Numerical analysis of a full scale load test on a hydraulic fill reinforced with rammed aggregate pier

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ABSTRACT: Among ground improvement alternatives, Rammed Aggregate Pier® (RAP) solution serves as an alternative to deep foundations or over excavation and replacement of compressible soils. RAP construction involves densely compacting successive lifts of high quality crushed stone in a 50 cm cavity by displacement method or to a 90 cm cavity by replacement method. The length of the pier varies depending on the type of patented ramming equipment used. In this paper, field performance of Rammed Aggregate Pier® (RAP) is evaluated based on the observed behaviour of a full scale load test performed on a hydraulic fill reinforced with rammed aggregate piers at a project site in Bursa, Turkey. Numerical modelling studies using finite element analysis are performed and the predictions are compared with the observed behaviour. The finite-element analysis is carried out using the PLAXIS 3D and PLAXIS 2D software packages. Analytical methods available in literature and problem specific finite element-based numerical analysis have shown that the RAP improved and reinforced soil had an increased bearing capacity and decrease compressibility compared to unimproved soil site. In general, reasonable agreement was obtained between settlement observations of the Impact® (displacement method) reinforced zone and predictions.

1 INTRODUCTION

1.1 *Rammed aggregate pier*

Rammed aggregate piers have traditionally been used to support compressive loads applied by footings, floor slabs, and steel storage tanks. The effectiveness of the piers is attributed to the lateral prestressing that occurs in the matrix soils during pier construction and to the high strength and stiffness of the piers. In the past few years, there has been a development towards using the elements below highway retaining walls and embankments to reinforce soft soils, control settlements, and accelerate settlements (Wissmann, et al. 2002). In this study, the results of a full scale load test performed on a hydraulic fill reinforced with rammed aggregate piers at a project site in Bursa, Turkey is evaluated and compared with the predictions of numerical analysis.

Construction of Impact® Piers

In the field, RAPs are installed using the Impact® System construction procedures: (1) a closed ended mandrel with a diameter of 36 cm is pushed into the design depth using hydraulically static force assisted with vertical dynamic energy, (2) the mandrel and hopper are filled with aggregate, (3) the ramming action is applied with 100 cm up / 67 cm down compaction efforts, during which vertical energy is also introduced (Figure 1). The vertical ramming actions expand the diameter from 36 cm to 50 cm, if 100 cm up and 67 cm down compaction procedure is selected. The significant increase in lateral stress combined with the high density of the stone created by the installation process provides the unique strength and stiffness of the RAP system (Handy 2001, Wissmann et al., 2001).

Figure 1. Construction of Impact ® Piers

1.2 *Construction area*

The project site is within a private harbor located at southern shores of Marmara Sea. The soil profile comprises alluvial deposits consisting of soft to stiff silty clay layers with sandy inclusions. In the western side of the harbor area, a 180m x 350m land was reclaimed by hydraulic filling using material dredged from the sea bottom. At the eastern side of this reclaimed land a piled port structure is constructed, whereas at other sides are protected by rock mound shore structures. The piled port side was used as container stock area and western half of this reclaimed land was used for temporary car storage. Due to increased demand, the western side was also needed to be used as container storage area.

Figure 2. Location of the Port Studied

As a result of container storage on the piled port side of this reclaimed land, excessive soil displacements were observed and many remedial measures had to be implemented. In order to avoid similar problems on the other half of the land reclaimed by storage of dredged sea bottom sediments, detailed soil investigations are carried to determine type of remedial measures which can be implemented.

Based on the findings of soil exploration borings drilled at the investigation area, soil profile is determined to be as shown in Figure 3. A surcharge load of 60 kPa was envisaged due to container storage. The almost unavoidable settlement problems expected could be somewhat tolerated under container storage, as long as the differential settlements are kept within limits not to hinder the operations. But the risk of large lateral soil movements and risk of soil strength and rigidity loss during a strong earthquake could not be tolerated.

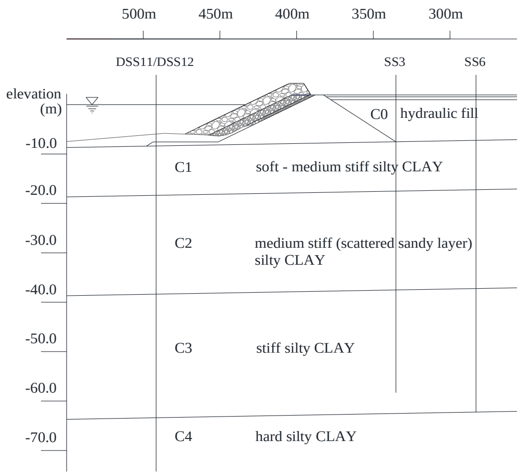

Figure 3. Soil Profile

Extensive numerical analysis studies are conducted to determine soil displacements and stability of shore structures of this reclaimed land under loads to be imposed. In the numerical analyses, the soil properties given in Table 1 are used.

Especially the hydraulic fill layer (C0) and the underlying soft clay layer (C1) shown in Figure 3 are expected to possess high level of risks. In order to increase the resistance against liquefaction and strength/ rigidity losses during a strong earthquake, to decrease problems which might arise as a result of excessive surface settlements and to limit the lateral soil movements, it is decided to implement soil improvement down to 16.0m depth.

The main goal of in-situ soil improvement to be implemented is chosen to be formation of homogeneous crust of improved soil properties. The elimination of settlements is considered be a task not easily (or economically) achievable, and found to be not necessary for the proposed use of this land. The detrimental effects of soil liquefaction and differential settlements to be reflected on the ground surface and lateral soil movements are expected to be minimized if a 16.0m thick crust is formed on top of the soil profile.

After careful review of soil improvement methods available and which can be implemented at the site to achieve the goals set, use of rammed aggregate piers (RAP's) is selected. A large number of load tests on individual piers and groups of 3 and 4 piers were executed to verify design assumptions regarding bearing capacity and pier (column) rigidity. In addition, a large scale areal load test was conducted in order to be able to better assess the settlement behavior.

2 LOAD TEST

A large scale instrumented load test (12.0m x 24.0m) has been executed on ground improved with rammed aggregate piers installed at triangular arrangement with 1.70m spacing.

2.1 *Test set-up*

A longitudinal section of the load test and a view of the field set-up are shown in Figure 4

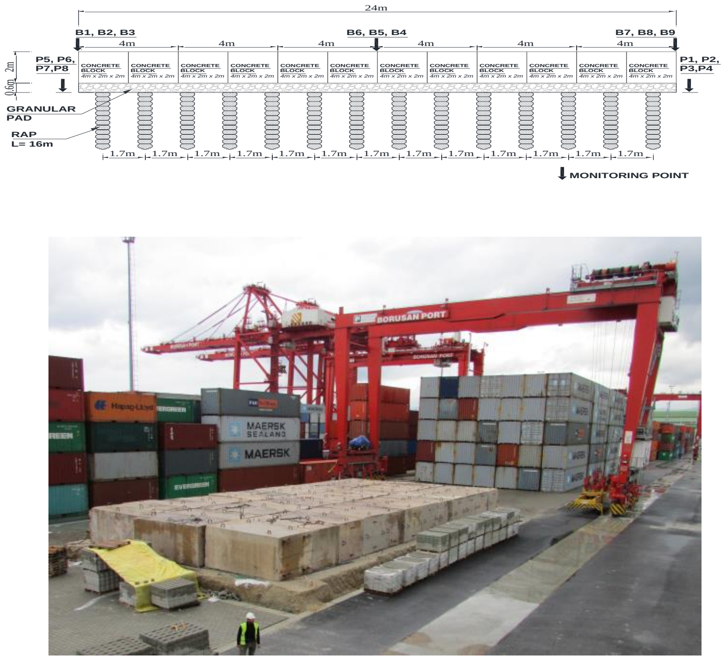

Figure 4. Load test set-up

2.2 *Soil parameters*

Soil parameters are given in Table 1.

Table 1. Soil parameters

Layer	SPT-N	φ (^{0})	E$'$ (MPa)	c_u (kPa)	k (cm/s)
C0 (Hydraulic fill)	1-10	24	5	10	$7.0x10^{-4}$
C1 (Soft clay)	1-3	25	8	25	$5.5x10^{-6}$
C2 (Medium clay)	4-9	26	12	40	$5.5x10^{-6}$
C3 (Stiff clay)	9-18	26	20	50	$5.5x10^{-6}$
C4(Hard clay)	20-30$^+$	28	30	80	$5.5x10^{-6}$

2.3 *Instrumentation and Monitoring*

A number of load tests are executed on the hydraulic fill layer improved with rammed aggregate piers. State of the art instrumentation is used to monitor the settlements, lateral soil displacements and pore pressure dissipation during the load tests. In this paper only the behavior recorded during one of these tests, the one in which 12.0m x 24.0m area is loaded is evaluated and the observed behavior is compared with the results of numerical analysis.

3 FINITE ELEMENT MODELING

For the numerical analysis of the load test behavior finite element modeling is employed using PLAXIS 3D and PLAXIS 2D softwares. Details of finite elements analysis and comparison of the results with recorded behavior is presented below.

3.1 *3D FEM Analysis*

In 3D FE modeling, ¼th of the loaded area is included taking into consideration the symmetry of the problem and an important degree of computer time is saved. In Figure 5, the FE model used in the analysis is shown. In the field, loading is achieved by placing 2.0m x 4.0m x 2.0m concrete blocks on the specially prepared ground, whereas in FE Model, a 6.0m x 12.0 areal fill of 2.0m height consisting of volumetric elements of linearly elastic material is considered. On the other hand, soil deposits are modelled as elastic-plastic and both drained and undrained behavior is considered in FE model. Utilizing the Hardening Soil model, undrained analysis is performed for modelling instantaneous loading and consolidation analysis is carried out to model the long term behavior under sustained loading. 3D FE model comprised 10x10 =100 RAP's of 50cm diameter installed at a triangular pattern as shown in Figure 5.

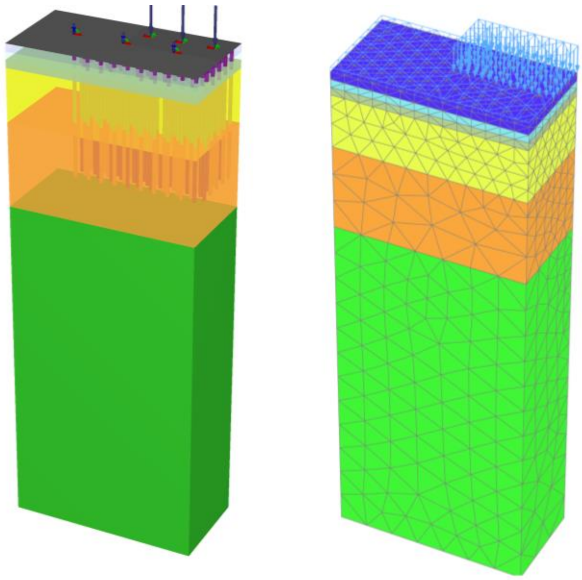

Figure 5. FE model

In the numerical analysis, after computation of initial in-situ field stresses for K_0 conditions, the volumetric elements representing the concrete blocks are activated and instantaneous loading stage is analyzed. At the instantaneous loading stage, a 60 kPa uniform surcharge is added to the pressure exerted by the concrete blocks, in order to take into account the loading arising from loading activities in the surrounding area (Fig.4).

The computed soil displacements at the end of consolidation stage using 3D FE analysis is shown in Figure 6.

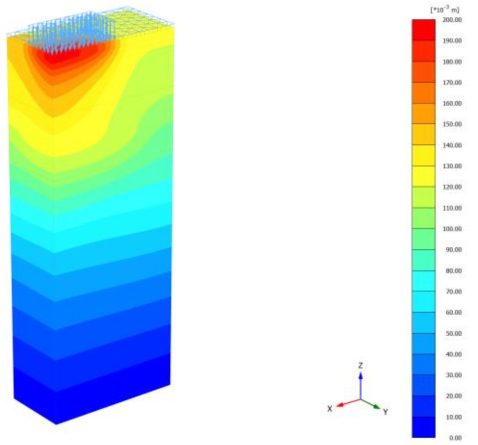

Figure 6. Computed soil displacements

The settlement- time curves computed under the corner and center of the loaded area from 3D FE analysis are shown in Figure 7 together with the measured values. It is observed that there is a reasonable agreement between the computed and measured settlements time up to 50 days, beyond which measured settlements deviate from expected consolidation behavior under sustained loading. One possible reason for this disagreement might be not to be able to reflect closely the field loading conditions arising from construction activities around the test location in the numerical analysis model. Another possible reason for the discrepancy might be the creep behavior not considered in the soil model used in the analysis but we believe the first reason mentioned is more likely because pier installation and other construction activity were in progress along with the test loading due to very tight work schedule.

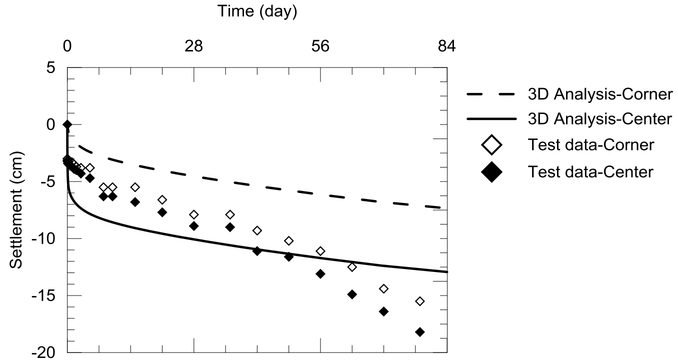

Figure7. Comparing test data with 3D analysis

3.1 *2D FEM Analysis*

The behavior of field loading test is also analyzed by 2D FE model shown in Figure 8 using Plaxis 2D 2012. This is a cellular axisymmetric model and the model width is taken to be equal to one half of the center-to-center spacing of RAP's. Same material properties as in 3D FE model are used. In the 2D FEM analysis, in addition to model the settlement-time behavior, modelling the effect of rammed aggregate pier (RAP) installation method is attempted. For this purpose cavity formation in the surrounding soil during pier installation similar in magnitudes as observed in the field, is modeled in the analysis by assigning prescribed displacements along the length of the pier(10cm-lateral and 10cm-vertical at the base) as shown in Figure 8.

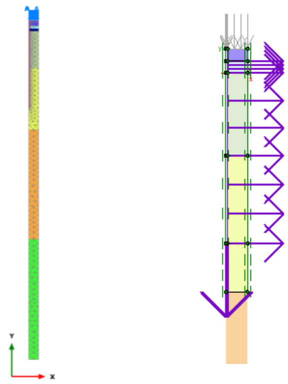

Figure 8. 2D FE model

In the 2D FEM analysis, after the computation of initial in-situ stresses corresponding to K_0 condition, RAP installation is modeled. Then 60 kPa surcharge load is applied and consolidation analysis is carried out until excess pore pressures dissipate to 1 kPa. As a second method of analysis, loading test is analyzed following the same steps but without modelling the cavity expansion due to ramming during stone column installation. The computed settlement-time behavior using two different approaches are shown in Figure 9 together with the measured values.

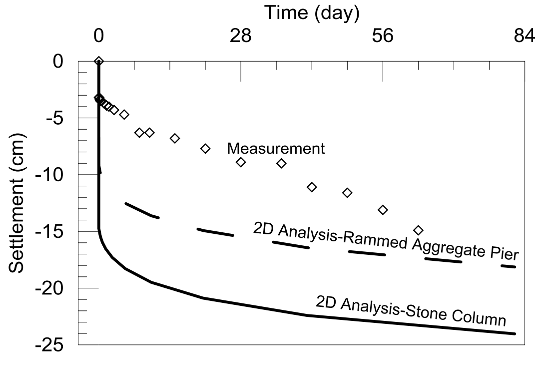

Figure 9. Comparing test data with 2D analyses

It is observed from Figure 9, there is poor agreement between results of 2D analysis and measured values of settlement behavior at the initial phases (up to 50 days) of loading compared to the results of 3D analysis. On the other hand, computed and measured settlements seem to match better at later stages. Considering that in the numerical analysis performed consolidation type behavior is attempted to be modelled, 3D modelling is observed to yield results more closely than 2D modelling. This believed to be mainly due to the difference in way the load application is modeled. In 2D analysis a surcharge load covering the total model surface area is applied as opposed to load being applied locally on the test area in 3D analysis.

CONCLUSIONS

In this paper, field performance of Rammed Aggregate Pier® (RAP) is evaluated based on the observed behaviour of a full scale load test performed on a hydraulic fill reinforced with rammed aggregate piers at a project site in Bursa, Turkey. Numerical modelling studies using finite element analysis are performed and the predictions are compared with the observed behaviour. The finite-element analysis is carried out using the PLAXIS 3D and PLAXIS 2D software packages. Analytical methods available in literature and problem specific finite element-based numerical analysis have shown that the RAP improved and reinforced soil had an increased bearing capacity and decrease compressibility compared to unimproved soil site.

1. The lateral expansion of the surrounding soil during installation of a rammed aggregate pier is known to lead to decreased field settlements compared to sites which are improved with conventional stone columns (Hand, 2001). Behavior of stone columns installed by different methods had been subject of 2D and 3D finite element analysis.

2. From the results of numerical analyses presented in this study, a better agreement between the computed and measured settlement- time behavior is observed when 3D FE modelling is used up to about 50 days, beyond which settlements deviating from expected consolidation behavior are recorded. One possible reason for this discrepancy might be not to be able to reflect the field loading conditions closely in the numerical analysis model, another possible reason might be creep type behavior even though we feel it is less likely under the given field conditions within the time period of observation.

3. A better agreement is observed between the results of 2D numerical analysis and measured field behavior when lateral soil displacements caused during installation are taken into account, but the agreement is poorer compared to the results of 3D numerical analysis.

4. Use of numerical modelling is very useful in geotechnical engineering design works, provided that valid soil parameters are used and field loading and boundary conditions are realistically taken into account. It is always advisable that results of numerical analysis are compared with field measurements and appropriate model is chosen accordingly. The results of this study has the implication that with current modeling abilities, 3D FE models can give results more compatible with the observed field behavior than 2D models. But the inability to reflect closely the field loading conditions arising from continuing construction activities around the testing area was a major reason for the discrepancy between recorded and observed behavior at later stages of testing.

4 REFERENCES

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