SETTLEMENT MONITORING OF DISCRETE REINFORCED SOIL LAYER BENEATH MAT FOUNDATIONS, CALIFORNIA, USA

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ABSTRACT

Determining deflections of discrete soil layers beneath large mats prone to settlement is difficult utilizing optical survey only. Site-specific instrumentation and test programs can provide this information. This paper describes support of mat foundations for two 18-story towers in California, USA, using Geopier® Rammed Aggregate Pier™ (RAP) foundations. RAPs provided a cost-effective reinforcement solution of a compressible layer. This paper presents results of modulus tests and extensometer instrumentation measuring RAP-reinforced layer settlements and represents the first published results of RAP performance using extensometer monitoring.

RESUME

Déterminer les déflexions de couches de sol discrètes en dessous des grands tapis enclins au règlement est difficile utiliser les études optiques seulement. L'instrumentation site-spécifiques et programmes de test peuvent fournir cette information. Ce papier décrit le soutien de fondations de tapis pour deux tours de 18 histoires en Californie, USA, utilisant Geopier® Rammed Aggregate Pier™ (RAP) les fondations. LES RAPs ont fourni une solution de renforcement rentable d'une couche compressible. Ce papier présente des résultats de tests de modulus et d'instrumentation d'extensometer mesurant les règlements de couche RAP-renforces et représentent les résultats premièrement publiés d'exécution de RAP utilisant l'interception d'extensometer.

1. INTRODUCTION

Large mat foundations present settlement challenges related to the large areal loading. Excessive settlement may result from shallow compressible soils where the bearing stresses are high or as a result of the deep zone of influence from the size of the mat. When significant settlement is anticipated from the relatively shallow compressible layers, soil reinforcement or replacement with engineered fill is typically performed to reduce settlement. Quality assurance or verification of the performance of the solution to reinforce a particular layer may be questionable as conventional surveying is not suitable to assign post-construction settlements to discrete layers, most importantly the reinforced layer. Instrumentation prior to construction can provide performance verification of the selected mitigating technique by measuring compression in a selected layer.

1.1 Project Description

The proposed development consists of two 18-story condominium towers occupying approximately 4,000 m^2 (43,200 ft^2) at a 2-acre site in Irvine, California, USA. The towers are built with cast in place concrete placed over two 3 m (10 ft) thick mats measuring approximately 55 x 37 m (180 x 120 ft). The resultant bearing pressures

Figure 1. Excavation at base of west tower showing compressible clay layer

determined by the project structural engineer are 344 to 196 kPa (7,200 to 4,100 psf) at the center and edge of the mats, respectively. The planned development includes two levels of below-grade parking placing subgrade for the bottom of the mat foundation at 9.1 m (30 ft) below grade. Figure 1 shows a picture of the bottom of the excavation prior to mat placement.

1.2 Subsurface Conditions

The project site is located on an alluvial plain with Holocene aged deposits extending to the maximum explored depth of 36.5 m (120 ft). The project geotechnical investigation identified a compressible clay layer extending 12 to 14 m (40 – 46 ft) below grade or 3 to 5 m (10 - 16 ft) below the proposed basement elevation. The clay was underlain by dense sand and very stiff to hard clay/silt layers. Groundwater was encountered at a depth of 13.7 m (45 ft) below grade. The clay exhibited moderate plasticity (PI = 25-50) and relatively high moisture content (20 – 35%). Figure 2 is a summary of the standard penetration blowcounts (SPT-N values) in the upper 15 m (50 ft).

1.3 Design Considerations

Because of the very high column loads, conventional shallow foundations were not considered feasible. The design team considered supporting the building with driven piles or a mat foundation. Although the mat foundation provided distinct economic advantages, the geotechnical engineer estimated total settlements on the order of 15 cm (6 in). Approximately 8.2 cm (3.2 in) was a result of settlement in the clay layer immediately below the mat. The total settlement criterion was specified at 10 cm (4 in) or less. Several reinforcement methods were considered to reduce the shallow settlement including pressure-grouting, soil-cement columns, overexcavation and structural fill, and Geopier® Rammed Aggregate Pier™ (RAP) reinforcement. The RAP solution was selected to provide settlement control in the clay layer while offering significant savings over alternative treatment methods.

2. *Geopier*® Rammed Aggregate Pier Construction

The construction of *Geopier* Rammed Aggregate Piers (RAPs) is well-described in the literature (Lawton and Fox 1994, Lawton et al. 1994, Wissmann et al. 2000) and illustrated in Figure 3. The 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 specially designed high-energy beveled impact 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. RAPs are installed to reinforce weak and compressible soils offering improvements in the composite shear strength and the composite compression characteristics of the reinforced deposit, thereby controlling settlement and improving bearing pressures.

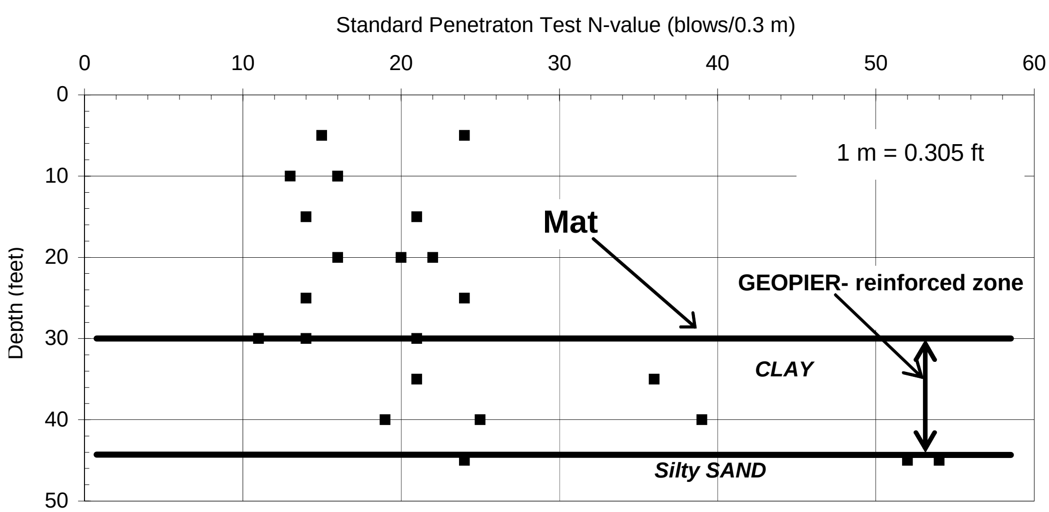

Figure 2. SPT N-values with depth

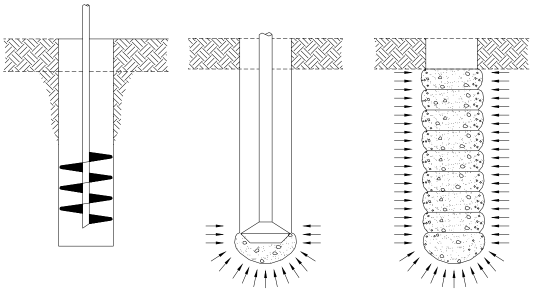

Figure 3. Geopier Rammed Aggregate Pier Construction

2.1 Geopier® RAP Design Approach

The solution involved installing a grid of 0.76 m (30 in) diameter Geopier RAPs spaced between 1.2 m and 1.8 m (4 and 6 ft) on-center across the mat footprints to reinforce the clay layer. The closest spacing was used beneath the center of the mat where the highest pressures are estimated. The spacing was then increased with distance towards the edge of the mat where pressures were lower to reduce the potential for differential settlement and provide a more economical solution. The piers were installed to drill depths generally ranging from 3 m to 5 m (10 to 16 ft). The design intent was to limit total settlement within the reinforced layer to less than 2 cm (0.75 in) and differential settlement to less than 1.3 cm (0.5 in).

The response of the RAP-reinforced zone beneath the mat is estimated as the ratio of the top-of-pier stress and the stiffness of the pier. The top-of-pier stress is calculated as:

$$q_g = q\,(R_s / (R_s * R_a - R_a + 1)) \qquad [1]$$

where q_g is the top-of-pier stress, q is the uniform footing stress, R_s is the ratio of pier stiffness to matrix soil stiffness and R_a is the ratio of pier area to footing area. The pier modulus is assumed as described in the literature (Fox and Lawton, 1994) based on known pier properties and the properties of the surrounding soil, and is then confirmed with a site specific modulus test.

The settlement analysis also considers the potential for settlement that may occur within the soil layers located below the reinforced zone resulting from the applied average foundation pressure. Conventional geotechnical analyses are used to estimate these settlements which are then added to the settlement within the RAP-reinforced zone to arrive at the total settlement estimate.

The support of large and heavy mats provided a unique opportunity to evaluate the correlation between predicted performance from individual RAP modulus load test results and the actual performance of the reinforced zone as measured by the extensometers.

3. SITE-SPECIFIC MODULUS TEST PROGRAM AND RESULTS

Traditional site-specific verification of the RAP design is performed by conducting a full-scale modulus test as depicted in Figure 4.

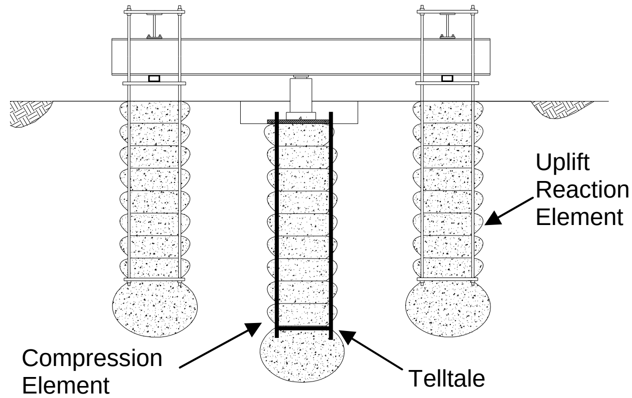

Figure 4. Modulus test setup

3.1 Modulus Test Procedures and Results

The modulus test set-up is similar to a pile load test configuration and the test is performed in general accordance with ASTM D-1143. During the installation of the compression test pier, a sleeved steel telltale is positioned near the pier bottom and extends to the surface allowing measurements of deflection near the pier bottom. Plots of the stress versus deflection for both the top of pier and telltale responses are constructed from the modulus test results and used to evaluate the stiffness of the modulus and deformation behavior of the RAP. One test was performed for each tower mat.

3.2 Modulus Test Interpretation and Discussion

The relationship between stress and deflection of the RAP measured during the modulus test is typically characterized by a bi-linear response. The stress level at the intersection of the two portions of the bi-linear stress-deflection curve is commonly referred to as the inflection stress. At pier stress levels less than the inflection stress the RAP is characterized by elastic deformation. At stress levels greater than the inflection stress, the pier experiences non-recoverable plastic deformation.

The modulus test results for the test configurations described above are presented in Figures 5 and 6 for Test Piers A and B, respectively and are summarized in Table 1.

Table 1. Summary of 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	1600 (33.3)*	128 (462)	N/A	N/A	1200 (25)
B	1293 (26.9)	103 (373)	1500 (31.2)	60 (217)	946 (19.8)

* = extrapolated from data plot
N/A = information unavailable from data plot

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 (Figure 6). RAPs undergoing primarily elastic deformation with little telltale movement indicate sufficient mobilization of shaft friction, without bulging, to resist the applied stress (Figure 5).

The design intent of the RAP solution is to reinforce the compressible clay layer and reduce the settlement potential. The modulus tests performed at the site indicated acceptable results with less than 10 mm of deflection at the maximum design stress of 946 kPa.

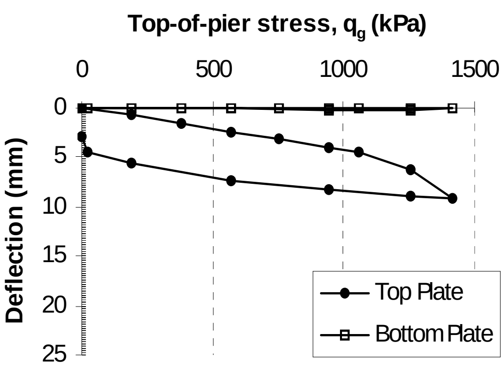

Figure 5. Modulus test results of test pier A

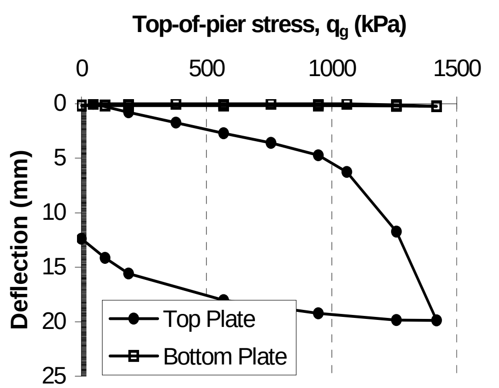

Figure 6. Modulus test results of test pier B

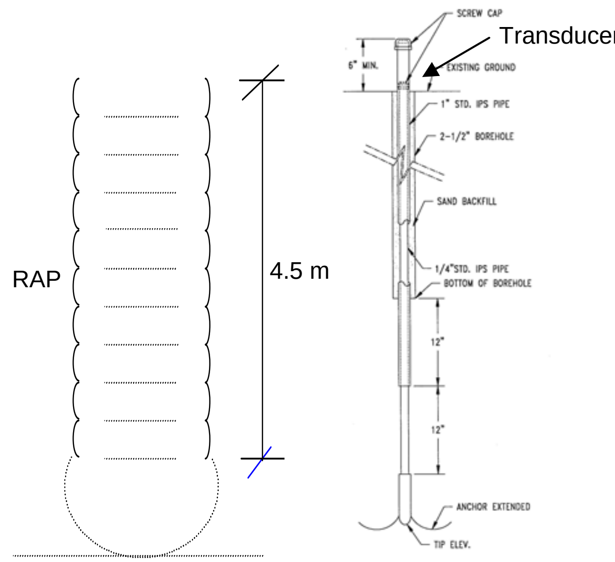

Figure 7. Extensometer schematic

4. EXTENSOMETER INSTRUMENTATION PROGRAM

With such a large loaded area it was deemed important to verify the effect of RAP installation on settlement reduction of the in-place mat. An instrumentation program featuring extensometers was initiated to obtain this verification. With provision of the extensometer monitoring results, we are able to compare this prediction with actual field measurements of the reinforced layer compression.

The measurement of total settlement within the discrete reinforced clay layer was accomplished with the use of vibrating-wire extensometer instrumentation. Two instruments were installed beneath each mat prior to construction; one at the center and one at the mat edge. The instruments are installed in a 6.3 cm (2.5 in) borehole that extends to the bottom of the reinforced zone. The hole is then backfilled with grout. The extensometer consists of 3 primary elements as depicted in Figure 7: a transducer, steel rod, and borros anchor. The transducer resides at the same level as mat bottom and contains a steel plunger in contact with a steel rod that extends to the bottom of the reinforced zone and terminates at the borros anchor.

As the reinforced clay layer compresses, the distance between the transducer and the borros anchor is measured by the deflection of the plunger at the transducer. The vibrating wire device provides a frequency calibrated for each instrument to provide a deflection reading. Readings were taken throughout construction corresponding to additional floor construction, and currently extend as long as 18 months after all dead load was applied to the structure.

4.1 Extensometer Settlement Monitoring

Installation and settlement monitoring began on December 8, 2003, prior to pouring the mat foundation. Readings were taken in such a manner to correspond approximately with concrete deck pours on each floor.

The full dead load of the structure was applied by approximately September 8, 2005. Settlement results are shown in Figure 8 on a calendar basis. Figure 9 provides a plot of deflection on a log-time basis. Instruments 304 and 306 are the center and edge of Tower A, respectively, while instruments 305 and 303 are the center and edge of Tower B, respectively.

4.2 Extensometer Settlement Interpretation

During the initial readings, absolute deflection values rise above the zero mark indicating extension rather than deflection of the extensometer. These values possibly reflect the continued rebounding of the clay layer following the 9.1 m (30 ft) excavation. The reinforced clay layer settlement readings indicate an elastic compression of the reinforced zone as the settlement occurs shortly after load application for each floor.

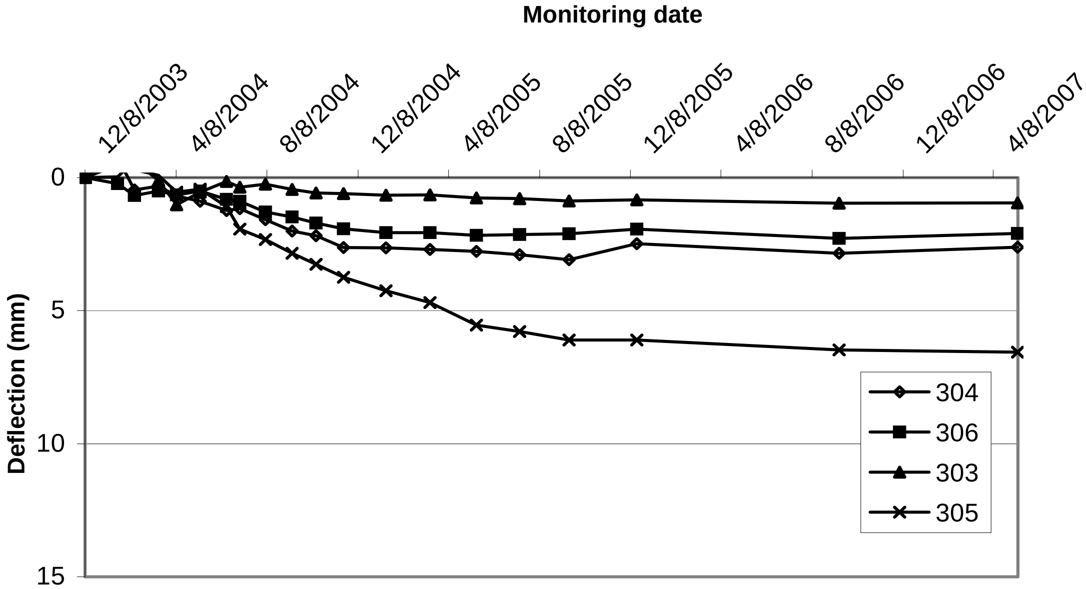

Figure 8. Compression of the reinforced zone vs. monitoring date

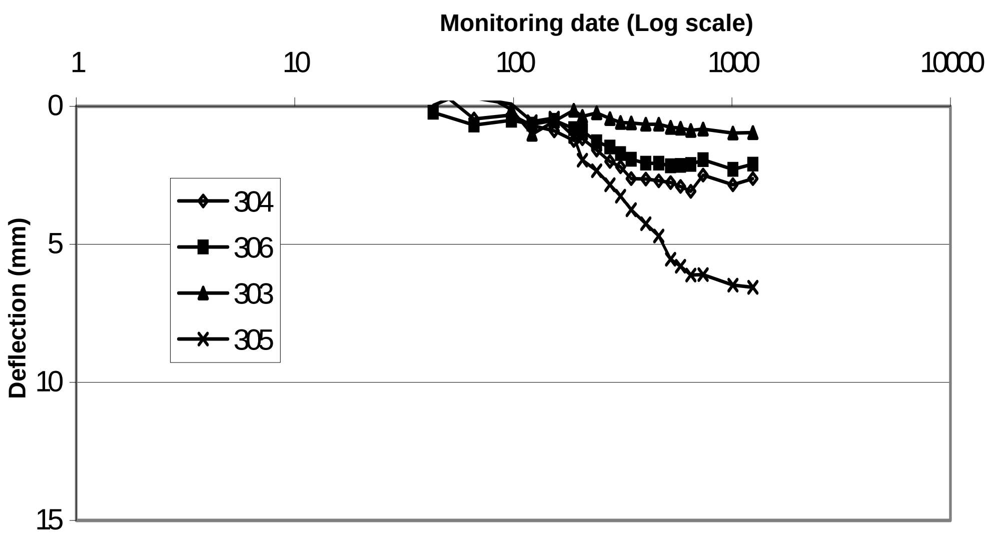

Figure 9. Compression of the reinforced zone vs. days of monitoring (log scale)

Instruments 303 and 305 are located in the footprint of Tower B where the average depth of clay is approximately 5 m (16 ft). The slightly higher deflection readings from 303 and 305 correlate well with the readings from Tower A where the average depth of clay was approximately 3 m (10 ft), about 2 m less than that in Tower B. Overall, total compression recorded in the reinforced layer was approximately ½ to ¼ of the design expectation using a design pier modulus assumption of 69 MN/m^3 (250 pci). However, the extensometer measured compression correlates much more closely with the results of modulus load testing that predict compression of approximately 4-5 mm (0.2 in) in the reinforced layer. This suggests that the use of the modulus load testing provides a valuable prediction tool to estimate the compression of reinforced layers under applied footing or mat pressures. Figure 10 shows a picture of the completed towers.

Figure 10. Picture of completed towers

5.0 CONCLUSIONS

This paper presents the results of modulus load testing on Rammed Aggregate Piers as well as discrete soil layer settlement monitoring performed in a clay layer reinforced by RAPs. After completing the RAP installation, performing testing, and monitoring settlement, the following may be concluded:

1. Rammed Aggregate Piers are a cost-effective and technically viable means to reinforce a compressible clay layer to reduce settlement and provide an elastic response. This elastic response was observed in both the full-scale modulus test and the extensometer instrumentation.

2. The majority of the total settlement within the reinforced layer was achieved by the time the full dead load of the structure was applied, suggesting limited to no long term compression associated with primary or secondary compression of cohesive soil.

3. The settlement estimates calculated using the presented design approach combined with site-specific modulus test results is confirmed with extensometer measurements indicating good agreement between design approach and measured field settlement performance within the reinforced zone.

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