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Seismic design of bilinear geosynthetic-reinforced slopes

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A R T I C L E I N F O

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A B S T R A C T

The scenario of two tiered geosynthetic-reinforced slopes, where the upper tier is vertical and the lower tier is inclined at an angle, is termed as a bilinear geosynthetic-reinforced slope (BGRS) in this note. This note presents a pseudo-static limit equilibrium approach employing a top-down log spiral mechanism to determine the resultant reinforcement force in the lower tier required for global seismic stability. An example was presented to illustrate steps for achieving the resultant reinforcement force required for internal seismic design of reinforcement rupture and show how much the maximum reinforcement force at each layer is in line with its distribution function. The reinforcement force in the BGRS is subsequently compared with that in the equivalent geosynthetic-reinforced slope under different case. In addition, it is found that the resultant reinforcement force in the lower tier increases first and then decreases with an increase of height ratio of the upper tier to the BGRS.

1. Introduction

A new geosynthetic-reinforced earth structure (GRES) is built into a two-tiered geosynthetic-reinforced slope that involves one with vertical upper tier and another with an inclined lower tier [1]. This structure mentioned herein can be called as the bilinear geosynthetic-reinforced slope (BGRS). Unfortunately, specialized design method of BGRSs is not existed in current guidelines [2–4]. However, using a rigorous limit equilibrium (LE) approach, one research paper explored the impact of the BGRS on the resultant reinforcement force required for global static stability, and showed that no reinforcement should be needed when the inclination of the lower tier got shallower [5].

Often, GRESs after major earthquakes achieved a better performance than unreinforced retaining structures in the field observation [6]. This is mainly due to the flexibility of GRESs and/or the redundancy in design [7,8]. In a seismically active region, however, the seismic design of GRESs is still essential during their service life. For BGRSs, there is no doubt that their seismic design cannot be also ignored in such region. Usually, the seismic design of GRESs has been performed using the pseudo-static LE approach because this approach is relatively simple to implement, tangible, and well accepted in practice [7].

The objective of this study is to formulate the resultant reinforcement force required for internal seismic design of BGRSs through extending the method of Ruan et al. [5], and then to determine the maximum reinforcement force at each layer according to its distribution function. In additional, an example is given to show the application of the approach presented in this study, and compare with the maximum reinforcement force in the BGRS and the equivalent geosynthetic-reinforced slope (EGRS) under seismic condition.

2. Analytical formulation

In global seismic stability analysis of BGRSs, log spiral slip surfaces as part of the LE formulation are assumed– refer to Fig. 1 for notation and convention. In the Fig. 1, the EGRS surface is OC, the resisting forces, T_{E1} and T_{E2}, are resultant reinforcement forces of all layers for the upper and lower tiers, respectively, while the driving force, W_E, is the weight of the entire failure mass (i.e., Region OBCE). The line of action of T_{E1}, D_1, is measured from the bottom of the upper tier while the line of action of T_{E2}, D_2, is measured from the bottom of the lower tier.

The line of action of the resultant reinforcement force cannot be known, nor can be derived by the formulation, but can only be assumed. Based on a set of experimental and numerical studies, Al Atik and Sitar [9] found that the line of action of the dynamic earth pressure force in LE analyses should be at one third of the wall height. This finding was subsequently adopted by some guidelines for seismic design of GRESs [2]. For D_1 in the upper tier, therefore, we assume that it is equal to $H_1/3$. Typically, the elevation of the resultant reinforcement force of the lower tier will move upwards

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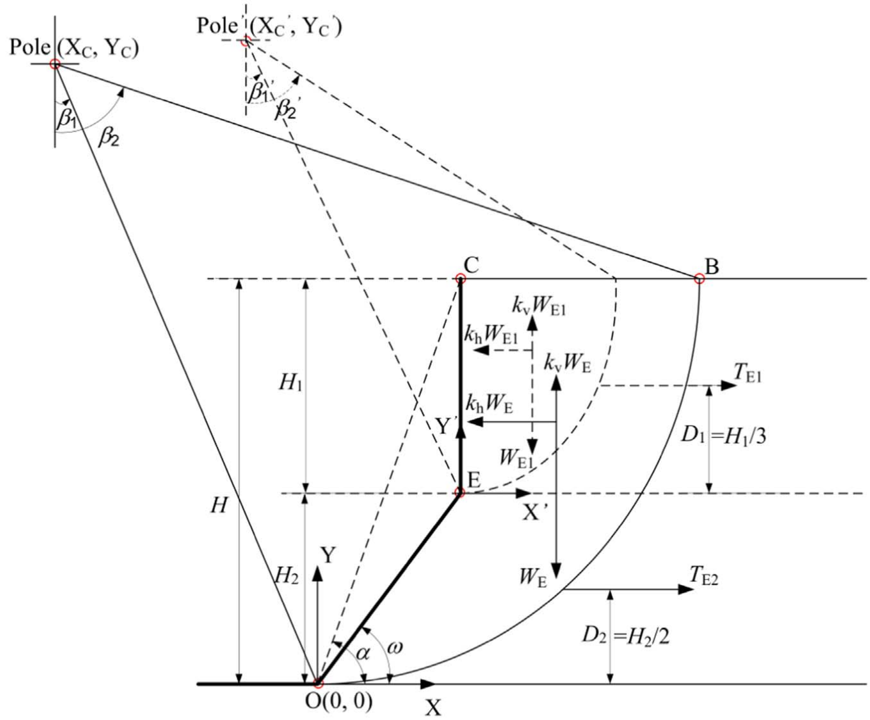

Fig. 1. Notation and convention for the presented LE approach.

when the load of the upper tier appears and/or the inclination of the lower tier occurs. Thereforce, it is reasonable to assume D_2 to act at $H_2/2$.

For completeness, the expression for the resultant reinforcement force in the upper tier, T_{E1}, is reproduced here from Vahedifard, et al. [7]

$$T_{\mathrm{E1}} = \Big\{\gamma_d(1-k_v)\int_{\beta_1'}^{\beta_2'}(A'e^{-\psi\beta'}\cos\beta' - A'e^{-\psi\beta_2'}\cos\beta_2')(A'e^{-\psi\beta'}\sin\beta')(A'e^{-\psi\beta'}) \times(\cos\beta' - \psi\sin\beta')d\beta' + \frac{\gamma_d}{2}k_h\int_{\beta_1'}^{\beta_2'}\Big[(A'e^{-\psi\beta'}\cos\beta')^2 - (A'e^{-\psi\beta_2'}\cos\beta_2')^2\Big]\times(A'e^{-\psi\beta'})(\cos\beta' - \psi\sin\beta')d\beta'\Big\}/(A'e^{-\psi\beta_1'}\times\cos\beta_1' - D_1) \quad (1)$$

where, γ_d is the unit weight of the reinforced soil; β_1' and β_2' are angles at points where the log spiral slip surface enters and exits the upper tier; β' is the angle in polar coordinates defined relative to Cartesian coordinate system translated to Pole' (X_C', Y_C') from the origin E – Fig. 1; A' is log spiral constant, i.e., $H_1/[\exp(-\psi\beta_1')\cos\beta_1' - \exp(-\psi\beta_2')\cos\beta_2']$, where, H_1 is height of the upper tier, $\psi = \tan\phi_d$, and ϕ_d is the design internal angle of friction.

In virtue of resultant force of normal and shear force along the log spiral surface going through the pole, the moment of this component is equal to zero. Consequently, at a LE state the resisting and driving moments are equal as shown:

$$M_{WE} = M_{TE1} + M_{TE2} \quad (2)$$

where, M_{TE1} and M_{TE2} are moments due to T_{E1} and T_{E2}, respectively, while M_{WE} is moment due to W_{E}. The computational formulae of M_{WE}, M_{TE1} and M_{TE2}, respectively are thus as follows:

$$M_{\mathrm{EW}} = \gamma_d(1-k_v)\int_{\beta_1}^{\beta_2}(Ae^{-\psi\beta}\cos\beta - Ae^{-\psi\beta_2}\cos\beta_2)(Ae^{-\psi\beta}\sin\beta)(Ae^{-\psi\beta})(\cos\beta - \psi\sin\beta)d\beta + \frac{\gamma_d}{2}k_h\int_{\beta_1}^{\beta_2}\Big[(Ae^{-\psi\beta}\cos\beta)^2 - (Ae^{-\psi\beta_2}\cos\beta_2)^2\Big](Ae^{-\psi\beta})(\cos\beta - \psi\sin\beta)d\beta - \gamma_d(1-k_v)(H_1\times H\cot\alpha)(Ae^{-\psi\beta_1}\sin\beta_1 + H\cot\alpha/2) - \gamma_d k_h(H_1 H\cot\alpha)\Big(Ae^{-\psi\beta_1}\cos\beta_1 - \frac{H_1}{2} - H_2\Big) - \gamma_d(1-k_v)(H_2 H\cot\alpha/2)(Ae^{-\psi\beta_1}\sin\beta_1 + H\cot\alpha/3) - \gamma_d k_h(H_2 H\cot\alpha/2)\Big(Ae^{-\psi\beta_1}\cos\beta_1 - \frac{2}{3}H_2\Big) \quad (3)$$

$$M_{TE1} = T_{\mathrm{E1}}(Ae^{-\psi\beta_1}\cos\beta_1 - H_2 - D_1) \quad (4)$$

$$M_{TE2} = T_{E2}(Ae^{-\psi\beta_1}\cos\beta_1 - D_2) \quad (5)$$

Using Eqs. (1)–(5), one can solve T_{E2} which is as follows:

$$T_{\mathrm{E2}} = (M_{WE} - M_{TE1})/(Ae^{-\psi\beta_1}\cos\beta_1 - D_2) \quad (6)$$

where, H_2 and H are heights of the lower tier and the BGRS, respectively; β_1 and β_2 are angles of points where the log spiral enters and exits the BGRS – Fig. 1; α is the angle of the EGRS; β is the angle in polar coordinates defined relative to Cartesian coordinate system translated to Pole $(X_{\mathrm{C}}, Y_{\mathrm{C}})$ from the origin O (0, 0); A is log spiral constant, i.e., $H/[\exp(-\psi\beta_1)\cos\beta_1 - \exp(-\psi\beta_2)\cos\beta_2]$.

For a dimensionless analysis using T_{E1} and T_{E2}, one can, respectively, define K_{TE1} and K_{TE2} as

$$K_{\mathrm{TE1}} = \frac{T_{\mathrm{E1}}}{0.5\gamma_d H_1^2} \quad (7)$$

$$K_{\mathrm{TE2}} = \frac{T_{\mathrm{E2}}}{0.5\gamma_d H_2^2} \quad (8)$$

3. Illustrative example

An illustrative example is presented to demonstrate the application of the extended approach in this study and compare with the maximum