USE OF *GEOPIER*® SOIL REINFORCING ELEMENTS TO SUPPORT A LARGE ABOVEGROUND STORAGE TANK FACILITY IN TEXAS

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ABSTRACT

Aboveground Storage Tanks overlying soft or variable fill soils pose technical and financial challenges. To reduce the risk of intolerable settlements that lead to instability problems, tank foundations are often supported by deep foundations or constructed by massive "overexcavation and recompaction" operations. Both options are costly and may significantly lengthen the time required for construction. *Rammed Aggregate Pier*™ elements were used to provide bearing support and limit settlements for ten 80,000-barrel tanks at the Houston Fuel Oil Company's Area 13 Tank Farm. A total of 3,150 elements were installed beneath the ten 100 foot diameter storage tanks. In addition to providing cost savings ranging from $400,000 to $700,000, the construction schedule was reduced by 40 working days. This paper describes foundation alternatives and the Geopier soil reinforcement solution used to stabilize the soil and control settlements at the Houston Fuel Oil project. This paper is of particular significance because it describes design and construction procedures used for an economical and fast-growing alternative to costly deep foundations and overexcavation.

INTRODUCTION

In the fall of 1999, Houston Fuel Oil Terminal Company, Inc. identified a need to increase its fuel storage capacity by constructing ten new 80,000-barrel tanks at its Area 14 tank farm in Houston, Texas. The tanks were to consist of 100-foot diameter, 56-foot tall aboveground cone-roof steel structures. The site of the new tanks consists of a 12-acre tract located at the northwest corner of the company's plant site along Jacinto Port Boulevard. The design and construction of the tank farm was met with only one major obstacle: the subsurface soil conditions were unsuitable to support the tanks on conventional ringwall foundations.

A review of historical area topographic maps and subsequent geotechnical explorations performed by Fugro South, Inc. revealed that the planned tank farm site was previously a reach of Carpenters Bayou and had been filled with unsuitable material excavated from the construction of an adjacent barge slip. The geotechnical engineers deemed that excessive settlements would occur without major modifications to the foundation soils. After much consideration, Houston Fuel Oil Terminal Company, Inc. opted to reinforce the subsurface soils with innovative *Geopier*® Rammed Aggregate Pier elements (Figure 1). This paper describes foundation support options, the design and construction of Geopier reinforcing elements, and the performance of the tank farm for the subject project. This paper is of particular interest because it describes design solutions for an economical and rapidly growing soil reinforcement system used to support tanks and other structures.

Figure 1: Photograph of Geopier construction operations

BACKGROUND

The Houston Fuel Oil Terminal Company is one of the largest fuel handling terminals in the Port of Houston. As part of the recent overall increase in the production and transportation of liquid fuels, the company recognized the need to add ten large tanks at its Area 14 tank farm in Houston. Foundation design studies for the aboveground steel structures were contracted to Fugro South, Inc., Houston, Texas.

Prior to performing geotechnical investigation work, Fugro engineers poured over historical topographic maps and aerial photographs made for the site dating back to 1920. The maps revealed that the area at one time was part of a reach of Carpenters Bayou, which is hydraulically connected to the Houston ship channel. Since 1944, the site has been filled with soil excavated from the construction of an adjacent barge slip and from other sources.

Fugro performed a total of 53 soil borings and CPT soundings to explore the site. Figure 2 presents a typical soil boring log. The explorations revealed that subsurface conditions consisted of 5 to 15 feet of highly variable clay fill soils overlying natural clay and sandy clay of variable strength. Table 1 presents a summary of the geotechnical characteristics of the explored fill soils. The fill soils were deemed by the engineers to be potentially too compressible to provide adequate support for the tank foundations. To make matters worse, the fill soils contained wood fragments and organic matter, thus leading to an increased potential for total and differential settlement.

Table 1: Summary of fill soil characteristics

Characteristic	Value
Soil moisture content (%)	20 to 50
Undrained shear strength (psf)	500 to 4,500
Liquid limit (%)	25 to 108
Plasticity index (%)	11 to 83

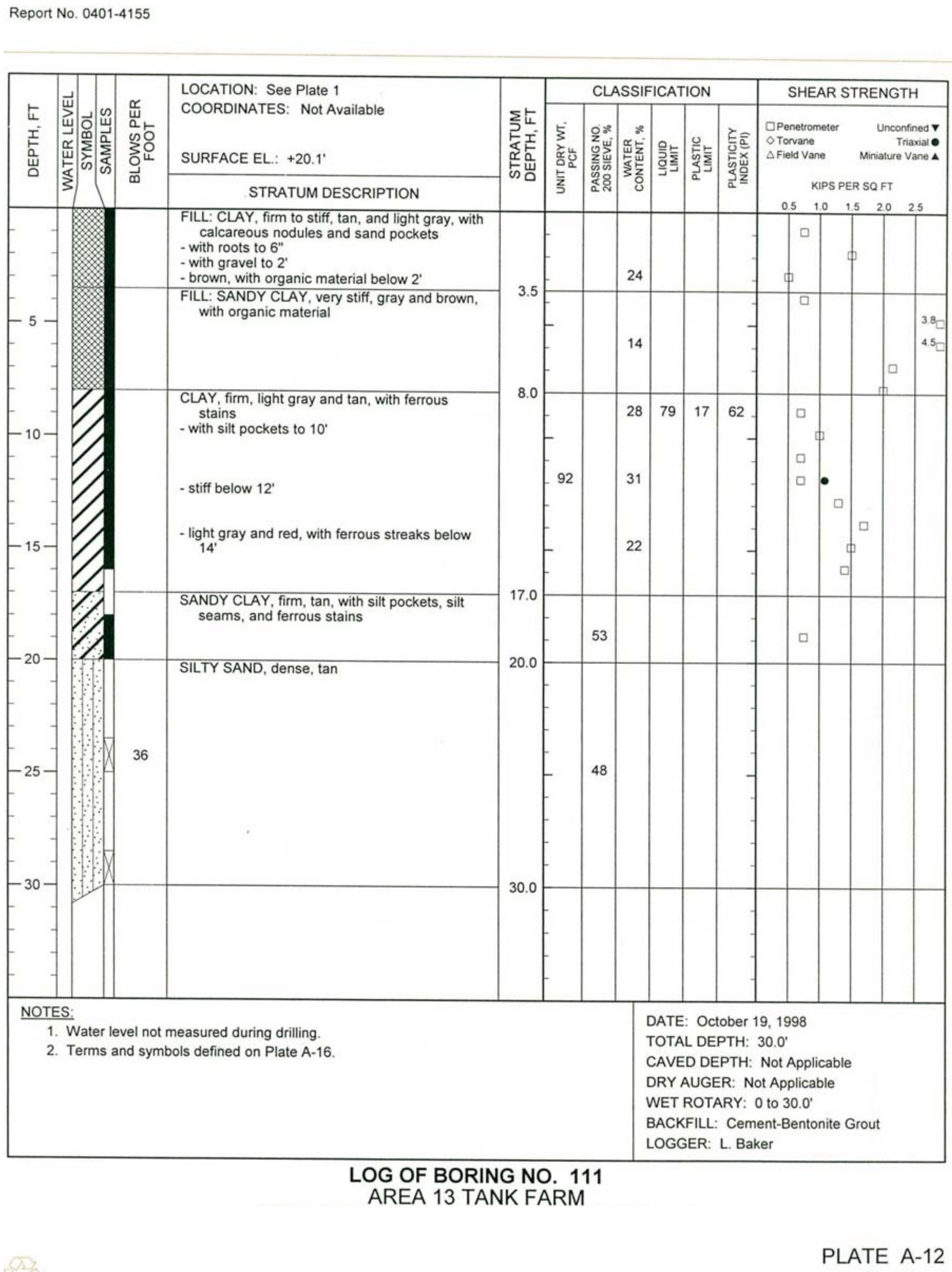


Figure 2: Typical soil boring log

TANK SUPPORT OPTIONS

To reduce the potential for total and differential settlement, project engineers considered the following foundation support options:

1. Excavate the existing fill soils to depths of up to 18 feet below grade, remove the existing unsuitable fill, and replace the fill with imported select fill material.

2. Install conventional driven or auger-cast piling systems and support the tank on a reinforced concrete slab connected to the piles.

3. Install conventional stone columns extending to a depth of 18 feet below grade.

4. Install *Rammed Aggregate Pier*™ soil reinforcing elements to effective depths of 17 feet below grade and support the tank on a granular fill pad overlying the aggregate piers. This option is depicted in Figure 3.

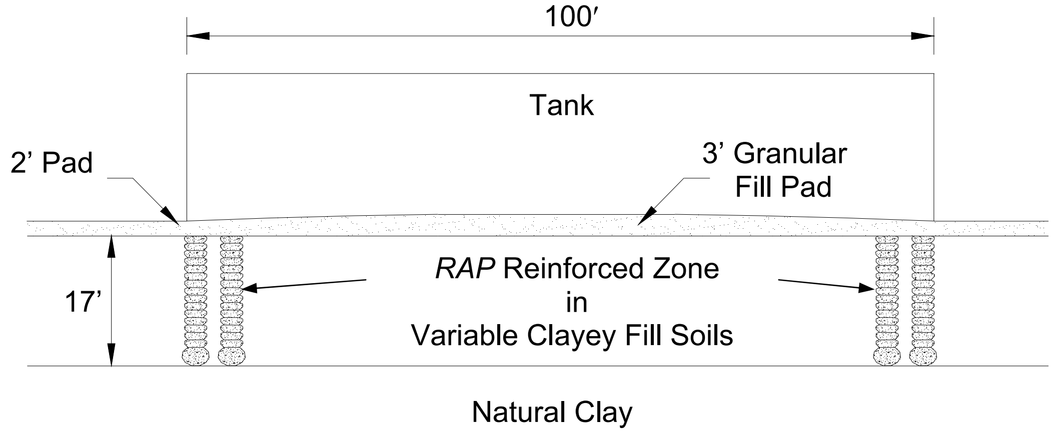


FIGURE 3: Schematic of *Rammed Aggregate Pier*™ installation

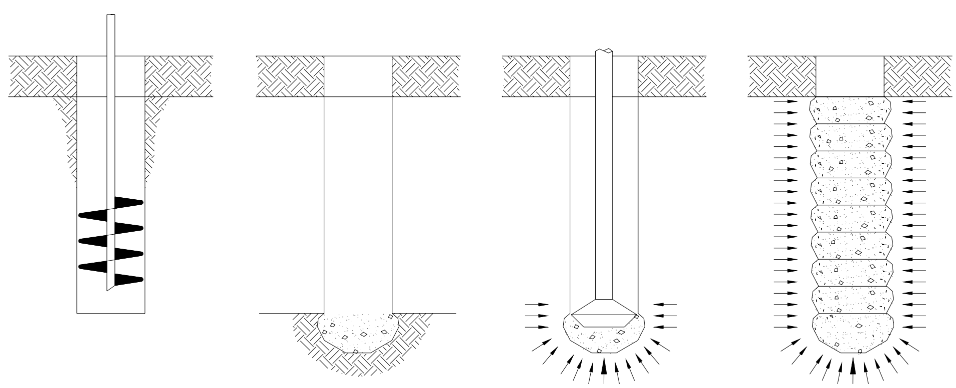
Although seemingly simple, excavation and recompaction was deemed to be fraught with risks and the potential for cost overruns as a result of the need for a deep excavation adjacent to the ship channel. Planners recognized that the disposal of the excavated soils would be a problem as would be importing vast quantities of structural fill. Importantly, this option was eventually discarded because of the time required for construction and the fast-track project schedule demands.

Tank support with deep piling was extensively considered but eventually discarded because of the extremely high costs associated with this option. Not only would high costs be accrued with pile driving, an expensive reinforced concrete slab would be required to transfer structural loads to the piles. Without consideration of the cost of the slab, it was determined that soil reinforcement with Geopier elements afforded an approximate cost savings of $700,000.

Traditional stone columns were considered as a means to improve the fill soils. This option was later discarded because of the demonstrated performance of Geopier soil reinforcement during modulus load testing and a considerable cost savings ($400,000) in favor of the Geopier system.

GEOPIER CONSTRUCTION AND DESIGN

The sequence of Geopier construction is shown in Figure 4. Geopier elements are installed by drilling 30-inch diameter holes and ramming thin lifts of well-graded aggregate within the holes to form very stiff, high-density aggregate piers. The drilled holes extended 14.5 feet below grade. The first lift of aggregate forms a bulb below the bottoms of the piers, thereby pre-stressing and pre-straining the soils to a depth equal to at least one pier diameter below drill depths thereby increasing the effective pier depth to 17 feet. Subsequent lifts are typically about 12 inches in thickness. Ramming takes place with a high-energy beveled tamper that both densifies the aggregate and forces the aggregate laterally into the sidewalls of the hole. This action increases the lateral stress in surrounding soil; thereby further stiffening the stabilized composite soil mass. The result of Geopier installation is a significant strengthening and stiffening of subsurface soils exhibit high lateral stresses and shear strengths and are able to support high bearing pressures with little associated settlement.



A. Make 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 4: Geopier construction sequence

Design for the project, conducted by GFC-Houston,Inc. and Geopier Foundation Company, Inc., is based on a two-layer settlement analysis as described by Lawton et al. (1994). Settlements within the "upper zone" (zone of soil that is reinforced with Geopier elements) are computed using a weighted modulus method that accounts for the stiffness of the Geopier elements, the stiffness of the matrix soil, and the area coverage of Geopier elements below supported footings. Calculations indicate that the Geopier element, because its stiffer than the surrounding matrix soil, will attract higher stresses. A design top-of-Geopier stress of 21,000 psf was estimated for the project. The stiffness of the Geopier elements is verified by modulus tests.

RESULTS OF MODULUS TESTS

Figures 5a and 5b present the results of two modulus tests performed for the project. The purpose of the tests is to verify the estimated design stiffness modulus of the Geopier elements at the design top-of-Geopier stress. As shown in Figures 5a and b, Geopier deflections of less than ¼-inch occurred at a Geopier stress of 21,000 psf for both tests. These values translate into a Geopier stiffness modulus value of about 730 psi/in.

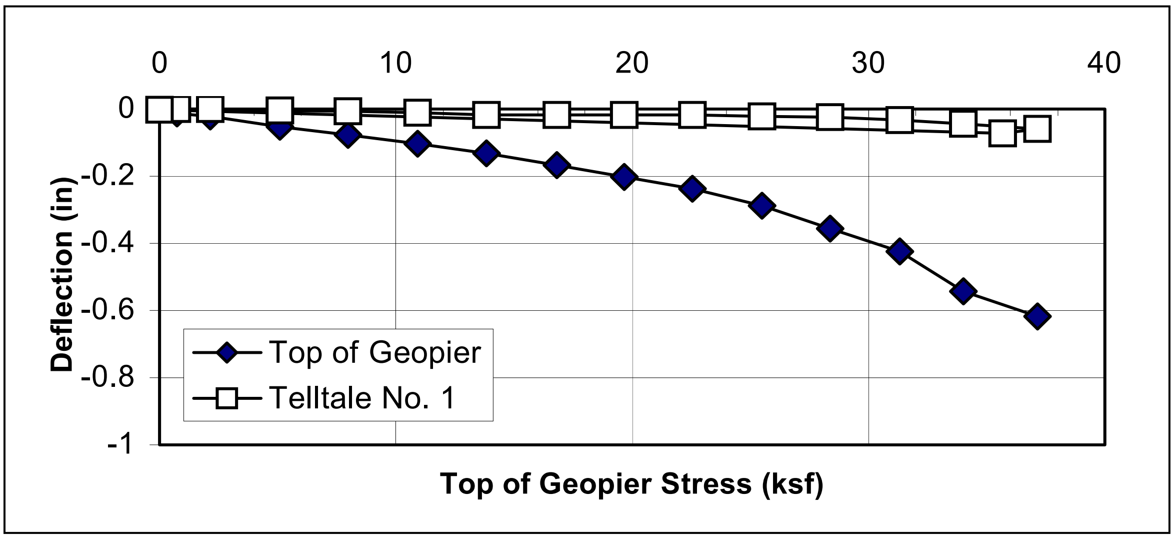


Figure 5a: Results of modulus test No. 1

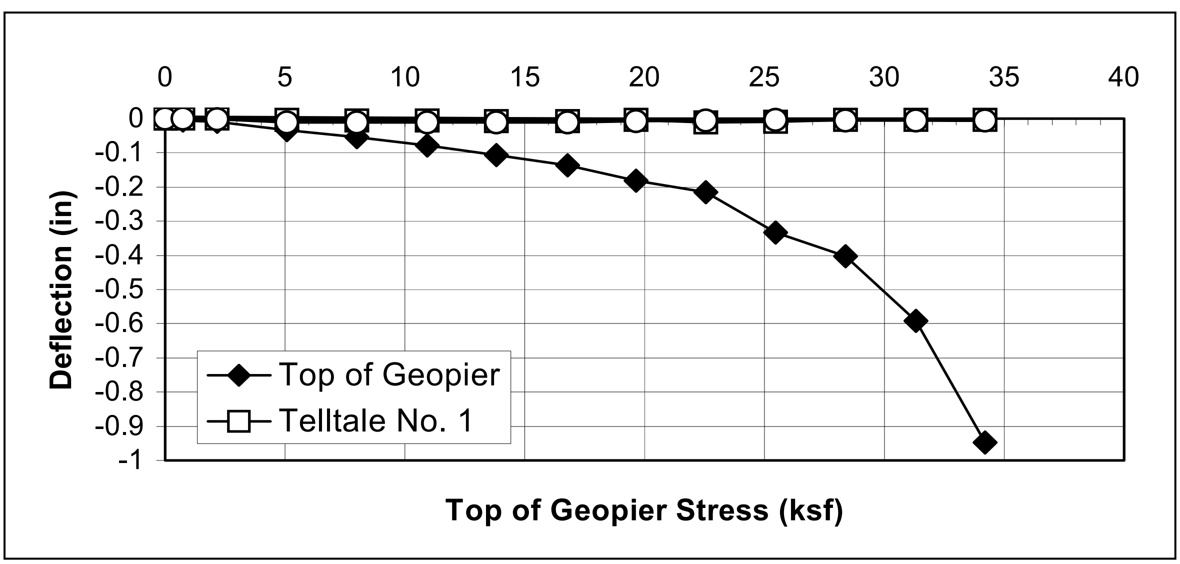


Figure 5b: Results of modulus test No. 2

Although the purpose of the Geopier modulus test is to verify design stiffness parameter values, the tests may also be used to add insight into the performance of the piers. This is done by observing the deflections of telltales installed into the bottoms of the piers. As shown on Figure 5, Test Pier A exhibited increasing top and bottom deformations with increasing top of pier stress greater than a stress of about 25,000. This behavior is interpreted to indicate the mobilization of tip stresses at applied stresses greater than 25,000 psf. Test Pier B, however, does not indicate similar behavior. At applied stresses greater than about 24,000 psf, the bottom of Test Pier B is shown to move only slightly while deformations at the top of the pier increase at a growing rate. This behavior is interpreted to indicate that the pier is bulging outward at applied stresses greater than about 24,000 psf. The test results were used to add a confining ring of Geopier elements around the tank perimeter to reduce the potential for radial expansion of the perimeter ring of piers.

FOUNDATION REINFORCEMENT CONSTRUCTION AND PERFORMANCE

A total of 315 Geopier elements were used to reinforce the foundation soils below each of the ten tank pads. A schematic of the installations is shown in Figure 3. The elements are 30-inches in diameter and are spaced approximately 5.5 feet on-center. The elements were constructed using recycled concrete aggregate that met Texas Department of Transportation specifications. As described above, a ring of elements was installed external to the tank perimeter to confine the row of elements installed below the tank shell. This feature was to reduce the potential for element bulging.

The granular pad overlying the aggregate pier elements was designed to transfer bottom-of-tank pressures to the tops of the piers. As shown in Figure 3, the thickness of the pad varied from 24-inches near the tank perimeter to 36 inches near the tank center. The thickness of the pad, constructed from cement-treated calcium sulfate, is greater than one-half the clear distance between reinforcing elements. The steel tank was placed on a two-inch thick layer of conventional Type-D modified asphalt that was installed over the granular pad to provide corrosion protection.

The construction of the 3,150 aggregate pier elements was completed in less than 6 weeks using two production crews. Each crew installed more than 50 piers per day. The quick Geopier installation schedule was a key ingredient to the success of the project.

Settlement surveys indicated that less than one inch of total settlement occurred after tank hydrotesting.

SUMMARY AND CONCLUSIONS

Houston Fuel Oil Terminal Company successfully supported ten 100-foot diameter tanks on soil reinforced with Geopier Rammed Aggregate Pier elements. This soil reinforcement system provided cost savings of $400,000 to $700,000 relative to competing systems and met the aggressive construction schedule demanded by the terminal. The performance of the tank foundations has been well within design criteria. The system demonstrated the provision of manageable settlements at a reasonable cost.

ACKNOWLEDGEMENTS

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REFERENCES

Fugro South, Inc. 1998. Geotechnical Investigation, Area 13 Tank Farm. A report prepared for Houston Fuel Oil Terminal Company, Houston, Texas. Report No. 0401-4155. November 13.

Lawton, E. C., and N. S. Fox (1994). "Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers." *Geotechnical Specialty Publication No. 40: Vertical and Horizontal Deformations of Foundations and Embankments*, ASCE, 2, 962-974.

Lawton, E. C., N. S. Fox, and R. L. Handy (1994). "Control of settlement and uplift of structures using short aggregate piers." *In-Situ Deep Soil Improvement,* Proc. ASCE National Convention, Atlanta, Georgia, 121-132.

Wissmann, K.J. and N.S. Fox (2000). "Design and Analysis of Short Aggregate Piers Used to Reinforce Soils for Foundation Support." *Proceedings, Geotechnical Colloquium.* Technical University Darmstadt. Darmstadt, Germany. March, 2000.

Wissmann, K.J., N.S. Fox, and J.P. Martin (2000). "Rammed Aggregate Piers Defeat 75-foot Long Driven Piles." *Performance Confirmation of Constructed Geotechnical Facilities*. ASCE Geotechnical Special Publication No. 94. April 9-12. Amherst Massachusetts.