" en centrifuge

T.M. Weber, J. Laue & S.M. Springman
Institute for Geotechnical Engineering, Swiss Federal Institute of Technology Zurich, Switzerland

ABSTRACT

Sand compaction piles are used in practice for ground improvement of weak subsoil. These columnar inclusions improve the consolidation behaviour as well as reduce the compressibility of the soft ground. The current design procedure of these sand piles is based on simple empirical calculations, which does not fully take account of the sand pile behaviour. In order to gain a deeper understanding of the behaviour of sand compaction piles, physical and numerical investigations are being conducted. The basic system behaviour of soft soil and column is simulated physically by centrifuge modelling. Because the stress situation in the soil changes significantly due to installation, a sand compaction pile installation tool was developed and applied successfully in the first tests. This allowed the stress paths encountered by the soil during the construction process of a displacement sand pile to be modelled realistically. The results will be compared to real geometries and the behaviour is also studied numerically by means of finite element modelling. These findings provide the basis for further analysis of this geotechnical interaction problem extending the model by including geotextiles below embankments to be able to formulate some recommendations for the design procedure of sand compaction piles under embankments.

RÉSUMÉ

Les colonnes ballastées de sable sont souvent utilisées dans la pratique pour l'amélioration des sous-sols faibles. Ces inclusions améliorent le comportement en consolidation et réduisent aussi la compressibilité du sol mou. La procédure actuelle de dimensionnement de ces colonnes de sable se base sur des calculs empiriques simples qui ne tiennent pas compte complètement du comportement du pieu de sable. Afin d'obtenir une meilleure compréhension du comportement des colonnes de sable ballastées, des études physiques et numériques sont conduites. Le comportement basique du système colonne – sol est simulé physiquement par une modélisation en centrifuge. L'état des tensions dans le sol changeant de manière significative à la suite de l'installation, un outil de mise en place de colonnes ballastées a été développé et utilisé avec succès dans les premiers essais. Ceci a permis de modéliser de manière réaliste les chemins des tensions subis par le sol durant la phase de construction d'une colonne ballastée. Le comportement est aussi étudié numériquement par la méthode des éléments finis et les résultats seront comparés aux résultats d'essais in situ. Sur la base de ces résultats, ce problème géotechnique d'interaction sera étendu à la modélisation supplémentaire d'un géosynthétique mis en place sous le remblai, dans le but de formuler des recommandations pour la procédure de dimensionnement des colonnes ballastées de sable sous les remblais.

1 INTRODUCTION

Sand compaction piles are widely used in practice in order to improve soft ground, such as soft clay or peat. In particular, when less settlement-sensitive structures such as embankments are designed, the more cost effective method of sand piles is often preferred, in comparison to creating a piled embankment with reinforced concrete piles.

In general, the methods of sand compaction pile installation can be distinguished into two major groups of displacement and replacement methods. Wet or dry processes are used to insert the columns into the ground. Two kinds of compaction methods of sand piles are common, using vibrating probes or rammed systems, (Mitchell, 1981; Van Impe, 1989; Van Impe et al., 1997).

Two the most frequently used installation methods are the vibroflotation method and the vibrodisplacement method. The vibroflotation method uses water in order to flush the probe into the ground and soil is removed out of the ground partially and replaced by sand. The vibrodisplacement method uses compressed air to flush the probe into the ground and the pile is inserted by displacing the soil. There are several different types of displacement probes, including one with the vibrator at the top and one at the base of the probe.

The design procedure for sand compaction piles is based on empirical and analytical approaches. The most commonly used method in German speaking regions is after Priebe (1995). Some key assumptions such as the even settlements of the soil body and the pile grid, do not apply to embankment loads. Also, the change in stress state due to the construction process of the sand piles is not taken into account. The method after Priebe (1995) gives an improvement factor referring to the unimproved ground. The calculation is fairly robust and usually gives a conservative value.

In order to overcome these deficiencies and to gain a better understanding of the behaviour of sand compaction piles, physical investigations are being carried out by means of the geotechnical centrifuge (Springamn et al., 2001). As a first step, an installation tool for sand pile construction was developed. The first experiences gained with this tool are presented in this paper.

2 SAND COMPACTION PILE INSTALLATION

In order to model the sand compaction pile installation process, an installation tool has been developed for the geotechnical drum centrifuge. This installation tool reproduces the production process of a displacement pile using a dry construction method similar to the vibrodisplacement method.

Earlier methods of sand pile installation in the centrifuge were conducted under 1 g, for instance the sand piles were frozen and pressed into holes previously augered into the clay, or simply sand was poured into predrilled holes. These methods are not able to model the stress situation that occurs during the installation process. Only piles installed 'in flight' are able to represent the stress situation of the prototype pile in the centrifuge (Lee et al., 2004; Kusakabe, 2002; Lee et al., 2001).

The new tool consists of mainly 4 parts: mounting, collection tube, transition piece and filling tube. All the parts are made of aluminium except the filling tube, which is made of stainless steel. A sketch of the tool and the assembly at the tool plate of the drum centrifuge are shown in Figures 1 and 2, respectively.

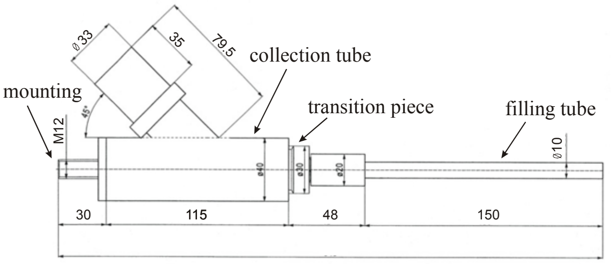

Figure 1. Technical drawing of the sand compaction pile installation tool, dimensions [mm]

In order to prevent plugging of the filling tube by clay during installation of the pile, a lost tip system is being applied. A drawing pin is simply stuck onto the surface of the clay model. When the filling tube is driven into the clay, the cap of the drawing pin closes the opening of the filling tube. When reaching the desired depth, sand is filled into the inlet sand hose from outside the centrifuge. Slowly the installation tool is withdrawn and the sand flows out of the filling tube. The drawing pin remains in the soil model.

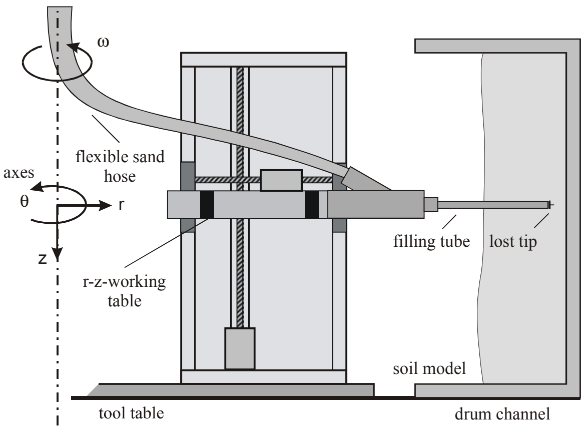

Figure 2. Construction of sand piles in the drum centrifuge

Compaction of the sand pile is achieved by slowly drawing out and re-inserting the installation tool again into the soil. Depending on the relationship between the degree of withdrawal and re-insertion, different sizes and densities of the sand pile can be obtained.

In order to produce a grid of sand compaction piles, the dimensions of the grid must be marked with drawing pins on the surface of the clay model in the z-θ axes before the beginning of the test. During the test, the positions of the drawing pins are approached by the tool and one pile after another can be produced without stopping the centrifuge.

3 CENTRIFUGE TEST

In summer 2004, two centrifuge tests had been conducted. The set up of both tests were similar in order to compare the results and to overcome the difficulties that occurred during the first test. The system itself is working, but the sand compaction pile installation tool still needs some improvement in order to perform more sophisticated centrifuge tests in the future. The second test gave better results and will be described subsequently. The aim of the test was to investigate the consolidation behaviour of sand compaction piles produced inflight in a soft clay model under a uniform one-dimensional sand load. The tests were performed in a round container filled with remoulded clay.

The model was divided into 4 regions. Three fields had a different pile grid spacing of 30x30 mm, 35x35 mm and 40x40 mm and the piles were not compacted. In the fourth field, a pile grid of 35x35 mm was installed and the sand piles were compacted by a ratio of 15/10 mm. This means the tool is withdrawn 15 mm and re-inserted 10 mm for compaction until the pile is finished. Each field consisted of 9 piles except the grid with the small spacings, which contained 12 piles.

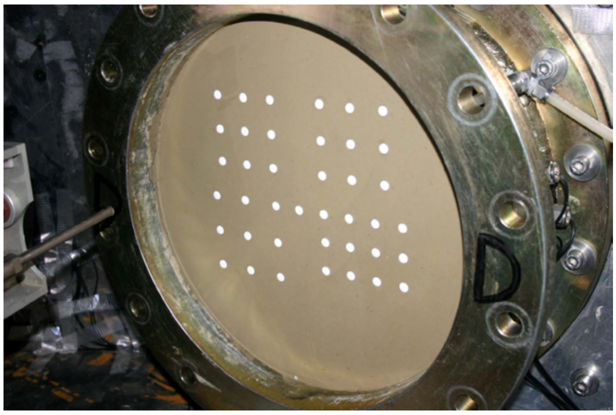

Figure 3. Lay out of the pile grids in the clay container using drawing pins as lost tips

The test was performed at a level of 50 times gravity. The thickness of the clay model was 14 cm. All the sand piles had a length of 10 cm ±2 cm and were functioning as floating piles. Due to constraint of the tool geometry, the piles did not always have the same length.

Quartz sand with a sieved fraction of 0.5-1.0 mm was used for the sand piles. Remoulded natural Swiss lacustrine clay from Birmensdorf was used for the clay model. The material properties are stated in Messerklinger et al. (2003). Consolidation data are given in Table 1 below. The clay was mixed to slurry at a water content of about 80 % and consolidated in a press in 6 steps up to 100 kPa consolidation pressure. The water content at the end of consolidation was 41 %. The clay model was drained at the top and bottom.

Table 1: Parameters of the clay from Birmensdorf after consolidation in the press at last load step, 50 - 100 kPa

1-d compression modulus M_E [kN/m^2]	817
permeability k [m/s]	$1.6 \cdot 10^{-9}$
coefficient of consolidation c_v [m/s^2]	$1.3 \cdot 10^{-7}$
saturated density γ_{sat} [g/cm^3]	1.82

Twelve pore pressure transducers were calibrated and inserted into the clay model. The water table was set 1 cm below the clay surface at the centre of the model and water could be filled in through a pipe at the bottom of the container.

A laser distance measuring device was used in order to measure the surface settlements of the soil model during the consolidation phases of the test.

A T-Bar penetrometer test was planned during the centrifuge test in order to measure the undrained shear strength of the clay inflight (Stewart & Randolph, 1994). The T-Bar cross piece has the dimensions of 28 mm in length by 7 mm in diameter. The tool was calibrated by clamping it into a vice with the tip directed vertically upwards. A strap was placed over the bar and a bowl hung on strings underneath the tool. By placing weights into the bowl and logging the output values of the T-Bar, the calibration curve of axial compressive force versus measured digits could be obtained.

The centrifuge test was scheduled over 60 hours non-stop. The model was consolidating under self weight for the first 12 hours. The T-Bar test was conducted after this, before beginning with the sand pile installation.

The installation of the sand piles took 12 hours. 12 out of 39 piles could not be produced properly, due to blocking of the flexible hose with sand and plugging of the filling tube with clay. The tool table had to be stopped several times to clean the blocks. Because of the independent control of the drum and the tool table, it was not necessary to stop the drum channel and the servicing of the tool table could be carried out protected by a safety shield (Springman et al., 2001).

After further consolidation, the sand layer of 3.5 cm thickness was built onto the soil model. The sand was filled into the centrifuge through the flexible hose. A scraping device was used to level the sand surface.

The settlements of the soil model were measured with the laser scanning device along certain profiles after placing the sand layer for a period of 12 hours.

After completion of the test, samples were taken from the model to determine the density of the sand piles and to carry out oedometer tests and fall cone tests.

4 RESULTS

The result of the T-Bar test is shown in Figure 4. After penetrating the surface, the bar needs about 3 to 4 diameters (20 to 30 mm) of insertion to develop the plastic mechanism. Based on an undrained response and fully plastic flow around the tip bar (e.g. after Randolph & Houlsby, 1984), a bearing value N_b of about 10.5 can be assumed and the undrained shear strength can be determined (Stewart & Randolph, 1994). The distribution of the undrained shear strength s_u gives a fairly constant value of 20 to 23 kPa over the model depth from 30 mm.

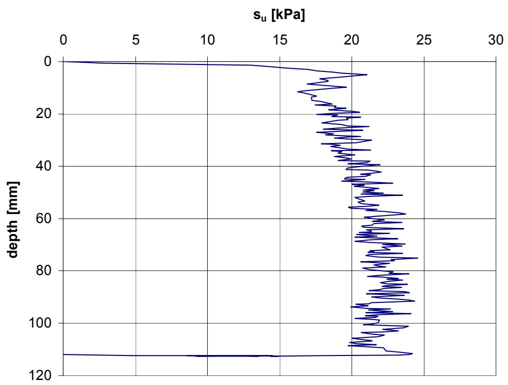

Figure 4. Distribution of undrained shear strength with depth in the clay model inflight after consolidation measured with T-Bar penetrometer

Figure 5 shows the development of pore pressures due to the installation of a single sand pile without compaction. The pore pressure transducer was located 3 cm, three times the pile diameter, away from the pile at a depth of 10 cm, while the sand pile had a depth of 12 cm. The stages of construction are marked with arrows: 1- the filling tube is penetrating the clay surface, 2- the tip of the filling tube passes the depth of the pore pressure transducer, 3- the filling tube reaches the desired depth of the pile and sand is filled into the pile installation tool, 4- the filling tube is withdrawn from the model, 5- the tip of the filling tube reaches the clay surface. An excess pore pressure of 27 kPa was measured immediately after pile construction. An interesting point is the slight dip of pore pressure, of magnitude of 2.5 kPa, when the tip of the filling tube penetrates the clay surface at the beginning of the construction process. A maximum value of the pore pressure is reached, when the tip of the tool passes the depth of the transducer (No. 2). After passing, the pore pressure development decreases. The filling the sand in causes a slight increase in pore pressures (No. 3). The steep decline at the beginning of the withdrawal of the tool gives a change in pore pressures of 134 kPa from 111 kPa to -23 kPa. The pore pressures recover above the initial values before construction during the withdrawal of the tool from the clay.

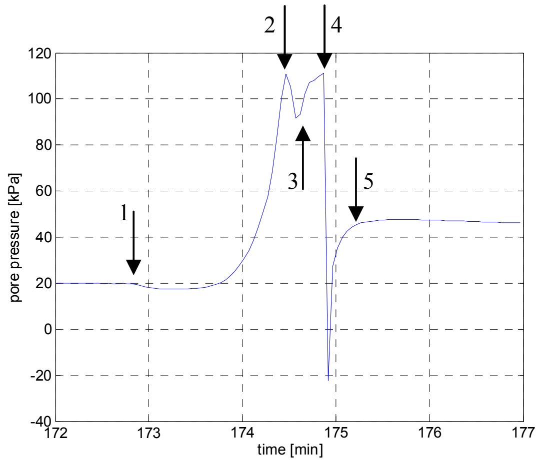

Figure 5. Pore pressure development due to construction of one un-compacted sand pile (transducer located 3 cm from pile)

Figure 6 shows the development of pore pressure near to a compacted sand pile. The stages of construction from 1 to 5 are similar to those mentioned for an un-compacted pile, except Phase 4 differs significantly. The pore pressure transducer was located 6.5 cm, or 6 times the pile diameter, away from the pile axis. The transducer was positioned 7.5 cm below surface. The investigated pile had a depth of 10 cm. The ratio of compaction was 15/10 mm, 15 mm withdrawal to 10 mm re-insertion.

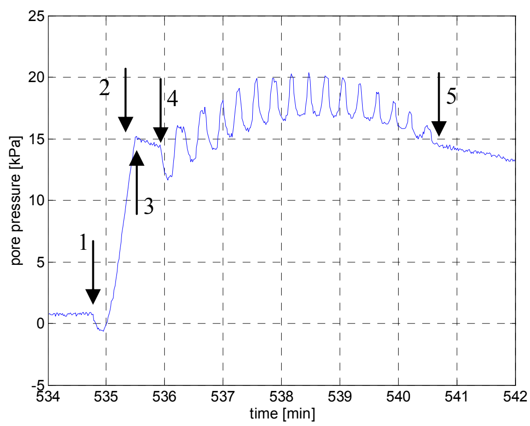

Figure 6. Pore pressure development due to construction of one compacted sand pile (transducer located 6.5 cm from pile)

At the beginning of the pile construction, a small dip of pore pressure of 1.5 kPa is also visible when the tool penetrates the clay surface before reaching a first maximum. The pore pressure does not respond, when the tool passes the depth of the pore pressure transducer. Also the filling of the sand into the tool is not visible in the pore pressure development. At the first withdrawal of the tool, the pore pressures drop slightly. After reinsertion of the tool the pore pressures increase above the initial maximum value. The excess pore pressures tend to decrease instantly after the insertion of the tool, but due to re-insertion, the pore pressures increase each stroke and are superimposed on a decreasing trend so that the development of pore pressures describes a cyclical and convex curve. Immediately after construction of the pile, an excess pore pressure of 13 kPa remains.

Figure 7 shows the section of 4 un-compacted sand piles. An average diameter of these piles is about 10 mm. A diameter of 12 mm with a compaction ration of 15/10 mm can be obtained for the compacted piles (no photo shown). The density of the sand piles can be increased due to compaction and was determined after the centrifuge test with a trepanning cylinder. Under the assumption that the pores of the sand piles are dry, water is injected into the piles and the mass of the water is measured. After sieving of the material the mass of the sand pile can be weighed and the density can be calculated. Un-compacted sand piles had an average density of 1.50 g/cm^3 in comparison to compacted piles with a density of 1.68 g/cm^3.

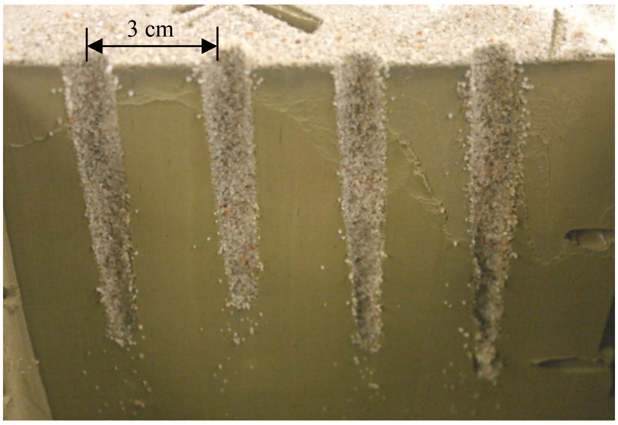

Figure 7. Section through un-compacted sand piles with 30 mm grid spacing

5 COMPARISON TO NUMERICAL CALCULATIONS

A finite element analysis of the sand pile construction process was carried out using PLAXIS. The first aim was to back-calculate the pore pressure development in the clay model during the construction process of a sand pile. An axis-symmetric model at prototype scale was used for a single pile analysis. The penetration of the sand pile installer into the clay was modelled after an approach from Debats et al. (2003) through stepwise cylindrical horizontal deformations of the bore hole in subsequent depths. The cylindrical expansion started from an inner core of 5 cm to the final pile radius of 25 cm. The modelled pile had a length of 6 m and floated 1 m above the bearing stratum. Modified Cam Clay was used as the constitutive model for the clay.

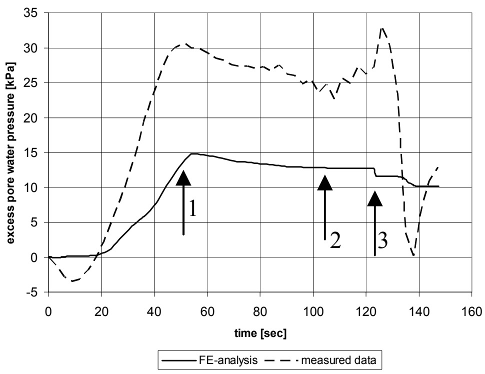

Figure 8. Excess pore pressure development due to sand pile installation, distance from pile to transducer is 3 pile diameters; 1- pile installer passing transducer depth, 2- reaching final pile depth, 3- withdrawal

Figure 8 shows the comparison of numerically modelled excess pore pressure development due to construction of an un-compacted sand pile in comparison to measured data. The quoted pore pressure transducer is located at a depth of 50 mm, representing 2.5 m in prototype scale and 30 mm away from the pile, representing 1.5 m. The numerical model can reproduce some of the characteristics of the measured graph. After about 50 seconds (1) the pile installer passes the depth of the transducer. Both curves show a maximum value at that time and level off afterwards. Quantitatively the calculated values of excess pore pressures are about half the magnitude of the measured values. Also more efforts need to be made towards the modelling of the withdrawal of the pile installer out of the clay.

6 CONCLUSION

The sand compaction pile installation tool is able to model closely the construction process of a sand compaction pile in the drum centrifuge. The system of using a lost tip was applied in the first tests. The diameter and the density of compacted sand piles are increased by withdrawal and reinsertion of the tool in comparison to un-compacted piles. Pore water pressure measurements show a significant increase of excess pore water pressure due to sand pile installation. Some qualitative characteristics of the development of excess pore water pressure due to pile installation could be modelled with a first FE-model.

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