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Research Paper

# Estimation of arching effect in geosynthetic-reinforced structures

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ABSTRACT

An analytical method is proposed to estimate arching effect in geosynthetic-reinforced structures. The method integratedly considers the stresses and deformations of soils and geosynthetics, and variation of settlement with depth in overlying soil. The stresses and deformations of soil and geosynthetics can be obtained considering equilibrium and settlement models of overlying soil, membrane effect of geosynthetics, and one-dimensional compression model of underlying soil. The method is verified using a field test, the stress reduction ratio (*SRR*) is precisely estimated. The results of parametric study indicate that the method has extensive applicability and is helpful for rational design of geosynthetic-reinforced structures.



## 1. Introduction

Soil arching often occurs in geosynthetic-reinforced structures (e.g., liners in landfills or piled embankments) where subsoil may have differential settlement, sinkholes due to karstic collapse, soil dissolution, fissures and cracks, and localized subsidence [1,2]. As soil arching develops, load transmission (i.e., stress redistribution) occurs, which reduces the load over the deflected geosynthetic reinforcements but increases the load over the surrounding areas with less deformation. This behavior has both advantages and disadvantages. For example, during the failure of Teton dam, the stress reduction caused by soil arching promoted further hydraulic fracturing at the interface with the stiff adjacent fill [3]. Conversely, due to soil arching, bearing capacity of piles and soils between them can be fully utilized by means of geosynthetic reinforcement [4,5]. Therefore, it is essential to have a better understanding of the load transfer mechanism in soil arching for rational design of geosynthetic-reinforced structures.

Although numerous methods are currently available for predicting stress redistribution by soil arching, none has been commonly agreed upon as the optimal. Marston [6] originally alluded to a critical-height arch in granular material and determined vertical stress based on the limiting balance principle. To expand its applicability to geosynthetic-reinforced structures, Terzaghi [7] imagined an infinitely high soil arch in which lateral load transfer is achieved through shear stresses along vertical planes located at the edges of the subsidence area. Hewlett and Randolph [8] then suggested a semi-spherical arch based on a model test and assumed that the soil element at the crown or the pile cap reaches the ultimate state. And based on this, Chen et al. [9] used reduction coefficient of tangential stress to consider the gravity balance of embankment filling above an equivalent area for one pile. Additionally, Low et al. [10] introduced a reduction factor to allow for the non-uniformity of vertical stress on soft ground based on the method proposed by Hewlett and Randolph [8]. All the above methods adopt a fixed scope of soil arching for estimating the arching effect, such as hemispheric or hemicycle arch. These methods are suitable for geosynthetic-reinforced structures with low height of overlying soil (e.g., piled embankments), in which the scope of soil arching and soil deformation with depth do not change significantly. However, the results of trapdoor experiments indicate that the scope of soil arching changes with different subsidence displacements [11–15]. Thus, these methods are not suitable for other engineering aspects, such as liners in landfills.

Differently, Villard et al. [16] postulated a beforehand unknown scope of soil arching that is calculated considering the overall equilibrium of a half-soil arch. Later, Lu and Miao [17] proposed a simplified method by evaluating the soil-geosynthetic interaction based on the arching effect considering non-fully mobilized shear stress with the assumption of minor principal stress trajectory [18]. However, to simplify the solution, the authors adopted a constant lateral earth pressure coefficient, independent of depth. This means all the soil elements in the scope of soil arching have

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the same deflection, which obviously flies in the face of the real scenario [19,20]. Therefore, it is necessary to improve the accuracy of estimation of arching effect.

The primary objective of this study is to develop an analytical method to better predict the stress-redistribution of geosynthetic-reinforced structures, which has more extensive applicability and is only applicable for active arching. The analytical model is developed by coupling the stresses and deformations of soil and geosynthetics. The stresses and deformations are determined by the equilibrium and settlement models of overlying soil, the membrane effect of geosynthetics and the one-dimensional compression model of underlying soil. The method is verified using a field test. Finally, the influences of geometry and properties of the geosynthetic-reinforced structures on arching effect are analyzed using the proposed method.

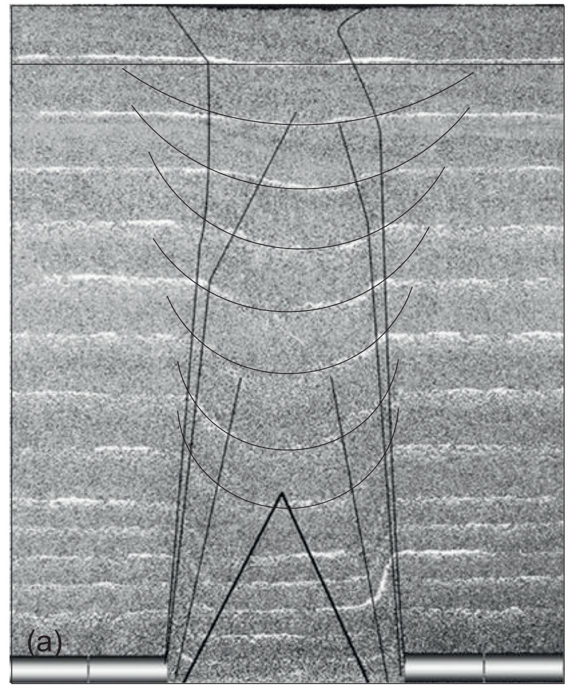
## 2. Analytical model

The analytical model is developed for estimating arching effect in geosynthetic-reinforced structures. Arching effect exists because of local subsidence of soil below geosynthetics, shown in Fig. 1. Deformation appears simultaneously in overlying soil, geosynthetics, and underlying soil. In Fig. 1, the soil affected by subsidence determines the geometry of soil arch. The soil arch causes the stress acting on the geosynthetics to be redistributed. To develop the analytical solution, some simplifications are made as follows:

(1) There is no disengagement between the overlying soil, the geosynthetics, and the underlying soil;
(2) The soil and geosynthethics are idealized to be uniform and isotropic;
(3) The friction between soil and geosynthetics is assumed to be zero;
(4) The structure is in the plane strain state;
(5) The pore water in the soils is not considered.

In this study, the deformed soil above the geosynthetics is assumed to slide along vertical planes located at the edges of subsidence area, which has been widely adopted (e.g., [1,7,16,17]. It has been pointed out that the arching effect can be approached based on the hypothesis of vertical planes [7] using an appropriate value for the coefficient of lateral earth pressure according to the full-scale experiment and numerical analysis [21,22]. All the points on the vertical planes are assumed to be in critical failure state. In the scope of soil arching, soil is divided into soil elements (Fig. 1b). The related geometry parameters are as follows: $\delta$ is the deformation in middle of a soil element; $\theta$ is the angle between tangential direction of the soil element at the edge and the vertical direction; $b$ is the width of subsidence area; $H$ is the height of overlying soil; $h_{arc}$ is the height of soil arch, which is unknown beforehand; $h_0$ is the height of soil unaffected by subsidence. The deformed soil element is depicted as a trajectory of minor principal stresses that approximates a catenary [18]. The model test conducted by Rui et al. [19] indicated that the deformation of soil elements gradually increases with depth (Fig. 1a). Thus, the stresses and deformations of all the soil elements should be analyzed.

Arching effect can be reflected by the mobilized shear stresses on the sliding surfaces after subsidence, which can be obtained by coupling the stresses and deformations of soil and geosynthetics. Therefore, estimation of arching effect can be achieved by three steps: (1) analyzing the mobilized shear stress of soil arch, (2) evaluating the vertical stress and settlement of soil over the deflected geosynthetics, and (3) calculating forces and deformations of the geosynthetics and the underlying soil.



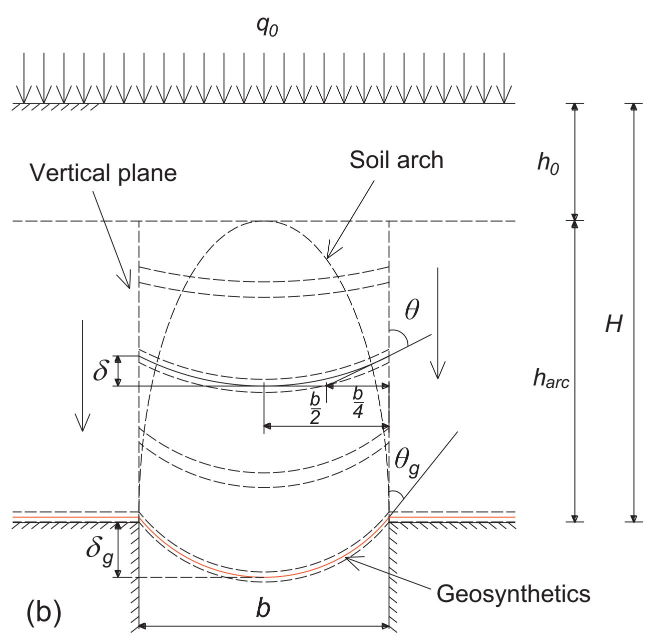




**Fig. 1.** Deformation of the overlying soil after subsidence: (a) model test [19]; (b) schematic diagram.

### 2.1. Mobilized shear stress

In order to estimate the arching effect, the mobilized shear stresses on the sliding surfaces must be determined first (Fig. 1). The soil elements in the scope of soil arching are analyzed. The shear stress acting on the vertical plane is related to its deformation and can be determined by the assumption of a trajectory of minor principal stresses. The deformation modes of soil elements are assumed to be the same as that of geosynthetics. The tangent at the edge of soil elements intersects the horizontal line at the midpoint of $b/2$ long [17,23], shown in Fig. 1b. Thus, the deformation in middle of the soil element, $\delta$, is correlated to $\theta$:

$$\tan\theta = \frac{b}{4\delta} \tag{1}$$