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USE OF RAMMED AGGREGATE PIERS IN PLACE DEEP FOUNDATIONS FOR SETTLEMENT AND UPLIFT CONTROL OF BUILDINGS AND RETAINING WALLS

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ABSTRACT

Rammed Aggregate Piers™ are increasingly being used to replace deep foundations for settlement and uplift control of structures. Rammed Aggregate piers are constructed by excavating or augering a cavity, filling it with aggregate, and densely compacting the aggregate using a modified hydraulic hammer and a unique tamper foot. The Rammed Aggregate Piers are eight to forty times stiffer than in-situ soils, and typically provide three times the bearing capacity of in-situ soils by creating a composite layer of improved soil. This high modulus layer is used in a two layer settlement analysis method to estimate footing settlement.

To control uplift, steel plate and threaded rod assemblies are placed within aggregate piers and connected to footings. The tamper applies high lateral stress approaching the passive soil limit, which allows development of high shear capacity on the aggregate pier shaft. Load tests on uplift piers have exceeded 140 kips.

The paper presents two value engineering case studies. In one study Rammed Aggregate Piers saved approximately 25 percent of foundation costs in comparison with caissons socketed into rock for a four-story commercial office and parking garage development. In the second study Rammed Aggregate piers saved more than 25 percent of foundation costs in comparison with minipiles to support retaining walls on a highway project.

INTRODUCTION

Rammed Aggregate Piers are constructed by first removing a volume of compressible material, either by drilling a hole or excavating a trench. A thin lift of opening graded stone is then placed at the bottom of the cavity. The soil at the bottom of the cavity is prestressed and prestrained by ramming the stone with a specially-designed tamper. A very stiff element is then constructed within the cavity using well-graded aggregate placed in thin lifts and highly densified by ramming with the same tamper used for bottom prestressing. The adjacent matrix soils are improved, not primarily by densification, but rather by lateral prestressing. The energy source applies impact ramming action, rather than a vibratory energy, to a 45-degree beveled tamping apparatus that maximizes lateral prestressing of the matrix soil. The buildup of lateral stresses in the surrounding matrix soils develops an over-consolidated soil surrounding each Rammed Aggregate Pier, resulting in a stiffened aggregate pier/matrix soil mass. In addition, the prestressing and prestraining of soils adjacent to the sides of the aggregate pier results in an undulated aggregate pier/matrix soil interface that provides excellent engagement of the aggregate pier with the surrounding soil. The lateral stress buildup

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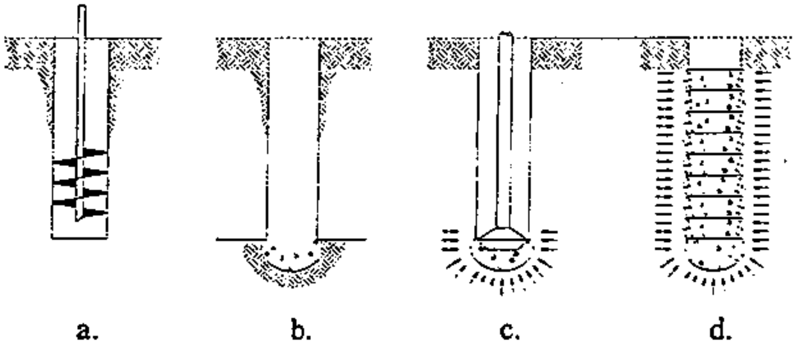


approaches the passive limit of the soil, thereby providing maximum shear strength along the aggregate pier shaft. Figure 1 shows the simple, four-step construction process that illustrates the basic concept of rammed aggregate pier construction.

Figure 1. Typical Construction Process – a. make cavity, b. place clean stone at bottom of cavity, c. densify aggregate and vertically prestress matrix soils beneath to create bottom bulb, d. make undulated-sided aggregate pier shaft with 12-inch typical lifts of graded aggregate, building up lateral stress in matrix soils during construction (Fox and Cowell, 1998).

KEY PROPERTIES OF RAMMED AGGREGATE PIERS

The stiffness modulus of a Rammed Aggregate Pier, k_s, is defined as the ratio of applied design stress divided by the corresponding displacement at the top of pier. The stiffness modulus is confirmed by performing a load test on an individual aggregate pier element at the project site. The load test measures the stress/strain behavior of the aggregate pier installed in the matrix soils.

Stress concentration occurs in the system due to the significance stiffness of the pier relative to that of the matrix soil. The stress ratio is the stiffness of the Rammed Aggregate Pier divided by the stiffness of the surrounding matrix soils. The concentration of the stress on the Geopier element is significant in analyzing its performance in terms of settlement, sliding and shear strength.

The stress on the Geopier element can be visualized by considering the analogy of a stiff spring within a matrix of less-stiff or soft springs. The stiff spring represents the Rammed Aggregate Pier and the less stiff spring matrix soils, respectively, as illustrated in Figure 2. Assuming that the footing and the stiff plate are perfectly rigid, if the footing or plate deflects under load, then the deflection must be the same at the aggregate pier/stiff spring as it is at the matrix soil/soft spring. For this example, a stiff spring constant of 10 and a soft spring constant of 1 result in stress ratio, R_s, of 10. Assuming that the footing/plate deflection equals 1, the load on the stiff spring equals the spring stiffness times the deflection, 10 x 1, or 10. Similarly, the load on each soft spring is 1 x 1, or 1, showing that the stiff spring carries ten times more load than each soft spring. Transferring this analogy to soil mechanics, the stress concentration has been measured, as predicted, in full scale, heavily instrumented footing load tests (Lawton, 1999).

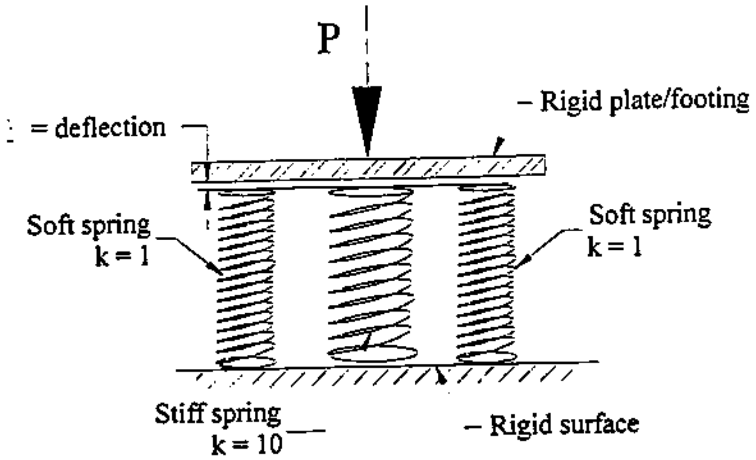


Figure 2. Stiff Spring Analogy (Fox and Cowell, 1998).

The high shear strength of a Rammed Aggregate Pier provides excellent resistance to sliding of footings under lateral loading conditions, such as for buildings with lateral seismic or wind loads, or for lateral retaining walls with earth pressure loads. The internal friction angle in excess of 50 degrees has been measured in full scale direct shear testing (Fox and Cowell, 1998). Combined with stress concentration, the shear strength provided by the Rammed Aggregate Piers substantially increases sliding resistance of footings subjected to lateral loads.

Uplift resistance is developed through shear along the interface between the Rammed Aggregate Pier and the surrounding matrix soil. Since the matrix soils have lower shear strength than Rammed Aggregate Piers, matrix soil shear strength controls uplift resistance. Where uplift resistance is required for a project, an uplift test is typically installed to confirm the design capacity. In early applications of Rammed Aggregate Piers for uplift resistance, when the prestressing effect was not considered in the design, the tested capacity was greater than anticipated by a factor of 4 to 5. The increase in capacity could only be accounted for by including passive earth pressure conditions within the calculations (Lawton, et. al., 1994) as illustrated in Figure 1.d. Rammed Aggregate Piers are more efficient for resisting uplift loads than are driven piles or drilled shafts because of this increase in lateral earth pressure and because of the high aggregate pier/soil friction angle. Further, relatively small deflections are required to mobilize shear strength at the passive soil limit, resulting in improved performance along with greater capacity.

GENERAL SETTLEMENT DESIGN APPROACH

To estimate settlement of footings supported by Rammed Aggregate Piers, the subsurface profile is divided into an upper zone and a lower zone. The upper zone extends from the bottom of footing to one pier diameter below the bottom of the drilled cavity, thus including the depth of prestressing and prestraining. Beneath the upper zone, the lower zone extends to a depth of two times the footing width for isolated spread footings, and four times the footing width for strip footings. Upper zone settlement is estimated by calculating the stress at the top of the aggregate pier and dividing by the pier modulus. For preliminary design purposes, modulus values are selected based on correlation to existing load test data in similar soils. Final design estimates of upper zone settlement are confirmed by full-scale modulus testing at the project site. Lower zone settlement is estimated using conventional soil mechanics approaches in conjunction with elastic or consolidation compressibility parameters. A complete discussion of the methods used for settlement estimate and design is provided by Lawton et al. (1994).

GENERAL SLIDING RESISTANCE DESIGN APPROACH

The first step in determining the sliding resistance of a footing supported by aggregate piers is to calculate the stress on the top of the aggregate piers. Often this has already been done to estimate footing settlement. The total vertical load supported by the pier is calculated by multiplying the contact stress by the sum of the cross-sectional areas of the piers. The total vertical load on the aggregate piers is then multiplied by the tangent of the internal friction angle of the aggregate piers to determine the component of sliding resistance within the aggregate piers. Because of the tendency for the aggregate to dilate during shearing, the angle of the internal friction is greater than 45 degrees and the tangent of this angle is greater than unity. The matrix soils will also provide some sliding resistance, which is calculated in the same way. However, the matrix soil stress is much lower than the aggregate pier stress, so the added resistance of the matrix soils provides a relatively small percentage of the total sliding resistance. Finally, the total sliding resistance is divided by the lateral load applied to the footing to determine the factor of safety.

GENERAL UPLIFT RESISTANCE DESIGN APPROACH

To determine uplift capacity, both the shear resistance of the aggregate pier shaft and the tensile capacity of the uplift anchor assembly, which includes steel plates and threaded rods. First, the shear resistance of the aggregate pier is calculated. Often it is possible to assign uniform soil parameters to the matrix soils in the upper zone, where the uplift capacity is developed. For a soil with given unit weight and drained shear strength, the shear resistance is calculated by assuming that the vertical stress at the middle of the aggregate pier shaft is the average vertical stress throughout the depth of the shaft. This vertical stress is multiplied by the Rankine coefficient of passive earth pressure to determine the average horizontal stress on the shaft of the aggregate pier. This stress is then multiplied by the tangent of the matrix soil's internal friction angle, and that product is multiplied by the surface area of the aggregate pier/matrix soil interface to arrive at the ultimate capacity of the uplift pier.

Once the shear capacity is determined and the working loads are established, allowable stress design techniques are used to size the structural steel elements that make up the uplift anchor assembly. It is important to note that allowable stress design often overestimates the size of the plate required. Therefore, the uplift anchor assemblies are sized based on acceptable load test results.

OFFICE AND PARKING GARAGE, DURHAM, NORTH CAROLINA

Rammed Aggregate Piers were used as foundation support for settlement control in the construction of a four story office building and adjoining parking garage. The cast-in-place concrete structures had typical column service loads ranging from 100 to 500 kips in the office building and 200 to 400 kips in the parking garage. The office building elevator core walls also served as shear walls with net uplift forces that had to be resisted by the foundation. Total settlement of the structure was required to be less than one inch with no more than one-half inch differential settlement. Construction was completed early in 1999.

SITE CONDITIONS

The site is located in Research Triangle Park in Durham, North Carolina, and the geology was of the Triassic Basin Geologic Formation of North Carolina. Upper Zone soils are residual clayey silts, silty clays, and silty sands. Partially weathered rock with $N_{SPT} > 50/6"$ was encountered at depths ranging from 4.5 to 10 feet below the ground surface. The sloping site required cuts and fills up to 15 feet to achieve proposed grades.

PROPOSED DESIGN

Project geotechnical engineers evaluated a variety of foundation alternatives including spread footings on virgin soil or controlled fill with 3,000 psf allowable bearing pressure, and moderate diameter drilled shafts bearing on partially weathered rock with 30 ksf allowable bearing pressure and 3,000 psf skin friction for resisting uplift loads. Shallow foundations were ruled out due to the potential for differential settlement and difficult excavation in the variable weathered rock surface. Structural drawings were prepared with drilled shafts providing the foundation support.

VALUE ENGINEERING PROPOSAL

A large, national design-build contractor was awarded the work, and was interested in evaluating foundation alternatives that could save time and money on the congested site. Potential for drilling overruns existed in the geologic conditions found at the site, and the hard rock would have required a large caisson drilling rig that might have difficulty accessing the site. Having heard about Rammed Aggregate Piers, the contractor investigated this system as an option for their project. GeoStructures, Inc., Leesburg, Virginia, was asked to prepare a value-engineering proposal for the design and installation of Geopier™ aggregate piers.

Initially, preparing the value engineering proposal involved discussions with the project geotechnical and structural engineers regarding the aggregate pier system and how it would be applied to their project. During the period after the geotechnical report was issued and before the project plans were drawn up, the geotechnical engineers had gained some experience with the aggregate pier system. They recognized the potential savings the system could provide, and suggested that they be allowed to review the final Rammed Aggregate Pier design.

One structural concern that arose during design was the net uplift loading on the shear walls. To resist the uplift loads, uplift assemblies were planned for the Rammed Aggregate Piers supporting the shear walls. Shear wall loading consisted of a 230-kip (±) couple that required a uplift anchors at each end of the wall, and the preliminary design included four uplift elements at each end of the shear wall footing. Since the wall was part of the elevator core, the bottom of the wall footing was much closer to the rock interface than the remainder of the footing locations at the site. Since conventional Rammed Aggregate Pier equipment can only drill in soil and not rock, the uplift capacity of aggregate pier elements would be severely limited by depth. As a result, grouted anchors were selected for resisting the uplift loads.

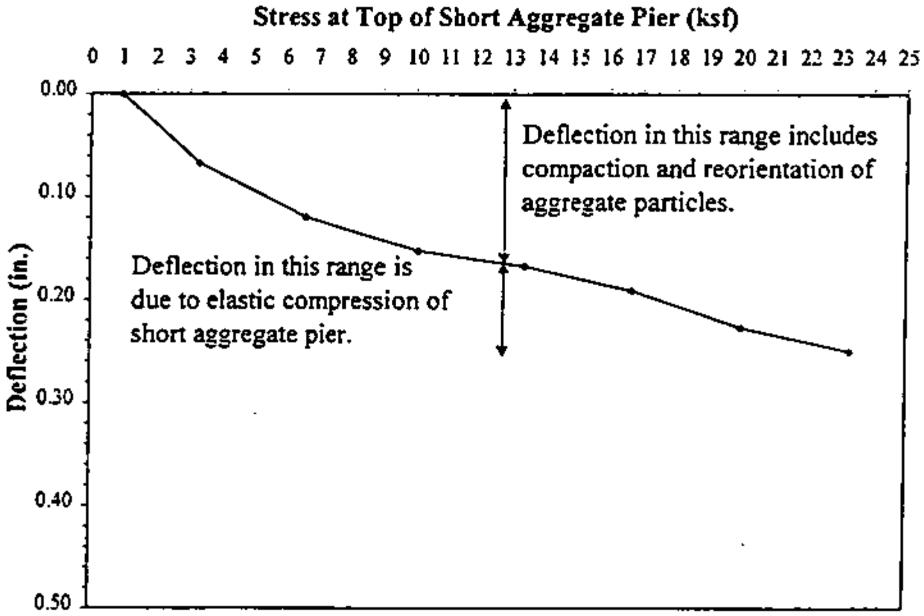
DESIGN ANALYSES

Prior to construction a detailed submittal was required, including analysis of potential settlement, bearing capacity failure due to high bearing pressures, and estimates of uplift anchor capacity. Settlement analyses were performed for two conditions. The first analysis considered the minimum required Rammed Aggregate Pier performance that would satisfy the requirements of one inch total and one-half inch differential settlement. The second analysis showed the anticipated performance based on correlation to other projects in similar subsurface conditions. The following design parameters were agreed upon by GeoStructures and the project geotechnical and structural engineers.

- Matrix soil modulus: 32 pci
- Maximum allowable bearing pressure: 10,000 psf
- Minimum Rammed Aggregate Pier modulus required for one inch settlement: 155 pci
- Anticipated Rammed Aggregate Pier modulus: 310 pci (results in 0.64 inch settlement)
- Maximum estimated Rammed Aggregate Pier design stress: 19,800 psf
- Rammed Aggregate Pier diameter: 36 inches
- Rammed Aggregate Piers to be founded in partially weathered rock with $N_{SPT} > 40$
- No lower zone settlement was included due to the proximity of weathered rock
- Grouted uplift anchor working bond strength in partially weathered rock: 30 psi

Rammed Aggregate Pier design modulus was confirmed by load testing a single, 36-inch diameter aggregate pier element at the project site. Since the test was installed in an area with deeper rock interface, aggregate piers were used as reactions for the load test. The load test was planned for a maximum test load of 100 tons, or about 150 percent of the maximum design stress acting on a 36-inch diameter aggregate pier. During the load test, which was performed in February, the jack equipment was affected by extreme change in ambient temperature, and experienced some leakage that made the maximum planned load unobtainable. However, at 116 percent of the design stress, or about 70 tons, the test pier exhibited far less deflection than anticipated. Stress vs. deflection was plotted, as shown in Figure 3, to determine if the test would be accepted. Typically a maximum safe design stress is taken as the point of inflection or steepening of the stress vs. deflection curve. Since no such inflection point was observed, the design was approved and crews began to install the aggregate piers at the site.

Figure 3. Rammed Aggregate Pier Modulus Load Test Stress vs. Deflection



RESULTING SAVINGS

Since the project required staged backfilling operations, construction was completed in two phases requiring two mobilizations. The tracked equipment used for aggregate pier installation had no difficulty moving around on the tight site, and construction was completed on time for a lump sum, except for the additional mobilization cost. Including that additional cost, the aggregate pier foundation resulted in about 25 percent savings over the drilled shaft alternative. Additional savings, although not quantified, resulted from the efficiency of the Rammed Aggregate Pier installation, and the time savings over the proposed caissons.

HIGHWAY RETAINING WALL, CLINTON, MARYLAND

A major highway widening project in the Washington D.C. metropolitan area required cast-in-place concrete retaining walls up to 14 feet tall for grade separation. The highway could not have lane closures during rush hour, so maintenance of traffic was a crucial part of the proposed construction schedule. Overhead power lines limited the foundation prospects to systems with low-overhead installation capability. Initial project documents included contractor incentives for providing foundation alternatives. Retaining wall construction was completed in late 1997.

SITE CONDITIONS

The site is located in Atlantic Coastal Plain, which locally includes the Potomac Formation consisting of interbedded, typically overconsolidated sands, silts and clays. The Potomac group soils are overlain by Pleistocene Terrace Deposits, which include layers of loose to dense rounded quartz gravel, or "bank run" gravel with varying amounts of silt and clay binder. Portions of the site are also located adjacent to a swampy area, so the near surface soils included recent, soft alluvial deposits including a weight-of-hammer clay layer ten feet thick. High groundwater and swampy conditions were major factors in determining the construction alternatives. Very tight site constraints were also serious considerations.

PROPOSED DESIGN

Original project documents required minipile foundations or an approved alternative. Eight-inch diameter minipiles were designed with compression capacity of 65 kips and uplift capacity of 15 kips to resist overturning loads. Sliding resistance was provided by battering the minipiles. The pile caps were designed to be five feet wide, and could not be enlarged on the narrow site.

VALUE ENGINEERING PROPOSAL

In order to satisfy the project design team, several iterations were required in the proposal process. Rammed Aggregate Piers were initially designed to provide settlement control and sliding resistance from each pier. Overturning resistance was provided by including uplift anchor assemblies in selected piers. Review comments generally favored the proposal, but made additional requirements with respect to the location of aggregate piers and their ability to serve multiple functions of settlement control, sliding and uplift resistance. It was agreed that only those aggregate piers that were located in the front two-thirds of the footing would provide settlement and sliding control. Due to the narrow footing width, that meant the uplift piers could not be used for settlement and sliding control, resulting in additional aggregate piers at closer spacing.

The additional design requirements caused a re-evaluation of construction feasibility, and the Rammed Aggregate Pier installer, GeoConstructors, Inc., decided to drill probe holes to provide a better assessment of the subsurface conditions. The probe holes encountered severe caving in the open graded bank-run gravel. Casing costs were included in the proposal to control the caving, and although the cost had increased after the value engineering proposal review, aggregate pier construction was estimated to be considerably less expensive than the minipile alternative.

DESIGN ANALYSES

A detailed submittal was prepared including estimation of settlement and analysis of sliding and uplift capacity. Providing an efficient design required sixteen design sections accounting for variable wall height and subsurface conditions. Additional consideration was given to the settlement influence from new backfill. On the north side of the site, swampy conditions controlled the design, and aggregate piers had to penetrate the soft clay. The south side had more favorable design conditions controlled by the bank-run gravel. Due to the layered subsurface profile, Upper and Lower Zone parameters for settlement analyses were correlated to minimum average N_{SPT} values. Uplift capacity was estimated by calculating the shear resistance contribution from each soil layer in the Upper Zone. Sliding resistance was calculated using the stress concentration and frictional resistance of the Rammed Aggregate Piers, and included the frictional resistance of the matrix soil. Footing bearing pressures ranged from 1,500 to 3,000 psf, which is considerably lower than typical Rammed Aggregate Pier foundations. The following design values were used. They were considered to be very conservative, since the project would be difficult to construct and would require a substantial financial risk on the part of the Rammed Aggregate Pier designers and installers.

- 36-inch diameter Rammed Aggregate Pier capacity: 65 kips
- 36-inch diameter Rammed Aggregate Pier capacity in soft clay: 45 kips
- 30-inch diameter Rammed Aggregate Pier capacity: 50 kips
- 30-inch diameter Rammed Aggregate Pier capacity in soft clay: 30 kips
- Rammed Aggregate Pier modulus: 180 pci
- Rammed Aggregate Pier modulus in soft clay: 80 pci
- Matrix soil modulus: 14 pci
- Lower Zone modulus, range of values (Bowles, 1988): 50 to 85 tsf
- Internal friction angle for uplift design: 28° silt, 20° clay
- Rammed Aggregate Pier internal friction angle for sliding: 37°, very conservative
- Maximum allowable settlement: one inch total, one-half inch differential
- Minimum factor of safety for sliding resistance: 1.5
- Minimum factor of safety for uplift resistance: 2.0

Actual load test results turned out to be far better than the values used for settlement control and uplift resistance analyses. Tested aggregate piers achieved modulus values of 240 pci in fair soil and 140 pci in very soft soil. Capacities were also increased to 110 kips and 90 kips, respectively. To reduce the risks associated with construction on a very soft subgrade in tight space constraints, the design submittal was revised to account for the improved performance and the number of Rammed Aggregate Piers was reduced. The total number of Rammed Aggregate Piers was revised and the final design was constructed.

RESULTING SAVINGS

Rammed Aggregate Pier installation was completed on time, in spite of the very challenging construction conditions. Caving soils were made worse during the rainy Fall season. The site was at a low point along the right of way, and any rain that infiltrated the soil would remain in the bank-run layer. Casing helped, but casing in the tight working conditions slowed production. Concrete crews were still able to work directly behind the Rammed Aggregate Pier crew, and often placed forms and concrete on the day following the aggregate pier installation. In the high pressure environment of highway construction under adverse site conditions, the Rammed Aggregate Pier system provided more than a $250,000 savings over the minipile alternative.

SUMMARY OF BENEFITS

- Rammed Aggregate Piers provide a cost-saving alternative for foundation support.
- Rammed Aggregate Piers can be used to replace deep foundation systems such as caissons and piles for settlement, uplift and lateral sliding applications.

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