Comparison of Load Test Results and Performance of the Rammed Aggregate Pier® System in Undocumented Fill in Urban Areas.

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ABSTRACT

As the already densely-populated City of Chicago, Illinois continues to expand towards the suburbs, developers look for innovative ways to develop the few remaining sites within the city limits often passed up because of poor site conditions resulting in expensive development costs.

One nation-wide retailer selected a challenging site within the City of Chicago. The site was filled with approximately 8 to 10 feet of contaminated material. Because of he extremely expensive cost of over-excavating and disposing of the contaminated fill materials, and because deep foundations would require redesign and additional time for the approval of the City's Board of Underground Committee, the design team decided that the most cost-efficient foundation support solution was to leave the contaminated soil in-place and reinforce it with Rammed Aggregate Pier® elements constructed with recycled concrete readily available in the area.

Instrumentation of the constructed piers with pressure cells along with extensive full-scale footing load tests and modulus tests were performed to confirm the field performance of the system.

This paper describes the results of the field tests and instrumentation program performed at the site. This paper further provides comparisons of the test results for individual piers and groups of piers beneath footings.

INTRODUCTION

A new big box retail store with a footprint area of approximately 140,000 square feet was planned in the McKinley Park neighborhood of Chicago, Illinois. The soils in the upper 8 to 10 feet consisted of contaminated urban fill and soft silt representing challenging conditions for the developers and designers. For developers and owners, finding ideally located sites to establish a retail store in the City of Chicago is a challenge because of the few undeveloped locations left available; now combined with the hurdle of dealing with problem soils. For designers, the presence of contaminated, undocumented urban fills represents a challenge in terms of selecting a cost-effective foundation solution for the structure that provides reliable performance and is accepted by the City of Chicago.

The combination of column loads varying from 25 to 140 kips, approximately 1 to 4 feet of grade-raise fill to attain finished grades across the site, and floor slab pressures of up to 250 psf, led the geotechnical engineer to conclude that the integrity of the structure could be compromised by allowing the foundations and floor slabs bear on the existing variable fill because of the heterogeneity and uncertainty with settlement performance. Among the foundation solutions evaluated by the design team, over-excavation and replacement with engineered material was deemed cost-prohibitive, and deep foundations combined with a two-way structural floor slab were not only expensive but also a challenge to get the approval of the City's Board of Underground Committee which is required when working at depths of 12 feet or greater.

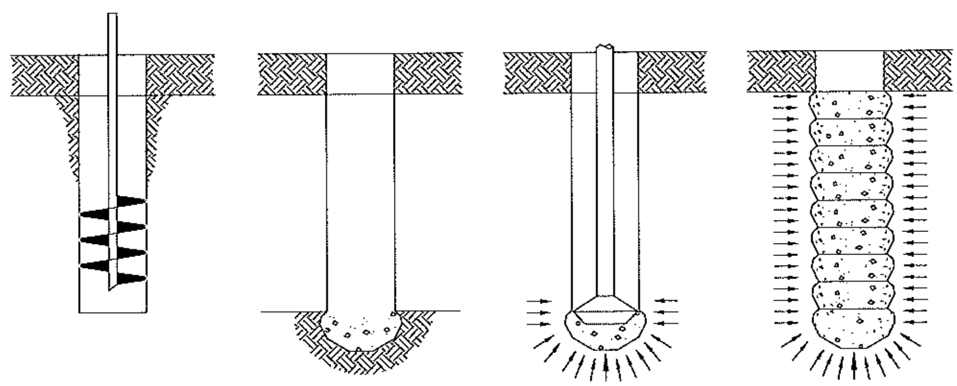
The use of the Rammed Aggregate Piers (RAP) soil reinforcement system was selected to reinforce the undocumented urban fill layer to provide support and settlement control for the floor slab and shallow foundations. This alternative eliminated the need for disposal of large volumes of contaminated fill. Because the intermediate shallow foundation system involved shallow depths, only building permits were required and there was no need for approval from the Board of Underground. Additionally, the RAP soil reinforcing system utilized locally available recycled concrete in pier construction which contributed to Leadership in Engineering and Environmental Design (LEED®) credits on the job. The RAP system was used for support of the footings and floor slab to control total and differential settlements below tolerable limits. Full-scale field tests including modulus tests and footing tests monitored with total pressure cells and telltales were used to confirm the design assumptions and design criteria established by the design team.

SOIL CONDITIONS

The soil conditions consist of approximately 3 to 7 feet of urban fill, underlain by a layer of loose silt to depths of 5.5 to 8 feet. The silt soils are underlain by soft to very stiff clay and loose to dense clayey sand. The urban fill was primarily granular in composition, but included limited zones of cohesive fill. SPT N-values in the fill ranged from 6 to greater than 20 blows per foot. Moisture content values ranged from 10 to 18 percent. SPT N-values in the silt soils beneath the fill ranged from 2 to 4 blows per foot, while the SPT N-values in the underlying clay ranged from 4 to greater than 40 blows per foot. Groundwater was observed at a depth of 18 feet below finished floor elevation.

CONSTRUCTION PROCEDURE

Rammed Aggregate Pier construction procedure is shown in Figure 1. The piers are constructed by drilling 24 to 36-inch diameter holes to depths typically ranging between 7 to 25 feet, placing controlled lifts of aggregate within the cavities, and compacting the aggregate using a specially designed beveled tamper attached to a high-energy, high-frequency, impact hammer. The first lift consists of clean stone and is rammed into the soil to form a bottom bulb below the excavated shaft. The piers are completed by placing additional thin lifts of aggregate in the drilled cavity and densifying the aggregate with the beveled tamper. During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil, thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface. For this project, recycled concrete was used for pier construction. Recycled concrete was a cheaper resource readily available in the area and allowed for contributions to the building's Silver Certified LEED status.



A. Drill cavity. B. Place stone at bottom of cavity. C. Ram stone to form bottom bulb. D. Place and ram thin lifts to form undulated-sided shaft.

Figure 1- Rammed Aggregate Pier Reinforcement Installation Procedure (Fox, N.S. and Cowell, M.J. (1998))

RAMMED AGGREGATE PIER DESIGN METHODOLOGY

Foundation settlements are estimated by summing the estimated settlement in the Rammed Aggregate Pier-reinforced zone (the "upper zone") and the estimated settlement in the zone of soil below the bottoms of the Rammed Aggregate Pier elements (the "lower zone"), in accordance with the methodology described by Lawton et al. (1994).

The top of pier stress, q_g, may be computed using Equation 1:

$$q_g = q\left[\frac{R_s}{R_sR_a - R_a + 1}\right] \tag{1}$$

where q is the average footing stress, and R_a is the ratio of the area coverage of the RAP elements to the gross footprint area. R_s, is defined as the ratio of the spring constants of the pier (k_g) and the matrix soil (k_m), where k_g and k_m are expressed in units of pressure/deflection. Assuming the footing is infinitely rigid and assuming strain compatibility between the piers and matrix soil, R_s may also be expressed as the ratio of the stress on the top-of-pier stress and the stress on the matrix soil. In this paper, R_s will be referred to as the stress ratio for further discussions.

Settlement in the upper zone (s_{uz}) is simply computed as the ratio of the top-of-pier stress, q_g to the pier spring constant (k_g):

$$s_{uz} = \frac{q_g}{k_g} \tag{2}$$

Lower zone settlements are estimated using conventional geotechnical approaches that consider the change in stress and soil compressibility within specific zones. Lower zone elastic settlements (s_{lz}) in granular soils or overconsolidated clay soils are often estimated with the equation:

$$s_{lz} = \frac{qIH_{lz}}{E_s} \tag{3}$$

where q is the average footing-bottom stress, I is the stress influence factor in the lower zone, H_{lz} is the thickness of the lower zone, and E_s is the secant modulus of the soil in the lower zone.

The estimated total settlement of RAP-supported footings (s) is determined by summing the upper zone and lower zone settlement values:

$$s = s_{uz} + s_{lz} \tag{4}$$

For this project, the Rammed Aggregate Pier soil reinforcing system was installed from existing grade and extended through the contaminated fill soils and soft silt to depths ranging from approximately 8 to 10 feet below existing grade, resulting in shaft lengths of 8 feet in most locations. The piers were installed beneath shallow footings and spaced in a 12.7-foot by 16-foot grid to support the lightly-loaded (150 psf) building floor slabs. In areas of heavier floor slab pressures (250 psf), the pier spacing was limited to 12 feet on-center. For foundation support, an allowable soil bearing of 4,000 psf was used for reinforced conditions. This allowable soil bearing pressure incorporated a factor of safety of 3.0. The RAP soil reinforcing system was designed to limit long-term footing and floor slab settlements to no more than one inch.

COST COMPARISON

Rammed Aggregate Pier construction was selected by the contractor (Walsh Construction of Chicago) and the owner (Target Corporation) over the option of remove and replacement primarily because of the high cost of disposal of the contaminated materials. Environmental testing of the on-site materials indicated high levels of heavy metals within the fill layer, thus necessitating special handling and disposal costs. Assuming a removal of an average of eight (8) feet of material throughout the building footprint, the disposal costs of these contaminated materials alone was on the order of $2.5 million (not including the cost of replacement fill and related construction costs). The cost of the Rammed Aggregate Pier soil reinforcing system was less than $800,000, saving in excess of $1.7 million. In addition, a total of approximately 900 Rammed Aggregate Pier elements were installed in less than 3 weeks, thus accelerating the construction schedule. It should be noted that spoil from the RAP installation was allowed to stay and re-used on-site, thus eliminating the need of any disposal of the contaminated materials off-site.

FIELD TEST PROCEDURES

Modulus test and full-scale footing tests were performed prior to construction with the purpose of verifying the design assumptions and confirming settlement performance and support characteristics of the RAP-supported footings. In addition, a unit cell footing was performed to compare the performance of a modulus test with a small unit cell footing response. Table 1 describes the details of the different tests performed.

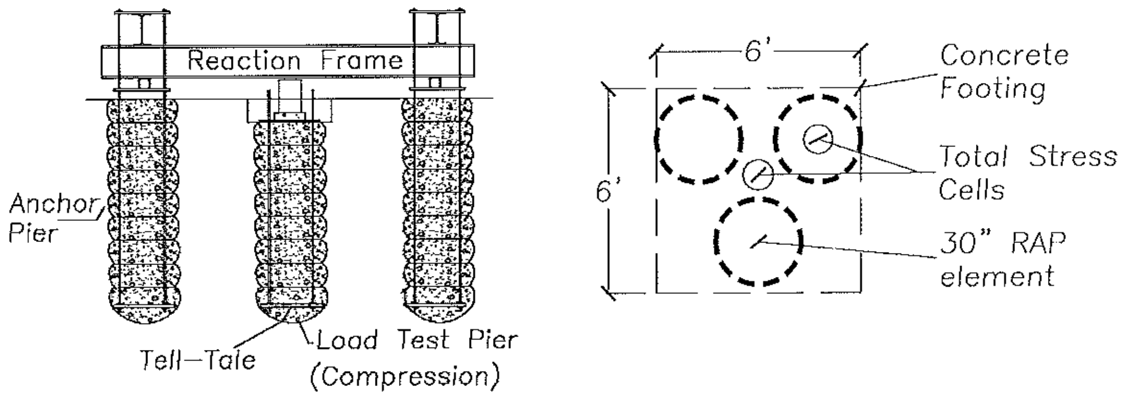
Table 1 – Summary of Field Tests Performed

Test Description	No. Piers/test	Square Footing Dimensions (ft)	R_a (%)	D_f (ft)	Instrumentation
Modulus Test	1	N/A	N/A	2	Tell-Tale
Unit Cell Footing Test	1	3.5	40	2	None
Full-Scale Footing Test	3	6	41	2	Tell-Tale and pressure plates

R_a = area replacement ratio

D_f = footing embedment depth

Figure 2 shows a sketch of the instrumentation. The tell-tales were installed at the bottom of the test piers after compaction of the bottom bulb. The tell-tales provide a mechanism to measure the deflection at the bottom of the pier to verify stress dissipation within the pier. The total stress cells were installed within full-scale load tests at the top of the piers and on the matrix soil between the test piers to measure total stress.



a) Cross-section of Modulus Test Pier with Tell-tale **b) Total Stress Cells**

Figure 2- Schematic of Instrumentation

The performance criteria established for the modulus test is based on standard acceptance criteria established by Geopier Foundation Company, Inc. The test is considered acceptable if the modulus value achieved at the design stress level is greater than or equal to the modulus value assumed in design. The performance criteria established for the unit cell footing and full-scale footing load tests were based on the procedures provided by the City of Chicago. The City Building Code specifies that the total net settlement under the total test load does not exceed 0.01 inch per ton of total test load. For example, the total settlement for a load of 50 tons should be no more than 0.5 inches.

FIELD TEST RESULTS

Figure 3 shows a summary of the results of the modulus test, unit cell footing test, and full-scale footing test. The graph illustrates load and deflection at the top of the piers and also deflection of the tell-tales. The response of the pier reflects a linear elastic behavior within the load range of the test. At design loads (50 kips), the deflection at the top of the test piers in all tests was less than 0.25-inch. The results indicate minimal movement of the tell-tales, evidence that the load was mainly transferred to the matrix soil through side friction along the pier shaft without mobilizing tip stresses. The dotted line indicates the acceptance deflection criterion established by the City of Chicago. The performance of the test piers in the modulus tests and the footing tests was acceptable and exhibited a stiffer than expected response, exceeding the design assumptions and requirements. Further, the results indicate that the individual modulus test pier performance validates the performance of a group of piers in a footing by obtaining very similar linear load-deflection responses. These results are consistent with previous research results conducted in different soil conditions where the load tests on groups of closely-spaced piers beneath a footing suggest an efficiency factor of unity afforded by the improvement of the soils around the piers and the increased composite bearing capacity. (White, et.al., 2007)

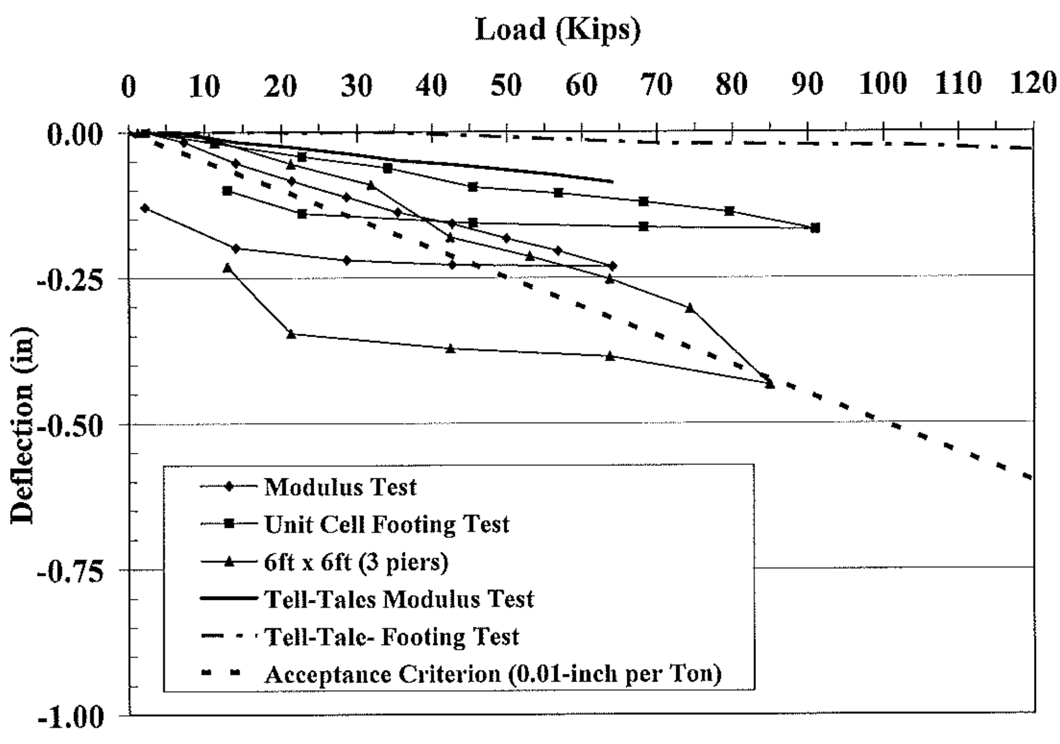


Figure 3- Modulus and Footing Load Test Results Showing Tell-Tale Movement

Figure 4 shows the total stress cell results measured in the full-scale footing load test. The total stress measurements on the tops of the piers and on the matrix soil between the piers indicate that the stress ratio, R_S, increases with greater compression load. At low compression load, the measured stress ratio value is on the order of 4. At higher loads, the stress ratio increases to a maximum of 6. The measured stress ratio values are significantly less than the stress ratio assumed for design. The stress ratio value assumed for design was 16, resulting in a conservatively higher estimation of the top-of-pier stress and upper zone settlement. The stress ratio assumed for design ignores the improvement of the matrix soil afforded by the installation of Rammed Aggregate Piers. Using a stress ratio value of 4 in the design calculations results in upper zone settlement consistent with the field measurements.

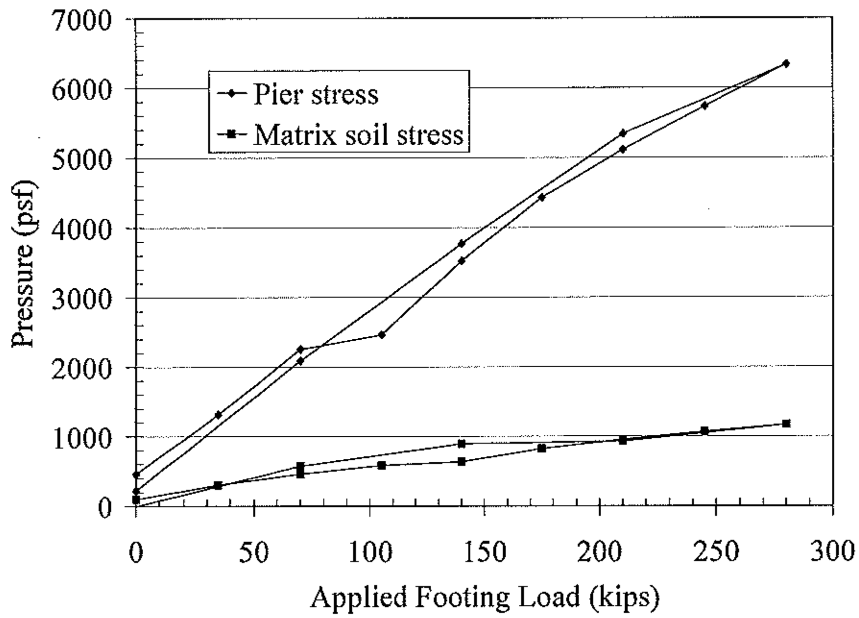


Figure 4 – Total Stress Cell Measurements During Full-Scale Footing Load Test

SUMMARY AND CONCLUSIONS

Rammed Aggregate Pier soil reinforcing elements were selected to reinforce undocumented urban fills and control settlement under spread footings and floor slab to less than 1-inch for a national retail store. Individual modulus tests and full-scale footing load tests instrumented with tell-tales and total stress cells were used to monitor the pier performance. The test results were acceptable and verified the design assumptions and design settlement criterion established by the City of Chicago. The modulus test results on individual piers were very similar to the performance of a group of piers within a footing, validating the results of previous research initiatives that indicate the modulus test results may successfully predict the performance of groups of piers installed at a very close spacing within a footing. This is explained by the relatively low stress ratio measured during tests, evidence of the significant improvement in the bearing capacity of the reinforced matrix soils produced by the pier installation process.

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