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Reduction of Settlement Risk at an Organic Soil Site in New England

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Abstract

This paper presents the results of modulus load testing on Geopier Rammed Aggregate Piers (RAPs) as well as settlement monitoring performed in an engineered fill preload supported by RAPs. Details of subsurface investigation, design considerations, test program and field monitoring are discussed in detail.

Introduction

The development of sites underlain by variable urban fill and compressible organic soils presents unique challenges to develop foundation support solutions that reduce the performance risk while minimizing the site preparation and foundation cost impacts to the project. Design considerations must consider the potential for settlement from compression of the fill and consolidation of the organic soils resulting from grade-raise fill, foundation stresses and floor slab pressures. While multiple systems may provide viable solutions, the selection of the appropriate system must consider the foundation support cost, ease of installation and owner's adversity to risk.

Site and Subsurface Conditions

Site. The proposed development consisted of 7,432 m^2 (80,000 ft^2) of retail stores at an 11-acre site in New Bedford, Massachusetts. The project site was occupied by construction debris fill and buried foundations from former industrial and commercial buildings. Grade needed to be elevated by 1.5 to 2.1 meters (5 to 7 ft) because the site was located in a flood plain. The planned development included the

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Figure 1. Rammed Aggregate Pier construction (left), preload (right)

construction of steel-framed buildings with column loads on the order of 890 kN (200 kips) and floor slab pressures ranging from 7.2 to 12 kPa (150 to 250 psf). Figure 1 shows the site during the grading activities prior to building construction.

Subsurface Conditions. The subsurface conditions, characterized in Table 1 and shown in Figure 2, consisted of a 0.9 to 4.3 meter (3 to 14 ft) thick layer of loose to dense urban fill, consisting of a mixture of concrete, bricks, ash, cinders, and wood debris in a granular soil matrix. The fill was underlain by a discontinuous layer of very soft to medium stiff, black silty peat and organic silt up to 2.7 meters (9 ft) thick. The fill and organic soils were underlain by medium dense to dense, fine to coarse glacial outwash sand and fine to coarse gravel. Groundwater was observed at approximately Elevation 1.4 m (El. 5 ft) within the fill.

Table 1. Subsurface Characterization

Characteristic	Urban Fill	Organic Silt	Silty Peat
SPT N-value (blows/0.3m)	5 - 50	0 - 6	0 - 6
Moisture Content (%)	-	87 – 197	276 – 452
Organic Content (%)	-	20 – 23	31 – 45
Coefficient of compression (c_c)	-	1.2	1.3
Initial void ratio (e_0)	-	2.4	3.0

Design Considerations

Foundation Type. The site was unsuitable for supporting conventional shallow spread footings at grade because of potentially high and variable settlements in the fill and peat layers. Four options were considered, including 1) over-excavation and replacement of both fill and organic soils followed by the use of shallow foundations, 2) pressure-injected footing (PIF) foundations supporting pile caps and structural floor slabs, 3) PIF foundations with slab-on-grade construction following a surcharge program, and 4) Geopier RAP soil reinforcement of the existing unsuitable fill and organic soils and support the engineered fill, shallow foundations, and slab-on-grade construction.

All four options provided viable solutions to satisfy the owner's post-construction settlement criteria of 25 mm (1-inch) total and 13 mm (½-inch) differential. The RAP system was selected because of the significant cost and schedule savings afforded by the elimination of the pile foundations and structural floor slab or surcharge program required for the pile foundations and slab-on-grade construction.

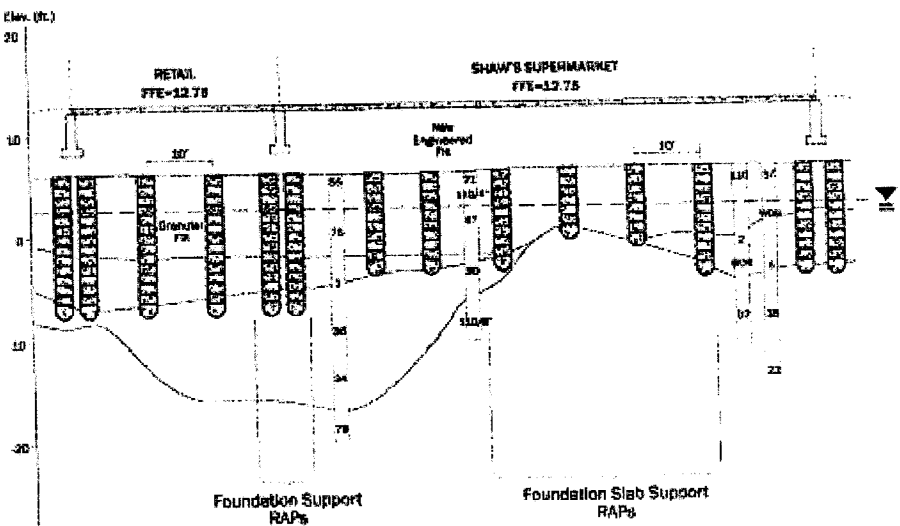

Figure 2. Cross-section of subsurface conditions and RAP solution

RAP Construction. 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. Densification increases matrix soil stiffness and increases normal stress perpendicular to the perimeter shearing surface.

Design Approach. The solution involved installing a grid of 0.76 m (30 in) diameter RAPs spaced 2.4 m to 3.0 m (8 to 10 ft) on-center across the building footprint to penetrate the fill and organic soils (Figure 2). The piers were installed to tag the underlying medium-dense to dense sand and gravel with drill depths generally ranging from 1.8 m to 4.6 m (6 to 15 ft). Additional RAPs were installed beneath the proposed foundation locations to increase stiffness and load carrying capacity. Following installation of the RAPs, up to 2.1 m (7 ft) of engineered fill was placed to floor level.

Settlement monitoring was performed to evaluate the time rate and magnitude of settlement. Construction of shallow foundations sized for an allowable bearing pressure in the engineered fill of 144 kPa (3 ksf) 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 limited to 25 mm (1-in) and 13 mm (½-in), respectively, by providing the reinforced crust of RAPs.

Support of Engineered Fill and Slab-on-Grade Floor Slabs

Behavior of RAP Reinforced Soil: Figure 3 shows a cross-section of a RAP-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. The applied pier pressure 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.

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 coupling action of the RAP to the matrix soil (Minks, et al. 2001). Matrix soil settlement from the fill wedge weight 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 reduces bulging, allowing the pier to support additional stress.

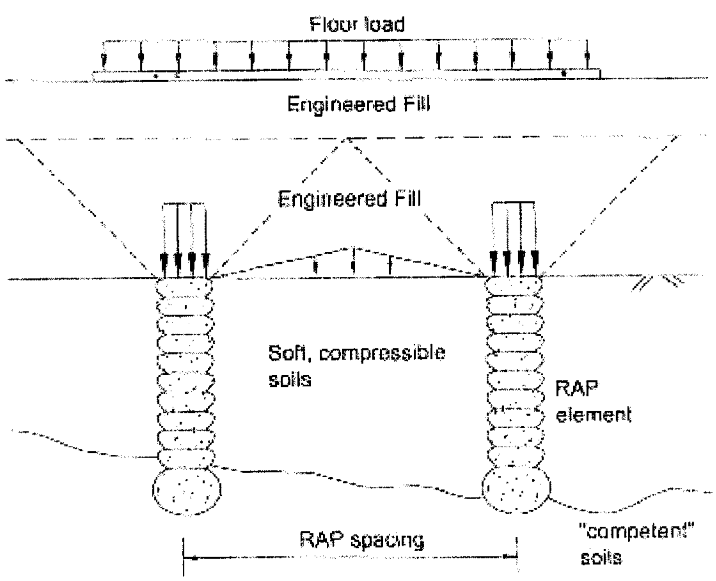

Figure 3. RAP support of engineered fill and floor slabs

The addition of engineered fill and the floor slab above the wedge of arching results in pressures on the reinforced soil mass that are 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 and floor slab pressures.

Behavior of RAPs in Soft Soils. When extending through soft soils, RAPs must be designed to resist bulging. The potential for bulging is commonly estimated using cavity expansion solutions initially developed by Vesic and further refined by Hughes and Withers (1974). The allowable stress ($q_{g,all}$) applied to the pier is estimated as:

$$q_{g,all} = \frac{\sigma_{r,lim} \tan^2\left(45 + \frac{\phi_g}{2}\right)}{FS} \quad 1$$

where FS is a factor of safety (typically of 2), ϕ_g is the RAP friction angle (typically 46 to 52 degrees), and $\sigma_{r,lim}$ is the limiting radial stress at the depth of bulging. The limiting radial stress is estimated using the following relationship

$$\sigma_{r,lim} = 2\sigma_v' + 5.2c \quad 2$$

where σ'_v is the effective vertical stress at the depth of bulging and c is the undrained shear strength of the matrix soil.

Test Program and Results

General. The project conditions and soil stratigraphy presented a unique opportunity to evaluate the impact of confinement on the stiffness and behavior of RAPs by performing a series of modulus load tests on constructed elements. In addition, the engineered fill required to achieve finish floor provided a chance to monitor the magnitude and time-rate of settlement of the RAP-supported fill pad over organic soils.

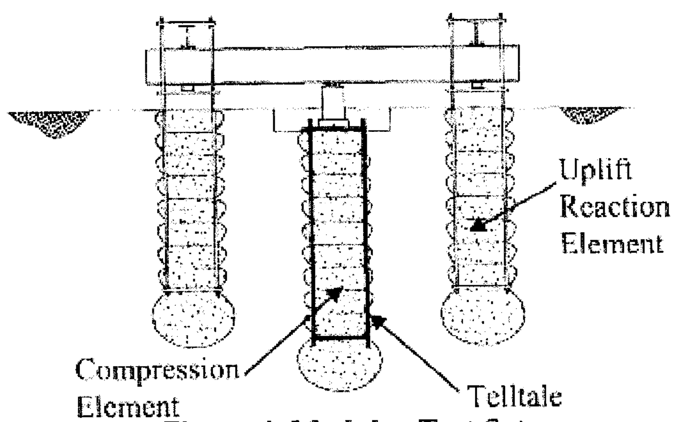

Figure 4. Modulus Test Setup

Modulus Test Procedures and Results. The modulus test set-up (Figure 4) is similar to a pile foundation load test and is performed in general accordance with ASTM D-1143. During the installation of the compression test pier, a steel telltale is positioned from top of the bottom bulb and sleeved to the surface to measure deflections at both the top and bottom of the pier. Plots of stress versus deflection are constructed from the modulus test results to evaluate stiffness and deformation behavior of the RAP.

Modulus Tests Configurations. Two modulus tests were performed to evaluate the performance of RAPs in peat. Test Pier A was installed to a depth of 2.9 m (9.5 ft) to penetrate 1.8 m (6 ft) of granular fill and 0.9 m (3 ft) of fibrous peat and tag the underlying sand. One telltale was installed near the bottom of the pier, 2.9 m (9.5 ft) below the existing ground surface. A 0.86 m (34 in) steel casing was vibrated to a depth of 1.5 m (5 ft) and cleaned of fill to serve as a sleeve that would isolate the applied test load from the granular fill. A 1.5 m (5 ft) thick, 0.75 m (2.5 ft) diameter concrete cap was embedded within the granular fill to apply loads to the top of the pier immediately above the peat.

Test Pier B was installed 4 m (13 ft) below existing grade to penetrate 2.1 m (7 ft) of granular fill and 1.5 m (5 ft) of fibrous peat and tag the underlying sand. One telltale was installed near the bottom of the pier, 3.4 m (11 ft) deep. A 0.86 m (34 in) steel casing was vibrated to a depth of 1.8 m (6 ft) immediately above the test pier and cleaned of fill to serve as a sleeve that would isolate the applied test load from the granular fill. Subsequently, 1.2 meters (4 ft) of engineered fill were placed around the casing to simulate the placement of the preload fill which provides additional confinement to the underlying peat. Finally, a 3 m (10 ft) thick, 0.76 m (2.5 ft) diameter concrete pedestal was then constructed within the temporary steel sleeve to apply loads directly to the top of the pier immediately above the peat.

Modulus Test Interpretation and Discussion. While performing the modulus test, the relationship between stress and deflection of the RAP is typically characterized by a bi-linear response. Stress at the intersection of the two legs of the bi-linear stress-deflection curve is referred to as the inflection stress. At levels less than the inflection stress, the RAP is characterized by elastic deformation. At levels greater than the inflection stress, the pier experiences non-recoverable plastic deformation. The relative movements of the top and bottom of the pier compared to inflection stress deflection provide an indication of the deformation mechanism. RAPs undergoing plastic deformation with little telltale movement, indicate deformation behavior from radial bulging into the matrix soil.

The modulus test results for Test Piers A and B are summarized in Table 2. Figures 5 shows variation of deflection with RAP stress for Test Pier B. Minor movement of the telltale rods observed during testing of both Test Piers A and B indicate the application of stress to the pier installed in soft soils results in the potential for bulging. A comparison of the two test results suggests added confinement provided by the fill platform increased the inflection stress of the pier by slightly less than 10 percent; the stiffness of the pier increased by up to 20 percent.

Table 2. Modulus Test Results

Test Pier	12.5 mm (1/2-in) Deflection		25 mm (1-in) Deflection		Inflection Stress (kPa / ksf)
	Applied Stress (kPa / ksf)	Pier Stiffness (MN/m^3 / pci)	Applied Stress (kPa / ksf)	Pier Stiffness (MN/m^3 / pci)	
A	450 (9.4)	35 (129)	600 (12.5)	24 (87)	360 (7.5)
B	490 (10.2)	39 (142)	720 (15.0)	28 (104)	382 (8.0)

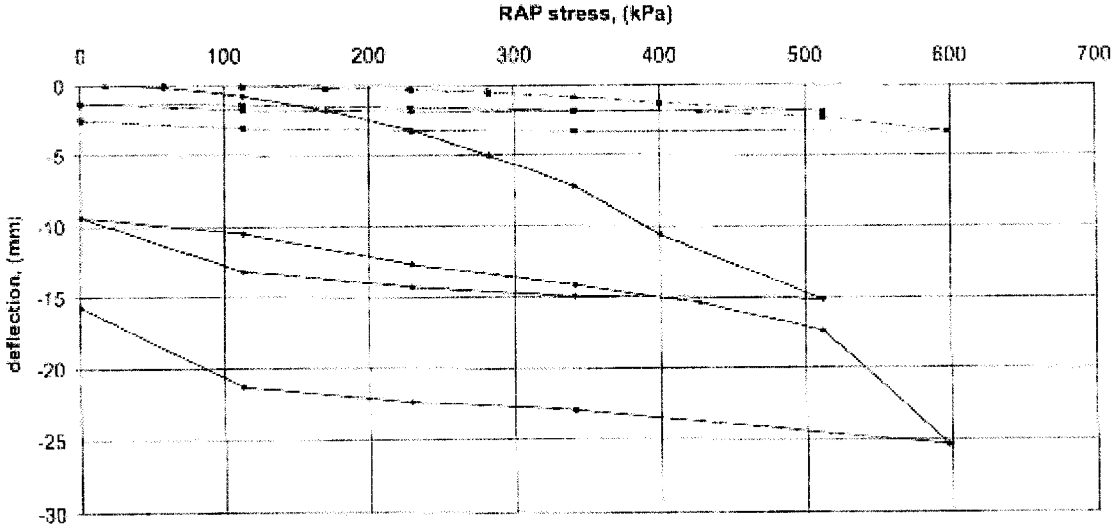

Figure 5. Modulus test results of Test Pier B

Measured Settlements. Three settlement platforms were installed prior to the placement of the grade-raise fill for the proposed retail building. The platforms were positioned between RAP locations. The height of the fill ranged from 2.49 to 2.71 m (8.2 to 8.9 ft) overlying peat thicknesses of 0.9 to 1.8 m (3 to 6 ft). Predictions for unreinforced peat suggested settlement on the order of 0.15 to 0.3 m (6 to 12 in) were anticipated. Actual monitoring results indicate settlements ranged from 20 to 46 mm (0.8 to 1.8 in). Results of the settlement monitoring indicate RAP installation significantly reduced settlement magnitude. In addition, the majority of settlement was complete within a 2 to 3 week period as a result of radial drainage to the RAPs and vertical drainage. Although the data suggest RAPs reduced the settlement magnitude by 3 to 12 times, portions of the site had been preloaded from stockpiling during building demolition likely contributing to reduced settlement.

Conclusions

This paper presents the results of modulus load testing on Geopier Rammed Aggregate Piers (RAPs) as well as settlement monitoring performed in an engineered fill preload supported by RAPs. After completing RAP installation, performing testing, and monitoring settlement, the following is concluded:

- RAPs provide a cost-effective solution for reinforcing soft or compressible fill or natural deposits to support engineered fill, spread footing foundations, and soil-supported floor slabs.
- Modulus test results performed on piers installed through granular fill and peat to tag sand where the load is applied near the fill and peat interface exhibit greater propensity for bulging in the peat soils which likely limits the maximum applied stress.

- When load is applied at the fill and peat interface, the presence of additional confining stress (provided by an engineered preload) increases the inflection stress and stiffness by 10 and 20 percent, respectively. Bulging resistance (inflection stress) is directly proportional to the confining stress.

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