Investigation of soil behavior in construction of rammed aggregate piers

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KEYWORDS: Stone column, ground improvement, rammed aggregate piers, GeoPier, model testing.

ABSTRACT: In compressible soft soils, rammed aggregate piers (RAPs) are one of the most effective soil improvement methods and compared with other deep foundation alternatives, RAPs typically offer a cost advantage ranging from 20% to 50%. RAPs are constructed as elements of high-density granular columns obtained through compaction, which translates to increased bearing capacity.

Rammed aggregate piers can be applied to both cohesive and cohesionless soils to increase bearing capacity, reduce liquefaction potential, and control excessive settlement. They also may have differing lengths and layouts based on layering and properties of the soil.

In this study, the behavior of soils improved with rammed aggregate piers is investigated through small-scale testing (1/3). A rammed aggregate pier apparatus developed within the Geotechnical Engineering laboratory at the Yildiz Technical University is used for model experiments, which are conducted in two steps. In the first step columns of rammed aggregate piers are constructed in soft kaolin clays consolidated in a one-meter diameter tank. Then the column is axially loaded to failure. The deformations of rammed aggregate piers under constant loads are presented. The improvement of the rammed aggregate piers constructed within a clayey soil and the load-displacement behavior is examined in the light of the findings.

1 INTRODUCTION

Rammed aggregate piers (RAPs) are used for more than 20 years particularly in the USA to limit settlements to a desired level and to enhance bearing capacity of foundations in soft soils (Lawton et al.1994). Rammed aggregate piers are constructed by the compaction of firm aggregate layers into previously drilled cavities by ramming a specially designed tamper having a conical tip (Fox & Cowell 1998). During the construction of rammed aggregate piers (RAPs), the aggregates placed in the cavity expand in the ground by vibratory compaction, thus creating a more stable layer overall. Bearing capacity is also increased by this procedure. The layers which are compacted by ramming laterally widen along the column and downward at the tip causing pre-stresses and deformation in the soil around the column (Kurt 2011, Demir 2011, Lawton &Warner 2004,Wissmann 1999,Wissmann et al. 2002, White et al. 2000).

This study examines the potential ground improvement ratio and load bearing mechanisms during the construction of rammed aggregate piers within a soft soil. Two load tests are conducted and their results are compared: the first test is performed on RAP build in a clayey soil, and the second test is conducted on a soil without any ground improvement.

2. MODEL TESTS

This study included model tests by examining the construction of rammed aggregate piers and their interaction with the surrounding soil under vertical load to obtain useful data for design and application.

2.1 TESTING SYSTEM

Test set-up, which is designed to produce model stone columns/rammed aggregate piers, consisted of a frame made of 1400 x 1400 x 2000 mm steel sections; an electric motor used to ram the column; another motor in the middle which enables the column to penetrate into soil and a 10 cm probe to dig a cavity on the ground and form the column (Figure 1). Testing system has a capacity to apply a 40 kN (4 ton) vertical load. The pressure applied on the casing is measured by a load cell placed on the system. Furthermore, the stone column apparatus can vertically hammer for constructing rammed aggregate piers. Testing frame is fixed to the ground in four points to allow the apparatus to reach sufficient power during model aggregate column production. Column material is placed through a tank placed on top of the casing in to the cavity formed by the pushed casing.

Figure 1. Model test system

2.2 PREPARATION OF CLAY BED

In model tests, a mixture containing 60% sand and 40% kaolin clay is placed in the tank. Index properties of the mixture are presented in Table 1. The sand used in the test is poorly graded sand (SP) according to Unified Soil Classification System (USCS). Index properties obtained from sieve analysis applied on gravel material which is used to model rammed aggregate piers in the laboratory are presented in Table 2. Based on these results, the gravel can be classified as well graded (GW) based on USCS.

Table1. Index Properties of the Mixture used in Test

Plastic limit, w_P	%16
Liquid limit, w_L	%27
Plasticity index, PI	%11
Specific density of soil, ρ_s	2.63 gr/cm^3

Table 2. Index properties of gravel

Symbol	GW
Coefficient of uniformity (C_u)	2.26
Coefficient of gradation (C_c)	1.275
Average grain size, D_{50} (mm)	6.0
Effective diameter, D_{10} (mm)	3.1

The soil on which model aggregate piers will be constructed is placed on the test tank in 10 days. A mixture containing 40% clay (kaolin) and 60% sand by dry weight is prepared. Water equal to 1.5 times the liquid limit of the mixture (40% of dry weight) is added to the soil with the help of a mixer. Water is added in stages to obtain a homogenous soil at the end of mixing, Water content of the mixture at each stage is determined so that average water content is (w_{ort}) 40%, i.e., 1.5w_L. As proposed in the literature (Murugesan et al., 2010), this value is sufficient for the consistency of the slurry to have a viscosity allowing easy placement in the tank.

Drainage is permitted at the top and bottom of the clay bed by placing 50-mm thick gravel layer sandwiched between geotextile layers. The consolidation of the clay bed is continued for a period of 10 days until the rate of settlement is less than 1mm/day.

After consolidating the soil with its own weight, a plate and an airbag is placed on the soil (Figure 2). The tank, on which the airbag is placed, is covered with a metal plate equipped with a connector system. For a total of 60 and 75 days, the soil sample in the tank is consolidated by applying 10 kPa, 30 kPa, 60 kPa and 100 kPa vertical pressures, respectively. During the consolidation, vacuum is applied both on the tap under the tank and drainage pipe on top of the tank allowing collected water to drain. Consolidation times at various pressure levels are observed and recorded with vertical displacement transducers.

Figure 2. A large size inner tube used as an airbag placed in the tank to apply pressure

2.3 INSTALLATION OF RAMMED AGGREGATE PIERS AND LOADING TESTS

After removing the pressure on the soil sample which is consolidated under 100 kPa pressure inside the tank, it is observed that its height decreased to 85 cm on average. In construction of model RAP, the probe is pushed down to 70 cm depth paying attention to the distance from the bottom of the tank. The probe is then pulled up 20 cm and filled with gravel from the tank attached on the top. The gravel, which filled the void at the bottom, is then compacted to 7 cm by a combination of applied ramming and vibration. The final height of rammed aggregate pier is reached by repeating these procedures for four times (Figure 3).

Figure 3. View of the tank following the installation of rammed aggregate piers

Plate loading test is performed to determine loading capacity of rammed aggregate pier. Considering that RAP has a greater column diameter than the probe diameter due to applied ramming procedures and that it also improved the surrounding soil, a plate having a diameter of 20 cm circular cross-section rather than 10 cm is used in loading tests. The plate is made of steel with a thickness of 2 cm. It is connected to the RAP apparatus as shown in Figure 4. Displacements during the loading test are recorded with a resistive linear position meter (Figure 4) connected to a computer through a data acquisition system and vertical displacements are measured.

Figure 4. Location of plate and displacement measurements for plate loading test

The first loading test (Test 1) is performed on soil which underwent no improvement. Then a second test (Test 2) is performed on the RAP constructed within koalin clay (improved soil). Loads up to 40 kN are applied for staged loading tests staying within the calculated allowable bearing capacity of the RAP. Displacements of the pier and the soil are also recorded. The measured load-displacements and fitted equations are presented in Figure 5. It can be seen that both of the soils (non-improved and improved) did not fail for the 40 kN maximum applicable load; however, they did reach a critical threshold value.

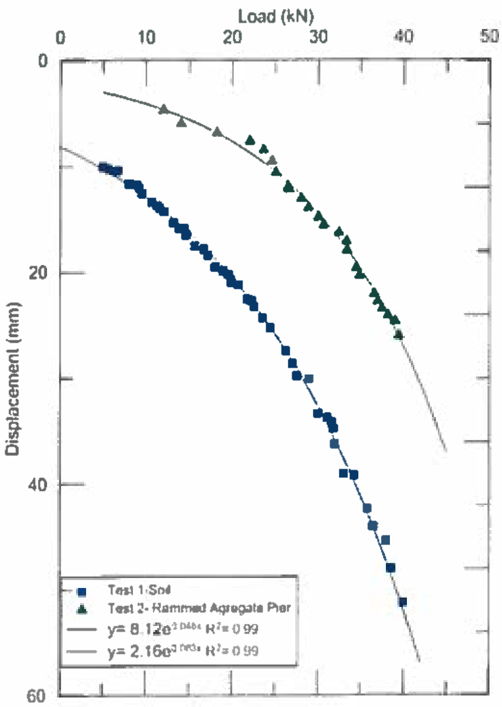

Figure 5. Load-displacement behavior of soil with and without RAP

After the completion of loading test on the RAP, approximately half of the clay material in the tank is removed in stages. It became possible to determine the amount and form of the developed volume changes, and shape of the undulated sides ("bulbs") in the RAP/soil interface. The cross-section is presented in Figure 6. It is observed that the RAP, which had an initial diameter of 10 cm, reached a width of 16 cm on the surface after loading test and formed four bulbs toward the bottom, largest of which was 22 cm.

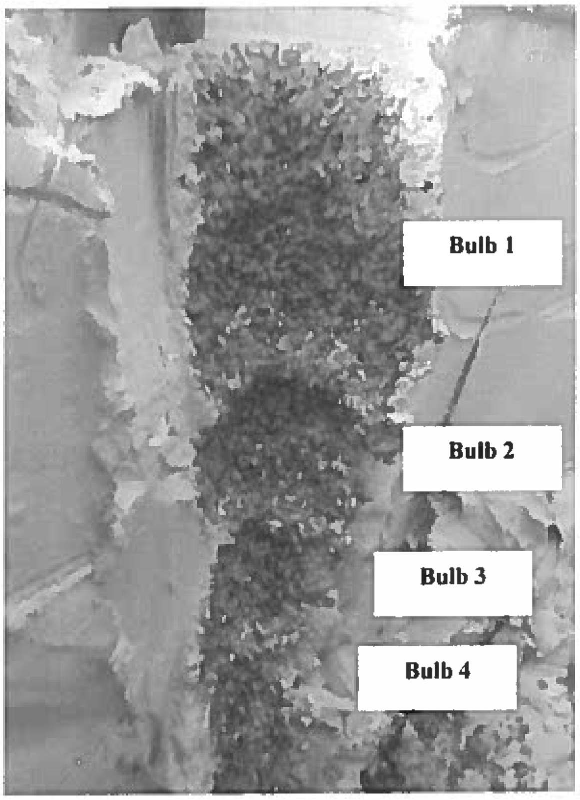

Figure 6. Undulated sides ("bulbs") formed in the column after the test

4 LABORATORY STRENGTH TESTS FOR CLAY AFTER PLATE LOADING TESTS

After the test performed in model test tank, the soil around the column is removed in stages. Following the removal of the soil, pocket penetrometer and hand vane tests are performed in four different locations of the tank at 90 cm, 70 cm, 50 cm and 30 cm depths, respectively. Averages of these tests results performed at four different depths and different areas of the tank are presented in Figure 7. Based on these results, an average 3-5 % improvement can be seen in undrained shear strength which is determined to be an average of 13 kPa in measurements on the tank surface on the soil which underwent no improvement. In addition, since soil consolidation was not completed, it is found that there was a decrease with depth in undrained shear strength.

5. CONCLUSIONS

In this study a rammed aggregate pier apparatus is developed to conduct model testing within the controlled laboratory environment and a rammed aggregate pier is constructed. Based on loading tests performed on soils which underwent and did not underwent improvement and tests performed to determine the change of undrained shear strength with depth, the following conclusions are reached:

1. According to pocket penetrometer and hand vane tests performed on samples of soil which underwent and did not underwent improvement, undrained shear strength (c_u) increased by 3-5 % as a result of RAP construction.

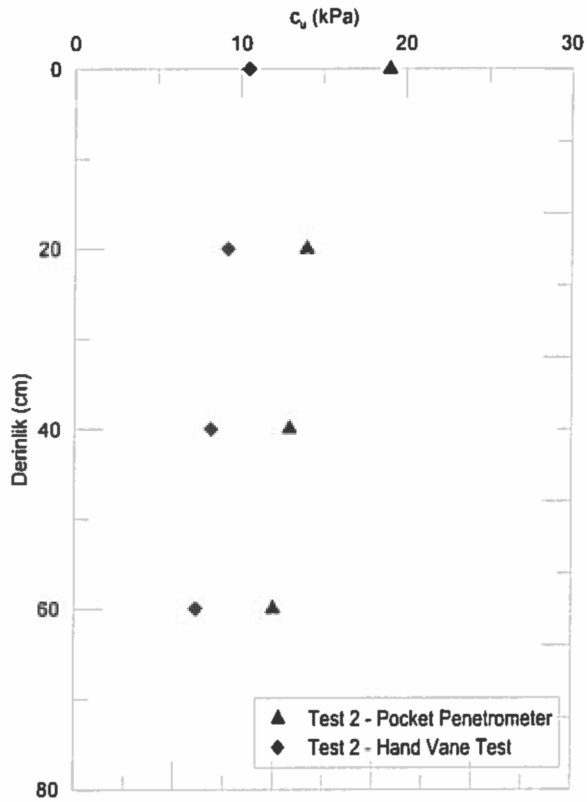

Figure 7. Pocket penetrometer-Hand Vane tests results

2. Volume increase occurring during the construction of rammed aggregate piers also increased the lateral earth pressure coefficient. Experimental observations showed that these layers, which consisted of four "bulbs", varied between 1.5 and 2 times of the initial nominal column diameter.

3. It is observed that in soil which was improved with RAP constructed in model test tank, laterally the improvement ratio decreased after approximately 30 cm distance from the edge of the RAP.

4. Analysis of the displacements, which occurred after axial loading test on the ground where rammed aggregate pier is constructed, indicated that the ground which underwent no

improvement collapsed quicker than the ground on which rammed aggregate pier is applied and that it created twice as much displacement under the same loading conditions (Figure 5).

5. Calculated capacity of rammed aggregate pier and the results obtained from loading test are approximately the same. These values are found to be around 40 kN for both tests.

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