Large scale tests on geotextile-encased stone columns

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ABSTRACT
Stone columns technique is one of the ground improvement techniques for supporting geotechnical structures such as embankments and storage tanks. The use of conventional stone columns in very soft soils can be problematic because a significant proportion of their bearing capacity depends on the confinement provided by the surrounding soil. In order to overcome little confinement by soft soils, stone columns can be encased with a geotextile and this encasement can provide enough confinement to the column material that will lead to increased stiffness and bearing capacity of the column. This paper investigates the influence of the geotextile tensile strength, stiffness and of the column material on column performance as well as the role of the column in dissipating the excess pore water pressure generated in the surrounding soft soil. To accomplish that large-scale laboratory tests were carried out using a tank with dimensions 1.6m x 1.6m x 1.2m. The soft soil was instrumented with piezometers installed at different locations from the column. The results of the tests show that geotextile tensile stiffness is of major importance for the column bearing capacity and performance. It was also found that the column has an essential function in dissipating excess pore water pressures.

Keywords: Geosynthetic, embankment, soft soil, encased column.

RESUMO
Colunas granulares é uma das técnicas de melhoria do solo para apoiar estruturas geotécnicas tais como aterros e tanques de armazenamento. O uso de colunas granulares convencionais em solos muito moles pode ser problemático porque uma proporção significativa de sua capacidade de suporte depende do confinamento fornecido pelo solo circundante. A fim de superar pouco confinamento por solos moles, as colunas granulares podem ser encamisadas com um geotêxtil e esse encamisamento pode fornecer confinamento suficiente ao material da coluna, o que levará a maior rigidez e capacidade de suporte da coluna. Este artigo investiga a influência da resistência e rigidez à tração do geotêxtil e do material da coluna no desempenho da coluna, bem como o papel da coluna na dissipação do excesso de poropressão gerado no solo mole circundante. Para tanto, foram realizados ensaios laboratoriais em grande escala, utilizando um tanque de dimensões de 1,6m x 1,6m x 1,2m. O solo mole foi instrumentado com piezômetros instalados em diferentes locais a partir da coluna. Os resultados dos ensaios mostram que a rigidez à tração do geotêxtil é de grande importância para a capacidade de suporte e o desempenho da coluna. Verificou-se também que a coluna tem uma função importante na dissipação do excesso de poropressão.

1. INTRODUCTION

Stone columns technique may have advantages over other improvement techniques when there is a short time for the construction, and it is not economically acceptable to let the foundation soil improve its shear strength and compressibility by going through the consolidation process. Based on the stiffness of stone columns, they work as semi-rigid piles considering the bearing capacity and also act like vertical drains regarding the dissipation of excess pore water pressure. When it comes to very soft soils, stone columns may not receive sufficient lateral confinements from the surrounding soil to bear the load above them. This shortcoming can be remedied by encasing the column material in a geotextile (Raithel and Kempfert, 2000; Alexiew et al., 2005).

The behavior of encased columns has been investigated in various studies using laboratory, and field tests as well as analytical solutions, and numerical simulations. Laboratory and field tests have focused mainly on the deformation of columns under loading, considering conventional columns, and partially or fully encased columns in soft (Murugesan and Rajagopal, 2007; Cimentada et al., 2011; Alkhorshid, 2012, 2017; Ali et al., 2012, 2014; Alkhorshid et al., 2014; Miranda et al., 2015; Xu et al., 2016; Geng et al., 2017; Alkhorshid et al., 2018; Xue et al., 2019; Alkhorshid et al., 2019a; Alkhorshid et al., 2019b).

Araujo et al. (2009) ran large scale tests on the columns encased with geotextile and geogrid using sand and gravel as column fill material in collapsible soil. They reported that the impacts of foundation collapse by using encased column could be reduced. Gniel and Bouazza (2009) conducted a series of small scale tests on encased columns in soft soil. The cylinder steel cell used in the experiments was of 550 mm height, and 150 mm internal diameter (6 mm steel wall thickness) and the columns were of 50.5 mm in diameter and 310 mm in length. They concluded that the length of encasement could significantly influence the bearing capacity of the column so that fully encasement increased the column stiffness and reduced the column strain compared to partially encasement and clay behavior alone.

Due to the complexity of the encased column behavior, a better assessment of the encasement effects on the functioning of the column could be beneficial to accomplish vigorous design procedures. This paper aimed to assess the behavior of a single encased stone column in very soft soil.

2. DESCRIPTION OF THE TEST

2.1 Materials

The soil that was used to simulate the soft soil foundation had a specific gravity of 2.7, and liquid limit and plasticity index of 60% and 21%, respectively. The soil paste was prepared using 60% moisture content and consolidated under self-weight, which led to the undrained shear strength of less than 5 kPa and a coefficient of permeability (k) of 4.2 x 10^{-5} cm/s. The columns were constructed using poorly graded sand and gravel as column fill materials. The properties of column fill materials are given in Table 1. The friction angle of the fill materials was determined by medium-scale direct shear tests. Three different geotextiles (G1, G2, and G3) were used to encase the columns. Since the encasement materials were not commercially available for the column diameter used, G1, G2, and G3 were prepared using seam. The tensile strength tests of the seam were carried out on 250 mm wide samples in general accordance with NBR-13134/ABNT (1994), and the results are presented in Table 2. Huesker Synthetic GmbH has provided G2 and G3 using flat seam and G1 was prepared domestically using butterfly seam to achieve the cylindrical encasement of 150 mm. The diameter of the model column was chosen to represent a prototype column diameter of 600 mm, resulting in a scale factor (λ=prototype diameter/model diameter) of 4. Therefore, the scaling factor for the encasement tensile/stiffness modulus has to be 16.

Table 1. Properties of the column fill materials.

Property	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u (-)	C_c (-)	e_{max} (-)	e_{min} (-)	φ (˚)
Sand	0.179	0.305	0.630	3.51	0.825	0.87	0.6	41
Gravel	4.440	5.560	7.110	1.60	0.980	0.74	0.41	43

Note: C_u = uniformity coefficient; C_c = coefficient of curvature; D_{10}, D_{30}, and D_{60} = diameters of the soil particles for which 10, 30, 50 and 60% of the particles are finer, respectively; e_{max} and e_{min} = maximum and minimum void ratio, respectively; G_s = specific gravity; φ = friction angle.

Table 2. Mechanical properties of the geotextiles.

Properties	Geotextile Type		
	G1 (Butterfly seam)	G2 (Flat Seam)	G3 (Flat Seam)
Maximum tensile strength of seam (kN/m)	30	16	8
Strain at maximum tensile strength (%)	22	16	15
Stiffness at 5 % strain (kN/m)	120	107	53.4

2.2 Preparation of Test

The tests were aimed to be done in an undrained condition. Thus, the inner sides of the tank were covered with thick plastic sheets. The soil paste, after preparation, was placed in large plastic sheets for about 24 hours to let the water content become uniform throughout it. Then, soil paste was placed in the tank in layers of 200 mm thick by manually molding and attempting to avoid the air voids as much as possible.

The column was constructed in layers of 200 mm and vibrated after placing each layer to reach a relative density of 85%. Then, the column was placed in a PVC pipe, which was sealed at the bottom by a geomembrane. The pipe, afterward, was driven into the soft soil until the bottom of the tank and carefully removed (Figure 1). In order to keep the column being installed perpendicularly, a wooden casing was used at the top of the soil surface, as shown in Figure 2.

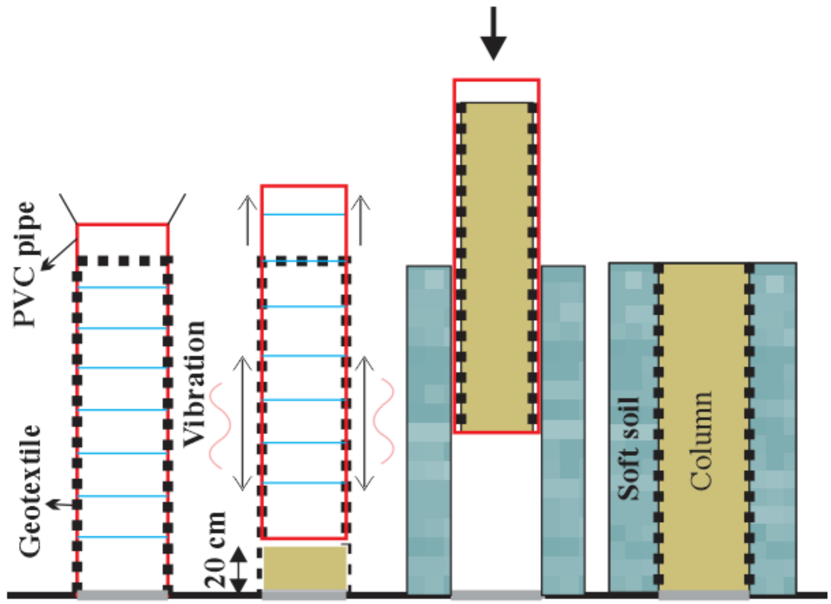


Figure 1. Column preparation and installation.

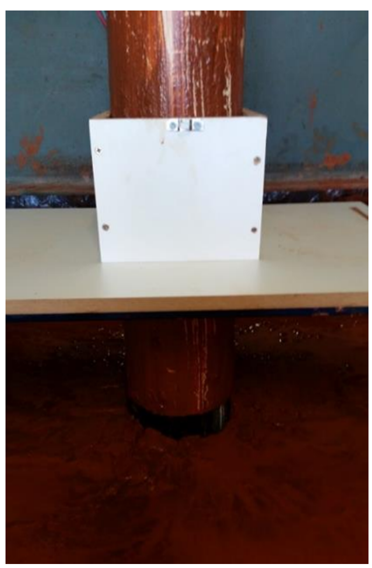


Figure 2. Use of the wooden casing for column driving.

The tank was instrumented by three pressure cells (PC1, PC2, and PC3) to monitor lateral earth pressure and six piezometers (P1 to P6) to assess the changes in excess pore water pressure during the column installation and loading (Figure 3). Four displacement transducers and a load cell were used to plot the load-settlement curve.

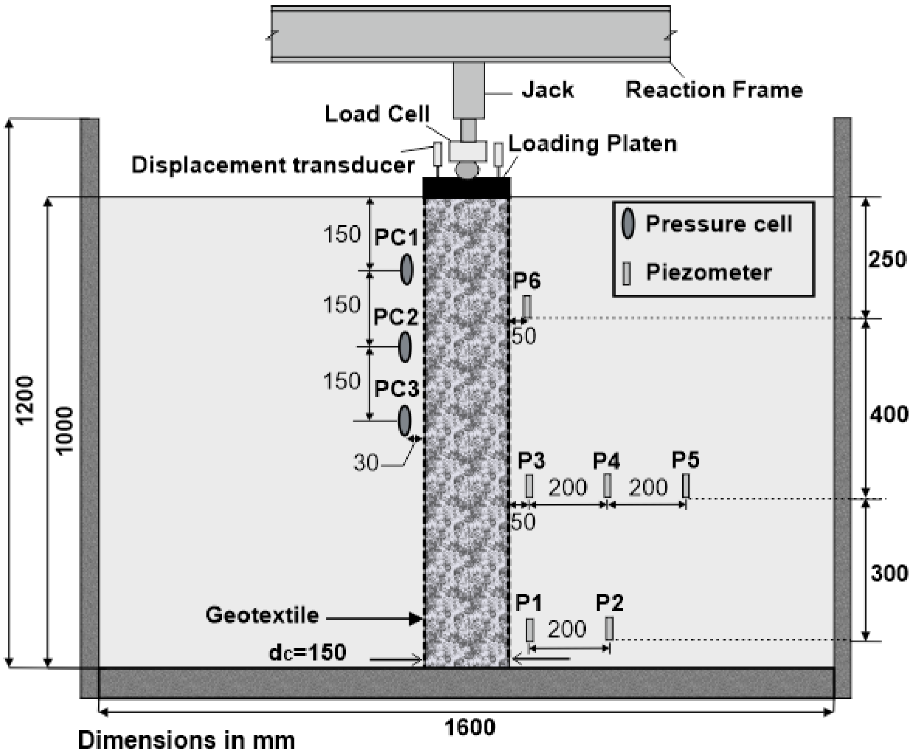


Figure 3. Sketch of the test setup.

3. TEST RESULTS

The results of the load-settlement curve for conventional columns (Figure 4a) present a slight improvement of the bearing capacity of the gravel column compared with that of the sand column. This small improvement may be due to the gravel higher internal friction angle. Still, these conventional columns do not offer excellent performance since the soft surrounding soil is not able to provide adequate confinement pressure to the column. Thus, the columns were encased by geotextile (G1, G2, and G3) to compensate for the lack of lateral support to the column. The results of the load-settlement curve for the encased sand column, as shown in Figure 4b, clearly show the importance of the geotextile tensile stiffness on the behavior of the encased column. In other words, by increasing the value of geotextile tensile stiffness, the bearing capacity of the encased column increases, and the settlement of the column decreases. For instance, the load capacity corresponding to a settlement value of 50 mm (5% of the column height) for G2 is approximately twice of that for G3.

Briaud (2013) presented an analytical method to estimate the ultimate bearing capacity of the encased columns. Figure 4c shows the comparison between the measured and calculated (Briaud, 2013) ultimate bearing capacity of the encased sand column. The results of the analytical method, generally, show a good agreement with those of the tests. There are slight variations between the results so that these variations for G-1, G-2, and G-3 were 0.13 %, 6.6%, and 6.17%, respectively.

Figure 4d shows the test results on the encased gravel column. Gravel, due to its higher internal friction angle, improved the bearing capacity of the column. By comparing the ultimate bearing capacity of gravel and sand columns, the improvements of bearing capacity for G-1, G-2, and G-3 were 12%, 16.7%, and 22.2%, respectively. The settlement obtained for the maximum bearing capacity of the gravel column indicated an increase of about 15% compared with that of the sand column. These increases in the settlement were 10.9% and 9.5% for G-2 and G-3, respectively.

The ultimate bearing capacity obtained from the loading tests is illustrated in Figure 5. It visibly shows the importance of the encasement and its tensile stiffness on the ultimate bearing capacity of the column. Conventional columns (Con.Column) are suffered from minimal bearing capacity. For instance, the ultimate bearing capacity of the conventional sand column was improved by a factor of about 71 (G-1), 40 (G-2), and 21 (G-3).

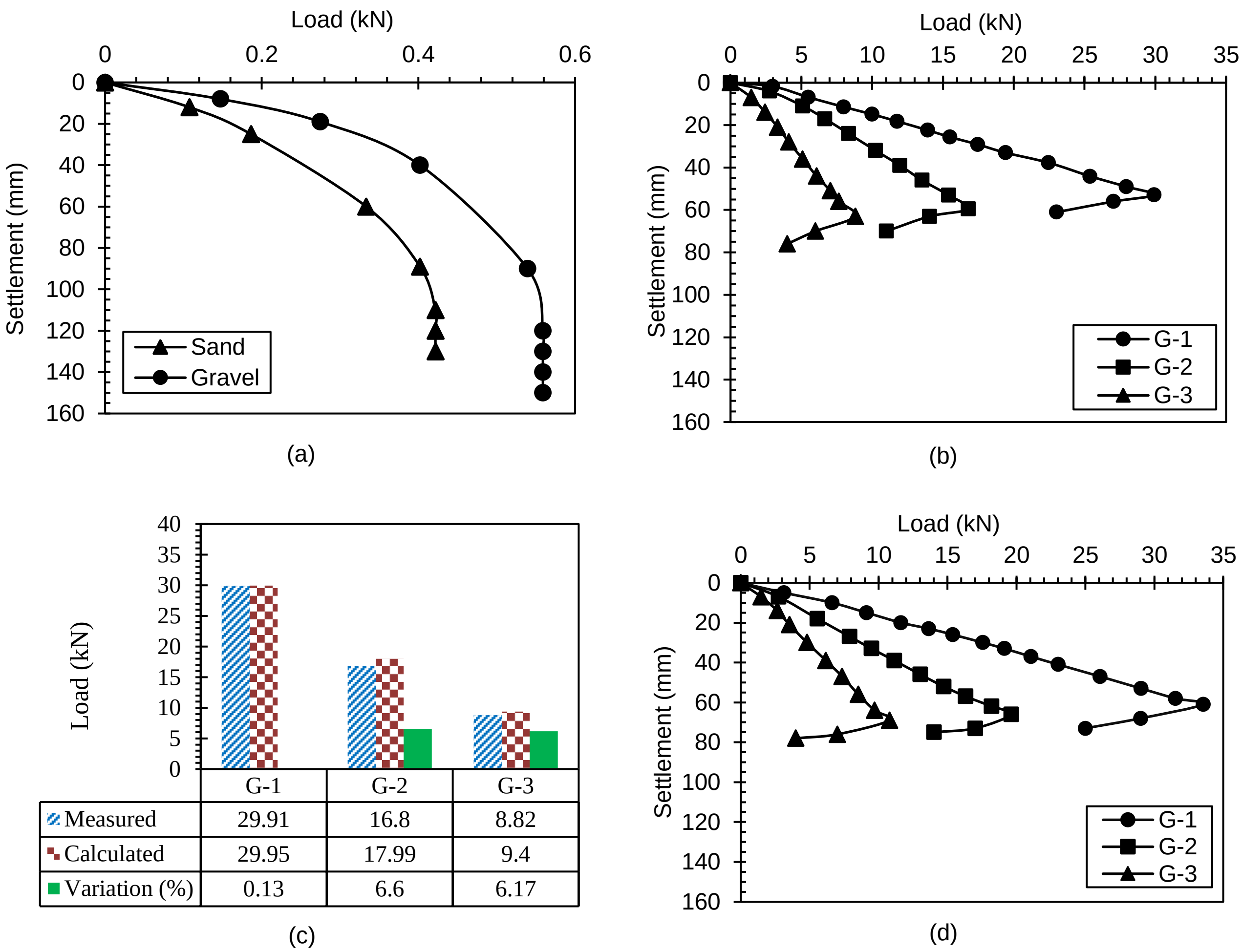


Figure 4. Load testing on (a) conventional sand and gravel column, (b and c) encased sand column, (d) encased gravel column.

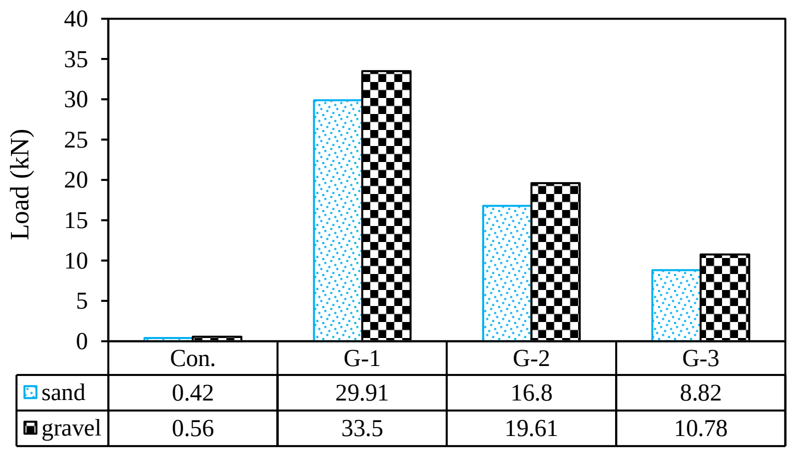
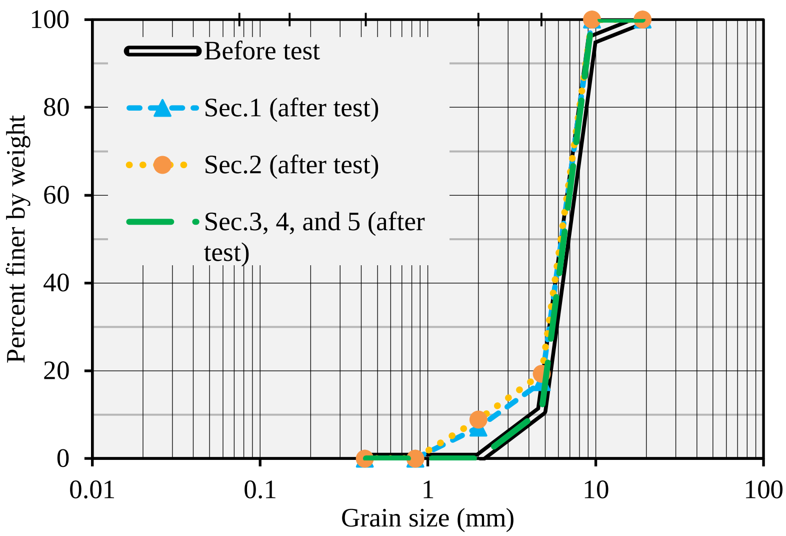
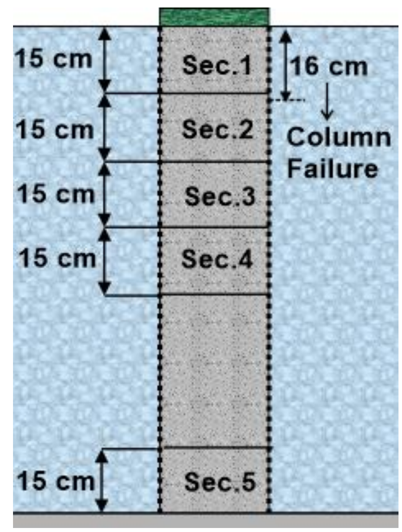


Figure 5. Ultimate bearing capacity of the encased and conventional columns.

As the settlement of the encased gravel column was higher than that of the encased sand column, these columns were analyzed after the loading tests to evaluate the breakage of the column fill materials. The encased gravel columns were divided into five sections, as shown in Figure 6b. For each section, the particle breakage index (B_g) proposed by Marsal (1967) was calculated. The results revealed some differences for sections 1 and 2 compared to those of before loading test, while sections 3, 4, and 5 did not show any significant differences. B_g for G1, G2, and G3 was 15.89%, 7.04%, and 1.55%, respectively, that may explain the higher settlements of encased gravel column compared with those of the encased sand column.



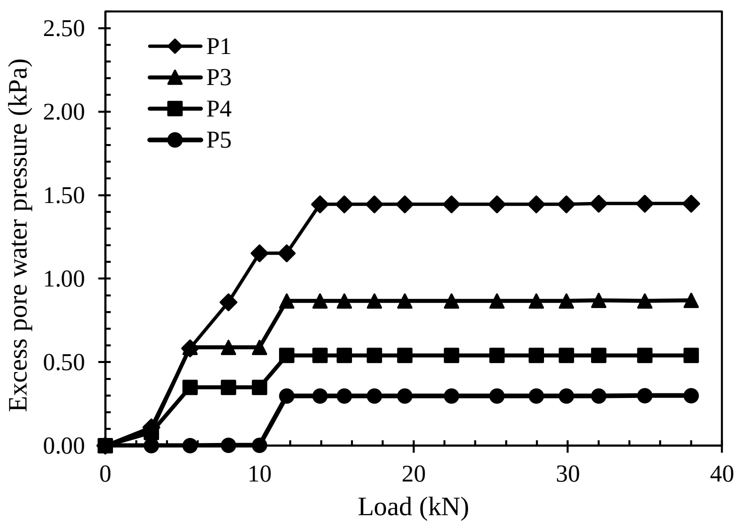
(a)



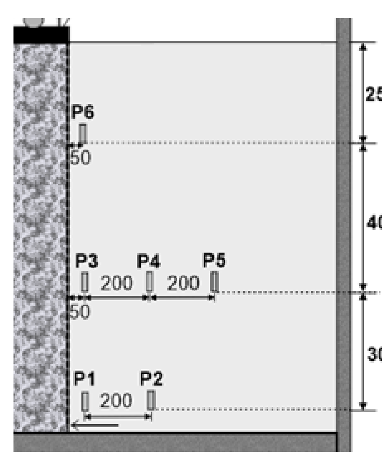
(b)

Figure 6. (a) Particle size distribution curve of the gravel column, (b) sections of the column.

The tests were carried out in an undrained condition and employed six piezometers in different depths and distances from the column were installed to monitor the changes in the excess pore water pressure. For P6 that was installed at a depth of 250 mm, no difference was registered. Figure 7 details the changes in excess pore water pressure during the loading of the column. P1 that was located close to the bottom of the column showed greater changes compared with other piezometers. The increases in excess pore water pressure reduced for the piezometers that were situated at shallower depths.



(a)



(b)

Figure 7. (a) Excess pore water pressure during loading stages, (b) position of piezometers installed.

4. CONCLUSIONS

Based on the obtained results, the main conclusions obtained in this study are presented below.

- The encasement contributed significantly to the performance of the column so that G1 improved the ultimate bearing capacity of the column by 7100% and 6000% for the sand and gravel column, respectively.
- Breakage index (Bg) measured for different sections of the column show the effect of stress increase to a depth of twice the column diameter.
- The results showed some increases in excess pore water pressure during loading. For piezometers installed in deeper depths, these increases were higher.

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