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Technical note

Laboratory analysis of encased stone columns

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ABSTRACT

Stone columns installed in extremely soft soils may significantly reduce the effectiveness of this treatment due to the insufficient lateral confinement provided by the soft soil. The encasement of columns with geotextiles is commonly used in these cases with satisfactory results thanks to the extra confinement provided by the geotextile to the column. The influence of the encasement on the behavior of stone columns is studied by means of drained triaxial tests performed on encased and non-encased samples of gravel. Two different densities of the gravel and two different geotextiles were tested. This study is focused on the increase in strength of encased samples compared with non-encased ones, the extra confining pressure provided by the geotextiles and the mobilized friction angle of the gravel. All of the results show the improvement achieved when the gravel is encased with the geotextiles. This effect is more significant at lower confining pressures.

1. Introduction

Stone columns with granular material are often used to improve bearing capacity, to accelerate the speed of consolidation and to reduce settlements on soft soil strata. Insufficient lateral support in extremely soft soils ($s_u < 15$ kPa) results in a significant reduction in the effectiveness of this treatment with stone columns. This lack of lateral confinement mainly occurs at shallow depths causing bulging failure in the upper portion of the columns (e.g. Huges and Withers, 1974; Madhav and Miura, 1994). In these cases, an improvement in stone column behavior can be further enhanced by encapsulating the column with a flexible sleeve (geotextile or geogrid), which can be a continuous sleeve or can be formed with a longitudinal union.

The behavior of encapsulated stone columns has been studied by numerous research initiatives through the development of experimental tests, theoretical and numerical analyses and field applications.

An important part of the experimental studies has been performed by small-scale laboratory tests, focusing on the analysis of load-settlement behavior (e.g., Black et al., 2007; Ghazavi and Afshar, 2013; Gniel and Bouazza, 2009; Malarvizhi and Ilamparuthi, 2007; Murugesan and Rajagopal, 2007, 2010). Different failure mechanisms of columns have also been analyzed in other studies, such as the ones presented by Ali et al. (2012, 2014) or Chen et al. (2015). For these experimental studies, the sleeves were mainly fabricated with geotextiles with a longitudinal union, which was commonly made by an overlap of the fabric that was sewn (e.g., Murugesan and Rajagopal, 2007, 2010), by a glued overlap of the fabric (e.g., Gniel and Bouazza, 2009), or by overlapping the encasement by a nominal amount and relying on the interlock between the aggregate and the section of overlap (e.g., Gniel and Bouazza, 2010). In any case, this union creates a weak point that reduces the strength of the geotextile. In addition to small-scale tests, some studies have also been developed based on field scale load tests (e.g., Yoo and Lee, 2012).

Other experimental analyses are based on triaxial compression tests on encased samples, such as the work of Rajagopal et al. (1999), who tested samples of granular soil encased in single and multiple geocells using different types of geotextiles, Wu and Hong (2009), who carried out triaxial compression tests on reinforced and non-reinforced columns mainly to assess the influence of the encasement on the radial strains of the sample and on the deviator stress, or Najjar et al. (2010) on normally consolidated kaolin samples reinforced with single sand columns.

Various analytical solutions have also been developed for soft soils reinforced with encased columns. Van Impe (1989) proposed one of the first solutions, and more recently, other authors such as

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Castro and Sagaseta (2011, 2013), Pulko et al. (2011), Raithel and Kempfert (2000) and Zhang et al. (2012) have also studied the problem and achieved different solutions.

In addition to the experimental and analytical studies, several numerical analyses have been carried out to study various factors that influence the behavior of the encased columns such as the stiffness of the encasement (e.g., Almeida et al., 2013; Chungsik, 2010; Khabbazian et al., 2010; Murugesan and Rajagopal, 2006), the stiffness parameters of the compacted stone (Lo et al., 2010), the encasement length (Keykhosropur et al., 2012), the shear-induced volumetric dilation of the fill material (Hong, 2012), the behavior under no monotonic loads (e.g., Prisco et al., 2006), or the influence of the finite element modeling approach (e.g., Yoo and Kim, 2009).

To complement the understanding of the behavior of encased columns, a study based on triaxial compression tests performed on gravel specimens encased with a geotextile is presented. Two different geotextiles were employed, and the tests were carried out on samples with two different gravel densities. This study is focused on the improvement of the column strength by encapsulating the column. This was done by analyzing different responses in laboratory tests with encased and non-encased samples, such as the increase of deviator stresses, volumetric and radial strains, the influence of the encasement on the confining pressure, and the mobilized friction angle of the gravel.

2. Experimental program

The experimental program was developed by focusing on the comparison of the behavior of encased and non-encased columns of gravel in consolidated-drained triaxial compression tests. With this aim, three series of triaxial tests were performed, the first one with samples of only gravel and the second and third ones with gravel encased with two different geotextiles. Each of the series was carried out with samples with two different relative densities of the gravel, $D_r = 50\%$ and 80%.

2.1. Test materials

Uniformly graded limestone gravel with particle sizes between 4 and 5 mm was employed for the laboratory tests. The maximum and minimum dry unit weights of the gravel are 16.5 kN/m^3 and 13 kN/m^3 corresponding to void ratios of $e_{mim} = 0.64$ and $e_{max} = 1.06$ respectively. This material is the same as that employed in Cimentada et al. (2011) and Miranda et al. (2015) for the study of the behavior of soft soils improved with non-encased stone columns.

Two different geotextiles were used in this research for column reinforcement, each made using a different flat fabric. Both geotextiles, along with the properties of both fabrics, were provided by Huesker Synthetic Gmbh. In both cases, the sleeve was prepared by cutting the fabric and preparing it in a cylindrical shape with a longitudinal union. It is important to note that, in real treatments, continuous sleeves without longitudinal unions are constructed with these fabrics such that this weak point does not exist.

Geotextile1 was made from Stabilenca120/120, which is a flat-woven fabric made of polyester threads and with a design tensile strength of 120 kN/m in longitudinal and transverse directions. An overlap of 2 cm of the material, glued with an epoxy adhesive, was employed for the longitudinal union. Due to the presence of the longitudinal union in the laboratory test samples, the strength and stiffness of the geotextile (fabric + joint) needed to be assessed. These properties were obtained from tests performed on 200-mm-wide samples following the standard DIN en ISO 10321 for tensile tests in joints for geotextiles. Fig. 1 shows the load-strain behavior of both the fabric and geotextile1 (fabric + joint). Selected values from the curve of this geotextile are summarized in Table 1, along with the corresponding secant modulus.

Geotextile2 was made from Robutec130/25 fabric, which is a woven fabric with polyvinyl alcohol filaments in the longitudinal direction and polypropylene filaments in the transverse direction. The design strength of this fabric is 25 kN/m in the longitudinal direction and 130 kN/m in the transverse direction. The longitudinal joint for this geotextile was made in the same manner as described for geotextile1. The strength and stiffness of geotextile2 (fabric + joint) were obtained from tests similar to those described for geotextile1. The results are presented in Fig. 1 and summarized in Table 2, including values of the secant modulus.

More details about the properties of these geotextiles can be found in Miranda (2014).

2.2. Specimen preparation

The triaxial compression tests were performed on 200-mm-high × 100-mm-in-diameter specimens of only gravel and gravel encased with a geotextile. Two different dry unit weights of the gravel were used in the research, 14.5 kN/m^3 and 15.8 kN/m^3, which correspond to relative densities of $D_r = 50\%$ and $D_r = 80\%$. The specimen preparation was as follows. First the geotextile was placed into a nylon mold that was then filled with the gravel needed to achieve the desired density. For samples with the lowest density of the gravel, the desired density was reached by pouring the gravel into the mold. However, to achieve the higher density, the gravel was placed in several layers and compacted using the same energy. Then, the mold with the gravel was filled with de-aired water and finally frozen for approximately 24 h. Afterward, the frozen sample was taken out of the mold and placed in the triaxial cell. Once in the triaxial cell, the sample was left to thaw for approximately 20 h under a low chamber pressure of approximately 10 kPa. A similar procedure was employed for samples without a geotextile.

2.3. Test procedure

Drained triaxial compression tests were employed for this research. The test procedure consisted of the following stages. First, the sample was saturated, and the desired confining pressure was applied with opened drainage until consolidation of the sample occurred. Four different confining pressures, p_c, of 25, 50, 150 and 300 kPa were chosen for the tests. Afterward, the sample was axially loaded under a constant vertical strain rate of 0.002 mm/s, keeping the drainage open. The vertical displacement of the sample was monitored by a linear-variable displacement transducer (LVDT), the volume change was controlled by measuring the amount of water expelled from or entering the pressure chamber by means of a volume gauge, and a load cell was used to record the increasing vertical stress on the sample. The test was repeated when anomalous behavior occurred during the test.

3. Experimental results

3.1. Gravel specimens

Deviator stress and volumetric strain versus axial strain have been plotted in Fig. 2 for tests performed on gravel specimens, including the two densities and the four confining pressures. The results show the influence of the density with higher deviator stresses, for the same axial strain, in specimens with $D_r = 80\%$ and different dilatancies for the two relative densities. This influence of the density is higher in samples with higher confining pressures.