TECHNICAL BULLETIN NO. 4

GEOPIER® LATERAL RESISTANCE

This Technical Bulletin discusses the behavior of Geopier® supported shallow foundation systems when subjected to lateral loads. Lateral loads are applied to foundation systems by wind or seismic events and by lateral earth pressures. Geopier supported shallow foundations provide resistance to lateral loads using mechanisms identical to those applicable to conventional shallow footings. These mechanisms include passive earth pressure adjacent to the footings and sliding resistance along the base of the footings. However, because of high stress concentration to the Geopier elements and the high friction angle of the Geopier aggregate, greater resistance is achieved in comparison to a footing supported by soil not reinforced by Geopier elements. This Technical Bulletin describes lateral load demands on structures, methods used to design Geopier supported footings to resist lateral loads, and results of full-scale footing lateral load tests.

1. BACKGROUND: LATERAL LOAD DEMANDS

Lateral load demands on structures, retaining walls, and buildings are generated by horizontal earth pressure, wind, and earthquakes. Lateral loads transmitted through a structure are resisted by the foundation system. Geopier supported shallow foundations resist lateral loads with mechanisms identical to those applicable to conventional shallow footings (Figure 1):

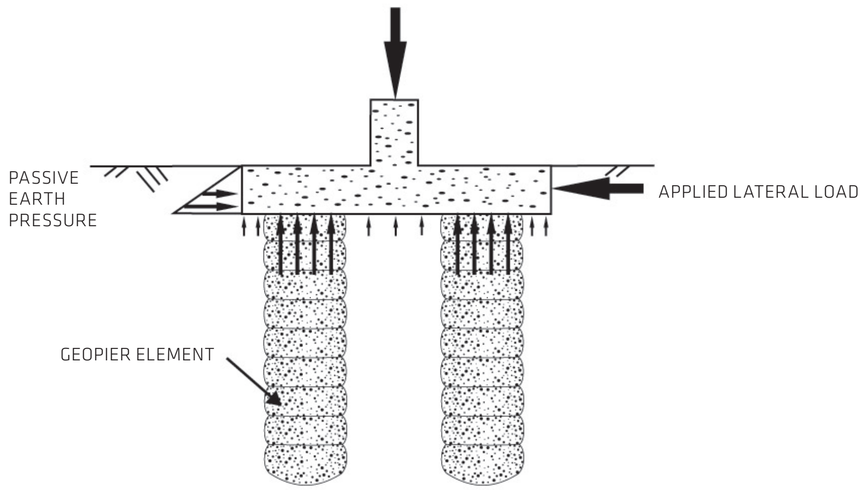
- ▷ Passive earth pressures adjacent to the footing.
- ▷ Base sliding resistance along the bottom of the footing.

The combination of stress concentration to the stiff Geopier elements and the high friction angle of the aggregate allows for the development of a significantly greater amount of lateral load resistance than developed by footings not supported by Geopier elements.

GEOPIER®

Tensar

Figure 1.
Lateral Load Resistance
of Geopier Supported Footing



2. CONSTRUCTION

Geopier 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. Geopier construction results in a very dense aggregate column, wherein the aggregate tends to dilate when subject to shearing stresses. This 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 direct 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. Geopier elements constructed using both well-graded base course stone and open-graded (#57) stone were tested.

Small-scale laboratory triaxial tests were performed at Iowa State University on reconstituted samples of well-graded Geopier aggregate (White 2001) compacted to densities consistent with those measured for installed Geopier elements. 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 aggregate produced during the high-energy ramming of the crushed stone used in Geopier elements.

Figure 2.
Results of Full-Scale Direct Shear Testing
Performed at the Tops of Geopier Elements

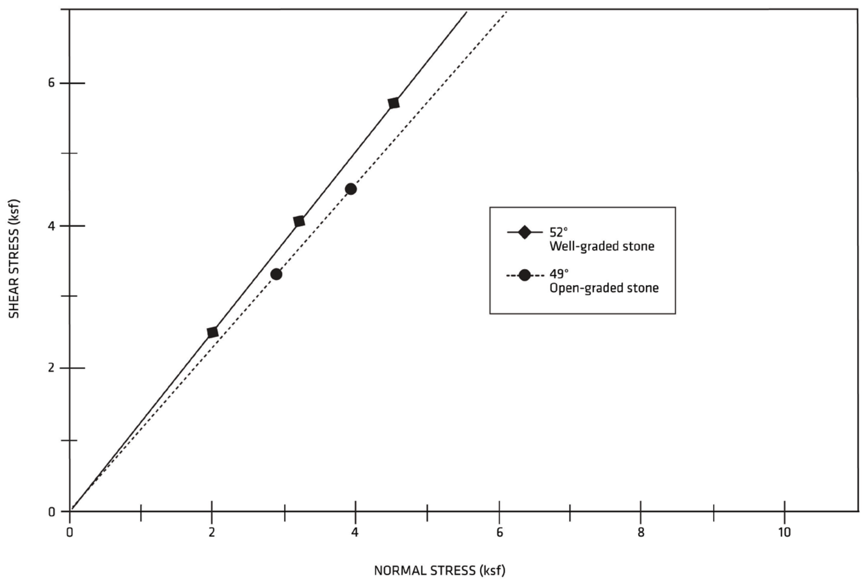
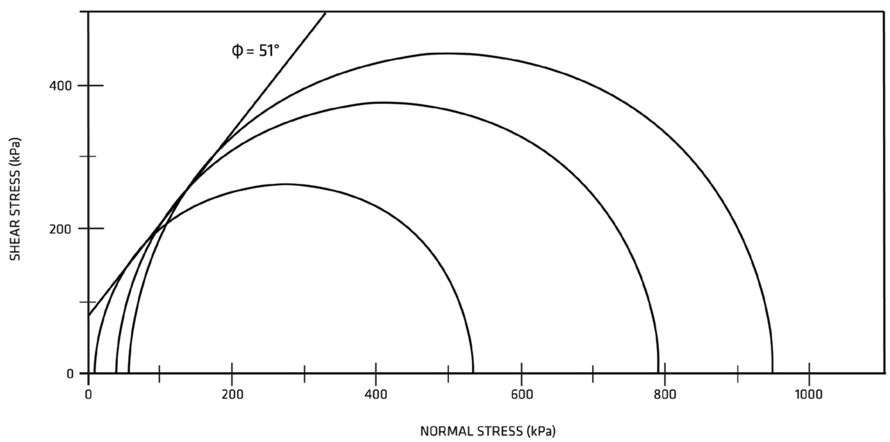


Figure 3.
Results of the Triaxial Testing of
Compacted Geopier Aggregate



4. LATERAL LOAD RESISTANCE

Lateral loads transmitted to shallow foundations are resisted by sliding resistance along the base of footings and by passive earth pressure that develops at the front of the footing as it is pushed into the adjacent soils (Figure 4). Although additional lateral load resistance is offered by the bending of the vertical bars in elements outfitted with uplift anchors, this additional resistance is small in comparison with other resistances at small values of lateral deflection. Computations indicate that the component of lateral loading resistance provided by sliding resistance is typically much greater than the component provided by passive earth pressure.

4.1 SLIDING RESISTANCE AT THE BASE OF GEOPIER SUPPORTED FOOTINGS

As shown in Figure 4, sliding resistance at the base of Geopier supported footings may be divided into two components: 1) sliding resistance between the footing at the tops of the Geopier elements and 2) sliding resistance between the footing and the matrix soil

4.1.1 SLIDING RESISTANCE PROVIDED BY GEOPIER ELEMENTS

The resistance to sliding provided by the Geopier elements (F_g) is computed as the product of the normal (downward) stress on the element (q_g), the tangent of the Geopier angle of internal friction (ϕ'_g) and the cross-sectional area of the Geopier elements (A_g):

$$F_g = q_g \tan \phi'_g A_g, \qquad \text{Eq. 1.}$$

For footings constructed of concrete poured in place directly on top of Geopier elements, no reduction in friction angle (ϕ'_g) is required because of the rough interface between the concrete and the angular aggregate.

As described in the literature (Lawton and Fox 1994, Lawton et al. 1994, Fox and Cowell 1998, Wissmann et al. 2000, Wissmann and Fox 2000), the normal stress on the Geopier elements depends on the average footing bearing pressure (q) the stiffness ratio (R_s) between the Geopier elements and the matrix soil, and the ratio of the sum of the Geopier element cross-sectional areas to the footing bottom area (R_a):

$$q_g = \{qR_s/[R_aR_s + 1\text{-}Ra]\}. \qquad \text{Eq. 2.}$$

The stress on the Geopier elements is significantly greater than the stress on the surrounding matrix soil because the Geopier elements exhibit a greater stiffness than the matrix soil. The stiffness ratio (R_s) was presented by Lawton (2000) to range between 30 and 45 at a soft soil site in Salt Lake City, Utah. As a result of the high normal stresses and the high internal angle of friction exhibited by the rammed Geopier aggregate, most of the lateral load resistance offered by Geopier supported footings is attributed to the sliding resistance at the tops of the Geopier elements.

4.1.2 SLIDING RESISTANCE PROVIDED BY MATRIX SOIL

The resistance to sliding provided by the matrix soil (F_m) depends on the product of the normal (downward) stress on the matrix soil (q_s), the tangent of the angle of internal friction of the matrix soil (ϕ'_m), and the matrix soil (A_m) and the cohesion intercept of the matrix soil (c_m):

$$F_m = q_s \tan \phi'_m A_m, \qquad \text{Eq. 3.}$$

The matrix soil area is the difference between the foundation footprint area and the sum of the Geopier element cross-sectional areas. For footings constructed of concrete poured in place directly on top of prepared excavations, no reduction in the friction angle (ϕ'_m) is required because of the rough interface between the concrete and the soil. The stress on the matrix soil is computed as the stress on the Geopier elements divided by the stiffness ratio between the Geopier elements and the matrix soil (Fox and Cowell 1998):

$$q_s = q_g / R_s, \qquad \text{Eq. 4.}$$

4.1.3 TOTAL RESISTANCE

The total resistance to sliding along the base of the footing (F_t) is computed by adding the resistance to sliding at the tops of the Geopier elements (F_g) and the resistance to sliding at the foundation/matrix soil interface (F_m):

$$F_t = F_g + F_m, \qquad \text{Eq. 5.}$$

4.1.4 COMPOSITE UNIT FRICTION COEFFICIENT

The allowable composite unit friction coefficient (f_{all}) is often used by structural engineers to determine footing resistance to lateral loads. The allowable composite unit friction coefficient (f_{all}) for any footing is simply computed as the ratio of the allowable lateral sliding resistance (F_{all}) to the downward dead load applied to the footing (P):

$$f_{all} = F_{all} / P, \quad \text{Eq. 6.}$$

where F_{all} is computed as the quotient of the ultimate resistance to sliding (F_t) and a factor of safety (FS):

$$F_{all} = F_t / FS \quad \text{Eq. 7.}$$

A factor of safety of 1.5 to 2.0 is typically used in conjunction with Equation 7. When dynamic loads are considered, the allowable load resistance is typically increased by a factor of 1/3 or more.

The composite unit friction coefficient for Geopier supported footings may be expressed by combining Equations 1-7:

$$f_{all} = [\{R_s R_a \tan \phi'_g + (1-R_a) \tan \phi'_m\}/\{R_a R_s + 1 - R_a\}]/FS, \quad \text{Eq. 8.}$$

Table 1 presents typical values of f_{all} for various soil types.

Table 1.
Typical Composite Unit Friction Coefficient Values

SOIL	TYPICAL ϕ	f_{all}*
SAND AND GRAVEL	28° - 45°	0.52 - 0.55
SILT AND CLAY	20° - 30°	0.51 - 0.52

*Values computed for R_s = 15, R_a = 33%, and FS =2

4.2 PASSIVE EARTH PRESSURE

Passive earth pressure develops within the matrix soil at the front of footings as the footings push laterally into the adjacent soils. The passive force (F_p) that resists lateral movement depends on the foundation width (B), unit weight of the soil (γ), the footing embedment depth (D_f), the Rankine passive earth pressure coefficient (K_p) and the cohesion intercept of the matrix soil (c_m) as shown in Equation 9 (Terzaghi and Peck 1967):

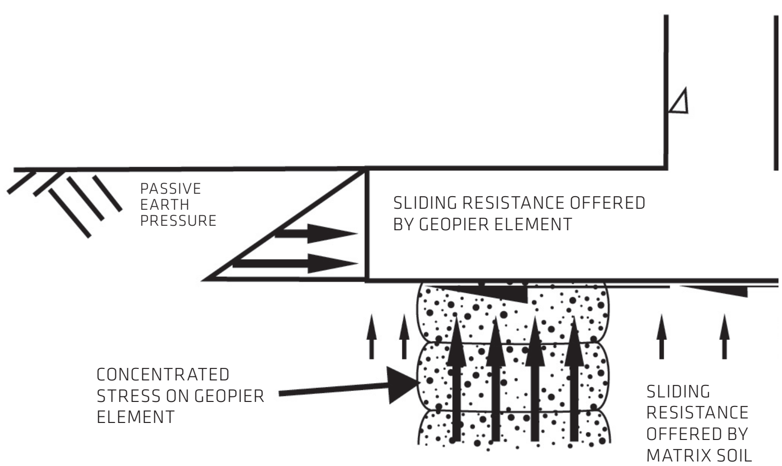
$$F_p = B K_p \gamma D_f^2/2 + 2 c \sqrt{K_p} B D_f, \quad \text{Eq. 9.}$$

where the Rankine passive earth pressure coefficient depends on the friction angle of the adjacent matrix soil (ϕ'_m):

$$K_p = \tan^2 (45 + \phi'_m/2) / FS. \quad \text{Eq. 10.}$$

A factor of safety (FS) of 2.0 is typically used in conjunction with Equation 10 to avoid appreciable lateral deformations. When dynamic loads are considered, the allowable load resistance is typically increased by a factor of 1/3 or more,

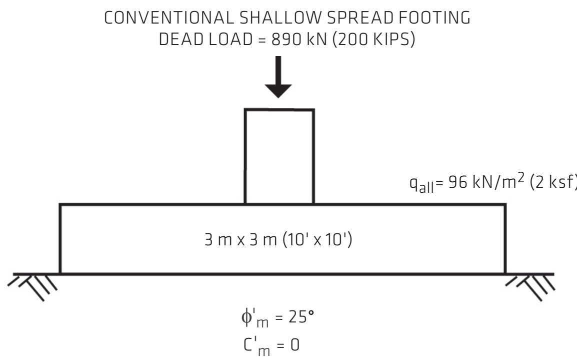
Figure 4.
Lateral Resistance
Along Bottom of Footing



5. EXAMPLE CALCULATIONS

Example calculations for estimating the sliding resistance of two footings, one supported by unreinforced matrix soil and one supported by Geopier elements are shown in Figures 5a and 5b. Both footings are subjected to a downward load of 200 kips. To maintain simplicity in the example calculations, it is assumed that neither footing is embedded in the matrix soil (no passive resistance will be developed). For the same vertical load, the Geopier supported footing resists 505 kN (allowable), compared to only 200 kN for the non-reinforced soils. The Geopier supported footing resists more than two and a half times the lateral load even though the footprint area of the footing is only 40 percent of the footprint area of the footing not supported by Geopier elements.

Figure 5a.
Sliding Resistance
Example for Footing
Supported by
Unreinforced Soil



CALCULATIONS

q = 890 kN / (3 m x 3 m) = 99 kN/m² (2000 psf)

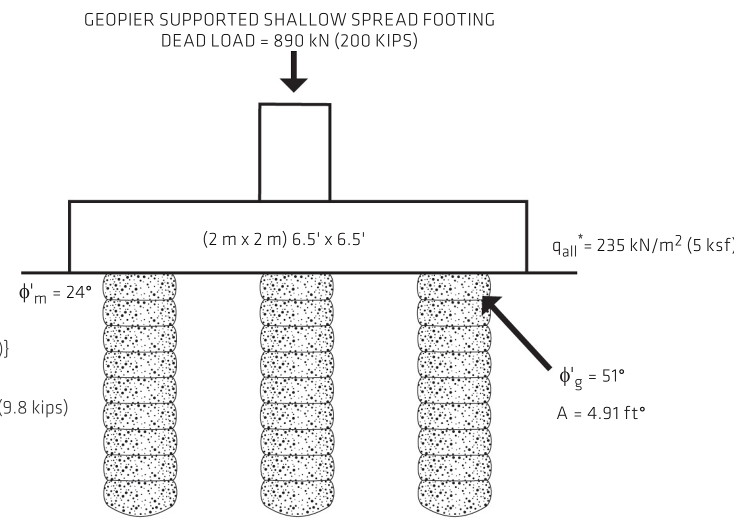
tan ϕ'_m = tan 24° = 0.445

F_m = 99 kN/m² (0.445)(3 m x 3 m) = 396 kN (89,000 lbs)

F_{all} = 396 kN / 2 = 198 kN (44.5 kips)

f_{all} = 198 kN / 890 kN = 0.22

Figure 5b.
Sliding Resistance
Example for
Geopier supported
Footing



CALCULATIONS

q = 890 kN / (2 m x 2 m) = 223 kN/m² (4,730 psf)

R_a = 3 (0.46 m²) / (2 m x 2 m) = 0.35

R_s = 15 (typical)

q_g = 223 kN/m² {15 / (15 x 0.35 + 1 - 0.35) = 567 kN/m² (12 ksf)}

q_s = 567 kN/m² / 15 = 37.8 kN/m² (800 psf)

F_m = 37.8 kN/m² (tan 24){(2 m x 2 m) - (3 x 0.46 m²)}= 44.1 kN (9.8 kips)

F_t = 44.1 kN + 966 kN = 1010 kN (228.1 kips)

F_{all} = 1010 kN / 2.0= 505 kN (114.1 kips)

f_{all} = 505 kN / 890 kN = 0.57

* q_{all} is greater for Geopier supported footings than for conventional footings because of the increased shearing strength afforded by the Geopier elements.

6. FULL-SCALE FOOTING LATERAL LOAD TESTS

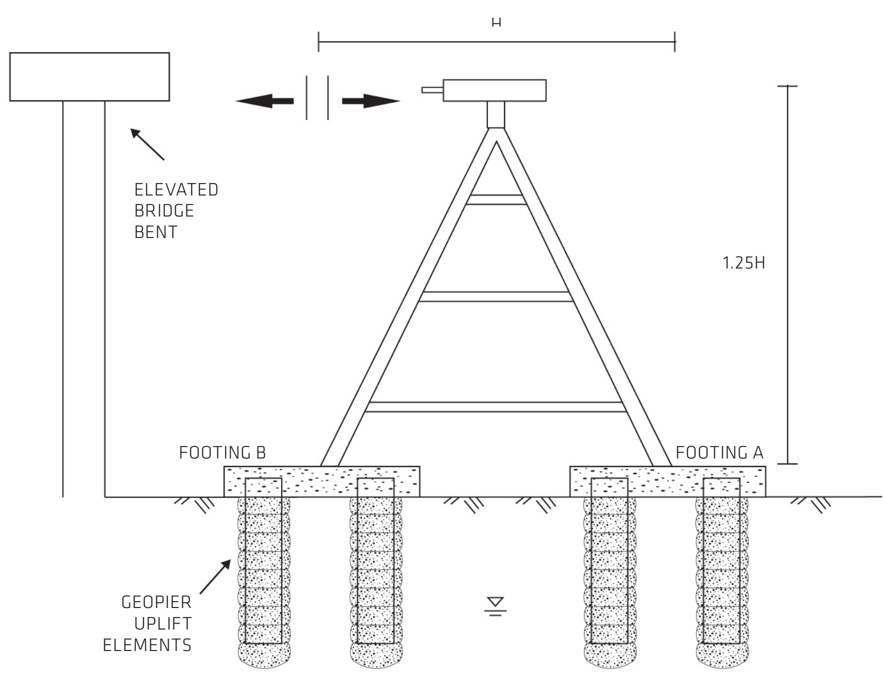
In 1998, researchers at the University of Utah under the auspices of the Utah Department of Transportation (UDOT) tested a full-scale elevated bridge bent to evaluate the response of bridge bents to simulated seismic loads induced by a M_w 7.5 earthquake (Lawton 2000). The testing required the construction of a reaction frame subjected to large cyclic lateral loads. The reaction frame was supported by Geopier elements. The testing program provided researchers with an opportunity to verify the load resistance mechanisms described in this Technical Bulletin.

6.1 LATERAL LOAD TEST BACKGROUND

The large reaction frame, shown in Figure 6, was required for the application of the cyclic loads to the elevated bridge bent. The reaction frame incorporated two footings supported by Geopier elements. Because the footings were placed on the ground surface and not embedded, passive earth pressure resistance could not be developed and lateral resistance was developed exclusively by sliding at the base of the footing.

Each of the reaction frame footings measured 7.47 m (24.5 feet) long by 2.54 m (8.25 feet) wide and 1.14 m (3.75 feet) thick. Ten 0.91 m (36-inch) diameter Geopier elements drilled to 4.6 m (15 feet) and fitted with uplift anchors were used to support each of the two reaction frame footings. The subsurface conditions underlying the footings consisted of Canyon outwash and Lake Bonneville deposits, comprised of soft to moderately stiff, low plasticity silt and clay soils with interbedded layers of sand. The groundwater table at the site varied between 1.2 m to 2.1 m (4 feet to 7 feet) below grade.

Figure 6.
Idealized Reaction Frame.



6.2 FOOTING LOADING CONDITIONS

When lateral loads were applied to the reaction frame, the inclined members transmitted both vertical and lateral forces to the footings. When the load was applied to the bridge by the frame in the direction shown in Figure 6, both footings were subject to lateral loads. Footing A was also subject to downward compression loads while Footing B was also subject to uplift loads. The geometry of the frame resulted in a ratio of applied vertical load to applied horizontal load of 1.25. The dead weight from the reaction frame and the dead weight of each footing resulted in a net dead load of 445 kN (100 kips) on each footing. Table 2 presents the total vertical load acting on each of the reaction footings at increasing applied horizontal loads.

As the applied horizontal load increased, the compressive load on Footing A also increased. At the same time, Footing B was subjected to an increasing amount of uplift load. When the uplift force applied to Footing B was greater than the dead load acting on the footing, the footing no longer applied compressive stress to the underlying soil and Geopier elements and no further lateral load resistance was offered by this footing. However, lateral load resistance continued to be developed by Footing A. The factor of safety against sliding, computed from equations 1 and 7, is also shown in Table 2.

Table 2.
Factors of Safety Corresponding
to Increasing Lateral Loads

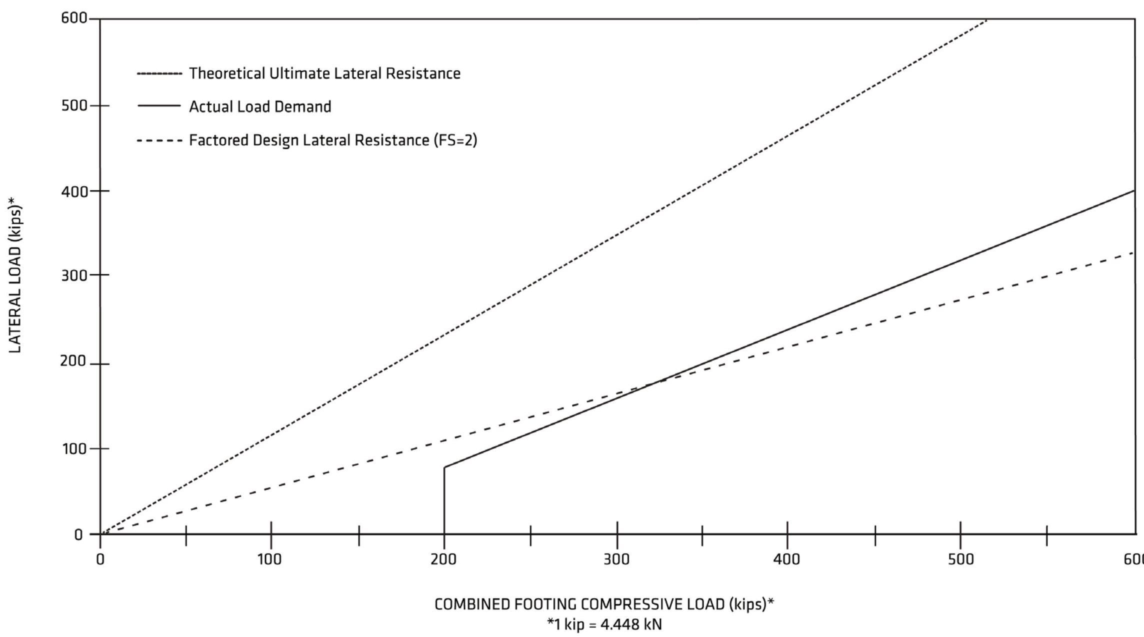
HORIZONTAL LOAD kN (KIPS)	COMPRESSIVE LOAD FOOTING A, kN (KIPS)	COMPRESSIVE LOAD FOOTING B*, kN (KIPS)	FACTOR OF SAFETY AGAINST SLIDING
0 [0]	445 [100]	445 [100]	--
178 [40]	667 [150]	222 [50]	4.17
356 [80]	890 [200]	0 [0]	2.78
534 [120]	1112 [250]	0* [0]	2.32
890 [200]	1557 [350]	0* [0]	1.95
1780 [400]	2669 [600]	0* [0]	1.67

*Indicates net uplift force on the footing. As a result, no lateral resistance is offered by footing.
**Neglects additional lateral load resistance provided by uplift bars installed in Geopier elements.

6.3 TEST RESULTS

During the testing, a maximum horizontal load of 1,779 kN (400 kips) was applied to the bridge bent. At the maximum value of lateral load, Footing A was subjected to a downward vertical load of 2,669 kN (600 kips) and Footing B was subjected to an uplift load of 1,779 kN (400 kips) that was resisted by the uplift anchors. The combined footing system was subjected to a net vertical load of 2,669 kN (600 kips) available for the development of lateral load resistance. Figure 7 presents a plot of the development of system compressive load as a result of applied lateral load. Figure 7 also illustrates envelopes of the theoretical ultimate lateral load resistance and the allowable lateral load resistance (factor of safety of 2.0). The research results presented in Figure 7 indicate that the lateral resistance provided by the Geopier supported system is greater than the factored design lateral load resistance.

Figure 7.
Lateral Load Demand on Reaction Frame



Note: Figure neglects additional lateral load resistance provided by steel uplift bars.

7. SUMMARY

Geopier supported shallow foundations provide resistance to lateral loads using the mechanisms identical to those of conventional shallow footings. Lateral loads are resisted by passive pressures at the leading face of the footing. The use of Geopier elements increases the resistance to lateral loads by increasing the available sliding resistance on the base of the footing. The sliding resistance is increased because of stress concentration to the tops of the Geopier elements and the high shear strength (high angle of internal friction) and the dilatent behavior of the rammed Geopier aggregate.

AUTHORS

Kord J. Wissmann, Ph.D., P.E.

Brendan T. FitzPatrick, P.E.

Evert Lawton, Ph.D., P.E.

REFERENCES

Fox, N.S. and M.J. Cowell (1998). "Geopier® Soil Reinforcement Manual, Geopier Foundation Company, Inc. 8283 North Hayden Road, Suite 291, Scottsdale, AZ.

Lawton, E. C. (2000). "Performance of Geopier Foundations During Simulated Seismic Tests at South Temple Bridge on Interstate 15, Salt Lake City, UT." Final Report, No. UUCVEEN 00-03, University of Utah, Salt Lake City, UT.

Lawton, E. C. and N. S. Fox. (1994). "Settlement of Structures Supported on Marginal or Inadequate Soils Stiffened with Short Aggregate Piers." Vertical and Horizontal Deformations of Foundations and Embankments, A.T. Yeung and G.Y. Fello (Editors), American Society of Civil Engineers, 2, 962-74.

Lawton, E.C., Fox, N. S., and R. L. Handy. (1994). "Control of Settlement and Uplift of Structures Using Short Aggregate Piers." In-situ Deep Soil Improvement, K.M. Rollins (Editor), American Society of Civil Engineers, 121-132.

Terzaghi, K. and R.B. Peck. (1967). Soil Mechanics in Engineering Practice. John Wiley and Sons, Inc. New York, NY.

White, D.J. (2001). Personal Communication. September 13, 2001.

Wissmann, K.J. and N.S. Fox. (2000). "Design and Analysis of Short Aggregate Piers to Reinforce Soils for Foundation Soils." Proceedings, Geotechnical Colloquium, Technical University Darmstadt, Darmstadt, Germany, March 25, 2000.

Wissmann, K.J. and N.S. Fox, and J.P. Martin. (2000). "Rammed Aggregate Piers Defeat 75-Foot Long Driven Piles." ASCE Proceedings, Performance Confirmation of Constructed Geotehcnical Facilities, University of Massachusetts, Amherst, MA, April 9-12, 2000.

SYMBOLS USED

A = Gross footing area

A_g = Footing area supported by Geopier elements

A_s = Footing area supported by matrix soil

B = Footing width

c_m = Cohesion intercept of matrix soil

D_f = Footing embedment depth

F_{all} = Allowable resistance to sliding developed by Geopier elements

f_{all} = Allowable composite unit friction coefficient

F_g = Sliding resistance provided by matrix soil

F_p = Passive lateral force

F_t = Total resistance to sliding along base of footing

FS = Factor of safety

ϕ'_g = Angle of internal friction of Geopier element

ϕ'_m = Angle of internal friction of matrix soil

γ = Unit weight of matrix soil adjacent to footing

K_p = Rankine passive earth pressure coefficient

P = Applied footing dead load

q = Average footing bearing pressure

q_g = Normal stress on the Geopier element

q_s = Normal stress on the matrix soil

R_s = Ratio of relative stiffness of Geopier element and matrix soil

R_a = Ratio of cross-sectional area of Geopier elements to gross footing area

GEOPIER IS GROUND IMPROVEMENT®

Work with engineers worldwide to solve your ground improvement challenges.
For more information call 800-371-7470, email info@geopier.com, or visit geopier.com.

130 Harbour Place Drive, Suite 280, Davidson, NC 28036
800.371.7470 | info@geopier.com | marketing@geopier.com
www.geopier.com

GEOPIER®

Tensar

GEOPIER_TB_4_01.16