GEOPIER® SOIL REINFORCEMENT TECHNOLOGY: AN OVERVIEW

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Abstract: *Geopier* soil reinforcement is an innovative ground improvement method developed in the 1980's with U.S. and foreign patents granted in the mid 1990's. In 12 years of commercial use, it has grown to become the leading ground improvement method for support of commercial buildings in the United States. Reliable performance coupled with cost and construction time savings, have made *Geopier* soil reinforcement a viable alternative to deep foundations and to overexcavation and replacement. This paper presents a technology overview of system capabilities, construction processes, technical fundamentals, design methodologies, system limitations, and an extensive *Geopier* system research and development summary.

INTRODUCTION

Construction of buildings, industrial plants, and transportation structures over the past two decades has increasingly involved the need to develop sites containing poor soils. The poor soils may include organic deposits, floodplains and dredged soil areas, marine and deltaic deposits, debris fills, uncompacted fills, solid waste landfills, and chemically contaminated soil sites. This paper describes a ground improvement method, *Geopier* soil reinforcement, tailored for poor soil site reinforcement, and in the short span of one decade, it has grown to become the leading ground improvement method for support of commercial buildings in the United States. Because *Geopier* technology is not yet well known in Asia, this paper is written to help the reader gain an understanding of both the underlying design concepts and successful applications for the technology.

COMMERCIAL BACKGROUND

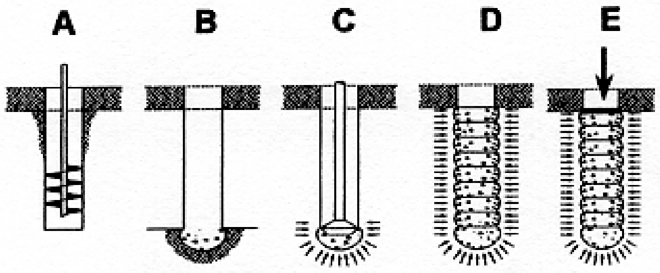
Geopier soil reinforcement was invented in the mid 1980's by Dr. Nathaniel Fox, as an improvement and refinement to the age-old method of overexcavation and replacement. U.S. Patent and foreign patents were granted in the mid-1990's. Commercial use of the system began in 1989. By the end of the present calendar year, a total of over 200,000 *Geopier* elements will have been installed, and annual volume for the year 2001 will exceed 55,000 piers.

The *Geopier* system was initially developed to replace overexcavation and replacement at poor soil sites and it continues to be used in that capacity. However, after twelve years of development and use, the system is now applied more often to increase the stiffness and support capacity of fair to good soils than of poor soils, and to replace the need for deep foundations – driven piles, cast-in-place piles, and drilled shaft foundations, more often than replacing the need for overexcavation.

CONSTRUCTION

Process

Geopier construction 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 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 hole diameter for *Geopier* elements is 750 mm. A stable bottom is then formed by placing a layer of clean, crushed aggregate into the hole and ramming the aggregate with a patented, high-energy beveled tamper. The energy applied is not vibration, but is impact ramming energy, with limited amplitudes (about 10 mm), and impact ramming frequencies ranging typically from 300 to 600 cycles per minute. Thin lifts (300 mm) of well-graded crushed aggregate are then placed into the hole and rammed with the same tamper to form a 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 adjacent matrix soils and effectively increases the stiffness and capacity of the system.



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 1: *Geopier* construction

Advantages of the *Geopier* soil reinforcement system in comparison with traditional overexcavation and replacement include: less adverse effects from high groundwater; greater compaction because of stable "platform" (bottom bulb) upon which to compact, and the special, highly efficient compacting means; efficient buildup of lateral stress to stiffen the adjacent soils; prevention of induced cave-ins from adjacent buildings because of limited hole volumes open at the same time; smaller volume of select materials needed; more efficient prestressing and prestraining of select aggregate material and matrix soils; higher and more verifiable capacity; and availability of more efficient quality assurance methods.

Tamper-Hammer

The patented *Geopier* tamper is fitted inside a modified hydraulic hammer. Two general types of tamper/hammer systems are in common use, a long stemmed tamper and a short-stemmed, down-hole tamper/hammer. The latter is quieter and quicker in installing pier elements. The hydraulic hammer is attached to a track-mounted medium-sized excavator. Other equipment includes a commercial drill to make the holes and a small front-end loader to place the aggregate. A normal crew consists of three operators, one for the excavator, one for the drill, and one for the loader.

RESULTS OF CONSTRUCTION

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, enhancing the matrix soils and making them stiffer. The composite pier and matrix soil is considerably stiffer than the pre-reinforced matrix soils, with a consequent reduction in 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 for pier shaft materials. 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 (Wissmann et al. 1999).

Stiffness And Shear Strength

The stiffness of *Geopier* elements is determined by full-scale modulus load tests (Figure 2). The pier modulus is conservatively assumed to be the ratio of applied vertical stress divided by movement at the top of pier and is typically expressed in English units as pci, and in S.I. units as MN/m^3.

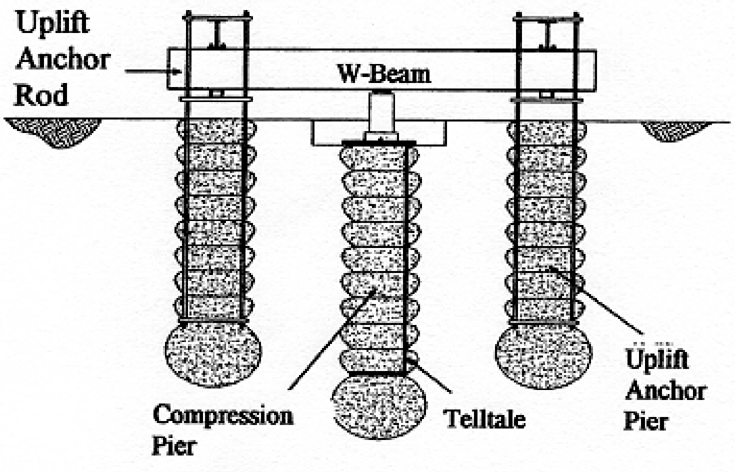


Figure 2: Modulus load test setup

Approximately 400 modulus tests covering a wide spectrum of soil conditions have been performed during the past eleven years. Figure 3 presents an example of the modulus load test plot. The results of the modulus tests indicate that pier stiffness is significantly higher than pre-reinforced matrix soil stiffness, and on the order of 10 to 50 times as high. This implies that 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 (Lawton 2000).

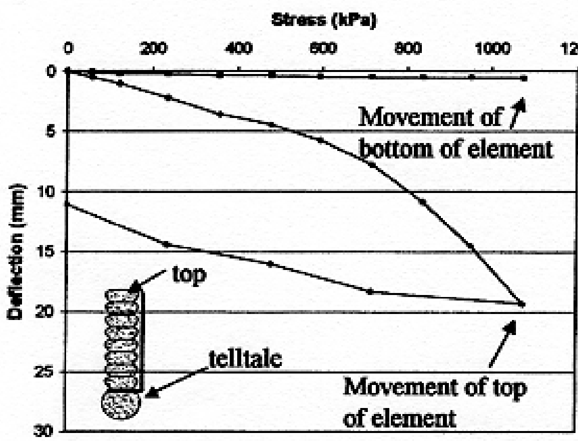


Figure 3: Typical *Geopier* modulus load test results

The shear strength of the *Geopier* element is represented by its angle of internal friction. The angles of internal friction have been measured in the field from full-scale direct shear tests performed on installed *Geopier* elements (Fox and Cowell 1998). The testing results indicate angles of internal friction of approximately 49 degrees for open-graded aggregate and 52 degrees for densified, well-graded aggregate (Figure 4). 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 (White et al. 2001). Laboratory results obtained indicate an angle of internal friction of 51 degrees.

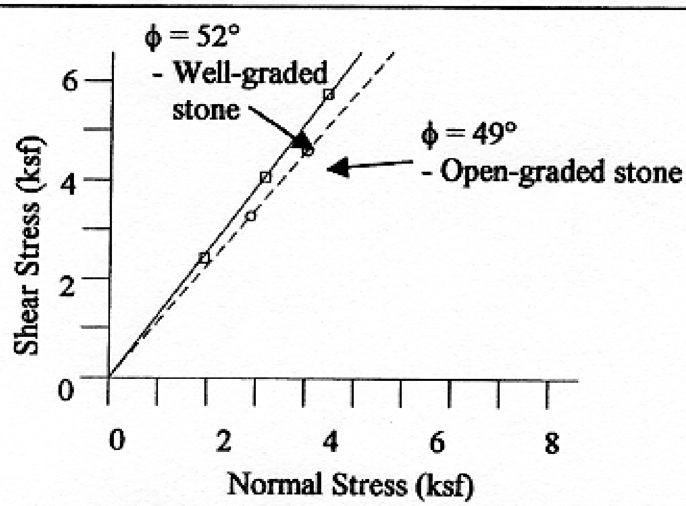


Figure 4: Results of full-scale Geopier Direct Shear Tests

Soil Lateral Stress Buildup

One principle fundamental to *Geopier* construction is the use of a beveled tamper to enhance pushing of aggregate laterally into the soil sidewalls. Forcing of the stone into the soil creates lateral stress in the soil as the soil "pushes back." Measurements have been made with the K_o Stepped Blade (Handy et al. 1990, White et al. 2000, Handy 2001) to determine the magnitude and horizontal extent of lateral stress buildup during the *Geopier* installation process. Measured results have consistently indicated that passive pressure conditions are developed in soils close to and between *Geopier* elements. Measurements also indicate that that a significant lateral stress buildup occurs to a distance of about three to four times the pier diameter.

Geopier-reinforced structures are observed to settle less than estimated (Lawton and Fox 1994, Lawton et al. 1994). In a study that investigates the influence of lateral stress on foundation settlement, Handy (2001) concludes that high lateral stresses defer consolidation settlement to a substantially greater foundation load. Additionally, pullout measurements of *Geopier* elements over a period of the past ten years show near-liner-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 *Geopier* elements.

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 are installed during pier construction to transfer loads to overlying footing or mat as shown on Figure 5. A steel bottom plate is typically installed on top of the bottom bulb with steel bars or threaded rods extended upward along the periphery of the hole to allow lowering the tamper between the bars during ramming of the aggregate. Uplift load tests are performed to determine load-deflection behavior. Typical uplift design capacity ranges for a 3 to 4 meter long shaft pier are from 20 tons to 40 tons per pier.

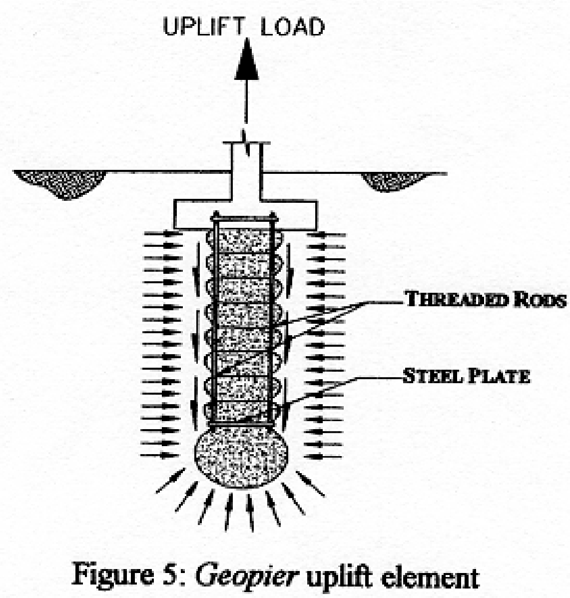


Figure 5: *Geopier* uplift element

Resistance To Lateral Loads

Lateral loads are applied on foundations by wind, lateral earth pressures, and earthquakes. Because of high stress concentrations to *Geopier* elements and the high angle of internal friction of *Geopier* elements, relatively high lateral load resistance is provided by *Geopier* soil reinforcement in comparison to lateral load resistance 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 between the footing and the tops of the *Geopier* elements plus the sliding resistance between the footing and the matrix soil (Fox and Cowell 1988). Because of the high concentrated normal stress 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 and the tops of the *Geopier* elements.

Earthquake Protection

During earthquake events, *Geopier*-reinforced foundations exhibit greater lateral load resistance, greater bearing capacity, and, when uplift anchors are incorporated in the *Geopier* elements, relatively high uplift resistance is provided. In addition, the installation of *Geopier* elements will provide some or substantial reduction in liquefaction potential within composite *Geopier*-improved soil zones, depending on gradation of aggregate utilized within the *Geopier* elements, earthquake intensity, soil characteristics, and pier spacing.

Geopier elements are ductile and can experience deformations without subsequent loss of strength in contrast to relatively brittle, rigid deep foundations, such as piles or drilled shafts. As such, the *Geopier*-reinforced footing system provides a greater confidence in the retention of post-earthquake integrity than that offered by traditional deep foundation systems. The ductility and retention of *Geopier* integrity and strength during a simulated 7.5 Richter scale earthquake was confirmed during a full-scale bridge-shaking research project in Salt Lake City, Utah in the late 1990's (Lawton 2000).

SUPPORT OF SHALLOW SPREAD FOOTINGS: DESIGN PROCESS AND APPLICATIONS

Stress Concentration On *Geopier* Elements

Assuming a footing is rigid, modeling the *Geopier* elements and matrix soil as stiff and less stiff elastic springs, respectively, and using the principle of static equilibrium, one can calculate that 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) (Lawton and Fox 1994). Because the stiffness modulus values of *Geopier* elements are typically 10 to 50 times greater than the stiffness modulus values calculated for corresponding matrix soils, vertical stress intensity on top of pier elements are typically 10 to 50 times greater than the vertical stress intensity on top of the matrix soils..

Two-Layer Approach

Approaches used for estimating settlements of a *Geopier* soil reinforcement system include two basic steps – 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 within the Upper and Lower Zones (Figure 6). Settlement design criteria of 25 mm total settlement and 12 mm differential settlement are commonly used in design practice.

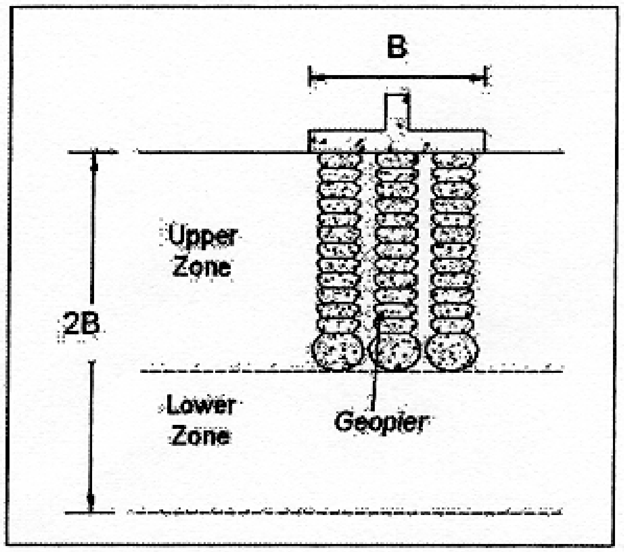


Figure 6 *Geopier-reinforced* Upper- and Lower-Zone

Upper Zone Analysis

A weighted modulus method is used to estimate the settlement contribution component from the Upper Zone. Detailed Upper Zone calculations are described by Lawton and Fox (1994) and Lawton et al. (1994), and are summarized herein for completeness.

- The total downward force (Q) on the footing is resisted by resistance provided by the *Geopier* (Q_g) and matrix soil (Q_m):

$$Q = q\,A = Q_g + Q_m = q_g\,A_g + q_m\,A_m \qquad (1)$$

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 the *Geopier* elements, q_m is the stress applied to the matrix soil, and A_m is the area of the matrix soil below the footing.

- Assuming that the footing is 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:

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

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

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

- 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):

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

- Rewriting q_g in terms of q:

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

- Upper-zone settlements are then computed using Equations 2 and 5.

Modulus values for the *Geopier* elements are selected based on empirical correlations derived from the previously performed modulus load tests. A design chart has been developed that relates assumed *Geopier* modulus values for different soil types (sands and sandy silts, silts and clays, and peat), consistencies based on Standard Penetration Resistance value, and unconfined compressive strength values (Fox and Cowell 1998). The assumed *Geopier* modulus values are confirmed for designed projects by performance of modulus load tests on the site. Modulus values for the matrix soils are estimated by evaluating the ratio of applied footing pressure to predicted footing settlement for the case of no *Geopier* reinforcement.

Lower Zone Analysis

Settlements in the Lower Zone soils are computed using conventional geotechnical stress distribution solutions (such as Westergaard solution) and settlement analysis procedures described in the literature (Terzaghi and Peck 1967). The conventional stress distribution assumption is believed to be conservative because the presence of the piers results in a more efficient stress transfer and stress dissipation with depth below the footing bottom than that which occurs for conventional spread footings (Lawton 2000).

Design Process

The *Geopier* design methodology has a built-in flexibility for adjustment if the initial analysis indicates that too much settlement will occur. A rule of thumb for one-inch settlement control in the USA, is to limit Upper Zone settlements to 1.25 cm (0.5 inch). This leaves a maximum of 1.25 cm (0.5 inches) remaining for settlement contribution from the Lower Zone. If settlement contribution calculations from the Lower Zone are higher, for example, 2 inches, then the normal procedure is to lengthen and deepen the *Geopier* element in order to reduce the thickness of the Lower Zone until the settlement contribution from the Lower Zone is less than 0.50 inches. A rough rule of thumb that works in most cases except for very soft and compressible soils, is that the *Geopier* shaft length (drill depth) should be approximately 1.3 times the footing width for a square footing. This often is a good assumption to make for the first calculation run.

Safety Factor Elements

Four important safety factors implemented in the *Geopier* design methodology are:

1. The procedure used in the Upper Zone analysis is to use modulus values based on a 2.5 cm deflection. Actual modulus values measured at 1.25 cm are considerably higher than those measured at 2.5 cm.

2. The actual stress concentration and stress distribution through *Geopier* elements is neglected by assuming Westergaard stress distribution of total footing stresses, when in actuality, most of load is concentrated on stiff pier elements, and stresses dissipate to insignificant levels at lesser depths than shown by Westergaard.

3. Prestressing and prestraining effects within the matrix soils surrounding the *Geopier* elements and below the *Geopier* elements are neglected.

4. Lower Zone modulus values are often underestimated because of lack of data, such as information on preconsolidation pressures.

APPLICATIONS TO "FLOATING FOUNDATIONS"

"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. *Geopier* elements are designed to create this stiff zone by increasing the composite stiffness of the subsurface soils at depths in which footing-induced stresses are the highest. The end result is to limit long-term total and differential foundation settlements to satisfy structural design criteria. 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.

Case histories of using *Geopier* floating foundation system are presented in a recent paper written about the feasibility of constructing *Geopier* elements for floating foundations in the Mekong Delta, Vietnam region of deep, soft soils (Fox and Lien 2001). The conservative nature built into *Geopier* design can be seen in Table 1, showing the *Geopier* design modulus values and measured modulus values at each project site.

Table 1: Design and measured stiffness modulus values at floating foundation sites

Project	Design *Geopier* stiffness modulus value (MN/m^3)	Measured *Geopier* stiffness modulus value (MN/m^3)
Condominium, Anacortes, Washington, USA	35	82
Marriott Courtyard Hotel, Portland, Oregon, USA	28	56
Pricesmart Superstore, Pasig City, Philippines	35	74

RESISTANCE TO UPLIFT LOADS

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 (Figure 5) are incorporated into *Geopier* elements to effectively resist tensile loads. Detailed discussions of the *Geopier* uplift elements are presented in Lien and Fox (2001). The unit uplift loading resistance of individual element is computed using either drained or undrained geotechnical analysis procedures both depending upon the surrounding soil drainage conditions.

Geopier uplift elements have been installed to resist uplift loads for tall structures subject to wind and earthquake loads, thin concrete retaining walls subject to tension at the heel of the walls, and airplane hangars subject to extreme wind loads.

SUPPORT OF FLOOR SLABS: DESIGN AND APPLICATIONS

Design Considerations

Geopier elements are often used to replace structural floor slabs required in areas of soft and compressible soils or areas of high live load on slabs, or both. The design procedures are identical to those outlined above for Upper Zone settlements below shallow spread footings. However, Lower Zone settlements are normally not considered, because floor slabs are seldom subject to large area pressures (design pressures are typically associated with moving live loads and discrete point loads).

The support of floor slabs on *Geopier*-reinforced soil offers significant advantages over the use of structural floor slabs spanning between deep foundations because cost savings are achieved both in the supporting elements (*Geopier* elements replacing deep foundation elements) and in floor slab concrete. Floor slab concrete cost savings are achieved because *Geopier* element spacings are typically closer than deep foundation spacings, *Geopier* element diameters are greater than most deep foundation diameters, and the compatibility of the *Geopier* elements with the matrix soils allows for the matrix soils to share in some of the support. These combined effects allow for a thinner concrete slab as shear stresses and bending stresses are reduced. *Geopier*-supported floor slabs are designed as lightly reinforced slabs on grade rather than true structural slabs, resulting in the need for less reinforcing steel.

For projects in which floor slab steel reinforcement is not desired, load transfer to the top of the *Geopier* elements may be achieved by placing a pad of granular material such as crushed stone or coarse sand over the tops of the *Geopier* elements and below the floor slab. The thickness of the supporting pad should be slightly thicker than one-half the *spacing between the edges* of the *Geopier* elements. Reinforcing the granular pad with a strong tensile geogrid may reduce this thickness.

Applications

Geopier elements have been used to support floor slabs at major chemical plants, aircraft hangars, retail centers, and warehouses. At a site near St. Louis, Missouri, USA, the tops of *Geopier* elements were instrumented with pressure plates and settlement plates prior to placing the overlying fill pad, floor slab, and surcharge load was used to simulate design live loads. The results of the instrumentation confirmed assumed design values of stress concentration to the tops of the elements and uniform settlement between the *Geopier* elements and reinforced matrix soil (Minks et al. 2001).

LANDSLIDE STABILIZATION: DESIGN AND APPLICATIONS

Design Considerations

The sliding action of a mass of unstable soil moving downslope may be as quick as a mud slide, or it may be almost imperceptible, as the soil mass creeps downslope. The unusually high internal shearing resistance of *Geopier* elements, results in *Geopier* soil reinforcement being highly effective as a means of stabilizing failing slopes, and providing global stabilization within weak foundation soils.

Composite shear strength parameter values are calculated for reinforced *Geopier*-soil zones acting to resist critical slip movements and to increase safety factors against slope instability, as shown in Figure 7. For drained conditions, the composite cohesion intercept is zero. The composite angle of internal friction (ϕ'_{comp}) is calculated as:

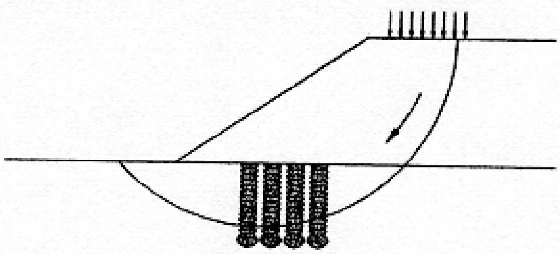


Figure 7 *Geopier* Uplift Element

$$\phi'_{comp} = \arctan\left[R_a \tan(\phi'_g) + (1 - R_a)\tan(\phi'_m)\right] \quad , \qquad (9)$$

where ϕ'_g is the friction angle of the *Geopier* element (51 degrees for well graded aggregate, 48 degrees for open-graded aggregate), ϕ'_m is the friction angle of the matrix soil, and R_a is the percent coverage of the *Geopier* elements in the reinforced zone.

Applications

Table 2 summarizes two recent unstable slope reinforcement projects involving massive landslides that were successfully and economically corrected by *Geopier* soil reinforcement:

Table 2: Summary of landslide reinforcement applications

Project	Matrix soil friction angle prior to *Geopier* reinforcement	Composite friction angle after *Geopier* reinforcement	Safety factor after *Geopier* stabilization
Lynn Road landslide, Raleigh, NC, USA	28 degrees	38 degrees	1.35
County Road P48, Dallas County, IA, USA	6 degrees	15 degrees	1.12

SUPPORT OF STEEL STORAGE TANKS: DESIGN AND APPLICATIONS

Design Considerations

Large diameter steel storage tanks are often constructed over soft, compressible soils and subjected to large settlements. Settlements greater than 300 mm or greater are not uncommon, and are not necessarily cause for alarm. To perform adequately, steel storage tanks must meet the following general criteria.

1. The foundation soils below the tanks must be sufficiently strong to prevent bearing capacity failure. The most common type of failure is localized shearing along the edge of the tanks ("edge shearing"). *Geopier* elements are used to provide shear reinforcement under the perimeter of the tank. The elements must be installed sufficiently deep to intercept critical slip surfaces and increase the factor of safety to the design requirement.

2. The total settlement of the tanks must not be so great that problems are experienced with piping connections between the tanks and adjacent facilities.

3. The differential settlement between the edge of the tank and the interior must not be so great that the roof of the tank loses its convex shape. The tendency is for the interior of the tank to settle more than the exterior because of greater applied stresses to the soils under the middle of the tank.

4. The differential settlement along the perimeter of the tank wall must not be so great that the tank becomes distorted inducing complex tensile and buckling stresses in the tank shell.

Of particular importance, the use of *Geopier* elements in lieu of conventional deep foundations for tank support allows for the replacement of the thick and expensive concrete pile cap with a layer of compacted crushed stone positioned between the tops of the *Geopier* elements and the tank bottom. As described above for floor slab support, the thickness of the crushed stone pad is designed to be slightly greater than one-half the distance between the edges of the *Geopier* elements.

Applications

Geopier elements have been used to support large-diameter tanks and grain bins constructed in many U.S. states. At a project site in Houston, Texas, USA, 315 *Geopier* reinforcing elements installed below 100-foot diameter tanks constructed over soft clay fill soils resulted in total measured settlements of less than one inch (Wissmann et al. 2001b).

TRANSPORTATION PROJECTS: RESEARCH AND APPLICATIONS

Applications, case histories, and research of using *Geopier* soil reinforcement in transportation projects are presented by Lien and Fox (2001). In the past several years, *Geopier* soil reinforcement has been utilized to support highway embankments, railroad embankments, MSE walls, stabilize failing slopes, support box culverts, and reduce the potential for liquefaction.

Research And Development

Major research efforts have been undertaken in the past 15 years to add insight into the mechanics of *Geopier* support. Partial listings of research objectives, descriptions, and references for research conducted to investigate basic behavior, foundation support characteristics, and special applications are presented in Tables 3 through 5.

Table 3: Listing of *Geopier* research on properties of constructed elements

Research objective	Description	Reference
Shear strength	Full-scale direct shear tests performed at the tops of installed elements	Fox and Cowell 1998
	Triaxial shear tests performed on reconstituted samples	White et al. 2001
Lateral pressure buildup	Lateral pressure increases measured using the K_o Stepped Blade test. Shear strength envelopes established using Borehole Shear Tests	Handy 2001
Magnitude of lateral prestraining	Inclinometer casings installed prior to pier construction to measure radial displacements during pier construction and testing	Unpublished
Geopier stiffness modulus	As part of production operations, over 400 modulus tests have been performed, many with telltales	Fox and Cowell 1998
Construction noise	Noise attenuations measured at a project site near Memphis, Tennessee, USA	Unpublished
Construction vibrations	Vibration attenuations measured at a project site near Memphis, Tennessee, USA	Unpublished
Behavior of piers constructed from alternate materials	Modulus tests have been performed at project sites using recycled concrete, cement-modified piers, and asphalt-modified piers	Unpublished

Table 4: Listing of *Geopier* research for footing support

Research objective	Description	Reference
Stress concentration to tops of piers	Pressure plates installed between constructed footings/*Geopier* elements and between footings/ matrix soils to measure stress concentration	Lawton 2000, Minks et al. 2001
Stress dissipation within piers	Pressure plates installed within *Geopier* elements subject to modulus tests and within elements supporting a footing	Wissmann & Minks 1999, Lawton 2000
Group interaction effects	Finite element studies	Lin 1996
	Full-scale instrumented *Geopier*-supported footing subjected to compression loads in Utah	Lawton 2000
	Full-scale instrumented footing subjected to compression loads at test site in Iowa	Unpublished
Resistance to lateral loads	Full-scale instrumented footing subjected to dynamic lateral loads	Lawton 2000
Seismic performance	A full-scale instrumented *Geopier*-supported footing was subjected to large (400 kip) vertical, lateral, and uplift loads simulating a M_w 7.5 earthquake.	Lawton 2000
Resistance to uplift loads	As part of production operations, uplift load test results are available for over 30 project sites. Uplift load testing research has been performed at the University of Utah.	Hsu 2000, Wissmann et al. 2001, Caskey 2002.

Table 5: Listing of *Geopier* research for special applications

Research objective	Description	Reference
Floor slab behavior	Heavily-loaded floor slab supported by *Geopier* elements instrumented with settlement plates and pressure plates and subjected to a test surcharge	Minks et al. 2001
Reinforcement of peat soils	Modulus tests performed at peat soil site. Three case histories presentations.	Fox and Edil 2000
Reinforcement of residual soils	30 modulus tests in Piedmont soils compared and contrasted with E values estimated for native soils	Wissmann et al. 2001c
Embankment settlement control	Full-scale earthen embankment supported by *Geopier* elements instrumented by researchers at Iowa State University	White and Wissmann 2002
Support of box culvert	Box culvert instrumented with pressure and settlement plates at project site in Iowa	Unpublished
Reduction of bridge abutment settlements	Settlement monitoring program for *Geopier*-reinforced bridge embankments	Unpublished

LIMITATIONS

No ground improvement or foundation support method can be the best at solving all problems. *Geopier* soil reinforcement's limitations are:

Economic Limitations

The *Geopier* system requires a drilled cavity. When soils are unstable and cave-in during drilling or during tamping, the holes have to be lined with temporary steel casing. This slows down production considerably and results in a significant increase in cost per element installed. Examples of areas that traditionally contain caving soils include coastal plain, high groundwater sands, alluvial sands, and very soft, saturated alluvial silts and clays.

Performance Limitations

The *Geopier* system is a short aggregate pier system. As such, it is designed for construction of relatively short reinforcing elements. Because of the unusually high capacity per pier, a shorter *Geopier* shaft element is often equivalent in support capacity to a pile 2 to 5 times as long. Yet, some load applications, and in particular, wide, heavy load applications such as large, heavily-loaded structural mats or large bridge abutments, result in significant applied stresses extending deep within the underlying soil profile. When those soils are soft and compressible to a great depth, then *Geopier* soil reinforcement, which usually is limited to treatment zone depths of about 8 m, is not the solution. *Geopier* designers realize this, and do not allow the system to be used on applications where positive performance results cannot be substantiated.

SUMMARY

Geopier soil reinforcement is increasingly being used within the United States and abroad, as a cost-effective, predictable and safe, ground improvement system. Growth in the use of this technology has averaged over 100% per year for the past seven years. It is characterized by simplicity, relatively small equipment with easy mobilization requirements, versatility, and a well-focused internal research and development effort. The system itself is not complicated. The concept is based on a specialized form of overexcavation and replacement. In the short span of twelve years, the system has grown to become the leading ground improvement method in the United States for support of commercial structures. Other applications are becoming more widely recognized and the system is increasingly being used for transportation and industrial applications, not only in the USA, but in Europe and Asia as well.

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