Design and Analysis of Short Aggregate Piers Used To Reinforce Soil for Foundation Support

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1 Introduction

Short, *Rammed Aggregate Piers*^{TM} are used in the United States to reinforce bearing soils for support of high capacity shallow spread footings. The system has been used to reinforce soils including from soft organic clays and peat, loose silt and sand, uncompacted fill soils, debris fill soils, stiff to very stiff clays, and medium dense to dense sands. After installation, aggregate piers are used to support structures ranging from one-story warehouses to a 16-story office building (Figure 1). Typical applications include soil improvement for the support of foundations for office buildings, parking garages, hospitals, schools, storage tanks, warehouses, manufacturing buildings, and other commercial and industrial structures; soil improvement for the support of floor slabs and pavements; soil reinforcement to add shear strength for embankments and slopes; and soil reinforcement for the control of soil liquefaction.

The design of aggregate pier systems is based on classical principals of soil mechanics and geotechnical analysis techniques. Allowable footing bearing pressures are governed by settlement considerations. Settlements within the upper zone of soil reinforced by the piers depend on only three factors: (a) the stiffness of the piers, (b) the stiffness of the matrix soils, and (c) the area coverage of the piers below the foundation elements. Settlements within the lower zone of soil underlying the piers are computed using classical soil mechanics techniques,

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which include the estimating the compressibility of the lower soils and the concept of load spreading below the footing in accordance with conventional elastic theory.

Fig. 1 16-story office tower supported by aggregate piers

This paper describes analysis techniques for the design of short aggregate pier systems used for foundation support. Design procedures are verified by instrumentation readings and settlement surveys of completed structures. The importance of the development of lateral earth pressures during aggregate pier construction is discussed. This paper is of particular significance because it presents theoretical methods employed for the design of aggregate pier systems and instrumentation readings supporting the design approach. A brief description of construction procedures is also included.

2 Background

Since 1989, aggregate piers have been used to support more than 250 major structures in the United States. The piers are constructed by auguring holes in the matrix soils below planned foundation bottoms, placing aggregate in thin lifts within the holes, and densifying the aggregate by ramming action. The use of a beveled tamper increases the lateral stress in the matrix soils surrounding the piers. The incorporation of the stiff piers in the less stiff soil matrix serves to strengthen and stiffen the aggregate behavior of the soils directly below the overlying spread footings. Aggregate piers are specifically designed to control foundation settlements to values of approximately 25 mm and less when the piers are subject to compressive loads induced by the overlying footing. The strength and stiffness of the piers is a product of the high lateral earth pressures that are induced in the matrix soils during pier construction, the resulting great resistance to bulging within the matrix soils, and the strength and stiffness of the well-compacted, well-graded highway base course stone.

Aggregate piers that are required to resist uplift loads are equipped with a steel uplift harness installed at the bottoms of the piers. Allowable uplift loads are governed by the shear strength along the interface between the piers and the matrix soils.

3 Aggregate pier construction

As shown on Figure 2, aggregate piers are installed by drilling 600 mm to 900 mm diameter holes to depths that typically vary from 3 m to 7 m from the ground surface and 2 m to 6 m below the footing or mat bottoms (Lawton and Fox 1994, Lawton et al. 1994). Casing is employed in caving soils. Controlled layers of well-graded aggregate stone are placed within the drilled cavity and densified by the ramming action of a patented, specially designed high impact energy tamping system. The first lift consists of clean stone without fine particles and is rammed 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 and serves to prestress the soils below the bottom of the pier. The piers are completed by placing additional 30-cm thick lifts of highway base course aggregate over the bottom bulb and densifying the aggregate with the beveled tamper. During densification, the beveled sides of the tamper force the stone laterally into the sidewalls of the excavated cavity, thereby building up lateral stresses within the adjacent matrix soils and densifying the soils near the aggregate pier perimeter. The completed product consists of undulated shaped, very dense and stiff aggregate elements surrounding by matrix soils containing high lateral stresses. The process and the tamping system is patented.

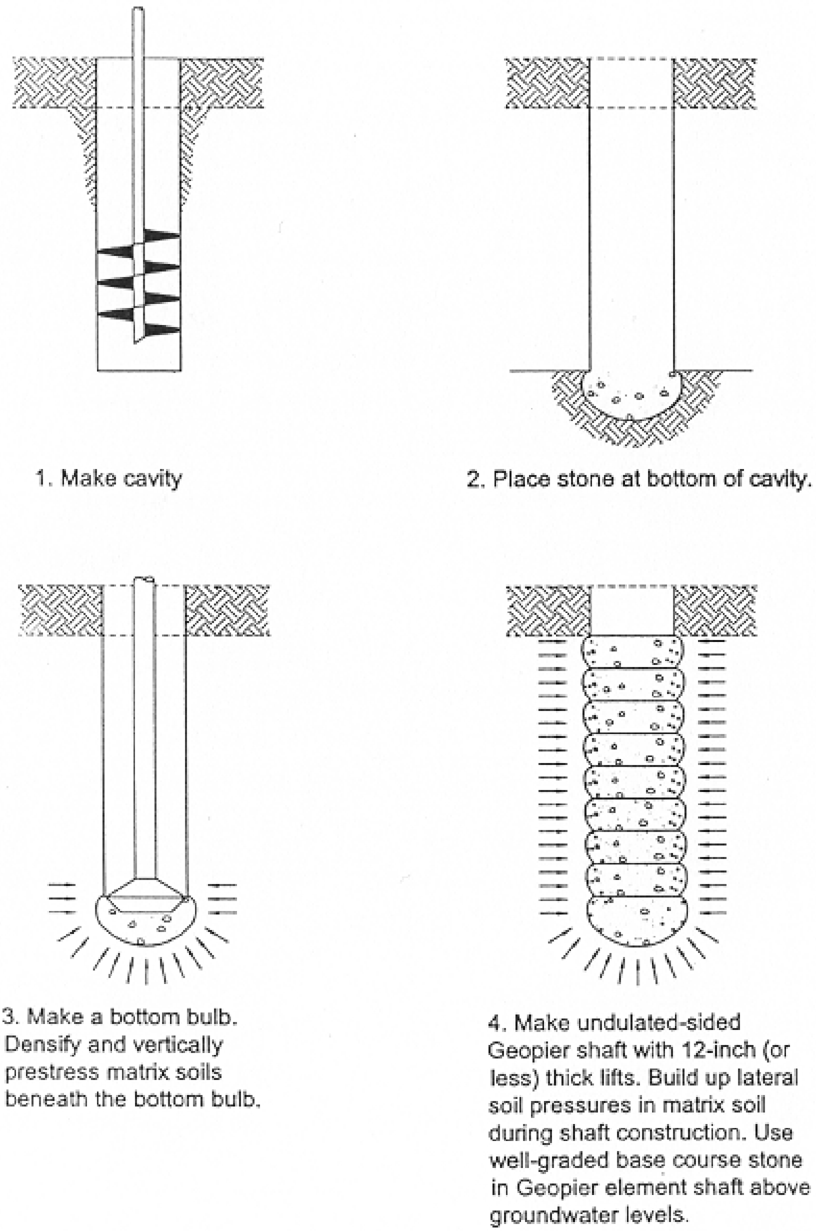
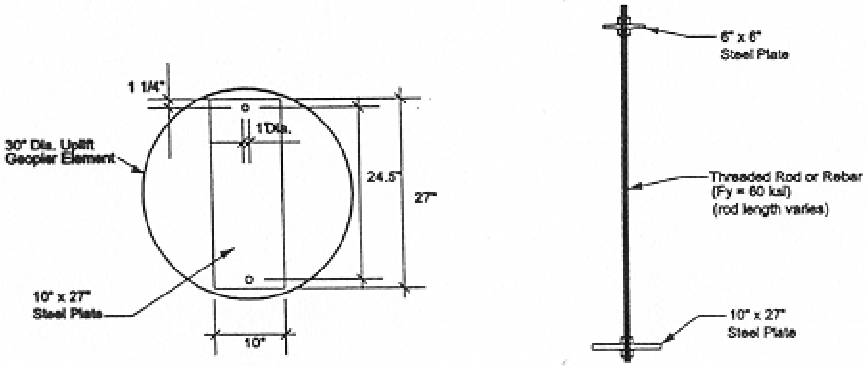


Fig. 2 Aggregate pier construction

Aggregate piers are typically designed and installed to cover approximately 30% to 40% of the gross area of the overlying foundation footprint. High bearing pressure spread footings, with an allowable composite bearing pressures ranging between 200 kN/m^2 and 450 kN/m^2, are constructed directly over the aggregate pier-reinforced soils. The allowable bearing pressure depends mostly on the consistency of the unreinforced matrix soil and the percent coverage of the installed aggregate piers. Because aggregate piers are designed to stiffen the soils immediately below the footings and not support foundation loads as independent, rigid, structural members, the piers are not considered to be end-bearing elements and do not need to extend to more competent soil layers.

When uplift control is required, a steel plate is installed at the bottom of the pier shaft and (Figure 3). Uplift forces are transferred from the overlying footing to the steel plate at the bottom of the pier via steel rods extending along the walls of the pier cavity. Uplift loads then are efficiently handled by shearing resistance between the installed piers and the matrix soils.



Plan View of Plate at Bottom of Geopier Element

Uplift Anchor Assembly Cross Section

Fig. 3 Uplift anchor details

4 Design methods for compressive loads

Aggregate piers greatly increase the stiffness of the reinforced soil matrix, significantly reducing foundation settlements. Settlement calculations are performed to estimate both the compression of the zone of matrix soil reinforced by the aggregate piers (upper zone) and the compression of the zone of soil that is s located below the tips of the piers and subject to appreciable footing stresses (lower zone).

4.1 Upper zone settlement calculations

As compressive loads are applied to aggregate pier-supported footings, the stiff piers attract a greater proportion of footing-bottom stress than the relatively soft matrix soils. The distribution of stress depends on the ratio of the stiffness of the aggregate pier elements to the stiffness of the matrix soil and on the ratio of the cross-sectional area of the aggregate pier elements to the gross footing area. 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. From static equilibrium, 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.

1. 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):

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

2. 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) where $R_s = k_g/k_s$:

$$q_s = q_g\,(k_s / k_g) = q_g / (k_g / k_s) = q_g / R_s\ . \tag{3}$$

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

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

$$\{q_g\,[R_a + 1/R_s - R_a/R_s\} = \{q_g\,[R_a R_s + 1 - R_a] / R_s\}\ . \tag{4}$$

4. Rewriting q_g in terms of q:

$$q_g = \{q\,R_s / [R_a R_s + 1 - R_a]\}\ . \tag{5}$$

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. Aggregate pier stiffness modulus values are measured in the field with full-scale load tests.

A simple example that describes the effectiveness of aggregate pier reinforcement is as follows. Consider a shallow footing that is loaded to a bearing pressure of 250 kN/m^2 and is supported by a sufficient number of aggregate piers such that an area ratio (R_a) of 0.35 is achieved. Consider an aggregate pier modulus (kg) value of 50 MN/m^3 and a soil matrix modulus value of 4 MN/m^3, which yield a stiffness ratio (R_s) value of 12.5. Using these values in conjunction with Equation 5, the stress on the tops of the aggregate piers is computed to be 622 kN/m^2. From Equation 2, the upper zone settlement is computed to be 1.2 cm. If aggregate piers were *not* used to reinforce the matrix soils, the computed settlement would be computed as the ratio of the footing stress to the matrix soil modulus, which is equal to 6.3 cm, a value much greater than the typical settlement criterion of 2 cm. The construction of the piers is computed to reduce settlements by 5.1 cm or to just 20 % of the settlement of unreinforced matrix soil.

4.2 Modulus load tests

To verify the assumed modulus values used for the aggregate piers, full-scale aggregate pier modulus tests are conducted prior to construction. The tests are 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 corresponds to at least 150% of the design stress computed at the top of the aggregate pier elements. Figure 4 presents the results of typical modulus load tests for the given soil profile and pier geometries.

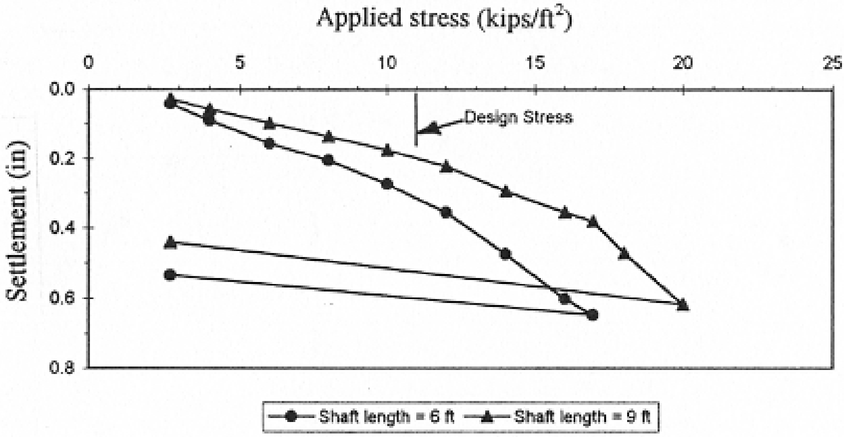


Fig. 4 Typical modulus load test results

The results of tests performed at over 100 project sites have been compiled and have been used to formulate design recommendations (Geopier Foundation Company, Inc. 1998). Test results indicate that allowable footing bearing pressures and aggregate pier element capacities may be correlated to matrix soil classification and penetration resistance.

4.3 Upper zone stress distribution verification

Full-scale field load tests performed on instrumented aggregate pier supported footings confirm the concept of stress concentration to the tops of the relatively stiff aggregate piers during compressive loading (Lawton 1999). The instrumented footings supported a reaction frame tower used by researchers at the University of Utah to apply dynamic lateral loads to a full-scale bridge bent (Figure 5) in an effort to simulate the bridge's response to earthquake loads. During cyclic loading, compressive and tensile loads of up to 112 kN were applied to the interior and exterior 2.5 m by 7.5 m (plan dimension) footings. Each footing was supported by ten 914 mm diameter aggregate piers installed to a depth of 4.6 m into the soft, low plasticity Lake Bonneville silt and clay deposits. The matrix soils exhibited Cone Penetration Test tip resistance values ranging from 0.5 MN/m^2 to 3.8 MN/m^2 (Lawton 1999).

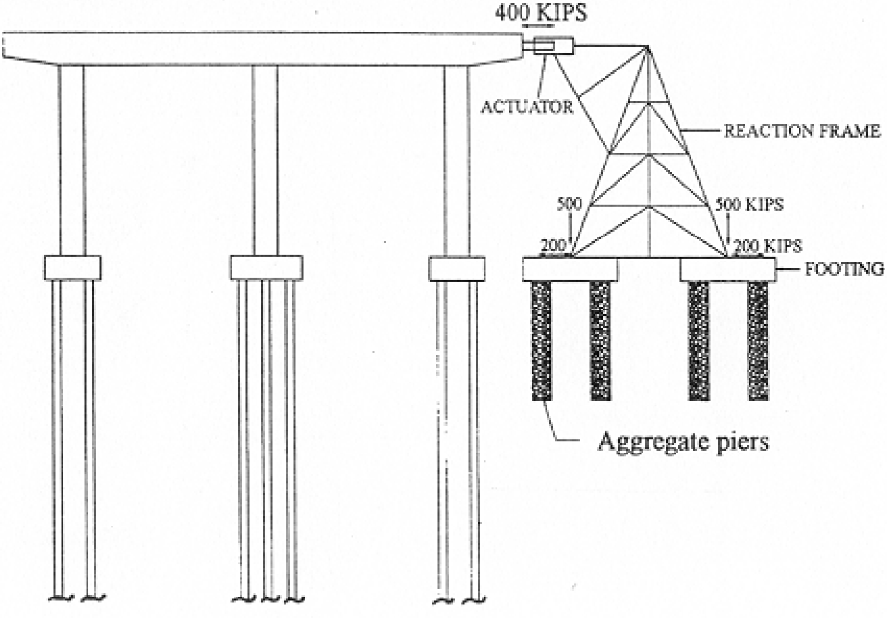


Fig. 5 Schematic of instrumented footing testing frame (after Lawton 1999)

Figure 6 presents the results of stress measurements taken during the main part of the push loading cycle by pressure cells installed between the bottom of the footing and the tops of the aggregate piers. The measured stresses are normalized by stresses measured by a pressure cell installed between the bottom of the footing and the top of the matrix soil. Assuming that the footing moves down uniformly during the applied loads, the ratio of the pier and matrix soil stresses is equivalent to the ratio of the pier and matrix soil modulus values, which are represented by the parameter R_s used in Equation 3, above. The results of the measurements presented in Figure 6 indicate that the ratio of pier to matrix soil stress ranges from about 30 to 45 at the test site. When these results are used in Equation 5, the ratio of aggregate pier to footing bottom stress is computed to range from about 2 to 3.5 for the tested footings. These values compare favorably to pier/footing bottom stress ratios of 2.5 to 3 commonly used for design (Fox and Cowell 1998).

4.4 Lower zone settlement calculations

Estimates of lower zone settlements 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 in-situ testing data or from the results of laboratory oedometer test measurements. 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, an assumption validated by the integral behavior of the deformable aggregate pier and its surrounding soil cell and supported by the settlement performance of hundreds of aggregate pier-supported footings.

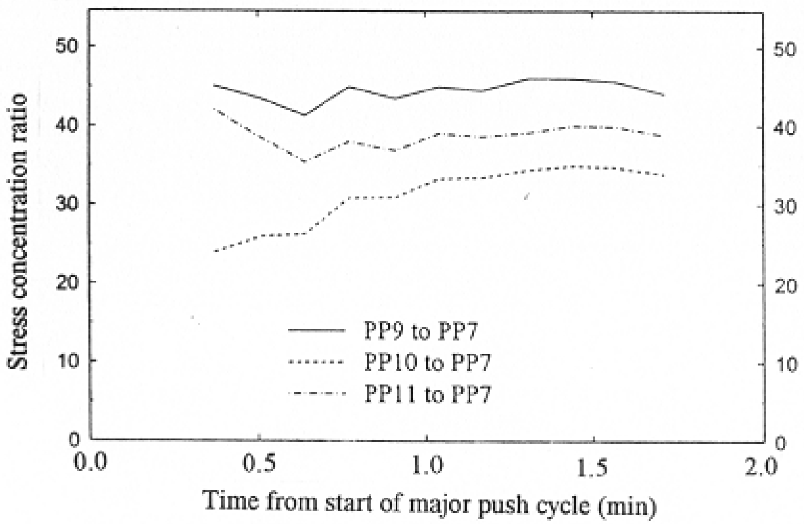


Fig. 6 Stress concentration to tops of aggregate piers (after Lawton 1999)

4.5 Settlement observations

The combined upper zone and lower zone settlement analysis methodology is based on classical soil mechanics approaches. The results of the analyses depend greatly on the modulus values of the upper and lower zone materials. High confidence levels in the upper zone modulus value are achieved because assumed design parameters are verified by modulus values developed from modulus load tests and because the process involves a systematic treatment of the foundation soils to depths in which the applied footing stresses are the greatest. Design assumptions for lower zone compressibility are best verified from the observed performance of completed structures. Observed settlements of aggregate pier-supported footings for a 5-story parking structure constructed in Hillsoboro, Oregon, are shown on Figure 7. The observations indicate maximum settlements of less than 1.2 cm, values appreciably lower than the design settlement criterion of 2.5 cm. These results are typical for aggregate pier-supported structures (Fox 1999).

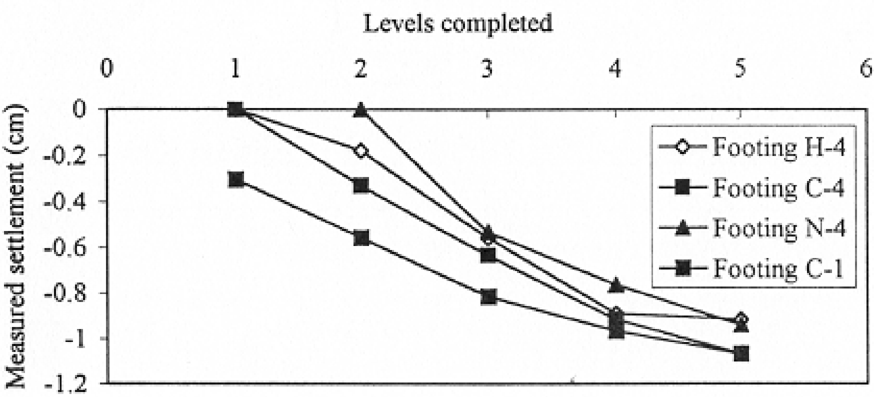


Fig. 7 Settlement observations

5 Lateral prestressing during pier construction

During the construction of aggregate pier elements, the ramming action of the beveled tamper forces the aggregate laterally into the sidewalls of the pier thus increasing the lateral earth pressure in the matrix soils. The increase in lateral earth pressure has been measured using in-situ testing devices and plays an important role in the deformation characteristics of the piers during compressive loads.

5.1 Measurement of matrix soil lateral earth pressure

The magnitude of the lateral stress increase within the matrix soil after the installation of aggregate piers has been measured at two project sites using K_o Stepped Blade in-situ testing techniques (Ferguson et al. 1993, Handy 1998). K_o Stepped Blade in-situ testing was developed by Professor Handy at Iowa State University and is accomplished by making a soil boring to the test depth and pushing an instrumented and incrementally thicker test blade into the underlying soils in four successive steps. The blade is thinnest at the bottom and the first push step involves the measurement of lateral stresses against this thinnest portion. Successive pushes involve the measurement of lateral stresses against incrementally thicker portions of the blade. The results are used to extrapolate the lateral stress on a hypothetical zero thickness blade. These extrapolated stresses indicate the in-situ lateral stresses in the matrix soils.

The results of the extrapolated in-situ horizontal stresses measured using the K_o Stepped Blade at two project sites are presented on Figure 8. Soil conditions at the Winterset, Iowa site consist of soft lean clay extending to a depth of about 3 meters. Lake Bonneville silt and clay deposits described in Section 4.3 above underlie the Salt Lake City, Utah site. Stepped Blade tests were performed at various depths and distances away from the installed aggregate piers after pier installation. The test results shown on Figure 8 present data collected in the "far-field", at horizontal distances greater than 15 m from the edge of the aggregate pier, and data collected in the "near-field", at horizontal distances of less than 3 m from the edge of the aggregate pier. The test results indicate that the construction of the piers significantly increased the lateral stresses in the matrix soil in the near field. When compared to far field conditions, average near field lateral stresses increased by a factor of about 2 over the entire depth of the installed piers and more than doubled near the upper portions of the piers. Although there exists considerable scatter in the data, the test results suggest that the lateral stress in the matrix soils adjacent to the aggregate piers may be limited by passive limit conditions (Ferguson et al 1993, Handy 1998). Similar conclusions have been made based on the results of Pressuremeter tests performed adjacent to installed aggregate piers (Handy 1999).

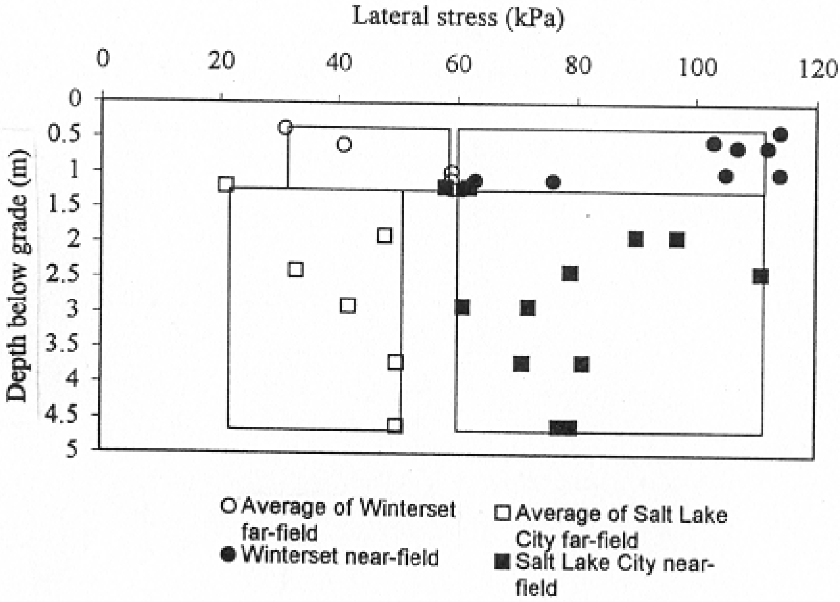
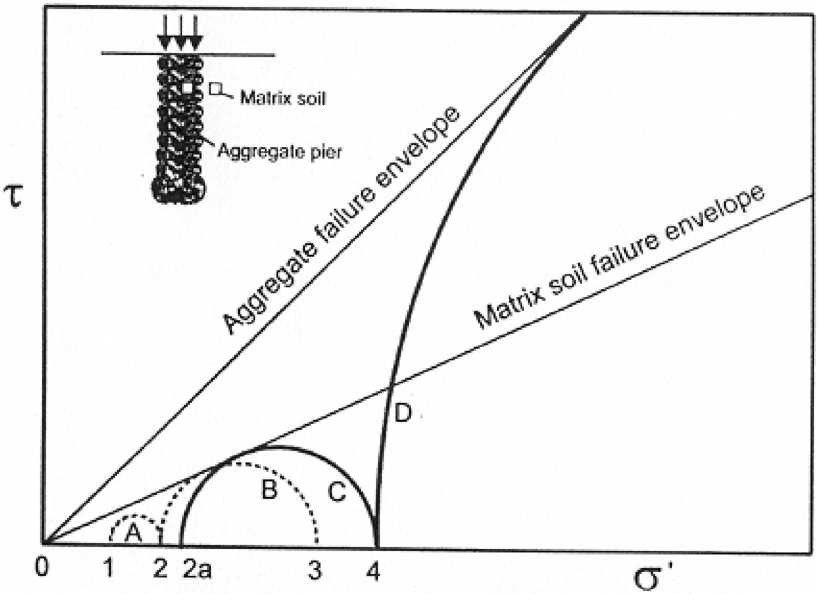


Fig. 8 Lateral earth pressures after aggregate pier construction

5.2 Importance of matrix soil prestressing and prestraining

The development of increased lateral earth pressures within adjacent matrix soils as a result of aggregate pier construction plays an important role in the minimization of pier bulging deflections during compressive loading (Handy 2000). Mohr's circles that describe the state of stress within the aggregate piers and within the matrix soil adjacent to the piers are presented on Figure 9. Prior to pier construction, the state of stress within the soil matrix is depicted by Circle A. The in-situ effective vertical stress (Point 2) is typically greater than the in-situ effective horizontal stress (Point 1). During pier installation, the effective vertical stress remains about the same and the effective horizontal stress increases to a value that approaches the passive earth pressure limit condition (Point 3); the stress state is represented by Circle B. If the aggregate pier is then loaded to a pressure that corresponds to the bulging of the pier into the matrix soil, the effective vertical stress in the matrix soil remains increases slightly (Point 2a) due to Poisson's ratio effects and the effective horizontal stress increases sufficiently

(Point 4) until the circle reaches the passive envelope to achieve a stress state described by Circle C. At this stress level, the effective horizontal stress within the aggregate pier is the same as that of the matrix soil and the vertical stress in the pier is limited by the active failure envelope for the aggregate material where Circle D represents the stress state in the aggregate pier at failure.



Circle A represents matrix soil in-situ stress prior to installation of aggregate piers.
Circle B represents the increase in matrix soil lateral stress during pier installation.
Circle C represents the increase in matrix soil stresses from pier bulging.
Circle D represents the potential ultimate stress state of the aggregate pier.

Fig. 9 Stress states as a result of aggregate pier installation

The importance of matrix soil prestressing, which is depicted by the change in stress conditions from Circle A to Circle B, is that by prestressing the soil during construction, the stress state need not change significantly during compression loading of the pier. This is represented by only a small change in stress from Circle B to Circle C. This is significant because changes in stress conditions are accompanied by strain. By prestressing the matrix soil, the construction of the piers also induces prestraining and results in significantly smaller lateral deflections of the matrix soil as the piers attempt to bulge outward during compression loading. Significantly larger matrix soil lateral deformations and corresponding aggregate pier vertical deformations occurs when the state of stress during compression loading changes from Circle A to Circle C.

6 Design methods for tensile loads

The design procedure used to estimate the tensile capacity of aggregate piers equipped with uplift harnesses are described in detail by Lawton et al. (1994) and briefly summarized herein. As the steel plate that is installed at the bottom of the pier is engaged, the plate pulls upward on the bottom of the pier and shearing is assumed to occur on the vertical cylindrical surface defined by the interface between the aggregate pier and the matrix soils. The unit resistance to vertical movement (f_s) is computed as the product of the effective horizontal earth pressure (σ_h') and the tangent of the friction angle of the unimproved matrix soil (ϕ_s):

$$f_s = \sigma_h' \tan(\phi_s) \quad . \qquad (6)$$

The horizontal soil pressure is assumed to be equal to the product of the effective vertical stress and the Rankine passive earth pressure coefficient. The maximum uplift load capacity (T_{max}) is computed by integrating the unit uplift resistance (f_s) over the area defined by the perimeter of the aggregate pier element (A_s):

$$T_{max} = f_s \, A_s \quad . \qquad (7)$$

The uplift capacity of aggregate pier elements computed using Equations 6 and 7 should be verified on a project-specific basis by performing uplift load tests on installed piers. A safety factor of 2.0 is typically applied for design.

7 Applications

Short, *Rammed Aggregate Pier*™ soil reinforcement has been used to reinforce bearing soils for the support of more than 250 major structures in the United States during the past 10 years. The system is used to support and reinforce soils including soft organic clays and peat, loose silts and sands, uncompacted fill soils, debris fill soils, stiff to very stiff clays, and medium dense to dense sands. Supported structures range from one story warehouses constructed on sites containing soft peat soils to a 16-story office building constructed on sites containing medium stiff silts and clays. Aggregate piers have been used to support hospitals, schools, commercial office buildings, parking garages, multi-level residential structures, storage tanks, and industrial facilities. For typical applications, footing loads range between 400 kN to 7,000 kN and have been used to support footings with column loads of up to 13,000 kN (GeoStructures 1999). Typical applications include:

- Soil reinforcement for foundation support and settlement control.
- Control of uplift loads for aggregate piers equipped with uplift harnesses.
- Soil reinforcement for the support of floor slabs and pavements.
- Soil shear strength improvements for slopes, embankments, and retaining walls.
- Soil shear strengthening for the control of soil liquefaction.

The use of short aggregate piers for foundation support is limited by several factors. Aggregate piers are typically installed to reinforce soils to depths ranging between 2 m and 6 m below foundation bottoms. If the combination of structural loading and foundation conditions are such that effective settlement control requires the installation of piers to depths greater than about 7 m, other foundation systems may be more suitable for construction. Aggregate pier soil reinforcement often provides little economic benefit for structures constructed at sites where the depth to rock is shallow or for structures constructed at sites containing clean sands combined with a high groundwater table because of the necessity for the use of casing during installation. The aggregate pier soil reinforcement system was developed principally to provide an economic alternative to the use of deep foundations or massive overexcavation and recompaction for foundations requiring better performance than afforded with conventional spread footings.

8 Summary and conclusions

The design of aggregate pier systems that support compressive loads is based on classical soil mechanics principals and verified by the results of instrumented footings and by modulus load tests performed at most project sites. The installation of the piers increases the matrix soil lateral earth pressure coefficient to the Rankine passive earth pressure coefficient. This increase in lateral stress is fundamental to the efficient use of aggregate piers to resist both compressive and tensile loads and inherent in the effective performance of the piers relative to shaft bulging. Settlement surveys of completed structures indicate that the design techniques are conservative. To date more than 250 major structures are supported by *Rammed Aggregate Piers (Geopier Foundation Company, Inc., 1999*).

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