Comparison of the results of load test done on stone columns and rammed aggregate piers using numerical modeling

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KEYWORDS: Rammed aggregate pier, stone column, loading test, numerical analyses

ABSTRACT: In this paper, performance of stone column (SC) and rammed aggregate pier (RAP) are compared with the results of loading tests done in the field. SPT and CPT tests were performed to obtain the engineering properties of soil on site. In the field, two stone columns and two rammed aggregate piers were constructed with three different methods and on all columns which have the same diameter and the length; the loading tests were performed to obtain the bearing capacity and stiffness of columns. The results of loading tests and numerical analysis were evaluated. All results indicate that the ratio of stiffness of columns constructed with Single Pier Displacement (SPD) method to columns constructed with Single Pier Replacement (SPR) method is about four. Also, the ratio of stiffness of rammed aggregate piers constructed with Single Pier Impact (SPI) method to columns constructed with SPD method ranges from 2.2 to 8.8 depending on the stress applied. The ratio of settlement of SPD to SPR is about two. Also, the ratio of settlement of SPR to SPI is about five. In conclusion, rammed aggregate piers are more suitable, cheap, and effective and have more stiffness compared to stone columns. The loading test results show that rammed aggregate piers perform better in terms of settlement and bearing capacity.

1 INTRODUCTION

Foundations of the buildings which will be constructed on loose and soft soil are usually improved by using one of the soil improvement methods, but in today's conditions the cost of these methods can exceed the budget. Therefore, economical methods that can provide solutions to the bearing capacity and other engineering problems have been developed. One of them is the Stone Column (SC) method which is quite practical at production phase. The foundations are also supported by Rammed Aggregate Pier (RAP) method which was developed by Dr. Fox at USA in 1980's. This paper presents the investigation of the behavior of RAP and SC using both experimental and numerical approaches. The full-scale field loading tests were done on rammed aggregate piers constructed by Single Pier Impact (SPI), Single Pier Displacement (SPD) and Single Pier Replacement (SPR) methods. The numerical method is verified by comparing the computed settlements with the measured ones. Rammed and un-rammed column elements of the same diameter (50cm) and length (6.5m) was analyzed to show the effect of installation method.

2 SITE INVESTIGATION

The rammed aggregate piers and stone columns were installed at a site in Kirklareli, Turkey. Site investigations included three boreholes, two CPT soundings, SPT and laboratory tests. The typical subsurface conditions at the project site consist of 1.2 meters of fill material below the existing ground surface, underlain by a 3.8 meters thick stiff to very stiff, fine gravelly clay layer. A 1 to 2 meter thick layer of medium dense to dense, clayey sand and gravel exists below the clay, which is underlain by very stiff to hard gravelly, sandy clay. The groundwater table was observed at approximately 1 meter below the ground surface at this site. Geotechnical field and laboratory design parameter values are presented in Table 1.

Table 1. Geotechnical field and laboratory design parameter values.

Depth (m)	Layer	SPT N_{60}	q_c (MPa)	c_u (kPa)	ϕ (^{0})	E (MPa)
0.0 – 1.2	Fill	-	-	-	-	-
1.2 – 5.0	fine gravelly clay	11	0.4 – 0.9	30 – 70	-	11
5.0 – 6.0	clayey sand – gravel	16 – 22	5.4	-	36	14
≥ 6.0	gravelly, sandy clay	23 - 41	2.6	120 - 200	-	18

3 CONSTRUCTION OF COLUMNS

In the field, two stone columns and two rammed aggregate piers were constructed with three different methods. The first method is called Single Pier Impact (SPI) is constructed with ramming of the aggregate (3 feet up, 3 feet down) using 36cm diameter beveled tamper. The second method is Single Pier Displacement (SPD) used 50cm diameter beveled tamper and the third one is Single Pier Replacement (SPR) used 50cm diameter auger was constructed without ramming. SPD and SPR are constructed as stone columns. All of them were constructed so that in the end the columns have a diameter of 50 cm. SPI was constructed with the following steps: (1) the plate is placed on the ground, (2) the mandrel with a diameter of 36cm is driven to the design depth, (3) the mandrel and hopper are filled with aggregate, (4) the ramming is performed with 3 feet up / 3 feet down and (5) the installation is completed. SPD was constructed with the following steps: (1) the plate is placed, (2) the mandrel with a diameter of 50cm is driven to the design depth, (3) the mandrel and hopper are filled with aggregate, (4) the mandrel is lifted up with vibration, without ramming and (5) the installation is completed. SPR was constructed with the following steps: (1) A pre-drilled hole is performed with an auger (diameter 50cm) to the design depth, (2) the mandrel is pushed down to the design depth, (3) the mandrel and hopper are filled with aggregate, (4) the mandrel is lifted up with vibration, without ramming and (5) the installation is completed.

4 EXPERIMENTAL RESULTS

The loading tests were performed to obtain the bearing capacity and stiffness of columns on four columns including two stone columns and two rammed aggregate piers. According to 8 ton design load, the test results indicate that the settlement measured is 5mm for SPI, 29 for SPD and 85mm for SPR as seen in Figure 1. The piers constructed with SPI method settles the least.

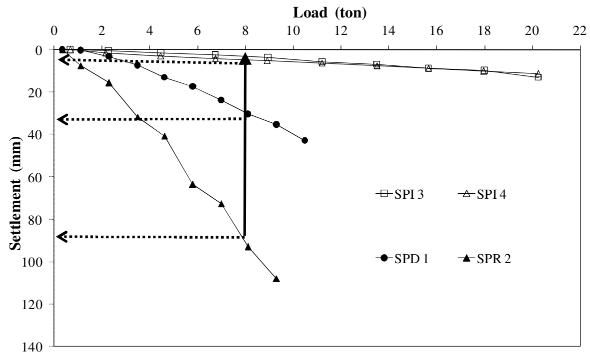

Figure 1. Comparative load-deformation plot for SPI, SPD and SPR.

Figure 2 presents the relationship between stiffness and applied stress for both the rammed and un-rammed column elements. Stiffness values of the un-rammed column elements decrease from about 20 – 40 MN/m^3 at low levels of applied stress to less than 10 MN/m^3 at a stress of about 400 kPa. Stiffness values of the rammed column elements decrease from about 180 MN/m^3 at low levels of applied stress to about 80 MN/m^3 at an applied stress of 800 kPa. Stiffness values for the rammed aggregate pier varies from 88 to 190 MN/m^3 depending on the applied stress.

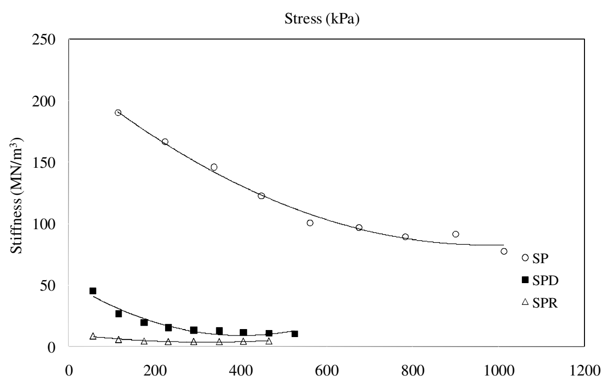

Figure 2. Stiffness versus stress for SPI, SPD and SPR

5 NUMERICAL ANALYSIS

The results of load tests done on un-rammed and rammed columns elements were analyzed with PLAXIS 2D program which uses finite element method. The analysis was carried out to compare the load-settlement behavior with the load test done in the field. An axisymmetric analysis was carried out using Mohr-Coulomb model for clay, rammed and un-rammed column elements. The overall model dimensions are 12 meter wide by 12 meter tall, as shown in Figure 3. In the analysis 15-noded triangular elements was used.

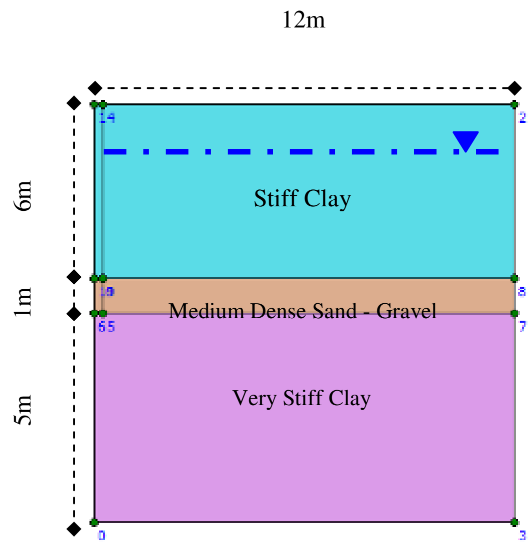

Figure 3. Representative soil profile (Kurt,2011).

Model parameters of the soil and column elements were assumed based on the data obtained from the in situ tests. Table 2 summarizes the values of the parameters used for the soil and the aggregate.

Table 2. Soil and column parameters used in the numerical analysis.

Parameters	1. Layer (Stiff Clay)	2. Layer (M. Dense Sand – Gravel)	3. Layer (Very Stiff Clay)	RAP	SC
γ_k (kN/m^3)	17	19	19	21	21
γ_d (kN/m^3)	19	20	20	22	22
e	1	0.5	1	0.3	0.3
E (kN/m^2)	10.000	20.000	25.000	150.000	10.000
c_u (kN/m^2)	50	0.01	120	0.01	0.01
ϕ (^{0})	-	35	-	45	40

γ_k : Dry unit weight, γ_d : Saturated unit weight, e : Void ratio, E : Elasticity Modulus,
μ : Poisson's ratio, c_u : Un-drained shear strength, ϕ : Friction angle.

5.1 Modeling of SPI

The modeling of SPI was done by defining deflections and loads. After the initial condition was assumed, the lateral displacement was applied along the column length and the lateral stress within the soil was increased. Thus providing additional stiffening and increasing the shear stress resistance within the soil. The friction angle of SPI was taken as 45^0. Finally, the stress applied in the field was defined in the program. Figure 4 compares the load-deformation curves computed from FE analysis with the measured ones from the full-scale load test for SPI. During the loading tests, SPI 3 and SPI 4 were loaded to %200 of its design capacity. The load-deformation responses in both field loading tests and numerical analysis are quite similar. The settlements measured and calculated were about 17mm.

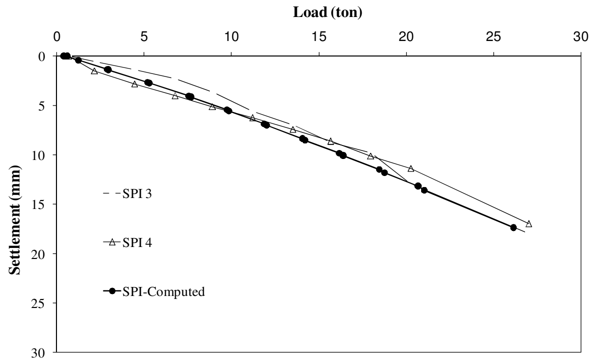

Figure 4. Measured and computed load-deformation curves for SPI.

5.2 Modeling of SPD

The modeling of SPD was done similar to the modeling of SPI. The friction angle of SPD was taken as 40^0. Figure 5 compares the load-deformation curves computed with the measured ones from the full-scale load test. During the loading test, SPD 1 was loaded to 150% of its design capacity of 7 ton. The load-deformation response in both field loading test and the numerical analysis is similar. The settlement measured is 43mm and the calculated one is 48mm.

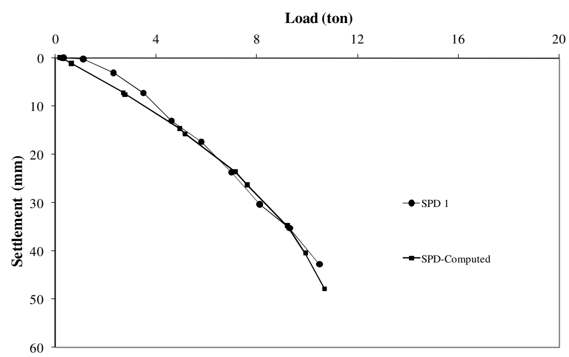

Figure 5. Measured and computed load-deformation curves for SPD.

5.2 Modeling of SPR

In the modeling of SPR, after the initial condition was applied, then, the stress applied in the field was defined. The friction angle of SPR was taken as 40^0. Figure 7 compares the load-deformation curves computed from the analysis with the measured ones from the full-scale load test for SPR. During the loading test, SPR 2 was loaded to 150% of its design capacity of 7 ton. The load-deformation responses in both field loading tests and the analysis are quite similar. The settlements measured and calculated were 108 mm and 110 mm respectively.

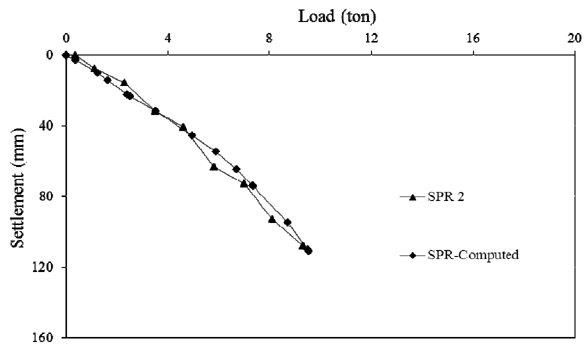

Figure 6. Measured and computed load-deformation curves for SPR

6 SUMMARY AND CONCLUSIONS

Full-scale loading tests were performed on two rammed and two un-rammed column elements of the same diameter and length. Two dimensional numerical analysis was used to simulate different installation methods, and the in situ load test conducted on the single columns. The computed settlement at top of the columns was in good agreement with the in-situ measurements. The following conclusions are drawn based on this study:

1. All results indicate that the ratio of stiffness of piers constructed with Single Pier Displacement (SPD) method to piers constructed with Single Pier Replacement (SPR) method is about four. Also, the ratio of stiffness of piers constructed with SPI method to piers constructed with SPD method ranges from about 2.2 to 8.8 as a function of the applied stress.

2. The ratio of settlement of SPR to settlement of SPD is about two. Also, the ratio of settlement for SPD to settlement for SPI is about four. Measured and computed settlement values are presented in Table 3.

Table 3. Measured and computed deformation values for SPI, SPD and SPR.

Construction Type		Applied Load (ton)	Measured Deformation (mm)	Computed Deformation (mm)
Type 1	SPI 3	18	9.77	11.4
	SPI 4		10.0	
Type 2	SPD 1	10.5	42.8	47.7
Type 3	SPR 2	8	92.0	82

In conclusion, rammed aggregate piers are more suitable, cheap, and effective and have more stiffness compared to stone columns. The loading test results show that rammed aggregate piers perform better in terms of settlement and bearing capacity.

ACKNOWLEDGEMENTS

This research was sponsored by Sentez Construction Co. and Istanbul Technical University Science and Technology Institute. The support of them is greatly acknowledged.

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