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An analytical model for arching in piled embankments☆

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ABSTRACT

Most analytical models for the design of piled embankments or load transfer platforms with geosynthetic reinforcement (GR) include two calculation steps. Step 1 calculates the arching behaviour in the fill and step 2 the load-deflection behaviour of the GR. A calculation method for step 2 based on the results of model tests has been published by Van Eekelen et al. (2012a,b). The present paper analyses and presents a new model for step 1, which is the arching step. Additional tests, which are also presented in this paper, were conducted for this purpose.

The new model is a limit-state equilibrium model with concentric arches. It is an extension of the models of Hewlett and Randolph (1988) and Zaeske (2001). The new model results in a better representation of the arching measured in the experiments than the other models mentioned, especially for relatively thin fills.

Introducing GR in a piled embankment results in a more efficient transfer of load to the piles in the form of an arching mechanism. The load is then exerted mainly on the piles and the GR strips between the piles, on which the load is approximately distributed as an inverse triangle. The new model presented in this paper describes this behaviour and is therefore meant to describe the situation with GR. The new model provides a physical explanation for observations of the arching mechanism, especially the load distribution on the GR. Other observations with which this model concurs are the dependency on fill height and friction angle. The amount of arching increases with increasing subsoil consolidation and GR deflection. The paper describes how the new model relates to the development of arching as a result of subsoil consolidation.

1. Introduction

Many analytical design models for the design of piled embankments include two calculation steps. The first step calculates the arching behaviour in the fill. This step divides the total vertical load into two parts: load part A, and the 'residual load' ($B + C$ in Fig. 1). Load part A, called 'arching A' in the present paper, is the part of the load that is transferred to the piles directly.

The second calculation step describes the load-deflection behaviour of the geosynthetic reinforcement (GR, see Fig. 1). In this calculation step, the 'residual load' is applied to the GR strip between each pair of adjacent piles and the GR strain is calculated. An implicit result of step 2 is that the 'residual load' is divided into a load part B which passes through the GR to the piles, and a part C resting on the subsoil, as indicated in Fig. 1.

Van Eekelen et al. (2012b) analysed and made proposals for calculation step 2. The present paper analyses and puts forward a new model for step 1, the arching step. Both papers compare the results with measurements from a model test series presented in the first part (Van Eekelen et al., 2012a) of this three-part study. These tests are particularly suitable for the validation of calculation steps 1 and 2 separately because A, B and C were measured separately. For the present paper, a number of additional tests were carried out with the same test set-up.

Several families of analytical models describing step 1 (arching) are available in the literature. Terzaghi (1943) listed a number of them. Current arching models comprise:

Rigid arch models, such as several Scandinavian models (Carlsson, 1987; Rogbeck et al., 1998, modified by Van Eekelen et al., 2003; Svanø et al., 2000) and the Enhanced Arching model (also called the Bush–Jenner model or the Collin, 2004 model) and the present design method of the Public Work

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Nomenclature

A	load part transferred directly to the pile ('arching A' in this paper) expressed as kN/pile = kN/unit cell, kN/pile
$A\%$	arching A presented as a percentage of the total load, $A\%$ is the same as the pile efficacy ("E") as used by several authors: $A\% = E = 1 - \frac{B+C}{A+B+C}$ or $A\% = E = \frac{A}{A+B+C} = \frac{A}{(\gamma H+p)\cdot s_x\cdot s_y}$, %
a	width of square pile cap. $B_{ers} = a$, m
B	load part that passes through the geosynthetic reinforcement (GR) to the pile expressed as kN/pile = kN/unit cell, kN/pile
B_{ers}	equivalent size of circular pile cap, $B_{ers} = 1/2\cdot d\cdot\sqrt{\pi}$ or the width of a square pile cap, m
C	load part that is carried by the soft soil between the piles (this soft soil foundation is called 'subsoil' in this paper) expressed as kN/pile = kN/unit cell, kN/pile
C	a constant to be calculated with boundary conditions (Eqs. (29)–(34) and (47)–(50) in the appendix)
d	diameter circular pile (cap), m
E	pile efficacy, the same as $A\%$, – (kN/kN)
F	force, kN
GR	geosynthetic reinforcement
h or H	height of the fill above bottom layer of GR, m
H_{g2D}	height of the largest of the 2D arches of the new concentric arches model, see Eqs. (2) and (13) and Figs. 10 and 12. H_{xg2D} refers to the height of a 2D arch that is oriented along the x-axis (perpendicular to the road axis), as indicated in Fig. 12. H_{yg2D} refers to the height of a 2D arch that is oriented along the y-axis, m
H_{g3D}	height of the largest 3D hemisphere of the new concentric arches model, see Eq. (4) and Fig. 10, m
h_g	arch height in EBGEO, $h_g = s_d/2$ for $h \geq s_d/2$ or $h_g = h$ for $h < s_d/2$, m
$J_{2\%}$	tensile stiffness of the GR at a GR strain of 2%, kN/m
k	subgrade reaction, kN/m^3
K_p	passive or critical earth pressure coefficient, –
L_{x2D}	part of the GR strip that is oriented along the x-axis (perpendicular to the road axis) and on which the 2D arches exert a force, see Fig. 23 and Eq. (12), m
L_{y2D}	part of the GR strip that is oriented along the y-axis (parallel to the road axis) and on which the 2D arches exert a force, see Fig. 23 and Eq. (12), m
L_{x3D}	width of square on which the 3D hemispheres exert a load, see Fig. 22 and Eq. (8), m
P_{2D}	calculation parameter given by Eq. (1). P_{x2D} refers to a 2D arch that is oriented along the x-axis, as indicated in Fig. 12 and Eq. (14). P_{y2D} refers to a 2D arch that is oriented along the y-axis, kPa/m$^{K_p-1}$
P_{3D}	calculation parameter given by Eq. (7), kPa/m$^{2K_p-2}$
p	uniformly distributed surcharge on top of the fill (top load), kN/m^2
Q_{2D}	calculation parameter given by Eq. (1), kN/m^3
Q_{3D}	calculation parameter given by Eq. (7), kN/m^3
r	radius of a 2D arch, m
R	radius of a hemisphere (in this paper a hemisphere is a 3D arch), m
R_b	total friction between fill/box walls and foam cushion/box walls and piles, see Van Eekelen et al. (2012a,b), kN/pile
s_d	the diagonal centre-to-centre distance between piles $s_d = \sqrt{s_x^2+s_y^2}$, m
s_x, s_y	pile spacing perpendicular to the road axis (x) or parallel to the road axis (y), m
W_n	net load ($= W_s - C - R_b$), kN/pile
W_s	total surcharge load on a unit area $W_s = p\cdot s_x\cdot s_y$, kN/pile
z	distance along the vertical axis as indicated in, for example, Fig. 3, m
φ	internal friction angle, °
γ	fill unit weight, kN/m^3
σ_r	radial stress in a 2D arch, kPa
σ_R	radial stress in a 3D hemisphere, kPa
σ_θ	tangential stress in 2D arch or 3D hemisphere, kPa
PET	polyester
PP	polypropylene
PVA	polyvinyl alcohol

Research Center in Japan (2000, discussed in Eskişar et al. 2012). In this class of models, it is assumed that an arch is formed that has a fixed shape. The shape of the arch is usually 2D or 3D triangular. It is assumed that the entire load above the arch, including the soil weight and the traffic load, is transferred directly to the piles (load part *A, or arching A*, see Fig. 1). The weight of the soil wedge is carried by the GR + subsoil (B + C). These models do not consider the mechanical properties of the fill, such as the friction angle, in their equations and they are therefore not discussed further in the present paper.

In equilibrium models, an imaginary limit-state stress-arch is assumed to appear above the GR + soft subsoil between the stiff elements. In the 3D situation, these stiff elements are piles; in the 2D situation, they are beams or walls. The pressure on the GR + subsoil ($B + C$) is calculated by considering the equilibrium of the arch. In most models, the arch has a certain thickness.

Two limit-state equilibrium models are frequently used in piled embankment design today. One of them is the Hewlett and Randolph model (1988), explained in Fig. 2, which was adopted in the French ASIRI guideline (2012) and suggested in BS8006 (2010) as an alternative for the original empirical model in BS8006. The other frequently used equilibrium model is Zaeske's model (2001, and also described in Kempfert et al., 2004), which is explained in Fig. 3. This model was adopted in the German EBGEO (2010) and the Dutch CUR226 (2010, described in Van Eekelen et al., 2010), and we refer to it here as 'EBGEO'.

Another family of arching models is the family of frictional models. Several authors have adopted the frictional model proposed by Terzaghi (1943), who in turn based his model on previous work from other authors such as Cain (1916) and Völlmy (1937). McKelvey (1994) extended Terzaghi by assuming that a 'plane of equal settlement' exists and combined this with a tensioned membrane theory.

Russell and Pierpoint (1997) extended the Terzaghi model to include a third dimension by assuming the presence of friction in the vertical planes along the edges of the square pile caps. McGuire et al. (2012) also adopted the idea of a 'plane of equal settlement', which they described as the 'critical height'. They conducted numerous tests and collected field data to determine and validate their equation for the critical height. This critical