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Simplified analytical solution for geosynthetic tube resting on deformable foundation soil

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ABSTRACT

When geosynthetic tubes are placed on soft ground, the ground settlement can be large enough to influence the design and performance of geosynthetic tubes. The existing method to model the ground deformation for the design of geosynthetic tubes is to use the Winkler model. In this paper, an analytical solution is proposed to calculate the impermeable geosynthetic tubes resting on deformable foundation soil. The proposed analytical method adopts the 1-D consolidation relationship (the $e - \log p$ curve) to describe approximately the stress–strain behavior of the soil. The vertical surcharge pressure distribution within the soil mass is calculated using the Boussinesq solution. The numerical analyses are also carried out using FLAC to evaluate the accuracy of the proposed method. The results from the analytical method agree well with those from the numerical analysis.

1. Introduction

Geosynthetic tubes have been widely used for coastal protection, dike construction, flood control and waste sludge dewatering in many countries (Leshchinsky et al., 1996; Saathoff et al., 2007; Katoh et al., 1994; Lee, 2009; Yan and Chu, 2010; Shin and Oh, 2007; Yee and Lawson, 2012; Yee et al., 2012). Sometimes, the geosynthetic tubes have to be placed on soft ground. In these cases, the ground settlement will influence the performance of the structures made by the geosynthetic tubes. So far, most of the methods for the design and calculation of the geosynthetic tubes assume the foundation soil is rigid (Leshchinsky et al., 1996; Plaut and Suherman, 1998; Cantré and Saathoff, 2011; Yan and Chu, 2010; Chu et al., 2011; Malik and Sysala, 2011; Plaut and Stephens, 2012; Guo et al., 2014a,b). The only method to analyze the geosynthetic tube by considering the deformation of soft ground is to use the Winkler model (Plaut and Suherman, 1998; Plaut and Klusman, 1999; Guo et al., 2011). However, the Winkler model has the following limitations: 1) it is hard to determine the stiffness of subgrade reaction from laboratory tests; 2) it is unable to model the nonlinear deformation of soil; and 3) it is unable to consider the variation of surcharge pressure within the soil mass. A more suitable analytical method for analysis of geosynthetic tubes resting on deformable foundation needs to be developed.

In this paper, the 1-D consolidation curve or the $e - \log p$ method is adopted to analyze the deformation of soft ground. The vertical surcharge pressure distributed within the soil mass is calculated using the Boussinesq solution. The external water levels on both sides of the geosynthetic tubes are considered. 2-D finite difference computer program, FLAC (Itasca Consulting Group, 2000), was adopted to verify the analytical solutions. Parametric studies were carried out to investigate the effect of key soil parameters. The application of the proposed analytical methods is confined to either impervious geosynthetic tubes resting on deformable foundation or permeable geosynthetic tubes at the time right after inflated by assuming consolidation during filling process can be ignored. For external water level, the proposed method can only consider the case when the water level on both sides of the geosynthetic tube is the same.

2. Analytical method

The following assumptions are made for the derivation of the analytical solution: (1) the geosynthetic tube is sufficiently long to be assumed as a plane strain problem; (2) the geosynthetic shell is thin and its weight can be neglected; (3) the extension of the flexible geosynthetic sheet was not considered; (4) frictions

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between the geosynthetic tube and the fill material, or that between the geosynthetic tube and the foundation are neglected; (5) the geosynthetic tube is inflated with the same type of material; and (6) the deformation of soil foundation is only along the vertical direction (i.e., 1-D settlement).

As the geometry is symmetric, a free body diagram of half of the cross-section of a geosynthetic tube is analyzed as shown in Fig. 1(a). The geosynthetic tube is assumed to be inflated with only one type of slurry material with a unit weight of γ. The coordinates are set up with x in the horizontal direction and y in the vertical direction. The origin of the coordinates is taken as the bottom of the cross-section shown as point O (0, 0) in Fig. 1(a). For the notations, the width of the cross-section is B, the height of the geosynthetic tube above the ground surface is H, the settlement of geosynthetic tube below the ground surface is H_f, and the contact width with ground surface is b. The circumferential tensile stress per unit width along the cross-section is denoted as $T(x, y)$ which is a function of the coordinate. In order to simplify the expression in the equations, the circumferential tensile force $T(x, y)$ is written as T in the following discussions.

The force equilibrium diagram for an infinite unit of the tube with a length ds at an arbitrary point $S(x, y)$ is shown in Fig. 1(b). Assuming the angle between the tangential direction and the axis horizontal x is θ, then two geometrical equations can be written as Eqs. (1) and (2). An external water level with a height of H_w can be also considered if the water level on both sides are the same. In this case, the hydraulic water pressure acting at point $S(x, y)$ is $\gamma_w (H_w - y)$ where y is its y-coordinate and γ_w is the unit weight of external water. The pressure acting internally by the fill at point $S(x, y)$ is $\gamma (H - y)$. Then the net hydraulic water pressure, p_w, acting at point $S(x, y)$ can be calculated as $p_w = \gamma_w (H_w - y)$ for $y < H_w$ and $p_w = 0$ for $y \geq H_w$. By denoting the stress increase in the circumferential tensile stress as dT and the reaction pressure of the soil as p_f', the force equilibrium equations along the normal and tangential directions can be written as Eqs. (3) and (4):

$$\frac{dy}{ds} = \sin\theta \tag{1}$$

$$\frac{dx}{ds} = \cos\theta \tag{2}$$

$$\frac{dT}{ds} = \alpha p_f' \sin\theta \tag{3}$$

$$\frac{d\theta}{ds} = \frac{1}{T}\left(p_0 + \gamma(H - y) - p_w - \alpha p_f' \cos\theta\right) \tag{4}$$

where α is a non-dimensional parameter, $\alpha = 1.0$ for $y \geq 0.0$, and $\alpha = 0$ for $y < 0.0$.

To calculate the reaction of the soil, the foundation soil is divided into a number of vertical slices as shown in Fig. 1(b). Assuming that the soil in each vertical slice deforms independently. Under a surcharge pressure, p_f', the additional vertical stress in the soil mass is calculated using the Boussinesq equation (Das, 2008):

$$\Delta\sigma_{zj} = \frac{2p_f}{\pi}\frac{1}{-y_j} \tag{5}$$

in which $\Delta\sigma_{zj}$ is the additional vertical pressure on the jth soil layer due to the load of the geosynthetic tube and y_j is y-coordinated of the central point (the negative sign indicates the position is below the origin). It should be pointed out that the magnitude of $\Delta\sigma_{zj}$ calculated by using Eq. (5) will be infinite when y_j trends to zero. This is not the case. Thus, $\Delta\sigma_{zj} = p_f$ when $\Delta\sigma_{zj} > p_f$ is used in this derivation. Each slice is divided into N layers, $j \leq N$. The total settlement of each soil layer, S_c, is calculated as follows:

$$S_c = \sum_{j=1}^{N} \Delta S_{cj} \tag{6}$$

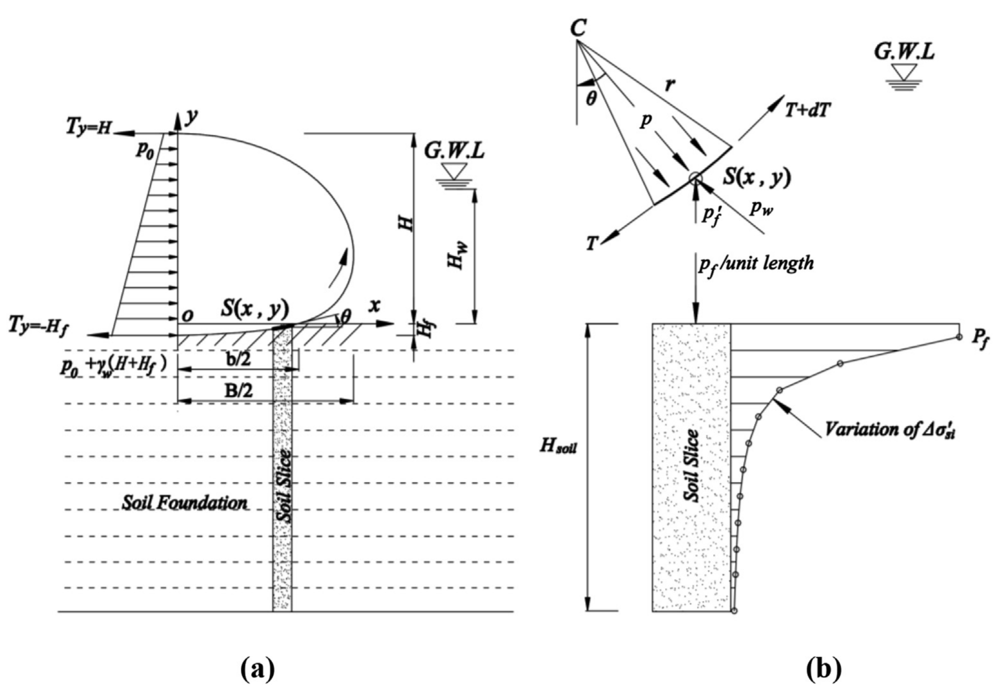

Fig. 1. Free body diagram (a) for half of a geotextile tube along a cross-section; (b) for an infinite unit.