Geopier® Intermediate Foundation Systems – Case Studies for Building Foundations over Soft Organic Soils and Peat

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ABSTRACT: Geopier® intermediate foundation systems incorporate very stiff aggregate piers to reinforce weak and compressible peat and highly organic soils. The Geopier system has been used as a soil improvement method in the United States since 1989, and more recently in the Caribbean, Europe and Asia. Traditionally, buildings supported on peat and highly organic soils require deep foundations or massive overexcavation of the poor soils and replacement with select fill materials. In the past ten years, several different ground improvement methods have attempted to treat such problematic soils, but without satisfactory performances. Within the past eight years, the Geopier system has been used within peat and highly organic soil sites to successfully support a number of large buildings. Two reasons for the unique success of the Geopier method in reinforcing peat and highly organic soils include: (1) the patented construction method prevents significant mixing and contamination of the highly organic soils and peat with the aggregate materials, unlike soil mixing or stone column methods; and (2) the unique prestressing and prestraining of the poor matrix soils during installation of the aggregate piers stiffens these soils and increases perimeter shear resistance of the constructed piers. The Geopier method requires complete penetration of the peat and highly organic soil layer. Yet the pier cavity often bears on soft and compressible inorganic soils since, by design, it does not have to extend to a good soil layer. Settlements of shallow foundations supported by Geopier elements in peat and highly organic soils are typically designed and controlled for maximum settlements of 25 mm or less. This paper discusses feasibility, design approaches, and case histories using the Geopier system to support structures constructed over peat and highly organic soils. Results of full-scale modulus tests to confirm the design parameters are also discussed.

***Key Words**: Geopier, rammed aggregate pier, intermediate foundation, soil improvement, soil reinforcement, prestressing, prestraining.*

1. INTRODUCTION

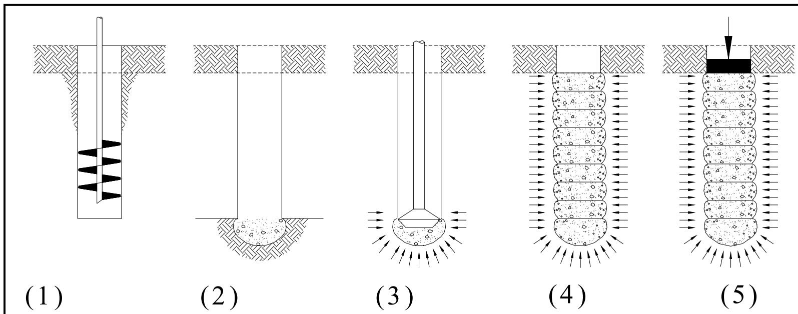
When structures are constructed at sites that contain deep soft soil deposits, deep foundation systems, such as driven piles or bored piles, are typically used to transfer structural loads to competent materials. For lightly to moderately loaded structures, engineers are now able to design a cost effective foundation system by increasing the rigidity of the uppermost soils sufficiently to limit settlements to design tolerances. This paper will present further challenges and successful project case histories of applying the Geopier intermediate foundation system to support structures over soft organic soils and peat.

Geopier intermediate foundation systems incorporate very stiff aggregate piers to reinforce weak and compressible peat and highly organic soils. Geopier rammed aggregate piers have been used as a soil improvement method in the United States since 1989, and more recently in Europe and Asia. An overview of the Geopier system is presented by Fox and Lien, 2001 [1].

Traditionally, when encountering peat or soft organic soils, engineers design deep foundations or choose to over-excavate the poor soils and replace with select compacted fill materials to support the structures. In the past ten years, several different ground improvement methods have attempted to treat such problematic soils, but often without satisfactory performances. The Geopier intermediate foundation system has been used within peat and highly organic soil sites to successfully support numerous large building projects since 1995, and has consistently controlled the maximum foundation settlement to 25 mm or less. Two reasons for the unique success of the Geopier method in reinforcing peat and highly organic soils include: (1) the patented construction method prevents significant mixing and contamination of the highly organic soils and peat with the aggregate materials, unlike soil mixing or stone column methods; and (2) the unique prestressing and prestraining of the poor matrix soils during installation of the aggregate piers stiffens these soils and increases perimeter shear resistance of the constructed piers (Handy, 2001 [2]). It is required that Geopier elements fully penetrate the peat and highly organic soil layer during the construction. Yet the pier cavity often bears on soft and compressible inorganic soils since, by design, it does not have to extend to a good soil layer. This paper discusses the feasibility, design approaches, and case histories of using the Geopier intermediate foundation systems to support structures constructed over peat and highly organic soils. Results of performing field full-scale modulus tests to confirm the design parameters used in Geopier design methodology are also discussed.

2. GEOPIER CONSTRUCTION

Geopier elements are typically constructed by drilling 760 mm diameter holes to depths ranging between 2 to 8 meters below the footing bottoms; placing controlled, 300 mm lifts of aggregate within the cavities; and densifying the aggregate using a specially designed and patented, beveled, high-energy impact tamper (Figure 1). The first lift consists of “clean open-graded stone” (typically 40 to 100 mm in diameter and without sand and soil fines) and is rammed into the soil to form a stabilized bottom bulb. The remainder of the pier is constructed of either open-graded or well-graded aggregate, densified in thin, 300-mm 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[2].



(1) Drill cavity.
(2) Place stone at bottom of cavity.
(3) Ram stone to form bottom bulb.
(4) Densify stone in lifts to form undulated-shaft.
(5) Preload top of the rammed aggregate element.

Fig.1 Geopier Rammed Aggregate Pier Construction

3. GEOPIER INTERMEDIATE FOUNDATION SYSTEM

Lawton and Fox, 1994 [3] and Lawton et al., 1994 [4] present fundamentals of the Geopier design approaches. Foundation settlements are estimated by adding the settlement contributions computed from the upper Geopier-reinforced zone and those from the lower non-reinforced zone (Figure 2). The design goal is to limit long-term total and differential foundation settlements to satisfy structural design criteria. Settlement design criteria of 25 mm total settlement and 12 to 19 mm differential settlement between columns are commonly used for most structures in the United States.

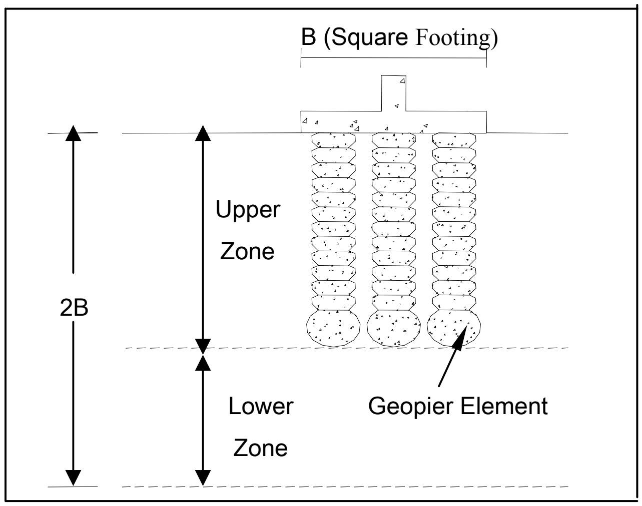


Fig.2 Schematic of Geopier upper- and lower-zone

The Geopier upper zone settlement, S is estimated by

$$S = q_g / k_g \qquad (1)$$

$$q_g = \{q R_s / [R_a R_s + 1 - R_a] \} \qquad (2)$$

Settlements contributed by the lower, non-reinforced zone soils are calculated using conventional geotechnical stress distribution (such as the Westergaard solutions) and traditional geotechnical settlement analysis procedures.

4. GEOPIER INTERMEDIATE FOUNDATION IN PEAT AND SOFT ORGANIC SOILS

When encountering peat or soft organic soil deposits, the most common design solution is to excavate and replace the peat or soft organic soil deposits with selected fill material. However, this solution is cost prohibitive if the peat deposit is extensive, or if satisfactory fill material is not readily available. Other foundation systems and soil improvement techniques that have been attempted in peat or soft organic soil deposits include:

- Deep pile foundation, which is usually expensive.
- Preloading, which is time-consuming.

- Deep in-situ soil mixing using lime and cement. Edil, 1999 [5] comments that its applications in organic soils have been unsatisfactory, because the organic matter restrains the cementitious reactions that are responsible for strength gain.
- Geopier intermediate foundation system.

The basic concept of an intermediate foundation system is that the bottom of the foundation system is able to remain within soft, compressible soil layers. The Geopier design practice for supporting foundations with peat or organic soils requires the Geopier aggregate elements fully penetrate the peat and organic soil layers.

The time typically needed to construct a Geopier element ranges from 10 to 20 minutes. Therefore the drilled hole remains a short duration. Temporary casing is not needed during the Geopier construction in peat, because the peat, especially if normally consolidated, exhibits zero or small effective cohesion and generally high effective friction angles (Edil, 1999 [5]). The open cavity in peat typically remains open for a relatively long period of time.

5. GEOPIER STIFFNESS MODULUS IN PEAT AND ORGANIC SOILS

The stiffness modulus value corresponding to 100% of the design stress applied to the top of the Geopier element is determined by performing full-scale field modulus tests. The stiffness modulus is typically expressed in English units as pci, and in metric units as MN/m^3. 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 behavior at high stress levels.

More than 600 Geopier modulus tests have been performed since 1989 over a wide spectrum of soil conditions. Results of these modulus tests indicate that the stiffness ratio between the pier stiffness and the soil stiffness is on the order of 10 to 50 times; in cases with Geopier installed in peat and soft organic soils, the stiffness ratio is on the high side of this range and even higher. From static equilibrium and with the assumption that the supported footing is perfectly rigid, one can determine the vertical stress concentration on piers. Vertical stresses on top of piers 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.

Fox and Cowell, 1998 [6] established a database based upon results of modulus tests performed in various soils with elements of various shaft lengths and diameters. Typical Geopier design parameters for peat and soft organic foundation soils are presented in Table 1.

Table 1 Typical Geopier Design Parameters for Peat and Organic Foundation Soils

Soil Classification	SPT N-Value	UCS (kN/m^2)	Geopier Element Support Capacity (Cell Capacity) Qcell (kN)	Geopier Stiffness Modulus, k_g (MN/m^3)
Peat	1-3	10-48	133	20
	4-6	48-110	200	30
	7-9	110-168	245	34

6. CASE STUDIES

6.1 Mini-Storage Building in Edina, Minnesota, USA

Geopier intermediate foundations were designed to support a thickened edge slab foundation for a mini-storage building in Edina, Minnesota, USA. The building is a two-story, rectangular-shaped structure of masonry and steel frame construction covering a footprint of 1800 m^2. The interior bearing wall loads are 67 kN per lineal meter, with perimeter wall loads of 44 kN per lineal meter or less. The allowable live floor loading is 6 kPa at the first floor level. A maximum fill thickness of 1 meter was placed to raise the site to the design finish grade.

The five soil borings encountered approximately 0.9 to 1.5 meters of silty sand and silt fill underlain by sapric peat, organic silt and clayey silt with organics, to depths of 1.8 to 4.0 meters. The Standard Penetration N-values in the organic soils varied from 2 to 11, and the moisture contents ranged from 40 percent to over 300 percent. Beneath the organic strata, the borings found loose glacial outwash sand deposits to 9 meters deep, underlain by stiff to very stiff clayey glacial till. The observed groundwater level was within or just below the organic soil zone.

One of the design alternatives was to use driven piles, 17 to 18 meters long, with a structural floor slab, grade beams and pile caps. The Geopier intermediate foundation system was selected because it was more economical than the deep foundation system, and a conventional thickened edge slab could be used.

A Geopier element stiffness modulus of 27.2 kN/m^3 and a unit cell capacity of 200 kN were estimated for design. A total of 237 Geopier elements were installed. Each 760-mm diameter pier extended through the fill and organic soil layers into the underlying sand and clay. The elements were constructed using clean crushed limestone (38 mm and greater) in the lower 0.6 to 1.2 meters of the shaft, followed by well-graded highway base course crushed limestone aggregate for the remainder of the shaft. No casing was required within the peat and organic soil layers. A short temporary steel casing was used during the construction to keep the shaft open due to caving wet sand layers above the organic zone.

6.2 Auto Parts Store Addition, Saint Paul, Minnesota, USA

Geopier intermediate foundations were used to support a new auto parts store addition in Saint Paul, Minnesota, USA. The tall one-story addition covers a footprint area of about 1020 m^2. The bearing wall loads range from 30 to 90 kN per lineal meter, with concentrated loads of 200 kN at column locations. The design floor elevation was set within 0.3 meter of the original grade.

The subsurface soils consist of 2 to 4 meters of miscellaneous soil fill (soft sandy clay and medium dense fine to coarse sand) with construction debris, underlain by fibrous peat and organic silt to depths of 0.7 to 7.6 meters. The N-values in the organic soils ranged from 3 to 10, and the moisture contents varied from 80 to 312 percent. A 0.6 meter thick stiff sandy clay was encountered below the peat layer, underlain by loose to medium dense fine to coarse sand. Groundwater was found within the peat and organic silt at depths of 3.7 to 4.0 meters below grade.

Other foundation alternatives considered by the designer included massive over-excavation of the unsuitable organic soils or the use of deep pile foundations greater than 15 meters. The Geopier system was selected to support the footings because over-excavation was impractical next to the existing building, and the pile foundation, with associated pile caps and grade beams, was more expensive. The floor slab was designed to be supported at grade without subgrade reinforcement.

Geopier reinforcing elements were constructed beneath the footings. Each 760-mm diameter element extended through the fill, peat and organic silt into the granular soils below. The fill and organic layers stood open during the construction, therefore use of temporary steel casing was not required. The piers were constructed using clean crushed limestone (38 mm and greater) in the lower 0.6 to 2.4 meters of the shaft, followed by well-graded highway base course crushed limestone aggregate for the remainder of the shaft.

6.3 Airplane Hangar at Holman Field, Saint Paul, Minnesota, USA

A new Airplane Hangar at Holman Field has a combination of masonry and precast concrete bearing walls with an interior steel frame. The wall loads range from 30 to 145 kN per lineal meter. There are columns on either side of the hangar doors with concentrated loads of 300 kips each. The Geopier system was selected as a more cost-effective method compared to a driven pile system. The pile system that was evaluated consisted of 300-mm concrete-filled steel pipe piles, with installation depths of 20 to 26 meters below grade.

The soil borings encountered 1.2 to2.4 meters of very loose to loose sand and silty sand fill, underlain by soft to very soft peat, organic clay and highly plastic clay to depths of 6.6 to 8.0 meters. The peat and organic clay and peat had moisture contents of 77 to 113 percent, and SPT N-values of 1 to 4. Beneath the organic and fat clay strata, the borings found fine to coarse alluvial soils composed of sand with occasional clay layers. Groundwater was encountered at about 2.4 meters below grade. The floor slab is supported on an unimproved subgrade and is structurally isolated from the foundations.

The Geopier elements were installed to fully penetrate the fill and organic soils, with shaft lengths of 5.5 to 6.5 meters below foundation level. Geopier elements were constructed of open-graded, 38 mm and larger aggregate below the groundwater, followed by highway base course aggregate for the remainder of the shaft. The soft soils were primarily highly organic with limited thickness of peat lenses. As a result, temporary steel casing was needed to keep the drilled holes open. The temporary casing was handled by a separate casing hammer that gripped the side of the casing. This allowed aggregate placement and compaction to go forward while the casing hammer moved the casing upward.

6.4 Geopier Modulus Test Results

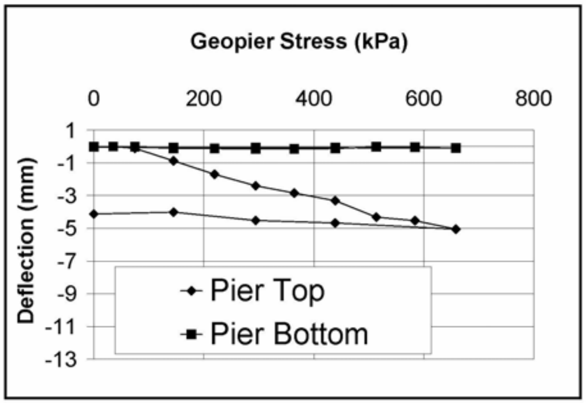
Full-scale modulus tests were performed at each of the three case study project sites during the construction to confirm the Geopier design parameters. Table 2 presents the comparisons between the field measurements and the selected design parameters.

Table 2 Geopier Design Parameters and Results of Modulus Tests

	Mini-Storage Building, Edina	Auto Parts Store Addition, Saint Paul	Airplane Hangar, Saint Paul
Design Geopier Cell Capacity - Estimate	200 kN	200 kN	178 kN
Design Pier Stiffness Modulus - Estimate	27 MN/m^3	22 MN/m^3	19 MN/m^3
Measured Pier Stiffness Modulus *	132 MN/m^3	58 MN/m^3	148 MN/m^3
Top of Pier Settlement at 100% Design Stress *	4.0 mm	8.0 mm	2.8 mm
Telltale Settlement at Bottom of Pier *	No Movement	2.5 mm	0.4 mm

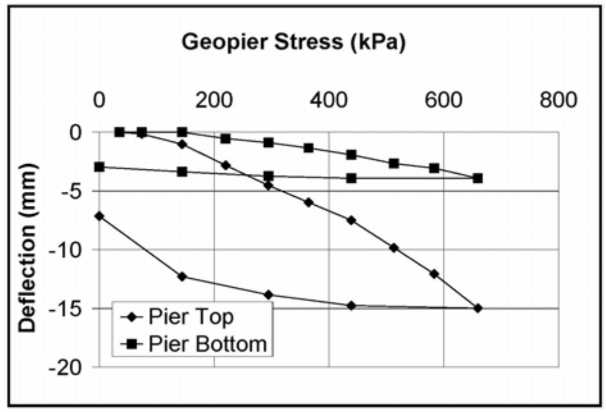
* From results of modulus tests

Results of the modulus tests are presented in Figures 3 to 5. Note that the measured Geopier element stiffness moduli were 2.5 to 7.5 times higher than the selected design parameters.



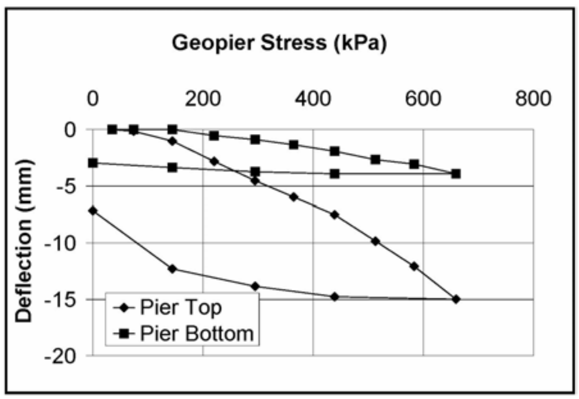
*Design Pier Top Stress = 439 kPa

Fig.3 Modulus Test at Mini-Storage Building, Edina, Minnesota



*Design Pier Top Stress = 439 kPa

Fig.4 Modulus Test at Auto Parts Store Addition, Saint Paul, Minnesota



*Design Pier Top Stress = 390 kPa

Fig.5 Modulus Test at Airplane Hangar at Holman Field, Saint Paul, Minnesota

7. CONCLUSION

The Geopier intermediate foundation system has been successfully applied to support footings and floor slabs with peat and soft organic soil conditions on numerous projects in the USA and in other countries. Geopier elements must fully penetrate peat and highly organic soil layers, but may terminate within soft, inorganic soil layers. Geopier construction in peat seldom requires temporary casing to keep the drilled hole from caving in, because cavities in peat usually stay open. Three cases studies in the United States are presented in this paper.

Applications of the Geopier soil reinforcement system to foundations over peat and soft organic soils are technically feasible and are usually highly cost effective compared to massive over-excavation and replacement methods, deep foundation systems, or other soil improvement techniques. The Geopier intermediate foundation system design methodology is conservative. By installing Geopier elements to create an upper stiff reinforced composite zone, the Geopier system can be utilized to control foundation settlements and satisfy reasonable structural design criteria.

APPENDIX: SYMBOLS USED

k_g = Stiffness modulus of Geopier.
k_s = Stiffness modulus of matrix soil.
q = Composite bearing pressure at base of footing.
q_g = Stress applied to top of Geopier.
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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