Computers and Geotechnics 65 (2015) 97–103

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

A simplified 2-D evaluation method of the arching effect for geosynthetic-reinforced and pile-supported embankments

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ARTICLE INFO

Article history:
Received 24 October 2012
Received in revised form 27 November 2014
Accepted 27 November 2014

Keywords:
Geosynthetic
Pile
Embankment
Arching effect
Critical arch height

ABSTRACT

The mechanical behavior of geosynthetic-reinforced and pile-supported (GRPS) embankments is under the influence of the soil arching effect. Several design methods have been proposed for estimating the magnitude of arching for GRPS embankments, but they are usually faced with two limitations: a pre-set constant critical arch height is assumed for the load calculation, and influences of the membrane effect of deflected geosynthetic and the resistance of compressible subsoil are poorly considered in supporting the embankment fill. To improve on these limitations, a new simplified method is presented for quantitatively evaluating the arching action, as well as the geosynthetic tension. During the derivation, the stress state and deformation condition within the arch rib can be coupled by mobilized shearing stress, which is correlated to the differential displacement between the pile (cap) and subsoil. Through comparative studies, it is found that the present method is validated as reasonable by field measurements and is in good agreement with several current design methods.

1. Introduction

Geosynthetic-reinforced and pile-supported (GRPS) embankment technology has wide application in many actual instrumented projects, including soft ground sites where new embankments are constructed or existing embankments are widened, due to their rapid construction, low costs, and small total and differential settlements compared to various other traditional soft soil improvement methods [2,20,12,21,10]. The interactions among embankment fill, piles (caps), geosynthetic and foundation soil can be schematically shown as in Fig. 1. Under the loading of fill weight and different stiffness between pile and subsoil, the inter-piles' (caps') fill mass has a tendency to yield downward but is resisted by the shearing stress along the potential slip plane between the stationary soil above the piles (caps) and the yielding parts. The shearing resistance reduces the pressure acting on the geosynthetic but increases the load on the piles (caps). This load transfer mechanism was termed the "Soil arching effect" by Terzaghi [30,31]. With the instrumented height of the embankment, the load distributed on the piles (caps) and on the subsoil should be correctly predicted when designing the pile space, length and diameter (or cap size), and it should minimize deflection of the soil between the piles (caps), as such deflection would be reflected to the embankment surface. Therefore, the key point is to quantitatively evaluate the soil arching effect that exists in GRPS embankments [24,8,14,18,22,17,27,7,6,4,29].

In arching theory, experimental and numerical analysis of piled embankments has demonstrated the existence of a plane of equal settlement, or a critical height (originally proposed by Marston [23]) in the arched fill mass. Numerous methods for estimating the arching effect have been proposed; they always utilize different pre-set critical heights in estimating the magnitude of arching, which are summarized in Table 1. For instance, Hewlett and Randolph [15] examined a piled embankment model in a sand box and broke the arch into two- and three-dimensional analysis, giving the former a critical height of 1.4 times the clear spacing between the piles (caps). In 1994, Low et al. [22] improved the calculation method such that the sand element critical state would be reached at the crown of the arch or just above the cap, but they still adopted the same critical height in the load calculation; BS8006 [3] also adopted a height of 1.4 times the clear spacing between piles (caps), but the calculated result is considered overly conservative by Kempton et al. and Love and Milligan [20,21]. Then, Abusharar et al. [1] presented a new method based on the method proposed by Low et al. [22]. They utilized the same pre-set critical height ratio and considered the influence of geo-reinforcement and

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http://dx.doi.org/10.1016/j.compgeo.2014.11.014
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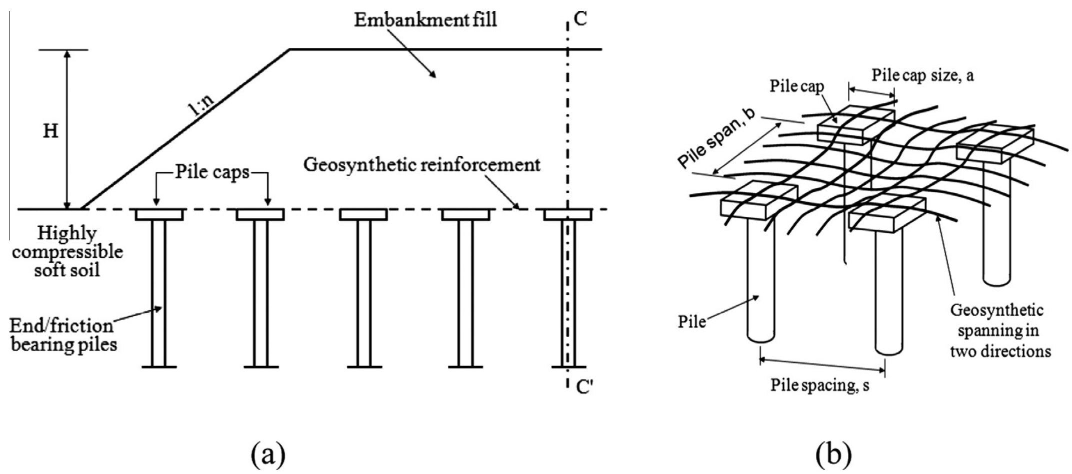

Fig. 1. (a) A section of a piled embankment and (b) the general layout of piles (caps) and reinforcements (after Kempton et al. [20]).

Table 1
Summary of the critical arch height for different methods.

Design method	Critical arch height, h_{arc}
Terzaghi [31]	2.5 $(S - a)$
Carlsson et al. (1987)	1.87 $(S - a)$
Guido et al. [11]	0.525 $(q_0 + \gamma H)$
Hewlett and Randolph [15]	1.4 $(S - a)$
Low et al. [22]	1.4 $(S - a)$
BS8006 [3]	1.4 $(S - a)$
Horgan and Sarsby [16]	(1.545–1.92) $(S - a)$
Russell et al. [28]	H (for ULS)
Kempfert et al. [19]	$S/2$
Nauthton [25]	(1.25–2.40) $(S - a)$
Abusharar et al. [1]	1.4 $(S - a)$

Note: S, pile space; γ, unit weight; q_0, equivalent live and dead load surcharge; a, cap size.

resistance from subsoil. Differently, Kempfert et al. [19] presented another design method on assumption of a critical height of half the pile spacing. However, in Naughton's [26] method, the critical height of the embankment varies from 1.24 to 2.40 times the clear space with increasing value of the angle of friction, φ_s^E, from 30° to 45°. Not only that, considerable studies into the area of soil arching have also been carried out, with the help of computer-based techniques (such as finite element methods) and information from actual instrumented projects. However, Gabr and Han [9] still argued that the effects of soil arching developed in GRPS embankments remained poorly understood, current design methods for such a system have not been well verified and that further studies must be performed. In this study, a new simplified method based on the arching effect is proposed and presented. The key improvement of this study is that the critical height of the soil arch is calculated, which is dependent on design parameters, and is not pre-assumed. In addition, the results of this method have been calibrated by field test results through an engineering case and compared with several current design methods.

2. Theoretical study

A GRPS embankment consists of piles installed through the unsuitable foundation soil. Caps are generally placed at the top of piles, and geosynthetic reinforcement is placed over the pile caps. The interactions among fill, piles (caps), and geosynthetic and foundation soil is schematically explained in Fig. 2. In developing the present method, the following simplifications are used:

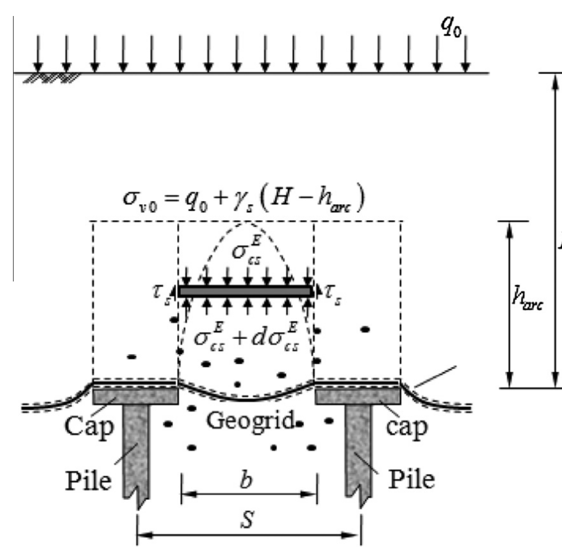

Fig. 2. Load transfer mechanisms of GRPS embankments and the arching effect.

(1) The embankment fill material and foundation soils are idealized to be uniform and isotropic; the plane strain state of two adjacent piles is adopted in analysis;
(2) The main tension of the geosynthetic reinforcement here is perpendicular to the road direction, and the membrane effect is simplified to be a uniformly upward stress due to deflection. There is no disengagement between geosynthetic reinforcement and the upper and lower fill materials;
(3) Support is given by the foundation soil to the yielding embankment fill and is assumed to be a uniform vertical upward resistance.

The theoretical study comprises the stress state analysis, the membrane effect assessment and the static equilibrium derivation of a half soil arch. Stress state and deformation can be coupled together in the calculation formula via the coefficient of lateral earth pressure modified from Handy's [14] proposed method.

2.1. Arching effect due to mobilized shearing stress

As realistically practiced in engineering, the embankment fill is compacted by layers, and the differential settlement between piles (caps) and compressible subsoil increases from zero to a limit