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Geopier Soil Reinforcement System – Case Histories of High Bearing Capacity Footing Support and Floor Slab Support

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ABSTRACT

The Geopier® Rammed Aggregate Pier system is an innovative ground improvement method developed in the 1980's that has grown in the United States and more recently in Asia and Europe, for supporting lightly to heavily loaded structures and highway and railroad embankments. The system is unique because it prestresses and prestrains adjacent matrix soils during installation of rammed aggregate piers. It has been successfully used on hundreds of project sites to support building foundations, floor slabs, storage tanks, and roadway embankments founded on both, poor and unsuitable soils as well as fair to good soils. The rammed aggregate pier system controls settlements effectively by reinforcing soils below structures and thus improving bearing capacities and allowable bearing pressures while controlling settlements. Two case histories of specialized applications are presented in this paper: (1) Wind tower projects in Germany, where the Geopier system provides high bearing capacity and overturning moment resistances to support the foundations in soft soils; and (2) Rammed Aggregate Pier soil reinforcement support of foundations and large area floor slab system for a commercial warehouse facility in the Philippines. This paper is of particular significance because it presents case histories of a relatively new soil improvement system tailored to increase foundation bearing capacities for dynamic footing loadings and provide positive settlement control for wide area loads including floor slabs. Design and implementation of the Geopier system are presented. Evaluations of the behavior of Geopier elements based on stiffness modulus test data and an analytical approach to compare modulus test results to the design assumptions are also discussed.

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 three case histories of applying Geopier Rammed Aggregate Piers to create floating foundation conditions at sites in Germany and the Philippines. Design approaches and construction techniques for the system are discussed and design examples are 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, soft soils

1.2 Geopier construction

Rammed Aggregate Piers 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).

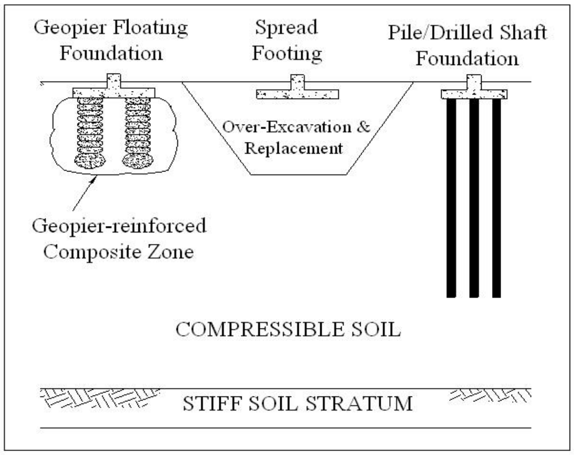

Fig.1 Concept of floating foundations

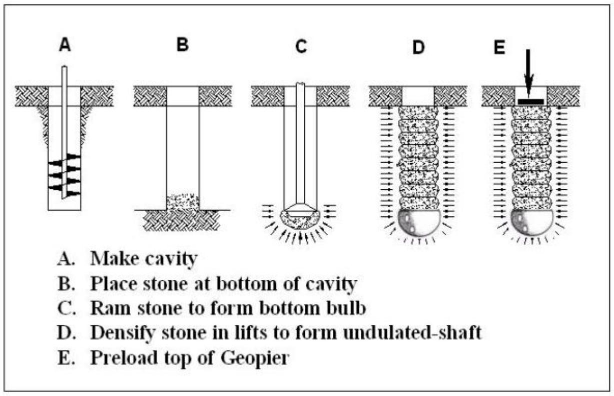

Fig.2 Geopier *Rammed Aggregate Pier* Construction

2. FLOATING FOUNDATIONS

Floating foundations do not extend completely through soft, compressible soil layers. Floating foundation systems consist 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. Rammed Aggregate Piers 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 result is the limiting of long-term total and differential foundation settlements sufficiently to satisfy the structural design criteria.

2.1 Geopier design approach

Foundation settlements are estimated by summing the settlement contributions computed from the upper Rammed Aggregate Pier reinforced zone and from the lower non-reinforced zone (Figure 3). Detailed upper zone calculations are described by Lawton and Fox (1994), Lawton et al. (1994), and Fox, Cowell and Wissmann (1998).

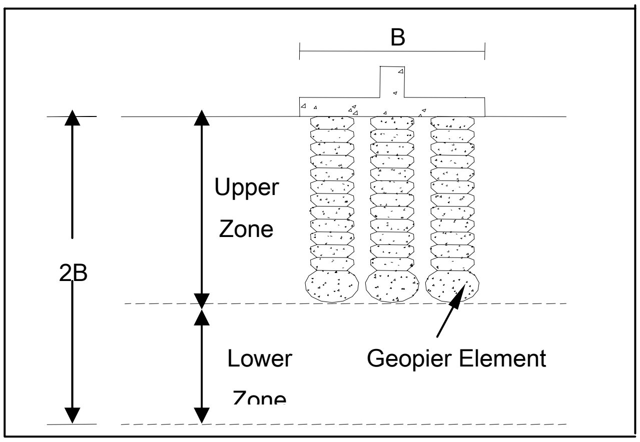

Fig.3 Schematic of upper- and lower-zone

Upper-zone settlements (S_{OZ}) are computed using the expression:

$$q_g = \{q R_s / [R_a R_s + 1 - R_a]\} / k_g$$

where q is the average footing-bottom pressure, R_s is the ratio of the stiffness of the Rammed Aggregate Pier element to the stiffness of the matrix soil, R_a is the ratio of the cross-sectional areas of the Rammed Aggregate Piers below a footing to the footing bottom area, and k_g is the stiffness modulus of the Rammed Aggregate Pier elements.

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), Rammed Aggregate Pier 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 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.

3. CASE STUDIES

3.1 Windpark Guntersblum, Germany

Five 71 m high wind towers at the wind energy station of Guntersblum, Germany were planned to be supported by shallow foundations. The circular foundations had a diameter of 12,5 m with maximum design edge pressures of 306 kN/m^2. Additionally, the Rammed Aggregate Pier system had to be designed to provide a stiffness modulus of 300 MN/m^2 and a rotational spring stiffness constant of 30.000 MNm.

Subsurface Conditions

Subsurface exploration at the site exhibited soft, sandy and clayey silts with SPT-N blow counts of 2 to 5 in the upper 4 m. The soft soils were underlain by medium stiff, loessial deposits to boring termination. Stiff soils with SPT-N values exceeding 12 were encountered at depths from 9 m below ground surface.

Geopier Design

Based on the results of the geotechnical exploration, 4 m long Geopier elements were designed to be arranged in three to five concentric circles below the circular foundation. Most of the Rammed Aggregate Piers were located near the perimeter of the foundation to provide edge pressure resistance. The elements were designed with cell capacities ranging from 311 kN to 378 kN.

Table 1 Geopier Design Parameter Example

WKA No.	1
Foundation Area [m^2]	120.8
Geopier Shaft Length [m]	4.0
Geopier Cell Capacity Q_{gp} [kN]	378
No. Geopier Elements	74
Geopier Stiffness Modulus, k_{gp} [MN/m^3]	47.5

Modulus Load Test

A modulus load test was installed at the area of the site that exhibited the most unfavorable soil conditions. Total deflection at the design stress of 705 kN/m^2 was measured to be 8,2 mm, resulting in a stiffness modulus value of 82 MN/m^3.

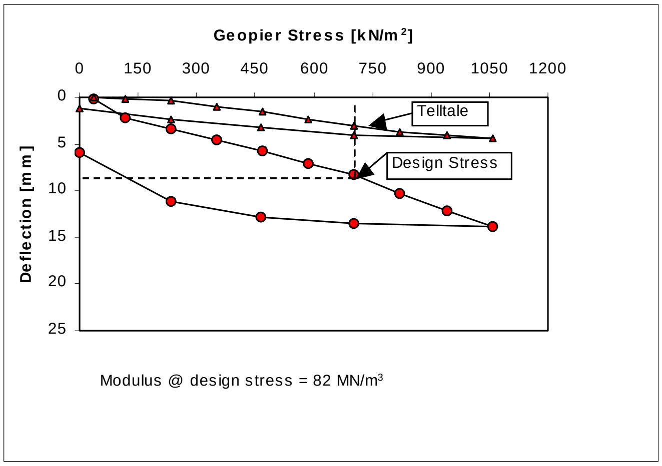

Fig.4 Modulus Load Test

Soil Stiffness

The required dynamic spring stiffness for the soil was c_φ = 30.000 MNm. It can be calculated as the compliance (quotient) of the acing overturning moment M and the angular rotation α of the foundation under triangular stress distribution, where the stress ordinate is equivalent to the maximum edge pressure.

$$c_\varphi = M / \alpha$$

Considering a simplification for absolut small angles:

$$\alpha = \Pi / 180 * \text{ARCTAN}\,(ds / L) \cong ds / L$$

The deflection can be expressed in a simplified manner considering the soil stiffness modulus and the maximum edge pressure :

$$ds = \sigma / k_S$$

The actual dynamic spring stiffness can then be calculated as:

$$\text{act. } c_\varphi = M / [(\sigma / k_S) / L] = M * L * ks / \sigma$$

$$= 28{,}18 \text{ MNm} * 11{,}0 \text{ m} * 82 \text{MN/m}^3 / 0{,}306 \text{ MN/m}^2$$

$$= 83.066 \text{ MNm} > \text{ req. } c_\varphi = 30.000 \text{ MNm}$$

The calculations indicate that the Rammed Aggregate Pier reinforced soil has a sufficient high dynamic spring constant to meet the design requirements.

Conclusions

Geopier elements were installed to support five windtower foundations in Guntersblum, Germany. The modulus load test carried out at the location with the worst soil conditions is the basis for evaluation of the performance of the

Geopier elements. It was shown, that the Geopier supported foundations exhibited:

- a sufficient high dynamic spring stiffness to limit angular distortion, and
- an allowable bearing capacity that exceeds the requirements.

Installation of 400 Geopier Rammed Aggregate Piers supporting a total of five wind towers was completed in 10 working days. The wind towers were erected in early summer 2002 and have been in service since. To date, nearly 100 wind towers with a height of up to 105 m have been successfully supported by Geopier elements.

3.2 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 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.

Pricesmart design soil conditions:

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

4. CONCLUSIONS

Over the past decade the Geopier Rammed Aggregate Pier floating foundation system has been successfully applied to a variety of sites with very soft to soft soil conditions. 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. Two case histories have been described in this paper.

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_{gp} = Stress applied to top of Geopier.
q_m = 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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