Innovative and Alternative Foundation System

Dr. Han Khee Kwong
IKRAM Runding Sdn. Bhd.
Malaysia

Dr. Nathaniel S. Fox
Geopier Global Corporation, USA

Dr. Bon H. Lien
Geopier Global Corporation, USA

ABSTRACT

An innovative ground improvement method developed in the 1980's has grown to become a floating foundation system to support lightly and moderately loaded structures. This floating foundation system consisting of very stiff, short rammed aggregate piers, is unique with stiffness modulus values of 10 to 55 times greater than unimproved matrix soils. This paper presents construction processes, design methodologies, and the feasibility of using this method as a floating foundation within the soft soils in Malaysia.

Key Words: *Floating foundation, ground improvement, soil reinforcement, stiffness modulus.*

1.0 INTRODUCTION

Rapid developments in Malaysia over the last few decades have increasingly required sites containing poor soils to construct buildings, industrial plants, and transportation structures. The poor soils include organic deposits, mined soil areas, marine and deltaic deposits, debris fills, uncompacted fills, and solid waste landfills. Some of these poor soils are several metres thick and are underlain by firm or loose strata extending to appreciable depths, which normally necessitate the use of deep foundation systems to transfer loads to competent strata in order to limit to tolerable settlements. Furthermore, the construction of lightly to moderately loaded structures at these sites is prohibitive when comparing the cost of foundation to the cost of constructing the superstructure. One technique to cope with this difficulty is to provide a floating foundation system to support the structure by increasing the stiffness of the uppermost soils sufficiently to limit settlements to design tolerances. Historical examples of this approach include making use of natural crust of stiff soil overlying softer deposits, over-excavating and replacing soft soils with stiffer materials, and installing friction piles. The *Geopier* soil reinforcing elements provide an alternative solution that is both cost effective and practical to the conventional methods of floating foundation (Fig. 1).

This paper describes engineering methods used to design *Geopier* soil reinforcing elements to create a floating foundation system for sites in Malaysia. Construction techniques and design background are discussed. Two case histories of *Geopier*-supported floating foundations are presented and followed by approaches formulated for two sites in Malaysia.

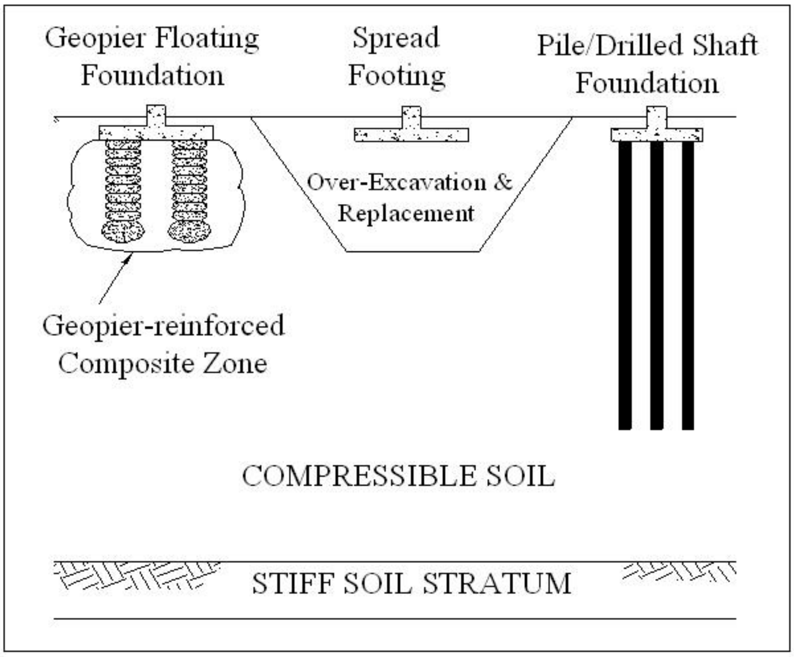

Fig. 1 Concept of floating foundations

2.0 DESCRIPTION OF *GEOPIER*

Geopier elements are constructed using the five-step process shown in Fig. 2. Holes of 0.6 m to 0.9 m diameter are drilled to depths that typically vary from approximately 3 m to 8 m below the ground surface. Temporary casing may be employed when the soil walls tend cave-in. The bottom of the drilled hole is stabilized by ramming a layer of aggregate/stone with a patented, high-energy beveled tamper. Thin lifts of well-graded aggregate are then placed into the hole and rammed with the same tamper to form a very dense, very stiff, undulating-sided pier. The final step is a preload application, applying a downward force on top of the completed pier for a preset period of time. This preload further pre-stresses and pre-strains the pier and surrounding matrix soils and effectively increases the stiffness and capacity of the system.

3.0 CHARACTERISTICS OF *GEOPIER* ELEMENTS

Geopier elements are approximately 10 to 55 times stiffer than pre-reinforced matrix soils, and exhibit high angles of internal friction. The ramming process increases the matrix soil lateral earth pressures in the vicinity of the piers and between piers, thus enhancing the matrix soils and making them stiffer. The composite reinforced zone of the *Geopier* elements and the matrix soils results in reduction the magnitude of settlements when subject to loading. Soil drainage within fine-grained soils is improved by the inclusion of *Geopier* elements, especially when open-graded stone is used in the pier construction. The *Geopier* elements are effective as uplift anchors when equipped with steel uplift harnesses. Because of high stress concentrations on *Geopier* elements, high friction angle of *Geopier* elements, associated stiffening of matrix soils, and the ductile nature of the composite system, *Geopier* soil reinforcement has proven highly effective in reducing earthquake-induced shear stresses within foundation bearing soils and in reducing the potential for soil liquefaction and associated potential for large movements of *Geopier*-reinforced foundation systems [1].

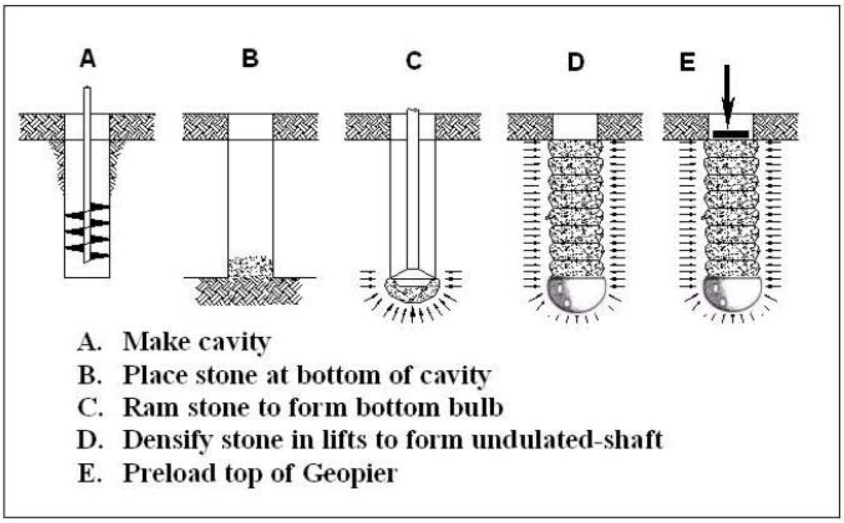

Fig. 2 *Geopier* construction

3.1 Stiffness And Shear Strength

The stiffness of *Geopier* elements is determined by full-scale modulus tests. A typical setup of modulus test is presented in Fig. 3. Tell-tale is used to record the settlement near the bottom of the pier. The modulus of a pier element is conservatively taken to be the ratio of applied vertical stress and the settlement at the top of pier.

Fig. 4 presents an example of the results of a modulus test on a *Geopier* element. Insignificant movement is observed at the bottom of the pier. This indicates a major portion of the applied load is distributed through the pier. The vertical stresses concentrated on piers are on the order of 10 to 50 times greater than vertical stresses on the matrix soils. Confirmation of the stiffness ratios of pier to matrix soils through field measurements was first obtained in 1998 during a research project in Salt Lake City, Utah [2].

The angle of internal friction representing shear strength of *Geopier* elements has been measured in the field from full-scale direct shear tests performed on installed *Geopier* elements [3]. The tested angles of internal friction are approximately 49 degrees for open-graded aggregate and 52 degrees for well-graded aggregate (Fig. 5). Angles of internal friction have also been measured in the laboratory for simulated *Geopier* elements with reconstituted samples of aggregate used in *Geopier* construction, compacted to relative densities approximating those of installed *Geopier* elements [4]. Laboratory results show an average angle of internal friction of 51 degrees.

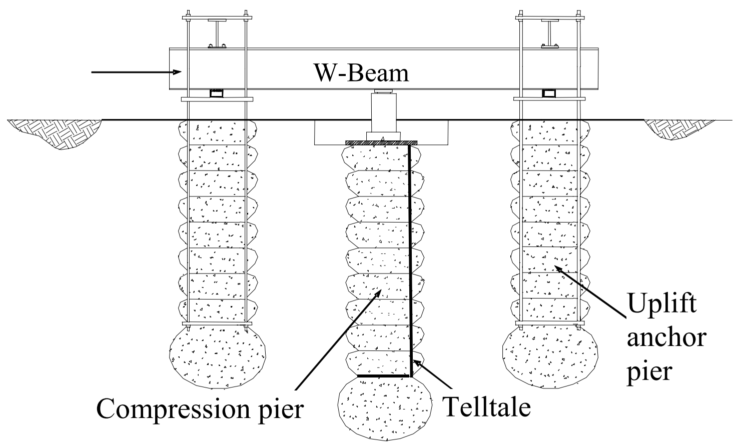

Fig. 3 Modulus load test setup

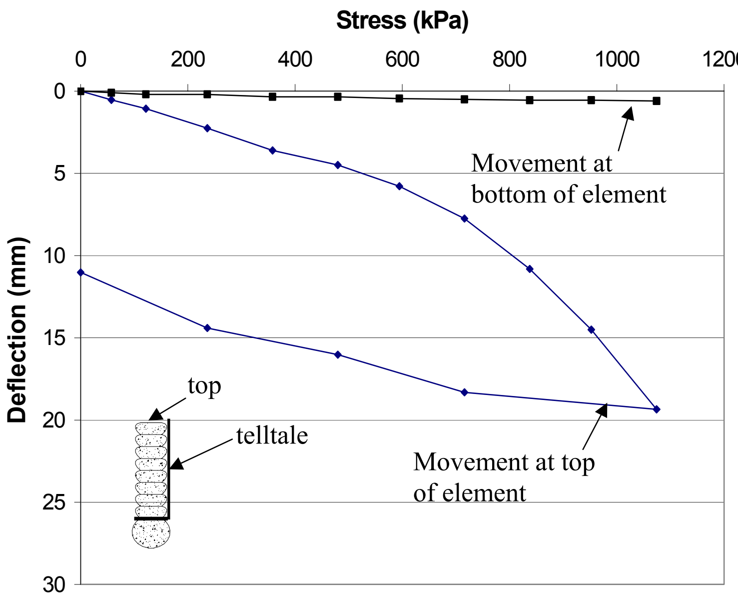

Fig. 4 Typical *Geopier* modulus load test results

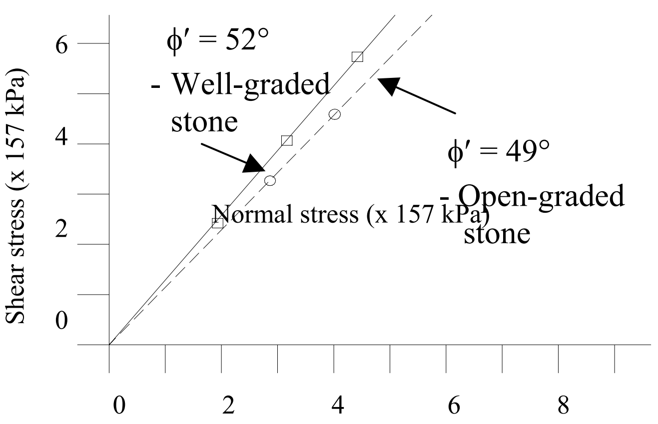

Fig. 5 Results of full-scale *Geopier* direct shear tests

3.2 Soil Lateral Stress Buildup

One principle fundamental to *Geopier* construction is the use of a beveled tamper for ramming the aggregate laterally against the hole sidewalls. As the soil "pushes back". Measurements have been made with the K_o Stepped Blade [5, 6, 7] to determine the magnitude and horizontal extent of lateral stress buildup during the *Geopier* installation process. Measured results have consistently indicated that passive lateral pressure conditions are developed in soils close to and between *Geopier* elements. Measurements also indicate that a significant lateral stress buildup occurs to a distance of about three to four times the pier diameter.

Geopier-reinforced structures are consistently observed to settle less than estimated [8, 9]. In a study that investigated the influence of lateral stress on foundation settlement, [7] concludes that high lateral stresses defer the onset of consolidation settlement to a substantially greater foundation load. Additionally, pullout measurements of *Geopier* elements over a period of the past ten years show near-linear-elastic load-deflection responses. These results provide a positive indication that there is a fundamental change in the soil behavior as a result of lateral stress buildup during installation of the *Geopier* elements.

3.3 Resistance to Uplift Loads

Because of the buildup of lateral soil stresses, the high internal friction angles of the piers, and the irregular, undulating pier surface, *Geopier* elements provide unusually high uplift resistance for their limited depth and length. Steel uplift harnesses installed during pier construction transfer loads from overlying footing or mat as shown on Fig. 6. Uplift load tests are performed to determine load-deflection behavior. Typical uplift design capacity ranges from 20 tonnes to 40 tonnes for 3 to 4 metre long shaft piers tested in pullout load tests.

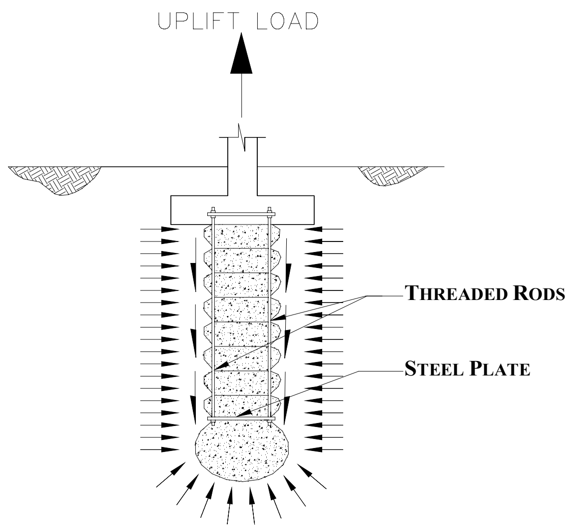

Fig. 6 *Geopier* uplift element

3.4 Resistance To Lateral Loads

Lateral loads are applied on foundations by wind, lateral earth pressures, and earthquakes. The lateral resistance provided by a *Geopier* soil reinforcement system is large compared to that provided by a footing that is not supported by *Geopier* elements. The sliding resistance for a *Geopier*-reinforced footing is the sum of the sliding resistance at the interface between the base of footing and the tops of *Geopier* elements plus the sliding resistance at the interface between the footing base and the matrix soil [3]. Because of the high concentrated normal stress acting on top the *Geopier* elements and the high angle of internal friction of the piers, most of the load resistance offered by *Geopier*-supported footings is attributed to the sliding resistance between the footing base and tops of the Geopier elements.

4.0 FLOATING FOUNDATIONS

Floating foundations do not extend completely through soft or compressible soil strata. Instead, these foundations consisting of a stiff composite layer penetrate sufficiently deep to distribute the applied load and reduce foundation settlement contributed by compression and consolidation of the underlying soft soils. *Geopier* elements are designed to create this stiff zone by increasing the composite stiffness of the subsurface soils within depths in which footing-induced stresses are the highest. The purpose is to limit long-term total and differential foundation settlements to satisfy structural design criteria. The design methodology does not require *Geopier* reinforcing elements to extend to a “better” soil layer.

4.1 Design Approach

To estimate settlements of a *Geopier* soil reinforcement system, two basic steps are used, i.e.,

- an analysis of the settlement contribution within the composite, *Geopier*-reinforced zone, also called the Upper Zone; and
- an analysis of the settlement contribution within the Lower Zone, below the bottoms of the *Geopier* elements.

The design methodology is to create a stiff *Geopier*-reinforcement zone and control total and differential settlements within the Upper and Lower Zones (Fig. 7). Settlement design criteria of 25 mm total settlement and 12 mm differential settlement are commonly used for normal buildings.

Modeling the *Geopier* elements and matrix soil as stiffer and less stiff elastic springs, respectively, and using the principle of static equilibrium, one can calculate stresses concentrate on tops of the stiffer piers in proportion to the stiffness ratio R_s, where R_s is the ratio of the stiffness modulus of the *Geopier* element (k_g) to the stiffness modulus of the matrix soil (k_m) [8].

The total downward force (Q) on the footing is balanced by resistance provided by the *Geopier* (Q_g) and matrix soil (Q_m), that is,

$$Q = q\,A = Q_g + Q_m = q_g\,A_g + q_m\,A_m \tag{1}$$

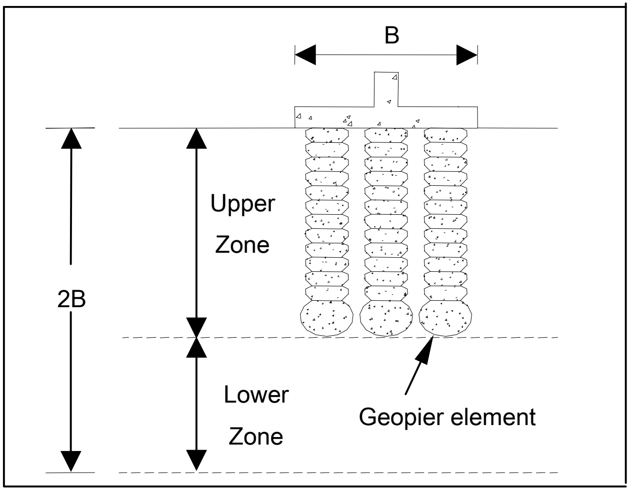

Fig. 7 Schematic of upper- and lower-zone

where q is the average contact pressure at the footing bottom, A is the footprint area of the footing, q_g is the stress applied to the *Geopier* elements, A_g is the cross-sectional area of all *Geopier* elements, q_m is the stress applied to the matrix soil, and A_m is the horizontal surface area of the matrix soil below the footing.

The footing can be considered to be rigid relative to the matrix soil and *Geopier* elements, the settlement of the footing portion bearing on the pier will equal the settlement of the footing portion bearing on the matrix soil, and the foundation settlement (s) can be estimated by applied stresses (q_g and q_m) and stiffness modulus (k_g and k_m) of *Geopier* and matrix soil, respectively:

$$s = q_g / k_g = q_m / k_m \quad (2)$$

Rewriting 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):

$$q_m = q_g \, k_m / k_g = q_g / R_s \quad (3)$$

Combining equations 1 and 3 and defining area ratio (R_a) as the ratio of the cross-sectional area of the *Geopier* elements (A_g) to the gross footprint area of the footing (A):

$$q = q_g R_a + q_g (1 - R_a) / R_s \quad (4)$$

Rewriting q_g in terms of q:

$$q_g = q R_s / (R_s R_a - R_a + 1) \quad (5)$$

Upper-zone settlements are then computed using equation 2 based on values obtained from equation 5.

Settlements in the Lower Zone soils are computed using stress distribution solutions (such as Westergaard solution) and conventional settlement analysis procedures. The conventional stress distribution assumption is believed to be conservative because the presence of the piers results in a stress transfer and stress dissipation with depth, which is more efficient than that occurs under non-*Geopier* reinforced spread footings [2].

5.0 CASE HISTORIES

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

5.1 Pricesmart Superstore, The 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 metres below ground. The original design called for 6,500 square metres of suspended structural floor slab to be supported by bored piles. Driven piles were ruled out because of potential damage to surrounding residential areas from excessive vibrations during pile driving. By adopting a Geopier floating foundation system, costly bored piling and suspended floor slabs were 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 metres were installed in 60 working days reducing the project completion schedule by 60 days.

Design soil profile data and Geopier modulus test results of the project are presented in Fig. 8. A modulus test performed on site produced a Geopier stiffness modulus value of 83 MN/m^3. The Geopier-reinforced upper zone settlements were estimated to range from 10 mm to 15 mm. The Geopier construction saved about 50% of foundation costs. Post-construction measurements of the floor slab flatness indicate that no measurable differential floor slab deformations have been taken place.

5.2 Marriott Courtyard Hotel, USA

The Marriott Courtyard Hotel in Portland, Oregon, USA, is a five-storey concrete and wood-frame building. Column loads range between 100 and 175 tonnes. The site is underlain by 12 m thick of very soft floodplain deposits that precluded the use of conventional spread footings on the original soils. Geopier elements were installed by drilling to a depth of 4.7 m to support the footings designed with a bearing pressure of 215 kPa, leaving approximately 7.3 m 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. Lower zone settlements were estimated to be 10 to 13 mm. The design soil profile data and Geopier modulus test results of the project are presented in Fig. 9.

0 to 5 m - Very soft to firm 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

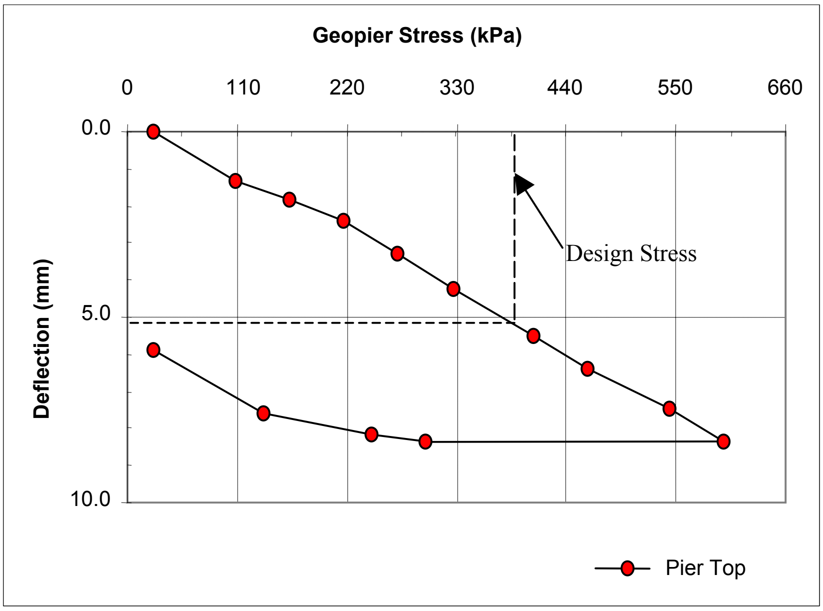

Fig. 8 Pricesmart design soil profile and modulus test results

0 to 12m - Very soft silty clay, SPT-N = 1 to 2
Groundwater table at 3 m deep

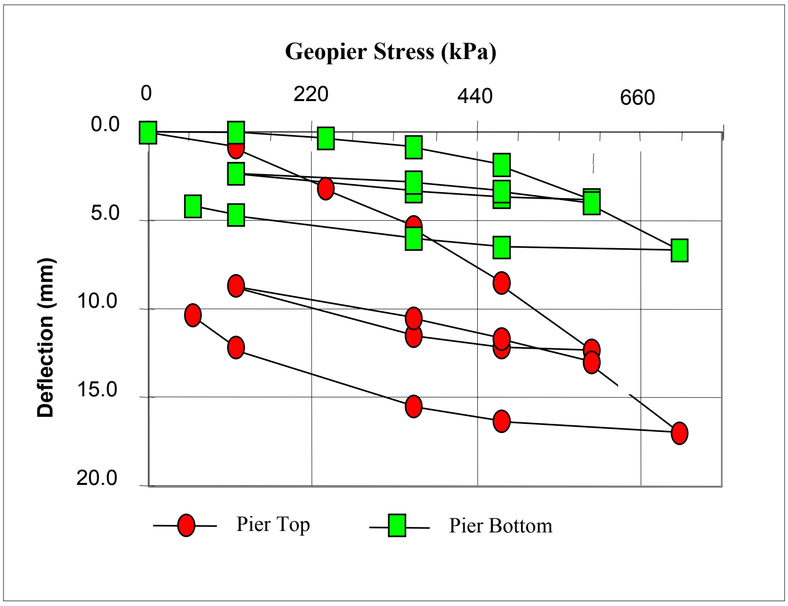

Fig. 9 Marriott Courtyard design soil profile and modulus test results

6.0 *GEOPIER* DESIGN FOR MALAYSIAN SOILS

Two project sites which had been previously designed using precast concrete piles are re-designed using *Geopier* floating foundations. It demonstrates that *Geopier* floating foundations designed for these two sites are more cost-effective compared to the driven pile foundation even though the piles are relatively short, 14 m to 20 m.

6.1 Site 1: Johor Bahru, Johor

The subsurface conditions are characterized by a layer of very loose clayey sand to depth of 3 m, followed by 1 m thick of very soft silt, which is then underlain by loose clayey sand of 2 m thick and medium stiff clay of 3 m thick. Below this depth, dense clayey sand was encountered down to about 14 m. Groundwater table was located at about 3 m below ground surface. The standard penetration resistance of the top clayey sand ranges from 2 to 3 blows/0.3 m while that of the bottom clayey sand and clay is about 8 to 9 blows/0.3 m.

A four-storey extension of an existing school was constructed on this site. Precast concrete piles of 300x300mm were driven to refusal in order to support column loads ranging from 650 kN to 1630 kN. The installed pile penetration depths were about 14m.

Geopier floating foundation systems are designed based on the column loads and soil conditions. Summary of the *Geopier* designs compared to the installed piles are presented in Table 1.

Because of the very weak subsoils, 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. 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 1 *Geopier* alternative design for Johor Bahru site

Column load	650 kN	1200 kN	1630 kN
Design square footing width	2m	2.2m	2.3
No. of *Geopier* elements per footing	3	4	6
Design *Geopier* drill depth below footing	3.5m	4.2m	4.5m
Design *Geopier* compacted shaft length	2.5m	3.2m	3.5m
Estimated Geopier Foundation Total Settlement	25mm	25mm	25mm
Installed RC pile size	300 x 300mm	300 x 300mm	300 x 300mm

No. of piles per pilecap	1	2	3
Driven length	14 m	14 m	14 m

6.2 Site 2: Pontian, Johor

The ground to a depth of 8m consists of very soft clay with an average shear strength of 12 kPa, which is underlain by medium stiff gradually becoming hard silty clay to a depth of 21 m. The groundwater table was located close to the ground surface. The very soft clay is normally consolidated with a sensitivity of about 4.

A mosque was constructed at this site by installing 200x200mm precast concrete piles to depth of about 20m. The column loads varied from 90 kN to 550 kN.

Geopier floating foundation systems are designed based on the column loads and soil conditions. Summary of the *Geopier* designs compared to the installed piles are presented in Table 2.

Table 2 *Geopier* alternative design for Pontian site

Column load	90 kN	372 kN	550 kN
Design square footing width	1.1m	2m	2.3
No. of *Geopier* elements per footing	1	3	5
Design *Geopier* drill depth below footing	2.5m	3.65m	4.25m
Design *Geopier* compacted shaft length	1.5m	2.65m	3.25m
Estimated Geopier Foundation Total Settlement	25mm	25mm	25mm
Installed RC pile size	200 x 200mm	200 x 200mm	200 x 200mm
No. of piles per pilecap	1	2	2
Driven length	20m	20m	20m

7.0 CONCLUSIONS

The *Geopier* floating foundation system has been successfully applied to a number of sites with poor soils, which normally required piled foundations to support lightly to moderately loaded structures. Applications of the *Geopier* soil reinforcement technique have been shown to be technically feasible and are cost effective and time saving compared to deep foundations and massive over-excavation and replacement methods.

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