Transmission of Surface Applied Load in Geosynthetic-Reinforced Soil Structures

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ABSTRACT: The mechanism of the transmission of stresses from a distributed surface load through geosynthetic-reinforced soil systems is still not fully understood. In particular, the roles played by fill compaction, confining action of the reinforcement, and the boundary interference of the wall facing are not well represented in the current design methods. This paper reviews current knowledge based on test results available from scale models and current approach used in analysis of load propagation in reinforced soil structures. A new analytical model based on the stochastic theory of stress diffusion is described. The model accounts for the effect of fill compaction and confinement as well as the boundary interference with the stress diffusion mechanism.

INTRODUCTION

Reinforced soil structures are being used more frequently in system infrastructures such as bridge abutments, pavements and railway foundations. Physical and numerical investigations show that the propagation of applied boundary loads in reinforced soil structures is influenced by: (1) confinement generated by soil-reinforcement interface friction, (2) construction procedure, and (3) the presence of the wall boundary.

Several design methods for reinforced soil structures have been proposed based on the limiting equilibrium concepts for gravity walls and slope stability analyses. A review of the available design approaches show that only a few of these methods consider the effect of external loads (Schlosser et al., 1978, Christopher et al., 1989). In these methods, the pressure increments due to the applied load are simply added to the gravity body forces. The superposition of stresses is significant simplification here because they are not analyzed for the same state of stress condition. The pressure increments are computed using elasticity theory while the gravity body forces are usually calculated for a yielding condition.

Finite element formulations have been used to study the performance of reinforced soil structures subjected to applied boundary loads. Although the formulations are good for detailed studies, they are not routinely used for design analysis of reinforced soil structures in non-critical situations. These formulations require: (1) detailed simulation of the interface responses, and (2) significant computation time with systems involving a large number of reinforcing members. These limitations render the approach impractical in many situations.

Alternative solutions stress distributions in reinforced soil can be derived from the stochastic theory of stress diffusion in particulate media. The theory provides a conceptual relationship between the transmission of applied loads and the state of lateral earth pressure mobilized by yielding of the wall. It also incorporates a multi-layer modeling capability and reflecting/absorbing boundary formulation to simulate the actual boundary and interface condition.

For uncompacted fill, the diffusivity parameter varies with depth from the at-rest pressure coefficient of the soil (K_o) at the top of the wall to K_a in the lower part of the wall. The compaction pressure applied during construction will affect the initial coefficient of lateral stress. Thus, it increases the diffusivity parameter at the upper part of the wall.

The confinement at the soil-reinforcement interface increases the diffusivity parameter by limiting the yielding of the wall.

The presence of a wall boundary will interrupt with the distribution of stress. Depending on the stiffness of the wall system, the stress could be absorbed into the boundary, or be reflected resulting in a stresses at the boundary.

PREVIOUS WORK

Some researchers have investigated the behavior of reinforced soil structures under applied boundary loads. Kennedy et al. (1980) conducted an experimental study on a small-scale model of a reinforced retaining wall subjected to a vertical strip load. The results showed that when the vertical strip load is placed inside the Rankine active wedge, the failure plane can be approximated by Cullmann's graphical solution. However, when the load was applied outside the Rankine failure wedge, the internal failure develops according to a rupture surface that starts at the back of the loading plate. The results also showed that the tensile force distribution in the reinforcing elements differs from that when no external load is considered.

The rare detailed study reported in the literature on the effect of horizontal strip loading was conducted by Laba et al. (1984). A horizontal surface load directed toward the wall face increased the tensile force in the reinforcement. The measurements suggested that the stress penetrates more into the backfill than estimated theoretically.

Full-scale investigations on a steep wall reinforced by woven geotextiles subjected to a vertical strip loading was conducted by Wichter et al. (1986). Observations showed that the failure started underneath the loading plate by deformation of the upper reinforcement layer. Compaction efforts applied during construction created a significant wall deformations and increased the tensile stress in the reinforcement. Similar conclusions can be derived from an experiment on geotextile and geogrid reinforced structures (Thamm et al., 1990a,b).

The possibility of using geotextile reinforced structures for bridge abutments was studied by Balzer et al. (1990). The study showed that failure occurred from a lack of anchorage at the upper geotextile layers. The measured vertical stress distribution within the reinforced soil body was higher than predicted theoretically. However, the horizontal earth pressure just behind the wall facing was significantly less than predicted. This finding was supported by a study of a wall reinforced by inextensible elements done by Bastick (1990). The maximum vertical pressure that occur below the loaded surface is nearly twice the theoretical values.

CURRENT APPROACH

In common design approach (Christopher et al., 1989), the pressure increments due to the applied surface loads are computed based on an elasticity formulation for stress distribution in semi-infinite media. The vertical stress increment due to an applied surface load ($\Delta\sigma_V$) is computed by assuming a uniform dispersion of load over an area bounded by a 2:1 inclined lines (Figure 1):

$$\Delta\sigma_V = q\left[\frac{B}{(B+h)}\right] \qquad when\ \ h \le 2d$$

$$\Delta\sigma_V = q\left[\frac{B}{(B+d+h/2)}\right] \qquad when\ \ h > 2d$$

where q is the load per unit width, B is the width of loading plate, d is the distance between the wall facing and front end of loading plate, and h is the depth of the reinforcement layer under consideration.

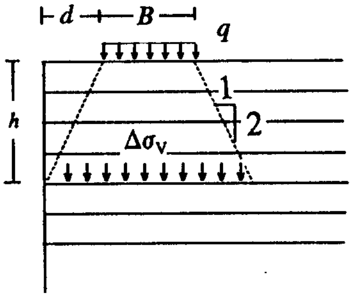

Figure 1 Uniform distribution of vertical applied load

The horizontal stress increment ($\Delta\sigma_H$) due to a horizontal force (F) applied toward the wall face is computed using the formula proposed by the French Ministry of Transportation (FMT) for Reinforced Earth walls (Figure 2):

$$\Delta\sigma_H = \frac{F}{l' + d}\left[1 - \frac{h}{h_o}\right] \qquad when\ \ h < h_o$$

$$\Delta\sigma_H = 0 \qquad when\ \ h > h_o$$

where $l' = (B-2e)$ is the effective width of loading plate, and $h_o = (2(B+d))$ is the depth of horizontal stress penetration.

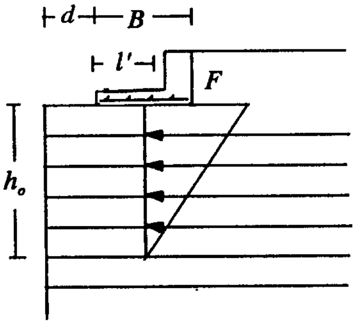

Figure 2 Horizontal distribution of horizontal applied load

These pressures are added to the gravity body force induced stresses to evaluate the stress transmitted to the facing of the retaining wall (σ_H):

$$\sigma_H = K(\sigma_V + \Delta\sigma_V) + \Delta\sigma_H$$

where K is the earth pressure coefficient and σ_V is the vertical stress in the soil mass due to body forces and uniform surcharges.

Alternatively, the vertical and horizontal stress increments due to an applied vertical load can be estimated using Terzaghi's (1943) formula:

$$\Delta\sigma_V = \frac{q}{\pi}(\beta + \sin\beta\cos2\alpha)$$

$$\Delta\sigma_{HV} = \frac{q}{\pi}(\beta + \sin\beta\cos2\alpha)$$

in which β is the angle of visibility at the point of interest and α is the angle between the vertical and the bisector of angle β (Figure 3).

The horizontal pressure due to a horizontal strip load (F) is computed using Scott's (1963) formula:

$$\sigma_h = \frac{F}{\pi}\left[\ln\frac{R_1^2}{R_2^2} - \sin\beta\sin(\beta+2\delta)\right]$$

where δ is the angle between the vertical line and a line connecting the point of interest and the closer edge of loading plate, and R_1 *and* R_2 are the distances between the point of interest and the edges of the loading plate (Figure 4). These formulations are used by Kennedy et al.(1980) to develop an analysis of load propagation in reinforced soil walls.

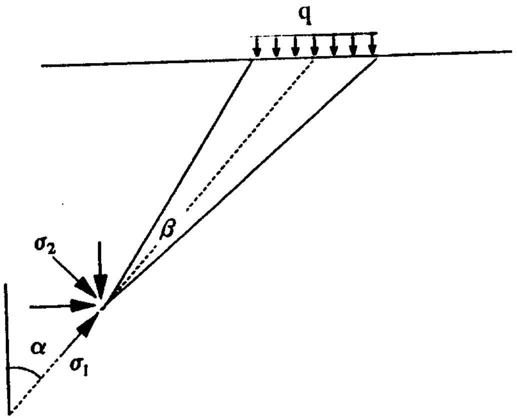

Figure 3 Vertical load induced stress

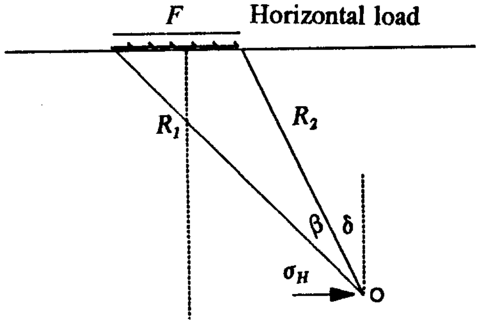

Figure 4 Horizontal load induced stress

The presence of the wall boundary and the reinforcing elements is estimated using the modification of the method of images (Mindlin, 1936). A perfectly rigid boundary imposes a reflection that doubles the intensity of pressure behind the wall facing. On the other hand, a flexible wall does not induce a change in the pressure behind the wall boundary. Assuming that the solution for reinforced soil walls lies between the two extreme conditions, the elastic solution for stress at the boundary (σ_H') can be computed as

$$\sigma_H' = 2\sigma_H = (2-R)\left(\frac{q}{\phi}\right)(\beta - \sin\beta\cos2\alpha)$$

where R is the reduction factor which varies with the stiffness characteristics (AE_t) of the soil backfill and the reinforcing element:

$$R = \frac{(AE_t)_{bf}}{(AE_t)_{bf} + (AE_t)_r}$$

in which A is the cross-sectional area and $(E_t)_r$ is the tangent modulus of elasticity of the reinforcement. The modulus of elasticity of the backfill ($(E_t)_{bf}$) can be estimated using the hyperbolic equation (Duncan and Chang, 1970) as

$$(E_t)_{bf} = \left[1 - \frac{R_f(1-\sin\phi)(\sigma_v-\sigma_h)}{2c\cos\phi + 2\sigma_h\sin\phi}\right]^2 KP_a(\sigma_h/P_a)^n$$

where R_f is the failure ratio of the soil, K and n are the modulus number and exponent respectively, P_a is the atmospheric pressure, and c and ϕ are the cohesion and the angle of internal friction of the soil.

CURRENT WORK

An analytical model for evaluating the transmission of an applied surface load in reinforced soil walls was developed based on the stochastic theory of stress diffusion in particulate media (Harr, 1977). It involves a formulation of a diffusivity parameter for stress diffusion in semi-infinite media. Effects of factors related to the reinforced soil structures are considered based on the way they influence the state of stress in the soil. Once the diffusivity parameter is obtained for a specific case, the stress distribution can be computed using a solution of the diffusion equation. The solution of this equation for various loading condition is given by Harr (1977).

The one-dimensional diffusion equation for stress distribution is:

$$\frac{\partial S_z}{\partial z} = \nu z\,\frac{\partial^2 S_z}{\partial x^2}$$

where ν is the diffusivity coefficient that represents the material's ability to laterally spread the load and z is depth. The corresponding normal horizontal stress (S_x) in terms of S_z is

$$S_x = \nu S_z + \nu^2 z^2\frac{\partial^2 S_z}{\partial x^2}$$

Harr (1970) noted that if the variation of the expected value of vertical stress in the horizontal direction is linear, then the second order term of the above equation can be neglected. Thus, the diffusivity coefficient (ν) is analogous to the coefficient of lateral earth pressure (K). The assumption that the second order term can be neglected is valid under two conditions (Bourdeau, 1986): (1) the second derivative of $S_z(x,z)$ with respect to x is equal to zero or negligible, and (2) the orientations of the principal stresses coincide with the vertical and horizontal stresses.

The vertical stress distribution below a loaded area in granular soil can be approximated by a normal Gaussian distribution; therefore the first condition is met only at points away from the loaded area. On the other hand, the second condition is met only at points along the centerline below the axis of loading. Apparently, the two conditions never exist simultaneously. Thus, although both parameters represent the state of stress in the material, the coefficient of lateral stress cannot be used to quantify exactly the diffusivity parameter.

The diffusivity parameter varies with the strength parameters of the soil and the applied load. It also varies with confining effect of the reinforcement, compaction force, and stiffness of the wall boundary. The following paragraph will describe the influence of each of these factors on the diffusivity coefficient.

Effect of reinforcing element

The benefits obtained from reinforced soil results from the generation of frictional forces at the soil-reinforcement interface. These forces are analogous to the increase of confining pressure, thus restricting the lateral strains in the soil. As strain increases, the frictional resistance between soil and geosynthetics is mobilized, thus the shear strength of the soil increases. More lateral strain in the soil is required in the reinforced system to mobilize active conditions.

When strains are small, the soil remains close to the "at-rest" condition. The yielding wall induces an active condition for unreinforced wall. In reinforced soil structures, wall movement depends on the stiffness and density of the reinforcing elements.

The confinement at the soil-reinforcement interface causes the lateral stresses to be distributed over a greater area compared to the unreinforced case. The amount of confinement depends on the stiffness of the reinforcement and the apparent friction coefficient. The confining pressure increases as the friction coefficient increases and as the relative stiffness of the reinforcement with respect to the soil increases. Thus, the diffusivity coefficient will increase with increased friction and reinforcement stiffness.

Effect of Construction Procedure and Compaction Force

When constructing reinforced soil structures, the soil fill is normally placed in layers and compacted to optimize its strength and compressibility properties. Construction procedures, including soil placement and compaction, ultimately reduce the vertical pressure below the loaded surface. However, initial distortion of the facing can result from these compaction efforts and generate higher forces within the reinforcement. This results in a higher diffusivity coefficient in the upper layers.

Effect of wall boundary

The presence of a retaining wall induces a boundary effect. This effect can be analyzed based on the probability that a transmitted intergranular force reaching the barrier will be reflected. In reinforced soil structure, the probability can be estimated based on the stiffness of the wall system, and the mobilization of friction at the interface between soil and the reinforcement.

SUMMARY

The lateral stress and deformation response of reinforced soil structures subjected to applied boundary loads induce a variation of the state of stress in the reinforced soil body. Thus, a rational approach for evaluation of tensile stress in reinforcing element should account for these stress conditions. The diffusivity parameter for stress diffusion equation can be used to model analytically this mechanism.

The diffusivity parameter depends on many factors associated with the reinforced soil system, i.e., (1) soil strength parameter (2) tensile modulus of the reinforcing element, (3) the state of stress in the structure.

A detailed study is currently underway based on this concept and will allow to express the stress diffusivity parameter for practical problems. Then, the vertical and horizontal stress distributions can be calculated using the diffusion equation and tensile stresses in reinforcements be derived.

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