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Geopier® Floating Foundations – A Solution for Roadway Embankments Over Soft Soils in Asia

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ABSTRACT: Geopier® soil reinforcement consisting of very stiff short aggregate piers, has been used as a ground improvement method in the United States since 1989 and is gaining popularity in Asia and Europe. This ground improvement technique is unique with stiffness modulus values of aggregate pier elements measured to be 10 to 45 times greater than unimproved matrix soils. The described system has been found to be effective and economical to reinforce peat, highly organic clays and very soft soils as well as fair to good soils. This paper discusses the feasibility of using Geopier soil reinforcement as a "floating foundation" system for roadway embankments to be constructed over very soft organic clays and peat found in Sarawak, Malaysia, and a very soft to soft sandy silt site in Korea.

INTRODUCTION

The design of embankment fill constructed over soft compressible native or fill soils is a common problem in geotechnical engineering practice. Engineers must consider total and differential settlements as well as global stability and their impacts on the performance of embankment and constructed pavement systems.

Sarawak state of Malaysia has 13% of its land covered by organic deposits found along its coastal lowlands. Road embankments constructed on these soils have experienced large total and differential settlements, slope failures, global instabilities and long-term excessive settlements. Conventional methods such as overexcavation and replacement of the compressible soils, staged construction with vertical drains, preloading and deep foundations can mitigate the problems associated with high compressible and very low strength soils. However, these methods are costly, and require long consolidation times. In recent years, an alternative solution has emerged involving the use of Geopier soil reinforcement technology.

The concept of the Geopier soil reinforcement method is to provide a "floating foundation" system for the road embankments by increasing the stiffness of the uppermost soils sufficiently to limit settlements to design tolerances. In addition, the permeable piers act as vertical drains to accelerate the dissipation of excess pore water pressure, and to increase consolidation rate in the soft clays.

This paper discusses Geopier soil reinforcement technology, construction and design background for the creation of floating foundation systems. Two roadway embankment design cases are also presented; one with embankment fill overlying relatively deep soft peat deposits in Kuching, Malaysia. The other project requires a high embankment fill overlying very soft to soft sandy silt soils for an embankment in Korea.

GEOPIER SOIL IMPROVEMENT TECHNOLOGY

Geopier soil reinforcement technology is regularly utilized to support compressive loads of footings, floor slabs, and steel storage tanks. The effectiveness of this technology is attributed to lateral prestressing and prestraining that occur within the matrix soils during construction, and to the high strength and stiffness of the installed aggregate piers. In recent years, Geopier soil reinforcement systems have expanded to include transportation-related sector applications such as stabilizing foundation soils below retaining walls and embankments (Figure 1) and stabilizing active landslides.

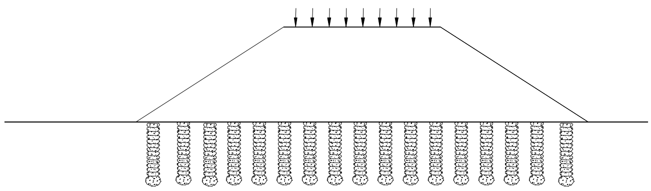


Figure 1 Geopier-reinforced soils beneath embankment

The design of the Geopier soil reinforcement system uses classical geotechnical engineering approaches in conjunction with results of field and laboratory tests to evaluate the shear strength and compressibility of the Geopier elements (Fox and Lien, 2001).

GEOPIER CONSTRUCTION

The patented Geopier construction process is well described in the literature (Lawton and Fox 1994, Lawton et al. 1994, Wissmann and Fox 2000, Wissmann et al. 2000, Minks et al. 2001) and involves the five-step process shown on Figure 2.

1. Cavities are created by drilling 600 mm to 900 mm diameter holes to depths that typically vary from about 2.5 m to 8 m below the ground surface. Temporary casing may be employed when the soil walls are not stable and cave-ins occur. The casing is placed to the

depth required, and is pulled up about 300 mm at a time, while each layer below the casing is being formed. The most common drillhole diameter for Geopier elements is 750 mm.

2. Place a layer of clean, crushed aggregate at the bottom of the drillhole.

3. A stable bottom is then formed by ramming the aggregate using a patented, high-energy beveled tamper. The applied energy is not a vibration energy, but is an impact ramming energy, with limited amplitudes (about 10mm), and impact ramming frequencies ranging typically from 300 to 600 cycles per minute.

4. Thin lifts (300 mm) of aggregate are then placed into the hole and rammed with the same tamper to form a dense, very stiff, undulating-sided pier. The beveled tamper forces the stone laterally into the sidewall of the excavated cavity. Consequently, the lateral stress within the matrix soil increases, thus providing additional stiffening, increasing the shear stress resistance within the matrix soils, and improving the compression characteristics of the reinforced composite materials. An analysis of the contribution to improving the compression characteristics due to soil lateral stress buildup was developed and presented by Handy (2001).

5. 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 adjacent matrix soils and effectively increases the stiffness and capacity of the system.

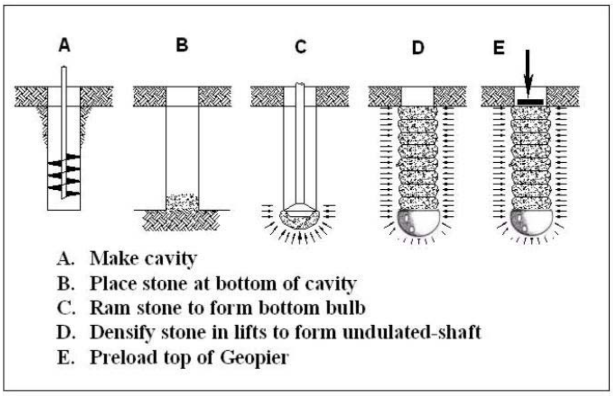


Figure 2 Geopier *Rammed Aggregate Pier™* Construction

GEOPIER STIFFNESS MODULUS

Stiffness modulus values of installed Geopier elements are determined by full-scale modulus tests . The test is performed by applying pressure in gradual increments over the full cross-section area at the top 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, and is typically expressed in English units as pci, and in metric units as MN/m^3. The Geopier modulus load 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 load test results. Geopier modulus tests are normally performed to a top of Geopier stress equal to 1.5 times the maximum design stress. The purpose of applying load to more than the design stress is mainly to observe the deformation characteristics at higher stress levels.

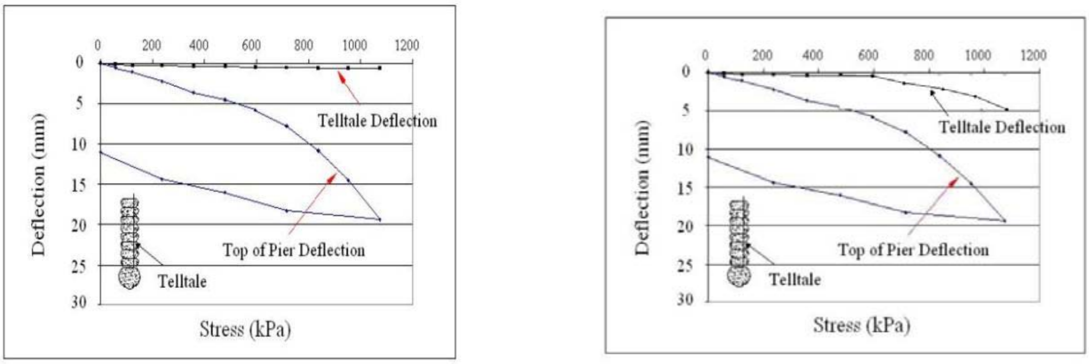
More than 400 modulus tests have been performed during the past twelve years covering a wide spectrum of soil conditions. Figure 3 presents an example of one modulus load test plot. Results of these modulus tests indicate that pier stiffness is significantly higher than pre-reinforced matrix soil stiffness, and is on the order of 10 to 50 times higher. From static equilibrium and with the assumption that the supported footing is perfectly rigid, one can determine the vertical stresses concentrated on piers, which are on the order of 10 to 50 times greater than the vertical stresses on the matrix soils since stresses must redistribute within the footing according to the ratio of stiffness of Geopier to matrix soil. 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 (Lawton 2000).

GEOPIER FLOATING FOUNDATIONS

Sites with soft, compressible soils extending to appreciable depths often specify the installation of deep foundation systems to transfer structural loads to competent soils and reduce settlements.

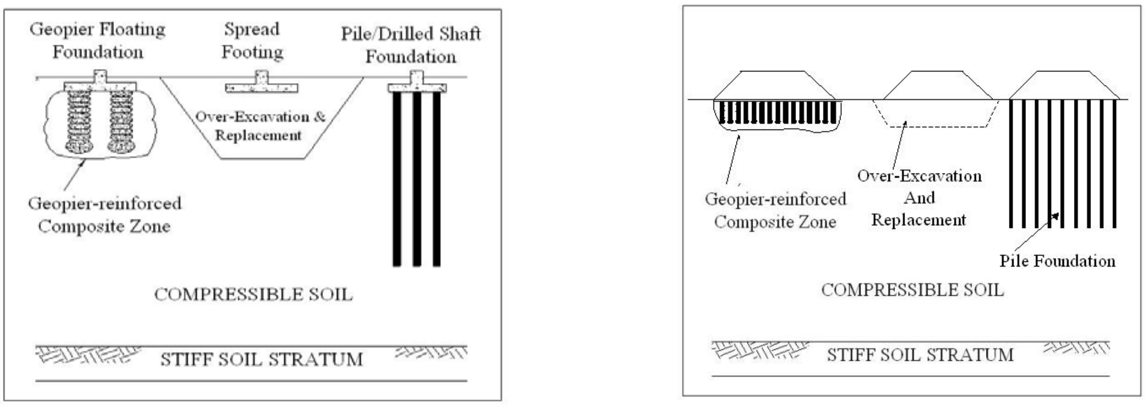
An alternate foundation system is to provide a “floating foundation” for the structure by increasing the rigidity of the uppermost soils sufficiently to limit settlements to design tolerances. Historical examples of the floating foundation system for shallow foundations are shown in Figure 4. The “floating foundations” do not extend completely though 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.

The Geopier design methodology does not require the Geopier reinforcing element to extend to a “better” layer. Thus, the normal Geopier design technique is compatible with a floating foundation system. By creating a Geopier-reinforced zone with an increased composite stiffness, the end result is to limit long-term total and differential foundation settlements to satisfy structural design criteria. If it is convenient to do so within a limited depth (typically less than 8 metres), then elements may be extended to the stiff layer depending on performance estimates and economics.



(a) (b)

Figure 3 Typical Geopier modulus test results (a) where pier bulging occurs at higher stress levels, (b) where pier bottom deflects at higher stresses



(a) (b)

Figure 4 Concept of floating foundations applied to (a) footings (b) embankments

ROADWAY EMBANKMENT DESIGNS

The design methodology of estimating embankment fill foundation settlement within the Geopier-reinforced zone is presented by Minks et al. (2001). Detailed discussions of improving global stability and controlling settlement with Geopier soil reinforcement are presented in Wissmann et al. (2002). Installation of the Geopier soil reinforcement system for roadway embankment support will increase the global stability, decrease the magnitude of foundation settlement, and increase the rate of consolidation settlement in the following ways:

- Discrete volumes of relatively compressible matrix soils are replaced with stiffer materials and the applied embankment stresses concentrate to the relatively stiff Geopier elements. Consequently, the vertical stresses on the consolidating matrix soils from the embankment loads are reduced. Significance of the stress concentration effect depends upon the stiffness ratio of the pier and matrix soil modulus values and on the relative rigidity of the interface between top of Geopier elements and bottom of embankment. The higher the stiffness ratio, and the greater the interface rigidity, the more stresses are concentrated on the top of the Geopier elements.

- The increase in lateral earth pressure that occurs as a result of aggregate ramming allows for greater applications of vertical stress prior to the onset of consolidation (Handy 2001).

- By utilizing aggregate to construct the Geopier, the piers act as a vertical drain and significantly reduce the drainage path for the dissipation of excess pore water pressure within the Geopier-reinforced zone. Consequently, the rate of consolidation settlement is increased. Han and Ye (2001) describe the combined effects of horizontal drainage and the reduction in matrix soil vertical stress from stress concentration.

- Installation of Geopier elements at a given spacing in either a square or equilateral triangular grid pattern will also accelerate the rate of consolidation in the compressible soil layer lying underneath the bottom of the Geopier elements by significantly reducing the length of drainage paths required for pore water to travel within the lower soils.

The Geopier soil reinforcement system design is to control post-construction settlements within appropriate project design allowable settlement criteria. The "post-construction settlement" is defined as the estimated future settlement after the proposed embankment fills are completed subsequent to the time of beginning of pavement operations. This is the settlement that will affect the performance of the roadway pavement when subjected to traffic loads.

Roadway Embankment Design Case I:

The Geopier soil reinforcement system design presented is for conditions of two embankment heights of 2.5 and 5 metres for a project site in Kuching, Malaysia. The typical subsurface conditions at the project site consist of 1.5 metres of sandy silt fill material below the existing ground surface, underlain by a stratum of peat 4.5-metres thick. A 2 to 3 metre thick layer of soft to stiff silty clay and clayey silt exists below the peat, which is underlain by competent limestone. The groundwater table was located close to the exiting ground surface. Geotechnical field and laboratory design parameter values are presented in Table 1.

Table 1 Geotechnical field and laboratory design parameter values for Kuching site

Soil Parameter	Field / Laboratory Value
Total unit weight, γ_t	9.9 kN/m^3 (63 pcf)
Moisture content, w_n	400 – 800
Compression index, C_c	0.28
Initial void ratio, e_o	9.72
Estimated coefficient of consolidation in radial direction, C_r	0.0057 cm^2/s (0.53 ft^2/day)

The Geopier soil reinforcement system has been successfully applied to many sites with peat, highly organic soil and very soft soil zones (Fox and Edil, 2000). Design details of the Geopier soil reinforcement system for the 2.5-metre and 5-metre embankments for this project are summarized in Table 2. Estimates of settlements within the reinforced soil zone were performed using the design methodology described by Minks et al. (2001). Assuming a 90-day embankment construction period of time prior to initiating pavement construction, the degree of consolidation within the Geopier-reinforce zone was calculated to be close to 95%. The rate of consolidation increases significantly due to the improved radial drainage and stress concentrations to the stiff pier elements. Conventional vertical consolidation calculations (without Geopier reinforcement) indicate a degree of consolidation equal to approximately 40% after the same duration of loading. The estimated post-construction settlements with Geopier reinforcement are 5.3cm and 7.3cm for embankment heights of 2.5m and 5.0m, respectively, compared to 45cm and 70cm, respectively, for the cases with no Geopier reinforcement. These values of post-construction settlements are within the tolerable limits for roadway embankments.

The design Geopier element stiffness modulus (k_g) values are 8 MN/m^3 (30 pci) and 11 MN/m^3 (40 pci) for cases with 2.5m and 5.0m design embankment heights, respectively. Please be noted that the pier elements must penetrate through the peat layer and tag the top of an underlying soil layer. The concept of a “floating foundation” system remains applicable since the pier elements are not extended to competent soil layers below the peat layer.

For this particular project, due to the existence of the highly compressible peat layer and the low to moderate heights of embankment, a thin structural slab or a geogrid-reinforced aggregate raft is planned to be constructed above the piers to facilitate distribution of the constructed embankment fill stresses to the stiffer Geopier elements. Based upon results of a recently completed research project (White et al. 2002), and with the application of the structural slab or geogrid-reinforced raft, differential settlements between the Geopier element and the matrix soils are anticipated to be insignificant.

Roadway Embankment Design Case II:

The Geopier soil reinforcement system design for an embankment project site in Korea contains 4 to 10 metres of very soft to soft sandy silt, with standard penetration test blow counts (N-values) ranging from 1 to 4 blows per 0.3m. The compressible sandy silt is underlain by a medium dense to dense sand and sandy gravel layer, with N-values ranging from 10 to 50. The groundwater table was observed at approximately 1m below the exiting ground surface. Geotechnical field and laboratory design parameter values are presented in Table 3.

Design details of the Geopier soil reinforcement system for the 4m and 10m embankment heights are summarized in Table 4. Assuming a 120-day embankment construction time, using the methodology presented above, the degree of consolidation within the Geopier-reinforced zone was calculated to be close to 95%. Conventional vertical consolidation calculations (without Geopier reinforcement) indicate a degree of consolidation equal to approximately 40% after the same duration of loading. The estimated post-construction settlements with Geopier reinforcement are 11cm and 17cm for embankment heights of 4 m and 10 m, respectively, compared to 38cm and 60cm, respectively, for the cases with no Geopier reinforcement.

Based upon the 4 to 10 metre thick stratum of sandy silt, with N-values = 1 to 4, the Geopier design stiffness modulus value estimated is 19 MN/m^3 (70 pci). Since the post-construction settlement within the medium dense to dense sand and sandy

Table 2 Design of 0.76m diameter, 6-m long Geopier elements

Design embankment height	Equilateral triangular spacing	Post-construction settlement			Estimated % of embankment load taken by	
		Zone I*	Zone II**	Total	Geopier	Matrix soils
2.5 m	3.25 m	2.0 cm (0.8 in)	3.3 cm (1.3 in)	5.3 cm (2.1 in)	86%	14%
5.0 m	2.15 m	2.0 cm (0.8 in)	5.3 cm (2.1 in)	7.3 cm (2.9 in)	93%	7%

* Zone I : Geopier-reinforced zone
** Zone II: Compressible layers below Zone I

Table 3 Geotechnical field and laboratory design parameter values for Korea site

Soil Parameter	Field / Laboratory Value
Total unit weight, γ_t	15.7 kN/m^3 (100 pcf)
Liquid limit, LL	45
Overconsolidation ratio, OCR	1.5
Compression index, C_c	0.45
Initial void ratio, e_o	1.32
Estimated coefficient of consolidation in radial direction, C_r	0.006 cm^2/s (0.56 ft^2/day)

Table 4 Design of 0.76m diameter, 6-m long Geopier elements

Design embankment height	Equilateral triangular spacing	Post-construction settlement			Estimated % of embankment load taken by	
		Zone I*	Zone II**	Total	Geopier	Matrix soils
4.0 m	3.50 m	2 cm (0.8 in)	9 cm (3.5 in)	11 cm (4.3 in)	75%	25%
10.0 m	1.90 m	2 cm (0.8 in)	15 cm (5.9 in)	17 cm (6.7 in)	95%	5%

* Zone I : Geopier-reinforced zone
** Zone II: Compressible layers below Zone I

gravel layer will be insignificant, the Geopier design needs to achieve a post-construction settlement contribution exclusively from the sandy silt layer to satisfy the project design allowable settlement requirements.

To complement the above designed Geopier soil reinforcement system, some options can be considered to further reduce the post-construction settlements and enhance the performance of the roadway pavement. These options include:

1. Plan the embankment construction to allow for longer period of time for consolidation settlements to occur prior to construction of the pavement, especially in areas with poorer, thicker compressible soil layer and higher embankment fill.

2. Rather than the nominal 6-metre Geopier element shaft length, construct an 8-metre long Geopier element. This will further reduce the total consolidation settlement within the compressible soil layer located below the bottom of the aggregate piers.

CONCLUSIONS

The Geopier floating foundation system has been successfully applied to numerous sites with very soft to soft soil conditions during the past decade. Two roadway embankment design cases utilizing Geopier floating foundations in Asia have been described in this paper.

Applications of the Geopier soil reinforcement system to support embankment fills overlying soft, compressible soils are technically feasible and are usually highly cost effective compared to deep foundation systems, massive over-excavation and replacement methods, or other soil improvement techniques. By installing Geopier elements to create an upper stiff reinforced composite zone, the floating foundation design approach can be utilized to control foundation settlements and satisfy reasonable structural design criteria.

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