
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 the 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.

I . 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 *Geopier* aggregate allows for the development of a significantly greater amount of lateral load resistance than developed by footings not supported by *Geopier* elements.



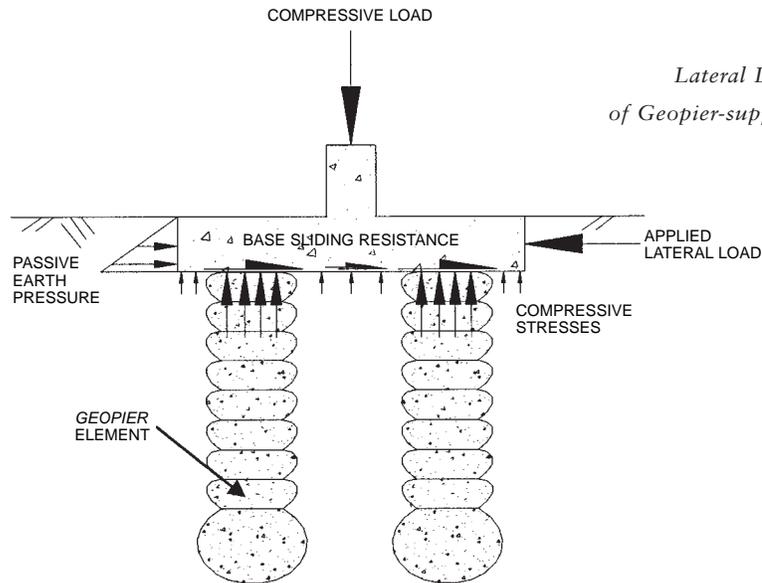


Figure 1.
Lateral Load Resistance
of Geopier-supported Footing.

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 the *Geopier Reference Manual* (Fox and Cowell 1998). *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 . G E O P I E R S H E A R S T R E N G T H

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.

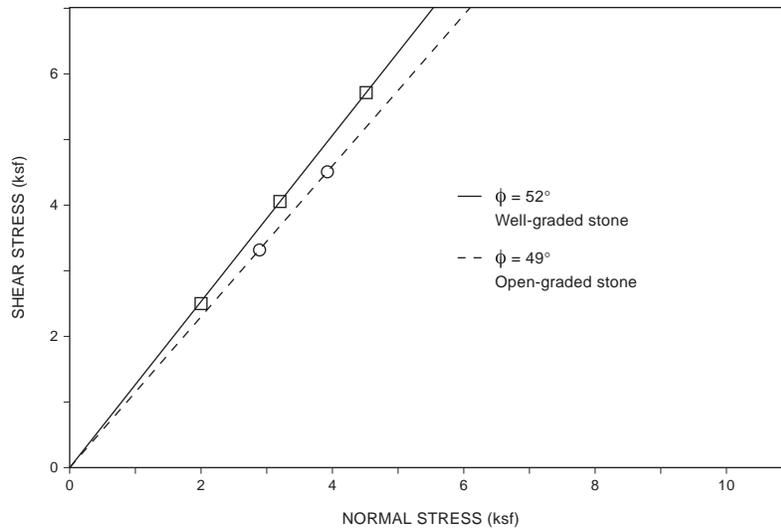
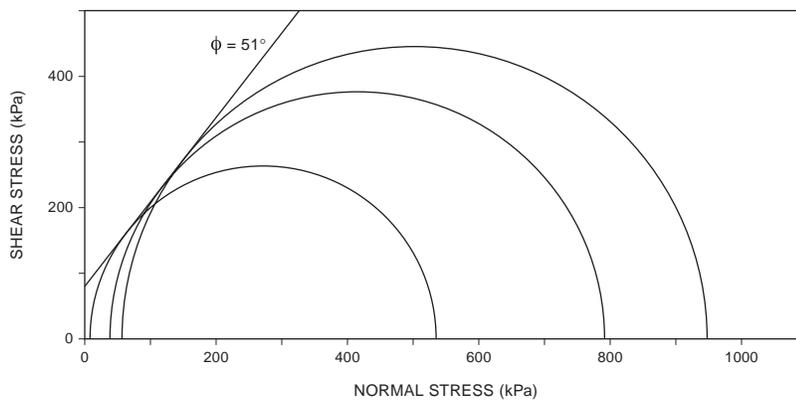


Figure 3.
Results of Triaxial Testing
of Compacted Geopier Aggregate.



4 . L A T E R A L L O A D R E S I S T A N C E

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 and 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):

$$F_g = q_g \tan \phi'_g A_g. \quad Eq.1.$$

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):

$$q_g = \{q R_s / [R_a R_s + 1 - R_a]\}. \quad Eq.2.$$

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 soils. 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 area (A_m) and the cohesion intercept of the matrix soil (c_m):

$$F_m = q_s \tan \phi'_m A_m + c_m A_m. \quad Eq.3.$$

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):

$$q_s = q_g / R_s. \quad Eq.4.$$

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):

$$F_t = F_g + F_m. \quad Eq.5.$$

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):

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

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

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

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 through 7:

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

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

Table 1: Typical Composite Unit Friction Coefficient Values

SOIL CLASSIFICATION	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):

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

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

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

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.

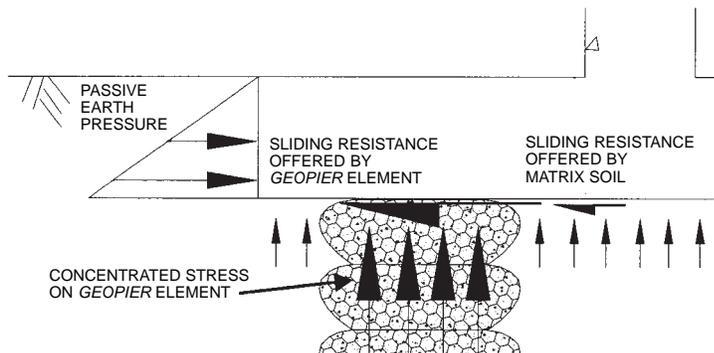


Figure 4. Lateral Resistance Along Bottom of Footing.

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 footings 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.

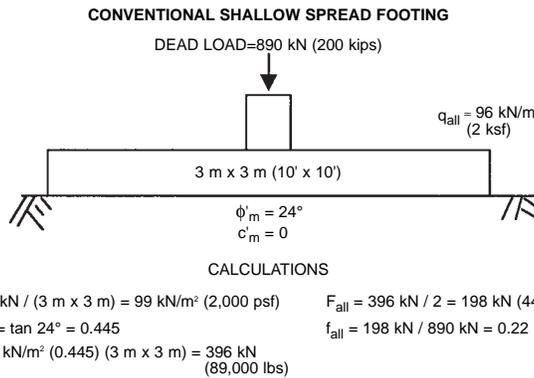


Figure 5a.
*Sliding Resistance Example
for Footing Supported by
Unreinforced Soil.*

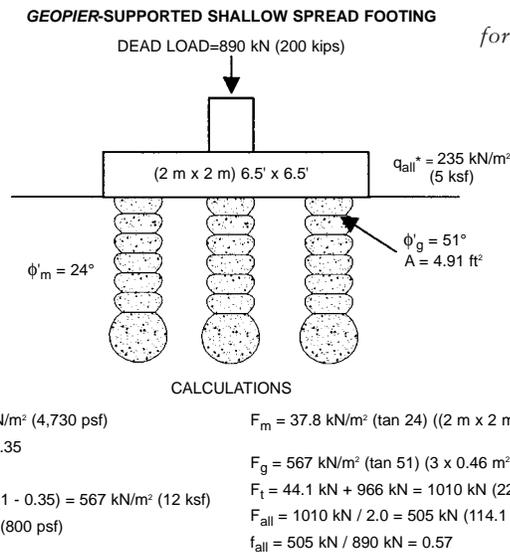


Figure 5b.
*Sliding Resistance Example
for Geopier-supported Footing.*

* 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 (Utah DOT) 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.

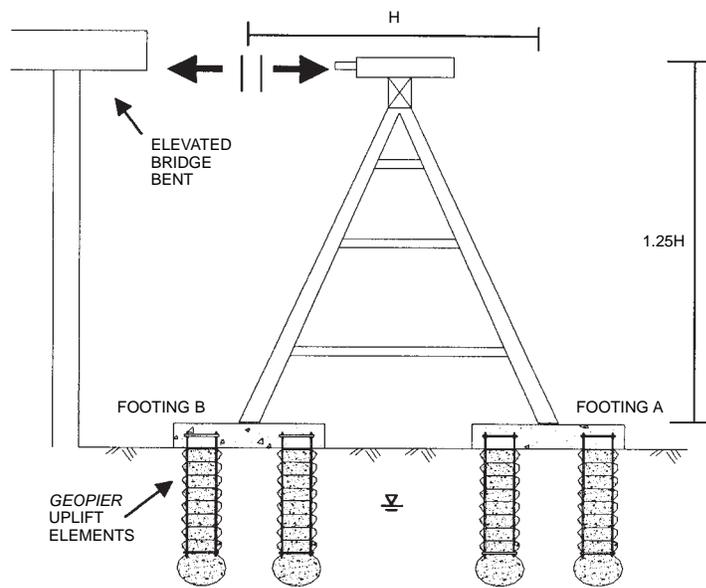
6.1. LATERAL LOAD TEST BACKGROUND

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 result, no lateral resistance is offered by footing.

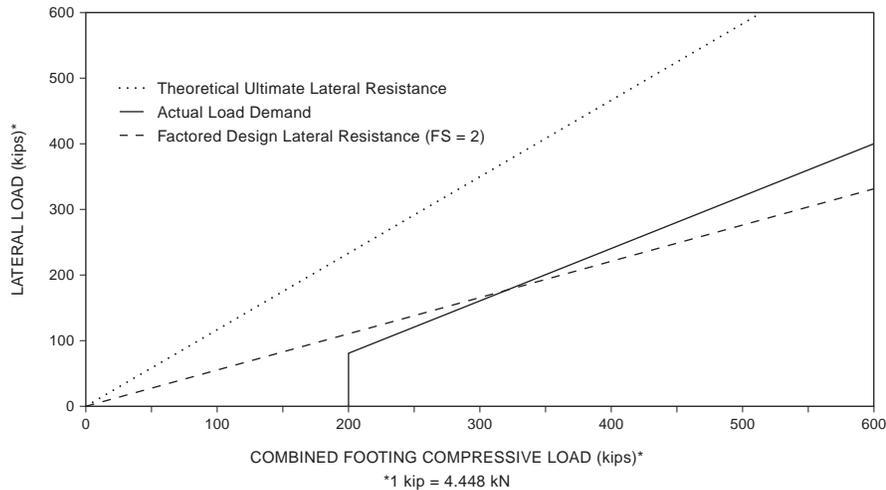
**Neglects additional lateral load resistance provided by uplift bars installed in Geopier elements.

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 and sliding resistance at the base 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 dilatant behavior of the rammed Geopier aggregate.

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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 Geopier elements.
- F_m = 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.

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