Investigating the effect of clogging in a granular column on the cyclic and post-cyclic behavior of soft ground improved with it

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ABSTRACT

An attempt was made in the present study to evaluate the pre-and post-liquefaction behavior of the soft ground improved by granular columns (with and without a geogrid encasement) by simulating a loose soil mass reinforced with a granular column in a triaxial cell. For this purpose, a series of large-scale monotonic compressive tests and also stress-controlled cyclic triaxial tests followed by drained and undrained monotonic compression tests were carried out on the loose sand specimens including the granular column with and without geogrid encasement. The pre-cyclic behavior of specimens showed that the deformation modulus improvement due to the use of a stiffer encasement would be less noticeable in case of clogged granular columns. It was found that during a cyclic loading, the use of geogrid encasement will be effective in reducing cumulative settlements and mitigating the liquefaction potential when its tensile stiffness is large enough. Moreover, the post-cyclic behavior of specimens showed that the use of granular columns (whether encased or non-encased) decreased the dependence of the ground deformation modulus on the CSR changes so that the evaluation of the cyclic-induced ground deformation can be done completely independent of the cyclic loading magnitude. It was also found that the use of an encasement with appropriate stiffness played an important role in minimizing the loss of the strength of the ground stabilized by granular columns after experiencing cyclic loads, especially under large earthquakes and after the occurrence of possible liquefaction.

KEYWORDS

Granular column; Geogrid encasement; Triaxial test; Pre-and post-cyclic behavior; Liquefaction.

1. Introduction

Installing granular columns (GCs) has been known as one of the cost-effective method for improving the bearing capacity of soft ground by creating a composite medium with considerable stiffness and mitigating the liquefaction by accelerating the dissipation of excess pore water pressure due to shortening the drainage path [1,2]. Occurrence of clogging in granular columns due to the entry of fine particles of soil into the column pores or growth of plants in their body and failure to provide required confining pressure by the loose soil around them are two factors that have always weakened their performance [3,4]. Badanagki et al. showed that the reduction in the drainage capacity of granular columns due to clogging can be so high that GCs can play no role in preventing liquefaction [5]. The idea of encasing granular columns with geosynthetics was proposed by Van Impe and Silence [6] for the first time to achieve the required confining pressure GCs. It was later proven that the use of geosynthetic encasement is also effective in reducing the possibility of clogging in granular columns [4].

Given the high probability of clogging in the granular columns, and consequently and resulting liquefaction in the ground improved by them, it is necessary to investigate both their undrained cyclic behavior and their post-cyclic behavior. Hence, an experimental attempt was made in the current study to evaluate the cyclic and post-cyclic behavior of GCs with and without encasement considering clogging phenomenon. For this purpose, a single granular column interacting with the surrounding soft sand was simulated in a triaxial cell based on the unit cell concept. The simulated models were evaluated in two separate phases. At the first phase, the short- and long-term behavior of the GCs models was evaluated using undrained and drained monotonic compression tests. At the second phase, stress-controlled cyclic triaxial tests followed by undrained and drained monotonic compression tests were carried out on the GCs models to evaluate their short and long term behavior after occurrence of liquefaction. By selecting two different geogrids for encasing GCs, the effect of encasement stiffness was also investigated on the behavior of granular columns.

2. Triaxial tests

Based on the unit cell concept, a single granular column interacting with the surrounding soft sand was simulated in a triaxial cell. The granular column diameter was considered to be 100 mm in all specimens, indicating an area replacement ratio of 25% in an equilateral triangular arrangement. The ratio between the diameter considered for the granular column in the current study and the diameter of the columns in practice (~1.0 m) shows that a scaling factor of about 1:10 is established between the tests and the prototype.

Firuzkooh #D3 sand at a relative density of 70% sand and Firuzkooh #161 sand at a relative density of 30% were used to simulate the granular column and surrounding loose soil, respectively. These two types of sand were silica synthetic soil composed of angular particles with a specific gravity of 2.66. The particle sizes of coarse and fine sands ranged between 3.00 to 5.00 mm and 0.06 to 0.7 mm, respectively. These particle size ranges satisfy both the ratio between the particle size of the surrounding soil and the column material as well as the ratio between the particle size of the column material (d) and the column diameter (D). Muir Wood et al. recommended a d/D ratio range of 12 to 40 for granular columns [7].

Two biaxial geogrids with different tensile stiffnesses were selected for encasing granular columns to investigate the effect of encasement axial stiffness on the seismic performance of EGCs. The type I and II geogrids were equivalent to low and high stiffness geogrids in real-scale with the secant tensile stiffness of 729 and 3183 *kN/m* at 5% strain, respectively. The ratio of the grid opening size to the grain size of granular column (*s/d*) was considered as the second factor in the selection of the geogrids. Among all proposed criteria in this regard, $s<D_{60}$ was used as the most popular criterion, where s and D_{60} are the spacing between ribs of geogrid and the effective size of granular column particles.

Three different ground situations were simulated: 1) the loose ground (LG), 2) the loose ground improved by granular column (LG-GC), and 3) the loose ground improved by geogrid-encased granular column (LG-GEGC(I) and LG-GEGC(II)). Using the moist tamping procedure in controlled volume fashion, the loose ground was simulated in the triaxial specimen by compacting Firuzkooh #161 sand. For this purpose, the moist sand was tamped into the mold loosely in twenty layers with equal height of 20mm. The weight of each layer was chosen so that its relative density became 30% after reaching a thickness of 20 mm. In order to simulate the ground improved by granular column (LG-GC), the replacement technique was used for constructing the granular column in the simulated loose ground. Based on this technique, a thin seamless steel pipe (with inner diameter of 100 mm and 0.5 mm wall thickness) was pushed into the center of the simulated loose ground. Then the sand inside the pipe was scooped out using a helical auger of 96 mm diameter. In the last step, the formed borehole was filled with twenty layers of Firuzkooh #D3 sand at a relative density of 70%. The same procedure used for the construction of LG-GC was also followed to construct LG-GEGC(I) and LG-GEGC(II) with the difference that a tube-shaped geogrid was placed inside the pipe after scooping out the sand inside it and then the coarse sand was compacted.

All the specimens were tested in two separate phases. In the first phase, the long- and short-term performance of the specimens under an effective confining pressure of σ'_c=100 kPa were determined using drained and undrained monotonic loading tests, respectively, before applying any cyclic load. In the second phase, after applying a specific undrained cyclic loading to the specimens, they were subsequently subjected to the strain-controlled monotonic loading to investigate the post-cyclic behavior. Similarly, to the first phase, the drained monotonic compression tests were conducted to evaluate the long-term post-cyclic behavior and the undrained ones were performed for short-term evaluation.

3. Results and Discussion

The pre-cyclic behavior of specimens showed that the use of a granular column improved the deformation modulus by 17% in drained conditions, while encasing it by low and high stiffness geogrids led to 41% to 84% increase in E_{S1}%, respectively. In undrained conditions, this stiffness improvement was found to be 40% and 71% to 123% when using a granular column and encasing it, respectively. Also, a 73% increase in deformation modulus due to an increase in encasement stiffness in undrained conditions compared to an 105% increase in drained ones indicated that the deformation modulus improvement due to the use of a stiffer encasement would be less noticeable in case of clogging granular columns.

Regarding the dynamic behavior of the samples, the variation of the degradation index versus the number of loading cycles in Fig. 1 showed that the improvement of a soft ground with granular columns reduced its cumulative settlement during a consecutive loading and the use of geosynthetic encasement was effective in reducing cumulative settlements, particularly with high tensile stiffness. Moreover, the imperceptible difference between the cyclic-induced excess pore-water pressure in SG-GC and SG-GEGC (I) emphasized the inefficiency of low stiffness geogrid encasements to delay and mitigate liquefaction in granular columns with the possibility of clogging.

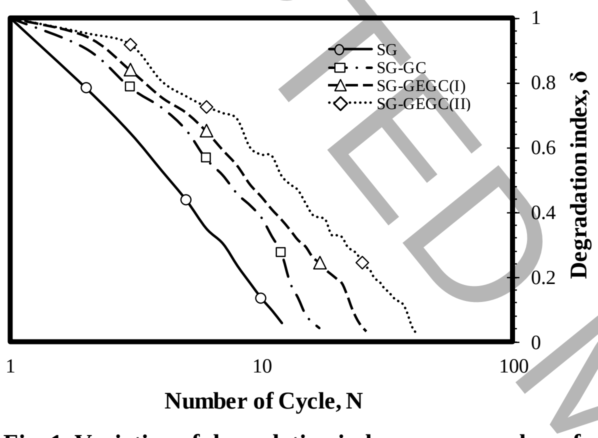

Fig. 1. Variation of degradation index versus number of loading cycles.

The post-cyclic behavior of specimens showed that the use of granular columns decreased the dependence of the ground deformation modulus on the CSR changes. This reduction, which was minimized using an encasement with suitable stiffness, means that the use of encased granular columns in a soft ground reduces the dependence of the ground deformation on the magnitude of seismic loading, and therefore the cyclic-induced ground deformation may be estimated independently of the seismic loading magnitude.

4. Conclusion

The main conclusions regarding triaxial tests can be summarized as follows:

1) It was found that the deformation modulus improvement due to the use of a stiffer encasement would be less noticeable in case of clogging granular columns.

2) The results emphasized the inefficiency of low stiffness geogrid encasements to delay and mitigate liquefaction in granular columns with the possibility of clogging.

3) The post-cyclic behavior of specimens showed that the use of granular columns decreased the dependence of the ground deformation modulus on the CSR changes. This reduction, which was minimized using an encasement with suitable stiffness, means that the use of encased granular columns in a soft ground reduces the dependence of the ground deformation on the magnitude of seismic loading, and therefore the cyclic-induced ground deformation may be estimated independently of the seismic loading magnitude.

4) The improvement of a soft ground with encased granular columns not only decreased the liquefaction-induced ground deformation, but also significantly reduced the effect of earthquake magnitude on the ground deformation.

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