IMPROVING GLOBAL STABILITY AND CONTROLLING SETTLEMENT WITH *GEOPIER* SOIL REINFORCING ELEMENTS

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Highway construction often requires the placement of embankments and earth retaining walls to facilitate grade separations. When these structures are placed on top of weak and compressible soils, stability and settlement are of concern. Historical measures that have been used to reduce the severity of these problems include construction of toe berms and use of surcharging techniques. To avoid the need for extending large right-of-ways required for toe berm construction or for time-consuming surcharging, *Geopier*® soil reinforcing elements have been used to reinforce weak and compressible foundation soils prior to constructing earth embankments and walls. The elements increase the factor of safety against slope instability because of their high angle of internal friction (48 to 52 degrees). The elements also reduce the magnitude and time of settlement by increasing the overall stiffness of the foundation soils, laterally prestressing the matrix soils, and providing a drainage pathway for dissipation of excess pore water pressure.

Although *Geopier*® soil reinforcing elements have been used to reinforce highway walls and embankments, railroad embankments, and landslides, design guidelines have not previously been published. This paper presents analytical methods used to design aggregate pier elements to reinforce weak soils and control settlements below embankments. This paper also presents a database of field and laboratory tests performed to establish design parameter values. This work is of particular significance because it provides design recommendations and test results for an effective ground reinforcement technique used both in the United States and in Asia.

1.0 Introduction

Geopier® soil reinforcing elements have traditionally been used to support compressive loads applied by footings, floor slabs, and steel storage tanks. The effectiveness of the piers is attributed to the lateral prestressing that occurs in the matrix soils during pier construction and to the high strength and stiffness of the piers. In the past few years, there has been a development towards using the elements below highway retaining walls and embankments to reinforce soft soils, control settlements, and accelerate settlements (Figure 1).

The design of the soil reinforcement system uses classical geotechnical engineering approaches in conjunction with field and laboratory tests performed to evaluate the shear strength and compressibility of the elements. This paper presents:

1. The results of field and laboratory tests performed to evaluate the strength and compressibility of the *Geopier* elements,
2. The design methods implemented to evaluate the effectiveness of soil stabilization with the elements, and
3. Descriptions of project conditions and design approaches used for two recent projects in Iowa, USA where *Geopier* elements were used to support MSE walls and a railroad embankment.

This paper is of particular significance because it provides descriptions of design methods for improving global stability and controlling settlement of embankments, as well as field and laboratory test results associated with this rapidly growing, patented soil reinforcement method.

2.0 GEOPIER Construction

The construction of *Geopier* reinforcing elements is well described in the literature and shown in Figure 2 [1], [2], [3], [4]. The piers are installed by drilling 610 mm (24 inch) to 915 mm (36 inch) diameter holes to depths ranging between 2 m and 8 m (7 feet and 26 feet) below working grade elevations (Figure 2, Panel 1), placing controlled lifts of aggregate stone within the cavities, and compacting the aggregate using a specially designed high-energy beveled impact tamper. The first lift consists of clean stone and is rammed into the soil to form a bottom bulb below the excavated shaft (Figure 2, Panels 2 and 3). The bottom bulb effectively extends the design length of the aggregate pier element by approximately one pier diameter. The piers are completed by placing consecutive 0.3 m (one-foot) thick lifts of aggregate over the bottom bulb and densifying the aggregate with the beveled tamper (Figure 2, Panel 4). During densification, the beveled shape of the tamper forces stone laterally into the sidewall of the excavated cavity. This action increases the lateral stress in the matrix soil thus providing additional stiffening and increased normal stress perpendicular to the perimeter shearing surface. 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 effectively prestresses and pre-strains the pier and adjacent matrix soils and further increases the stiffness and capacity of the system.

The elements may be installed to penetrate through weak and compressible soils thus offering improvements in the composite shear strength and the composite compression characteristics of the reinforced deposit.

3.0 Field and Laboratory Tests

Field and laboratory tests have been performed to investigate the engineering properties of *Geopier* elements. The high shear strength afforded by the elements has been measured by means of full-scale direct shear tests performed at the tops of installed elements [5] and triaxial shear tests performed on reconstituted samples [6].

Full-scale direct shear test results, shown on Figure 3, indicate a friction angle of about 49 degrees for piers constructed from open-graded stone (no fines) and a friction angle of about 52 degrees for piers constructed from well-graded stone (5 to 10 % fines). Triaxial test results indicate a friction angle of 51 degrees for piers constructed from well-graded stone [7].

Full-scale *Geopier* modulus tests are performed at nearly every project site. The test setup includes an installed test element and uplift elements. A telltale, consisting of a steel plate attached to sleeved threaded bars, is installed at the bottom of the element during construction. During testing, the jack applies downward loads and deflections are measured at the top of the element and for the telltale.

A database has been developed by Fox and Cowell [5] for the results of modulus tests performed in various soils with elements of various shaft lengths and diameter (Table 1). Stiffness modulus is defined as the ratio of top-of-element stress to top-of-element deflection.

Table 1: Stiffness modulus values for generalized soil conditions

Soil Classification	Unconfined Compressive Strength (kPa)	Stiffness Modulus, k_g (MN/m^3)	Soil Classification	SPT N-value	Stiffness Modulus, k_g (MN/m^3)
Clay	10-110 111-220 221-380	34-48 48-68 68-75	Sand	1-6 7-12 13-25	45-71 71-77 77-88

4.0 Analysis Methods

Analysis methods used in the design of *Geopier* elements are based on classical geotechnical engineering approaches combined with the shear strength and stiffness characteristics of the aggregate elements.

4.1 Shear reinforcement

Geopier reinforcing elements are installed under retaining walls and embankments to intersect critical shearing surfaces thereby increasing the factor of safety against global instability (Figure 4). Design methods used to analyze the factor of safety against instability for slopes, embankments, and walls are performed using conventional computer programs [8].

The composite shearing strength parameter values of *Geopier* reinforced soils are computed using the conventional method of simply calculating the weighted average of the shear strength components of the aggregate piers and matrix soil materials [9]. The composite cohesion intercept (c_{comp}) is computed with the expression:

$$c_{comp} = c_g R_a + c_m (1-R_a) \quad , \tag{1}$$

where c_g is the cohesion intercept of the aggregate, c_m is the cohesion intercept of the matrix soils, and R_a is the ratio of the sum of the element cross-sectional areas to the gross footprint area of the reinforced soil zone. The cohesion intercept of the aggregate is zero. The composite friction angle (ϕ_{comp}) is computed with the expression:

$$\phi_{comp} = \arctan [R_a \tan \phi_g + (1-R_a) \tan \phi_m] \quad , \tag{2}$$

where ϕ_g is the friction angle of the aggregate and ϕ_m is the friction angle of the matrix soils. The composite cohesion and friction angle values.

4.2 Settlement

Geopier elements decrease the magnitude of foundation soil settlement in the following ways:

- Portions of the relatively compressible matrix soils are replaced with stiffer materials and the applied embankment stresses concentrate to the relatively stiff elements.
- The increase in lateral earth pressure in the matrix soil surrounding the *Geopier* elements that occurs as a result of aggregate ramming allows for greater applications of vertical stress prior to the onset of consolidation.

4.2.1 Stress concentration to the stiff aggregate pier elements

The settlement of the composite *Geopier* elements and matrix soils may be computed using the conventional expression:

$$s = q\,H / E_{comp} \quad , \tag{3}$$

where s is the settlement within the zone of reinforced soil, q is the average surcharge pressure applied by the embankment to the reinforced soil, H is the thickness of the reinforced soil, and E_{comp} is the composite elastic modulus of the reinforced soil. The composite elastic modulus of the reinforced soil is computed as:

$$E_{comp} = E_g\, R_a + E_m\, (1\text{-}R_a) \qquad , \tag{4}$$

where E_g is the elastic modulus value of the *Geopier* reinforcing elements and E_m is the elastic modulus value of the matrix soil. The elastic modulus value of the reinforcing elements may be computed from the tabulated values of *Geopier* stiffness modulus (Table 1) by recognizing that the *elastic* modulus value is simply the product of *stiffness* modulus (k_g) and element length (H).

For normally-consolidated cohesive soils, the appropriate value for E_m may be computed from compression indices using the following expression established by equating consolidation settlement to elastic settlement:

$$E_m = q_m\, I_\sigma / [c_{\varepsilon c} \log ((I_\sigma\, q_m + \sigma'_{vo}) / \sigma'_{vo})] \quad , \tag{5}$$

where q_m is the pressure applied to the matrix soil, I_σ is the stress influence factor within the zone of reinforced soil, $c_{\varepsilon c}$ is the slope of the consolidation test results plotted on a log pressure versus strain graph, and σ'_{vo} is the initial effective vertical stress in the soil layer. At the level of the top of the piers, the calculated pressure applied to the matrix soil is generally on the order of 10 percent to 20 percent of the average surcharge pressure (q) as a result of stress concentration to the stiff *Geopier* elements. This range depends on the relative stiffness between the reinforcing elements and the matrix soil (R_s), the areal coverage of the reinforcing elements (R_a), and the consolidation behavior of the matrix soil. For overconsolidated cohesive soils, Equation 5 may also be used to evaluate E_m if $c_{\varepsilon c}$ is replaced by $c_{\varepsilon r}$, the slope of the consolidation test unload-reload response. The assumption implicit in Eq. (5) that the matrix soil is consolidating should be on the conservative side because of a constraining influence of lateral stress that is imposed during pier compaction.

4.2.2 Increase in lateral earth pressure

Handy [10] suggested stress relationships indicated by a sequence of Mohr circles shown in Figure 5. The left circle A indicates the stress condition in a normally consolidated soil, such that consolidation will initiate as soon as an additional vertical stress is applied. The middle circle B shows the change wrought by *Geopier* ramming, which remolds the soil and can increase lateral stress to the passive limit. This has been confirmed with in-situ stress measurements. For consolidation to occur, vertical stress must be raised to that indicated at the right of the third Mohr circle C, which as will be seen is many times higher than that of the vertical stress at the right of A. In overconsolidated soils that already area at stage B, the advantage from *Geopier* ramming is to reinstate the lateral stress that is relieved by boring, keeping the behavior elastic.

4.3 Settlement rate

Granular columnar elements reduce the time of consolidation settlement by two primary mechanisms [11]:

- When open-graded stone is used for pier construction, the piers act as a vertical drain and reduce the drainage path within the matrix soils for the dissipation of excess pore water pressure.
- The stress concentration that occurs to the tops of the stiff *Geopier* elements reduces the vertical stress on the consolidating matrix soils.

A design chart formulated by Han and Ye [11] is used to estimate the average rate of consolidation by horizontal drainage based on modified time factor in radial flow (T_r') and diameter ratio (N). The time factor for vertical flow is modified for radial flow (T_r') by the expression:

$$T_r' = c_r'\, t / d_e^2 \quad , \tag{6}$$

where c_r' is the modified coefficient of consolidation in the radial direction, t is time, and d_e is the diameter of the influence area. The modified coefficient of consolidation in the radial direction (c_r') is computed by modifying the coefficient of consolidation in the radial direction (c_r) by a factor that accounts for both stress concentration ratio (R_s) and diameter ratio (N):

$$c_r' = c_r\, (1+R_s / (N^2 - 1)) \quad , \tag{7}$$

where R_s is the ratio of E_g to E_m and N is expressed as the ratio of the diameter of the influence area (d_e) to the diameter of the reinforcing element (d_g).

5.0 Case History: Highway MSE Wall Support

At the 50th street overpass project in Des Moines, Iowa, USA, a new bridge was being constructed across Interstate Highway 235. Mechanically Stabilized Earth (MSE) retaining walls, 8.5 m (28 ft) tall, were constructed to support the ramps as they rise towards the new bridge overpass (Figure 6). The subsurface conditions at the project site consisted of a 5.5 m (18 ft) thick layer of weak clay underlain by stiff glacial till (Figure 6). Geotechnical field and laboratory design parameter values are presented in Table 2.

Table 2: 50th Street MSE wall soil parameter values

Soil Parameter	Field / Laboratory Value
Total unit weight, γ_t	19.0 kN/m^3 (121 pcf)
Average undrained shear strength, S_u	26 kPa (550 psf)
Overconsolidation pressure, P_p	105 kPa (2200 psf)
Coefficient of compression, $C_{\varepsilon c}$	0.20
Coefficient of recompression, $C_{\varepsilon r}$	0.02
Estimated coefficient of consolidation, C_r	0.01 cm^2/s (0.9 ft^2/day)

The design incorporated 0.76 m (2.5 ft) diameter *Geopier* elements spaced at 1.8 m (6 ft) on center, extending to depths of 5.5 m to penetrate the soft clay soils. The *constructed* elements exhibited diameters of 0.9 m (35 inches), resulting in an area replacement ratio (R_a) of 0.19. Using Table 1, estimated stiffness modulus (k_g) value for the elements was 34 MN/m^3 (125 pci).

Settlement estimates within the reinforced soil zone incorporated a stress influence factor of 1.0 and the assumption that the pressure applied to the matrix soil ranges between 15% and 20% of the average embankment pressure. The composite elastic modulus (E_{comp}) is computed to range between 41.1 MN/m^2 (859 ksf) and 41.5 MN/m^2 (867 ksf). From Equation 4, the settlement within the reinforced zone is estimated to be approximately 2.5 cm (1.0 in), only 10 percent of the predicted settlement with no *Geopier* reinforcement.

The degree of consolidation was calculated using the methodology presented above with a stiffness ratio (R_s) of 25, a diameter ratio (N) of 2.3, and a duration of 10 days. The computed modified time factor (T_r') is approximately 1.2. Using these parameter values, an average degree of consolidation of nearly 100 percent is obtained from the Han and Ye design chart [11]. Conventional vertical consolidation calculations (without reinforcement) indicate a degree of consolidation equal to 20 percent after the same duration of loading. Thus, the rate of consolidation is shown by the approach to be significantly increased because of the contributions of radial drainage and stress concentration to the stiff elements.

6.0 Case History: Railroad Embankment Stabilization

Construction of a 5.6 km (3.5 mile) long railroad spur in southeast Iowa, USA, was needed to connect a major industrial facility to the mainline of the railroad. The proposed spur included the construction of a 8.5 m (28 ft) tall earthen embankment across a 335 m (1100 ft) section of floodplain. Subsurface conditions at the embankment location consisted of 3.7 m (12 ft) of soft to medium stiff alluvial clay overlying weathered limestone (Figure 7).

Global stability calculations resulted in a short-term factor of safety of 1.2, a value lower than the design criterion. Using the estimated design shear strength parameter values provided in Table 3 for embankment soils, subsurface soils, and aggregate piers, stability analyses incorporating *Geopier* soil reinforcement were then performed.

Table 3: Railroad embankment stability analysis parameter values

Soil Type	ϕ (degrees)	c (kPa)	γ (kN/m^3)
Clay embankment	20	16.8	19.9
Alluvial clay	5	21.5	17.9
Weathered limestone	5	38.3	22.0
Geopier aggregate	49	0	22.8

A composite friction angle (ϕ_{comp}) of 15 degrees and a composite cohesion intercept (c_{comp}) of 17.7 kPa (370 psf) were calculated for the *Geopier* reinforced zone using Equations 2 and 3 with an area replacement ratio (R_a) of 17 percent. The results of the undrained stability analysis indicate that the designed *Geopier* installations increase the safety factor from 1.2 to 1.3. To achieve the required area replacement ratio, the 0.76 m (30-inch) diameter elements were installed in triangular grid with an element spacing of 1.8 m (6 ft) on center.

7.0 Conclusions

This paper details the design methods associated with *Geopier* soil reinforcing elements for improving global stability, controlling settlement, and increasing the rate of settlement below embankments. The high shear strength exhibited by the aggregate elements allows for substantial increases in the composite shearing resistance within slopes and beneath embankments, thereby providing higher global factors of safety against instability. The combination of the element stiffness and the lateral pre-stressing induced within the matrix soil during pier installation significantly increases the composite stiffness of the reinforced zone, thus reducing settlement magnitudes. Settlement rate is increased as a result of both radial drainage provided by the elements and reduction of applied surcharge pressure on the matrix soil from stress concentration to the pier elements. Case histories are presented where *Geopier* soil reinforcing elements are used to provide economical solutions to improve global stability, increase settlement rates, and reduce settlement magnitudes.

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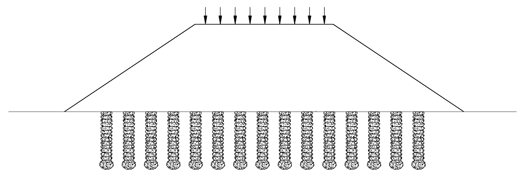

Figure 1: *Geopier* reinforcement of soils beneath embankments and retaining walls

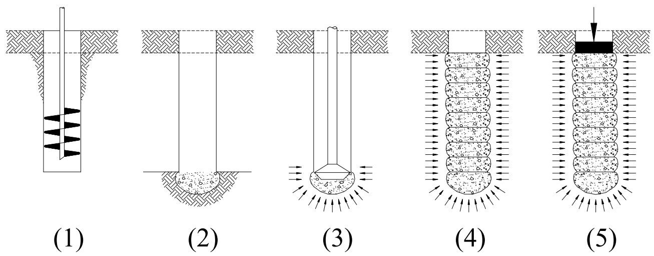

Figure 2: Construction Process

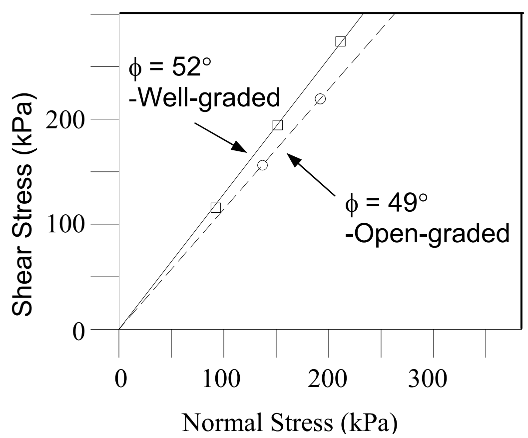

Figure 3: Results of full-scale direct shear tests

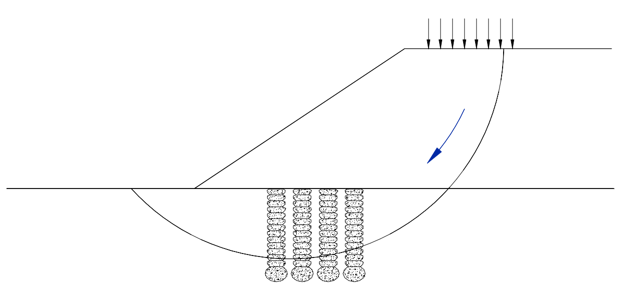

Figure 4: Global stabilization using *Geopier* elements

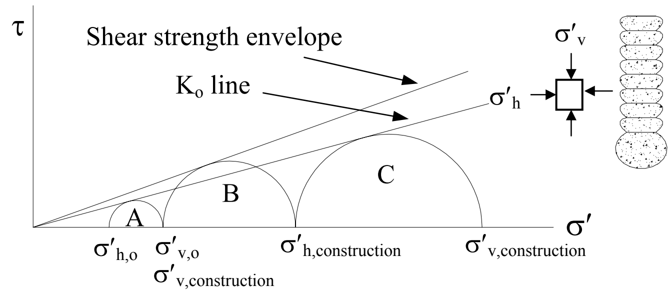

Figure 5: Effect of increasing lateral earth pressure in decreasing settlement magnitude, after Handy, (2001).

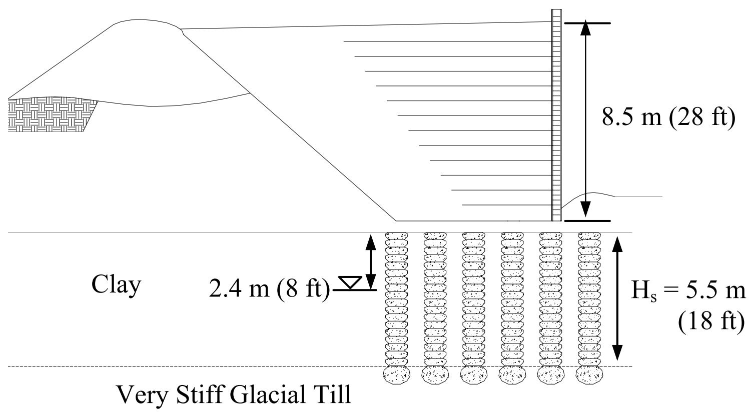

Figure 6: 50th Street project soil profile

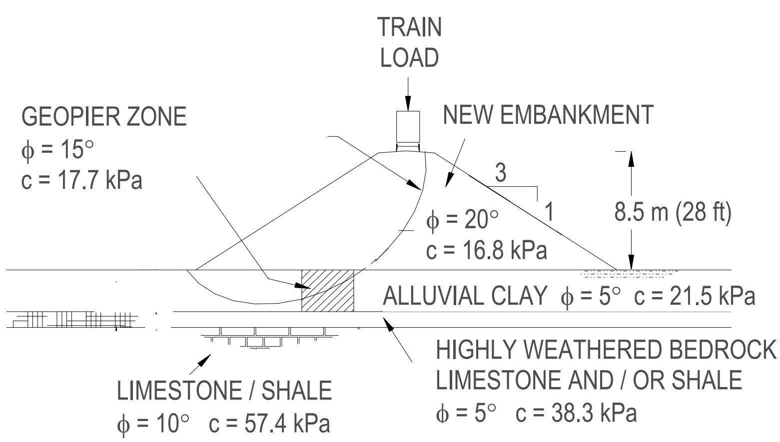

Figure 7: Iowa railroad embankment stability results