Soft Soil Engineering – Chan & Law (eds)

Stabilization of soft clay site for development using Rammed Aggregate Piers™

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ABSTRACT: This paper describes the use of Geopier® Rammed Aggregate Piers to reinforce and stabilize a soft clay site at a new retail development outside of Chicago, Illinois (USA). The paper describes the design approaches for using Rammed Aggregate Piers to reduce settlement magnitudes, increase the time rate of settlement and improve subgrade support capacity for new construction. Settlement monitoring data from the site are included to provide comparison between predicted and observed performance. In addition, the data is used to draw conclusions about the effects of stress concentration on the Rammed Aggregate Piers and its influence on settlement magnitudes and drainage times. This paper is significant because it provides a documented case history that describes an option for addressing development of challenging soft soil sites when cost and schedule are major considerations.

1 INTRODUCTION

The continued growth and development of large urban areas within the United States and other countries is leading to a lack of "good" building sites. Developers are now investing in sites with challenging soil conditions that were viewed in years past as being too difficult or costly for construction. These sites often necessitate foundation support with deep foundations, massive overexcavation and replacement, subgrade improvement, or wick drains and surcharge to provide site construction and building foundation support. The subgrade stabilization solution selection often involves a balance between cost and time.

2 PROJECT DESCRIPTION

A 177,250 m^2 (43.8-acre) site in the Village of Orland Park, Illinois, a suburb of Chicago, Illinois, USA, remained undeveloped for years as challenging soil conditions presented significant remediation costs and long construction schedules to potential developers. With help from an innovative design team, Lowe's Companies, Inc. decided to face the hurdles to develop the property for new retail development. The proposed development shown in Figure 1 included a 10,777 m^2 (116,000 square foot) Lowe's Home Improvement Store, a series of up to 10 outlot parcels for future retail development and infrastructure (roadways, parking, utilities and detention ponds) to support the development.

The Lowe's Home Improvement store was a single-story, steel-frame and masonry block wall structure. Maximum column and wall loads were on the order of 445 kN (100 kips) and 88 kN/m (6 kips/ft), respectively. Floor slab pressures for design were 14.3 kPa (300 psf). The existing site grade across the site ranged from El. 208.8 m (685 ft) to El. 211.9 m (695 ft). Proposed finished floor elevation (FFE) for the building was El. 211.6 m (694 ft) while the parking lot was up to 0.5 meters lower. As much as 3 meters (10 ft) of new engineered fill was required in many areas of the site to achieve the building and parking lot finished elevations.

Figure 1. Picture of site during earthwork construction.

3 SITE GEOLOGY AND SUBSURFACE CONDITIONS

3.1 *Site geology*

According to Illinois State Geological Survey, "Circular 460, Summary of the Geology of the Chicago Area", dated 1971, the unconsolidated sediments underlying the subject property is part of the Carmi Member of the Equality Formation and also part of the Wadsworth Member of the Wedron Formation. Soil types located with in the Equality Formation consist of lake deposits (silts with sand facies near shorelines). The Carmi Member consists of quiet-water lake sediments, dominantly well bedded silt, locally laminated and containing thin beds of clay. The site is also located in the Valparaiso Morainic System of the Wadsworth Member of the Wedron Formation. More specifically, a portion of the site is located in the Clarendon Moraine which is located within the Valparaiso Morainic System. Moraines located within the Valparaiso System are slightly pebblier and contain local areas of sandy and gravelly till in the outer (older) moraines. Bedrock underlying the unconsolidated surficial deposits is Silurian aged dolomite. The unconsolidated deposits range from 90 to 100 feet thick at the site.

3.2 *Subsurface conditions*

Borings performed by Malcolm-Pirnie, Inc. revealed extremely variable site conditions. In many areas of the site, stiff clay was encountered below the ground surface extending to maximum explored depths of over 18 meters (60 feet). In other areas, where quiet-water glacial lake sediments had accumulated, very soft to soft silty clay was encountered to depths of up to 7 meters (23 feet) below existing grade. The zones of soft silty clay exhibited moisture contents approaching the liquid limits and ranging from about 30 to 40 percent. Undrained shear strengths in the soft silty clay were on the order of 12 to 24 kPa (250 to 500 psf). SPT N-values in the soft silty clay ranged from WOH (weight-of-hammer) to 3 blows per 0.3 meters. Underlying the soft clay, the stiff to very stiff clay was encountered. SPT N-values in the stiff clay were between 10 and 25 blows per 0.3 meters. Figure 2 shows a cross-section illustrating the presence of the zones of soft clay.

Consolidation tests performed on samples of soft (weak) clay retrieved from depths of 3 to 5 meters indicated the soils were normally or only slightly overconsolidated. The results of the consolidation tests are contained in Table 1.

Although not encountered in all boring locations, groundwater levels at the site were generally near a depth of 1.9 m (6 feet) below existing grade.

4 DESIGN CHALLENGES AND OPTIONS

After reviewing the results of the geotechnical exploration, laboratory testing and proposed civil design, Malcolm Pirnie realized that site preparation and foundation support was challenged by the deep compressible silty clay which coincidentally corresponded to the locations requiring the largest amounts of new engineered fill. Figure 3 illustrates contours of estimated soft soil thicknesses within the building area and proposed roadways. As detailed in the figure, the compressible clay soils were encountered within approximately one-half of the building footprint, while the compressible soils also extended beneath the roadways in three different locations. The challenge posed to the Malcolm-Pirnie was to develop a solution to raise the site grade and provide foundation support while maintaining acceptable levels of settlement beneath the building and across the site all in the shortest amount of time possible to facilitate the opening of the retail development.

With as much as 3 meters (10 feet) of new engineered fill required to achieve final grades, driven piles and structural floor slabs, preloading and wick drains,

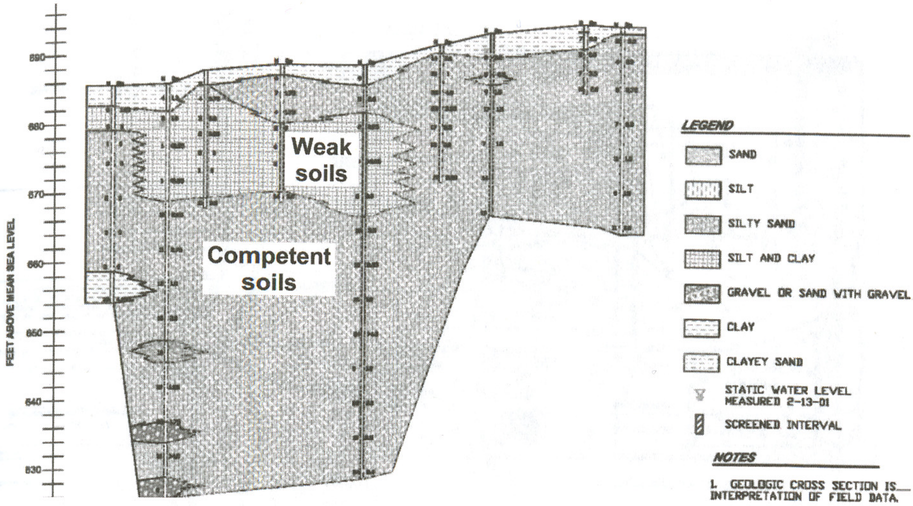

Figure 2. Cross-section of subsurface conditions.

Table 1. Consolidation test results.

Characteristic	Sample MB-5	Sample MB-6
Sample depth (m)	4.6–5.2	3.0–3.6
Initial moisture content (%)	34	39
Initial dry density (g/cm^3)	1.48	1.33
Compression ratio ($c_c/1+e_0$)	0.07	0.08
Recompression ratio ($c_r/1+e_0$)	0.011	0.015
Estimated OCR[1]	1.0	1.5
Coefficient of consolidation (cm^2/s)	0.00084	0.0010

[1] Overconsolidation ratio.

EPS blocks and light weight fill were initially considered as options for support of building pads and roadways. The deep foundation and structural slab, along with light-weight fill and EPS block options were determined to be very costly, while the preloading and wick drain solution would require an extensive construction delay period. To meet the demanding project schedule, Geopier® Rammed Aggregate Piers were also identified for stabilization of the soft soils at the site and were ultimately selected as a cost-effective solution to provide a significant reduction in construction schedule and acceptable levels of settlement control

5 RAMMED AGGREGATE PIER CONSTRUCTION

Rammed Aggregate Piers™ (RAPs) are installed by drilling 610 mm (24 inch) to 915 mm (36 inch) diameter holes to depths ranging between 2 m and 8 m (7 feet and 26 feet) below working grade elevations, placing controlled 0.3 m (1 ft) thick lifts of stone within the cavities, and compacting the aggregate using a high-energy beveled impact tamper. During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity, thereby increasing the lateral stress in the matrix soil. The lateral stress increase improves the stiffness of the matrix soil and also increases the normal stress perpendicular to the perimeter shearing surface, resulting in improved RAP stiffness and positive coupling behavior between the matrix soil and the pier. Rammed Aggregate Pier site improvement increases the composite site stiffness to provide settlement reduction under new fill and foundation pressures. In addition, the RAPs act as vertical drains when constructed using open-graded stone, thereby providing the additional benefit of accelerated durations for consolidation settlement. Figure 4 pictures RAP installations at the project site.

6 RAMMED AGGREGATE PIER DESIGN APPROACH

The solution involved installing a grid of 0.76 m (30 in) diameter Rammed Aggregate Piers spaced 3 meters (9.5 ft) on-center within portions of the building footprint (Area 1) to penetrate the compressible silty clay soils. Piers were also installed beneath the proposed wall and column foundation locations to increase stiffness and load carrying capacity. In building areas where the compressible soils were not encountered, shallow foundations were placed to bear in the stiff clay

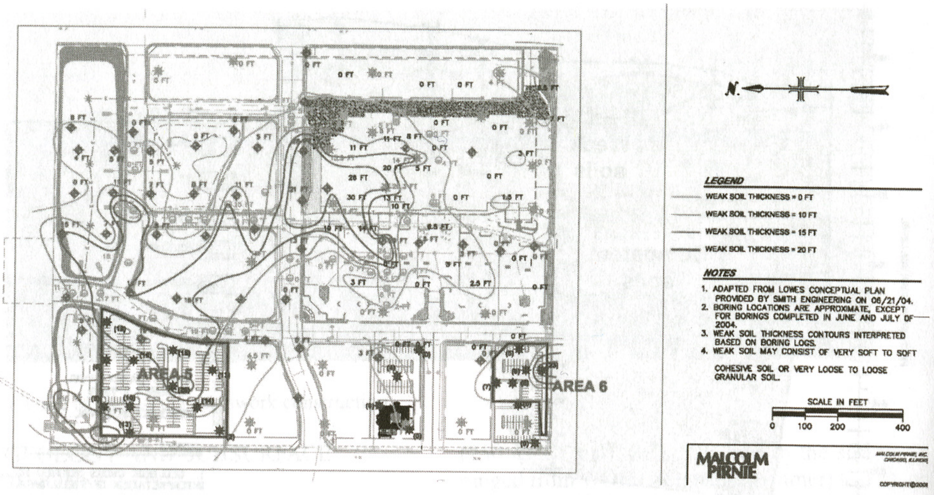

Figure 3. Contours of compressible soils.

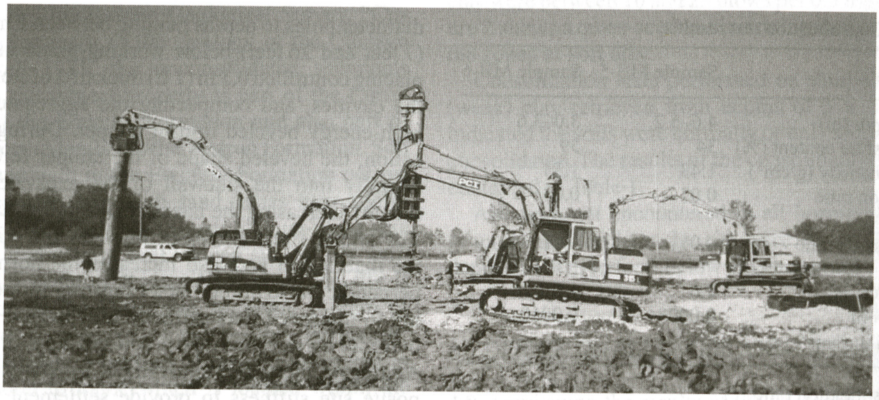

Figure 4. Rammed Aggregate Pier installations using casing (left).

or engineered fill. Beyond the building area (Areas 2, 3 & 4), additional piers were installed within areas of the proposed roadways that crossed the zones of the thick, compressible soils and were subject to thicknesses of new engineered greater than about 1.5 meters (5 ft).

Figure 5 shows the specific areas of the site selected for RAP reinforcement.

The piers were installed from a working pad established at the existing site grade after stripping the topsoil and prior to the placement of the new engineered fill. The piers were installed to depths ranging from 3 to 7 meters (10 to 26 ft) to tag the underlying stiff clay. The piers were installed using open-graded (clean) stone to allow the piers to act as vertical drainage, thereby facilitating radial drainage and more rapid settlement rates. Following installation of the RAPs, one layer of geogrid (i.e. Tensar BX-1200) was placed over the tops of the piers to help transfer fill pressures to the stiffer piers as well as to improve the compaction of the initial fill lifts. Up to 3 m (10 ft) of engineered fill was then placed over the reinforced zones up to the floor and parking levels.

Settlement monitoring was performed to evaluate the time rate and magnitude of immediate and primary consolidation settlement from the fill placement. Construction of shallow foundations sized for an allowable bearing pressure of 144 kPa (3 ksf) in the engineered fill and in the native stiff clay and a 150 mm (6-inch), lightly-reinforced slab-on-grade followed completion of primary measured settlement induced by the engineered fill. Post-construction total and differential building settlements were estimated to be 25 mm (1-in) and 13 mm (½-in), respectively, for structures constructed on the top of the new engineered fill supported by the reinforced crust of RAPs.

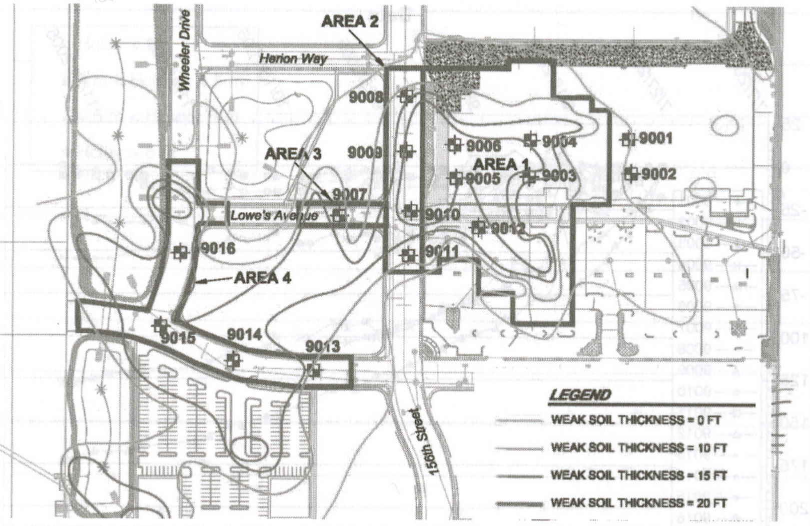

Figure 5. Rammed Aggregate Pier reinforcement areas and settlement platform locations.

6.1 *RAP support of engineered fill and Slab-on-grade floor slabs*

Figure 6 shows a conceptualized cross-section of a Rammed Aggregate Pier-reinforced soil mass supporting new engineered fill and a floor slab. Following RAP installation, new fill placed over the piers arches to the stiff piers in a conical wedge for supporting the subsequently placed fill, floor slab and foundations. The applied pressure to the pier is related to the volume of the cone of arching and the unit weight of the engineered fill. The engineered fill between the cones of arching applies pressure on the matrix soil, causing settlement of the matrix soil between the piers. The use of a structural geogrid layer allows additional pressure to be transferred to the stiff RAP, further reducing the pressure applied from the fill on the matrix soil and therefore the settlement of the matrix soil between the piers.

Differential settlements between the RAPs and the zone of soil between the piers have been shown to be minimal as a result of the reduced compressibility of the matrix soil and the positive pier-matrix soil coupling action created during installation of the RAPs (Minks, et al. 2001, White 2006). Matrix soil settlement from the fill wedge pressure typically occurs within days or weeks after the RAPs are constructed. Open-graded stone, used in RAPs, provides reduced drainage path lengths and accelerates dissipation of excess pore water. The stress applied to the matrix soil also increases the confining stress on the RAP and increases the bulging resistance, allowing the pier to support additional stress.

The addition of engineered fill and the floor slab above the wedge of arching results in pressures on

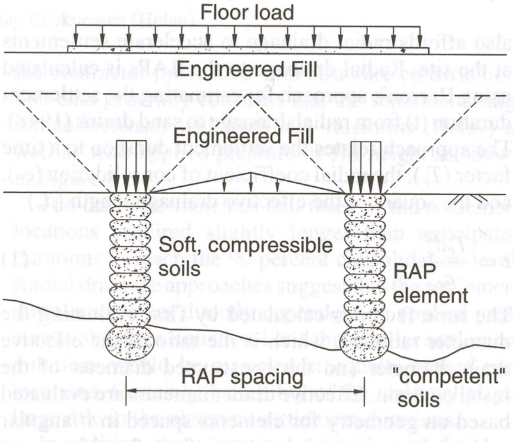

Figure 6. RAP support of engineered fill and floor slabs.

the reinforced soil mass that are then transferred to the RAPs and the matrix soil in proportion to their stiffness. The significantly stiffer RAPs attract greater applied pressures resulting in minor settlement of the pier. Pressure applied to the matrix soil induces settlement but occurs quickly as a result of radial drainage to the piers. The inclusion of the RAP-reinforced soil mass significantly increases the composite stiffness of the soil, increases the time rate of settlement, and reduces total settlement from applied fill, floor slab and foundation pressures.

6.2 *Time rate of settlement estimates using RAPs*

The presence of stiff granular Rammed Aggregate Piers not only increases the composite stiffness, but

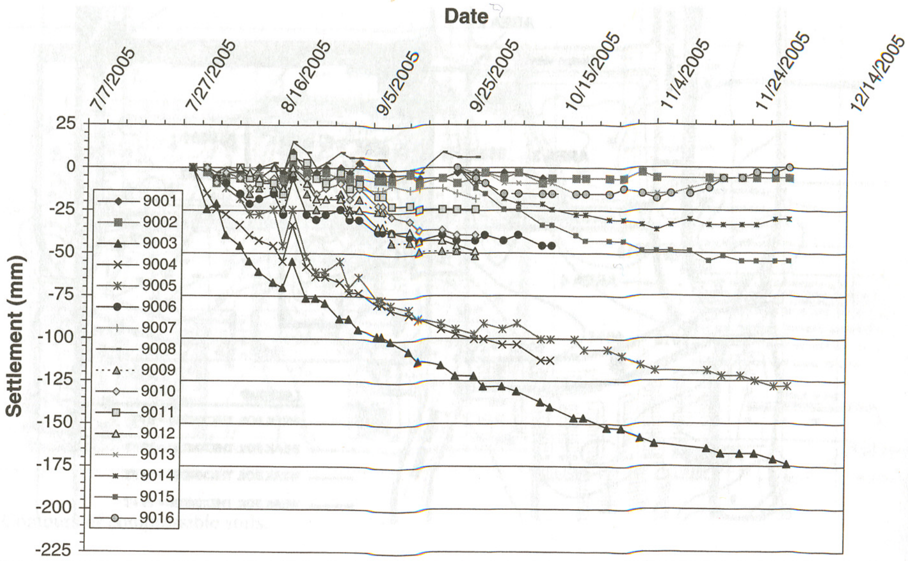

Figure 7. Settlement monitoring results.

also affords radial drainage to accelerate settlements at the site. Radial drainage to the RAPs is calculated using Barron's approach for estimating the settlement duration (t) from radial drainage to sand drains (1948). The approach relates the settlement duration to a time factor (T_r), the radial coefficient of consolidation (c_r), and the square of the effective drainage length (d_e):

$$t = \frac{T_r d_e^2}{c_r} \quad (1)$$

The time factor is calculated by first evaluating the diameter ratio (n), which is the ratio of the effective drain diameter and the constructed diameter of the installed drain. Effective drain diameters are evaluated based on geometry for elements spaced in triangular grids and square grids but range from 5 to 13 percent greater than the center-to-center spacing for triangular and square spacing, respectively.

The value of the *radial* coefficient of consolidation is commonly assumed to be between equal to or greater than the vertical coefficient of consolidation value (c_v). This ratio may be significantly higher in varved or horizontally stratified soils where depositional history has created natural radial drainage pathways. Coefficient of consolidation values (c_v) are related to many factors including soil mineralogy, gradation, and depositional history of the matrix soil (Terzaghi et al. 1996). For cohesive soils, these values are evaluated from consolidation tests or may be estimated from correlations with liquid limit values and stress history (over-consolidation).

Recent research performed by Han and Ye (2001) describes a modified radial drainage approach that accounts for stress concentration to stiff aggregate columns. Stress concentration to the stiff piers reduces the amount of stress on the matrix soil, which causes settlement to occur faster and yields a modified (increased) radial coefficient of consolidation. Han and Ye suggest that a modified radial coefficient of consolidation be used in the Barron approach:

$$c_r' = c_r\left(1 + n_s\left(\frac{1}{n^2 - 1}\right)\right) \quad (2)$$

where n_s is the stress concentration ratio. The modified radial coefficient of consolidation is substituted for the radial coefficient of consolidation in Equation 1 to determine the time required for the dissipation of a particular percentage of excess pore water pressure. Research has shown that RAP stress concentration ratios for footing support range from 4 to 45 (Lawton and Merry 2000, Hoevelkamp 2002). Stress concentration values in the lower half of the range are typically used for design.

7 SETTLEMENT ESTIMATES AND MEASUREMENTS

Based on the compressibility of the soft soil, analyses performed to estimate the immediate and primary consolidation settlement magnitude and duration of the unreinforced compressible clay suggested the pressure of up to 10 feet of new fill could result in as much as 0.6 m (24 in) of settlement. More importantly, this settlement was expected to occur over a period of at least 2 years.

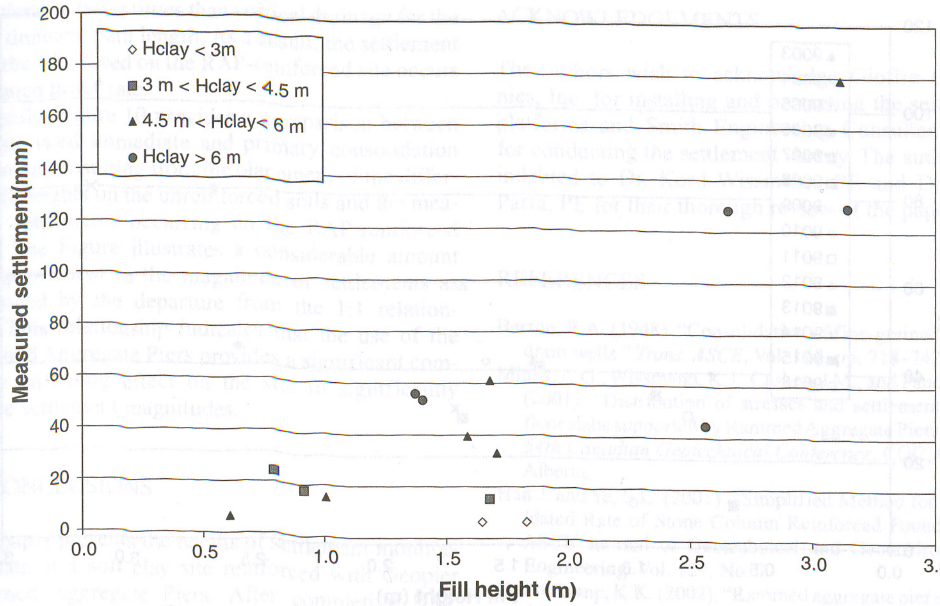

Figure 8. Settlement under varying fill heights for different clay thicknesses (Hclay).

Additional analyses estimated the fill-induced settlement for the RAP-reinforced conditions to generally range from less than 25 mm (1 in) up to 150 mm (6 in). Considering the effects of stress concentration to the piers, the estimated settlement duration was on the order of 2 months using increased values for the coefficient of consolidation to account for radial drainage effects as recommended by Han and Ye's approach.

A total of 16 settlement platforms were established by Gioffre Companies, Inc., general contractor for the site, prior to the placement of the new engineered fill. Figure 5 (above) shows the locations of the settlement platforms around the site. Elevations of the tops of the platforms were surveyed during a period of time ranging from July, 2005 through November, 2005. The settlement monitoring results are plotted with time in Figure 7.

8 RESULTS AND DISCUSSION

The results of the settlement monitoring indicate that the magnitudes of total settlements ranged from less than 12 mm (0.5 in) up to 175 mm (7 inches). Importantly, the majority (90 percent) of the settlements occurred within a week up to slightly greater than 3 months. Twelve of the sixteen survey locations (75 percent) indicate that the settlement of the RAP-reinforced soil mass occurred within a period of 45 days or less from the start of fill placement and with settlements of less than 55 mm (2.2 in). Survey of several platforms was terminated after the settlement readings reached an asymptotic level and the contractor proceeded with structure construction. The data generally confirms that the settlement magnitude increases with both clay thickness (Hclay) as well as with applied pressure or fill height as shown in Figure 8.

The data also indicates that three of the settlement locations required slightly longer than anticipated durations to reach the 90 percent consolidation level. Radial drainage approaches suggest that the settlement durations are not directly dependent on applied pressure as shown in Equation 1 and that similar settlement durations would be expected at equally-spaced pier locations. Certainly, variability of the soil may play a large role in the observed settlement durations.

In addition, these locations coincide with the areas of the site containing the thickest deposits of compressible clay as well as larger than average amounts of new engineered fill. In these areas, the pressure from the new fill applied to the RAPs is higher than in other locations. This higher pressure is believed to result in more deformation of the reinforced zone and ultimately result in lower stress concentration levels between the piers and the matrix soil. From the studies of Han and Ye, the lower stress concentration level results in a lower estimated radial coefficient of consolidation value. This reduced value of radial coefficient of consolidation provides possible explanation for the increased settlement durations experienced within certain locations at the site. This relationship is shown in Figure 9 that plots times required for 90 percent of the settlement to occur with the corresponding fill height (applied pressure).

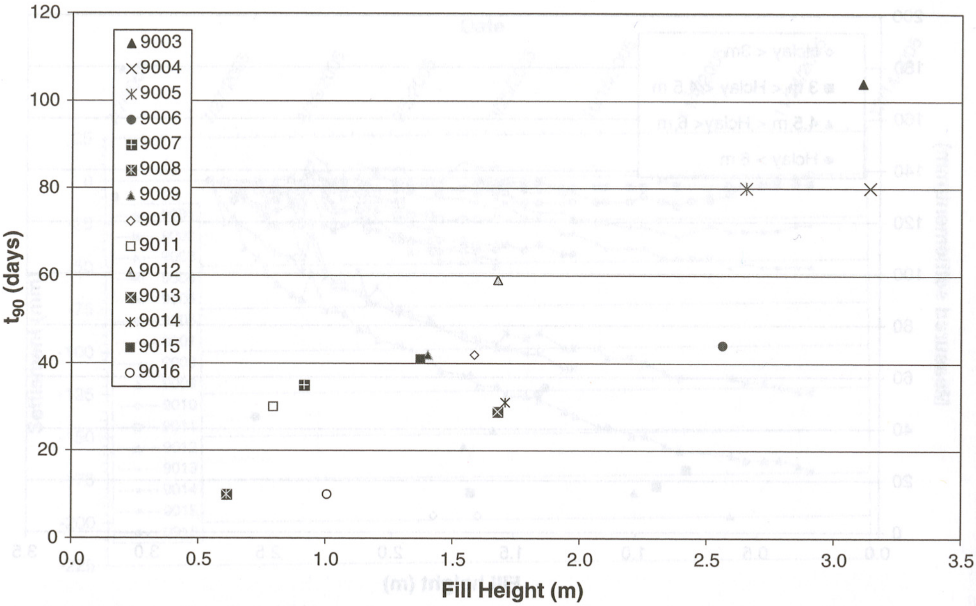

Figure 9. Effect of fill height (applied pressure) on drainage times required to reach 90% settlement.

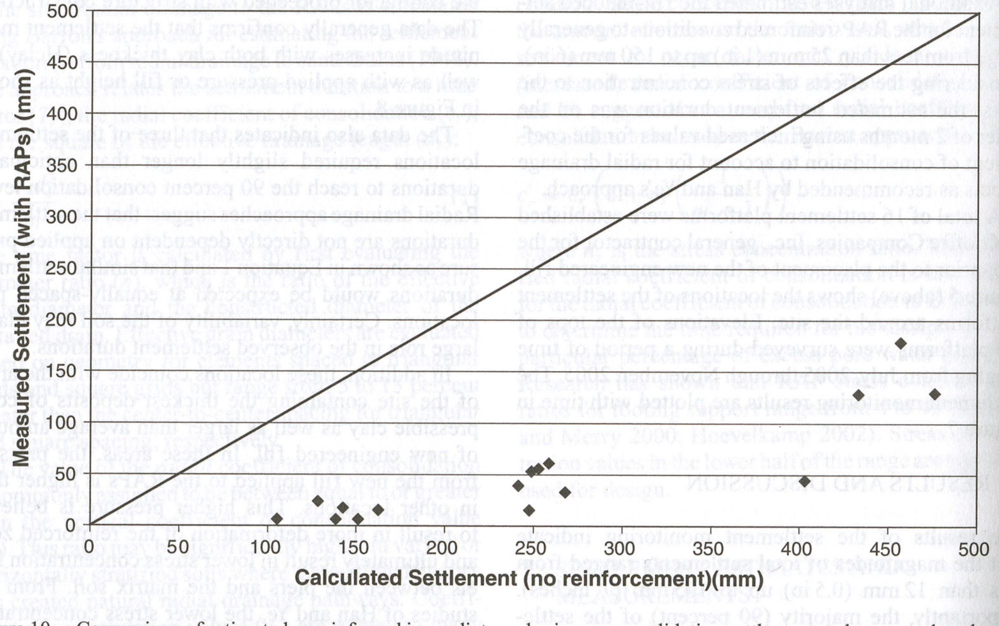

Figure 10. Comparison of estimated unreinforced immediate and primary consolidation settlement and measured settlement with RAP-reinforcement.

Based on estimated stress concentration values between the RAPs and the matrix soil, modified radial coefficient of consolidation values were calculated. The results show values that range from 0.006 to 0.066 cm^2/second with an average value of 0.015 cm^2/second. It is important to note that the average of the results is at least an order of magnitude greater than the values measured for the coefficient of consolidation in the vertical direction in laboratory tests, indicating that the radial drainage provides considerably faster times than vertical drainage for the same drainage path length. As a result, the settlement from the fill placed on the RAP-reinforced site occurs at a much faster rate.

Finally, Figure 10 provides a comparison between the estimated immediate and primary consolidation settlements resulting from the placement of the different fill heights on the unreinforced soils and the measured settlements occurring on the RAP-reinforced soils. The Figure illustrates a considerable amount of improvement in the magnitude of settlements as evidenced by the departure from the 1:1 relationship. This relationship indicates that the use of the Rammed Aggregate Piers provides a significant composite stiffening effect on the site to significantly reduce settlement magnitudes.

9 CONCLUSIONS

This paper presents the results of settlement monitoring data at a soft clay site reinforced with Geopier Rammed Aggregate Piers. After completing RAP installation and monitoring settlement, the following is concluded:

- RAPs provide a cost-effective solution for reinforcing soft or compressible soils to support engineered fill, spread footing foundations, and soil-supported floor slabs as an alternative to more traditional subgrade improvement methods (surcharging, overexcavation and replacement, etc.).
- Measured settlement magnitudes of the RAP-reinforced site are considerably lower compared to the estimated settlements resulting from the placement fill on unreinforced soils.
- Measured settlement durations suggest that the presence of the RAPs provides reduced drainage path lengths and increased consolidation rates, affording significantly reduced drainage times to achieve primary consolidation of compressible deposits.
- Settlement monitoring data combined with estimates of stress concentration values suggest general agreement with Han and Ye's suggested model for increased values for radial coefficient of consolidation for increasing levels of stress concentration.

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