CPT-Based Assessment of Densification After Ground Improvement with Rigid Inclusions and Rammed Aggregate Piers® (RAP)

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Abstract. Within the scope of this manuscript, the mitigation performance of a composite ground improvement solution, which is composed of 18 m long 40 cm diameter GeoConcrete® Column (GCC) and 50 cm diameter Impact® Rammed Aggregate Pier® (RAP) along with 40 m long 80 diameter piles is assessed by pre- and post-cone penetration testing (CPT). These elements are designed for controlling excessive total and differential settlements, and liquefaction triggering at a paper mill site. In this paper, the site geology, geotechnical model, design aspects of GCC and Impact® RAP patented systems and QA/QC measures are discussed. As a mitigation solution, 18 m and 40 m long elements are designed to be constructed in the soft to medium stiff silty clay with scattered silt and sand interlayers. Improvement expectations from GCC and Impact® RAP elements are partially verified by pre- and post-CPT data, and are listed as: (i) densification of cohesionless silt and sand layers, (ii) shear stress transfer to rigid columns during cyclic (seismic) loading, reducing seismic demand from foundation soils (iii) increased horizontal stresses, leading to increased soil (and column) stiffness and strength, (iv) vertical drainage through aggregate columns to dissipate cyclically – induced excess pore water pressures. The results show that due to ramming and vibration induced-densification, cone tip resistance has increased by a factor of 1.3–1.6 in cohesionless layers.

Keywords: Impact® Rammed Aggregate Pier® · GeoConcrete® Column · Cone Penetration Test (CPT) · Densification

1 Introduction

Rigid columns in the form of deep soil mixing, bored piles, rigid inclusions, sand drains, stone columns or Rammed Aggregate Pier (RAP) elements are widely used as a liquefaction mitigation solution. Despite their similarity with stone columns, rammed piers differ from them, since crushed stone is very densely compacted by vertical

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ramming action applied to 0.33 m thick layers. The rammer is driven by a high-energy hydraulic hammer so there is uniform compaction and lateral stress along the length of the pier [1]. 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. Rigid inclusions can be constructed as a densified aggregate pier or as a ground improvement element that typically has cementitious binding element, providing bulging resistances resulting in increased bearing and settlement control in poor soil environments [2]. These systems have been widely used to treat liquefaction in heterogeneous soil layers through densification and shear stress redistribution. In the literature, there exist differences in opinion regarding the effectivity of these rigid columns in reducing cyclic shear stresses acting on the natural soil. As discussed in Rayamajhi et al. [3], current design practice often assumes that rigid columns and soil exhibit shear strain–compatible deformations as also supported with centrifuge test results presented in Adalier et al. [4]. Since these columns are usually stiffer than the soil, they attract more shear stress, hence reduce the shear stresses left to be resisted by the soil. Rayamajhi et al. [3] numerical findings question the validity of the strain-compatibility assumption for design. Rayamajhi et al. [5] suggested a better performance when these rigid elements are fixed against rocking and Rayamajhi et al. [6] suggested a modified design equation to estimate the reduction in cyclic stress ratio provided by dense granular columns.

This paper presents a case history in Aydin, Turkey, where a composite ground reinforcement system was constructed by GCC, a type of cemented rigid inclusion, and Impact® RAP stone column elements, recommended to control excessive settlements and a mitigation solution against liquefaction triggering. The aim of this paper is to assess the densification of cohesionless soils after the construction of rigid inclusions by comparing pre and post CPTs.

2 Project Description

In the western part of Turkey, a paper mill was to be constructed in Aydın. The facility is composed of a number of structures with gross foundation stresses varying in the range of 150 kPa to 300 kPa. Due to facility requirements, allowable settlement criteria were defined to be unusually low varying in the range of 7 to 25 mm. Plan view of the site is shown in Fig. 1.

A detailed site investigation program was implemented including the execution of in-situ penetration tests, disturbed and undisturbed soil sampling. Following the site investigation studies, on the extracted disturbed and undisturbed soil samples, a laboratory testing program was executed. The generalized soil profile, as well as SPT N_{60} values obtained from standard penetration tests, corrected cone tip resistance (q_t) obtained from cone penetration tests, natural water content (ω), liquid limit (LL), plasticity index (PI) and fines content (FC) are shown in Figs. 2 and 3. All tests were performed consistent with ASTM Standards [7–12]. The soil profile is composed of a

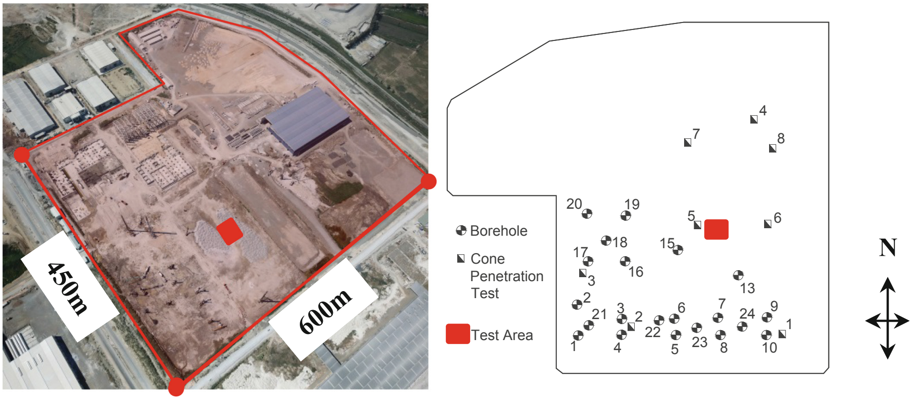

Fig. 1. Plan view of the project site.

surface soil with a thickness of 0.3–0.5 m overlying a soft-medium stiff silty clay (CL) and clayey, sandy silt (ML) layer up to a depth of 5 m. Below the silty-clay layer, there exists a well graded to silty sand (SM-SW) layer with varying thickness in the range of 1.5–8 m. A silty clay layer follows this sand layer. The ground water table is reported to be 1.5–4.0 m below natural ground surface.

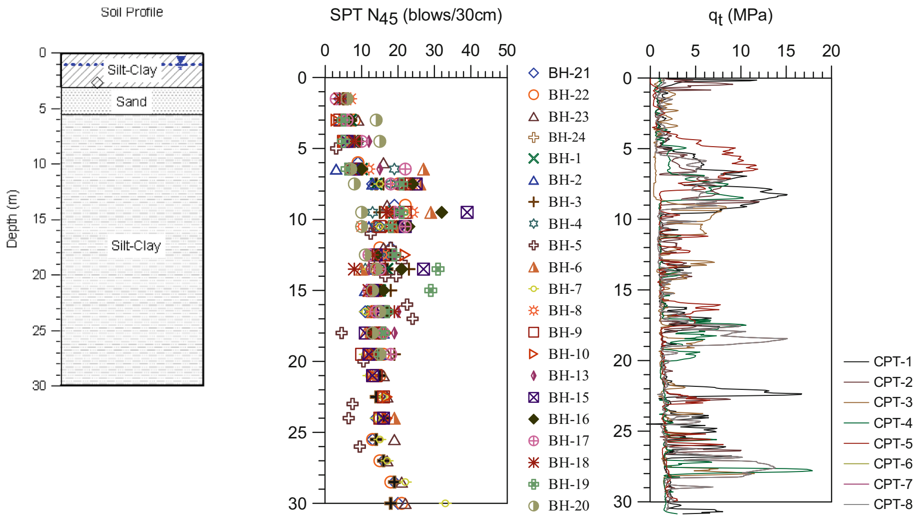

Fig. 2. The representative soil profile, the variation of SPT N_{45} and q_t vs. depth.

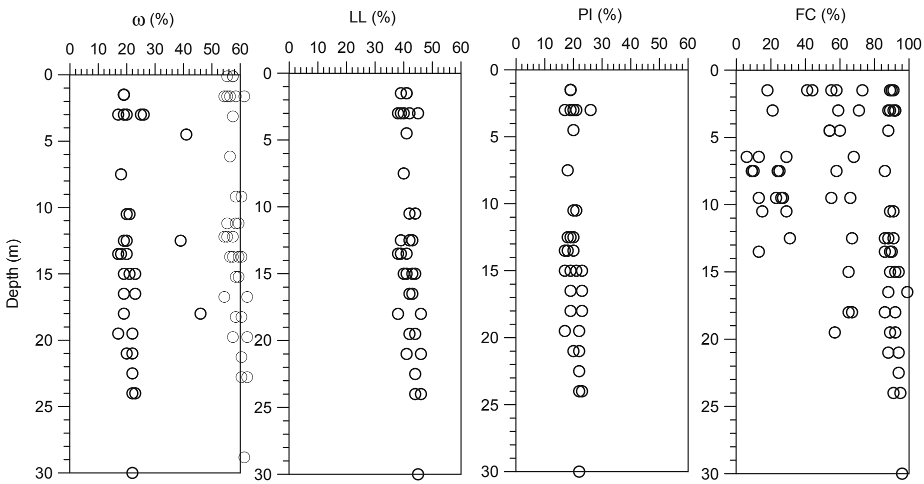

Fig. 3. The variation of ω, LL, PI and FC vs. depth.

3 Improvement with Impact® RAP and GCC Composite System

A ground improvement solution was designed to eliminate concerns regarding excessive settlements and liquefaction triggering. The site is located in a seismically active region of Turkey with 0.47 g peak ground acceleration due to a $M_w = 6.5$ event which defines the seismic demand. A composite system including bored pile and/or vibrex pile, rammed aggregate pier and rigid inclusion column solution was determined as one of the most cost effective solution for this project. 40 m long 80 cm diameter vibrex/bored piles are designed as the major load bearing elements, whereas 18 m long Impact® RAP and GCC elements around these piles were served to eliminate liquefaction hazard surrounding the piles and forms a rigid crust supporting the mat. Design lengths and patterns are chosen to specifically comply with the (i) the allowable settlement criterion of 7 to 25 mm, (ii) minimum factor of safety criterion of 1.20 against seismic soil liquefaction. The main goal of the in-situ soil improvement is defined as to form a thick homogeneous crust with improved soil properties under the foundations. The detrimental effects of 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. Additionally, 40 m long piles are designed to be fixed to stiffer deeper layers to eliminate a possible racking deformation of the improved upper crust.

Impact® Rammed Aggregate Piers and GeoConcrete® Columns used on this project were constructed by driving a closed ended displacement system which uses hydraulic crowd pressure and vertical vibratory hammer energy to displace and densify the liquefiable soils. Figures 4 and 5 present the construction methodology of the columns and a view from the field construction, respectively. Installation steps are summarized next:

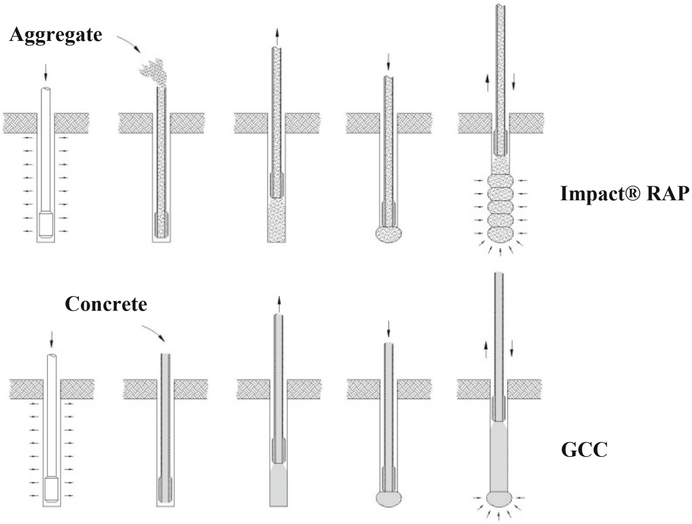

Fig. 4. Construction methodology of Impact® RAP and GeoConcrete® Column elements.

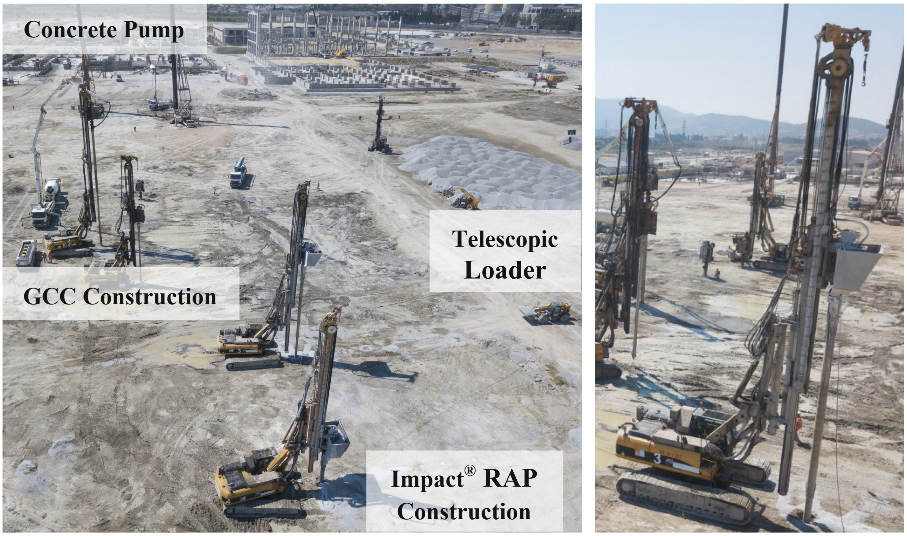

Fig. 5. A view from the field construction.

RAP Construction. RAP elements are installed using the Impact® System construction procedure: (1) a closed ended mandrel with a diameter of 36 cm is pushed into the design depth using hydraulically applied 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. The ramming actions expand the diameter from 36 cm to 50 cm if 100 cm up and 67 cm down compaction procedure is chosen.

Crushed gravel (typically graded at 13 to 38 mm in particle size) is fed through the mandrel from a top mounted hopper and compacted in the displaced cavities to create 50 cm diameter, dense, stiff, aggregate pier elements. 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 [13, 14].

GCC Construction. GCC elements are installed using the displacement method as well: (1) a specially designed, patented mandrel with a diameter of 40 cm and tamper foot is driven into the design depth using strong static force augmented by dynamic vertical impact energy, (2) the mandrel is filled with concrete, (3) the tamper foot and mandrel are then raised 100 cm and then driven back down 67 cm, forming a bottom bulb, (4) following bottom bulb installation, GCC elements are installed by extraction of the mandrel.

4 Ground Improvement Testing Program

The purpose of the ground improvement testing program was to verify the densification effects in cohesionless soil layers, of the composite ground improvement method through pre- and post-test results. The testing phase comprised pre- and post-improvement cone penetration testing (CPTu and seismic CPTu) and shear wave velocity testing in three test groups. Figure 6 shows CPT test locations and direction of the seismic test lines. In this paper, pre- and post-improvement CPT investigations for a test group, which comprises CPT-B2, CPT-P2 and CPT-P3, are presented. Additionally, as shown in Fig. 6, an 80 cm diameter of bored pile installed at the center of a unit cell was also monotonically loaded to test the performance of the system. The unit cell includes 8 GCC and 4 RAP elements, which were constructed in a square pattern with 3.5 m and 2.0 m centre-to-centre spacing and extended to a depth of 18 m, respectively. The work sequence was as follows:

- The bored pile extended to a depth of 40 m was constructed at the center of the ground improvement test area.
- Pre-improvement CPTu was executed.
- GCC elements were installed.
- 32 days after the construction of GCC elements, first phase of the post-improvement CPTu was were executed.
- Impact® RAP elements were installed.
- 15 days after the construction of RAP elements, second phase of the post-improvement CPTu was were executed.

Figure 7 shows plots of all of the pre- and post-improvement CPT tip resistance (q_t), pore water pressure (P_w) and soil behavior type index (I_c) vs depth, respectively. Testing conducted prior to installation of the elements described first, followed by testing conducted within 32 days of GCC installation and, finally, testing conducted 15 days following RAP installation.

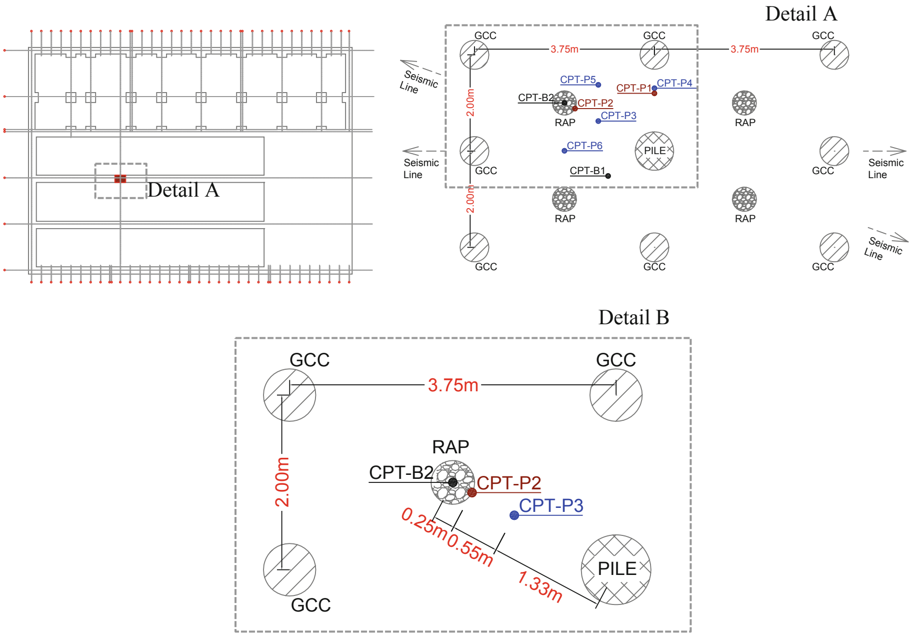

Fig. 6. In situ test layout.

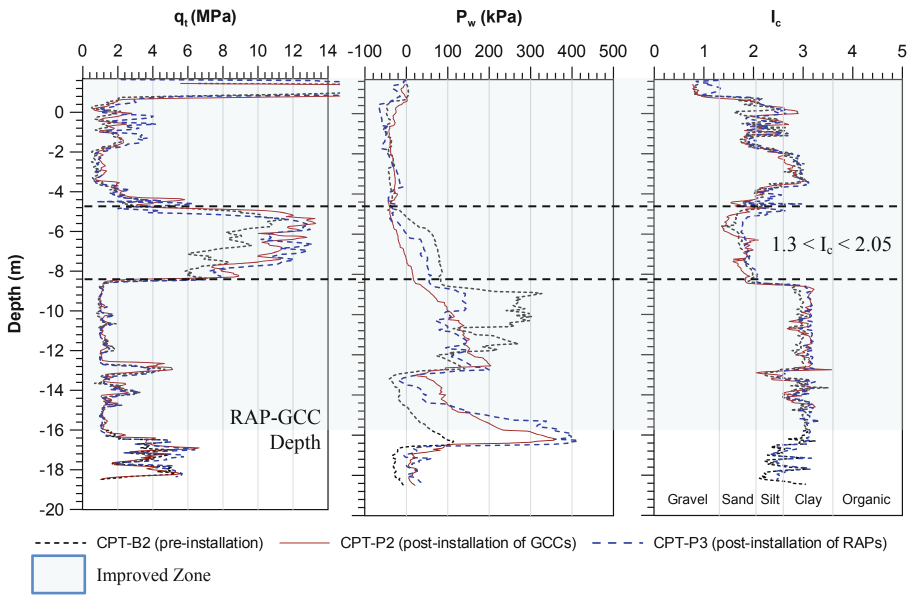

Fig. 7. Pre- and post-improvement CPT traces of GCC - Impact® RAP improved soil.

As shown in Fig. 7, following GCC installation, cone tip resistance, q_t increased roughly 27%, while pore water pressure, P_w decreased in the range of negative values in sandy levels from ~ −5 and −8 m indicating a more dilative sand response. Following RAP installation, tip resistance values remained generally the same after the construction of GCC, while P_w values increased addressing squeezing effects of the RAP element. In the long term, after the dissipation of these excess pore pressures, q_t values are expected to increase. Please note that some post CPT's were performed only 15 days after the installation of RAP elements which may not be enough for dissipation of pore water pressures. These findings support the conclusions of Saftner et al. [15] stating that one month after installation of the piers, the q_c in the sand layer increased roughly 33% as compared to the values obtained before the installation of piers.

In cohesive soil layers, there was no significant and systematic changes in penetration resistances. As shown in Fig. 7, GCC – Impact® RAP installations increased q_t values in soil layers with I_c values ranging between 1.3 and 2.05 (i.e. coarse material). q_t measurements confirmed that the GCC and Impact® RAP displacement method effectively densified clean sand deposits with $I_c < 1.8$ but did not provide measurable densification for the soil horizon with $I_c > 1.8$ [16].

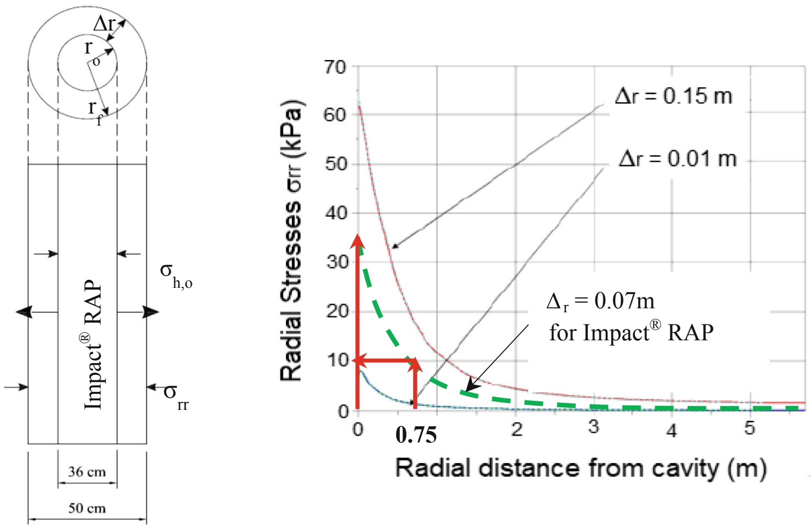

Fig. 8. Radial stresses σ_{rr} in relation to the distance from the cavity surface for an expansion of 0.01 m and 0.15 m [17].

To clarify the mechanism of tip resistance increase, the stress influence of stone column construction will be discussed. Figure 8 illustrates the installation effect of stone column ground improvement and radial stresses σ_{rr} in relation to the distance from the cavity surface for an expansion of 0.01 m and 0.15 m, respectively [17].

The increase in the radial stresses at CPT locations following the installation of RAP is given in Fig. 7 as green-dash line on the basis of Kirsch [18] findings. The increase in radial stresses due to the installation of the piers governs the increased tip resistance response along with densification of the cohesionless soil layers.

5 Conclusions

A composite ground improvement solution, which is composed of 18 m long 40 cm diameter GeoConcrete® Column (GCC) and 50 cm diameter Impact® Rammed Aggregate Pier® (RAP), along with 40 m long 80 cm diameter vibrex/bored piles, is designed to control excessive settlements and eliminate liquefaction triggering hazard at a paper mill site. The densification of cohensionless soils due to installation of these rigid elements is assessed through pre- and post-CPTs. The results revealed 30–60% increase in cone tip resistances after their construction. The mechanism leading to this increase was speculated as mostly the increase in radial stresses due to installation of GCC and RAP rigid elements along with modest densification of the cohesionless layers due to shaking induced during construction.

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