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A Generic Design Protocol for Geosynthetic Reinforced Soil Foundation

Jonathan T. H. Wu[1]

Abstract This technical note presents a generic step-by-step design protocol based on consideration of bearing capacity of reinforced soil foundation (RSF) on a level ground. The technical note begins with a synopsis of notable studies on bearing capacity of geosynthetic reinforced soil (GRS) and a brief description of an analytical model for load-carrying capacity of closely-spaced soil-geosynthetic composites. The generic RSF design protocol was developed based on findings of the notable studies and the analytical model. Specifically, the design protocol determines (i) reinforcement configuration of RSF (including reinforcement depths, spacing, and width), (ii) required reinforcement stiffness and strength for selection of reinforcement in RSF, and (iii) the increase in ultimate bearing capacity of RSF if the width of RSF is increased to fulfill design requirements A design example for RSF of a GRS bridge abutment is also given to illustrate how the design protocol can be applied.

Keywords Reinforced soil · Bearing capacity · Geosynthetics · Foundation · Design · Example · GRS · RSF

Introduction

Geosynthetic reinforced soil (GRS) comprises compacted fill and horizontal layers of geosynthetic inclusion. The term *geosynthetics* refers to polymeric materials that are manufactured and used to help solving civil engineering problems. Many types of geosynthetics have been manufactured to serve various functions, of which four

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(geotextiles, geogrids, geocells, and geocomposites) are to serve the function of soil reinforcing. For certain geotextiles and geocomposites, the reinforcing effect can be a result of *synergistic* improvement of the system performance. In other words, the function of separation, filtration, drainage, and soil grain containment of these geosynthetic products can work synergistically in conjunction with reinforcing function to improve performance of an earth structure. The synergistic effect is often neglected in the selection of geosynthetics for reinforcing applications. As a result, geogrids have often been chosen because of their relatively high stiffness and strength values which are generally considered required for reinforced soil foundation (RSF). Geogrids, however, possess hardly any synergistic effects.

Recent studies have demonstrated that geosynthetic inclusion on close spacing (i.e., spacing not greater than 0.2 to 0.3 m or 8 to 12 in.) would allow the fill material and geosynthetics to behave as a composite mass and exhibit much increased load-carrying capacity and reduced settlement [18, 27, 28]. GRS reinforced with geosynthetic products of medium to high stiffness and strength values (such as some woven geotextiles and a handful of heavy nonwoven geotextiles) have seen successful applications in construction of earth retaining walls, steepened slopes, roadways, bridge abutments/approach slabs, and shallow foundations Applications of GRS in shallow foundation are not as common as in other types of earth structures. This is mostly because design concept of reinforced soil foundation (RSF) is generally not well perceived and there is no consensus on how RSF should be designed.

In 2011, the Federal Highway Administration (FHWA) developed a GRS integrated bridge system known as GRS-IBS which employs closely-spaced geosynthetic inclusion to support bridge loads [2, 3]. A typical cross-section of the GRS-IBS is shown in Fig. 1. When the capability of the foundation soil to safely support a bridge abutment is in question, the GRS-IBS manual suggests that RSF be incorporated beneath the abutment as seen in Fig. 1. The manual provides a simple guide for construction of the RSF as follows:

–   Excavate a pit that is approximately $0.25B$ deep (B = reinforcement length at the base of the GRS abutment).
–   Replace the soil in the pit with compacted road base material and reinforce the material by the same reinforcement used in the GRS abutment on 0.3 m (or 12 in.) vertical spacing.
–   The width of the RSF (B') should at least be the length of reinforcement at the base of the abutment (i.e., $B' = B$), and preferably extend to $0.25B$ or greater in front of the abutment wall face.
–   If the abutment is to cross a river way the RSF should be encapsulated with geotextile.

A general guide for the RSF in GRS-IBS is given in the manual, but it does not provide a well-established design protocol. For example, the manual simply states that the reinforcement strength needs to be at least 850 kN/m (4,800 lb/in) for abutments and 425 kN/m (2,400 lb/in) for integrated approach; reinforcement spacing is typically 0.3 m; and depth of RSF is 0.25B, irrespective of the loading conditions and foundation soil properties. Design of RSF for shallow foundation is even less consensual than for bridge abutments. Design of RSF for shallow foundation is
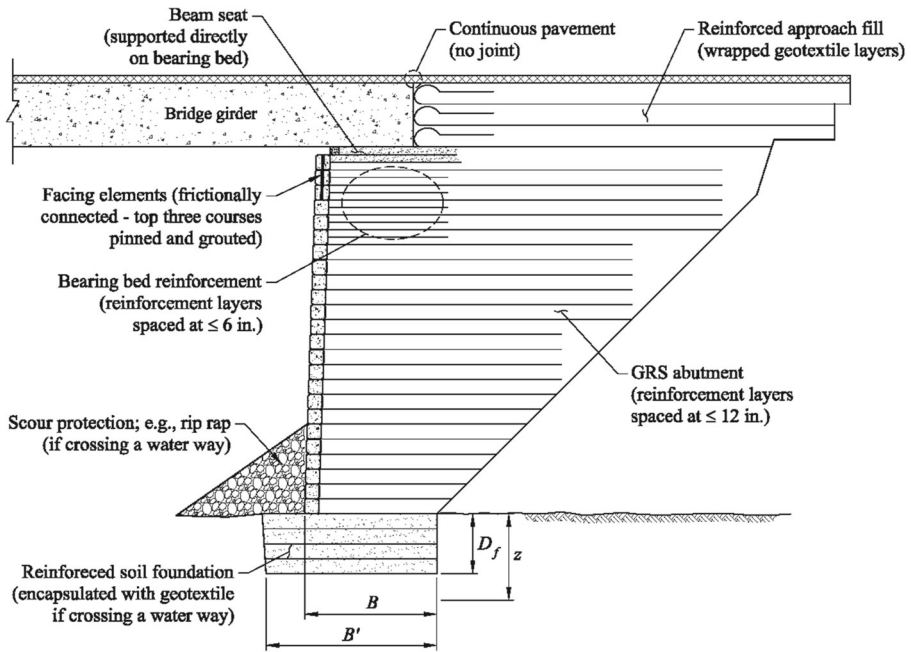
Fig. 1 Typical cross-section of GRS-IBS (modified after [2, 3])

typically performed by using software developed by geosynthetics manufacturers for their specific products, which usually produced satisfactory designs. However, failure of RSF happened occasionally, but the causes of failure have hardly been reported for litigation reasons.

A generic step-by-step design protocol for RSF on a level ground is presented in this technical note. The design protocol was developed based on findings of notable studies on RSF and an analytical model for closely-spaced soilgeosynthetic composites. The design protocol determines (i) reinforcement configuration of RSF (including reinforcement depths, spacing, and width), (ii) required reinforcement stiffness and strength for selection of the reinforcement in RSF, and (iii) the increase in ultimate bearing capacity of RSF if the width of RSF is increased to satisfy design requirements. A design example for RSF of a GRS bridge abutment is also given to illustrate how the design protocol can be applied.

Notable Studies on RSF

Reinforced soil foundation (RSF) has been the subject of many studies in the past few decades (e.g., [1, 4–10, 12–14, 16, 19–21, 29]. A brief summary of four notable studies are given below

1. Huang and Tatsuoka [9] conducted a series of reduced-scale experiments on reinforced clean sand foundation and identified two important effects: the "deep

footing effect" and the "secondary reinforcement length effect." The former states that placing geosynthetic reinforcement up to depth z below the ground surface is equivalent to embedding a footing at depth z. The latter states that extending the length of reinforcement (B') in the RSF beyond the width of the footing (B) increases the bearing capacity only moderately; e.g., the bearing capacity for $B'/B = 2$ is only about 20% higher than $B'/B = 1$, and the bearing capacity for $B'/B = 3.5$ is about 40% higher than that of $B'/B = 1$.

2. Yetimoglu et al. [29] conducted over 60 reduced-scale experiments on reinforced sand foundation. They concluded that (i) for single-layer reinforcement, the optimum reinforcement depth is at $z = 0.3B$ (z = depth measured from the ground surface; B = width of footing), and (ii) for multiple-layer reinforcement, the optimum reinforcement depth is at $z_t = 0.25B$ (z_t = depth of the top layer reinforcement), and the effective depth of reinforcement is up to $1.5B$.

3. Adams and Collin [1] conducted 35 field-scale experiments of reinforced soil foundation with biaxial geogrids and geocells as reinforcement. The experiments include single and multiple layers of reinforcement. The effects of a number of parameters were investigated, including number of reinforcement layers, vertical spacing of reinforcement, plan area of reinforcement, type of reinforcement, and fill density. These experiments show that (i) BCR increased significantly for $z_t < 0.5B$, where BCR = ratio of bearing capacity of reinforced soil foundation to that of unreinforced soil foundation, and z_t = depth of top reinforcement layer; (ii) BCR is about 1.5 for 1 to 2 layers of reinforcement, and about 2.5 for 3 layers of reinforcement; (iii) the maximum improvement for reduction in settlement is observed for $z_t \leq 0.25B$; and (iv) geogrids are more effective than geocells for strengthening granular foundation soil.

4. Barreire and Wu [5] developed a unified analytical model for evaluation of load-carrying capacity and settlement of reinforced soil foundation. The analytical model for load-carrying capacity assumes that the deep footing effect prevails for evaluation of the bearing capacity of RSF. The load-carrying capacity model was based on classical bearing capacity equations, such as the Vesić equation [22], with an accuracy of $\pm 15\%$ compared to measured data from field-scale experiments. The model appears to be applicable to RSFs of single-layer reinforcement and multiple-layer reinforcement. Further validation of the model is still needed.

An Analytical Model for Load-Carrying Capacity of Soil-Geosynthetic Composites

Pham [18] and Wu et al. [26] developed an analytical model for soil-geosynthetic composites where the reinforcement spacing (s_v) is not more than 0.2 to 0.3 m. The ultimate load-carrying capacity (q_{ult}) in the analytical model has been expressed by an equation, referred to as the "Wu-Pham equation". The Wu-Pham equation involves a semi-empirical factor, known as the "W-factor" which characterizes the relative influences of reinforcement spacing and reinforcement strength on the ultimate load-

carrying capacity. The q_{ult}, as effected by reinforcement spacing, reinforcement strength, soil strength parameters, and soil particle size, can be expressed as:

$$q_{ult} = \left[\sigma_c + W\left(\frac{T_{ult}}{s_v}\right)\right] K_p = \left[\sigma_c + 0.7^{\left(\frac{s_v}{6d_{\max}}\right)}\left(\frac{T_{ult}}{s_v}\right)\right] K_p \qquad (1)$$

where

σ_c lateral confining pressure;
W a factor to account for soil-geosynthetic interaction;
s_v selected vertical reinforcement spacing ($s_v \leq 0.2$ to 0.3 m);
d_{max} maximum grain size of the soil in the soil-geosynthetic composite;
T_{ult} ultimate tensile strength of the reinforcement; and
K_p coefficient of Rankine passive earth pressure, $K_p = \tan^2(45° + \phi/2)$

Details of the Wu-Pham equation (Eq. 1) have been described in a technical report published by the Federal Highway Administration [28]. The equation has been validated by 16 field-scale experiments where the GRS mass was loaded to failure [3]. In the 16 experiments, the soil ranged from poorly graded sand to crushed gravel, the geosynthetic reinforcement varied from light-weight nonwoven to heavy-weight woven geotextiles, and the reinforcement spacing varied from 0.15 to 0.3 m. The Wu-Pham equation was shown to be capable of predicting the load-carrying capacity of soil-geosynthetic composites with good accuracy It should be noted that the W-factor can be used to determine an apparent cohesion and an apparent increase in confining pressure resulting from the presence of geosynthetic inclusion. These "apparent" strength parameters are useful when using a conventional stability analysis approach to evaluate stability of a reinforced soil structure [27].

A Generic Design Protocol for RSF

The generic design protocol for RSF on a level ground is presented below. The design protocol is based on findings of the afore-mentioned four studies, the analytical model described earlier on behavior of closely spaced soil-geosynthetic composites, and the author's experience with GRS and RSF.

Step 1:   Check if RSF is needed
Use Terzaghi's bearing capacity equation [23] to calculate the ultimate bearing capacity of a footing without reinforcement, $q_{ult(unimproved)}$:

$$q_{ult(unimproved)} = 0.5\,\gamma_1 B\,N_\gamma + \gamma_2\,D_f N_q + c\,N_c \qquad (2)$$

in which,

γ_1 "operational" unit weight of the foundation soil beneath the footing ($\gamma_1 = \gamma_{submerged}$, if the free water level is above the base of footing; $\gamma_1 = \gamma_{moist}$, if the free water level is deeper than about $2B$ below the base of footing; and $\gamma_1 = \gamma_{weighted}$, if the free water level is between 0 and $2B$ below the base of footing);

$\gamma_{weighted}$	weighted soil unit weight depending on the portion of the soil failure wedge that is submerged;
γ_2	"operational" unit weight of the soil surrounding the embedded area;
B	the width of the loaded area (e.g., B = length of reinforcement at the base of a GRS abutment wall, length of bridge approach slab in the direction of traffic, or length of building in the direction of reinforcement);
D_f	the embedment depth of the footing measured from the ground surface (note, for unimproved ground, D_f = 0);
c	the cohesion of the foundation soil;
N_γ, N_q, and N_c	bearing capacity factors and are a function of friction angle (ϕ_f) of the foundation soil, as given in Fig. 2. For a purely cohesive foundation (ϕ = 0), N_γ = 0, N_q = 1, and N_c = 5.14.

Since the bearing capacity factors depend strongly on the friction angle (ϕ_f), a range of ϕ_f ($\pm$ 1°) should be used to establish a set of upper
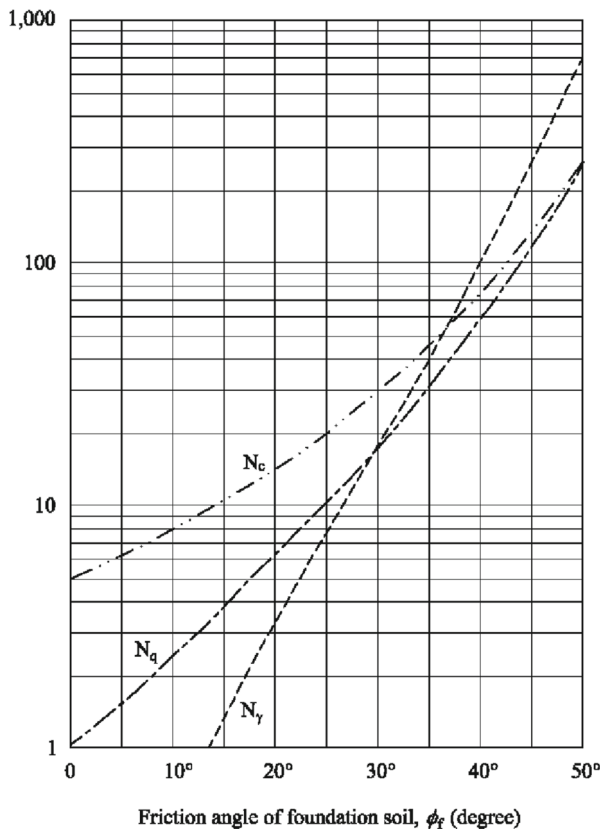
Fig. 2 Bearing capacity factors N_γ, N_q, and N_c as a function of soil friction angle (modified after [17])

and lower bounds of q_{ult} for design decisions. This is especially needed if the friction angle is obtained from a correlation with standard penetration test (SPT) blow count N (e.g., a correlation given by [15]). For structures approaching a plane strain condition (e.g., footing of basement walls), the friction angle should be corrected. A commonly used correction is to multiply the friction angle corresponding to the triaxial testing condition by a factor of 1.1. For loose to medium sands, the friction angle correction is not needed because the friction angles obtained from triaxial tests and from plane strain tests are about the same. Lade and Lee [11] suggested no correction for soils with $\phi \leq 34°$.

To achieve a certain degree of safety margin in design, allowable bearing pressure q_{allow} should be employed (in place of q_{ult}) in design. Allowable bearing pressure can be obtained by applying a safety factor (F_s) to q_{ult} i.e.,

$$q_{allow} = \frac{q_{ult\,(unimproved)}}{F_s} \tag{3}$$

A safety factor of 3.0 is recommended for an "isolated" loaded area, e.g., RSF of isolated buildings. For RSF of a reinforced soil wall since one side of reinforced zone is supported by the adjacent soil behind the reinforced zone, a smaller safety factor of 2.5 is recommended.

In design, the applied load on the ground surface ($q_{applied}$) due to all forms of dead loads and live loads over the ground surface should then be determined. If q_{allow} determined from Eq. 3 is found larger than $q_{applied}$, a RSF is not needed unless settlement is determined to be larger than desirable (note that the design protocol presented here addresses only bearing capacity).

Step 2: Determine the depth of RSF, D_f

Based on the concept of deep footing effect described earlier in the Section "Notable Studies on RSF" the smallest depth of RSF can be determined by requiring the ultimate bearing capacity (as determined by the Terzaghi's equation, Eq. 1) divided by the applied pressure ($q_{applied}$) be no less than a prescribed safety factor (F_s). That is, the minimum depth of the RSF (D_f) can be determined as:

$$D_f \geq \frac{q_{applied}\,F_s \; - \; 0.5\,\gamma\,B\,N_\gamma - c\,N_c}{\gamma\,N_q} \tag{4}$$

where B is the width of the loaded area ($B = B'$, B' is the width of the RSF). Other parameters in Eq. 4 are as defined previously for Eq. 2.

If the D_f value determined by Eq. 4 is found smaller than or equal to the width of the loaded area (B), the value of D_f is then the depth of RSF, and the design should proceed to Step 3. Otherwise, the design should skip Step 3 and proceed to Step 4 to examine if $q_{allow} \geq q_{applied}$ can be achieved by increasing the width of the RSF from B to B' (note, the reinforcement in RSF is generally made constant at all depths).

It is important to note that Eq. 2 is applicable only to a level ground. When applying (2) to a bridge abutment crossing a river way, the design protocol would overestimate the load-carrying capacity; hence, the design

will be on the unsafe side. Further study to extend the design protocol to RSF for bridge abutments crossing a river way is needed. Until then, RSF of bridge abutments crossing a river way may be designed by using the protocol described in this technical note by adopting a larger safety factor in Eq. 3, and/or by measuring the depth D_f (determined from Eq. 4) from the riverbed (as opposed to measuring from the ground surface).

Step 3: Select a trial value of reinforcement spacing and determine the configuration of RSF

The configuration of RSF is to be determined as follows: Select a trial value of reinforcement spacing (s_v) for the RSF (s_v = 0.2 to 0.3 m is recommended). Preferably, a number of s_v values between 0.2 and 0.3 m should be checked to obtain a better design based on consideration of safety margin and costs. Note that reinforcement of higher stiffness and higher strength will be required for s_v = 0.3 m than for s_v = 0.2 m. A uniform reinforcement length should be used within RSF. The depth of the top layer of reinforcement, z_t, should generally be the smaller of 0.2 m and $0.25B$ below the ground surface. However, if only one layer of reinforcement is needed, z_t = 0.3 m or $0.25B$ (whichever is smaller) is recommended. The depth of the bottom layer reinforcement should generally be the D_f value determined in Step 2.

Step 4: Determine the adjusted ultimate bearing capacity of RSF with enlarged width, and check if the $q_{allow} \leq q_{applied}$ requirement can be met by increasing the width of RSF from B to B' [skip this step if the bearing capacity of RSF with $B' = B$ is found satisfactory]

The bearing capacity of a RSF can be increased moderately by increasing the length of reinforcement in the RSF. By increasing the width of the RSF (i.e., the reinforcement length in RSF) from B to $2B$ and to $3.5B$, the bearing capacity would increase by approximately 20 and 40%, respectively. The influence of B'/B on the ultimate bearing capacity can be estimated by Fig. 3, which is derived from the findings of Huang and Tatsuoka [9].

$$q_{ult}/q_{ult\,(B'=B)} = (B'/B)^{0.27}$$
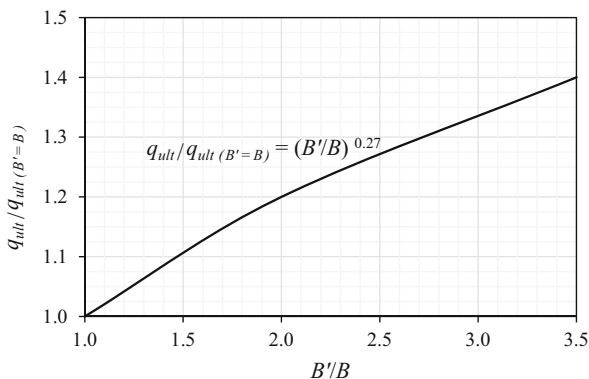
Fig. 3 Influence of B'/B on the ultimate bearing capacity (B = width of loaded area, and B' = width of RSF)

If the D_f value determined by Eq. 4 is larger than the width of the loaded area (B), the width of RSF may be increased to check if $q_{allow} \geq q_{applied}$ can be achieved by increasing the width of the RSF from B to B', while maintaining D_f as the depth of the RSF (primarily because the Terzaghi's bearing capacity equation, Eq. 1, is valid for $D_f \leq B$). The following steps should be taken: (i) set $D_f = B$ and calculate a corresponding q_{ult} by Eq. 2 and an updated q_{allow} by Eq. 3; (ii) increase the width of RSF to B'(B' needs to be a site-specific practical value) and determine the improved $q_{ult(B'>B)}$ and the corresponding $q_{allow(B'>B)}$ from Fig. 3; (iii) check if $q_{allow\ (B'\ >\ B)} \geq\ q_{applied\ (B'\ >\ B)}$ can be satisfied by increasing B to B'($q_{applied}$ is the value determined as part of Step 1). If the answer is positive, B' becomes the new width of the RSF, the design should return to Step 3, then revert to Step 5. If otherwise, the idea of RSF (alone) should be abandoned, and an alternative ground improvement technique, such as preloading, deep foundation, micro-pile, stone column, and grouting, may be considered.

Step 5: Determine required minimum tensile stiffness and tensile strength of the reinforcement in RSF, and select a geosynthetic product

The required minimum tensile strength of the reinforcement (T_{ult}) is determined as:

$$T_{ult} \geq \left[\frac{q_{ult(RSF)}}{K_p} - \sigma_c \right] (s_v) \Bigg/ \left[0.7^{\left(\frac{s_v}{6\,d_{max}} \right)} \right] \tag{5}$$

where $q_{ult(RSF)}$ is the ultimate load-carrying capacity of RSF as determined by Eq. 2 using the D_f value determined in Step 2 for $B' = B$ or the q_{ult} determined in Step 4 for $B' > B$. All parameters are as defined previously in Eq. 1.

To ensure the RSF will possess adequate ductility, the tensile strain of the reinforcement corresponding to T_{ult} needs to be 5 to 7% or greater depending on the degree of conservatism desired. Note that the strain level of 5 to 7% was deduced from limited experience. As a greater data base for the design protocol becomes available, the strain level may be revised.

The required minimum value of tensile stiffness at strain = 2% of the geosynthetic reinforcement in the direction perpendicular to wall face, $T_{@\ \varepsilon = 2\%}$, can be determined by the following equation [28]:

$$T_{@\ \varepsilon = 2\%} \geq \frac{T_{ult}}{F_{dl}} \tag{6}$$

in which, F_{dl} is a *ductility and long-term factor* employed to ensure adequate ductility and satisfactory long-term performance. The values below for F_{dl} are recommended for design of RSF with geosynthetic inclusion; they are based on the author's own experiences:

(a) Plasticity index (*PI*) of fill material passing No. 40 sieve is 3 or less, $F_{dl} = 3.5$ for all geosynthetics

(b) Plasticity index (*PI*) of fill material passing No. 40 sieve is between 4 and 6,

$F_{dl} = 5.5$ for polypropylene geosynthetics
$F_{dl} = 5.0$ for polyethylene geosynthetics
$F_{dl} = 4.0$ for polyester geosynthetics

Note that the use of RSF for improving bearing capacity is effective if the foundation soil is granular (especially in a dense condition), but is ineffective if the foundation soil is purely cohesive. This can be seen by examining the Terzaghi's bearing capacity equation (Eq. 2). The bearing capacity of RSF can be increased by increasing embedment depth D_f. The effectiveness of increasing D_f on bearing capacity is associated with the value of N_q, which varies from 17 to 60 for friction angle varying from 30° to 40°. For purely cohesive soil foundation, however, $N_q = 1$. In other words the effect of embedment depth (reflected by $\gamma \times D_f$) is "amplified" 17- to 60-folds for a granular foundation soil, whereas there is zero amplification for a purely cohesive foundation soil.
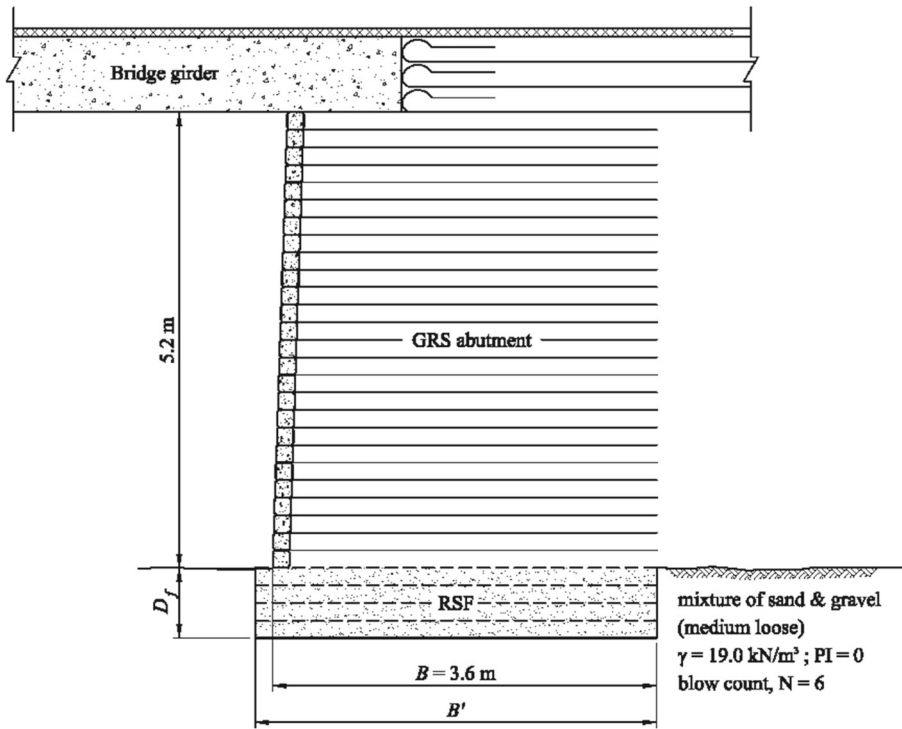
Design Example

A design example is given below to illustrate how the design protocol can be used to design RSF to support a GRS bridge abutment constructed over a weak ground.

Given Conditions As depicted in Fig. 4, a GRS bridge abutment of 5.2 m (17 ft) in height and 7.3 m (24 ft) in width is to be constructed over a relative flat ground. The abutment is to support an arch steel bridge with $DL + LL = 250$ kPa. The foundation soil is a mixture of sand and gravel ($PI = 0$) in a medium loose state and the ground is deemed unacceptable to marginally acceptable for supporting the abutment loads. The ground has a unit weight of 19.0 kN/m³ (120 lb/ft³) with a maximum grain size of 0.025 m (1.0 in.), and the STP blow count "N-value" is approximately constant at $N = 6$ from the ground surface down to about 18 m (or 60 ft) deep. The free water level is stable and approximately 15 m (50 ft) below the ground surface.

Design

Step 1:   Check if RSF is needed
           Without RSF, the embedment depth, $D_f = 0$. Assuming reinforcement length at the base of the GRS abutment $B = 0.7 \times$ (wall height) $= 0.7 \times (5.2) = 3.6$ (m). For SPT blow count $N = 6$ and length/width of loaded area $= 7.3$ m/3.6 m $= 2$, the angle of the foundation soil ϕ_f is taken as 28° hence $N_\gamma \approx 15$, and $N_q \approx 15$ Note that a range of ϕ_f of $\pm 1°$ should generally be used to establish the likely upper and lower bounds of q_{ult} for making design decisions. In this case, however, the blow count N is quite low and the ϕ value obtained from N is rather "rough"; therefore, the $\pm 1°$ rule is not exercised. $F_s = 2.5$ will be used because one side of the abutment is partially supported by frictional resistance with the soil behind the reinforced zone of the abutment.

Fig. 4 Design example for RSF to support a GRS bridge abutment

The ultimate bearing capacity of the unimproved ground, $q_{ult(unimproved)}$ is

$$q_{ult\,(unimproved)} = 0.5\,\gamma_1\,B\,N_\gamma \,+\, \gamma_2\,D_f\,N_q \,+\, c\,N_c$$
$$= 0.5\,(19.0)\,(3.6)\,(15) + 0 + 0$$
$$= 510\,(kPa)$$

The allowable bearing capacity, $q_{allow\ (unimproved)}$, is

$$q_{allow\ (unimproved)} = q_{ult\ (unimproved)}/F_s = 510/2.5 = 200\,(kPa)$$

The applied load on the ground surface, $q_{applied}$, is

$$q_{applied} = \gamma H + (DL + LL) = (19)\,(5.2) + 250 = 350\,(kPa)$$

$$q_{applied} > q_{allow\ (unimproved)} = 200\,(kPa)\,(N.G.)$$

Consider adopting RSF to increase allowable bearing capacity Note that this agrees with a general rule-of-thumb (source unknown) "*A footing cannot rest directly on foundation soil of N < 8.*" Also, note that the largest bearing pressures that can be applied to GRS abutments under different conditions have been reported by Wu et al. [24, 25].

Step 2:   Determine the depth of RSF, D_f
           From Step 1, $q_{applied} = 350$ kPa, $F_s = 2.5$, $\gamma = 19.0$ kN/m^3, $c = 0$,
           $N_q = 15$, $N_\gamma = 15$, and $0.5\ \gamma_1\ B\ N_\gamma = 510$ (kPa). From Eq. 4,

$$D_f \geq \frac{q_{applied}\ F_s - 0.5\gamma\ BN_\gamma - cN_c}{\gamma\ N_q} = \frac{(350)\ (2.5) - 510 - 0}{(19.0)\ (15)} = 1.3\ (\text{m})$$

$D_f \geq 1.3$m use $D_f = 1.4$m; therefore,

$$q_{ult(RSF)} = 510 + (19.0)\ (1.4)\ (15) = 910(\text{kPa}) \geq q_{applied}\ (F_s)$$
$$= 350\ (2.5) = 880\ (\text{kPa})\ (\text{OK})$$
$$D_f = 1.4\ \text{m} \leq B = 3.6\ \text{m}\ (\text{OK})$$

Step 3:   Select a trial value of reinforcement spacing and determine the configura-
           tion of RSF
           Because bridge abutment is considered a more critical structure, $s_v =$
           0.2 m is selected for the entire RSF.
           The depth of top layer reinforcement is at 0.2 m below the ground sur-
           face, and the bottom layer reinforcement is at 1.4 m below the ground
           surface. Reinforcement layers are to be placed between the top and bottom
           layers on 0.2 m spacing.
Step 4:   Determine the adjusted ultimate bearing capacity of RSF with enlarged
           width, and check if the $q_{allow} \leq q_{applied}$ requirement can be met by
           increasing the width of RSF from B to B'.
           Skip this step because $B' = B$ is shown able to produce a satisfactory
           design (satisfying the requirement of $q_{allow} \leq q_{applied}$ and also $D_f \leq B$).
           In this case, the width of the RSF (B') may be increased 0.2 m in front of
           the bridge abutment for added safety, as seen in Fig. 4.
Step 5:   Determine required minimum tensile stiffness and tensile strength of the
           reinforcement in RSF, and select a geosynthetic product.
           The required minimum ultimate tensile strength of the reinforcement,
           T_{ult}, can be determined by Eq. 5, with $q_{ult(RSF)} = 910$ (kPa) (as deter-
           mined in Step 2); $\sigma_{c(@mid-height)} = K_A\gamma\ z = (0.24)(19.0)\ (1.4/2) =$
           3.2 (kPa); $s_v = 0.2$ m; $d_{max} = 0.025$ m; $K_p = \tan^2(45° + 38°/2) = 4.20$
           (note: the friction angle of a road base compacted to 95% of T99 is taken
           as 38°); i.e.,

$$T_{ult} \geq \left[\frac{q_{ult(RSF)}}{K_p} - \sigma_c\right](s_v) \Big/ \left[0.7^{\left(\frac{s_v}{6d_{max}}\right)}\right]$$
$$= \left[\frac{910}{4.20} - 3.2\right](0.2) \Big/ \left[0.7^{\left(\frac{0.2}{6(0.025)}\right)}\right] = 69\ (kN/m)$$

The tensile strain corresponding to T_{ult} (69 kN/m) needs to be at least 5 to
7% or greater depending on the degree of conservatism desired.

The minimum values of tensile stiffness of the geosynthetic product at 2% tensile strain, $T_{@ \, \varepsilon = 2\%}$ can be determined by Eq. 6, with $F_{dl} = 3.5$ (for $PI = 0$),

$$T_{@ \, \varepsilon = 2\%} \geq \frac{T_{ult}}{F_{dl}} = \frac{69}{3.5} = 20 \text{ (kN/m)}$$

Design Summary of RSF

(i)   Geometry: width of RSF $(B') = 3.8$ m, depth of RSF $(D_f) = 1.4$ m
(ii) Reinforcement: multiple-layer reinforcement; depth of the top reinforcement layer below the ground surface $(z_t) = 0.2$ m; depth of the bottom reinforcement layer $(z_b) = 1.4$ m; uniform reinforcement spacing $(s_v) = 0.2$ m; reinforcement length $(B') = 3.8$ m (i.e., 0.2 m wider than B in front of abutment face, see Fig. 4); tensile stiffness @ $(\varepsilon = 2\%) \geq 20$ kN/m; tensile strength @ $(\varepsilon \geq 5\% \, to \, 7\%) \geq 69$ kN/m (a medium to heavy-weight woven polypropylene geotextile will meet these criteria)
(iii) Fill: a free-draining road base, compacted to 95% of Standard Proctor (AASHTO T99) maximum dry unit weight, with $\phi \geq 38°$ per direct shear tests or drained triaxial tests

Concluding Remarks

Reinforced soil foundation (RSF) is formed by incorporating horizontal layers of planar geosynthetic products (e.g., geotextiles, geogrids, or geocomposites) in compacted fill material. RSF is typically installed in the foundation soil to support applied loads. RSF has been found to increase the bearing capacity of the soil foundation by 50 to 200% and decrease the settlement by 20 to 60%. In terms of bearing capacity, the deep footing effect first identified by Huang and Tatsuoka [9] and confirmed by others is used as the fundamental for design of RSF Much like embedding footing, RSF is known to be effective when installed in a granular foundation soil (especially a dense granular soil) but ineffective in purely cohesive soil foundation.

This technical note presents a generic design protocol for RSF in a level ground. The RSF design protocol was developed based on findings of four notable studies and an analytical model that describes the load-carrying capacity of soil-geosynthetic composites with closely spaced reinforcement. Specifically, the design protocol determines (i) reinforcement configuration of RSF (including reinforcement depths, spacing, and width), (ii) required reinforcement stiffness and strength for selection of the reinforcement in RSF, and (iii) the improved ultimate bearing capacity of RSF.

It is important to note that the design protocol presented in this technical note considers only bearing capacity. In situations where settlement of RSF is judged to play a compelling role, settlement of RSF must also be included as part of the design. In these situations, the design obtained from the design protocol should be considered only as a preliminary design.

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