Design and commissioning of a novel large scale multi-sectional cyclic shear box for evaluating the lateral dynamic response of geosynthetic encased granular columns

Conception et mise en service d'une nouvelle boîte de cisaillement cyclique multi-sections à grande échelle pour l'évaluation de la réponse dynamique latérale de colonnes granulaires encastrées géosynthétiques

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ABSTRACT: Improvement of soft clays by installing ordinary stone columns (OSC) and more recently geosynthetic-encased granular columns (GEC) is a state-of-the art technology. In order to quantify the dynamic lateral load capacity of OSCs and GECs, a novel large-scale cyclic shear test device has been developed. It is capable of housing clay samples of 0.46 m diameter up to a height of 1.85 m and is subdivided by horizontal joints into three sections. GECs and OSCs are placed in the centerline of the cylindrical clay body and the mid-section of the test device is subjected to cyclic dynamic excitations. The lateral response of OSCs and GECs with various geotextile encasement types is investigated based on the hysteresis data obtained from the dynamic shear load tests. The results are evaluated and compared both from the point of view of general behavior differences of encased versus non-encased columns and of the influence of the type of geotextile encasement as well.

RÉSUMÉ : L'amélioration des argiles molles par l'installation de colonnes de pierre ordinaire (OSC) et plus récemment des colonnes granulaires géosynthétiques (GEC) est une technologie de pointe. Afin de quantifier la capacité de charge latérale dynamique des OSC et des GEC, un nouveau dispositif de test de cisaillement cyclique à grande échelle a été développé. Il est capable de contenir des échantillons d'argile de 0,46 m de diamètre jusqu'à une hauteur de 1,85 m et est subdivisé par des joints horizontaux en trois sections. Les GEC et les OSC sont placés dans l'axe du corps d'argile cylindrique et la section médiane du dispositif d'essai est soumise à des excitations dynamiques cycliques. La réponse latérale des OSC et des GEC avec différents types d'encaissement de géotextile est étudiée sur la base des données d'hystérésis obtenues à partir des essais dynamiques de cisaillement. Les résultats sont évalués et comparés à la fois du point de vue des différences générales de comportement des colonnes encastrées par rapport aux colonnes non encastrées et de l'influence du type d'encaissement de géotextile.

KEYWORDS: unit cell approach, dynamic excitation, shear, geosynthetic encased column, ordinary stone column

1 INTRODUCTION

Ordinary stone columns (OSCs) offer a cost and energy efficient, and environmental friendly method for the remediation of soft soils. When the undrained shear strength of soil is too weak, stone columns may lose their effectiveness as the surrounding weak soils may not provide enough confinement to the columns, which may result in bulging or crushing failure of the columns at the upper section of the columns (Hughes et al., 1975). The shortcomings associated with OSCs are even more pronounced when they are implemented in very weak soils ($c_u < 15$ kPa). In such cases use of high modulus low creep geotextile reinforcement to confine the column constituents is a possible solution. The lateral confinement offered by the reinforcing geotextile significantly reduces bulging and increases the load carrying capacity of the geosynthetic encased column (GEC). The geotextile further aids in preventing the inflow of the surrounding low permeability soil into the stone column which reduces the drainage capability of the column.

The behavior of GECs and OSCs under vertical loads has been studied theoretically (Raithel and Kempfert, 2000) practically (Almeida et. al., 2014) and is believed to be quite well understood. However, knowledge and experience (although significant) are until now limited mainly to vertical static loads acting on the GECs. The knowledge regarding the behavior of GECs under lateral static loads is quite limited, but experiments demonstrate a strong positive influence of encasement. There is no experimental study known at present dealing with the behavior of GECs especially under cyclic lateral loading, which can be decisive e.g. under seismic impact. It has to be expected, that the encasement should have a positive influence also in this latter case. Failure of GECs due to lateral spreading of the foundation soil, at least in model scale, has been reported by Chen et. al. (2015). Figure 1 depicts the failure of a model embankment (Chen et. al. 2015) where the lateral load carrying capacity of the GECs are exhausted. Determination of the lateral load capacity of GECs therefore is a relevant problem.

Current literature on GECs offers very little on the behavior of GECs under the action of shear stresses with the notable exceptions of Murugesan and Rajagopal, 2009; and Mohapatra et. al. 2016. The dimensions of the apparatus in these studies are 300x300x200 mm (length, width, depth) in the former and 305x305x203.2 mm in the latter. Given the slender geometry of GECs, with the geometries specified above, where the aspect ratio (height/diameter) of the model GECs are in the range of 4, there may be deficiencies in modelling the physical phenomena where GECs are sheared. To better represent the effects of shear loads on GECs an apparatus that allows for higher aspect ratios is needed. Moreover the apparatus should be capable of inducing cyclic exactions on the entirety of the unit cell.

In this study, preliminary findings of an experimental program conducted with a novel large scale testing apparatus which is devised to test the behavior of GECs under the action of dynamic shear loads is discussed. Sinusoidal cyclic shear excitation is applied on model GECs (with an aspect ratio of nearly 15) embedded in a soil layer which resembles the weak soil strata in a unit cell. The device delivers cyclic shear displacements to the entirety of the unit cell remediated with GECs and OSC.

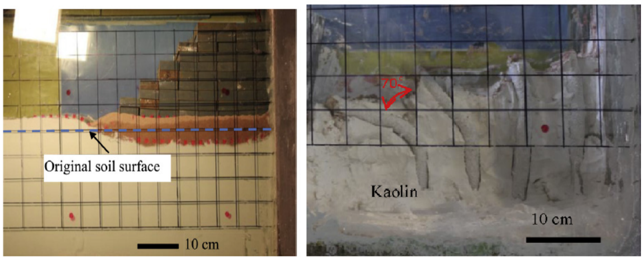

Figure 1. Failure of model scale GECs (Chen et. al. 2015)

2 TESTING APPARATUS: DYNAMIC UNIT CELL SHEAR DEVICE

Dynamic Unit Cell Shear Device is designed and commissioned at Bogazici University, Turkey. The apparatus is comprised of four cylindrical vessels which house weak soil material with a geosynthetic encased stone column (GEC) or an ordinary stone column (OSC) at the center. The schematics of the apparatus are illustrated in Figure 2. The device is capable of shearing a unit cell with a diameter of 46 cm and a height of 150 cm. There are a total of four vessels (see Figure 3) in which the soil sample is placed. The top vessel (vessel 1 in Figure 3) which has a height of 35 cm, is placed in the assembly to compensate for the consolidation settlement for the cases where clay is used to simulate the weak soil strata surrounding the model column (GEC or OSC). Once the consolidation of the clay is completed the top vessel will be removed from the assembly. The vessel 2 and 4 have a height of 60 cm and vessel 2, which is the moving part with yellow color, has a height of 30 cm. The shearing is archived by virtue of converting the circular output of an electric motor to pure axial movement with a Scotch yoke type mechanism. A 5 ton capacity load cell is deployed on the moving part of the apparatus in order to record the magnitude of horizontal force during dynamic shearing. The displacement of the moving part is tracked by virtue of a laser displacement sensor. A hollow tube with a diameter of 11 cm is kept in the center of the weak soil during consolidation of weak clay/placement of weak soil sample. Upon completion consolidation or placement of the weak soil, a GEC or OSC is formed inside the hollow tube. The tube is then retracted and thusly a unit cell with a GEC or OSC in the center is formed.

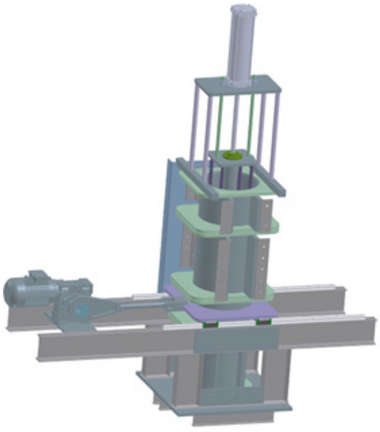

Figure 2. Schematics of the testing apparatus

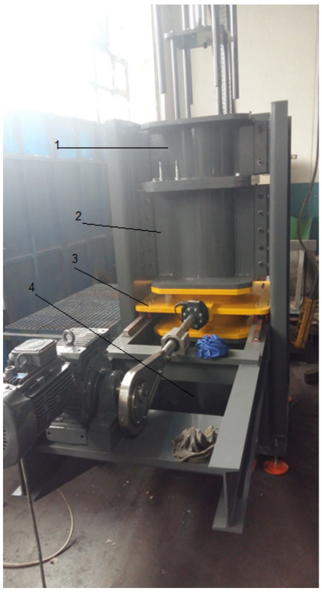

Figure 3. Dynamic unit cell device

3 MATERIALS AND METHODOLOGY

In order to understand the mechanisms involved better, sand was used in the initial tests instead of a normally consolidated clay. This approach was adapted from di Prisco et al. (2006). The testing program focused on determining the lateral resistance of a unit cell remediated with OSC and GEC. As such, whether the surrounding soil is a sandy or a clayey soil is not important as long as that lateral resistance can be estimated with reasonable accuracy. As long as the baseline shear strength of the surrounding soil can be estimated and deducted from the shear stress mobilized by the sand-OSC or sand-GEC system, it should be possible to isolate the behavior of OSCs and GECs from the test results (Mohapatra et. al. 2016).

A poorly graded sand with a specific gravity of G_s=2.62, coefficient of uniformity C_U=3.0 and coefficient of gradation Cc=1.08 was used to model the weak soil surrounding the column. D10, D30, and D60 values of the sand used were 0.25, 0.4, and 0.8, respectively. The maximum and minimum void ratios of the sand (e_{min}, e_{max}) determined in accordance with ASTM D4253 and ASTM D4254 was 0.39 and 0.81, respectively. The sand was pluviated from a constant height of 3 meters into the testing assembly. The pluviation technique revealed samples with a void ratio of 0.54 which gives a relative density (Dr) value of approximately 65 % (medium dense sand).

The soil used for forming the model stone columns and GECs was an angular crushed rock aggregate with an internal angle of friction of 43 degrees and a specific gravity of 2.66. The crushed rock was initially wet sieved through ASTM No. 200 sieve with an opening size of 0.075 mm. The soil was then oven-dried and it was sieved through No 4 and No 10 sieves (aperture size 4.75 and 2 mm respectively). The soil retained sieve no 4 was discarded and soil retained on sieve No 10 was used as the aggregate in the stone column and GEC fillings (Cengiz et. al. 2016).

A sinusoidal displacement was applied with a frequency of 1 Hz and amplitude of 3.5 cm. The displacement-time plot of the measured displacement is given in Figure 4. The inertia of the testing apparatus was considered by operating the apparatus while it was empty. Zero readings from the testing apparatus was taken and thusly the magnitude of force required to move the assembly was measured. The average inertia force for a given time step in each hysteresis loop was reduced from the measured force value by making use of the principle of superposition. An average of these readings was subtracted from the force readings by using the principle of superposition. The hysteresis curves pertaining to zero readings of the device are given in Figure 5.

Two different geotextiles were used in the making of GEC samples. The geotextiles were provided by HUESKER and the designations of the reinforcements were Sefitec and Stabilenka which shall henceforth be referred as R1 and R2, respectively. Both samples were subjected to wide-width tensile tests in accordance to DIN EN ISO 10319. The stiffness (J) for R1 and R2 were 400 and 1050 kN/m respectively. The testing program consisted of four experiments. The first experiment was intended as a bench mark experiment where the dynamic shear response of the medium dense sand was investigated. An OSC consisted of angular crushed rock aggregate only and two GECs reinforced with R1 and R2 were implemented in the third and the fourth tests. The tests were conducted at an overburden stress of 25 kPa which was induced on the column head plane by a rigid steel plate. The surcharge stress was derived from a pneumatic piston located at the top of the testing assembly (Figure 2).

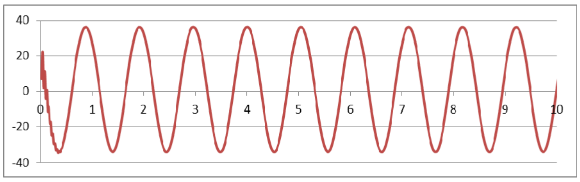

Figure 4. Measured sinusoidal displacement in time domain

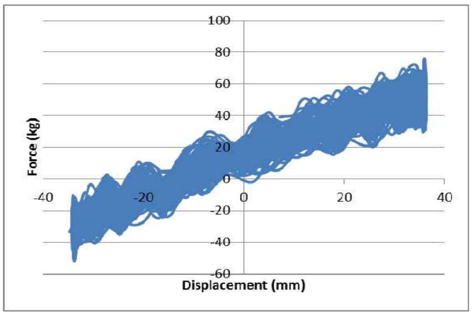

Figure 5. Zero readings of the apparatus (50 cycles)

4 RESULTS AND CONCLUSIONS

Dynamic lateral excitations were applied to all four configurations. The benchmark experiment that consisted solely of sand material revealed the hysteresis behavior depicted in Figure 6. The maximum force readout was in the order of of 6.15kN. The behavior of the sand under the prescribed testing conditions is given in Figure 7 in time domain. In Figure 7, the behavior of sand exhibits a certain level of softening as the number of cycles increases. At the end of the 50th cycle the maximum force required was around 5.58 kN which indicates a reduction of 9 % in the overall shear resistance. Figure 8 gives the hysteresis loops associated with the unit cell remediated with a GEC reinforced with R2 in displacement domain. Figure 9 exhibits the same behavior in time domain. The peak force readout for unit cell with GEC reinforced with R2 is 11 kN and lowest absolute force reading (close to 50th cycle) was 9.44 kN which indicates a reduction of 14 % in the lateral shear resistance. The results of the entire test program are given in Table 1.

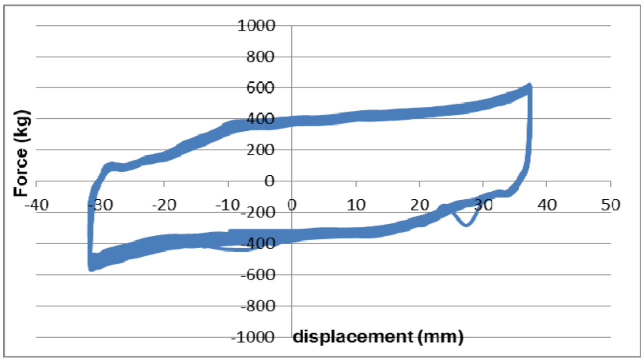

Figure 6. Hysteresis loops for the unit cell consisting of sand only

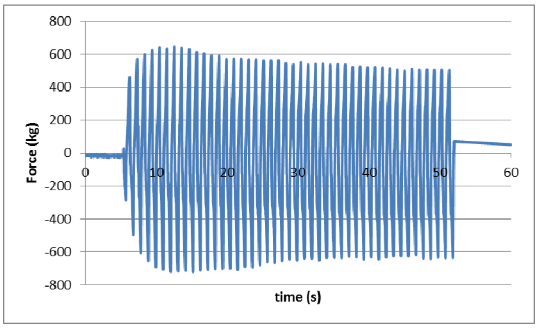

Figure 7. Hysteresis loops for the unit cell with sand only in time domain

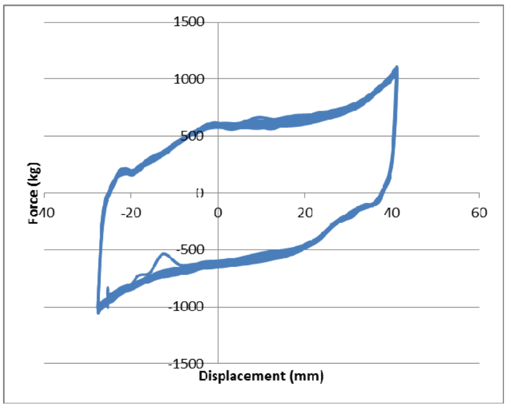

Figure 8. Hysteresis loops for the unit cell enhanced with GEC with R2 type reinforcement in displacement domain

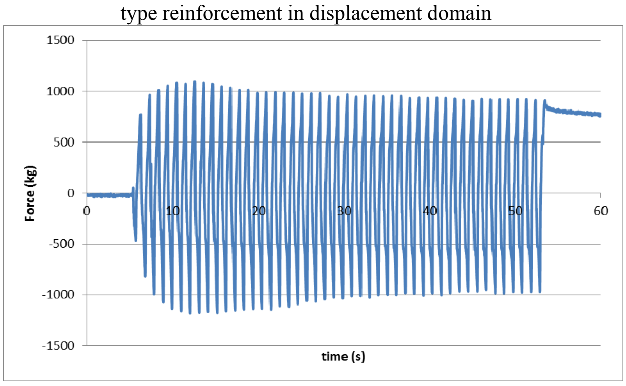

Figure 9. Hysteresis loops for the unit cell enhanced with GEC with R2

type reinfrocement

Table 1. Lateral shear resistance data for the tests

Column Type	*Force in the first cycle(kN)*	*Force in the last cycle(kN)*	*% Reduction*
None*	*6.15*	*5.58*	*9.2*
OSC	6.95	6.32	9
R1	8.79	7.83	11
R2	11.00	9.44	14

*Benchmark experiment

The shear resistances for OSC during the first and the last cycle are 6.95, 6.32 kN, respectively while the results for the GEC reinforced with R1 are 8.79 and 7.83 kN. Form the tabulated data in Table 1, it can be deducted that the increasing stiffness of the reinforcement causes a higher percentage reduction in the lateral shear resistance of the unit cell. It should also be noted that the lateral shear resistance reduction percentage for OSC and untreated sand are in close agreement. The seemingly high percentage of lateral shear resistance reduction in reinforced unit cells is attributed to the probable existence of a failure zone in the close proximity of the GECs. These zones may undergo excessive shear deformations since there is a highly rigid element in the center which opposes shear deformations. Consequently while the shear given by the GEC remediated units cells are high, the drop in the lateral resistance is more pronounced due to the existence of highly stressed zones around the GEC.

Figure 10 depicts the hysteresis loops by each unit cell where the peak lateral shear resistance is achieved. The pinching behavior on the curves pertaining to R1 and R2 at high displacement levels could be indicative of GECs' reinforcements taking loads upon themselves. The amplitude of lateral force required to move the unit cell dramatically increases as after a displacement value of about 20 mm. This displacement may be magnitude of the necessary lateral deformation for the mobilization of the lateral shear resistance in the GECs. This assumption seems valid as the curves presented in Figure 10 are otherwise not significantly different from one another at displacement values smaller than 20 mm.

The overall performance of the GEC modified unit cells was better than that of the counterparts. It should be noted that the magnitude of the lateral deformation, under the studied conditions was not enough to evoke pronounced levels of modulus reduction in the unit cells. Higher displacement demands should be applied for future studies.

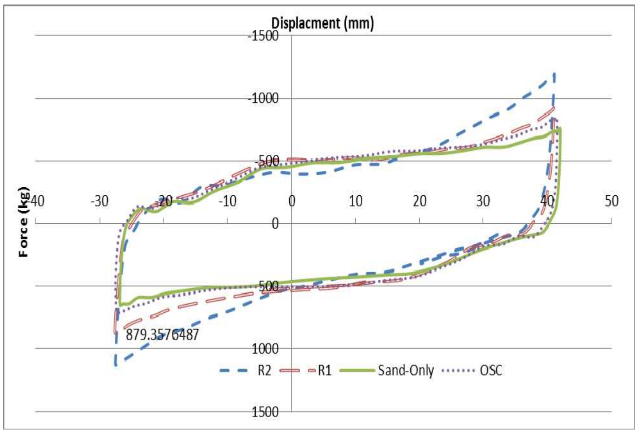

Figure 10. Hysteresis loops for the unit cell consisting of sand only in time domain

5 ACKNOWLEDGEMENTS

This research is supported by Scientific and Technological Research Council of Turkey under grant no 213M359, authors wish to express their gratitude for the support provided. Authors also acknowledge the support provided by HUESKER GmbH for the financial support and consultancy provided in this project.

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