Innovative Ground Improvement for Liquefaction Control Near Charleston, South Carolina

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April 29 - May 4, 2013 CHICAGO
Seventh International Conference on
Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

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ABSTRACT

Liquefaction remediation solutions often encompass high prevailing costs particularly in heterogeneous soil profiles. Common liquefaction control measures consist of deep foundations, soil mixing, and stone columns. Rammed Aggregate Pier methods have been used in the past two decades to support structures in cohesive and cohesionless soil profiles and control foundation settlements to building tolerances. These methods have recently been adapted to treat liquefiable soil profiles by improving the soil through densification, drainage, and shear stress redistribution.

This paper focuses on a case history on Daniel Island, SC where a new variation of RAP methods, called the Rammed Compaction Point™ (RCP) method, was utilized to treat a layer of liquefiable sand that was overlain by a non-liquefiable layer of clay. The paper presents the results of pre- and post-improvement CPT tip resistances and design methods used to calculate liquefaction susceptibility and post-liquefaction settlement. This paper is of particular significance because it shows how a cost-effective treatment method is used to treat difficult soil conditions at liquefiable sites.

INTRODUCTION

The magnitude 7.3 Charleston, South Carolina earthquake of August 1886 was unprecedented for its location, size and impact, resulting in widespread building damage, sixty fatalities, and liquefaction throughout the greater Charleston area (Algermissen 1983). At present, design methods using IBC2009 / ASCE 7-05 procedures results in typical Peak ground accelerations range from 0.3g to 0.5g for the 2% probability of exceedance (PE) in 50 year design event, a value sufficiently large to render many sites liquefiable. The Daniel Island site consists of a luxury condominium development situated near the confluence of the Cooper and Wando Rivers approximately 10 miles northeast of downtown Charleston, SC (Figure 1). Similar to many sites in the greater Charleston Area, Daniel Island is not immune to challenging geotechnical issues of compressible and particularly liquefaction susceptible soils.

Fig. 1. Site location

REGIONAL GEOLOGY

South Carolina is generally composed of two broad physiographic regions, the Atlantic Coastal Plain and the Piedmont Provinces. The Charleston area lies within the lower coastal plains consisting primarily of upper Holocene age deposits of varying thickness, consisting of interbedded layers of silts, sands and low permeability clays with moderate to high liquefaction susceptibility. The Holocene deposits overlie 30 to 60 meters of older stiff to very stiff clayey to sandy silt known as the Cooper Marl formation.

SUBSURFACE CONDITIONS AND LIQUEFCTION SUSCEPTIIBLITY

The typical soil profile consists of loose to medium dense sand in the upper 1.5 meters followed by soft to stiff clay to 4 meters over loose to medium dense sand to silty sand to 9 meters over the Cooper Marl formation. The fines content of the sand layers range from 5% to 15%. Groundwater is generally encountered at depths of 2.5 meters from finished grades.

Liquefaction susceptibility was evaluated using the simplified procedure (Seed and Idriss, 1971) in accordance with the NCEER procedures (Youd and Idriss, 1997). The project design team deemed that the intermixed soils extending from 4 to 9 meters below grade are liquefiable and, using CPT methods recommended by Zhang, et al (2002) estimated that post-liquefaction ground surface settlements of 40 to 140 mm are likely to occur during and after the design seismic event of $M_w = 7.3$, PGA = 0.43g (design earthquake with 2% PE in 50 yrs). The design team concluded that the performance of the structure could be acceptable provided that post-liquefaction settlements be limited to approximately 75 mm.

LIQUEFACTION CONTROL OPTIONS

Typical options for liquefaction abatement in the Charleston area include undercutting the site and recompacting the surficial soils to reduce liquefaction effects, bypassing the liquefiable soil with deep foundations; installing drains to reduce liquefaction induced pore water pressures, and improving the site with ground improvement techniques such as Dynamic Deep Compaction (DDC), vibroflotation, stone columns, and Rammed Aggregate Pier (RAP) elements. The Rammed Compaction Pont method was considered as an additional option to abate the liquefaction settlements. Table 1 shows these traditional options with associated required design considerations.

Table 1. Typical liquefaction mitigation options in the Charleston SC region

Liquefaction Treatment Options	Relative Cost	Considerations
Excavation and replacement	Low	Limited to depths generally less than about 10 feet; shoring and dewatering often required.
Vibroflotation	Low to medium	Less effective in soils with lower permeability.
Drains	Low	Less effective in soils with lower permeability; post-earthquake settlements likely to occur after drainage.
Stone columns	Medium	Wet method requires site drainage considerations during construction.
Rammed Aggregate Pier®	Medium	Can be installed using either drilled (replacement) or driven (displacement) methods.
Soil Mixing	Medium to High	Generally expensive for smaller projects, spoil handling needs to be considered
Deep foundations	High	Generally most expensive option. Piles must be designed for reduced lateral load resistance and increased downdrag during the design liquefaction event.
Rammed Compaction Points	Low to medium	This paper

The project design team rejected the excavation/replacement and deep foundation options because the former could not sufficiently treat the liquefiable soils and the latter was too expensive. Ultimately, the design team selected the RCP method because this method was relatively inexpensive and because the RCP method could effectively extend through the upper soil layers to treat the lower liquefiable layers meeting the settlement criteria.

RAMMED COMPACTION POINTS

Rammed Compaction Points are constructed by driving a proprietary specially-designed compaction mandrel into the ground to the prescribed depth. The mandrel shown in Figure 2 is 6.0 m long and consists of six 200-mm diameter tines spaced 445 mm on-center. The device is driven with a high-energy impact hammer to the design depth and then retracted forming six cavities in the soil after tine retraction. The cavities are then filled with fine aggregate and the mandrel is re-inserted into the ground to compact the placed backfill. The number and depths of the mandrel insertions depend on the subsurface conditions and required performance.

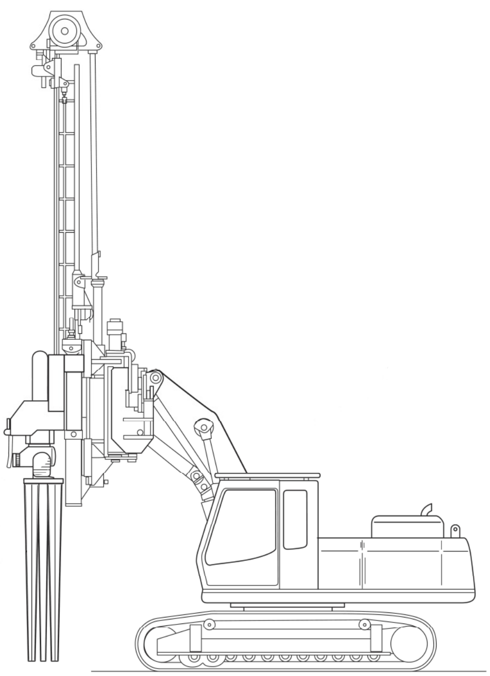

Fig. 2. RCP tooling and installation equipment

RCP treatment was applied in clusters below the foundation elements and at wider spacings below the floor slabs of the structures. This pattern was applied to allow for improved performance of the foundation elements relative to the ground floor slabs, facilitating a process that provides both life safety and great economy.

Figure 3 shows the results of CPT soundings that were advanced for both pre- and post-treatment condiitons. The RCP treatment increased the uncorrected CPT tip resistance values (q_c) from an initial value of about 6 MPa to post-installation values of 10 to 12 MPa at depths of 4.5 to 5.5 meters and from an initial value of about 8 MPa to 14 to 20 MPa in the zone of liquefiable soil extending from elevations 5.5 to 7 meters. Less improvement is noted from depths of 4 to 5.5 meters where the soil conditions contain greater amounts of fine sized particles and in the clay layers less than 4 meters deep. The improvement by the RCP treatment program reduced computed post-liquefaction settlement values from 118 mm to 75 mm or less at slabs and 50mm or less at the foundations.

Notable is the improvement below the penetration depths of the RCP installations and that the liquefaction within the RCP depths was nearly 100%. This method of construction provides for a stiffened crust to further enhance liquefaction control.

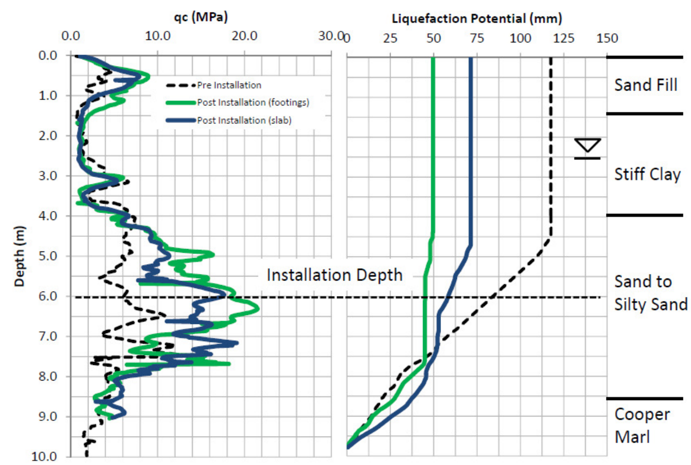

Fig. 3. Pre and post liquefaction improvements and settlement potential

VIBRATIONS

Vibration monitoring was performed during RCP installations to verify that vibration would not negatively adjacent residential development located about 15 to 30 meters from the site. Figure 4 shows the results of the vibration monitoring indicating that peak particle velocity (PPV) of 50 mm per second or less (typical construction threshold for potentially damaging vibrations) was achieved at horizontal distances of 1.5 to 2.5 meters from the operations and less than 25 mm per second was achieved at horizontal distances of 3 meters. The results demonstrated that the high frequency RCP method is advantageous to reducing potentially damaging vibrations at relatively close distances and broadens the applicability of the system within distances of about 2.5 to 3 meters from adjacent structures.

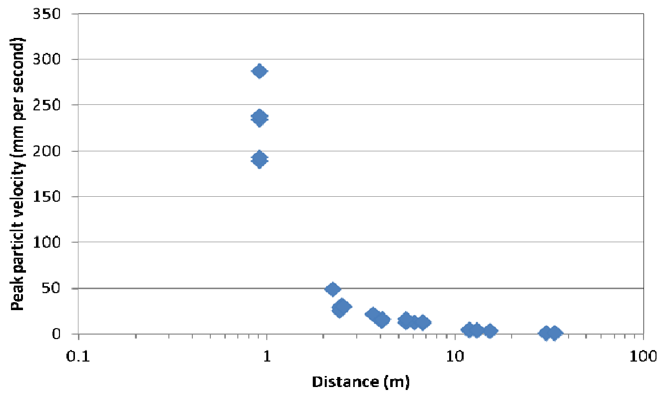

Fig. 4. Peak particle velocity with distance

CONCLUSIONS

The Eastern seaboard of the United States in the Charleston SC area is prone to large earthquakes and subject to relative high design level PGAs. When combined with the alluvial soils characteristic of the area, the high PGAs result in a high risk of soil liquefaction with related instability and settlement. Charleston engineers have many options for the treatment of the seismic risks. A new, robust, and cost-effective option is treatment with the proprietary RCP method. This method, which involves densification with a multi-tined driven mandrel is highly effective in mixed soil conditions providing design engineers and contractors with an effective solution to treat seismic risks.

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