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# An analytical method for predicting load acting on geosynthetic overlying voids

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A B S T R A C T

Soil arching often occurs in geosynthetic-reinforced structures, where the underlying soil has voids, resulting in load transmission from the subsided area to surrounding less deformed area. A new method is proposed to predict load acting on gensynthetic overlying voids. The shape of soil arch and stress states of all the points at the soil arch can be obtained by combining nonlinear M-C yielding criterion, non-associated flow rule with static equilibrium of segmental arch through a dilatancy coefficient. The load applied to the geosynthetic can be determined by load transmission from the overlying soil, to the soil arch, and onto the collapsed soil. The model is verified using a model test conducted by Zhu et al. (2012), the soil pressure acting on the deflected geosynthetic is reasonably predicted. Due to the inherent nonlinear behaviour of soil, nonlinear failure criterion can better describe the stresses and deformations of the soil and geosynthetic. Soil nonlinearity has significant influence on the evaluation of arching effect. Ignoring the nonlinear behaviour of soil tends to underestimate the soil pressure acting on the geosynthetic. There exists an optimal subsidence width for which the soil pressure acting on the geosynthetic is minimal. The method used in this study is more appropriate where a large deflection occurs in the geosynthetic and provides a novel approach to evaluating soil arching under these conditions.



## 1. Introduction

Soil arching often occurs in geosynthetic-reinforced structures (e.g., liners in landfills, pile-supported embankment) where the underlying soil has voids, resulting in load transmission from the subsided zone to the surrounding less-deformed zone. Evaluation of it directly affects the design of geosynthetic for reinforcement (e.g., Giroud et al., 1990; Han and Gabr, 2002; Briançon and Villard, 2008; Abusharar et al., 2009; Zhu et al., 2012; Feng and Lu, 2015; Zhang et al., 2015). For example, deflection or even rupture may occur in geosynthetic when the arching effect is overestimated. Conversely, an underestimation of the soil arching effect overvalues the load applied to the geosynthetic and then stronger geosynthetic is required. Therefore, it is of importance to accurately predict the load acting on geosynthetic overlying voids.

To calculate the distributed vertical load acting on the geosynthetic, BS8006 (2010) originally proposed empirical equations for arching coefficient. But the applicability of the semi-empirical method is limited to specific situations and the prediction tends to be conservative. Analytical solutions were also proposed for predicting the load acting on the geosynthetic. For quantifying the transferred load by shear stress, the overlying soil is assumed to slide along vertical planes on both sides of the subsided area (Terzaghi, 1943). Based on the assumption, the lateral pressure coefficient and height of the soil arch are continuously amended to match the real value. These values would be different for different geotechnical engineering problems (Terzaghi, 1943; Giroud et al., 1990; Villard et al., 2000; Aubertin et al., 2003; Chen et al., 2010; Lu and Miao, 2015). In order to better describe the shape of soil arch, the collapsed soil is assumed to form wedge-shaped (Rogbeck et al., 2003) or hemispheric or hemicycle arch (Hewlett and Randolph, 1988; Low et al., 1994; Chen et al., 2004; Kempfert et al., 2004; Van Eekelen et al., 2013). To simplify the calculation, it is assumed that there is no exterior stress applied to arch and only soil element at the crown or foot of the hemispheric or hemicycle arch reaches the limit state.

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However, the real scope of soil arch is governed by the properties of soil and geosynthetic, void size and loading conditions, and is unknown before analysis. Recent studies (Chevalier et al., 2007; Costa et al., 2009; Eskişar et al., 2012; Rui et al., 2016a, 2016b) have also shown that the shape and height of the generated arch in overlying soil would change as subsidence width or depth increases. Then the simplified conditions or assumptions adopted by the aforementioned methods cannot accurately account for the load changes induced by the shear stress on the true failure surface (i.e., soil arch), which can cause deflection error of the geosynthetic reinforcement. Such behaviour can lead to increasing risk of reinforcement failure or likelihood of material waste. Therefore, a new method for accurately predicting stresses and deformations surrounding the soil arch and geosynthetic is desirable.

The objective of this study is to develop a method for precisely determining the shape of soil arch and the load acting on the geosynthetic overlying voids. The analytical model is introduced in Section 2, including basic assumptions, load transfer mechanism of the soil arch, limit equilibrium of the soil arch, and membrane effect of the geosynthetic. In Section 3, the method is verified using a model test. In Section 4, the model is applied to study the influence of properties of soil and geosynthetic, and subsidence width on arch shape, stress state and deformation of the soil and geosynthetic.

## 2. Analytical model

A geosynthetic-reinforced structure consists of overlying soil, geosynthetic and underlying soil. Local subsidence in the soil substratum results in the occurrence of soil arching in the overlying soil. The geosynthetic reinforcement is placed at the foot of the soil arch. The structure after subsidence is schematically shown in Fig. 1. Some assumptions are made to develop the analytical model:

(1) The structure is analyzed using the plane strain model; the overlying and underlying soils are idealized to be uniform and isotropic; the behaviour of the geosynthetic is assumed to be linear elastic;
(2) The pore water in the overlying soil is not considered in the analysis;
(3) The analyzed soil arch is deemed to be at the quiescent state after subsidence; the same soil is set up on the geosynthetic;
(4) The sinking soil below the geosynthetic has no support for the geosynthetic.

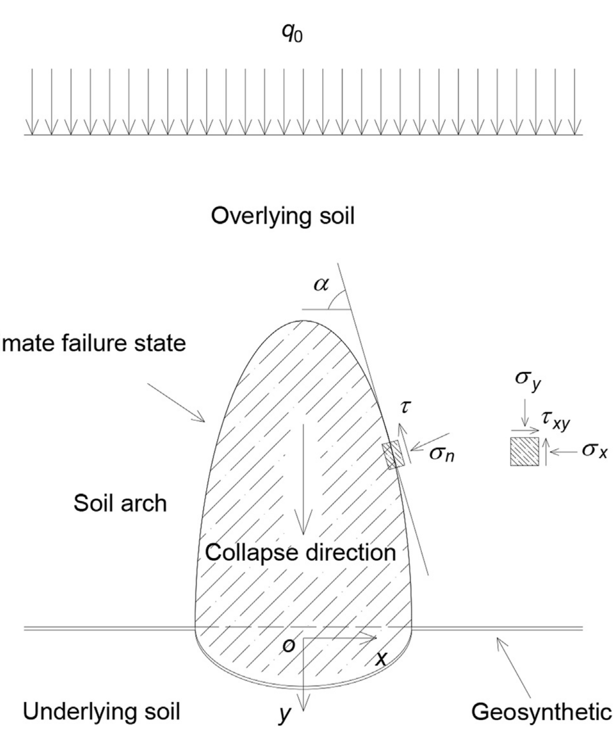


**Fig. 1.** Schematic diagram of the geosynthetic-reinforced structure after subsidence.

Modeling geosynthetic-reinforced structure overlying voids comprises study of soil arching effect, equilibrium analysis of soil arch, and force analysis of geosynthetic. Arch shape and stress state can be coupled together through the coefficient of dilatancy. The soil arch is used to transfer a large proportion of the load to the underlying soil and a small proportion of the load to the soil inside the arch. The load acting on the geosynthetic resting on voids can be obtained by the soil inside the arch. It is noteworthy that the proposed method cannot be applied to cases with surface subsidence or wherein the height of soil arch is greater than the thickness of overlying soil.

### 2.1. Load transfer mechanism of the soil arch

In order to estimate the soil arching effect, it is necessary to determine the shape and load of the soil arch (Fig. 1). The arch shape is the critical failure surface in the overlying soil after subsidence. Linear M-C failure criterion is widely used in the limit analysis of such problems (Hewlett and Randolph, 1988; Low et al., 1994; Fraldi and Guarracino, 2010; Lu and Miao, 2015). The yield surfaces for the linear criterion have a linear form in the principal stress space for plane strain problems, which makes it possible to accurately predict failure mechanisms for geotechnical structures (e.g., critical slip surface search problems). However, a substantial amount of experimental evidence suggests that the strength envelope of geomaterials exhibits nonlinearity (Hoek, 1983; Agar et al., 1985; Maksimovic, 1989; Baker, 2004; Anyaegbunam, 2013). And the shear dilatancy of the soil near the failure surface determined by combining the linear M-C yield condition and associated flow rule is overestimated (Mandel and Luque, 1970; Kabilamany and Ishihara, 1990). To get a more reasonable arch shape, a nonlinear M-C failure criterion (Fig. 2) is applied and can be expressed as follows:

$$\tau = c_0\left(1+\frac{\sigma_n}{\sigma_t}\right)^{\frac{1}{m}} \tag{1}$$

where $c_0$ and $m$ are the dimensionless parameters characterizing the overlying soil; $\sigma_n$ and $\sigma_t$ are the compressive and tensile stresses at failure, respectively.

In the limit analysis, the plastic normal strain rate, $\dot{\varepsilon}_n^p$, and plastic shear strain rate, $\dot{\gamma}^p$, are parallel to the corresponding stresses and have the following relation:

$$\frac{\dot{\varepsilon}_n^p}{\dot{\gamma}^p} = \frac{\partial F}{\partial \sigma_n}\bigg/\frac{\partial F}{\partial \tau} = -\tan\varphi \tag{2}$$

where the yield function, $F$, is the same as the plastic potential function, $G$, and the angle of dilatancy, $\psi$, is equal to $\varphi$ for the associated flow rule. In this paper, the non-associated flow rule is adopted; namely $F \neq G$ and $\psi \neq \varphi$ (Fig. 2). Additionally, their relationships are assumed to be as follows:

$$\tan\psi = k\tan\varphi \tag{3}$$

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