# Case Histories and design of floating foundations with Geopier® Rammed Aggregate Pier™ elements

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Abstract: Geotechnical engineers have used "floating foundations" for decades to support light to moderate loads on soft soils. Floating foundations do not extend through deep, compressible soils; rather, they rely on an improvement in the stiffness of the soils directly beneath the bearing elements. Historical examples include: concrete mats overlying excavated subgrade, shallow spread footings or mats constructed on top of a crust of stiff native soil, overexcavated and replaced select improved fill soil overlying soft soil, and short friction piles not extending through the compressible materials. In recent years, the patented Geopier *Rammed Aggregate Pier™* soil reinforcing method has been used extensively to "float" spread footings on top of soft in-situ soils. A crust of soil with a higher composite stiffness is formed by the installation of the aggregate piers and associated increase in lateral stresses within the matrix soils. Stiffness modulus values of the installed aggregate piers have been measured to be 30 to 45 times greater than unimproved soft matrix soils.

This paper presents descriptions of the methods used to create a two-layer floating foundation support system with *Rammed Aggregate Pier* elements, and the analytical procedures used to estimate foundation settlements. Modulus testing and performance data are presented for two projects constructed on deep soft soil sites. Design examples for sites with very soft soils are also presented. This paper is of particular significance because it provides both analytical tools and project performance data for a rapidly growing ground modification system.

***Key Words***: Geopier®, *Rammed Aggregate Pier™, floating foundation, ground improvement, soil reinforcement, settlement control, spread footing*

## 1. GEOPIER® SOIL REINFORCEMENT

### 1.1 Introduction

Sites with soft, compressible soils extending to appreciable depths typically require the installation of deep foundation systems to transfer structural loads to competent soils and reduce potential settlements. Consequently, construction of lightly to moderately loaded structures at such sites is not cost effective when the cost of the foundation system becomes disproportionate to the cost of constructing the superstructure. However, an alternate foundation system to cope with this difficulty is to provide a "floating foundation" for the structure by increasing the rigidity of the uppermost soils sufficiently to spread the load and limit settlements to design tolerances. Historical examples of floating foundation systems (Figure 1) include making use of natural crusts of stiff soil overlying softer deposits, over-excavating and replacing soft soils with stiffer materials, and driving or hydraulically pushing relatively short friction piles and connecting the piles to the structure with concrete caps or a mat. This paper presents two case histories of applying Geopier elements to create floating foundation conditions at sites in the Philippines and in the United States. Design approaches and construction techniques for the Geopier system are discussed; design examples for two very soft soil sites are also presented. This paper is of significance because it provides design approaches for a technically feasible and cost effective solution to a costly problem of foundation support in deep, very soft soils.

### 1.2 Geopier construction

Geopier elements are constructed by drilling 750 mm diameter holes to depths typically ranging between 2 to 8 meters below the footing bottoms; placing controlled, 300 mm lifts of aggregate within the cavities; and compacting the aggregate using a specially designed and patented, beveled, high-energy impact tamper (Figure 2). The first lift consists of clean stone and is forced into the soil to form a bottom bulb. The bottom bulb extends the effective design length of the aggregate pier element by one pier diameter. The remainder of the pier is constructed of well-graded aggregate, densified in thin lifts. During the densification, the beveled tamper forces stone laterally into the sidewall of the excavated cavity. This ramming action increases the lateral stress in the surrounding matrix soil thus providing additional stiffening. Detailed discussions on the soil prestressing and prestraining effects are presented by Handy (2001).

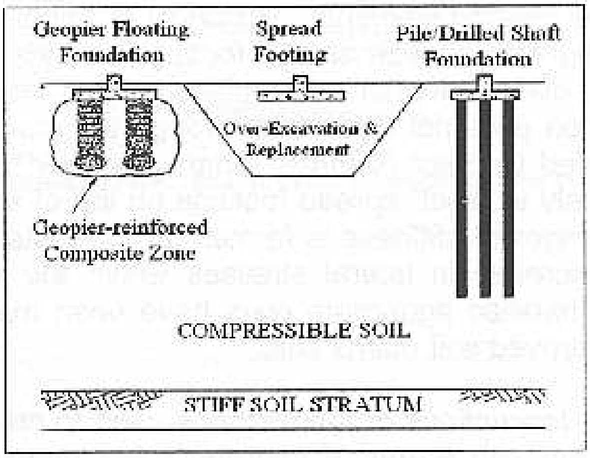

**Fig.1** Concept of floating foundations

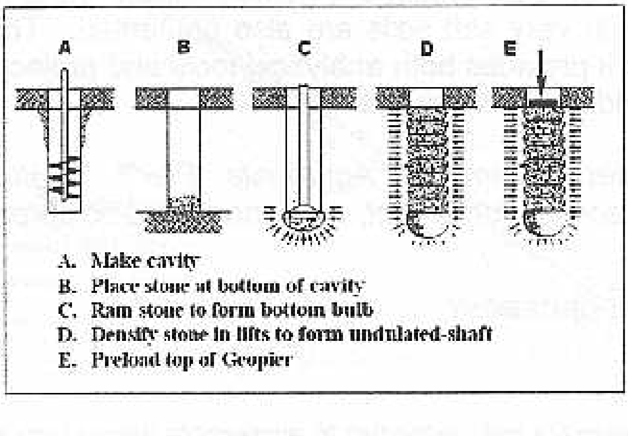

**Fig.2** Geopier *Rammed Aggregate Pier* Construction

## 2. FLOATING FOUNDATIONS

Floating foundations do not extend completely through soft, compressible soil layers. One form of floating foundation system consists of a stiff composite layer that extends sufficiently deep to reduce the applied pressure and reduce foundation settlement contributed by compression and consolidation of the underlying soft soil. Geopier elements are designed to create this stiff zone by increasing the composite stiffness of the surrounding soils to depths in which footing-induced stresses are the highest. The end result is to limit long-term total and differential foundation settlements to satisfy structural design criteria.

### 2.1 Geopier design approach

The Geopier design methodology is to create a stiff layer of composite material that exhibits sufficient rigidity to control foundation settlements to meet design tolerances. Settlement design criteria of 25 mm total settlement and 12 mm differential settlement between columns are commonly used in design practice for commercial and industrial structures in the United States.

Foundation settlements are estimated by summing the settlement contributions computed from the upper Geopier-reinforced zone and from the lower non-reinforced zone (Figure 3). Detailed upper zone calculations are described by Lawton and Fox (1994) and Lawton et al. (1994), and are summarized herein for completeness.

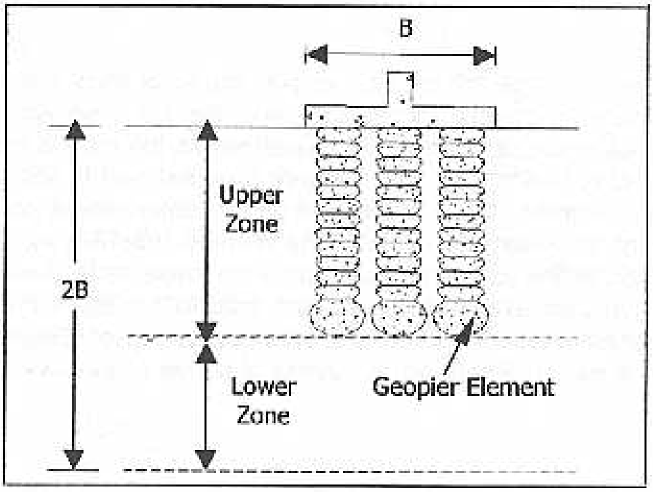

**Fig.3** Schematic of upper- and lower-zone

- Assuming the footing is rigid relative to the foundation materials, stresses applied to the Geopier elements and to the matrix soil depend on their relative stiffnesses ($R_s$) and area coverage. The total downward force (Q) on the footing is resisted by the Geopier element ($Q_g$) and matrix soil ($Q_s$):

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

- Because the settlement of the footing portion bearing on the pier will equal the settlement of the footing portion bearing on the matrix soil, foundation settlement (s) can be estimated by the ratio of the applied stresses ($q_g$ and $q_s$) and stiffness modulus ($k_g$ and $k_s$) of Geopier and matrix soil:

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

- Rewriting equation 2 to express the matrix soil stress in terms of the top of Geopier stress and the ratio of the pier and matrix soil modulus values ($R_s$):

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

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

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

- Rewriting $q_g$ in terms of q:

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

- Upper-zone settlements are then computed using Equations 2 and 5.
- Settlements contributed by the lower, non-reinforced zone soils are calculated using conventional geotechnical stress distribution (such as the Westergaard solutions) and settlement analysis procedures described in the literature (Terzaghi and Peck 1967) combined with soil deformation modulus values interpreted from field or laboratory testing. This assumption is believed to be conservative because the presence of the piers results in a stress concentration on the piers and a more efficient stress transfer and stress dissipation with depth below the footing bottom than that which occurs for conventional spread footings (Lawton, 1999).

### 2.2 Modulus tests

To verify the pier stiffness modulus value ($k_g$), Geopier modulus tests are conducted. The test is performed by applying pressure in gradual increments over the full cross-section area of a Geopier element. The stiffness modulus value used for design is defined as the ratio of the design top of Geopier stress to the shaft corresponding deflection. The Geopier modulus test is not a bearing capacity type test, such as a pile load test. Rather, it is a settlement test to determine a conservative value of pier stiffness. The Geopier foundation system design uses the stiffness modulus value measured at the point of maximum anticipated design stress (or at the maximum acceptable deflection) from the modulus test. The Geopier modulus tests typically extend the maximum load to 1.5 times the design top of Geopier stress. The purpose of extending the load more than the design top of Geopier stress is primarily to observe the behavior pattern of pier deflection versus stress at higher stress levels.

## 3. CASE STUDIES

The design approaches described above are illustrated by the following selected case histories:

### 3.1 Pricesmart Superstore, Philippines

The Pricesmart Superstore project constructed in 2001 was the first Geopier application in the Philippines. Subsurface conditions are characterized by soft soils extending to 18 meters below ground. The original design called for 6,500 square meters of suspended structural floor slab to be supported by drilled shaft/bored pile foundations. Driven piles were ruled out because of potential damage to surrounding residential areas from excessive vibrations induced within the very poor subsoils. By adopting a Geopier floating foundation system, costly bored piling and suspended floor slabs were each eliminated. This allowed the heavily loaded floor slabs to be supported by the Geopier soil reinforcement and designed as a slab-on-grade system. This floating foundation system was designed to control the foundation and floor slab total and differential settlements to meet the project design criteria. A total of 1,900 Geopier elements with lengths of 3 to 3.5 meters were installed in 60 working days reducing the project completion schedule by 60 days.

A modulus test performed on site produced a Geopier stiffness modulus value of 83 MN/m$^3$, which was greater than the 35 MN/m$^3$ used in the design analysis. The Geopier-reinforced upper zone settlements were estimated to range from 10 mm to 15 mm. The Geopier construction saved more than 50% of foundation costs compared to alternative solutions. Design soil profile data and Geopier modulus test results of the project are presented in Figure 4. Performance of the completed Geopier floating foundation system exceeded the Client's and project engineer's expectations. Post-construction measurements of the floor slab flatness indicate that no measurable differential floor slab deformations are occurring.

0 to 5 m - Very soft to medium clay, SPT-N=2 to 9
5 to 8 m - Very loose to medium dense silty sand, SPT-N = 2 to 11
8 to 15 m - Very soft to soft silty clay, SPT-N = 2 to 4. Groundwater table at 1.2 m deep

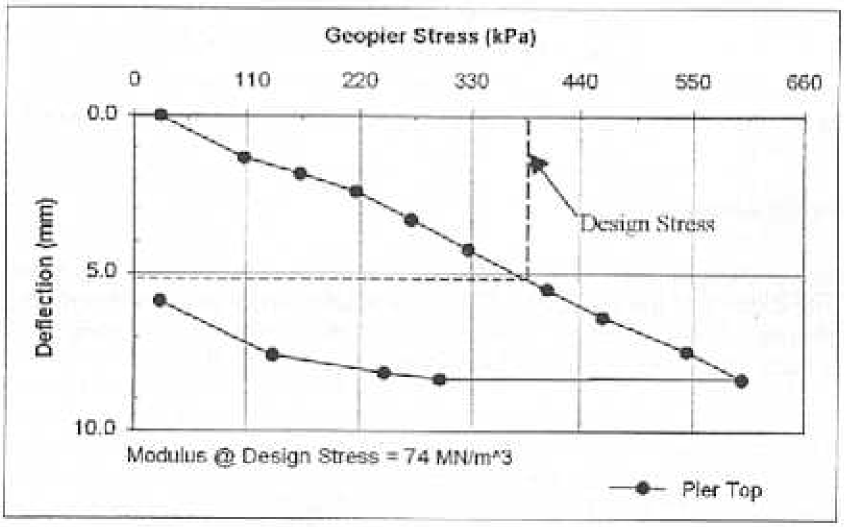

**Fig.4** Pricesmart design soil profile and modulus test results

### 3.2 Marriott Courtyard Hotel, USA

The Marriott Courtyard Hotel in Portland, Oregon, USA, is a five-story concrete and wood-frame hotel building. Column loads range between 100 and 175 tons. The site is underlain by 12 meters of very soft floodplain deposits that precluded the feasibility of using conventional spread footings on the native soils. Geopier elements were installed by drilling to a depth of 4.7 meters to support the footings designed with a bearing pressure of 215 kN/m$^2$, leaving approximately 7.3 meters of soft soil under the Geopier elements. The Geopier modulus test confirmed that a design bearing pressure of at least 285 kN/m$^2$ was feasible for limiting upper zone settlements to 12 mm or less. Based upon the results of the modulus test, the Geopier-reinforced upper zone settlements were calculated to range from 10 mm to 12 mm. Lower zone settlements were estimated from 10 to 13 mm. The design soil profile data and Geopier modulus test results of the project are presented in Figure 5.

Thickness of compressible, very soft silty clay = 12 m with SPT-N = 1 to 2
Groundwater table at approximately 3 m deep

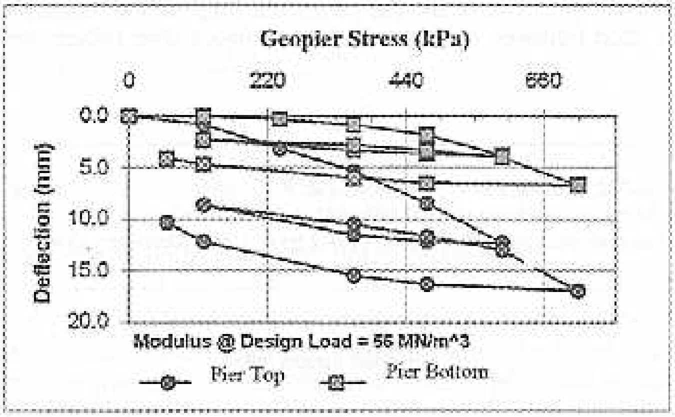

**Fig.5** Marriott Courtyard design soil profile and modulus test results

## 4. GEOPIER DESIGN EXAMPLES

This section presents Geopier design examples for floating foundations for two sites characterized by unusually soft soils that extend to great depths. Typical soil undrained shear strengths range from 3 to 15 kN/m$^2$, and soil moisture contents range from 65 to 120% within these sites. Figure 6 presents representative profile data of soil conditions at the two sites.

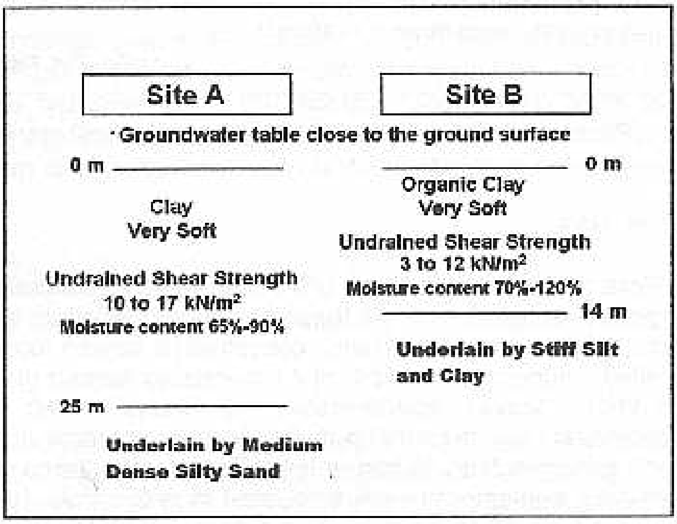

**Fig.6** Design soil profile data of very soft soil sites

To evaluate the feasibility of the Geopier *Rammed Aggregate Pier* system for the creation of floating foundations, preliminary Geopier soil reinforcement designs were formulated for the two sites. The Geopier system designs for these sites are summarized in Table 1 and Table 2.

**Table 1** Geopier preliminary design for Site A

| Design Column Load | 22 t | 68 t | 113 t | 205 t |
|---|---|---|---|---|
| Allowable Footing Bearing Pressure (kPa) | 190 | 190 | 190 | 190 |
| Design Square Footing Width | 1.1m | 1.9m | 2.5m | 3.25m |
| No. of Geopier Elements per footing | 1 | 3 | 5 | 9 |
| Design Geopier Drill Depth Below Footing | 2.75m | 3.75m | 4.75m | 6.25m |
| Design Geopier Compacted Shaft Length | 1.75m | 2.75m | 3.75m | 5.25m |
| Estimated Foundation Total Settlement | 25mm | 25mm | 25mm | 25mm |

**Table 2** Geopier preliminary design for Site B

| Design Column Load | 18 t | 54 t | 91 t | 164 t |
|---|---|---|---|---|
| Allowable Footing Bearing Pressure (kPa) | 168 | 168 | 168 | 168 |
| Design Square Footing Width | 1.1m | 1.8m | 2.3m | 3.1m |
| No. of Geopier Elements per Footing | 1 | 3 | 5 | 9 |
| Design Geopier Drill Depth Below Footing | 2.75m | 3.75m | 4.60m | 6.10m |
| Design Geopier Compacted Shaft Length | 1.75m | 2.75m | 3.60m | 5.10m |
| Estimated Foundation Total Settlement | 24mm | 23mm | 23mm | 23mm |

Because of the very weak subsoils, a special construction procedure is required to install the Geopier elements. The elements will have to be "over-drilled", and a thicker layer of clean stone placed for the bottom bulb than is normally used in Geopier construction for sites with better soil conditions (Wissmann and Fox, 2000; Wissmann et al., 2000; and Wissmann et al., 2001). The drilled shaft will be over-drilled one meter deeper than required by the Geopier shaft length calculations. Clean stone is then dumped to a height of about 1.5 meters above the cavity bottom, and tamping of the bottom bulb begins. This will prevent shearing of the weak soil from the high energy impact ramming action of the Geopier Tamper, and will produce a reasonably stable bottom bulb prior to constructing the 300 mm compacted Geopier shaft layers. An example design configuration of the floating foundation system for site A is shown in Figure 7.

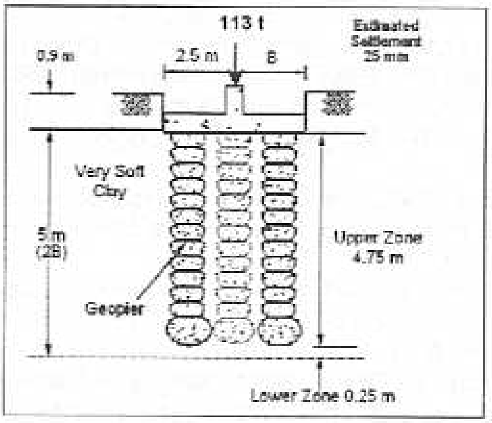

**Fig.7** Floating foundation design for Site A – Square footing with 5 Geopier elements

## 5. CONCLUSIONS

The Geopier floating foundation system has been successfully applied to a number of sites with very soft to soft soil conditions during the past decade. Two case histories and design examples of Geopier floating foundations have been described in this paper.

Applications of the patented Geopier system in providing efficient floating foundation systems in soft, compressible soils are technically feasible and usually cost effective compared to deep foundations or massive over-excavation and replacement methods. By installing the Geopier elements to create a stiff composite upper reinforced zone, the floating foundation design approach can be utilized to control foundation settlements and satisfy reasonable structural design criteria.

## APPENDIX: SYMBOLS USED

$A$ = Gross footing area.
$A_g$ = Footing area supported by Geopier elements.
$A_s$ = Footing area supported by matrix soil.
$k_g$ = Stiffness modulus of Geopier.
$k_s$ = Stiffness modulus of matrix soil.
$Q$ = Total downward force on footing.
$Q_g$ = Resisting force of Geopier.
$Q_s$ = Resisting force carried by matrix soil surrounding Geopier elements.
$q$ = Composite bearing pressure at base of footing.
$q_g$ = Stress applied to top of Geopier.
$q_s$ = Stress applied to matrix soil surrounding Geopier elements.
$R_a$ = Ratio of cross-sectional area of Geopier to gross footing area.
$R_s$ = Ratio of relative stiffness of Geopier and matrix soil.
$S$ = Footing settlement.

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