GEOPIER FOUNDATION CO INC
TECHNICAL BULLETIN

No. 6

SETTLEMENT CONTROL FOR EMBANKMENTS AND TRANSPORTATION-RELATED STRUCTURES USING GEOPIER® SOIL REINFORCEMENT

This Technical Bulletin discusses the use of Geopier soil reinforcement for support of transportation structures including Mechanically Stabilized Earth (MSE) retaining walls and large embankment fills. The installation of stiff Geopier elements provides a significant increase in the composite stiffness of otherwise soft and compressible foundation soils. Geopier construction using open-graded stone affords radial drainage to the elements. The result of Geopier installation is a significant decrease in both settlement magnitude and duration within the Geopier-reinforced zone. This Technical Bulletin describes design methods used for the reinforcement of poor foundation soils to support transportation structures, such as MSE walls and embankments, using Geopier soil reinforcing elements.

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1. BACKGROUND: DESIGNING EMBANKMENTS AND TRANSPORTATION-RELATED STRUCTURES

Without soil reinforcement, the construction of MSE retaining walls and embankment fills on compressible soils can result in significant settlement. Settlement durations may be on the order of months or years before the majority of the settlement is completed, depending on the soil compressibility, the thickness of the compressible layer, and groundwater level. Controlling post-construction settlement for these types of structures is critical to prevent excessive differential settlement resulting in cracking of roadway pavements or visible movement of MSE wall facing panels.

Geopier soil reinforcing elements are installed prior to construction of MSE walls, embankment fills, and other transportation structures to reinforce and stiffen compressible foundation soils to reduce the magnitude and duration of settlement and control stability. The use of Geopier soil reinforcement to increase shear resistance and improve global stability is described in Technical Bulletin 5. Geopier elements used to reinforce matrix soils beneath an MSE wall and an embankment are illustrated in Figures 1a and 1b on page three.

2. GEOPIER CONSTRUCTION

Geopier construction is described in detail in the Geopier Reference Manual (Fox and Cowell 1998) and in the literature (Lawton and Fox 1994, Lawton et al. 1994). 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 a patented beveled tamper. The ramming action causes the aggregate to compact vertically as well as to push laterally against the matrix soil, thereby increasing the horizontal stress in the matrix soil and reducing the compressibility of the matrix soil between the elements. Geopier construction results in a very dense aggregate pier with a very high stiffness that yields a significantly increased composite stiffness within the Geopier-reinforced zone. The use of open-graded stone during construction affords radial drainage of excess pore water pressures to the elements, which act as vertical drains to increase the time-rate of settlement.

Figure 1a.
Geopier Soil
Reinforcement Support
of MSE Wall

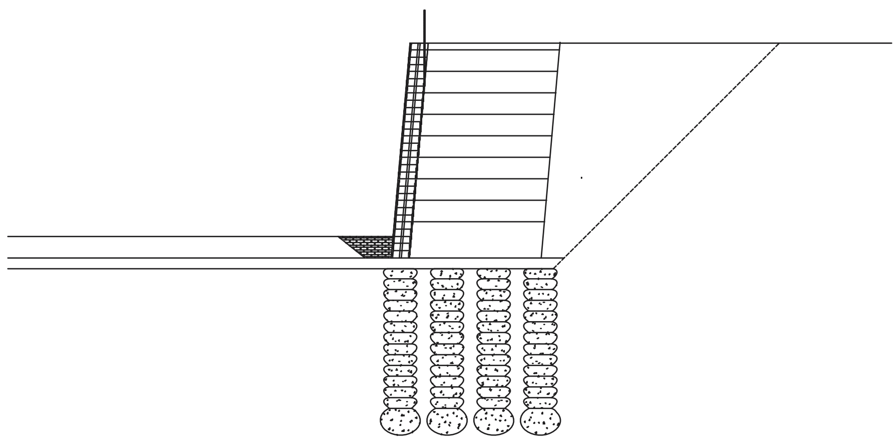
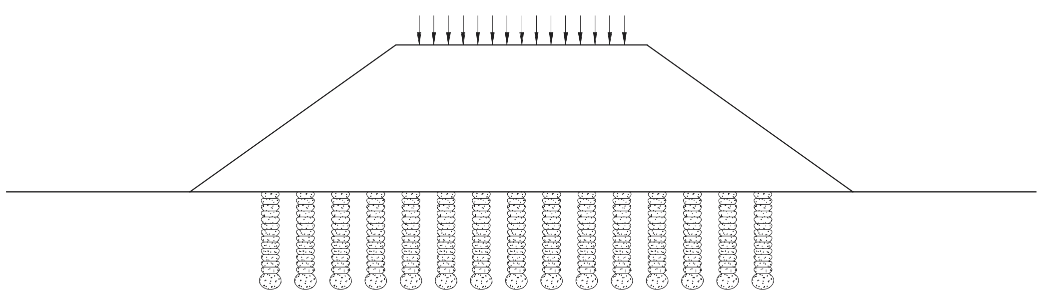


Figure 1b.
Geopier Soil
Reinforcement Support
of Embankment



3. Geopier Settlement Control Design Methodology

The Geopier soil reinforcement settlement control design methodology is based on a two-layer settlement approach as described by Lawton et al. (1994), Lawton and Fox (1994), Fox and Cowell (1998), and Wissmann et al. (2002). The installation of Geopier elements within the Geopier-reinforced zone, referred to as the upper zone, creates a stiffened, engineered zone with reduced compressibility that reduces settlement of embankments and transportation-related structures. The settlement below the Geopier-reinforced zone, referred to as the lower-zone, is evaluated using conventional geotechnical analysis approaches. The total settlement (s_{tot}) of the transportation structures is evaluated as the sum of the upper zone settlement (s_{uz}) and the lower zone settlement (s_{lz}):

$$s_{tot} = s_{uz} + s_{lz} \,. \qquad \textit{Eq.1.}$$

3.1 Settlement in the Geopier-Reinforced Zone

Settlement in the Geopier-reinforced zone (upper zone) is estimated by first calculating the top-of-Geopier stress (q_g) using the following equation:

$$q_g = q \left[\frac{n_s}{n_s R_a - R_a + 1} \right], \qquad \textit{Eq.2.}$$

where q is the average applied bearing pressure, R_a is the ratio of the cross-sectional area coverage of the Geopier elements to the matrix soil, and n_s is the stress concentration ratio between the Geopier elements and the matrix soil. Stress concentration ratios have been measured and range between four and 45 for rigid footings. Because embankments and most MSE walls are not rigid structures, stress concentration ratios may be lower than those observed for rigid footings and should be selected with care.

The settlement of the Geopier-reinforced zone is estimated as the top-of-Geopier stress (q_g) divided by the Geopier stiffness modulus (k_g):

$$s_{uz} = \frac{q_g}{k_g} \,. \qquad \textit{Eq.3.}$$

The upper zone settlement methodology provides for a determination of the deflection of the Geopier Rammed Aggregate Pier, but not of the matrix soil between the piers. Field instrumentation results, however, show that only minor differential settlement is observed between the top of the rammed aggregate pier and the matrix soil under embankment loading (Minks 2001, White 2002). More rigorous analyses may be used to evaluate the potential for differential settlement between the rammed aggregate piers and the matrix soil. However, the impacts on surficial settlement caused by differential settlement between the piers and matrix soil are minor when considering large embankment heights. This is related to the development of a plane of equal settlement caused by soil arching of the embankment material to the stiff rammed aggregate piers (Terzaghi 1936).

3.2 Settlement below the Geopier-reinforced zone

Settlement below the Geopier-reinforced zone is evaluated using conventional geotechnical approaches, consisting of either elastic settlement analyses or consolidation analyses using the familiar expressions:

$$s_{lz} = \frac{\Delta q H}{E}, \qquad \textit{Eq.4.}$$

and

$$s_{lz} = c_c \left[\frac{1}{1 + e_o}\right] H \log \left[\frac{p_o + \Delta q}{p_o}\right], \qquad \textit{Eq.5.}$$

where H is the thickness of the lower zone, E is the matrix soil elastic modulus within the lower zone, c_c is the matrix soil coefficient of compressibility, e_o is the matrix soil void ratio, p_o is the vertical effective stress at the mid-point of the compressible layer, and Δq is the average bearing pressure applied by the wall and embankment. The average applied bearing pressure is the product of the applied pressure and the stress influence factor, I_σ. The stress influence factor within the lower zone is typically assumed to be 1.0 because of the large lateral extent of MSE walls and embankment fills.

Typically, elastic modulus settlement approaches are used to estimate settlement in granular soils and heavily over-consolidated cohesive soils. Matrix soil equivalent elastic modulus values may be estimated using published correlations from SPT N-values, undrained shear strengths, CPT tip resistances, or other insitu tests. Consolidation settlement approaches are used to evaluate settlement in normally-consolidated or lightly over-consolidated cohesive soils.

4. Time-Rate of Settlement

The magnitude of post-construction settlement is often as important as the overall settlement of the MSE wall or embankment. Post-construction settlement may be dramatically reduced by using Geopier soil reinforcing elements constructed with open-graded stone to act as vertical drains, allowing radial drainage to occur to the elements. Radial drainage calculations can be performed to evaluate the percentage of excess pore water pressure dissipation that occurs within the estimated construction period and to determine the remaining post-construction settlement.

4.1 Time-rate of settlement in the Geopier-reinforced zone

Radial drainage to the Geopier element is calculated using Barron's approach for estimating the settlement duration (t) from radial drainage to sand drains (1948). The approach relates the settlement duration to a time factor (T), the radial coefficient of consolidation (c_r), and the square of the effective drainage length (d_e):

$$t = \frac{T_r d_e^2}{c_r} \ . \qquad \textit{Eq.6.}$$

The time factor is calculated by first evaluating the diameter ratio (n), which is the ratio of the effective drain diameter and the constructed diameter of the installed drain (d_w). Effective drain diameters are evaluated based on geometry for elements spaced in triangular grids and square grids, respectively:

$$\text{Triangular grid: } d_e = 1.05s \ , \qquad \textit{Eq.7a.}$$

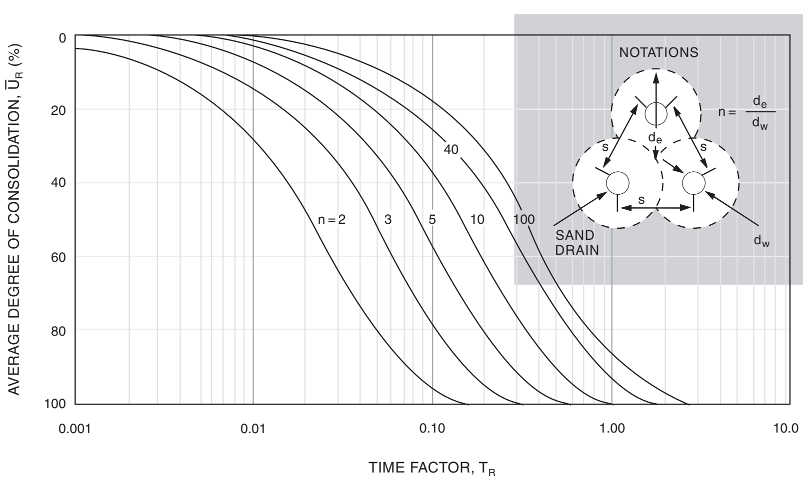
$$\text{Square grid: } d_e = 1.13s \ , \qquad \textit{Eq.7b.}$$

where s is the center-to-center spacing of the elements. The spacing of elements is selected to provide a sufficient increase in the upper zone stiffness to achieve tolerable post-construction settlement magnitudes (as described in Section 3), considering that a significant percentage of the settlement will occur during the construction period as a result of radial drainage.

The value of the radial coefficient of consolidation is commonly assumed to be between two and four times the vertical coefficient of consolidation value (c_v). This ratio may be significantly higher in varved or horizontally stratified soils. Coefficient of consolidation values (c_v) are related to many factors including soil mineralogy, gradation, and depositional history of the matrix soil (Terzaghi et al. 1996). For cohesive soils, these values are evaluated from consolidation tests or may be estimated from liquid limit values and stress history (over-consolidation).

Based on the diameter ratio (n) and the desired percentage of excess pore water pressure dissipation (U), a time factor value can be interpreted from Figure 2.

Figure 2.
Degree of Consolidation for Radial Drainage Applications (NAVFAC 1982)



The time factor (T_R) is then used in conjunction with the drainage path length (d_e) and the radial coefficient of consolidation value (c_r) to estimate the time of drainage (t) from Equation 6.

Recent research performed by Han and Ye (2001) describes a modified radial drainage approach that accounts for stress concentration to stiff aggregate columns. Stress concentration to the stiff Geopier elements reduces the amount of stress on the matrix soil, which causes settlement to occur faster and yields a modified (increased) radial coefficient of consolidation. Han and Ye suggest that a modified radial coefficient of consolidation be used in the Barron approach:

$$c'_r = c_r \left[1 + n_s \left[\frac{1}{n^2 - 1} \right] \right], \qquad \textit{Eq. 8.}$$

where n_s is the stress concentration ratio. The modified radial coefficient of consolidation is substituted for the radial coefficient of consolidation in Equation 6 to determine the percentage of excess pore water pressure dissipation for a given time period.

Research has shown that Geopier stress concentration ratios for footing support range from 4 to 45 (Lawton and Merry 2000, Hoevelkamp 2002). Conservative values of stress concentration are suggested for design. This approach to evaluate radial drainage periods is supported by settlement monitoring results with time (Hoevelkamp 2002).

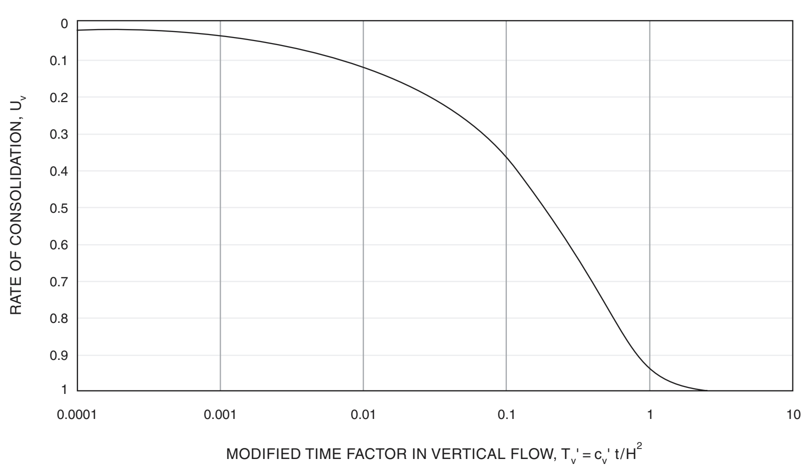
4.2 TIME-RATE OF SETTLEMENT BELOW THE GEOPIER-REINFORCED ZONE

The time-rate of settlement below the Geopier-reinforced zone is calculated using traditional expressions for vertical consolidation as shown in the following equation and described in the literature:

$$t = \frac{T_v (H_{dr})^2}{c_v}, \qquad \textit{Eq. 9.}$$

where t is drainage time c_v is the vertical coefficient of consolidation, and H_{dr} is the vertical drainage path length and T_v is the vertical time factor corresponding to a particular percentage of excess pore water pressure dissipation as determined from Figure 3.

Figure 3.
Degree of Consolidation for Vertical Drainage (Han and Ye 2001)

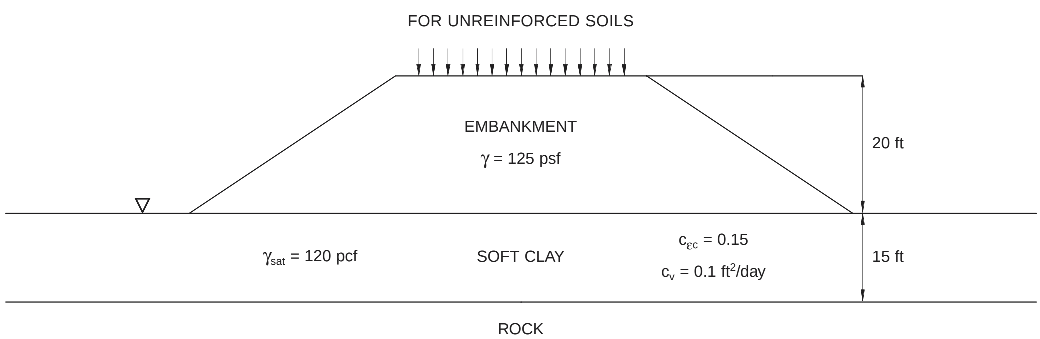


5. SETTLEMENT MAGNITUDE AND TIME-RATE EXAMPLE

Example calculations performed for the placement of a 20-foot tall embankment constructed on a 15-foot thick layer of soft clay underlain by bedrock are presented in Figures 4 and 5. Figure 4 provides an example of conventional settlement magnitude and duration calculations for the embankment.

Figure 5 illustrates the settlement magnitude and duration calculations for foundation soils reinforced with Geopier soil reinforcement as described above. Lower zone settlements are assumed to be negligible in both examples because the piers extend to rock.

Figure 4.
Settlement Magnitude and Duration Example Calculation
for ***Unreinforced Soils***



SETTLEMENT MAGNITUDE

$$P_o = z(\gamma_{sat} - \gamma_w) = 7.5\text{ ft}(120\text{ pcf} - 62.4\text{ pcf}) = 432\text{ psf}$$

$$q = \gamma H = 125\text{ pcf }(20\text{ ft}) = 2{,}500\text{ psf}$$

$$I_\sigma = 1.0\text{ (for areal loads)}$$

$$E_m = \frac{(I_\sigma q)}{c_\varepsilon \log\left[\dfrac{P_o + I_\sigma q}{P_o}\right]} = \frac{(1.0)(2{,}500\text{ psf})}{0.15 \log\left[\dfrac{432 + 2500}{432}\right]} = 20\text{ ksf}$$

$$s_{unreinforced} = \frac{I_\sigma q H}{E_m} = \frac{(1.0)(2.5\text{ ksf})(15\text{ ft})}{20\text{ ksf}} = 1.875\text{ ft} = 22.5\text{ in}$$

TIME RATE OF SETTLEMENT (FOR 90% EXCESS PORE WATER PRESSURE DISSIPATION)

$$t_{90\%} = \frac{T_{90}(H_{dr})^2}{c_v} = \frac{0.848(7.5\text{ ft})^2}{0.1\text{ ft}^2\text{ / day}} = 480\text{ days}$$

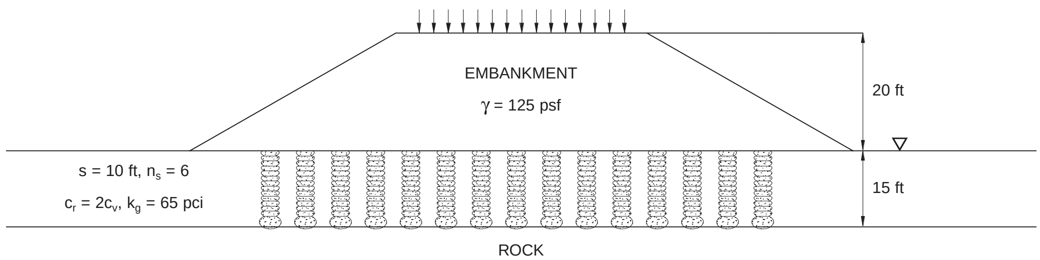
POST-CONSTRUCTION SETTLEMENT (AFTER 90 DAY PERIOD)

$$T_{90\text{ days}} = \frac{tc_v}{(H_{dr})^2} = \frac{90\text{ days}(0.1\text{ ft}^2\text{ / day})}{(7.5\text{ ft})^2} = 0.16$$

At T = 0.16, U% is equal to 45% from Figure 3
Remaining settlement after 90 days is (1-U%)s = (1-0.45)(22.5 inches) = 12.4 inches

Figure 5.
Settlement Magnitude and Duration Example Calculation
*for **Geopier-reinforced Soils***

FOR GEOPIER-REINFORCED SOILS
WITH AN ASSUMED STRESS CONCENTRATION RATIO OF 6



SETTLEMENT MAGNITUDE

$$R_a = \frac{A_g}{A} = \frac{5.94\ ft^2}{(10\ ft)^2} = 0.0594$$

$$q = \gamma H = 125\ pcf\ (20\ ft) = 2{,}500\ psf$$

$$q_g = q\left[\frac{n_s}{n_s R_a - R_a + 1}\right] = 2{,}500\ psf\left[\frac{6}{6(0.0594) - 0.0594 + 1}\right] = 11{,}565\ psf$$

$$s_{uz} = \frac{q_g}{k_g} = \frac{11{,}565\ psf}{(65\ pci)(144\ in^3 / ft^3)} = 1.25\ in$$

TIME RATE OF SETTLEMENT (FOR 90% EXCESS PORE WATER PRESSURE DISSIPATION)

$$n = \frac{d_e}{d_w} = \frac{1.13s}{d_w} = \frac{1.13(10\ ft)}{2.75\ ft} = 4.1$$

$$c'_r = c_r\left[1 + n_s\frac{1}{n^2 - 1}\right] = 0.2\ ft^2 / day\left[1 + 6\frac{1}{(4.1)^2 - 1}\right] = 0.28\ ft^2 / day$$

POST-CONSTRUCTION SETTLEMENT (AFTER 90 DAY PERIOD)

$$T = \frac{t_{90\ days}\ c'_r}{(d_e)^2} = \frac{90\ days(0.28\ ft^2 / day)}{(11.3\ ft)^2} = 0.20$$

For a time factor (T) = 0.20, N = 4.1, U% is equal to 90% from Figure 2
Remaining settlement after 90 days is (1-U%)s = (1-0.90)(1.25 inches) = 0.1 inches

The results of the example calculations shown in Figures 4 and 5 illustrate how the installation of Geopier soil reinforcement significantly reduces the settlement magnitude. Additionally, the settlement occurs at an increased rate resulting in the majority of the settlement taking place during construction.

6. SUMMARY

Geopier soil reinforcement is used to reinforce and stiffen compressible foundation soils and increase the time-rate of settlement in order to control post-construction settlement magnitudes. The design methodology utilizes conventional settlement and radial drainage approaches with minor modifications based on advanced research to determine the Geopier element spacing required to control settlement and meet project settlement criteria.

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AUTHORS

Brendan T. FitzPatrick, Associate Project Engineer, Geopier Foundation Company, Inc.

Kord J. Wissmann, Ph.D., P.E., Chief Engineer, Geopier Foundation Company, Inc.

David J. White, Ph.D., Assistant Professor, Iowa State University

SYMBOLS USED

c_c = Coefficient of compression of matrix soil
c_r = Radial coefficient of consolidation
c'_r = Modified radial coefficient of consolidation
c_v = Vertical coefficient of consolidation
d_e = Effective drain diameter
d_w = Diameter of well (constructed Geopier element)
e_o = Void ratio of matrix soil
E_{comp} = Composite elastic modulus of the Geopier reinforced zone
H = Thickness of the compressible layer
H_{dr} = Vertical drainage path length
I_σ = Stress influence factor
k_g = Geopier stiffness modulus value
n = Diameter ratio
n_s = Stress concentration ratio between Geopier elements and matrix soil
p_o = Effective vertical stress
Δq = Embankment or wall bearing pressure
R_a = Ratio of cross-sectional area of Geopier elements to gross footing area
s = Geopier element spacing
s_{tot} = Total settlement
s_{uz} = Settlement within the Geopier-reinforced zone
s_{lz} = Settlement below the Geopier-reinforced zone
t = Time duration for settlement
T_r = Time factor for consolidation with radial flow
T_v = Time factor for consolidation with vertical flow

NORTH AMERICA AND SOUTH AMERICA

Geopier Foundation Company
1997 South Main Street, Suite 703
Blacksburg, VA 24060
Telephone: (540) 951.8076 or (800) 371.7470
Fax: (540) 951.8078
Email: info@geopiers.com
www.geopiers.com

EUROPE AND ASIA

Geopier Global Corporation
7600 North 71st Street
Paradise Valley, AZ 85253
Telephone: (480) 998.3522
Fax: (480) 998.3542
Email: natfox@geopierglobal.com
www.geopierglobal.com

Geopier Foundation Company, Inc.

800.371.7470
www.geopiers.com