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ABSTRACT

A 230,000 ft^2 (21,367 m^2).addition was planned for construction at the Plaza Bonita shopping mall in San Diego, CA. The soil profile at the site consisted of fill soils underlain by alluvial deposits followed by San Diego Formation. The saturated loose sand layers were liquefiable and would result in significant settlement under the site design earthquake. In addition, soft clay layers would undergo excessive settlement under heavy building column loads. The geotechnical contractor proposed soil treatment with vibro replacement stone columns to mitigate the site liquefaction and to reduce static settlement under building column loads. Building design changes were ongoing and when two floors were added, soil mix columns were proposed to supplement the stone columns to accommodate the heavy column loads. The geotechnical contractor installed 305 soil mix columns to depths up to 35 ft (10.6 m), and 4,085 stone columns to depths up to 50 ft (15.2 m), across the site between November 2006 and March 2007. These ground improvement techniques reduced the excessive settlements by densification and/or reinforcement of the soils. Extensive site investigation and post treatment verification was conducted. Fifty borings and nearly 100 CPTs were performed at the site. During the production work, the shopping mall design evolved from a single storey department store to a four-storey structure, including a theatre. The geotechnical contractor met the schedule, regulatory and technical requirements while keeping up with the constant design changes to the project. This paper focuses on the design, production work, as well as dynamic and static settlement analysis derived from post-treatment CPTs performed by the geotechnical contractor.

INTRODUCTION

A 230,000 ft^2 (21,367 m^2)., one-story addition was planned for construction at Westfield Plaza Bonita shopping mall in San Diego, California. The special architectural design created very complicated foundation load distribution. The concerns of footing static settlement and soil liquefaction induced settlement from the subsurface inter-bedded soft clays and loose sands imposed a big challenge to the specialty ground improvement contractor. The specialty ground improvement contractor designed a site-specific program of vibro stone columns.

As construction of the vibro stone columns progressed, the design of the addition underwent significant revision, including expansion of the building to four stories. This resulted in the specialty ground improvement contractor ultimately designing and building a site-specific program of vibro stone columns as well as deep cement soil mixing, for each foundation and covering the footprint of the 230,000 ft^2 (21,367 m^2).building.

GEOTECHNICAL CONDITIONS

The soil conditions at the Westfield Plaza Bonita Site consisted of fill soils underlain by alluvial deposits followed by San Diego formation.

The geotechnical investigation consisted of 79 borings to depths over 50 ft (15 m) and cone penetration tests to depths up to 75 ft (22.8 m) within the footprint of the building. The site design earthquake of magnitude 7.2, based on the 10% probability in 50 years, had a design peak ground acceleration of 0.3g. Ground water was found at an approximate depth of 12 ft (3.6 m). The soil condition varies significantly under the very large building footprint. An idealized soil profile is difficult to present herein, as each SPT and CPT was analyzed individually. The site liquefaction induced settlement under the design earthquake was calculated to be in the range of 1.5 to 5 inches (3.8 to 12.7 cm) based on over 50 pre-treatment

CPTs. The layered nature of the site is evident in pre-treatment CPT-67 and a typical soil profile shown in Figure 1.

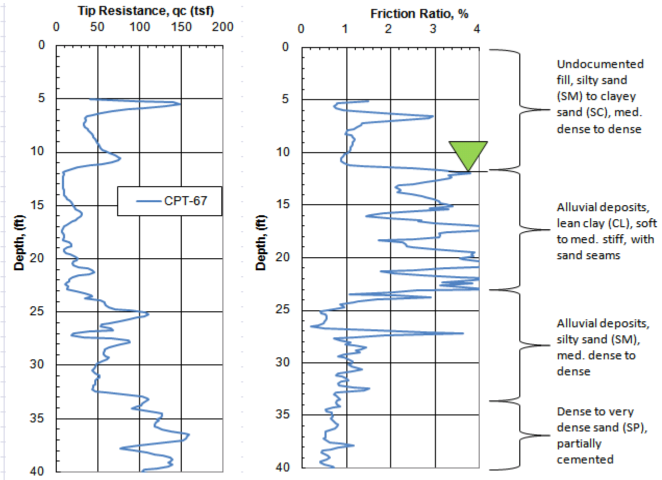

Fig 1. The pre-improvement CPT-67 shows the inter-bedded soft clay and liquefiable sands, a typical soil profile at the job site.

The presence of soft compressible fine-grained soils and liquefiable sands led the owner to consider ground improvement to mitigate static and dynamic settlements. A deep foundation system of piles was considered as well. However, the down drag loads from the liquefiable soil layer caused the piling solution to be more expensive than the ground improvement approach.

DESIGN

Vibro replacement stone columns were to be exclusively used for complete seismic remediation foundation support.

Several vibro replacement design criteria were considered, including options to perform the vibro replacement to a certain relative density, to a minimum tip resistance measured by post-treatment CPTs, or to a minimum factor of safety against liquefaction. The site being highly layered and classified as SP, SM, SC, CL, ML, CH, MH, with many of the granular layers consisting of sands with over 25% fines. In such inter-bedded soil profiles, it was difficult to define the required minimum post treatment CPT tip resistance or to interpolate the minimum soil relative density, especially at the clay and sand layer interface. The authors did consider using the average factor of safety against liquefaction as criterion. However, it was quite difficult to work with the statistics in this highly layered soil profile, because the factor of safety against liquefaction is not defined in non-liquefiable soils, such as high plastic clay (CH). The calculated average factor of safety against liquefaction still cannot reflect the real site risk level for soil liquefaction.

Some geotechnical engineers suggest a criterion that requires a minimum factor of safety against liquefaction greater than 1.15 or 1.3. In order to achieve the minimum factor of safety value in the relatively thin sandy layers, usually less than 1 ft (0.6 m) thick, ground improvement contractors would have to install stone columns on a very tight spacing, resulting in high cost.

The best price alternative for the client was to design the vibro replacement program to meet a deformation criterion that would satisfy the structural requirements of the building. The site liquefaction induced settlement, calculated from the post improvement CPTs, is a weighted average and reflects the real liquefaction risk level. This method considers the thickness of the liquefiable soil layers, relative density, fines content, site design peak ground surface acceleration, and CRR/CSR ratio. It reflects the real soil behavior under earthquakes; the loose sandy soil lost volume under cyclic shear.

The ground improvement was specified to meet a combined static and liquefaction induced differential settlement of 1 inch (2.5 cm) over 100 ft (30.4 m), a maximum allowable post-construction differential settlement less than 0.5 inches (1.2 cm) over 30 feet (9.1 m), and a maximum allowable total uniform or differential settlement less than 3 inches (7.6 cm) over the entire length of the building.

Using the footing settlement as the ground improvement criteria, a performance criteria directly linked to the building structural safety, saved significant ground improvement cost, compared with the minimum densification criterion in terms of CPT tip resistance or SPT blow count under such a large-size building with a footprint of 230,000 ft^2 (21,367 m^2).

DESIGN CHANGES

Vibro work continued for several months while the building footprint, the structural design, the loading, and the building lines constantly changed. During this time, the building design evolved from a single storey department store to a four storey structure including a theatre and a heavy parking structure.

A histogram of the building foundation loads are plotted in Figure 2, with the maximum building column loads tripled from 300 to 950 kips. Such wide load distribution on the shallow footing system created a big challenge to control the footing differential settlement, requiring additional strategically placed stone columns, as well as soil mix columns to address the higher loads.

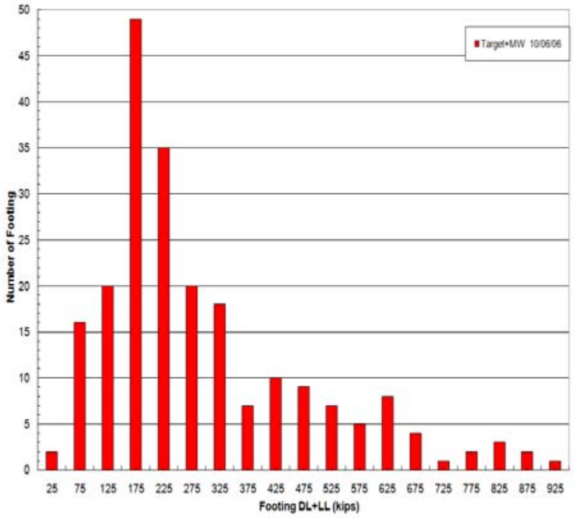

Fig 2. Footing load distribution of the building.

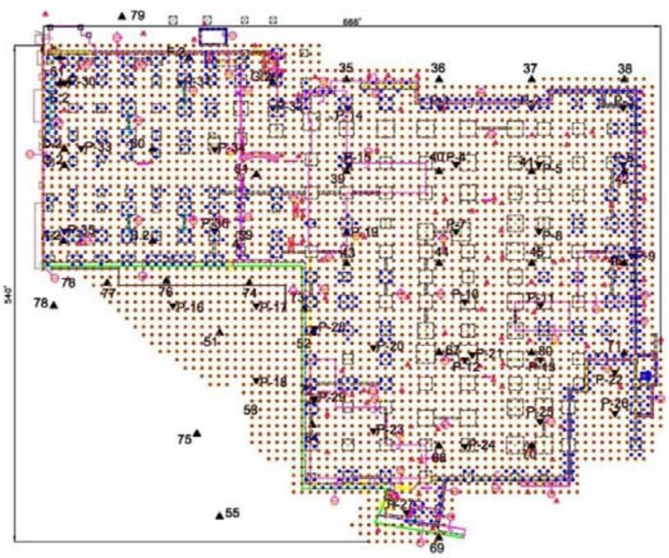

Fig 3. Stone column layout, the red and blue dots show the primary and secondary columns.

Ultimately, the specialty contractor designed and installed a combination of 4,085 vibro replacement stone columns to depths up to 50 ft (15.2 m) (Figure 3), and 305 soil mix columns to depths up to 35 ft (10.6 m) to mitigate the site liquefaction and reduce static settlement under the building's heavy column loads (Figure 4).

The spacing between stone columns was kept constant at 9 ft (2.7 m) on center. The 3-ft-diameter (0.9 m) of the stone columns created an 8.7% area replacement ratio. In some heavy loading areas, secondary columns were added as necessary to reduce the static settlement potential to acceptable levels.

Fig 4. Soil mix columns under heavily loaded footings. Blue dots = 25 ft (7.6) and brown dots = 35 ft (10.6 m) columns.

INSTALLATION

<u>Stone Columns</u>

The vibro replacement method of stone column installation employs purpose-built depth vibrators/vibro probes to impart vibratory energy to in situ granular soils to densify and reinforce them while constructing a stone column.

The vibratory energy is generated by eccentric weights that rotate on an internal shaft near the tip of the vibrator. A hydraulic or electric motor is used to turn the weights. Usually, the vibrator and backfill follower tubes are suspended from a crane as a single unit; however, the follower tubes may be mounted to base units. The unit is lowered to the ground and penetrates by means of its own weight, vibrations, and air or water jetting. Once design depth is reached, the vibrator is lifted in stages as the stone backfill is fed from a stone hopper through the follower tubes and expelled at the vibrator tip. For each stage, or "lift", the vibrator penetrates the stone which expands the diameter of the column. These actions continue until the column is completed, as illustrated in Figure 5.

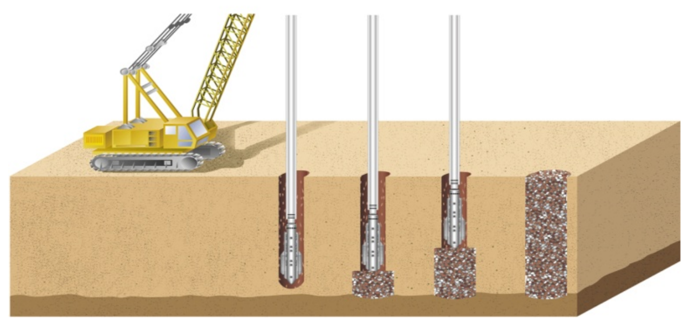

Fig 5. Stone column installation procedure, left to right..

The stone column backfill material used was clean crushed rock, meeting the following criteria: (1) 100% passing one inch sieve, (2) less than 5% passing #4, (3) durability index less than 40. Upon completion of stone column installation, the top 2 ft (0.6 m) of soil was removed and re-compacted to a minimum of 90% relative compaction based on ASTM D 1557.

It should be noted that in some areas with sandy silts that many of the original stone columns were increased in diameter from 36 inches (0.9 m) to 42 inches (1.0 m) to aid in densification and reduce secondary treatment.

Fig 6. Equipment used for vibro stone column installation.

To assist the vibro probe penetration through the near-surface hard desiccated clay in part of the project site, the specialty contractor pre-drilled 24-inch (0.6 m) diameter holes before stone column installation. Figure 6 shows field operations of the pre-drilling and the stone column installation.

Soil Mix Columns

Soil Mixing is the mechanical blending of the in situ soil with cement binder using a hollow stem auger and paddle arrangement. The intent of the soil mixing program is to achieve improved engineering properties, usually a design compressive strength or shear strength and/or permeability.

As the mixing tool advances into the soil, the hollow stem is used as a conduit to pump the binder and mix it with the soil in contact with the paddle. Mixing energy is combined with binder dosage to achieve the design soil-cement product. The production binder mix is determined by making test batches using soil from the site to be mixed.

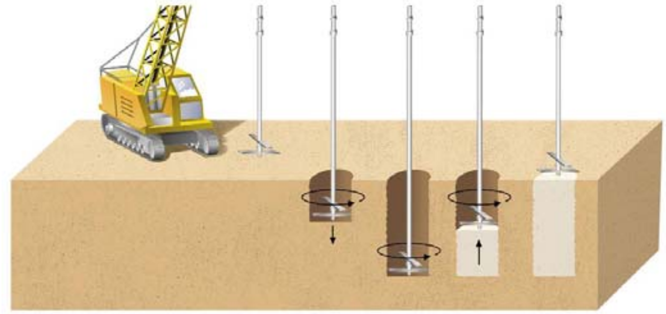

Fig 7. Soil mix column installation procedure.

Prior to the production soil mixing at the site, a lab mixing program was performed to evaluate the effectiveness of the cement mixing and to find the optimum cement dosage rate. The soft silt and clay samples obtained from the field, with their natural water content, were blended with cement slurry at different dosage rates in the lab, and tested for Unconfined Compressive Strength (UCS) at the age of 3, 7, 14, 28, and 56 days. The cement dosage rates used were 100 kg/m^3, 150 kg/m^3, and 200 kg/m^3 in the lab test program, and compared with the soilcrete strength development as a function of curing time. The cement dosage rate was defined as the ratio between the cement weight to the combined soil and grout weight. The strength of the soilcrete developed much slower than the strength of conventional concrete. The specialty contractor set the soilcrete criteria as the average UCS value higher than 150 psi at 56 days of age. Based on this criteria, a optimized field dosage rate was determined.

The UCS values were obtained from wet grab soilcrete samples in 7, 14, and 56 days of age. The early age soilcrete UCS values were extrapolated to 56 days UCS according to the lab test curves, which provided the contractor an early quality check during the production stage.

STATIC SETTLEMENT ANALYSIS

The geotechnical engineer ran many consolidation tests on samples of untreated soft clays taken with Shelby tubes. These soil consolidation parameters varied over a wide range. The maximum strain based C_{ce} and C_{re} values from the consolidation tests were 0.40 and 0.05, respectively. The soft clay OCR values ranged from 1.0 to 3.0.

Terzaghi's one-dimensional consolidation theory was used to calculate settlement of the fine grained soils. All loading conditions near each CPT location were analyzed, from 5 ft x 5 ft (1.5 m x 1.5 m) footings to 18 ft x 18 ft (5.4 m x 5.4 m) square footings under various load pressures, before the ground improvement production work.

As shown in Figure 8, the Westergaard method was used to compute stress as a function of depth for a 10ft x 10 ft (3 m x 3 m) square footing under 3 ksf load. Based on the consolidation lab test data, a C_{ce} of 0.40 and a C_{re} of 0.05 were used. The OCR values in cohesive soils were calculated as presented in Lunne et al, 1997, for each CPT. This OCR value derived from the CPTs was then compared to the value obtained from the lab testing, and the lower of the two values was then used in the consolidation analysis. Figure 8 provides a typical Ic curve and calculated OCR values from CPT HBI-P-36 after vibro stone column treatment. Consolidation settlement was then computed for all cohesive soil layers with a soil index, I_c (Robertson, et al), greater than 2.6.

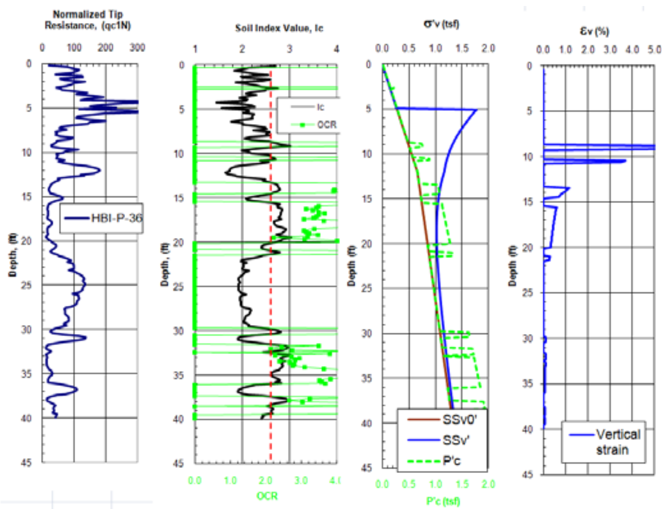

Fig 8. Settlement in cohesive soils under 10 ft x 10 ft (3 m x 3 m) footing with 3 ksf load from a CPT after stone column improvement.

A settlement reduction factor was then applied to the computed static settlements to account for the presence of the stiffer stone column elements within the fine grained soils. The settlement reduction factor, "n", is computed based on the procedures outlined in Priebe 1976 and 1995, and is a function of area replacement ratio, stone column stiffness, and surrounding soil strength. The "n" value ranged from 1.5 for the primary stone columns, to 2.0 in the secondary stone column treated footings. The area replacement ratio is simply the ratio of the area of a stone column to its tributary area. The area replacement ratio is thus a measure of the pattern spacing. The stone column stiffness is accounted for in the Priebe procedure by the angle of internal friction of the crushed rock and some surrounding soils mixed into the stone columns during construction. In the design, a conservative number of 42.5 degrees was utilized as the stone column friction angle. The settlement in cohesive soil under a 10ft x 10ft (3 m x 3 m) footing with 3 ksf loads at CPT HBI-P-36 was 0.6 inch (15.2 mm).

Typically the vibro stone columns improve cohesive soils through reinforcement rather than through densification. By comparing the pre-treatment CPT-67 with post-treatment HBI-P-12 in Figure 9, it is evident that in cohesive soils (with Ic > 2.6) there was little to no change in tip resistance. Static settlement in sands was computed using Schmertmann, 1970. The static settlement of the sands occurred as the structure was constructed.

Bearing capacities were calculated under the static and seismic condition according to the Meyerhof method and the stone column reinforcement was considered based on the Priebe method (1995). The authors also took into account the increasing strength in sandy soil through densification, and eliminated the site liquefaction induced bearing failure. The calculated factor of safety against bearing failure for various footings was well above 2.0 at most CPT and SPT locations. The combined vertical and lateral loading conditions under the design earthquake were also considered. These analyses suggested that the footing settlement controlled the site ground improvement design.

There were a total of 219 footings under the building's interior structural columns, with the combined dead load and live load ranging from 50 kips to 950 kips. After calculating the soft clay layer consolidation settlement based on above method, for footing loads higher than 200 kips and with significant normally consolidated soft to medium stiff clay, the authors found that the spread footing settlement could be excessive with the vibro stone column treatment only. To further reduce settlement of these heavily loaded footings, soil mix columns provided additional settlement reduction. The wet soil mix column installation process creates a hardened column of soil-cement and transfers the footing load to the deep stiff clay layer or dense sand layer.

In order to maintain strain compatibility with the bearing soil below the soil mix columns, the authors designed 6–ft-diameter (1.8 m) soil mix columns with an average UCS value of 150 psi. The soil mix column working stress is below 50 psi, which yields a structural column factor of safety value of 3.0. Two to six soil mix columns were installed below large size footings, as shown in Figure 4, in order to minimize the differential settlement between footings with significantly different loads. The elastic deformation of the soil mix columns is controlled around 0.33 inchs (8.3 mm). FLAC analysis and tests were performed by Shao, 2009, in the past in similar soil profiles, proving low-strength soil mix columns to be a cost-effective solution to support heavy footing loads. Because of the relatively low soil mix column to soil contact stress, the soil mix columns do not need to penetrate deeper, as is the case with conventional pile design.

DYNAMIC SETTLEMENT ANALYSIS

Liquefaction analyses were performed in accordance with the procedures of Youd and Idriss (NCEER, 1997), and Martin and Lew (SCEC, 1999). Fines contents were determined from actual field samples, and when not available, were estimated from the CPT data using Baez et al., 2000. Liquefaction evaluations were performed for nearly 100 pre-treatment and post-treatment CPT locations, based on the following design assumptions:

Table 1.Design assumptions for liquefaction evaluations.

Design groundwater table depth	12 ft
Design earthquake magnitude, Mw	7.2
Design peak ground acceleration	0.30 g

Dynamic settlement analyses were performed following Tokimatsu and Seed, 1984, using CPT tip resistances converted to $N_{1,60}$ blow counts. By using post-treatment CPTs, any densification that occurs as a result of the vibro replacement procedure is automatically accounted for. A typical stone column layout and CPT locations are presented in Figure 9. All post-improvement CPTs were positioned at the middle point of the stone column grid, taking into account the worst densification conditions with the largest distance to stone columns.

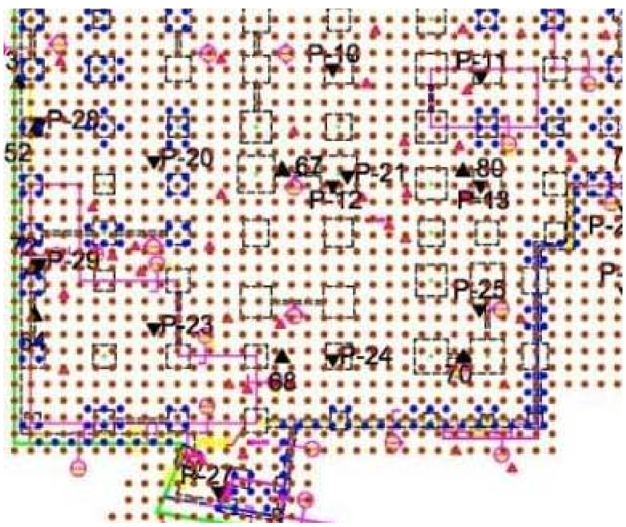

Fig 9. A partial stone column layout, as well as the locations of pre-improvement and the post-improvement CPTs

As occurs in the static case, the stone columns themselves reinforce the ground during the seismic event. For those layers still considered potentially liquefiable even after the vibro replacement program, the settlements that occur during and just after the seismic event are reduced by the presence of the stiffer stone column elements. Note that this is a layered site and the thicker, cleaner sand layers did exhibit significant densification that put those layers beyond the liquefaction threshold, as shown in Figure 10. The thinner, silt layers exhibited only moderate increases in tip resistance and could potentially undergo liquefaction, and hence, deformations.

The presence of the stone columns, even within liquefied ground, will provide a stiffening effect, as evidenced in centrifuge testing presented in Adalier et al 2003. Adalier et al measured the dynamic settlement with stone columns installed in liquefiable loose silt. Previously performed FLAC finite difference analyses allowed the use of a seismic settlement reinforcing factor of 1.65 in both sands and silts for areas with a 10.2% area replacement ratio. A seismic settlement reduction factor of 1.6 was attained in both sands and silts for areas with an 8.7% area replacement ratio. In the FLAC analysis, the residual strength of the liquefiable silt surrounding the stone column was used to evaluate the stone columns' vertical and radial deformations.

A seismic settlement computation is shown graphically herein as Figure 10. Post-treatment HBI-P-12, conducted 10 days after the surrounding stone column installed, was compared with pre-treatment CPT-67. The vibro replacement stone column treatment significantly densified the sand layer at depths between 22 ft (6.7 m) and 27 ft (8.2 m), and marginally improved the sandy silt/silty sand layer between 14 ft (4.2 m) and 16 ft (4.8 m). Dynamic settlement under the design earthquake was calculated to be 4.1 inches (10.1 cm) for the pre-treatment CPT and 1.6 inches (4 cm) for the post-treatment CPT.

The evaluation of vibro through post-improvement testing is quite complicated, especially in the inter-bedded soil layers. The vibro densification caused sandy soil liquefaction, and increased the soil pore water pressure. The excess pore water pressure dissipated very slowly from the sand layers sandwiched between clay layers. To investigate this pore water pressure dissipation effect, HBI-P-21 was tested 38 days after vibro treatment, and four weeks after HBI-P-12 at about 11.3 feet away from HBI-P-12, as shown in Figures 9 and 10. Between 12 ft (3.6 m) to 17 ft (5.1 m) and 27 ft (8.2 m) to 32 ft (9.7 m), the CPT tip resistance was significantly increased; therefore, the liquefaction induced settlement was reduced to 1.1 inch (2.7 cm). Below 33 ft (10 m), the soil condition was more cohesive, as the Ic value near or above 2.6, where the site soil condition changed significantly between CPT-67, HBI-P-12, and HBI-P-21, near or in the San Diego formation.

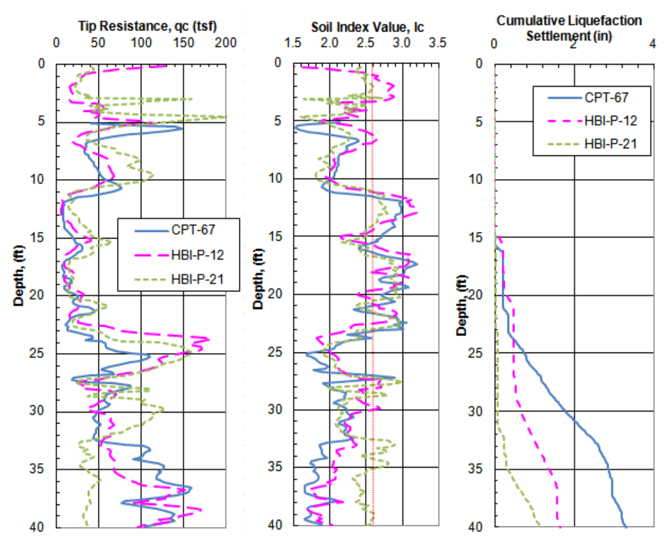

Fig 10. The comparison between the pre-improvement CPT-67 and post-improvement HBI-P-12 and HBI-P-21.

Thin layer corrections to the CPT tip resistances were not used. By adding the results obtained from the static settlement computations, the combined static and dynamic post-construction settlements were computed to be below the specified values.

QUALITY ASSURANCE/QUALITY CONTROL

A total of 36 post-treatment CPT tests were performed across the ground improvement site. Each CPT was analyzed for static and seismic settlement using the procedures previously described. A minimum 10-day waiting period from end of stone column installation was used to allow for dissipation of excess pore pressures. Most CPTs were performed about 4 weeks after nearby stone columns were installed.

During production soil mixing, installation parameters were monitored to ensure consistent installation. Samples of the soil mix from each shift were taken for laboratory testing, confirming that the design mix characteristics were achieved. A mass flow meter at the grout batching plant constantly monitored the grout specific gravity. The mixing tool penetration depth, penetration speed and rotation rate were monitored with the drill rig on-board computer.

The constructed 230,000 ft^2 (21,367 m^2).addition at the Westfield Plaza Bonita shopping mall (Figure 11) has been in operation for over 2 years and no distress of its foundations has been observed.

Fig 11. The constructed 230, ft^2 (21,367 m^2) *addition at the Westfield Plaza Bonita shopping mall in San Diego, California, USA.*

CONCLUSIONS

The ground improvement program was a successful and cost effective alternative to driven piles. The CPTs verified that the vibro replacement stone columns effectively mitigated the liquefaction potential of the targeted site soils. Soil mix columns can spread heavy structural loads to stiff clayey soils and dense sand layers, with acceptable settlement. The shopping mall has been in operation for over two years and no distress of its foundations has been observed.

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