

TECHNICAL BULLETIN NO. 5

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 Rammed Aggregate Piers® (RAP). 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 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.

1. 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 RAPs 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 RAPs 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

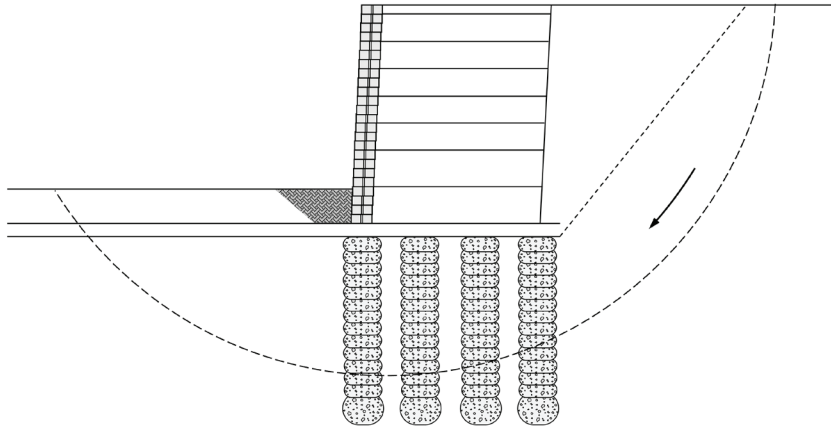


Figure 1b.
Geopier Soil Reinforcement of Embankment

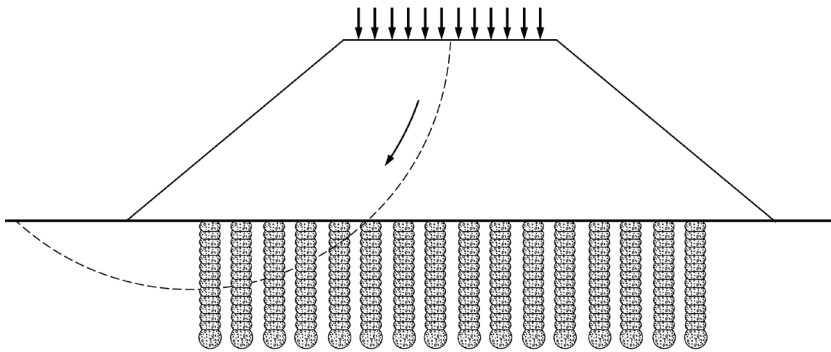
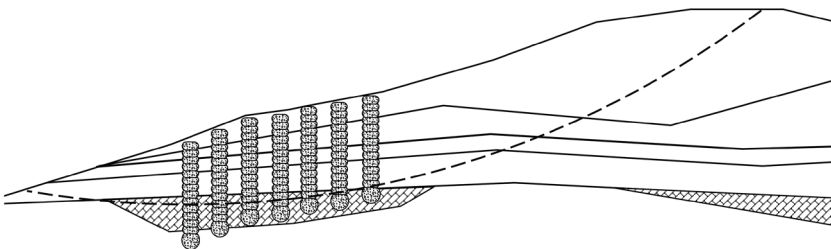


Figure 1c.
Geopier Soil Reinforcement of Natural Slope



2. GEOPIER CONSTRUCTION

Geopier RAPs are constructed by creating a cavity and then ramming select aggregate into the cavity in thin lifts using the patented compaction tip. 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

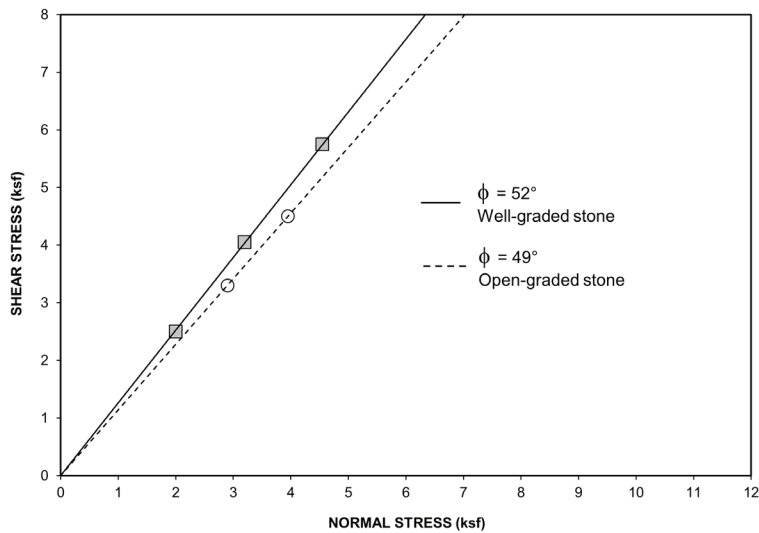
very dense aggregate pier with high stiffness and high angle of internal friction resulting from the dilation of the aggregate when subject to shearing stresses. The construction process allows for a high level of confidence in the design friction angle used for rammed Geopier aggregate.

3. GEOPIER SHEAR STRENGTH

Full-scale field shear tests performed on 30-inch diameter Geopier RAPs 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 RAPs are shown in Figure 2. The tests were performed by applying incremental normal loads to the top of installed Geopier RAPs followed by the application of horizontal loads until shear failure. Geopier RAPs constructed using both well-graded base course stone and open-graded (AASHTO#57) stone were tested.

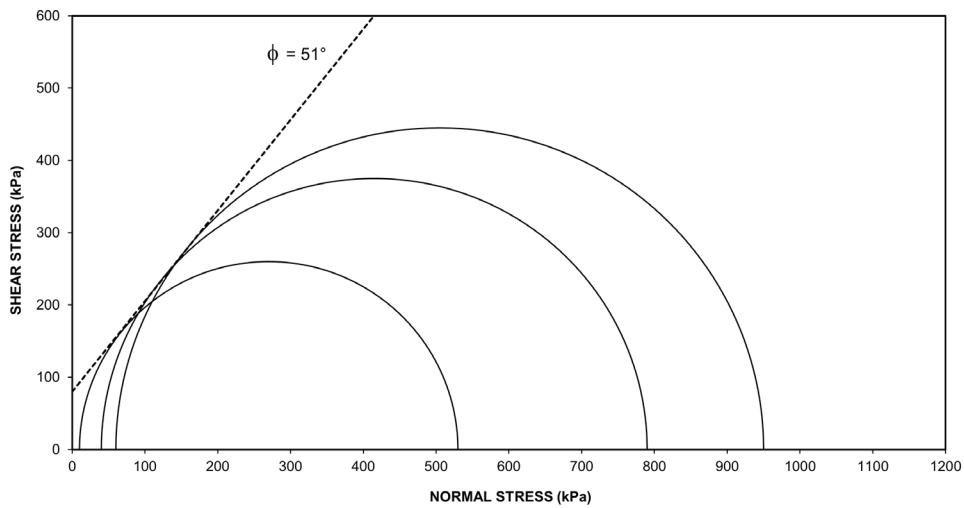
Figure 2.
Results of Full-scale Field Shear Testing
Performed at the Tops of Geopier RAPs



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 RAPs (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 dilatant behavior of the very stiff aggregate produced during the high-energy ramming of the crushed aggregate. For design purposes, slightly lower friction angles (typically 45 degrees) are often employed.

Figure 3.
Results of Triaxial Testing of
Compacted Geopier Aggregate



4. SHEAR REINFORCEMENT DESIGN METHODS

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 ration of the resisting moment to the destabilizing moment (Duncan 1987). Many computer programs, such as PCSTABL, SLIDE, 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 RAPs 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:

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

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:

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

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

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

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 CONCENTRATIONS

In situations where Geopier RAPs 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 RAP stiffness results in a concentration of stress to the tips of the Geopier RAPs. 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:

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

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

Where n_s is the ratio of stress applied to the Geopier RAP and the stress applied to the matrix soil (Mitchell 1981). For perfectly rigid (e.g. concrete) foundations, values for n_s are the same as those for stiffness ratio, n_s , defined as the ratio of the Geopier RAP stiffness to the matrix soil stiffness. Typical stiffness ration values range from 10 to 40 when considering traditional foundation support applications (Lawton and Fox 1994, Lawton 2001). However, for MSE and other structures that do not include rigid foundations, the stress concentration ratio, n_s , is often less than the stiffness ratio, n_s , because the flexible foundation does not impose a rigid boundary condition. Further, because RAP elements transfer load to the soil with depth, the stress concentration ratio also decreases with depth depending on the pier length, width of the loaded area, and stiffness of the soil at the bottom of the piers. Typical values of n_s range between 1 to 5 for flexible structures (Thompson, et. al. 2009) and must be selected with engineering judgement.

4.3 INCORPORATION OF COMPOSITE PARAMETERS

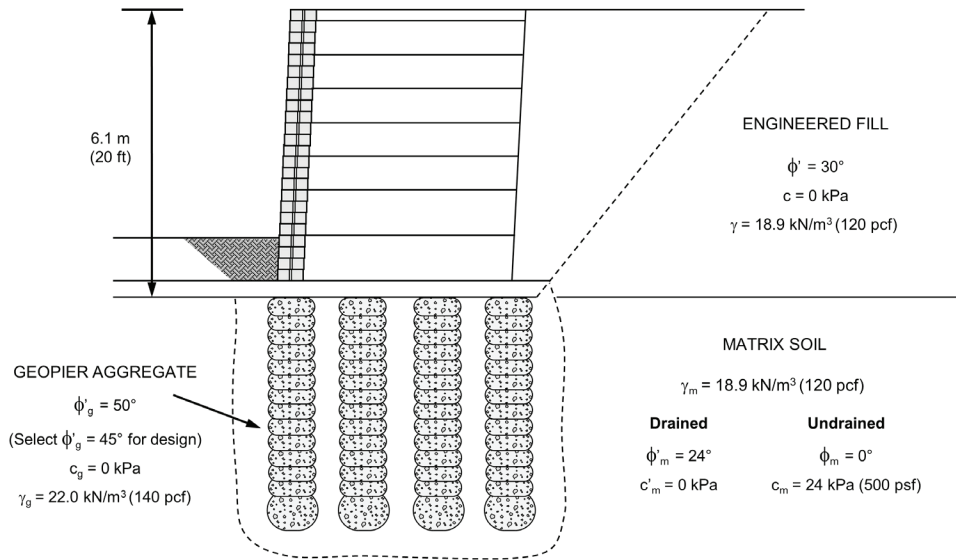
The Geopier-reinforced zone is designed to intersect the critical shearing surfaces located beneath the retaining walls and the embankment slopes. Within the reinforced zone, the composite cohesion and friction angle values (Equations 2 through 6) represent the composite shear strength of the soil zones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

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

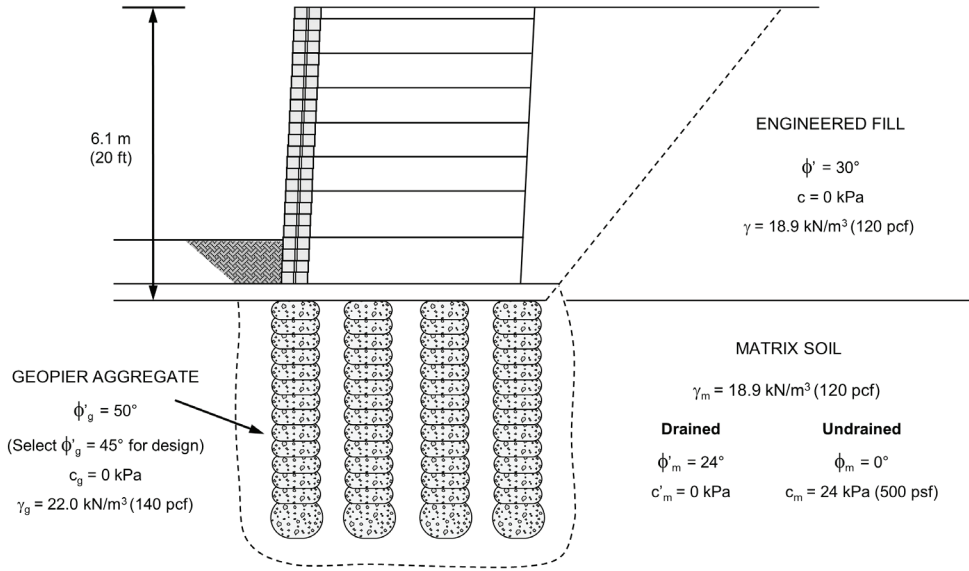
$$\phi'_{\text{comp}} = \arctan [0.20 \tan 45^\circ + (1 - 0.20) \tan 24^\circ] = 29.1^\circ$$

Undrained Composite Parameter Values

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

$$\phi'_{\text{comp}} = \arctan [0.20 \tan 45^\circ + (1 - 0.20) \tan 0^\circ] = 11.3^\circ$$

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



COMPOSITE SHEAR STRENGTH PARAMETER VALUES (STIFFNESS RATIO = 5, SELECT $n_s = 2$ FOR DESIGN)

Drained Composite Parameter Values

$$c'_{comp} = \left[\frac{1}{2(0.20) - 0.20 + 1} \right] (1 - 0.20) 0 \text{ kPa} = 0 \text{ kPa}$$

$$\phi'_{comp} = \arctan \left[\left[\frac{2}{2(0.20) - 0.20 + 1} \right] 0.20 \tan 45^\circ + \left[\frac{1}{2(0.20) - 0.20 + 1} \right] (1 - 0.20) \tan 24^\circ \right] = 32.2^\circ$$

Undrained Composite Parameter Values

$$c'_{comp} = \left[\frac{1}{2(0.20) - 0.20 + 1} \right] (1 - 0.20) 24 \text{ kPa} = 16.0 \text{ kPa} (333 \text{ psf})$$

$$\phi'_{comp} = \arctan \left[\left[\frac{2}{2(0.20) - 0.20 + 1} \right] 0.20 \tan 45^\circ + \left[\frac{1}{2(0.20) - 0.20 + 1} \right] (1 - 0.20) \tan 0^\circ \right] = 18.4^\circ$$

Figure 5a 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. Using an area ratio of 0.20 and a stiffness ratio of 1.0 (no stress concentration), the factor of safety is increased to approximately 1.26 (Figure 5b). The factor of safety increases to approximately 1.39 when a stiffness ratio of 2 is incorporated into the analysis (Figure 5c).

Figure 5a.
Unreinforced Slope Stability Analysis

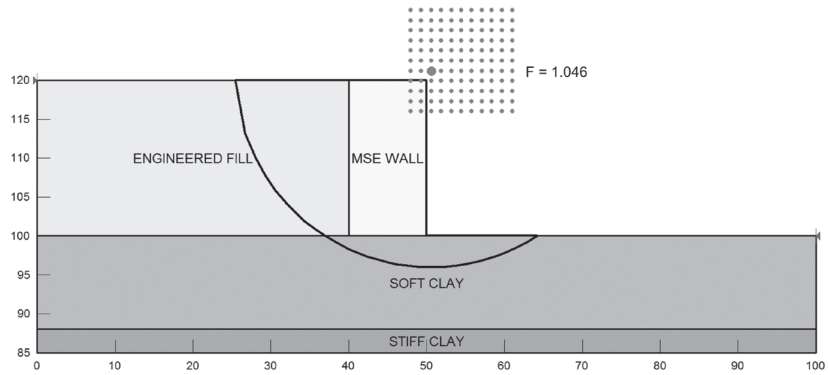


Figure 5b.
Slope Stability Analysis Incorporating
Geopier Reinforced Zone

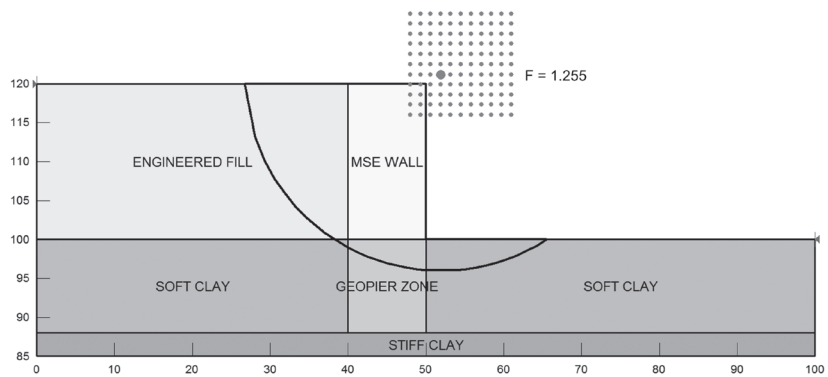
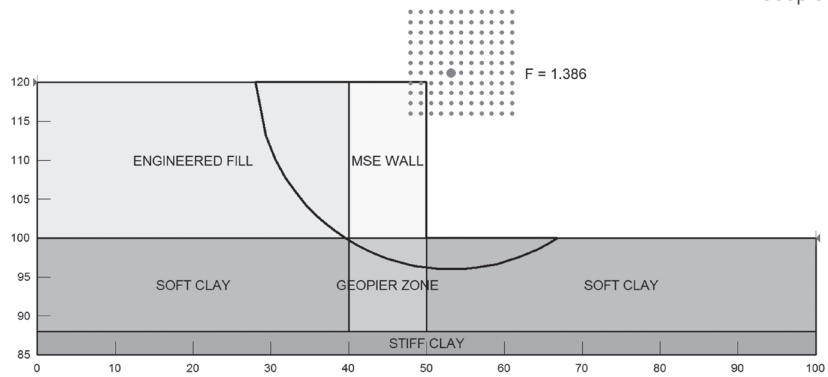


Figure 5c.
Slope Stability Analysis Incorporating
Stress Concentration Within the
Geopier Reinforced Zone



6. SUMMARY

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 RAPs are installed within the zone of critical shearing surfaces, the high angle of internal friction exhibited by the Geopier RAPs provides significant increases in the shear resistance, thus improving the factor of safety for global/slope stability.

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SYMBOLS USED

c'_{comp}	=	Composite cohesion intercept
c'_g	=	Cohesion intercept of the Geopier aggregate
c'_m	=	Cohesion intercept of the matrix soil
n_s	=	Ratio of stress applied to the Geopier RAP and the stress applied to the matrix soil
ϕ'_{comp}	=	Composite friction angle of the reinforced soil
ϕ'_g	=	Friction angle of the Geopier aggregate material
ϕ'_m	=	Friction angle of the matrix soils
R_a	=	Ratio of the area coverage of the Geopier elements to the gross area of the reinforced soil zone
σ'_v	=	Vertical effective stress
τ_{comp}	=	Composite shear strength

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