
GEOPIER[®] SHEAR REINFORCEMENT FOR
GLOBAL STABILITY AND SLOPE STABILITY

This Technical Bulletin discusses the increase in the soil shear strength afforded by the installation of *Geopier*[®] elements. Increases in shear strength are often required in weak soils where construction of Mechanically Stabilized Earth (MSE) retaining walls, concrete retaining walls, and earthen embankments may result in global instability. Increases in shear strength are also required for natural slopes subject to sliding. *Geopier* construction results in very dense aggregate pier elements that exhibit high angles of internal friction. This Technical Bulletin describes design methods used for the improvement of soil shear strength with *Geopier* soil reinforcing elements.

I. BACKGROUND: GLOBAL STABILITY
AND SHEAR STRENGTH

Construction of MSE retaining walls, concrete retaining walls, and earthen embankments often results in high shearing stress in the underlying soil. If the shear strength of the foundation soils is less than the applied shear stress, failure will occur as the structure rotates on slip surfaces extending through the foundation soils. Similarly, if the shear strength of natural or fill slopes is less than the shear stress in the inclined soil mass, a landslide will occur.

Geopier soil reinforcing elements are installed in weak matrix soil to improve the composite shearing strength and increase the factor of safety against global instability or sliding. Depictions of *Geopier* elements to reinforce matrix soils beneath an MSE wall, an embankment, and within a sliding soil mass are illustrated in Figures 1a, 1b, and 1c, respectively.



Figure 1a.
Geopier
Soil Reinforcement
of MSE Wall.

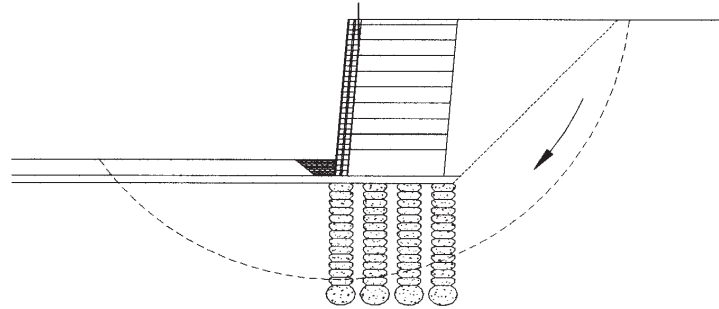


Figure 1b.
Geopier
Soil Reinforcement
of Embankment.

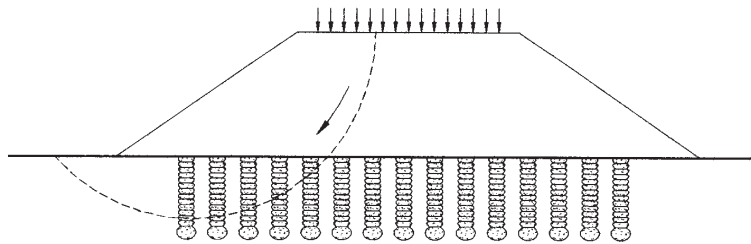
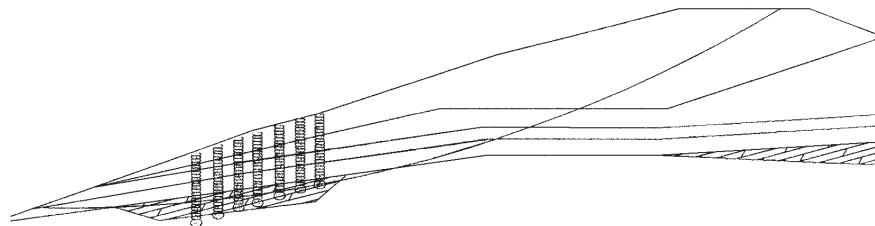


Figure 1c.
Geopier
Soil Reinforcement
of Natural Slope.



2 . G E O P I E R C O N S T R U C T I O N

Geopier construction is described in detail in the *Geopier Reference Manual* (Fox and Cowell 1998). The elements are constructed by drilling out a volume of compressible soil to create a cavity and then ramming select aggregate into the cavity in thin lifts using the patented beveled tamper. The ramming action causes the aggregate to compact vertically and to push laterally against the matrix

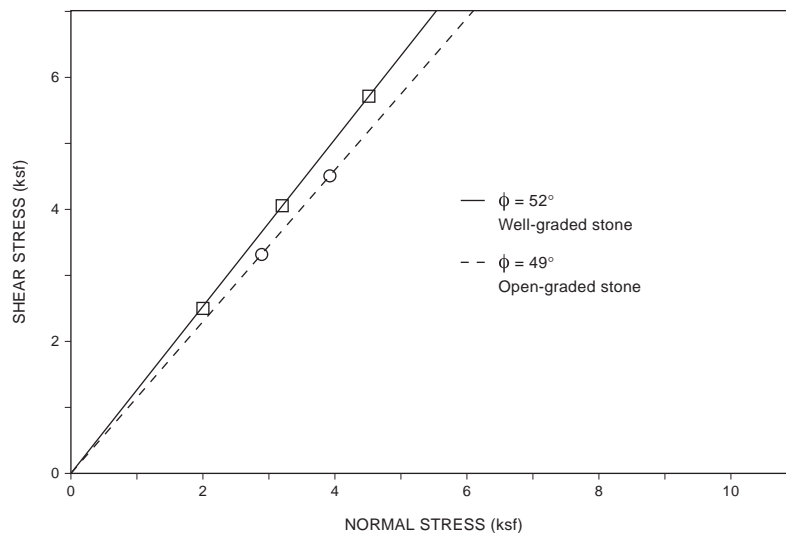
soil, thereby increasing the horizontal stress in the matrix soil. *Geopier* construction results in a very dense aggregate pier with high stiffness and high angle of internal friction resulting from the dilation of the aggregate when subject to shearing stresses. The construction process allows for a high level of confidence in the design friction angle used for rammed *Geopier* aggregate.

3 . G E O P I E R S H E A R S T R E N G T H

Full-scale field shear tests performed on 30-inch diameter *Geopier* elements and small-scale laboratory triaxial tests performed on reconstituted samples demonstrate that the angle of internal friction for *Geopier* aggregate ranges from 49 degrees to 52 degrees, depending on gradation. Results obtained from the full-scale direct shear tests performed on *Geopier* elements (Fox and Cowell 1998)

are shown in Figure 2. The tests were performed by applying incremental normal loads to the top of installed *Geopier* elements followed by the application of horizontal loads until shear failure. *Geopier* elements constructed using both well-graded base course stone and open-graded (#57) stone were tested.

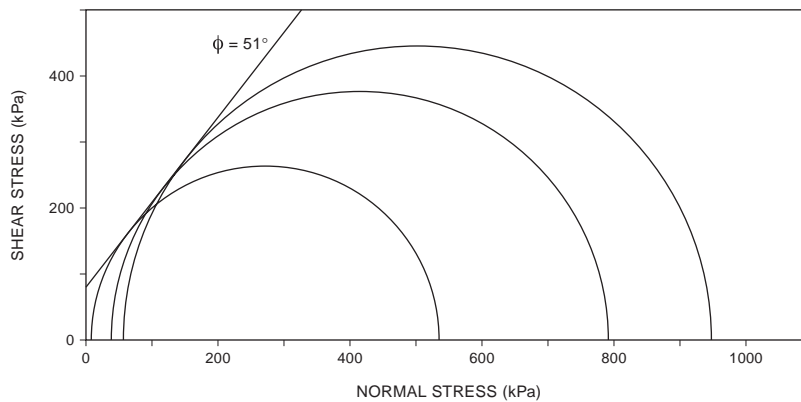
Figure 2.
Results of Full-scale Field Shear Testing
Performed at the Tops of Geopier Elements.



Small-scale laboratory triaxial tests were performed at Iowa State University on reconstituted samples of well-graded *Geopier* aggregate compacted to densities consistent with those measured for installed *Geopier* elements (White 2001). Test results, illustrated in Figure 3, indicate

an angle of internal friction of 51 degrees. The high friction angles measured in the field and laboratory tests are attributed to the high density and the dilatent behavior of the very stiff aggregate produced during the high-energy ramming of the crushed aggregate.

Figure 3.
*Results of Triaxial Testing
of Compacted Geopier Aggregate.*



4 . S H E A R R E I N F O R C E M E N T D E S I G N M E T H O D S

The design of shear reinforcement for slopes, embankments, and walls is performed by determining the factor of safety against global instability. The factor of safety against instability is the ratio of the resisting moment to the destabilizing moment (Duncan 1987). Many computer programs, such as PCSTABL, UTEXAS, SLOPE/W, and GSLOPE, are currently available for performing these conventional analyses. The input parameters required to perform the analysis include slope or wall geometry, soil unit weight, soil shear

strength (cohesion and friction angle), and the level of the phreatic surface.

4.1 COMPOSITE SHEAR STRENGTH PARAMETERS

The composite shearing strength of *Geopier*-reinforced soils is computed using the conventional method of calculating the weighted average of the shear strength components of the *Geopier* elements and matrix soil materials (FHWA 1999). The composite shear strength

is expressed in the following equation:

$$\tau_{\text{comp}} = \sigma'_v \tan \phi'_{\text{comp}} + c'_{\text{comp}} \quad \text{Eq. 1.}$$

The composite cohesion intercept (c'_{comp}) is computed with the expression:

$$c'_{\text{comp}} = c'_g R_a + c'_m (1 - R_a), \quad \text{Eq. 2.}$$

where c'_g is the cohesion intercept of the *Geopier* aggregate, c'_m is the cohesion intercept of the matrix soils, and R_a is the ratio of the *Geopier* area to the gross footprint area of the reinforced soil zone. Because the cohesion intercept of the *Geopier* aggregate is zero, Equation 1 reduces to:

$$c'_{\text{comp}} = c'_m (1 - R_a). \quad \text{Eq. 3.}$$

The composite friction angle (ϕ'_{comp}) is computed with the expression:

$$\phi'_{\text{comp}} = \arctan [R_a \tan \phi'_g + (1 - R_a) \tan \phi'_m], \quad \text{Eq. 4.}$$

where ϕ'_g is the friction angle of the *Geopier* aggregate and ϕ'_m is the friction angle of the matrix soils.

4.2 COMPOSITE SHEAR STRENGTH PARAMETERS INCORPORATING STRESS CONCENTRATION

In situations where *Geopier* elements supporting MSE walls or embankments extend through weak soils to a firm bearing layer, the significant difference between the matrix soil stiffness and the *Geopier* element stiffness results in a concentration of stress to the tips of the *Geopier* elements. This results in a significant

further increase in the composite shear strength (Mitchell 1981).

The composite shear strength of the *Geopier*-reinforced zone is computed in a manner similar to that discussed above utilizing a weighted average approach as presented in Equation 1. However, the calculations to determine the composite friction angle and cohesion values incorporate additional terms to account for the stress concentration:

$$\phi'_{\text{comp}} = \arctan \left[\frac{R_s}{R_a R_s - R_a + 1} R_a \tan \phi'_g + \frac{1}{R_a R_s - R_a + 1} (1 - R_a) \tan \phi'_m \right], \quad \text{Eq. 5.}$$

$$c'_{\text{comp}} = \frac{1}{R_a R_s - R_a + 1} (1 - R_a) c'_m, \quad \text{Eq. 6.}$$

where R_s is the ratio of the *Geopier* element stiffness to the matrix soil stiffness (Mitchell 1981). Typical stiffness ratio values range from 10 to 40 when considering traditional foundation support applications (Lawton and Fox 1994, Fox and Cowell 1998, Lawton 2001). Design values of stiffness ratio must be selected with care.

4.3 INCORPORATION OF COMPOSITE PARAMETERS

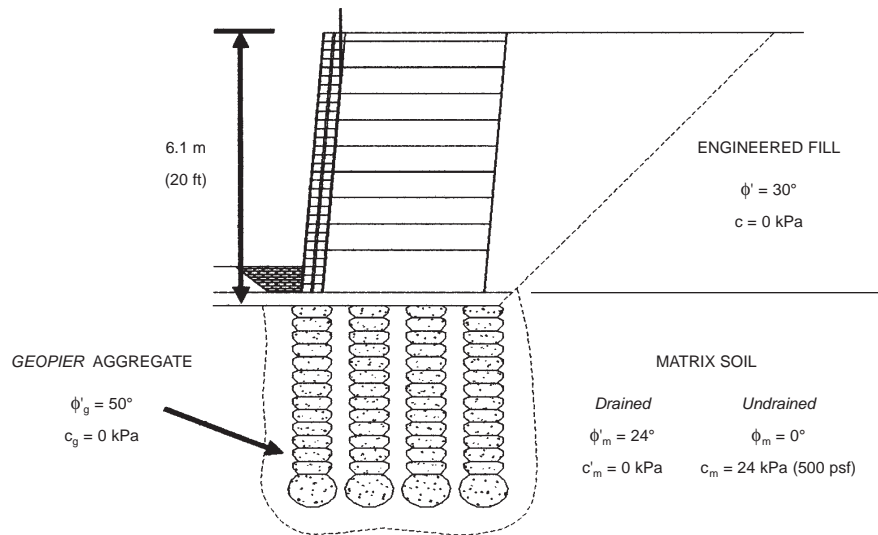
The *Geopier*-reinforced zone is designed to intersect the critical shearing surfaces located beneath the retaining walls and the embankment slopes. Within the reinforced zone, the composite cohesion and friction angle values (Equations 2 through 6) represent the composite shear strength of the soil zones reinforced by the aggregate elements. Analyses are performed on a trial and error basis; the area coverage (R_a) of the *Geopier* elements is varied until the acceptable factor of safety is reached.

5 . EXAMPLE CALCULATIONS

Example calculations for estimating the composite shear strength parameter values using the procedures outlined above are shown in Figures 4a and 4b. The

matrix soil and Geopier aggregate shear strength parameter values are provided in the figure. An area ratio (R_a) of 0.20 is assumed for the calculations.

*Figure 4a.
Determination of
Composite Shear Strength
Parameter Values.*



COMPOSITE SHEAR STRENGTH PARAMETER VALUES (NO STRESS CONCENTRATION)

Drained Composite Parameter Values

$$c'_{\text{comp}} = (1 - 0.20) 0 \text{ kPa} = 0 \text{ kPa}$$

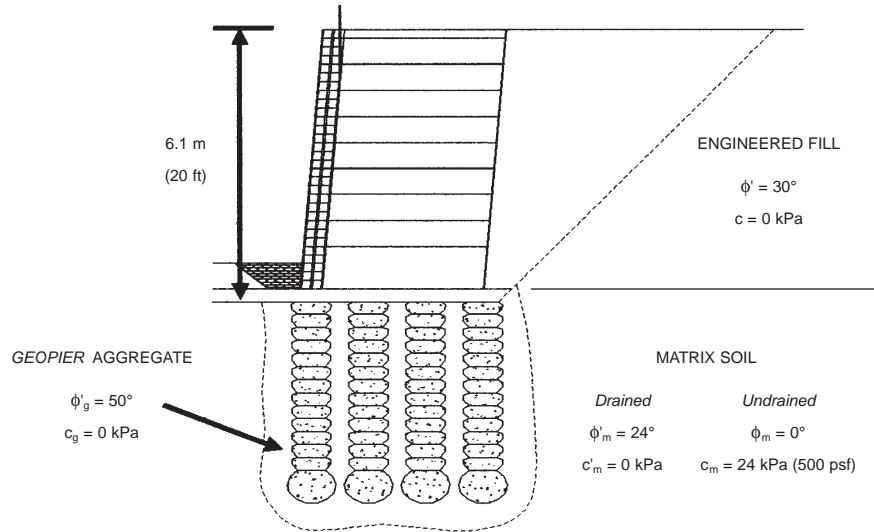
$$\phi'_{\text{comp}} = \arctan [0.20 \tan 50^\circ + (1 - 0.20) \tan 24^\circ] = 30.7^\circ$$

Undrained Composite Parameter Values

$$c_{\text{comp}} = (1 - 0.20) 24 \text{ kPa} = 19.2 \text{ kPa (400 psf)}$$

$$\phi_{\text{comp}} = \arctan [0.20 \tan 50^\circ + (1 - 0.20) \tan 0^\circ] = 13.4^\circ$$

Figure 4b.
Determination of Composite Shear Strength Parameter Values
Using Stress Concentration.



COMPOSITE SHEAR STRENGTH PARAMETER VALUES (STIFFNESS RATIO = 5)

Drained Composite Parameter Values

$$c'_{\text{comp}} = \left[\frac{1}{10(0.20) - 0.20 + 1} \right] (1 - 0.20) 0 \text{ kPa} = 0 \text{ kPa}$$

$$\phi'_{\text{comp}} = \arctan \left[\left[\frac{10}{10(0.20) - 0.20 + 1} \right] 0.20 \tan 50^\circ + \left[\frac{1}{10(0.20) - 0.20 + 1} \right] (1 - 0.20) \tan 24^\circ \right] = 44.4^\circ$$

Undrained Composite Parameter Values

$$c_{\text{comp}} = \left[\frac{1}{10(0.20) - 0.20 + 1} \right] (1 - 0.20) 24 \text{ kPa} = 6.9 \text{ kPa (143 psf)}$$

$$\phi_{\text{comp}} = \arctan \left[\left[\frac{10}{10(0.20) - 0.20 + 1} \right] 0.20 \tan 50^\circ + \left[\frac{1}{10(0.20) - 0.20 + 1} \right] (1 - 0.20) \tan 0^\circ \right] = 40.4^\circ$$

Figure 5a (page eight) presents the results of an undrained global stability analysis performed using the same wall geometry and matrix soil properties as provided in Figure 4. The results of the analysis for *unreinforced* conditions indicate that the factor of safety is on the order of 1.0. The results of the analyses incorporating a Geopier-reinforced zone to intersect

the critical failure surface are presented in Figures 5b and 5c (page eight). Using an area ratio of 0.20 and a stiffness ratio of 1.0 (no stress concentration), the factor of safety is increased to 1.3 (figure 5b). The factor of safety increases to approximately 1.7 when a stiffness ratio of 5 is incorporated into the analysis (Figure 5c).

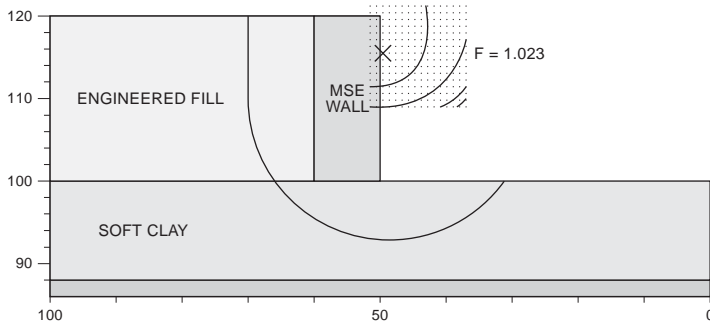


Figure 5a.
Unreinforced Slope
Stability Analysis.

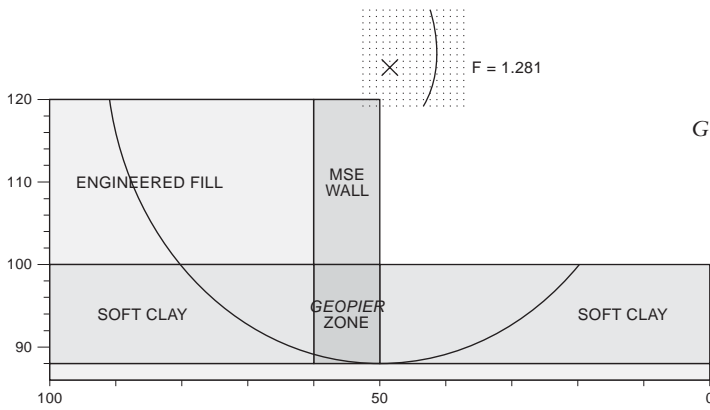


Figure 5b.
Slope Stability Analysis
Incorporating
Geopier-reinforced Zone.

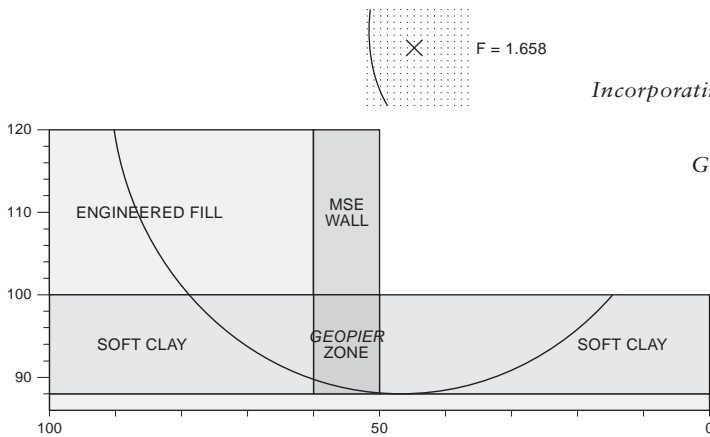


Figure 5c.
Slope Stability Analysis
Incorporating Stress Concentration
within the
Geopier-reinforced Zone.

6 . S U M M A R Y

Geopier soil reinforcement effectively increases the factor of safety against global instability of retaining walls, embankments, and slopes. Global instability occurs when the destabilizing moment exceeds the resisting

moment. When *Geopier* elements are installed within the zone of critical shearing surfaces, the high angle of internal friction exhibited by the *Geopier* elements provides significant increases in the shear resistance.

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S Y M B O L S U S E D

c'_{comp} = Composite cohesion intercept of the *Geopier*-reinforced zone.

c'_g = Cohesion intercept of *Geopier* aggregate.

c'_m = Cohesion intercept of matrix soil.

ϕ'_{comp} = Composite angle of internal friction of the *Geopier*-reinforced zone.

ϕ'_g = Angle of internal friction of *Geopier* element.

ϕ'_m = Angle of internal friction of matrix soil.

R_a = Ratio of sum of the cross-sectional area of *Geopier* elements to the gross reinforcement area.

R_s = Ratio of *Geopier* element stiffness to matrix soil stiffness.

τ_{comp} = Composite shear strength.

τ_m = Matrix soil shear strength.

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