Deformation behaviour of single and meshed stone columns in centrifuge tests

R. Girout
Federal University of Rio de Janeiro, Rio de Janeiro, Rio de Janeiro, Brazil, rgirout@gmail.com
J.R.M.S. Oliveira, M.S.S. Almeida
Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, jrmso70@gmail.com, marciossal@gmail.com
M.V. Riccio Filho
Federal University of Juiz de Fora, Juiz de Fora, Minas Gerais, Brazil, mario.riccio@ufjf.br

ABSTRACT: Soft soils are a major issue in civil engineering, and the stone/sand column technique, among several techniques developed to ensure serviceability, has been intensively used in Europe since the 1950s. The process consists of installing a vertical stone/sand column, which acts as a stiffer element as well as a drain, thus supporting load and decreasing both consolidation time and soft soil settlements. The stone columns are also useful to improve the bearing capacity of the soft soil foundation, preventing the need for basal reinforcement or berms. Their failure occurs due to excessive lateral expansion, generalized shearing, or base punching. The use of this technique in very soft soils is normally associated with geosynthetic encasements installed around the stone columns to ensure confinement. This paper aims to use centrifuge modelling to investigate the deformation behaviour of stone columns subjected to constant loading and how the geometrical parameters of stone column networks affect their overall behaviour. For this purpose, different clay samples with different undrained shear strengths were built to investigate the influence of the installation method and the area replacement ratio. Additionally, tests were carried out with conventional and encased stone columns to evaluate the effect on settlements and total stress redistribution.

1 INTRODUCTION

Soft soils are a major issue in civil engineering, and the stone/sand column technique, developed in the 1950s, has been widely used since then to ensure serviceability. The process consists of installing a vertical stone/sand column that acts as a stiffer element and a drain, thereby supporting loads and reducing both consolidation time and soft soil settlements. The stone columns are also useful to improve the bearing capacity of the soft soil foundation, preventing the need for basal reinforcement or berms.

There are two installation techniques mainly used in stone/sand encased columns with geosynthetic: the displacement method and the replacement method. The first one uses a closed-tip steel pipe, which is driven into the soft clay. The stone/sand material is placed inside the pipe and forced out towards the soil while the pipe is withdrawn, leaving the tip behind. The second method consists of inserting an open steel pipe, which is driven until it reaches the bearing layer when the soil is removed by an auger and replaced by a stone/sand material and the pipe is removed.

If the geosynthetic encasement is not used, the most widespread and used process is the vibro replacement method. Priebe (1995) is normally applied for piled embankment designed with this method. In this study, the stone columns were installed using the displacement method and replacement method, unlike the vibro replacement method.

The stiffness of the material that fulfils the columns is much lower than the stiffness of a concrete pile. Their failure occurs by excessive lateral expansion, generalized shearing, or base punching (Muir Wood et al., 2000). The use of this technique in very soft soils is normally associated with geosynthetic encasements when the undrained shear strength s_u is equal or lower than 15 kPa (EBGEO, 2011). Moreover, the geotextile also works as a filter, avoiding permeability reduction with time of the granular filling by clay infiltration.

Yoo et al. (2015) investigated column meshes in clay layers consolidated in the centrifuge. Gautray et al. (2013) and Gautray (2014) developed an original in-flight device to install the stone columns and load them with the prescribed displacement of a rigid footing. Their results show a significant bulging of the columns with increasing diameter at mid-depth.

This paper aims to use centrifuge modelling to investigate the deformation behaviour of single and meshed stone columns subjected to constant loading and how the geometrical parameters of the stone column networks affect their overall behaviour. For this purpose, different clay samples with undrained shear strength varying from 11 kPa to 28 kPa were built to investigate the influence of the installation method in single columns and the area replacement ratio in meshed columns. Additionally, tests were carried out with conventional and encased stone columns to evaluate the effect on settlements and total stress redistribution.

2 SOIL PARAMETERS

An artificial kaolin clay soil was used to simulate the soft soil layer in the tests and increase repeatability since natural soils tend to be more variable. A series of soil characterization tests was undertaken to assess the main geotechnical parameters (Trejo, 2015): $G_s = 2.567$, $\gamma_s = 25.2$ kN/m^3, $w_L = 54\%$, $w_P = 20\%$, and $I_P = 34\%$.

The clay beds were built using the well-established clay lumps technique (Manivannan et al. 1998, Cheuk et al. 2007) with the kaolin at a water content of $1.5w_L$, which was found to improve workability and facilitate collapse of the macro voids during consolidation. Water content measurements taken after the tests confirm decreasing values with depth, as expected, and a very homogeneous layer.

The stone columns were modelled using a well-studied sand from the São Francisco site in Rio de Janeiro, which has been previously used in different studies (Guimarães et al., 2015). According to the authors, the main minerals found in this soil, weathering products of gneisses which are predominant in the region, are the milky white, yellow, and colorless quartz with dark deposits, indicating the presence of biotite mica in the form of yellow and brown lamellae. The shape of the grains varies from sub-rounded to sub-angular. The soil has a percentage of 62% of fine sand (0.06 to 0.20mm) and 38% of medium sand (0.20 to 0.60mm). The main geotechnical properties of this sand are: $G_s = 2.64$, $e_{max} = 0.92$, $e_{min} = 0.60$, $\gamma_{max} = 16.5$ kN/m^3, $\gamma_{min} = 13.8$ kN/m^3, $\phi' = 40°$ at $D_r = 80\%$.

3 EQUIPMENT AND METHODS

The tests were undertaken at the Federal University of Rio de Janeiro (COPPE/UFRJ) 1.6 m diameter beam centrifuge (Almeida et al., 2014), which comprises a 0.10 m wide, 0.30 m long, and 0.18 m high strong box.

A dual-axis step motor and drive system actuator mounted at the strong box can apply downward and upward movements (z-axis) as well as horizontal movement along the length of a sample (x-axis).

A pre-calculated amount of clay lumps is placed inside the strong box to build the layer. The main purpose was to test two different clay layer scenarios, with undrained shear strength values at the mid-depth of the consolidated layer around 15 kPa for the weaker one and 30 kPa for the stronger one. After placing the lumps, temporary surcharges are applied on the clay surface, and the centrifuge is accelerated to 100g until the clay reaches 85% consolidation. A transducer is used to monitor the pore-pressure dissipation during consolidation, and a laser distance sensor is used to track the clay settlement.

After the consolidation phase, the centrifuge is stopped, the surcharge is removed, and the clay layer is then considered ready for the stone column construction phase, with tests conducted at N = 65g.

After the actuation, T-bar penetration tests are carried out in each container to assess the undrained shear strength profile of the clay layer, which can vary from 11 kPa to 28 kPa at mid-depth (around 3.0 m). Figure 1 presents a sample T-bar profile for s_u = 15 kPa. The columns are built along the entire length of the clay layers, which are normally near 6.0 m thick.

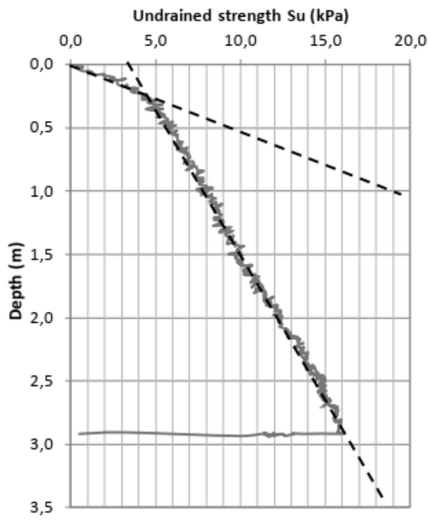

Figure 1. Typical T-bar undrained shear strength profile after clay consolidation (U=85%).

4 CENTRIFUGE TEST SET-UP

Regarding the stone column construction phase, two different building techniques were adopted: the displacement method, where a solid shaft is inserted through the soil, displacing the clay sideways and then removed; and the replacement method, where a hollow tube is inserted in the soil and then extracted along with the clay trapped inside the tube. The first method is expected to disturb the soil around the shaft, while the second one is expected to minimize the influence of the column installation.

The 1g installation might lead to different soil-structure interaction responses since it is carried out under low effective stress levels, while in-flight installation (*N*g) replicates the higher stress levels of the prototype. However, works such as Fan et al. (2021) simulating monopile installation show that this influence may be of limited relevance.

The sand was poured into the soil cavity at 1g using the pluviation technique through a manual funnel. Both the falling height and the flow rate were controlled to keep the sand's relative density as close as possible to 80%.

In order to examine the performance of a single column and a group of columns, two different approaches were considered, as follows.

4.1 Single-column tests

For these tests, a 15.4 mm diameter and 92 mm long single column at 65 g, equivalent to a 1.0 m diameter and 6.0 m long prototype column (N = 65), was built in the clay layer using the displacement or the replacement methods. The columns were loaded using circular rigid plates, which were kept in position by means of a very light styrofoam frame. Friction between the loading plates and the surrounding styrofoam is considered negligible. Three different loading situations were considered, where the total load was kept constant at 117 kN (prototype scale) while varying the plate diameter d_p = 15 mm, 20 mm or 25 mm, thus applying different stress levels as shown in Figure 2. The main idea of these tests was to evaluate the influence of the clay layer strength on the loading distribution around the column, as well as the influence of the installation method on the final settlements.

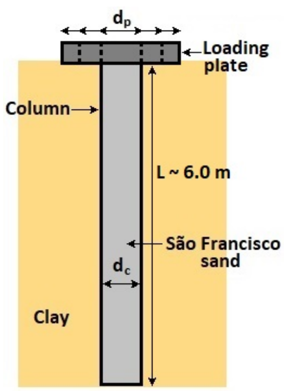

Figure 2. Sigle-column configuration.

4.2 Column mesh tests

For these tests, sets of 15.4 mm diameter columns at 65 g, equivalent to a 1.0 m diameter prototype column, were built using only the displacement technique with spacing between the centre of columns of *s* = *2.4* cm and *2.8* cm, leading to area replacement ratios of α = 32.3% and 23.2%, respectively, as defined in:

$$\alpha = \frac{A_{Column}}{A_{Total}} \tag{1}$$

Two sets were constructed per container, as shown in Figure 3, with rigid loading plates calculated to apply 150 kPa to the network area. A transversal subdivision completely isolates the two sets of columns, allowing both tests to happen simultaneously.

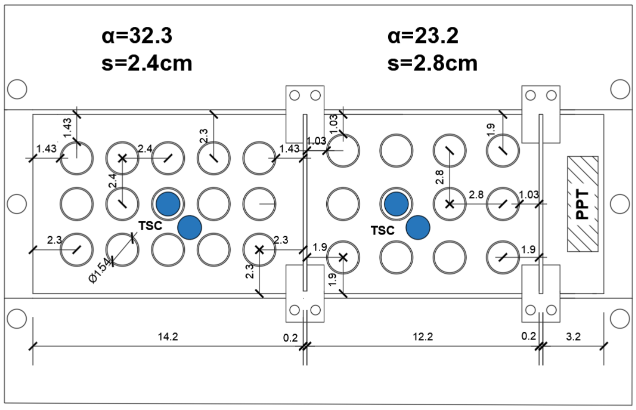

Figure 3. Column pattern distribution for the mesh tests (dimensions in cm).

Two different surcharge configurations were adopted: a rigid plate placed directly on top of the clay layer and a sand mattress constructed between the clay layer and the rigid plate. The main difference between these two configurations is that the rigid plate placed directly over the soil does not allow any relative deformation between the columns and the clay layer, involving both materials in the load transfer mechanism, while the sand mattress allows some relative deformation between them. The first configuration was used to compare settlements between different area replacement ratios, while the second one was used to assess stress values on top of the columns and on top of the clay.

A 1.95 m (prototype scale) height sand mattress was constructed in three stages of 0.65 m thickness (prototype scale) above the clay layer to an 80% relative density. Two 70 bar EPL-D1 mini total stress cells (TSC) from Measurement Specialties were used to measure the stresses. The first TSC was placed on top of a column, and the second TSC was placed over the clay layer, both below the sand mattress.

Regarding the encased stone column tests, the reinforced columns were built using a one-layer wrap of J = 11,000 kN/m stiff Hatelit geotextile in prototype scale (J = 2.60 kN/m in model scale), which was previously sewed and installed using a hollow tube to remove the soil and a wrapped solid tube to insert the geotextile.

5 TESTS RESULTS

5.1 Single-column tests

Table 1 presents the single-column test program with the main parameters, while settlement results (δ_v) against applied stresses are presented in Figure 4. In Table 1, the s_u value is at mid-depth.

Table 1. Single-column test program.

Test	s_u	d_p / d_c	σ_v	δ_v	Method
1	14	1.6	58	3.3	Repl.
2	17	1.0	149	7.4	Repl.
3	14	1.3	88	2.7	Displ.
4	14	1.3	88	2.5	Repl.
5	17	1.6	58	1.8	Displ.
6	17	1.6	58	1.8	Repl.
7	15	1.0	149	4.7	Displ.
8	15	1.0	149	5.4	Repl.
9	28	1.3	88	3.2	Displ.
10	28	1.3	88	1.9	Repl.
11	17	1.6	58	2.5	Displ.
12	17	1.6	58	3.5	Repl.
13	14	1.6	58	3.1	Repl.

Units: s_u (kPa); σ_v (kPa); δ_v (mm).

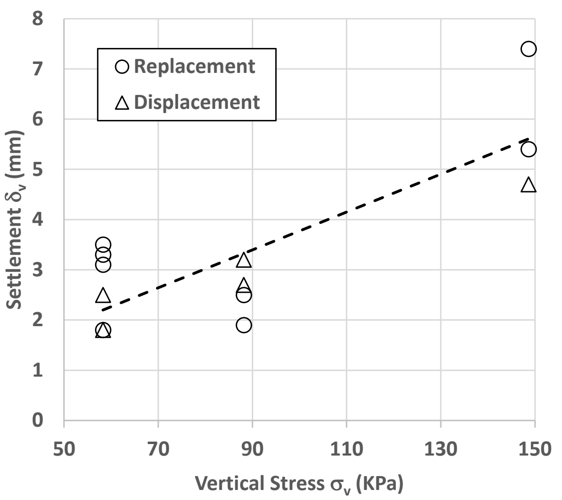

Figure 4. Settlements against applied vertical stresses.

Settlements have an increasing trend with stress levels even if the total load is the same, showing that the clay surrounding the columns contributes to the deformation behaviour.

In order to consider the influence of the variation of the undrained shear strength (s_u) and the applied vertical stress (σ_v) in the settlement values, a corrected settlement ($\delta_{v,c}$) was proposed and defined as:

$$\delta_{v,c} = \frac{s_u}{\sigma_v}\delta_v \qquad (2)$$

Figure 5 shows that $\delta_{v,c}$ results are close to a constant mean value of 0.65 ± 0.21 mm, which supports that the column settlements for this specific situation depend mainly on the surrounding s_u values and the applied stresses.

$$\beta = \frac{\delta_{v,uni}}{\delta_v} \qquad (3)$$

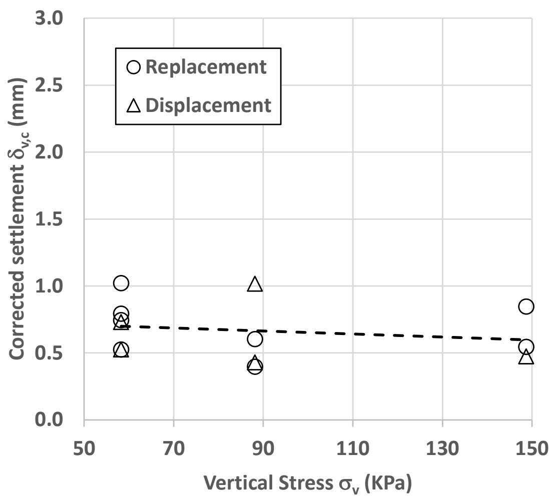

Figure 5. Corrected settlements against applied vertical stresses.

Figure 6 shows the comparison between the settlement improvement factor (β), as defined in Equation (3), and the d_p/d_c ratio, where $\delta_{v,uni}$ is the reference settlement for an unimproved clay layer, which is the case where no column is built: The settlement improvement factor decreases with d_p/d_c ratio and increases with stress levels. Again, no significant difference was observed between the two installation methods.

5.2 Column mesh tests

Column mesh test data are presented in Table 2, and settlement results (δ_v) over area replacement ratio (α) for the 150 kPa rigid plate surcharge without sand mattress are presented in Figure 7.

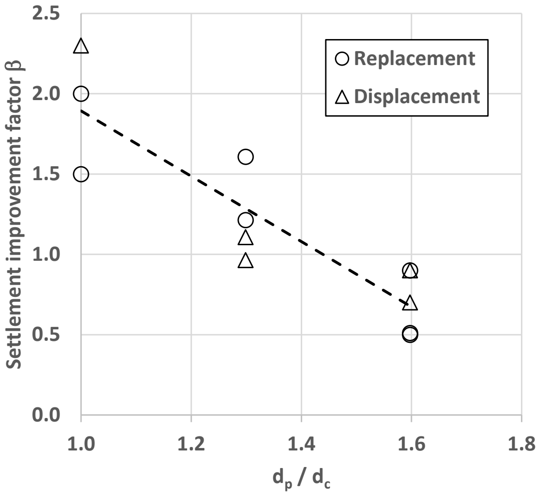

Figure 6. Settlement improvement factor (β) with d_p/d_c ratio.

Table 2. Column mesh test program.

Test	s_u	α (%)	δ_v	β	Method
1	11	0	7.2	1.00	-
2	11	23.2	3.5	2.06	Repl.
3	18	0	7.5	1.00	-
4	18	32.3	3.9	1.92	Repl.
5	19	23.2	3.4	2.21	Repl.
6	19	32.3	3.7	2.03	Repl.

Units: s_u (kPa); δ_v (mm).

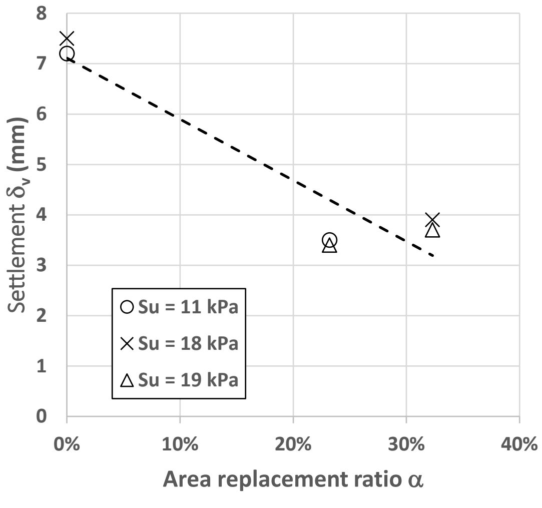

Figure 7. Settlements against the area replacement ratio for column meshes.

Tests show that no significant difference was observed for $\alpha = 23.2\%$ and 32.3%, maybe due to the small variation in the area replacement ratio. No considerable difference was also noticed between tests with different s_u values.

Tests with α = 0%, where no column was used, also show very close displacements, regardless of the s_u variation from 11 kPa to 18 kPa. However, comparisons between settlements on unimproved soil ($\alpha = 0\%$) and those where column mesh was adopted show a reduction of around 50%.

Figure 8 compares field settlement improvement values from literature presented by Kempfert (2003) and Raithel et al. (2005) with results from the present work, showing good agreement.

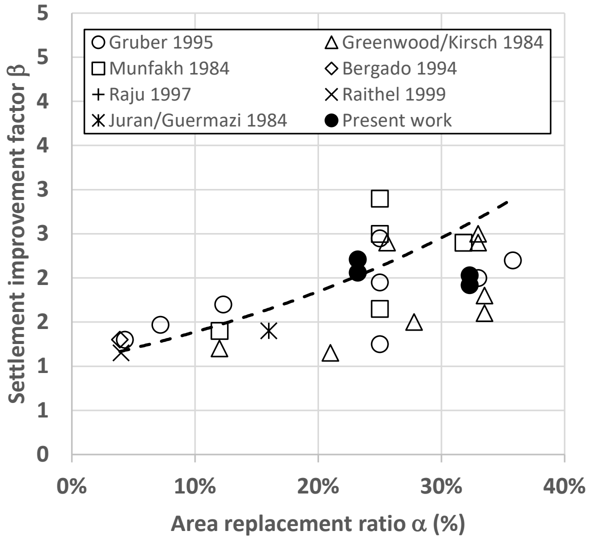

Figure 8 Settlement improvement factor β against area replacement ratio α from different authors.

Total stress cells (TSC) data after 30 days in prototype scale are presented in Figure 9 regarding conventional (J = 0 kN/m) and encased (J = 11,000 kN/m) stone column meshes with $\alpha = 23.2\%$. The results show the load distribution at the top of the soil and at the top of the column for a 150 kPa rigid plate surcharge. The mid-depth undrained shear strength for the clay layer is s_u = 19 kPa.

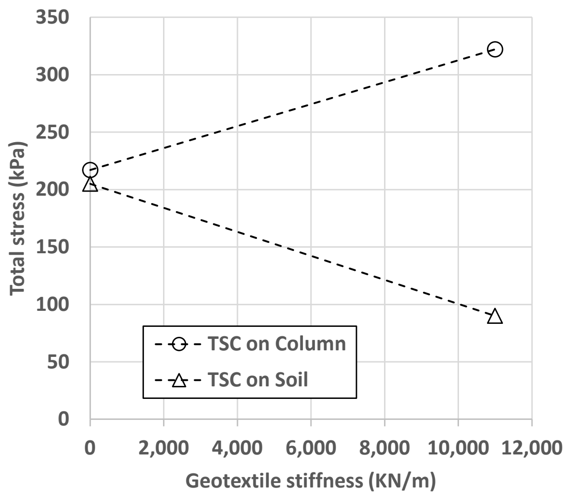

Figure 9 Total stress cell measurements for conventional and encased column meshes in prototype scale.

Conventional column mesh presents very close total stress values on top of the soil and on top of the columns, whereas encased column mesh shows stress values on top of the columns 3.5 times greater than those on top of the soil. These results highlight the relative influence of the encasement on the column mesh behaviour. Lack of confinement in soft and very soft clays might lead to column bulging, which can compromise the settlement improvement.

Figure 10 shows a cross-sectional view of an exhumed soil container.

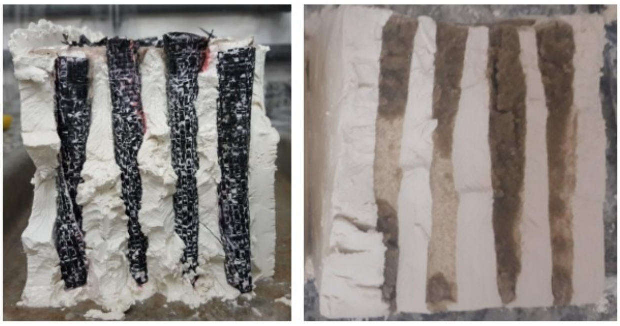

Figure 10 Exhumed soil container of: (a) Geotextile reinforced column pattern; (b) Conventional column pattern.

6 CONCLUSIONS

Centrifuge modelling is a very powerful tool to adequately simulate the use of stone columns as a solution for soft soils.

Conventional column settlements seem to be more influenced by the stress levels and the undrained strength of the surrounding soil than by the installation method. The settlement improvement factor decreased with the increase in the plate diameter relative to the column diameter. The highest settlement reduction was observed for a plate with the same column diameter.

Regarding column mesh, settlements seem to be directly affected by the area replacement ratio, although, for the present case, the small α variation, from 23.2% to 32.3%, does not show a clear deformation reduction.

Additionally, the use of encasement might highly increase stress levels in the columns and decrease those in the soil, depending on the confinement characteristics of the clay layer. This behaviour is associated with the higher stiffness of the encased columns, which helps keep their shape and prevent from bulging, thus attracting more load.

REFERENCES

Almeida, MSS, Almeida, MCF, Trejo, PCN, Rammah, KI, Lukiantchuki, JA, Guimarães, MPP and Oliveira, JRMS (2014) The geotechnical beam centrifuge at COPPE geotechnical laboratory In: *International Conference of Physical Modelling in Geotechnics*, Perth. Physical Modelling in Geotechnics. London: Taylor & Francis Group, 2014. v. 1. p. 271-277.

Cheuk, CY, Take, AW, Bolton, MD and Oliveira, JRMS (2007). Soil restraint on buckling oil and gas pipelines in lumpy clay fill. *Engineering Structures*, v. 29, p. 973-982. doi:10.1016/j.engstruct.2006.06.027

EBGEO (2011). *Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements*. John Wiley & Sons. ISBN 978-3-433- 02983-1.

Fan S, Bienen B and Randolph MF (2021) Centrifuge study on effect of installation method on lateral response of monopiles in sand. *International Journal of Physical Modelling in Geotechnics*, 21(1): 40–52, https://doi.org/10.1680/jphmg.19.00013.

Gautray, J., Laue, J., Springman, S.M., Almeida, M., (2013), Development of pore water pressure around a stone column, *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris.

Gautray, J, N, F, X., (2014), *Inlfuence of smear and compaction zones on the performance of stone columns in lacustrine clay*, PhD thesis, ETH Zürich, Switzerland.

Guimarães, MPP, Norena, PCT, Oliveira, JRMS, Lukiantchuki, JA, Almeida, MSS and Almeida, MCF. (2015) Centrifuge Modeling of Lateral Soil-Pipe Interaction. *XV Panamerican Conference on Soil Mechanics and Geotechnical Engineering*, Buenos Aires.

Kempfert, H.-G. (2003) Ground improvement methods with special emphasis on column-type techniques. *International Workshop on Geotechnics of Soft Soils – Theory and Practice*. Vermeer, Schweiger, Karstunen & Cudny (eds.). Noordwijkerhout, Netherlands. P. 101-112.

Manivannan, R, Wong, JC, Leung, CF and Tan, SA (1998) Consolidation characteristics of lumpy fill, *Proc. of the International Conference Centrifuge 98*, Tokyo, Vol. 1, pp. 889-894.

Muir Wood D, Hu W, Nash DFT (2000), "Group effects in stone column foundations: model tests". *Geotechnique*, Vol. 50 No. 6 pp. 689–698, doi: https://doi.org/10.1680/geot.2000.50.6.689

Priebe, HJ (1995) The design of vibro replacement, reprint from Ground Engineering, Technical paper GT 07-13 E.

Raithel, M., Kirchner, A., Schade, C. and Leusink, E. Foundation of constructions on very soft soils with geotextile encased columns – state of the art. *Geotechnical Special Publication*, n. 130-142, Geo-Frontiers. P. 1867-1877.

Trejo, PCN (2015) *Soil-pipe cyclic interaction in soft clay: physical modeling in centrifuge*, DSc Thesis, Graduate School of Engineering COPPE, Federal University of Rio de Janeiro, Brazil, 2015.

Yoo, C (2015) Settlement behavior of embankment on geosynthetic-encased stone column installed soft ground – A numerical investigation. Geotext. Geomembr., *Special issue on Soft Ground Improvement using Geosynthetics Applications* 43, 484–492. doi:10.1016/j.geotexmem.2015.07.014.