TP08

Reprinted from Performance Confirmation of Constructed Geotechnical Facilities
Proceedings of the conference
American Society of Civil Engineers
Held April 9-12, 2000, Amherst, Massachusetts

RAMMED AGGREGATE PIERS DEFEAT 75-FOOT LONG DRIVEN PILES

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ABSTRACT: A six-story parking garage was designed to be supported by 23 m (75 foot) long steel pipe piles driven through loose silts and silty sands. Rammed Aggregate Piers with shaft lengths ranging between 2.1 m and 2.7 m (7 feet and 9 feet) were proposed and accepted as an alternative to the driven piles. In this system, highly densified aggregate piers are incorporated within the upper weak and compressible soils resulting in a composite bearing material that is substantially stiffer than the unimproved soil, and on which shallow foundations can be supported with tolerable settlements. Methods for analyzing and predicting settlements of footings supported on aggregate pier-reinforced soils are discussed. Design parameters were verified by the performance of aggregate pier modulus load tests. Total settlements of footings were estimated to be less than 4 cm (1-1/2 inches). Measured footing settlements were less than 1.3 cm (0.5 inch). The implementation of the aggregate pier system saved the project owner $187,000.

INTRODUCTION

The new six-story Justice Center parking garage in Washington County, Oregon was supposed to be supported by 23 m (75 foot) long steel pipe piles driven through loose silts and silty sands. Instead, the parking deck was designed using high bearing pressure spread footings supported by soil reinforced with 2.1 m to 2.7 m (7 foot to 9 foot) long *Rammed Aggregate Piers™*. The project owner saved $185,000 in foundation costs, a value that is greater than 50% of the bid price for driven piling. The performance of the foundation system may seem astonishing – foundation settlements have been less than 1.3 cm (0.5 inch). This paper describes how such a dramatic change in foundation concepts is possible, the engineering mechanics that govern the behavior of Rammed Aggregate Piers, the results of aggregate pier load tests performed for the project, and the settlement performance of the completed structure.

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BACKGROUND

The six-story parking garage, built by the Hoffman Construction Company, is a cast-in-place reinforced concrete structure with a ductile frame design (Figure 1). Column loads were determined by KPFF structural engineers to range between 180 kN and 8000 kN (40 kips and 1,800 kips).

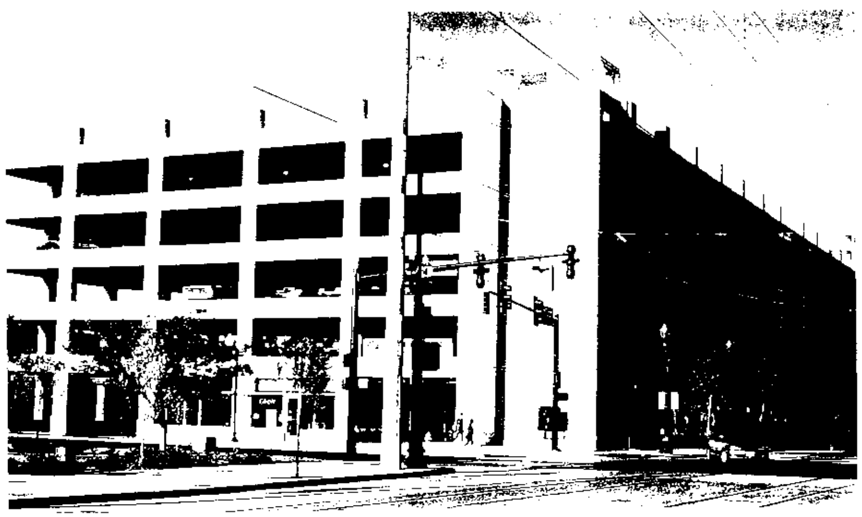


FIGURE 1: PHOTOGRAPH OF COMPLETED PARKING GARAGE

Geotechnical Subsurface Conditions

Figure 2 presents profiles of the soil boring and Cone Penetration Test (CPT) sounding that were performed at the parking garage site. The explorations indicate the following generalized stratigraphy:

- **Loose silty fine sand and sandy silt** extends from below the surficial pavement to a depth of about 6.1 m (20 feet). Standard Penetration Test (SPT) N-values ranged between 6 and 8 (average of 7). CPT tip resistances generally ranged between 1.4 MN/m^2 and 5.7 MN/m^2 (15 tons per square foot (tsf) and 60 tsf) with an approximate average of 2.9 MN/m^2 (30 tsf). Laboratory test results indicate an average dry density of 1420 kg/m^3 (89 pcf) and an average soil moisture content of 33 % for this layer.
- **Medium-dense silty fine sand** extends from a depth of about 6.1 m (20 feet) to depths greater than 15.2 m (50 feet) below grade. SPT N-values ranged between 11 and 31 (average of 17). CPT tip resistances generally ranged between 3.8 MN/m^2 and 15.2 MN/m^2 (40 tsf and 150 tsf) with an approximate average of 9.5 MN/m^2 (100 tsf).

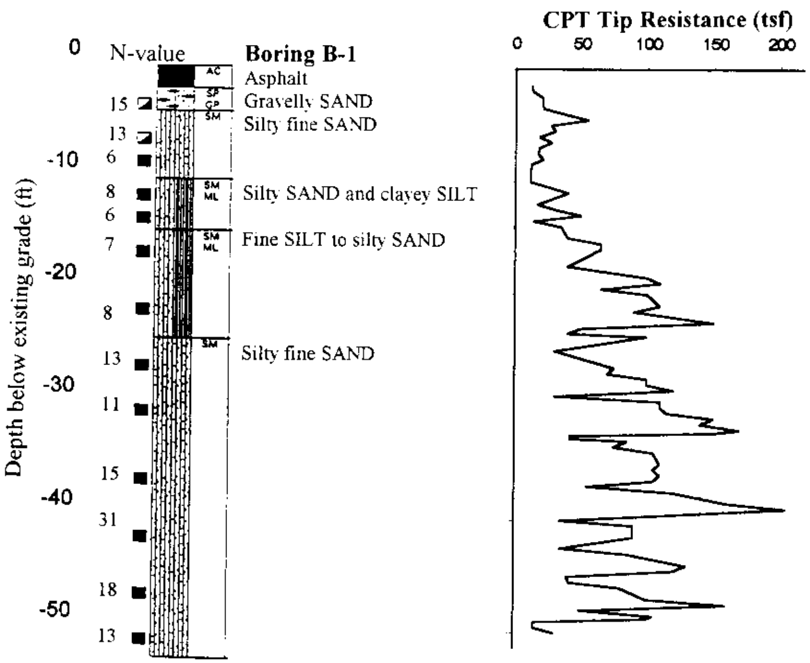


FIGURE 2: SUBSURFACE CONDITIONS

Foundation Challenges

The design of parking garage foundations posed a significant challenge because of the heavy column loads combined with the weak and compressible soil conditions. Conventional shallow spread footings were deemed not to be feasible because of the likelihood of excessive settlements that would exceed the settlement criterion of 3.8 cm (1.5 inches). Consequently 23 m (75 foot) long 30.5 cm (12 inch) diameter concrete-filled driven steel pipe were specified. The low-bid cost of the pipe piles was $360,000.

An Innovative Proposal

As a value-engineering alternative to the deep foundations, Rammed Aggregate Piers were proposed for construction by *Geopier*™ Foundation Company – Northwest. The patented system is designed to improve the subsurface soil conditions and allow the use of high-bearing pressure shallow spread footings for foundation support. The proposal included providing design calculations, performing two modulus load tests to confirm assumed design parameters, installing 521 production piers for foundation support, and recommending foundation settlement monitoring. The total cost of the design-build Rammed Aggregate Pier system was $175,000. The project owner accepted the proposal on the basis of technical merit and the large foundation cost savings exceeding 50% of the cost of the driven piles.

CONSTRUCTION

Prior to the construction of the Justice Center parking garage, Rammed Aggregate Piers were used to support structures at approximately 45 project sites in 11 different states including 4 project sites in Oregon. Generalized construction methods are described by Lawton and Fox (1994) and Lawton et al. (1994).

The aggregate piers installed at the Justice Center parking garage were constructed by drilling 84 cm (33 inch) diameter holes to depths ranging between 2.1 m and 2.7 m (7 feet and 9 feet) below the footing bottoms, placing controlled lifts of aggregate stone within the cavities, and compacting the aggregate using a specially designed high-energy impact tamper (Figure 3). The first lift consists of clean stone and is forced into the soil thus forming a bottom bulb below the excavated shaft. The bottom bulb effectively extends the design length of the aggregate pier element by one pier diameter. The piers were completed by placing additional one-foot thick lifts of aggregate over the bottom bulb and densifying the aggregate with the beveled tamper.

The piers were designed and installed to cover approximately 35% of the gross area of the overlying footing elements. High bearing pressure spread footings, with an allowable composite bearing pressure of 270 kN/m^2 (5,600 psf), were

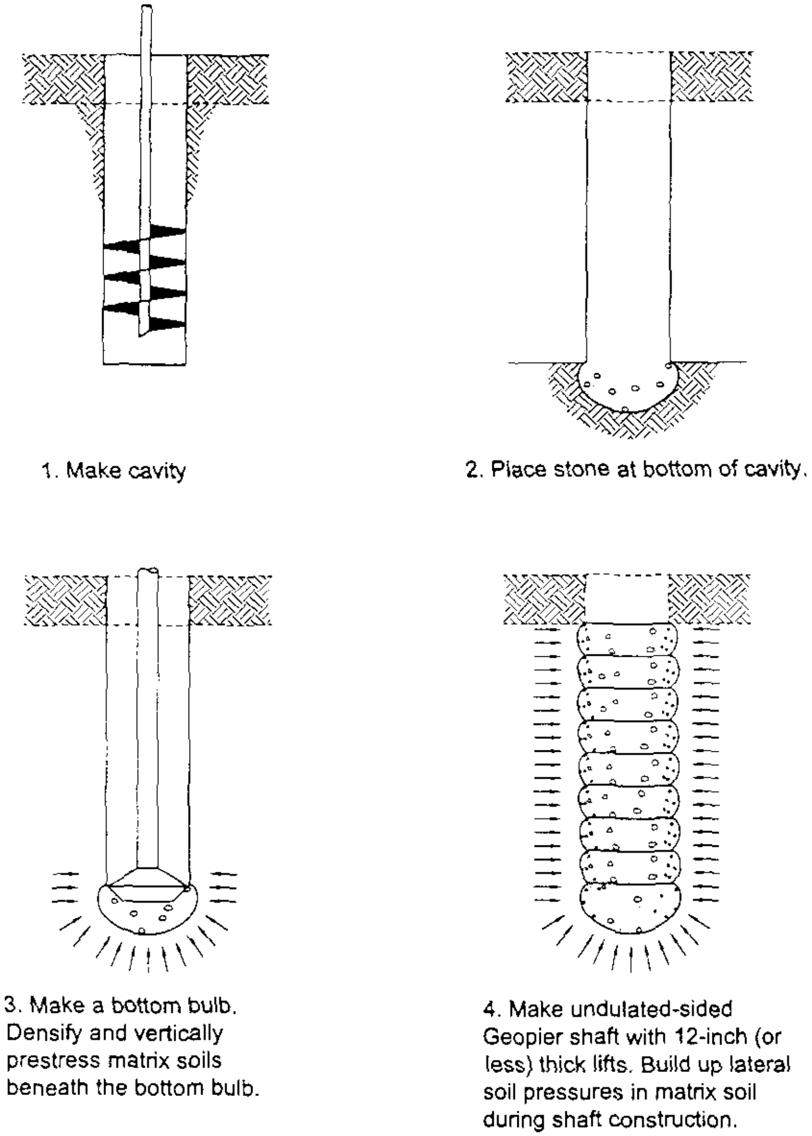


FIGURE 3: RAMMED AGGREGATE PIER CONSTRUCTION

constructed directly over the aggregate piers installed at the parking garage site. The smallest square footings were 2.3 m (7.5 feet) wide and were supported by 3 aggregate piers. The largest square footings were 6.7 m (22 feet) wide and were supported by 25 aggregate piers.

As shown on Figure 2, the 2.1 m to 2.7 m (7 foot to 9 foot) long aggregate piers do not extend completely through the Layer 1 silts and are not considered to be end-bearing elements. Rather, the piers are designed to improve the overall stiffness of the subsurface soils at depths in which footing-induced stresses are the highest in order to limit long-term foundation settlements to the design criterion.

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.

MECHANICS

The aggregate piers greatly increase the bearing capacity of the reinforced soil matrix and significantly reduce foundation settlements. Settlements calculations are performed to estimate the compression of the zone of matrix soil reinforced by the aggregate piers (upper zone) and to estimate the compression of the zone of soil that is subject to footing stresses and is located below the tips of the piers (lower zone).

Upper zone calculation procedures are based on a spring analogy (Lawton and Fox 1994 and Lawton et al. 1994) as described in the following:

1. The footing is assumed to be perfectly rigid relative to the foundation materials. Thus, the stresses applied to the composite foundation materials depend on their relative stiffnesses (R_s) and area coverage. The total downward force (Q) on the footing, which may be expressed as the product of composite stress (q) and footing area (A), is resisted by a total upward resisting force in the rammed aggregate piers (Q_g) and soil (Q_s) materials:

$$Q = q\,A = Q_g + Qs = q_g\,A_g + q_s\,A_s\ , \qquad (1)$$

where q_g is the stress at the top of the aggregate pier elements, A_g is the area of the pier elements below the footing, q_s is the vertical stress on the matrix soil below the footing, and A_s is the area of the matrix soil in contact with the bottom of the footing.

2. Because the footing is essentially rigid compared to the bearing materials, the settlement of the pier will equal the settlement of the matrix soil. The settlement of the foundation (s) can be written in terms of aggregate pier

stress and aggregate stiffness modulus (k_g) or in terms of the matrix soil stress and matrix soil stiffness modulus (k_s):

$$s = q_g / k_g = q_s / k_s \qquad (2)$$

3. Equation 2 can be rewritten to express the matrix soil stress in terms of the aggregate pier stress and the ratio of the pier and matrix soil modulus values (R_s):

$$q_s = q_g (k_s / k_g) = q_g / (k_g / k_s) = q_g / R_s \qquad (3)$$

4. Combining Equations 1 and 3 and defining area ratio (R_a) as the ratio of A_g to A:

$$q = \{q_g A_g / A + q_g A_s /(A R_s)\} = [q_g R_a + q_g (1 - R_a) / R_s\} =$$
$$= \{q_g [R_a + 1/R_s - R_a/R_s\} = \{q_g [R_a R_s + 1 - R_a] / R_s\} \qquad (4)$$

5. Rewriting q_g in terms of q:

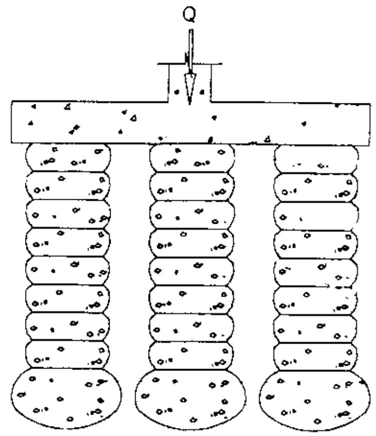
$$q_g = \{q R_s / [R_a R_s + 1 - R_a]\} \qquad (5)$$

6. Upper-zone settlements are computed using Equations 2 and 5 which depend on the applied composite footing stress, the relative stiffness of the aggregate pier and soil materials, the area ratio of the aggregate pier elements, and the aggregate pier stiffness modulus.

Estimates of settlements in the lower zone material below the bottom of the aggregate pier bulb are computed using conventional geotechnical settlement analysis procedures well described in the literature (Terzaghi and Peck 1967) combined with soil elastic modulus values interpreted from the results of the penetration tests. The analysis includes the assumption that the lower zone footing-induced stress may be estimated using solutions for a footing supported by an elastic half-space. This assumption is believed to be conservative because the presence of the piers results in a more efficient stress transfer with depth below the footing bottoms than the stress transfer that occurs for conventional spread footings. Example design calculations are shown on Figure 4.

DESIGN PARAMETER VERIFICATION: MODULUS LOAD TESTS

To verify the assumed modulus values used for the aggregate piers, two full-scale aggregate pier modulus tests were conducted prior to construction. The tests were performed by placing circular steel plates over the full cross-sectional area of an installed aggregate pier element and then applying pressure in gradual increments. The maximum applied stress corresponded to 150% of the design stress computed at the top of the aggregate pier elements.



Q = 375 kips

Footing width, B = 9.5 ft.

$q = Q/B^2 = 4160$ psf.

No. piers, N = 5

Pier diameter, d = 33 inches.

$R_a = A_g/A = 0.33$.

Design pier stiffness modulus, kg = 240 pci.

Assumed soil stiffness modulus, ks = 20.8 pci.

Stiffness ratio, $R_s = k_g / k_s = 11.5$.

<u>Settlement Calculations</u>

Aggregate pier stress, $q_g = q R_s / (R_s R_a - R_a + 1) = 11{,}495$ psf.

Upper-zone settlement = q_g / k_g = 11,495 psf / 240 pci = <u>0.33 inch</u>.

Thickness of upper zone = 7 feet + 33 inches = 9.8 feet.

Thickness of compressible lower zone, H_{lz} = 2 B – 9.8 feet = 9.2 feet.

Ratio of depth to center of lower zone to footing width, z/B = 14.4 ft / 9.5 ft = 1.5.

Westergard influence factor for z/B, $I_\sigma = 0.12$.

Estimated lower zone modulus of elasticity, E = 150 ksf

Lower-zone settlement = $(q I_\sigma H_{lz} / E)$ = <u>0.37 inch.</u>

Total settlement = 0.33 inch + 0.37 inch = <u>0.7 inch.</u>

FIGURE 4: DESIGN CALCULATIONS

Test results indicate that top of pier deflections ranged between 0.5 cm (0.20 inches) and 0.81 cm (0.32 inches) for 2.7 m (9 foot) long and 1.8 m (6 foot) long piers, respectively, when subjected to 100% of the pier design stress (Figure 5). These values were used to compute aggregate pier modulus values ranging between 65.4 MN/m^3 (241 pounds per cubic inch) and 104 MN/m^3 (385 pci) in accordance with Equation 2. The measured values confirmed and exceeded the design-level modulus value of 65.1 MN/m^3 (240 pci).

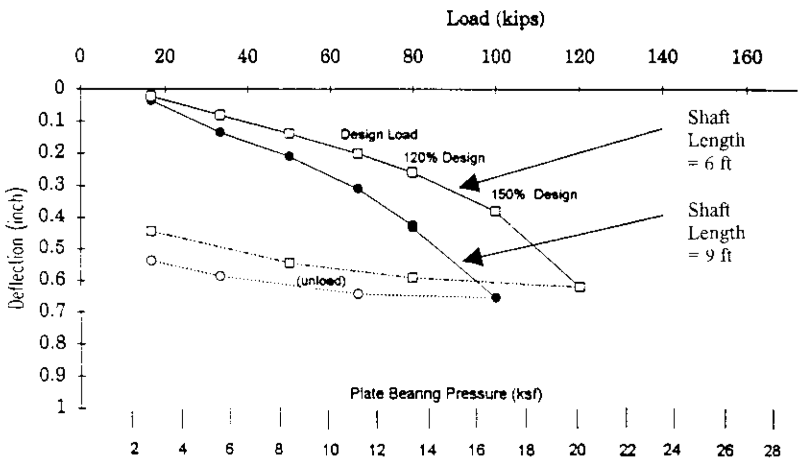


FIGURE 5: MODULUS LOAD TEST RESULTS

FOUNDATION SETTLEMENTS

The results of settlement measurements are presented on Figures 6 and 7. Measurements were taken on the top of the concrete footings overlying the aggregate piers. The measurements indicate that less than about 0.25 cm (0.1 inches) of settlement occurred per each completed floor of construction. Measurements are available for the first five floors of the parking garage. Measurements are not available for the last floor of construction because the project owner decided to halt construction after the fifth level and to add the sixth level at a later date. Total settlements are estimated to be on the order of 1.27 cm (0.5 inches) for the instrumented columns when loaded by all 6 floors of the parking garage with major column loads ranging from 2,700 kN to 8,000 kN (600 kips to 1,800 kips).

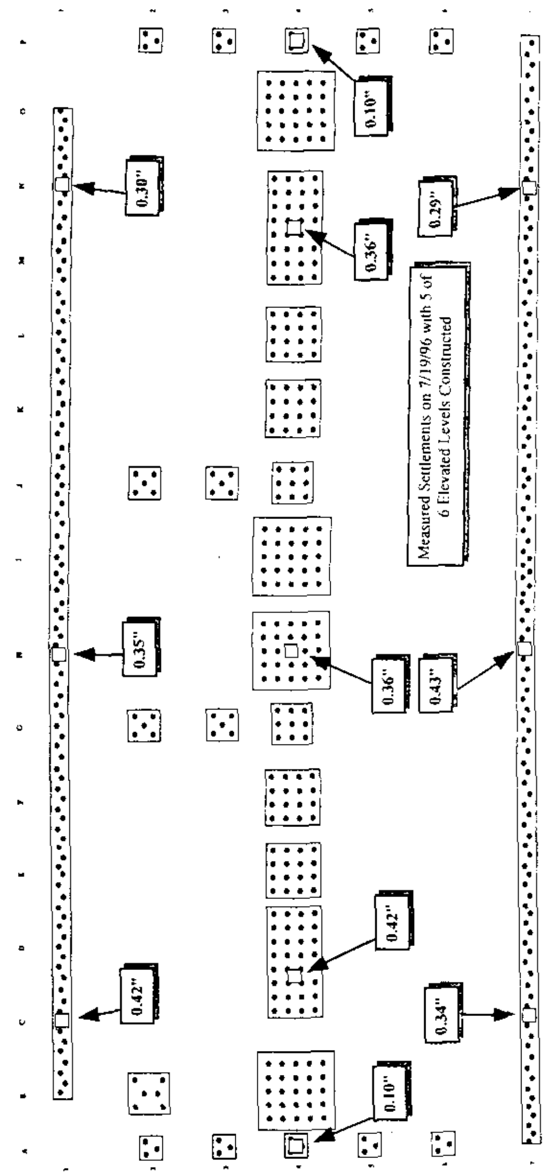
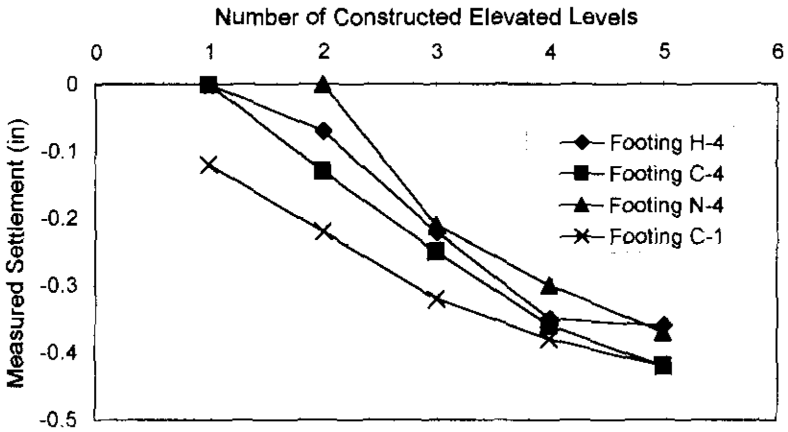


FIGURE 6: FOUNDATION FOOTPRINT

The spatial distribution of settlements after the completion of five floors of construction is shown on Figure 6. It is interesting to note that small, lightly-loaded footings settled only about 0.25 cm (0.1 inches) or about one-fourth as much as the adjacent heavily-loaded large footings despite the fact that footing-bottom stresses are comparable. While this observation appears to confirm the notion that footing settlement magnitudes are proportional to footing width, it calls into question the commonly held belief that a large, heavily-loaded footing will have a great influence on the settlements of adjacent footings. One explanation for this observation is that the stress regime below footings supported by aggregate piers is so markedly changed that conventional concepts of foundation load spreading are not applicable.



Note: Column loads at instrumented footings ranged between 600 kips and 1200 kips after construction of 5 elevated levels

FIGURE 7: SETTLEMENT MEASUREMENTS

SUMMARY AND CONCLUSIONS

The Washington County Justice Center Parking Garage is supported by an innovative intermediate foundation system consisting of high capacity spread footings supported by Rammed Aggregate Piers. This foundation system was selected because of sound engineering mechanics used for design and because of the significant cost savings available to the owner. The following itemized statements summarize foundation construction:

1. The 2.1 m to 2.7 m (7 foot to 9 foot) long aggregate piers replaced steel piles designed to be driven to 23 m (75 feet) below grade.
2. The aggregate piers do not extend to the underlying medium-dense silty sand layer but, rather, are terminated within the upper silt stratum.
3. Spread and strip footings placed above the rammed aggregate piers were designed for a composite bearing pressure of 270 kN/m^2 (5,600 psf).
4. Assumed design parameters were verified by field modulus tests.
5. The settlements of footings supported by the aggregate pier elements have been measured to be less than 2.5 cm (1 inch).
6. The aggregate piers facilitated a 50% savings in foundation costs to the project owner.

To date approximately 70 major structures are supported by Rammed Aggregate Piers in the Pacific Northwest; aggregate piers nationwide support more than 250 structures (Fox 1999).

APPENDIX-I. REFERENCES

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APPENDIX-II. SYMBOLS USED

A = Gross footing area.
A_g = Footing area supported by aggregate piers.
A_s = Footing area supported by matrix soil.

k_g = Stiffness modulus of aggregate pier.
k_s = Stiffness modulus of matrix soil.
Q = Total downward force on footing.
Q_g = Resisting force of aggregate pier.
Q_s = Resisting force carried by matrix soil surrounding aggregate pier.
q = Composite bearing pressure at base of footing.
q_g = Stress applied to top of aggregate pier.
q_s = Stress applied to matrix soil surrounding aggregate pier.
R_a = Ratio of cross-sectional area of aggregate piers to gross footing area.
R_s = Ratio of relative stiffness of aggregate pier and matrix soil.
s = Footing settlement.