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Earth pressure coefficients for reinforcement loads of vertical geosynthetic-reinforced soil retaining walls under working stress conditions

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ABSTRACT

Based on the nonlinear elastic theory and stress-dilatancy theory, two earth pressure coefficients were proposed to analyze the reinforcement loads at the potential failure surface of vertical geosynthetic-reinforced soil retaining walls under working stress conditions. The earth pressure coefficients take into account the force equilibrium and compatible deformations between soil and reinforcement, and can be obtained by solving two implicit functions by an iterative or graphic method. The effects of backfill compaction and facing restriction are taken into account in the earth pressure coefficients by two additional stress factors, which have been derived analytically using straightforward approaches. To validate the effectiveness of the proposed methods, comparisons were made with the results from large scale tests and numerical simulations. It was demonstrated that the reinforcement loads predicted by the proposed methods were in good agreement with the experimental or numerical results.

1. Introduction

The conventional design methods for the internal stability of Geosynthetic-Reinforced Soil (GRS) retaining walls (BS 8006-1 2010; NCMA, 2010; AASHTO, 2012) are based on the earth pressure theories or the limit equilibrium methods. For example, according to AASHTO (2012), the maximum reinforcement load for a reinforcement layer in a GRS retaining wall can be calculated as:

$$T = K_r \sigma_z S_v \tag{1}$$

Here, σ_z is the vertical soil stress at the elevation of the reinforcement layer, and S_v is the vertical reinforcement spacing. K_r is the lateral earth pressure coefficient. Since it is assumed that the soil strength is fully mobilized in most design methods (e.g. BS 8006-1 2010; NCMA, 2010; AASHTO, 2012), K_r is generally taken as the Rankine's or Coulomb's active earth pressure coefficient K_a. However, the measured reinforcement loads from many case histories under working stress conditions differed considerably from the predictions using the active earth pressure coefficients (e.g., Ehrlich and Mitchell, 1994; Allen et al., 2003; Allen and Bathurst, 2014a; b; Riccio et al., 2014; Chen et al., 2016; Cristelo et al., 2016; Ferreira et al., 2016; Jiang et al., 2016; Khosrojerdi et al., 2016; Yu et al., 2016a; Ardah et al., 2017; Li and Espinoza, 2017; Song et al., 2017; Yu et al., 2017). Extensive studies in recent years have shown that the reinforcement loads are determined by the reinforcement stiffness, soil stiffness, compaction effect, facing restriction, among others (Ho and Rowe, 1994, 1996; Rowe and Ho, 1997, 1998; Ehrlich and Mitchell, 1994; Rowe and Skinner, 2001; Rowe and Li, 2003; Bathurst et al., 2008; Liu and Won, 2014; Ambauen et al., 2016; Chen et al., 2017; Gu et al., 2017; Liu, 2016a; Ehrlich and Mirmoradi, 2016; Mirmoradi et al., 2016; Nicks et al., 2016; Scotland et al., 2016; Sukmak et al., 2016; Xiao et al., 2016; Xie et al., 2016; Yu et al., 2016b; Zheng and Fox, 2016; Mirmoradi and Ehrlich, 2017; Liu et al., 2017; Portelinha and Zornberg, 2017; Vahedifard et al., 2017; Weerasekara et al., 2017; Zheng and Fox, 2017), and the lateral earth pressure coefficient K_r is generally different for different reinforcement layers in a GRS retaining wall.

To improve the prediction of reinforcement loads under working stress conditions, a few non-conventional analysis methods were proposed (Ehrlich and Mitchell, 1994; Allen et al., 2003; Bathurst et al., 2008; Liu and Won, 2014; Ehrlich and Mirmoradi, 2016; Liu, 2016a; Liu et al., 2017). Among these methods, the K-stiffness method (Allen et al., 2003; Bathurst et al., 2008; Allen and Bathurst, 2015) is an empirical method based on the statistical regression analysis of a large number of measured data. It takes into account the influence of reinforcement stiffness, facing batter, facing stiffness, and soil strength by a series of influence factors, which are employed to modify the coefficient K_r in Eq. (1). As a statistical method, the K-stiffness method does not explicitly address the interaction mechanisms among the components of a GRS retaining wall, including the backfill soil, the reinforcement layers, and the facing elements, which have led to some questions on its

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reliability (Leshchinsky, 2009; Leshchinsky and Vahedifard, 2012).

In contrast, some analytical methods attempted to address the interaction mechanisms explicitly. The EM method was first proposed by Ehrlich and Mitchell (1994) and then simplified by Ehrlich and Mirmoradi (2016). It emphasizes the importance of backfill-compaction effect and takes into account the compatible deformations between soil and reinforcement. The hyperbolic stress-strain relationship (Duncan et al., 1980) assuming a constant Poisson's ratio is employed to describe the nonlinear behavior of soil under working stress condition.

The concept of compatible soil-reinforcement deformations was also used in the analytical methods proposed by Liu and Won (2014), Liu (2015), Liu (2016a, 2016b), and Liu et al. (2017), which employ the Rowe's dilatancy theory (Rowe, 1962) or a variable Poisson's ratio (Liu and Yang, 2016) to describe the lateral soil deformation, respectively. However, in these analytical methods, incremental analysis is required to obtain the reinforcement loads in a GRS retaining wall.

In this study, based on the incremental methods by Liu (2016a) and Liu and Won (2014), two approaches to determine the earth pressure coefficient in Eq. (1) are proposed, which eliminate the necessity for incremental analysis. The proposed methods result in two implicit functions of the lateral earth pressure coefficient for a reinforcement layer at which the vertical soil stress is σ_z. Modifications of the earth pressure coefficients to take into account the compaction effect (Liu, 2016a) and the facing restriction effect (Liu et al., 2017) are also proposed. The proposed methods, which were validated by the results from numerical simulations and large-scale tests, are more convenient and intuitive compared with the incremental methods. Only the final state of the reinforced soil element at the end of construction (vertical soil stress σ_z, reinforcement stiffness J and parameters of soil) are needed, which eliminates the necessity to carry out a step-by-step incremental analysis.

2. Assumptions

In the proposed methods, assumptions are made as follows:

a) Reinforced soil retaining walls are assumed to be in a plane-strain condition.
b) Reinforced soil retaining walls are assumed to have vertical facing elements.
c) Reinforcement layers remain in a horizontal position under working stress conditions.
d) The vertical earth pressure σ_z and lateral earth pressure σ_l are considered as the major and minor principal stresses of the soil element, respectively.
e) The maximum load in each reinforcement layer occurs at the location of the potential failure surface, at which the deformations between the soil and reinforcement are compatible (Liu and Won, 2014).

3. Earth pressure coefficients without facing restraint and compaction effect

3.1. Nonlinear elastic approach – Method I

As shown in Fig. 1, at the intersection between the ith reinforcement layer and the potential failure surface, the lateral earth pressure coefficient K_{r0} without facing restraint and compaction effect is determined by the stiffness of the backfill soil as well as that of the reinforcement (Liu, 2016a). The stress conditions of this reinforced soil element are shown in Fig. 2, in which the vertical soil stress is σ_z, and the corresponding lateral soil stress is σ_l. σ_l could be expressed as:

$$\sigma_l = K_{r0}\sigma_z \tag{2}$$

The lateral earth pressure coefficient K_{r0} is obtained by the following derivation process. It is now assumed that the vertical soil stress is increased to $\sigma_z + \Delta\sigma_z$, in which $\Delta\sigma_z$ is a virtual stress increment with very small magnitude. The numerical value of K_{r0} would vary only very slightly with $\Delta\sigma_z$. That is to say, $\frac{\sigma_l+\Delta\sigma_l}{\sigma_z+\Delta\sigma_z} = K_{r0}$ is still valid. $\Delta\sigma_z$ is a virtual vertical soil stress increment which is used to establish the relationship with incremental methods (Liu and Won, 2014; Liu, 2016a) and will be cancelled out in the derivation process.

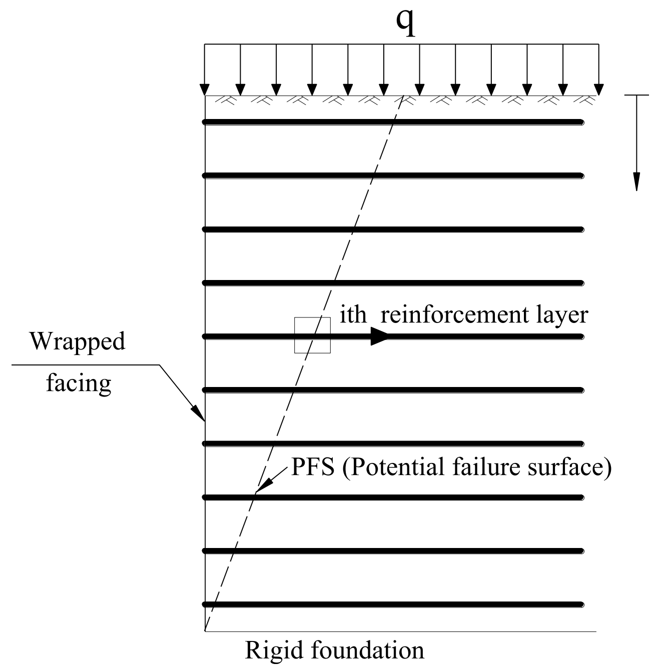

Fig. 1. Wrapped-face reinforced soil retaining wall with surcharge loading.

According to the force equilibrium and the assumption that $\frac{\sigma_l+\Delta\sigma_l}{\sigma_z+\Delta\sigma_z} = K_{r0}$, the increased reinforcement load can thus be expressed as:

$$\Delta T = K_{r0}S_v\Delta\sigma_z \tag{3a}$$

Under working stress condition, the compatible deformations between soil and reinforcement are still valid with the virtual soil stress $\Delta\sigma_z$ (Liu and Won, 2014). According to Liu (2016a) the increased reinforcement load can thus be written as:

$$\Delta T = J\Delta\varepsilon_r = \frac{J\mu_t(1+\mu_t)\Delta\sigma_z}{(1-\mu_t^2)J/S_v + E_t} \tag{3b}$$

In which J = reinforcement stiffness, $\Delta\varepsilon_r$ = increased reinforcement strain, μ_t = tangential Poisson's ratio of the backfill soil, and E_t = tangential Young's modulus of the backfill soil.

According to Duncan et al. (1980) and combined with Eq. (2), E_t can be written as a function of K_{r0} and σ_z as:

$$E_t = kp_a\left(\frac{K_{r0}\sigma_z}{p_a}\right)^n\left[1 - R_f\frac{(\sigma_z - K_{r0}\sigma_z)(1-\sin\varphi)}{2c\cos\varphi + 2K_{r0}\sigma_z\sin\varphi}\right]^2 \tag{4}$$

In which c = soil cohesion, φ = internal friction angle of the backfill soil, p_a = atmospheric pressure, k = modulus number, R_f = failure ratio, and$n$ = modulus exponent. The tangential Poisson's ratio μ_t can also be expressed as a function of K_{r0} and σ_z

$$\mu_t = 0.5 - \frac{E_t}{6B} \tag{5}$$

In which the bulk modulus B of the backfill soil would be obtained as (Duncan et al., 1980; Boscardin et al., 1990)

$$B = k_b p_a\left(\frac{K_{r0}\sigma_z}{p_a}\right)^m \tag{6a}$$

or