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GEOPIER® FLOATING FOUNDATIONS - A SOLUTION FOR THE MEKONG DELTA REGION, VIETNAM

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ABSTRACT: Geopier® soil reinforcement, consisting of very stiff short aggregate piers, has been used in the United States since 1989 and is gaining acceptance in Asia and Europe. This ground improvement system is unique with stiffness modulus values measured to be 10 to 45 times greater than unimproved matrix soils. The described method effectively and economically reinforces peat, highly organic soil and very soft soil zones (Fox and Edil, 2000). This paper discusses the feasibility of using *Geopier* elements as a "floating foundation" system within the very soft soils of the Mekong Delta region of Vietnam.

TÓM TẮT: Gia cố đất nền bằng cọc đá dăm Gieopier được ứng dụng ở Mỹ từ những năm 1989 và dần được chấp nhận ở châu á và châu Âu. Với phương pháp gia cố nền này đất có mô đun độ cứng lớn gấp 10 đến 45 lần so với đất chưa gia cố. Phương pháp được trình bày trong bài gia cố hiệu quả và kinh tế cho các loại đất bùn, đất hữu cơ cao và đất yếu. (Fox và Edil, 2000). Bài viết thảo lận về khả năng ứng dụng cọc đá dăm như hệ móng nổi trên đất yếu của vùng đồng bằng sông Cửu long Việt nam.

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

1. GEOPIER® SOIL REINFORCEMENT

(1) 1.1 Introduction

Sites that contain soft soils extending to appreciable depths typically require the installation of deep foundation systems to transfer structural loads to competent soils and reduce potential settlements. Construction of lightly to moderately loaded structures is not cost effective at these sites because the cost of the foundation system becomes disproportionate to the cost of constructing the superstructure. One method to cope with this difficulty is to provide a "floating foundation" system for the structure by increasing the rigidity of the uppermost soils sufficiently to limit settlements to design tolerances. Historical examples of this approach 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. *Geopier* soil reinforcing elements have been used to create floating foundation systems at sites in the United States, the Philippines, and Germany (Figure 1).

This paper describes engineering methods used to design *Geopier* soil reinforcing elements to create a floating foundation system for sites in the Mekong Delta region of Vietnam. Construction techniques and design background are discussed. Three case histories of *Geopier*-supported floating foundations are presented and followed by approaches formulated for two sites in Vietnam. 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 the very soft Mekong Delta soils.

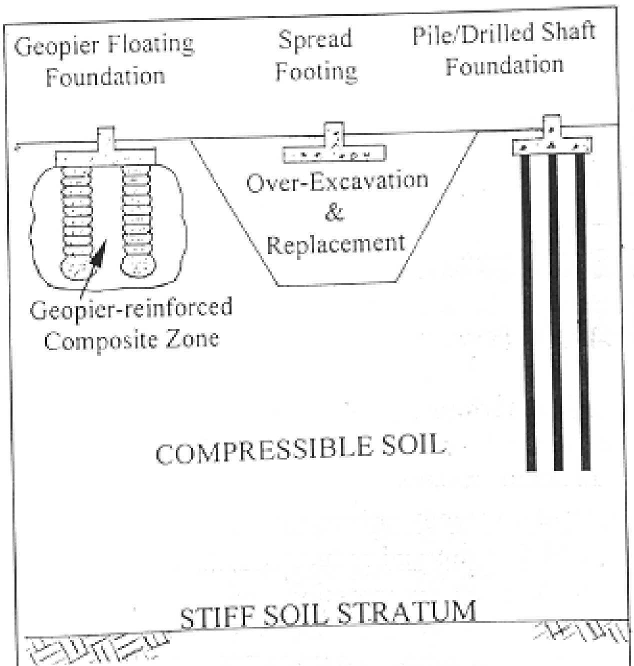

Fig.1 Concept of floating foundations

1.2. Geopier construction

Geopier soil reinforcing elements are constructed by drilling 760 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, beveled, high-energy impact tamper (Figure 2 and Picture 1). The first lift consists of clean stone and is forced into the soil thus forming 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 action increases the lateral stress in the surrounding matrix soil thus providing additional stiffening. Detailed discussions on the soil pre-stressing and pre-straining effects are presented by Handy (2001).

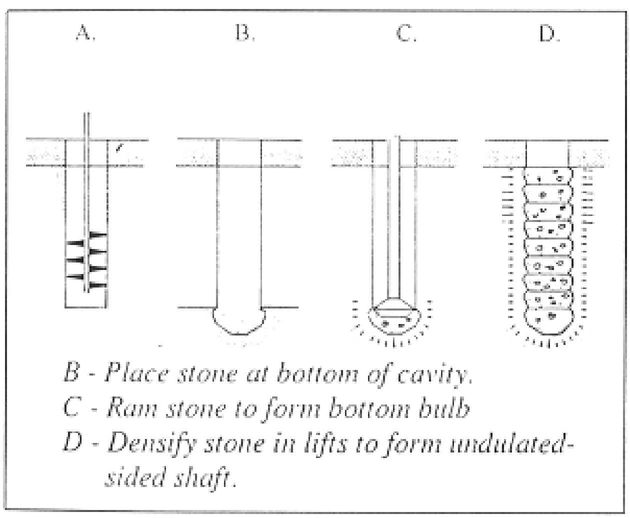

Fig.2. Geopier Construction

2. FLOATING FOUNDATIONS

Floating foundations do not extend completely through soft, compressible soil layers. Rather, the 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 subsurface soils at 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.

Picture 1. Geopier construction site

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 the design tolerances. Settlement design criteria of 25 mm total settlement and 12 mm differential settlement between columns are commonly used in design practice.

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.

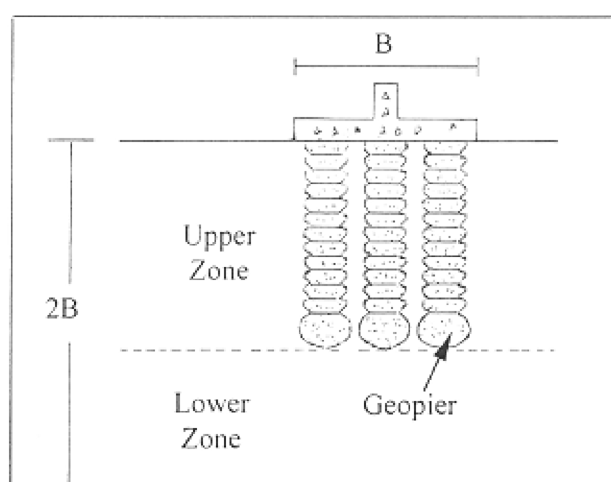

Fig.3 Schematic of upper- and lower-zone

- Assuming the footing is rigid relative to the foundation materials, stresses applied to the composite foundation materials depend on their relative stiffnesses (R_s) and area coverage. The total downward force (Q) on the footing is resisted by resistance provided by the *Geopier* (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, the foundation settlement (s) can be estimated by applied stresses (q_g and q_s) and stiffness modulus (k_g and k_s) of *Geopier* and matrix soil:

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

Rewrite equation 2 to express the matrix soil stress in terms of the *Geopier* stress and the ratio of the pier and matrix soil modulus values (R_s):

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

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

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

- Rewriting q_g in terms of q:

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

- Upper-zone settlements are then computed using Equations 2 and 5.
- Settlements in the lower, non-reinforced zone material are computed using conventional geotechnical stress distribution (such as Westergaard solution) 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 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 load test

To verify the assumed *Geopier* stiffness modulus value (k_g), modulus load tests are conducted prior to construction. The test is performed by applying pressure in gradual increments over the full cross-section area of a *Geopier* element. The stiffness modulus value corresponding to 100% of the design stress applied to the top of the pier is determined based upon the load test results.

3. CASE STUDIES

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

3.1 Puget Sound Condominium, USA

A waterfront site was selected for the development of a condominium project in Anacortes, Washington, USA. The site was underlain by 18 to 22 meters of deep, soft to firm clay. The structure produced typical column loads of 160 tons and continuous wall loads of 15 t/meter.

Geopier soil reinforcing elements were installed to depths of 3.5 to 4.5 meters beneath foundation bottoms. A modulus load test performed on site confirmed the *Geopier* stiffness modulus value of 82 MN/m^3, which was greater than the 35 MN/m^3 used in the design upper zone settlement analysis. Based upon calculations using equations 2 and 5, and results of the modulus load test, the *Geopier*-reinforced upper zone settlement contribution ranged from 10 mm to 12 mm. Lower zone settlement contribution, computed using results of consolidation tests and Westergaard stress influence factors, was calculated to be less than 13 mm. The condominium has been constructed with exemplary foundation performance. Design soil profile data and *Geopier* modulus load test results of the project are presented in Table 1 and Figure 4.

Table 1. Design soil profile data, Puget Sound condominium

0 to 3 m - Sand and Silt, SPT-N = 3 to 13
3 to 22 m - Very soft to firm clay, SPT-N=2 to 7
Groundwater table close to the ground surface.

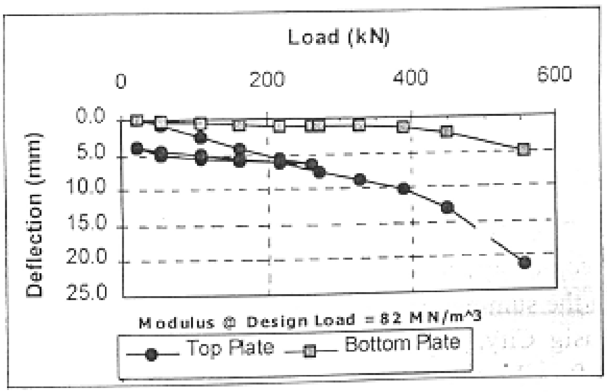

Fig. 4. Puget Sound modulus load test results

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 14 meters of very soft floodplain deposits that precluded the feasibility of using conventional spread footings on the native soils. *Geopier* elements were installed to depths of only 3.7 meters below footing bottoms to support footings with design bearing pressures of 215 kN/m². The *Geopier* modulus load test confirmed that a design bearing pressure of at least 285 kN/m² was feasible for limiting upper zone settlements to 12 mm or less. Based upon the results of the modulus load test, the *Geopier*-reinforced upper zone settlements were calculated to range from 10 mm to 12 mm. Lower zone settlements were estimated ranging from 10 to 13 mm. Design soil profile data and *Geopier* modulus load test results of the project are presented in Table 2 and Figure 5.

Table 2 Design soil profile data, Marriott Courtyard Hotel

Thickness of compressible, very soft silty clay = 14 m With SPT-N = 1 to 2
Groundwater table at approximately 3 m deep

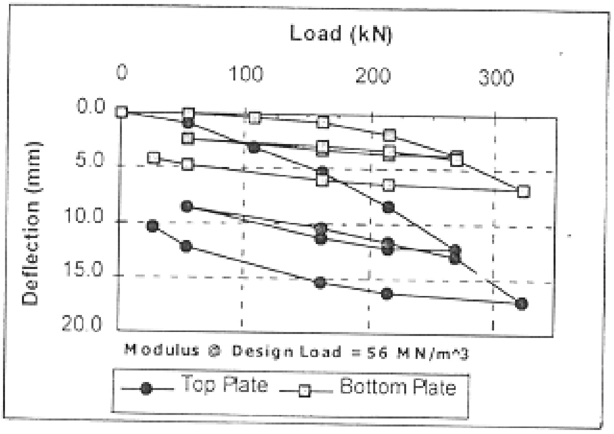

Fig.5 Marriot Courtyard modulus load test results

3.3. Pricesmart, Philippines

The Pricesmart Superstore project was the first *Geopier* application in the Philippines constructed in the summer of 2001. The project site, located in Pasig City, is situated in poor swampland where soft soils extend down to 18 meters below ground. The original design called for the floor to be structurally supported by drilled shafts (bored piles). *Geopier* soil reinforcement eliminated the costly bored piling and suspended structural floor system, and allowed the heavily loaded floor to be *Geopier*-supported as a lightly reinforced slab-on-grade system. The *Geopier* elements were installed to an average length of 3 to 3.5 m below slab and footing bottoms. A modulus load test performed on site produced a *Geopier* stiffness modulus value of 83 MN/m³, which was greater than the 35 MN/m³ used in the design upper zone settlement analysis. The *Geopier*-reinforced upper zone settlements were estimated to range from 10 mm to 15 mm. *Geopier* construction saved more than 50% of foundation cost compared to alternative solutions. Design soil profile data and *Geopier* modulus load test results of the project are presented in Table 3 and Figure 6.

Table 3 Design soil profile data, Pricesmart

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

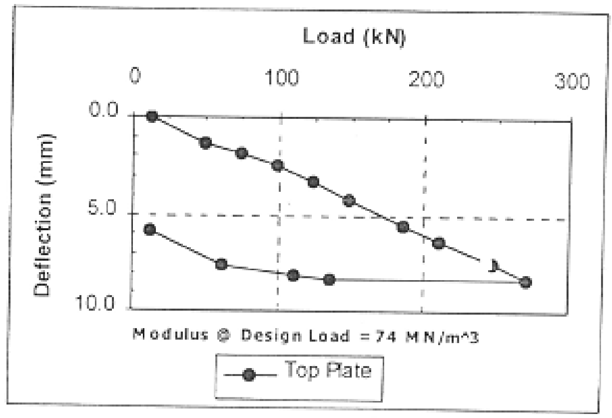

Fig.6 Pricesmart modulus load test results

4.GEOPIER DESIGNS FOR MEKONG DELTA

The Mekong Delta region of Vietnam is characterized by very soft soils that extend to great depths. Typical soil undrained shear strengths range from 3 to 15 kN/m², and soil moisture contents range from 65 to 120%. Table 4 presents representative profile data of soil conditions at the two sites.

Table 4 Design soil profile data of Mekong Delta sites

Vung Tau Site • 0 to 25 m – Very soft clay • Undrained shear strength of clay = 10 to 17 kN/m² • Soil moisture contents 65 to 90%. • Groundwater table close to the ground surface
Nha Be Site • 0 to 14 m – Very soft fat organic clay • Undrained shear strength of clay = 3 to 12 kN/m² • Soil moisture contents 70 to 120%. • Groundwater table close to the ground surface

To evaluate the feasibility of *Geopier* soil reinforcement for the creation of floating foundations, preliminary *Geopier* soil reinforcement designs were formulated for the two Mekong Delta sites described above, where unconfined compressive strength of the silty clay within depths of interest was 24 kPa (0.244 kg/cm^2) and 6 kPa (0.063 kg/cm^2). The *Geopier* soil reinforcement system designs for these sites are summarized in Table 5 and Table 6.

Because of the very weak subsoils within the Mekong Delta, a special construction procedure will be 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 should be over-drilled one meter deeper than required by the *Geopier* shaft length calculations. Clean stone is then dumped to a height of about 1.4 to 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.

Table 5 Geopier preliminary design for Vung Tau site

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 6 *Geopier* preliminary design for Nha Be Site

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

5. CONCLUSIONS

The *Geopier* floating foundation system has been successfully applied to a number of sites with similar subsurface conditions to the Mekong Delta. Three case histories of *Geopier* floating foundations in comparable subsurface conditions have been described in this paper.

Applications of the *Geopier* soil reinforcement system in supporting floating foundation systems in the Mekong Delta region of Vietnam have been shown to be technically feasible and appear to be cost effective compared to deep foundation systems and 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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