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Performance Monitoring of Rammed Aggregate Piers: A Stockyard Case History Site

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Abstract. This paper investigates the design aspects of Rammed Aggregate Pier® (RAP) treatment as a composite treatment for the unfavourable ground conditions, the construction, QA/QC measures and the verification of the performance via a comprehensive instrumentation scheme. For this purpose, instrumented full scale load test was performed for the stockyard project site in Izmir, Turkey. The soil profile is comprised of fill and soft sandy clay layers overlain by the pyroclastic (tuff and agglomerate) bedrock. 6 to 18 m long RAP elements were installed in a square grid spaced between 1.5 m and 2.0 m to improve bearing capacity and settlement responses, to accelerate the time rate of settlement (i.e.: consolidation) and to mitigate the liquefaction potential at the project site. The foundation settlement was estimated by RocScience-Settle 3D software, which was observed to be 30 % smaller than the measured values. After the ground improvement with RAP elements, the foundation settlements were measured as less than 10 cm as compared to 40 - 60 cm settlement predictions of the untreated system.

Keywords: Impact® System, Rammed Aggregate Pier®, Stiffness, Instrumented Full Scale Load Test.

1 INTRODUCTION

Rammed Aggregate Pier® elements support compressive loads applied by footings, floor slabs, and steel storage tanks. This system is a ground improvement system that uses compacted aggregate to create stiff pier elements. The effectiveness of the piers is attributed to the lateral pre-stressing that occurs in the matrix soils during pier construction and to the high strength and stiffness of the piers. Rammed Aggregate Pier® System is widely used in Turkey over the recent years as an alternative to other stone column elements. In this study, the performance of Rammed Aggregate Pier® elements, which were designed to control settlements and mitigate liquefaction-induced problems in the container stockyard site, was assessed. Within this scope, a test embankment was constructed to confirm the geotechnical parameters determined in the preliminary design. The monitoring results and the evaluation of the performance of the test embankment founded on Impact RAPs, are presented in this paper. Also, the field performances of soil layers improved with Impact RAP are evaluated based on field monitoring results and are compared with the predictions of the numerical modelling studies.

2 PROJECT SITE DETAILS AND SOIL PROFILE

The project site is located within a private harbour located in Izmir, Turkey. In the harbour, a 193 m x 308 m area was reclaimed by using the material dredged from the sea bottom as a hydraulic fill. The project site, planned to be used as container stock area, is shown in Fig. 1.

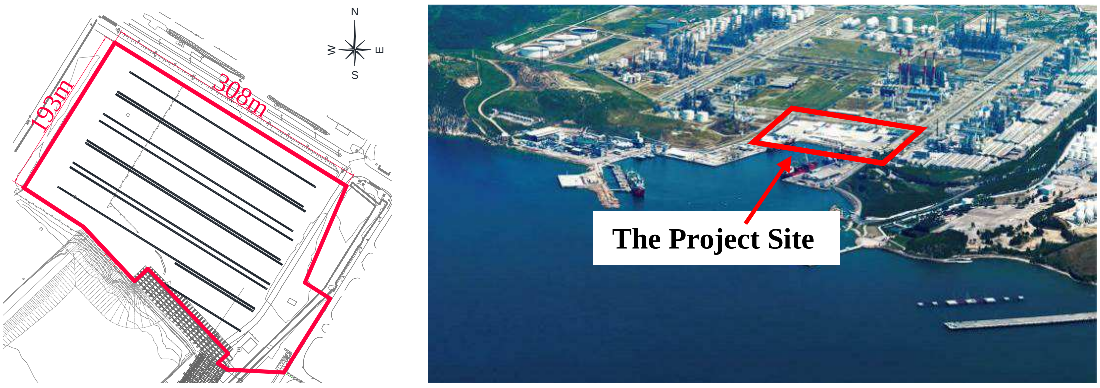

Figure 1. Plan of the project site

An extensive site investigation program, involving 35 to 38 m deep boreholes at 9 different locations was executed. At various depths, standard penetration tests were performed along with the disturbed and undisturbed soil sampling. On the retrieved disturbed and undisturbed soil samples, soil classification and triaxial shear strength tests were performed. Fig. 2 presents the idealized soil profiles.

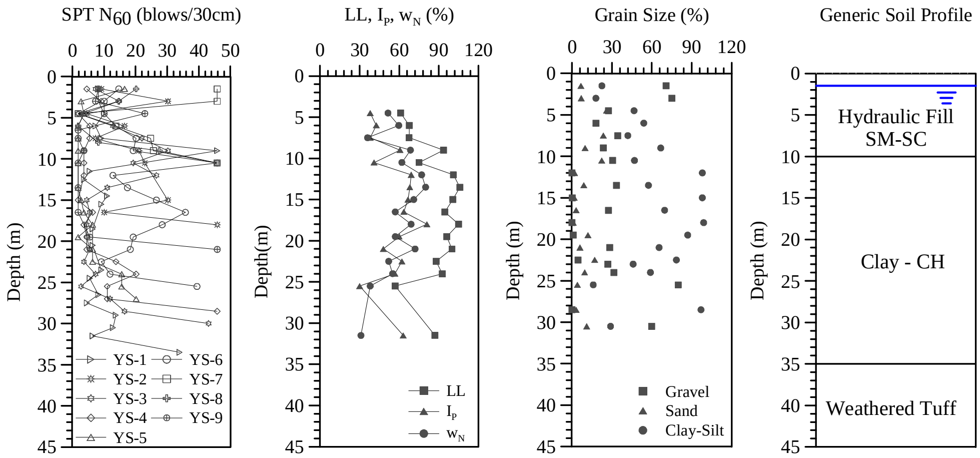

Figure 2. Idealized soil profile; and the variation of N_{60}, LL, I_P, w_N (%), grain sizes with depth

The bore logs confirm the presence of a 3 to 10 m thick hydraulic fill (gravelly silty sand, SM, and clayey sand, SC). Under this fill layer, a soft high plasticity clay layer with a thickness between 2 to 25 m overlies pyroclastic (tuff and agglomerate) bedrock layer. Groundwater table is reported to be at 0.6 to 2.3 m depth from the ground surface.

3 GROUND IMPROVEMENT WITH RAMMED AGGREGATE PIER® (RAP)

The project site has been used as a fill stockyard in the last 10 months for placing fill material (randomly dumped rock fill). The height of the fill varies in the range of 2 to 15 m. The preloading effects by this random fill has been carefully modelled as the initial stage of modelling. The area loaded by random fill material was divided into two zones where the stresses due to fill material was estimated as 54 and 108 kPa. A "flexible" foundation model is used in RocScience-Settle 3D software to assess the consolidation and differential settlement potential of the site. Similarly, Boussinesq stress distribution option is selected for the estimation of induced stresses beneath the fill area. The sum of the elastic settlement of fill layer by using modulus of elasticity E=7 MPa; and consolidation settlement of soft clay layer by using the ratio of $c_c/1+e_0$=0.22 and OCR=1.0, is estimated to vary in the range of 40 cm to 60 cm under the service foundation stress of 85 kPa. The liquefaction triggering

potential of silty sandy gravelly fill sublayers with varying fines content (2% to 30%, typically 15%) were identified under a seismic scenario of maximum acceleration a_{max} = 0.4 g and moment magnitude M_w=6.5. Total settlement values (excluding post-liquefaction settlements) are beyond tolerable limits, which are defined as 200 mm and 300 mm in 2 and 20 years, respectively. In order to eliminate liquefaction-induced strength and rigidity losses, excessive surface settlements, it is decided to implement a soil improvement solution. The elimination of the settlement is considered be a task not easily (or economically) achievable, and found to be not necessary for the proposed use of this land. Hence, the main goal of the in-situ soil improvement is defined as to form a homogeneous crust with improved soil properties. The detrimental effects of soil liquefaction and the differential settlements reflected on the ground surface are expected to be minimized if a thick crust is located at the top of the soil profile. After the careful review of soil improvement methods available, and which can be implemented at the site to achieve the goals set, the use of Impact® Rammed Aggregate Piers® (RAPs) is preferred. The project site is separated into the seven zones considering the foundation stresses and the variability of soil profiles. Therefore, 50 cm stiff Impact RAP elements reaching to 6 m - 18 m lengths from the excavation depths of 1.5 m with 1.5 to 2.0 m square pattern, were installed. Installation steps for this system are summarized below:
(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 (Fig. 3).

Figure 3. The construction of Impact® RAPs.

In this project, 6 modulus load tests were performed on Impact® RAPs installed to assess the bearing capacity and stiffness response of individual RAPs. The modulus load test is similar to a pile load test defined by ASTM D 1143. Loading, starting with 5 % is increased until the pier is tested up to 150 % of its service load. Then, an unloading procedure is followed. The tests are also used to show how the RAP behaves in the soil matrix. This is done by observing the deflection of tell-tales installed at the tip of the test piers. The modulus load test of RAPs may also incorporate tell-tales at different elevations within the pier (Brain et al., 2006). A representative load-settlement curve is shown in Fig. 4a, while Fig. 4b presents the applied stress vs. settlement responses of all tests. The results indicated that a RAP average stiffness can be assumed as 50 MN/m^3. This value was observed to be nearly twice the stiffness values selected during preliminary design.

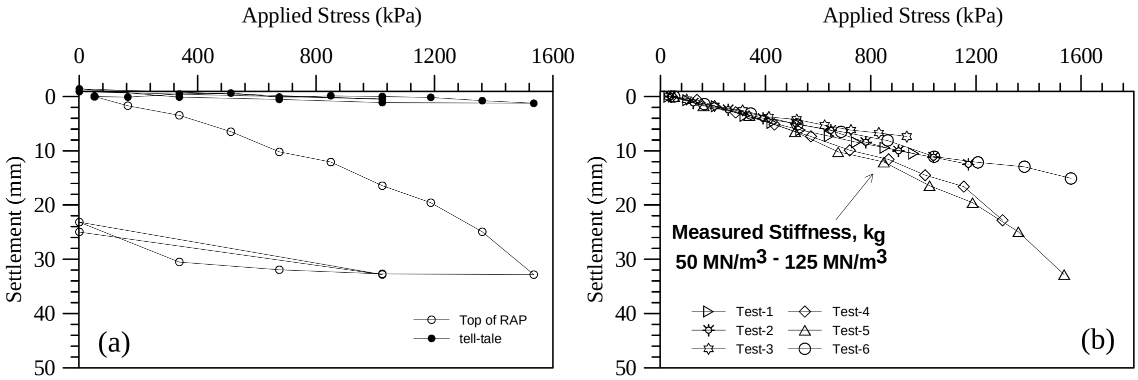

Figure 4. Modulus load test stress - settlement curve

4 TEST EMBANKMENT AND ASSESSMENT OF MONITORING RESULTS

A full scale load test was performed by using the test embankment with 1V:1H side slopes, 4.25 m height (the elevation from +1.00 m to +5.25 m) and dimensions of 21.5 m x 31.5 m in plan view. Trial embankment was located at an area, where soil conditions were relatively unfavourable as suggested by the boreholes. The total thickness of the fill and the soft to firm clay varied between 24.8 m - 26.2 m from the elevation of ±0.0 as shown in Fig. 5 and Fig. 6. Vertical deformations of the test embankment were monitored by geodetic measurements at 9 points (SP) for a period of 111 days. Also, three vibrating wire piezometers (three levels for each piezometer), four inclinometers and two vibrating wire borehole extensometers were installed under the trial embankment for measuring lateral deformations, pore water pressures and vertical deformations, respectively. Transducers were monitored daily for 43 days during the installation of trail embankment, and then measurements were continued on weekly basis.

Figure 5. Test embankment and installation of instruments

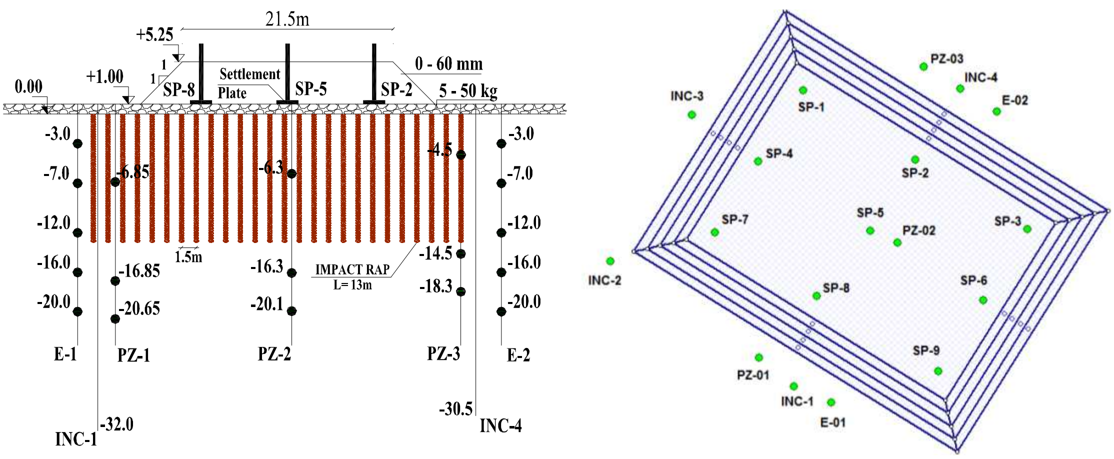

Figure 6. Test embankment section and RocScience-Settle 3D model

The total settlement response of the test embankment is assessed by using Settle 3D, RocScience software. The geometry of the trial embankment was realistically modelled as shown in Fig. 6. Necessary input parameters were estimated and used in Settle 3D model, as given in Table 1.

Table 1. Soil parameters used in numerical assessments

Material	γ	E	$E_{comp.}$	C_c	C_r	C_a	C_{ar}	e_0	OCR
	(kN/m^3)	(MPa)	(MPa)	-	-	-	-	-	-
Hydraulic Fill	18.0	7.0	-	-	-	-	-	-	-
Soft Clay	16.1	-	-	0.65	0.12	0.025	0.0083	1.96	1.0
Stiff-Very Stiff Clay	19.0	30	-	-	-	-	-	-	-
Weathered Tuff	20.0	45	-	-	-	-	-	-	-
Impact RAP	20.0	95-200	-	-	-	-	-	-	-
Impact RAP Zone - 1	18.2	-	16.5-23.8	-	-	-	-	-	-
Impact RAP Zone - 2	18.2	-	7.5-11.0	-	-	-	-	-	-

γ - unit weight, E - elasticity modulus of soil, $E_{com}=E_{RAP}$ x R_a+E x (1-R_a) - composite elasticity modulus (E_{RAP} – RAP elasticity modulus, R_a - area replacement ratio), C_c - compression index, C_r - recompression index, C_a - creep coefficient, C_{ar} - secondary recompression index, e_0 – void ratio, OCR – over consolidation ratio

Monitoring points (SP), extensometers (E) and 3D model settlement responses are shown in Fig. 7. It is observed that extensometers indicate settlements smaller settlements than the ones at geodetic monitoring points, because they are located in the vicinity but not within the test embankment area. Also, it is observed that about 2/3's of total settlements are due to compression of untreated lower zone and the remaining 1/3 due to the upper improved zone.

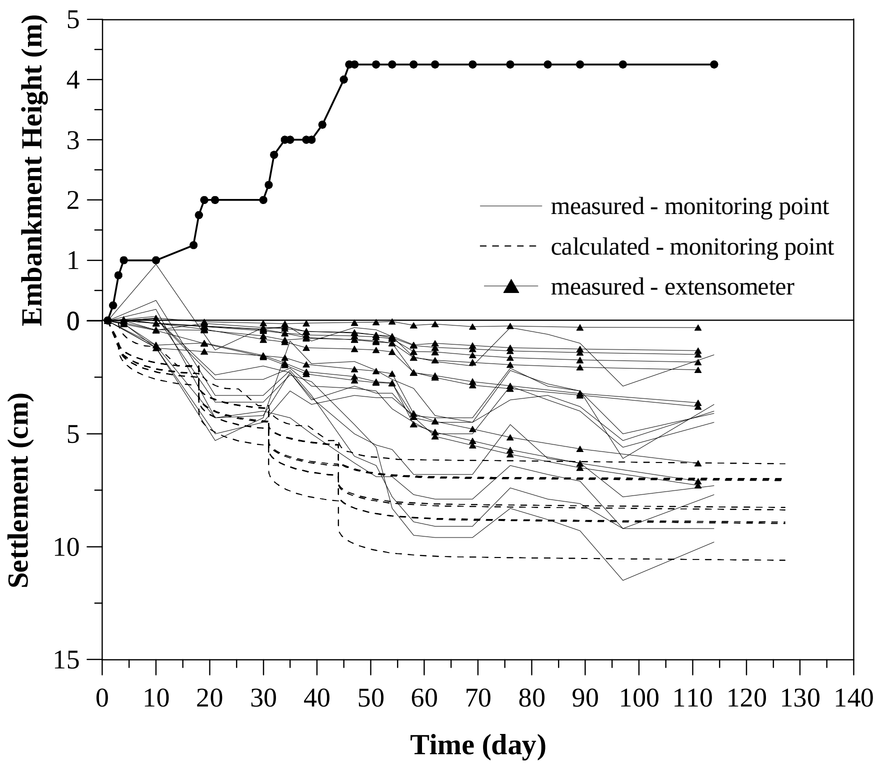

Figure 7. 3D model and field data responses: settlement vs time curves

5 SUMMARY AND CONCLUSIONS

In this paper, the settlement performance of a stockyard site, beneath which series of Impact® Piers were installed, is presented. For this purpose, a trial embankment was constructed at an area where soil conditions were relatively unfavourable as suggested by available bore logs. Vibrating wire piezometers, vibrating wire borehole extensometers and settlement plates were installed to monitor the pore water pressure and settlement responses of soils beneath the test embankment during a period of 111 days. Followings are the specific conclusions of the assessments performed:

- The total surface settlements recorded in the field were 30 % smaller than those predicted by 3-D settlement assessments.

- The settlement readings from extensometers indicate that an elastic compression of the upper zone takes place, which are completed shortly after the full embankment construction, as expected. The majority of the total settlements (about 2/3's) are observed to be due to time dependent compression of non-improved lower soil layers which are underlying RAP elements.

As a conclusion, the proposed Impact RAP elements are judged to produce an effective solution to control large settlements and to eliminate soil liquefaction-induced bearing capacity and deformation problems.

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