CASE HISTORIES OF *GEOPIER*® SOIL REINFORCEMENT FOR TRANSPORTATION APPLICATIONS

B.H. Lien
Geopier Global Corporation

N.S. Fox
Geopier Foundation Company, Inc.

Abstract: *Geopier*® soil reinforcement system incorporates very stiff aggregate piers to reinforce matrix soils. The innovative ground improvement technology has been used in the United States since 1989. This paper discusses construction methods and applications of *Geopier* soil reinforcement for transportation related facilities. Three case histories are presented discussing *Geopier* soil reinforcement design approaches for stabilization of an existing unstable slope, reinforcement of foundation soils and settlement control of an earth retaining wall, and the use of *Geopier* uplift elements for tensile load resistance.

INTRODUCTION

Geopier soil reinforcement technology is regularly utilized to support compressive loads applied by footings, floor slabs, and steel storage tanks. The effectiveness of this technology is attributed to lateral prestressing and prestraining that occurs 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.

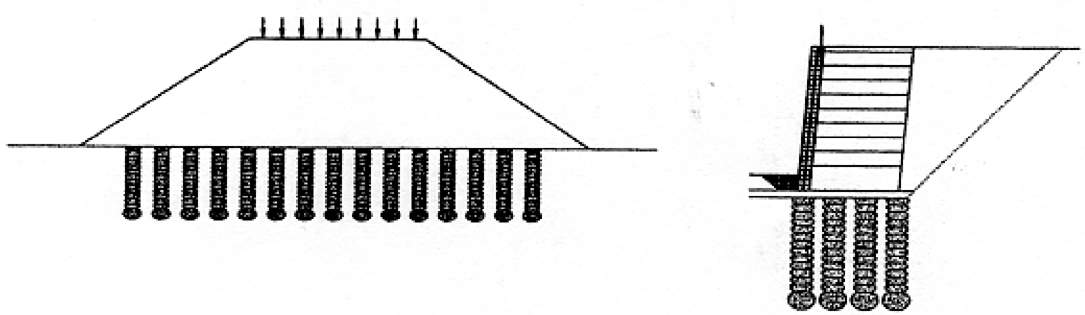


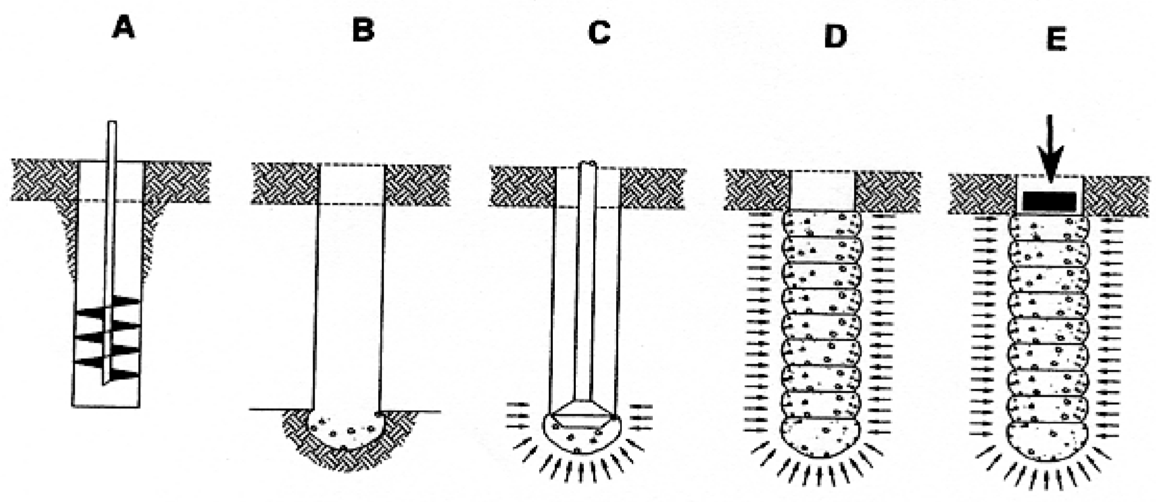
Figure 1 *Geopier* reinforcement of soils beneath embankments and retaining walls

Proceedings, Asian Institute of Technology Conference. Bangkok, Thailand. November, 2001. TP-0017

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 *Rammed Aggregate Pier* elements. Design approached used for supporting footings, floor slabs, and tanks, and for providing shear reinforcement for unstable soils are described by Fox and Lien (2001). This paper provides a description of *Geopier* soil reinforcement construction and presents three case histories that describe applications for transportation-related facilities, including stabilizing slope movements, minimizing settlements below MSE walls, and resisting uplift loads.

GEOPIER CONSTRUCTION

Construction of *Geopier* reinforcing elements is described in the literature (Lawton and Fox, 1994; Lawton et al., 1994; Lawton, 2000; Wissmann and Fox, 2000; Wissmann et al., 2000; Wissmann et al., 2001; Minks et al., 2001; and Fox and Lien, 2001) and summarized herein for completeness. The elements are installed by first drilling holes typically 750 mm (30 inch) in diameter to depths ranging between 2 and 8 m (7 and 26 ft) below working grade elevations. Aggregate is placed in 0.3 m (1 ft) thick lifts within the cavities and compacted using a specially designed high-energy beveled impact tamper. The first lift, consisting of clean stone, is rammed into the soil to form a bottom bulb. The bottom bulb effectively extends the design length of the aggregate pier element by approximately one pier diameter. During densification of the aggregate, the beveled tamper also 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 deposit. Installing the *Geopier* elements through weak and compressible soils creates a composite soil reinforcement zone.



A. Drill cavity.
B. Place stone at bottom of cavity.
C. Ram stone to form bottom bulb.
D. Densify stone in lifts to form undulated-shaft.
E. Preload top of *Geopier* element.

Figure 2: *Geopier* construction

SLOPE STABILIZATION: A NORTH CAROLINA LANDSLIDE CASE STUDY

Geopier elements have been used to reinforce existing unstable or failed slopes, and offer a particular advantage in critical areas where toe berms cannot be used. The aggregate piers exhibit a very high friction angle, on the order of 50 degrees. The installation of aggregate piers within weak matrix soils provides significant increases in the composite shearing resistance of the reinforced zone. In addition to the high shear strength exhibited by the aggregate pier, lateral compaction during construction provides increases in both shear strength and stiffness modulus of the matrix soil between the *Geopier* elements.

The combination of heavy rains and an excessively steep fill slope resulted in a landslide at a commercial development in Raleigh, North Carolina, USA during the winter of 1997-1998. A parking lot and loading dock for a large commercial superstore were located at the top of the 20-m tall fill slope. Lynn Road, a heavily traveled thoroughfare, is located adjacent to the toe of the slope.

The slope consisted of compacted residual silty sand and sandy silt fill derived from parent Piedmont physiographic soils. These soils typically have long-term effective friction angles on the order of 28 to 30 degrees. The compacted soil slopes were built at slope ranging from 2 horizontal to 1 vertical (2H:1V), to as steep as 1.5H:1V. The steep slope inclinations, combined with heavy seasonal rainfall, contributed to a series of shallow compound slides. The resulting slides encroached on the parking area at the crest and the adjacent property and roadway at the toe.

The initial repair scheme consisted of excavating a trench below the slide mass and backfilling with a gabion wall toe buttress. The planned depth of the excavation required staged construction and shoring, as well as the removal of a significant amount of soil. Significant drawbacks to such a repair solution included substantial costs as well as a long construction schedule.

In lieu of the planned excavation, *Geopier* soil reinforcing elements were installed to support the gabion wall (Figure 3). The elements have 3-m long shafts that extend through the critical failure surface of the slope. Figures 4 and 5 illustrate the installation of elements at the site and the final constructed slope, respectively. As a result of *Geopier* element installations, construction risks and costs associated with the slope repair were reduced and the construction schedule was accelerated in comparison with alternative repair options.

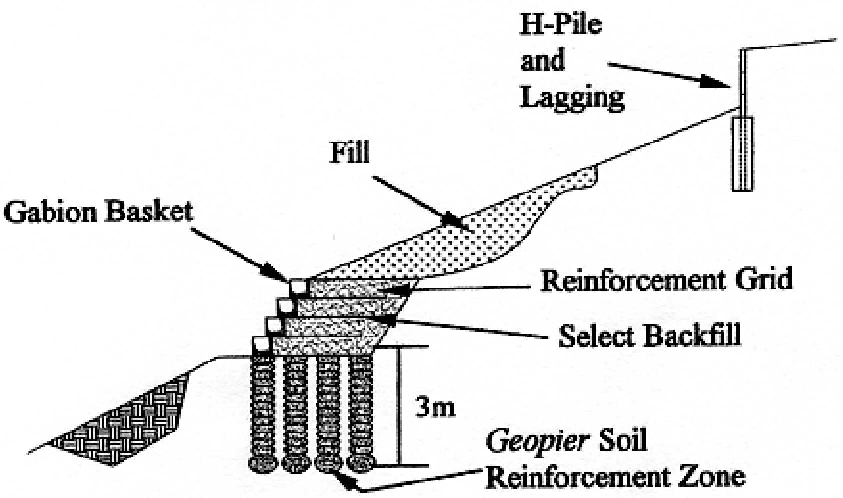


Figure 3: Slope stabilization using *Geopier* elements

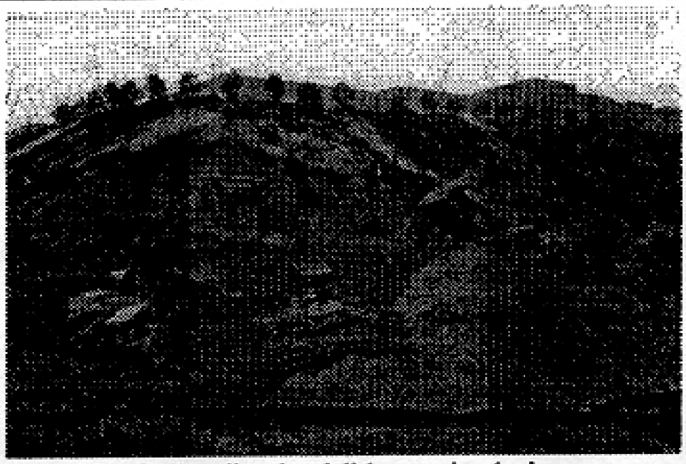


Figure 4: North Carolina landslide repair: during construction

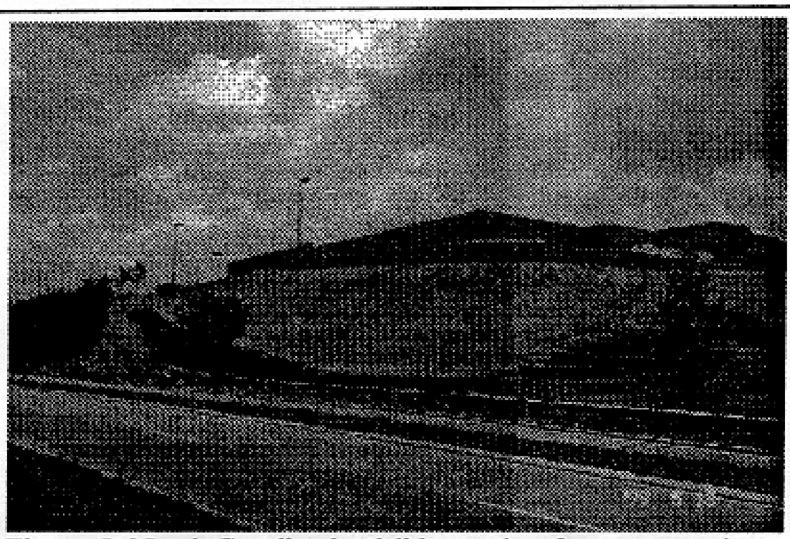


Figure 5: North Carolina landslide repair: after construction

FOUNDATION SOIL REINFORCEMENT AND SETTLEMENT CONTROL: AN MSE WALL SUPPORT CASE HISTORY

Background

For embankment and retaining wall support applications, *Geopier* foundation elements are unique because the installation method increases lateral stress within the matrix soil up to the passive earth pressure limit. The installation of the stiff Geopier elements coupled with the increase in lateral stress results in a stiff composite reinforced zone of soil, thereby controlling settlements induced by applied vertical pressures.

The Geopier stiffness modulus, defined as the top-of-element stress divided by the corresponding top-of-element deflection, is used to predict the settlement in the zone of reinforced soil. Full-scale modulus tests have been performed on an estimated 400 installed *Geopier* elements since 1988 to evaluate the stiffness modulus of individual elements. The basic modulus load test setup, as shown in Figure 6, includes a test pier element, two reaction (uplift) elements with a steel uplift anchor installed at the bottom and along the sides of the element, steel reaction test beams, a testing jack, and dial gauges. A telltale, consisting of a steel plate attached to sleeved threaded bars, is also installed at the bottom of the pier. Stress and deflection responses at the top of the element and deflection of the telltale are measured. Modulus load test results for a 3.4 m (11 ft) long *Geopier* element installed in cohesive soils are shown in Figure 7. The test plot reveals a bi-linear stress-deflection response at the top of the element and a linear response with little total deflection at the bottom of the element. As indicated by the limited deflection at the bottom of the element, the applied stresses result in elastic compression of the element until the top-of-element inflection point is reached, followed by increased non-recoverable outward bulging of the element with increased loading.

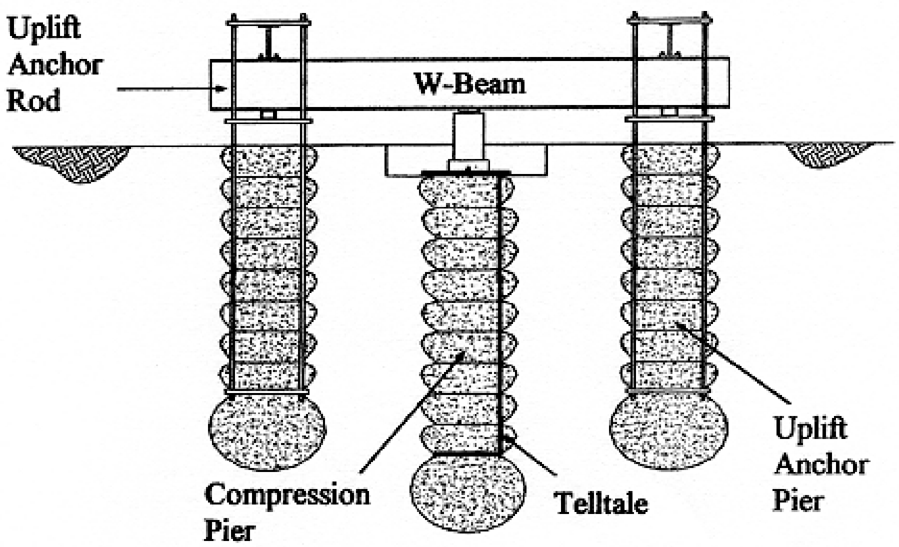


Figure 6: Modulus load test setup

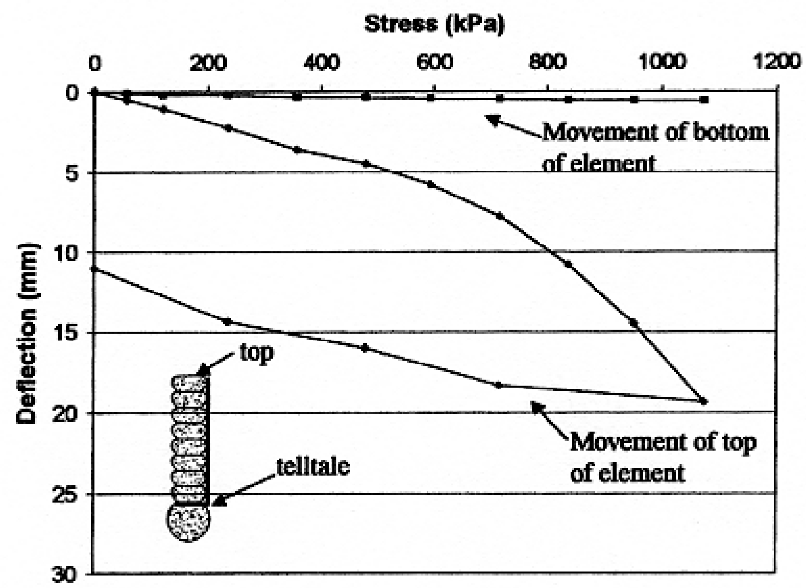


Figure 7: Typical *Geopier* modulus load test results

A database of *Geopier* element load-deflection response has been developed by Fox and Cowell (1998) based on results of monitored project performance and modulus load tests performed in various soils with elements of various shaft lengths and diameters. Typical stiffness modulus values for soils of various generalized soil classifications and consistencies are presented in Table 1. The database is currently used in design calculations to evaluate the effectiveness of the elements in controlling settlement.

Table 1 Stiffness modulus values for generalized soil conditions

Soil Classification	UCS for fine-grained (kPa)	SPT N-value	Stiffness Modulus k_g (MN/m^3)
Sand, Silty Sand, and Sandy Silt	-	1-6 7-12 13-25	45-71 71-77 77-88
Clay, Clayey Silt, and Silt	10-110 111-220 221-380	1-6 7-12 13-25	34-48 48-68 68-75

Geopier elements decrease foundation soil settlement in the following ways:

- A portion of the relatively compressible matrix soils is replaced with stiffer materials and the applied embankment stresses concentrate to the relatively stiff *Geopier* elements.

- The increase in lateral earth pressure within the matrix soil that occurs as a result of ramming the aggregate during construction allows for applications of greater vertical stress prior to the onset of consolidation.

- The magnitude of differential settlements is a function of the variability of the subsurface conditions. The *Geopier*-reinforced composite soil layer will not only effectively reduce the magnitude of total settlement, it also functions as an engineered crust layer that reduces the magnitude of differential settlement.

In addition to settlement control, *Geopier* elements offer other advantages for reinforcement of foundation soils. *Geopier* elements consisting of open-graded aggregate act as vertical drains. The drainage path within the upper (reinforced) zone is governed by radial drainage and is a function of the element spacing. The equivalent drainage path within the lower zone of compressible soil is shortened because of the existence of the *Geopier* elements acting as drains within the upper zone. As a result, installation of the *Geopier* elements has a dramatic impact on the consolidation times within both the upper zone and lower zone. The reduction in consolidation durations offers the advantage of avoiding the timely delays associated with preloading.

Park Center MSE Wall Support Project

The Park Center development project is located in Alexandria, Virginia, USA close to Highway I-395, and a few kilometers away from the Pentagon and the Nation's Capitol. Located in the Atlantic Coastal Plain, the site is underlain by sedimentary deposits, dominated by Potomac Group soils. Within the Potomac Group, the stratum of most concern among geotechnical engineers consists of very stiff and highly plastic clay, locally referred to as "marine clay." The marine clay is known for its very low residual shear strength and associated problems with global instability. At the Park Center site, deep uncontrolled fill soils including large areas of marine clay mixed with other variable materials were encountered. The variability of the fill soil and the potential instability in the marine clay were considered during the design.

To maximize the limited area for development, four-story luxury condominiums were constructed on top of parking garages, and retaining walls were employed to level the sloping site. A major site challenge was the construction of a 6 m (20 ft) tall, 140 m (450 ft) long retaining wall with a major access road directly on top of the wall and a building immediately beyond the road. From experience, engineers and developers in the area knew that conventional measures would be costly to treat the marine clay soils underlying the proposed retaining wall. Project geotechnical engineers recognized that the shear strength of the soil was inadequate to support the proposed segmental retaining wall. Typically, large diameter drilled shafts are used to stabilize such a wall. Because of the prohibitive costs, the project team chose *Geopier* soil reinforcement to control settlement and also increase factors of safety against global instability of the retaining wall. Consequently, the retaining wall was constructed as a Mechanically Stabilized Earth (MSE) wall.

As shown in Figure 8, the *Geopier* design included four rows of 750-mm diameter *Geopier* elements installed in a triangular grid pattern on 1.5 m centers. Shaft lengths extended to depths of up to 6 m. During drilling, the auger holes were observed to determine when natural ground was reached after penetrating the fill soil. *Geopier* shafts were then advanced a few more feet into the natural marine clay. Because the access road would be the primary access for emergency vehicles and equipment, a 10 kPa surcharge was used in the analysis. Although the steep, tight site was a challenge, compounded by large concrete debris encountered during *Geopier* drilling operations, the soil reinforcement and wall were installed without affecting the project schedule (Figure 9). In addition to providing increases in global stability, the installation of Geopier elements provided control of settlement beneath the MSE wall.

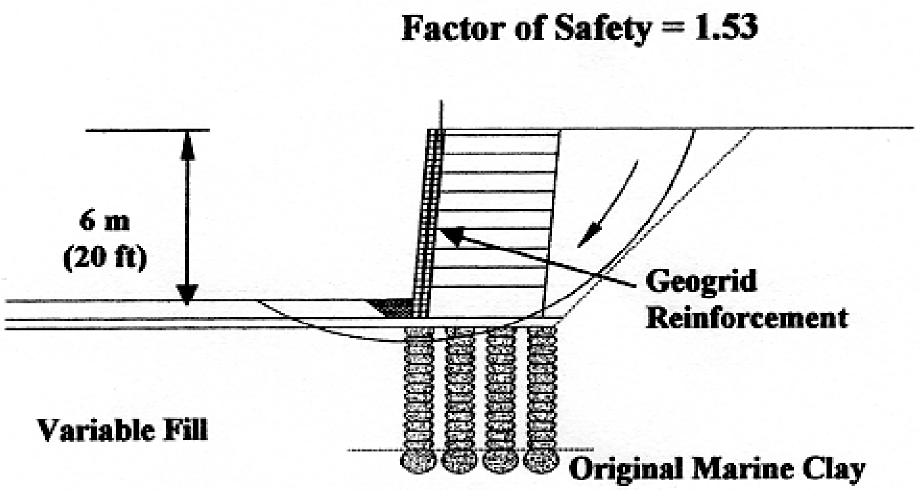


Figure 8: *Geopier* MSE wall support


Figure 9: Park Center MSE wall support project – during construction

UPLIFT LOAD RESISTANCE: A RETAINING WALL CASE HISTORY

Background

Uplift loads are often applied to foundation systems when the supported structures are subject to loads from wind, seismic, or soil pressure from backfills. Uplift anchors are incorporated into *Geopier* elements to resist tensile loads and provide overturning resistance. A constructed *Geopier* uplift element with matrix soil stress response is shown on Figure 10. An uplift anchor is lowered into the hole to the top of the densified bottom bulb. The anchor consists of a round or rectangular steel plate with tie rods connected at the outer edge of the plate. The uplift rods are spaced sufficiently far apart so that the tamper can fit between the rods as the pier is constructed. The tie rods are connected to the overlying footing via standard hooks and other structural connections.

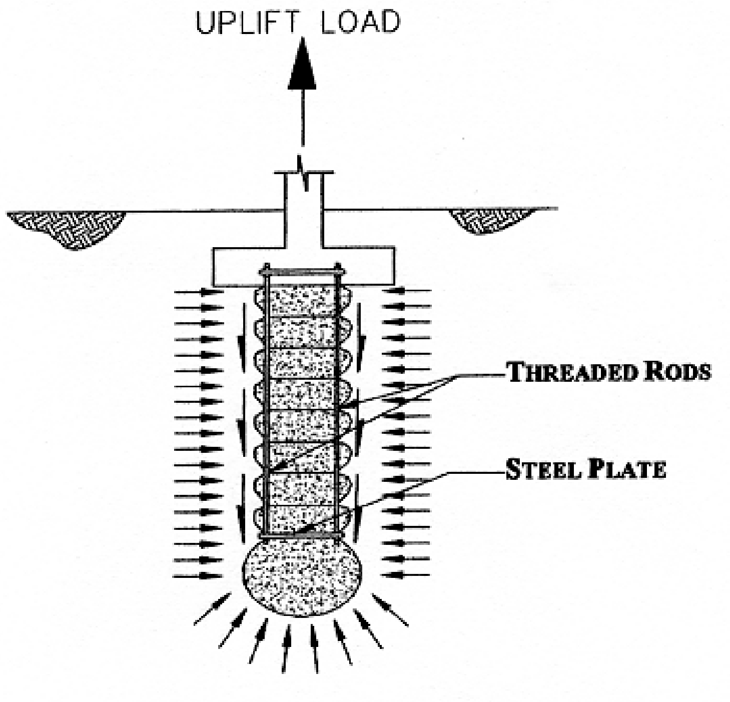


Figure 10: *Geopier* uplift element

Observations of *Geopier* elements that have been pulled completely out of the ground during *Geopier* uplift research efforts indicate that the critical shearing surface is cylindrical and occurs near the perimeter of the installed element. Prior to complete pullout failure, radial and circumferential cracks are often observed at the ground surface. These cracking patterns are consistent with the near surface inverted conical failure surfaces described in the literature for embedded anchors loaded in tension (Kulhawy, 1985). Detailed discussions on the uplift *Geopier* design approach and applications are presented by Wissmann et al. (2001b).

In cohesionless soils, the rate of drainage is typically faster than the net increases in uplift during cumulative cycles of loading. The unit uplift loading resistance (f_s) of individual elements is therefore computed using drained geotechnical analysis procedures. The unit frictional resistance is calculated as the sum of the drained cohesion intercept (c') and the product of the lateral pressure in the soil surrounding the *Geopier* elements (σ'_h) and the tangent of the angle of internal friction of the matrix soils (ϕ'_m):

$$f_s = c' + \sigma'_h \tan(\phi'_m) \quad , \qquad (1)$$

where the drained cohesion intercept (c') is zero for clean sands and gravels.

The ramming action inherent in *Geopier* construction increases lateral earth pressure in the matrix soils surrounding the *Geopier* elements. The increase in lateral stress is dependent upon soil type, drainage, overconsolidation ratio, and confinement offered by adjacent *Geopier* elements (Fox and Cowell 1998). Post-construction lateral earth pressure is typically computed as the product of the geostatic vertical stress in the matrix soils (σ'_v) and the Rankine passive earth pressure coefficient (K_p):

$$\sigma'_h = \sigma'_v \; K_p \qquad (2)$$

where:

$$K_p = \tan^2(45 + \phi'_m/2) \qquad (3)$$

As shown in Figure 11, the applied lateral earth pressure is limited by a value ranging between approximately 96 kPa (2,000 psf) to 144 kPa (3,000 psf) to conservatively account for the maximum energy that is normally imparted by the *Geopier* tamper to the surrounding soils (Wissmann et al. 2001b).

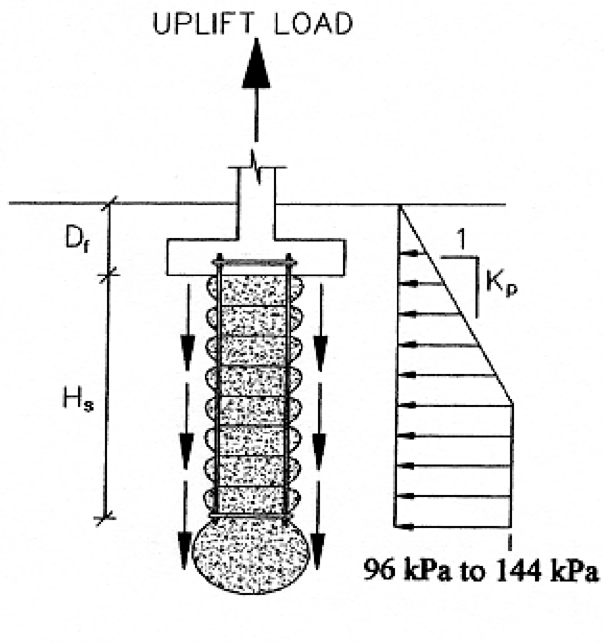


Figure 11: Individual *Geopier* pullout resistance

When *Geopier* elements are installed in cohesive soils the rate of uplift loading may or may not be less than the rate of draining. Therefore the unit frictional resistance, (f_s) is computed as the smaller of: 1.) the undrained shear strength (s_u) of the matrix soils and 2.) the drained unit friction of the matrix soils using Equation 1.

Maryland Route 5 Retaining Wall

Like many major transportation corridors in the Washington, D.C. metropolitan area, Maryland Route 5 needed more lanes and interchange improvements to handle the traffic flow. Plans to improve the highway, which extends southeast from the Nation's Capital through rapidly developing Prince George's County, incorporated retaining walls at many locations where right-of-way access was restricted. At the site of a small creek crossing, not only was the proposed highway improvement confined by wetlands, but also by local primary roads, and residential and commercial properties. The existing highway was supported on an embankment extending from 3 to 6 m above the surrounding grades. With only a narrow footprint available for the required retaining walls, overturning, sliding, settlement and bearing capacity were major design considerations. The Maryland State Highway Administration (MSHA) originally decided that pile foundations would provide the best solution to support the walls. Recognizing the overhead restriction of nearby power lines, the geotechnical consultant initially recommended micropiles installed on a batter, but also looked into other value-engineering options. Driven by the high cost and extended schedule required for micropiles, the contractor decided to utilize *Geopier*-supported foundations for the project (Figure 12).

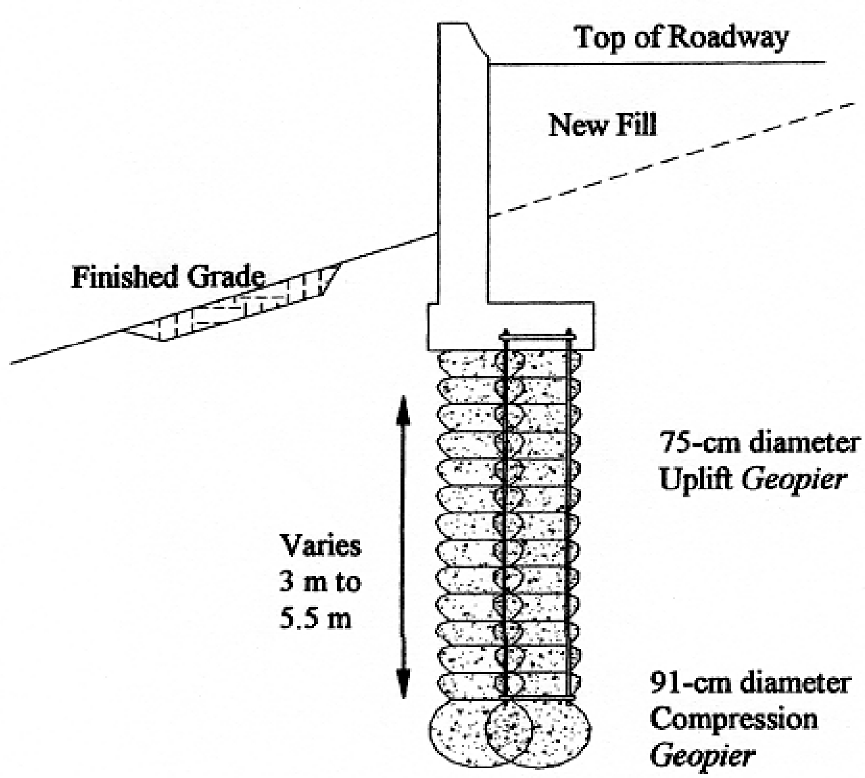


Figure 12: Uplift *Geopier* for retaining wall

The project site is located in the Atlantic Coastal Plain, with subsurface conditions consisting of layered sediments that were deposited in various geologic settings. Soils near the ground surface include rounded quartz gravel fill materials, with varying amounts of silt, clay and sand. The gravel layer is underlain by a 3 to 6 m deep deposit of very soft saturated silt and clay. Standard Penetration Test results revealed weight-of-hammer penetration resistance for a significant portion of the cohesive and slightly organic deposit.

Geopier soil reinforcing elements were designed to provide settlement control, bearing capacity, sliding resistance, and overturning resistance for the planned reinforced concrete retaining walls. With the narrow, five-foot wide footing there was limited space to install the *Geopier* elements (Figure 13). The applied overturning loads were considered to be sufficiently large to unload the heel of the footing and compression elements were confined to the front two-thirds of the footing. These elements were also used to provide sliding resistance. Uplift anchors were installed in *Geopier* elements within the back one-third of the footing to resist uplift loads. The final design was approved by MSHA as an alternative to the more costly and time-consuming micropiles. Four load tests were conducted at the site: one for uplift resistance and one for *Geopier* modulus confirmation at each of two wall sites.

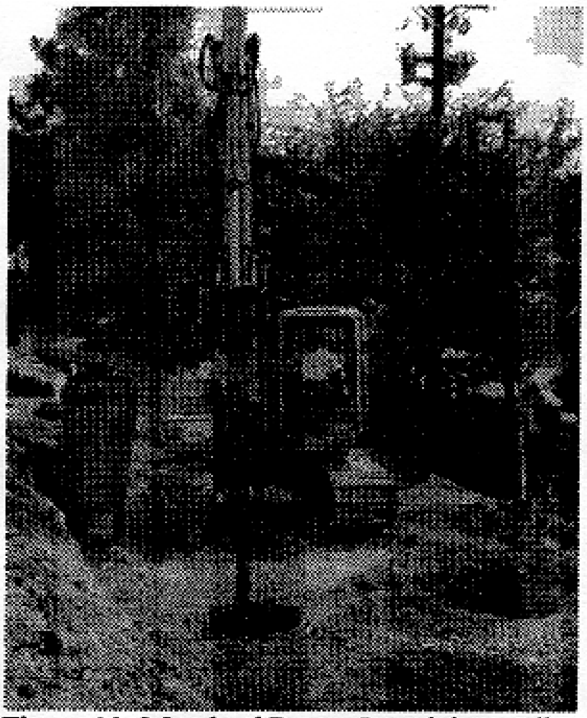


Figure 13: Maryland Route 5 retaining wall: during construction

The resulting *Geopier* foundation layout was densely spaced in a narrow site with limited access and overhead obstructions. Soft saturated soils and heavy rains presented a need for casing the drilled *Geopier* shafts. In spite of extremely difficult site conditions, the *Geopier* value-engineering proposal provided for both cost savings and an accelerated construction schedule (Figure 14).

Figure 14: Maryland Route 5 retaining wall: after construction

RESEARCH AND OTHER APPLICATIONS

As a result of relatively high cost of construction and the massive volume of work involved, innovative construction technologies are often accepted for transportation-related projects in the USA. The United States Federal Highway Administration (FHWA) and various state highway Departments of Transportation (DOT's) have sponsored *Geopier*-related research in efforts to improve understanding of the technology. In 1998, FHWA and the Utah DOT funded a research project that incorporated *Geopier* elements into a major research effort that involved determining the dynamic response of a full-scale elevated bridge span subjected to a simulated 7.5 Richter scale earthquake (Lawton 2000). That same year, the Maryland MSHA approved *Geopier* soil reinforcement (the third case history presented in this paper) solutions for supporting a thin cantilever retaining wall utilizing both uplift capacity to resist uplift forces at the heel of the wall, and compressive resistance provided by the stiff aggregate pier system.

Research sponsored by Iowa DOT provided an opportunity to compare the effectiveness of *Geopier* soil reinforcement relative to traditional stone column methods in reducing settlements below highway embankments. Insitu testing and instrumentation, including settlement plate and pressure plate readings collected at the two adjacent sites, one supported by *Geopier* elements and the other supported by stone columns, provide the following observations (Gaul 2001):

- Even though matrix soils were stiffer in the stone column test area prior to ground improvement installation, the stiffness of the *Geopier* elements ranged from 2 to 10 times that of the stone columns.

- The embankment supported by *Geopier* soil reinforcement settled 50% as much as embankments supported by stone columns, even though the pre-improved matrix soils were 120% stiffer in the stone column area.

- Standard Penetration Tests performed within installed stone columns and *Geopier* elements showed average penetration resistances of 11 blows per foot within the stone columns and 17 blows per foot within *Geopier* elements, demonstrating the differences in the strength and stiffness of the installed elements.

Geopier elements also have been used at other transportation sites in Iowa to reinforce soils for:

- Controlling settlements of a large box culvert installed under an existing bridge on Iowa Highway 191 near Neola, Iowa, USA. The design goals were to reduce excessive settlement, reduce down drag on the existing bridge piles, and to reduce differential settlement to 10 cm or less under the box culvert.

- Control or prevent the bump at the end of the bridge at a site in Floyd County, Iowa, USA. The bump is caused by bridge approach settlement and requires significant cost for regular maintenance. Settlement of the natural foundation soils and compression of the embankment fill material are the two most significant factors contributing to the formation of the bump. An ongoing research effort is to evaluate the effectiveness of reducing the differential settlement at the bridge approach using the *Geopier* soil reinforcement system.

On-going research projects in the transportation sector are presently being performed at the University of Utah, the University of Massachusetts, Iowa State University, and Virginia Tech.

CONCLUSIONS

The high shear strength exhibited by the *Geopier* aggregate piers allow for substantial increases in the composite shearing resistance within slopes and beneath embankments, thereby providing higher factors of safety. Combination of the *Geopier* element stiffness and the lateral prestressing and prestraining induced within the matrix soil during installation significantly increases the composite stiffness of the reinforced zone, thus reducing settlement magnitudes. Application of uplift harness allows the *Geopier* elements to resist tensile loads and provides overturning resistance for retaining walls. Case histories are presented where *Geopier* soil reinforcing elements are used to provide economical solutions to improve global stability, control and reduce settlement magnitudes, and provide uplift load resistance for transportation applications.

ACKNOWLEDGEMENTS

The authors are indebted to Professors Richard Handy, Iowa State University, Evert Lawton, University of Utah, and David White, Iowa State University for their pioneering work upon which much of information contained in this paper is based. Gratitude is extended to Dr. Kord Wissmann, Cork Peterson, Michael Cowell, and Brendan FitzPatrick for providing much of the case history information and preparing of the figures in this paper.

REFERENCES

Fox, N.S. and M.J. Cowell (1998). *Geopier* Foundation and Soil Reinforcement Manual. *Geopier* Foundation Company, Inc., Scottsdale, AZ.

Fox, N.S. and B.H. Lien (2001). "*Geopier*® soil reinforcement technology: an overview." Symposium 2001 on Soft Ground Improvement and Geosynthetic Applications, 22-23 November 2001, Asian Institute of Technology.

Gaul, A.J. (2001). "Embankment foundation reinforcement using rammed aggregate piers in Iowa soils." Master of Science Thesis. Iowa State University, Ames, IA.

Lawton, E.C. (2000). "Performance of *Geopier* foundations during simulated seismic tests at South Temple Bridge on Interstate 15, Salt Lake City, Utah." Report No. UUCVEEN 99-05, University of Utah Department of Civil and Environmental Engineering, Salt Lake City, Utah.

Minks, A.G., K.J. Wissmann, J.M. Caskey, and M.A. Pando. (2001). "Distribution of Stresses and Settlements Below Floor Slabs Supported By *Rammed Aggregate Piers*." Proceedings. 54th Canadian Geotechnical Conference. Calgary, Alberta, Canada. September 16-19, 2001.

Wissmann, K.J. and N.S. Fox. (2000). "Design and analysis of Short Aggregate Piers to reinforce soils for foundation soils." Proceedings, Geotechnical Colloquium, Technical University Darmstadt, Darmstadt, Germany, March 25, 2000.

Wissmann, K.J., N.S. Fox, and J.P. Martin (2000). "*Rammed Aggregate Piers* Defeat 75-foot Long Driven Piles." *Performance Confirmation of Constructed Geotechnical Facilities*. ASCE Geotechnical Special Publication No. 94. April 9-12, 2000. Amherst Massachusetts.

Wissmann, K.J., K. Moser, and M.A. Pando. (2001). "Reducing Settlement Risks in Residual Piedmont Soils Using *Rammed Aggregate Pier* Elements." *Foundations and Ground Improvement*. ASCE Geotechnical Special Publication No. 113. June 9-13. Blacksburg, Virginia.

Wissmann, K.J., J.M. Caskey, B.T. FitzPatrick, and N.S. Fox. (2001b). "Technical Bulletin No. 3: *Geopier* Uplift Resistance." *Geopier* Foundation Company, Inc. Scottsdale, AZ.

Dr. Bon Lien is Chief Engineer, Geopier Global Corporation. 3183 Liberty Bell Road, Green Bay, Wisconsin 54313. (920) 434-8847. Geopierglobal@aol.com.

Dr. Nathaniel Fox is President, Geopier Foundation Company, Inc. 8283 N. Hayden Road, Suite 291, Scottsdale, Arizona 85258. (480) 998-3522. Geopier6@aol.com.