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Deformation analysis of a geosynthetic material subjected to two adjacent voids

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ABSTRACT

This paper presents a new model for analyzing the behavior of geosynthetic material subjected to two adjacent voids. A simplified form of interface friction generated between geosynthetic materials and soil is examined to facilitate the development of an analytical model, and the effectiveness of the model is discussed. A field test and numerical analysis are also introduced to verify the analytical model. Based on the developed model, the coupling effect generated by two adjacent voids and the influence of several geometric and material parameters on the behavior of geosynthetic materials are investigated to develop a deeper understanding of this issue. The limitations of the model are discussed, and practical recommendations and conclusions on means of controlling geosynthetic tension and strain above two adjacent voids are presented.

1. Introduction

In landfills, geosynthetics compose part of the liner system, which is a hydraulic barrier that protects foundational soil and ground water from leachate contamination (Cazaux and Didier, 2000; Bouazza, 2002; Rowe et al., 2004; Rowe, 2005; Jaisi et al., 2005; Benson et al., 2010; Rowe 2012; Hornsey and Wishaw, 2012; Narejo, 2013). In embankments, geosynthetics are used as components of the geotechnical structure that supports the embankment soils (Mandal and Joshi, 1996; Hinchberger and Rowe, 2003; Rowe and Li, 2005; Villard and Briançon, 2008; Zhang et al., 2013). However, voids (localized subsidence, crack, sinkholes, etc.) are commonly encountered under geosynthetics and are difficult to predict with practical engineering. Several cases of geosynthetic materials with voids have been reported in both the international literature and the media. Localized voids may develop in landfills with the collapse of large, hollow objects (e.g., household refrigerators or large furniture items) or when waste in old landfills is poorly compacted when a new liner system is placed over the top of the old landfill during a landfill vertical expansion project (Spikula, 1997; Kuo et al., 2005). Similarly, sinkholes are often encountered in karst terrain during and after the construction of engineered embankments (Briançon and Villard, 2008; Galve et al., 2012; Ponomaryov and Zolotozubov, 2014). In fact, the existence of underground voids renders the use of geosynthetics dangerous, as these materials can undergo substantial changes in stress and strain levels when suspended over voids; substantial tensile stress and strain can be produced within geosynthetics subjected to the weight of the overlying soil. Once the tensile capacity of geosynthetics is exceeded, tension cracking or failure can occur, thereby compromising the effectiveness of the materials.

Consequently, problems arising from the exposure of geosynthetics to voids or sinkholes have been studied extensively by several scholars. Giroud et al. (1990) computed the overlying pressure and tensile strain levels within a geosynthetic layer utilizing soil arching theory and tensioned membrane theory, respectively, thereby determining geosynthetic shape and surface settlement values based on geosynthetic stiffness and cavity size. The authors assumed that the geosynthetic material is fixed at the edge of the cavity and that the geosynthetic strain in the subsidence area remains constant. Given these assumptions, however, the actual bearing conditions and mechanical behavior of the geosynthetic layer cannot be reliably described. Assuming a parabolic-shaped subsidence of the geosynthetic material without slippage outside of the cavity, Bridle and Jenner (1997) developed a design

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method by establishing a series of mechanical equilibrium equations. Villard and Briançon (2008) considered the displacement effect of geosynthetic stretching in anchorage areas and developed an analytical solution to calculate tension and strain levels within a geosynthetic sample. These authors then conducted an interesting full-scale field test, in which a sinkhole was formed through the deflation of two balloons in a trench, to verify the method. Based on soil arching and tensioned membrane theories, Chen et al. (2008b) divided a geosynthetic sample into slide and subsidence zones and established an analytical model in which an iterative calculation is carried out to determine geosynthetic stress and displacement levels. Moreover, numerical models have been established to analyze the mechanical behaviors of a geosynthetic material subjected to local sinkholes (Finley and Holtz, 2001; Wang et al., 2009; Huang and Han, 2010). In addition, LaGatta et al. (1997) compared the resistance levels of various geosynthetic materials against non-uniform settlements.

As indicated above, the existing analytical methods for analyzing the behavior of geosynthetics are only suitable for studies that involve a single underlying void. Unfortunately, situations in which more than one void is present have been reported in practical engineering, especially in relation to drilled shaft-supported embankments (Wang et al., 2009; Zheng et al., 2009). When narrowly distributed or situated adjacent to one another, voids will complicate the bearing conditions of geosynthetic materials and thereby obstruct reliable evaluations of the serviceability of these materials. Furthermore, analyses of geosynthetic sheets will be complicated by the coupling effect produced by these voids to the point where traditional methods are no longer applicable.

A simplified analytical model, incorporating several assumptions, for evaluating geosynthetic tension and strain over two adjacent voids is proposed in this paper. A field test and numerical study were introduced to validate the effectiveness of the analytical model. Based on this model, the coupling effect of two adjacent voids and the influence of several geometrical and material parameters on geosynthetic tension, stress, and strain were investigated to develop a deeper understanding of this phenomenon.

2. Plane-strain analytical model

The analytical model is based on the research of Villard and Briançon (2008), which focuses on the behaviors of geosynthetics subjected to a single void. The load applied to the geosynthetic material was determined in consideration of the soil arching effect. Interface frictional forces between the geosynthetic material and soil were simplified due to the complexities and diversity of actual situations analyzed using previous methods. Several assumptions were made in constructing this model:

1. The plane-strain model was adopted under the assumption that higher degrees of geosynthetic deformation and slippage occur in the direction of the line connecting the two void centers. The model should in fact be built in three dimensions, and this assumption therefore deviates from the actual situation. Although there are some differences between this model and the conditions encountered in actual engineering, the results and conclusions produced by the model are still helpful in analyzing the behaviors of geosynthetics subjected to two adjacent voids.
2. The vertical load per unit length that acts on the geosynthetic material above the void is uniformly distributed.
3. The behavior of the geosynthetic material is assumed to be linear elastic.
4. The soil under the geosynthetic material is assumed to be non-deformable.

2.1. Geosynthetic behavior in the subsidence area above a single void

In a study by Villard and Briançon (2008), a geosynthetic material positioned above a single void was divided into slide and subsidence areas (Fig. 1). In the subsidence area, the increase in geosynthetic length, Δl_1, for half of the void could be expressed in two different forms, as is shown in Eq. (1):

$$\Delta l_1 = \int \mathrm{d}s - \frac{l_1}{2} = U_A + \int \varepsilon_Q \,\mathrm{d}s \tag{1}$$

where l_1 is the width of the void, $\int \mathrm{d}s$ is the length of geosynthetic deformation curve s; U_A is the displacement of point A located on the geosynthetic at the edge of the subsidence area; and ε_Q is the strain of point Q located above of the geosynthetic in the subsidence area.

After including geometrical and physical relationships, Eq. (1) becomes:

$$\frac{l_1}{4\beta_1}\left(\beta_1\sqrt{1+\beta_1^2}+\mathrm{argsh}\,\beta_1\right)-\frac{l_1}{2}=U_A+p_\mathrm{v} l_1^2\frac{3+\beta_1^2}{12\beta_1 J} \tag{2}$$

where β_1 is the tangent value of λ_1, which is defined as the angle of geosynthetic diversion at the edge of the subsidence area; argsh (or arsinh) is the arc-hyperbolic sine function; p_v is the vertically distributed load imposed on the geosynthetic material; and J is the geosynthetic tensile stiffness.

However, Eq. (1) requires symmetrical conditions. If the load applied on the left side of the void differs from the load applied on the right side of the void (i.e., p_OL is not equal to p_OR), Eq. (1) is not applicable and can be modified as follows:

$$\frac{l_1}{2\beta_1}\left(\beta_1\sqrt{1+\beta_1^2}+\mathrm{argsh}\,\beta_1\right)-l_1=U_A+U_B+p_\mathrm{v} l_1^2\frac{3+\beta_1^2}{6\beta_1 J} \tag{3}$$

where U_A is the displacement of point A located above the geosynthetic at the edge of the subsidence area, U_B is the displacement of point B located above the geosynthetic at the edge of the subsidence area, and the other terms are as defined above (Fig. 1).

The change in geosynthetic orientation that occurs at the edge of the void (Fig. 2) will lead to a decrease in the tensile force of the geosynthetic sheet ($T_A < T_{A\max}$).

The relation between T_A and $T_{A\max}$ (algebraic values) based on the equilibrium limit of a geosynthetic material resting on a circular arc (Villard and Briançon, 2008) is given by Eq. (4):

$$T_A = T_{A\max}\Big/e^{k\varphi_A \tan\phi_\mathrm{lower}} = T_{A\max}\Big/e^{k\arctan\beta_1\tan\phi_\mathrm{lower}} \tag{4}$$

where φ_A is the angle of the change in direction ($\varphi_A = \arctan\beta_1$); ϕ_lower is the peak friction angle at the interface between the geosynthetic sheet and the underlying soil; k is the interface friction coefficient, with $k = 1$ when the interface friction is fully mobilized; and the remaining terms are as defined above.

2.2. Load imposed on the geosynthetic sheet

In the presence of local subsidence or voids, soils overlying the subsidence area will warp in a similar way as the geosynthetic sheet. As a result, soil arching (Terzaghi, 1943; Handy, 1985; Mckelvey, 1994; Van Eekelen et al., 2013) may occur, which leads to a decline in soil pressure on the geosynthetic sheet. Giroud et al. (1990) produced Eq. (5) for calculating load pressure imposed on a geosynthetic sheet positioned over a void: