

Equilibrium models for arching in basal reinforced piled embankments

Modèles d'équilibre par effet voute pour l'amélioration des sols de fondation par inclusions rigides

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ABSTRACT: Several analytical models are available for describing arching in basal reinforced piled embankments using geosynthetics. Some of them are limit state equilibrium models. Two of them are frequently applied in Europe: the model of Zaeske (2001), the model of Hewlett and Randolph (1988), but both models have only been described very briefly in the English language. This paper considers these two models along with another, new one: the Concentric Arches Model (Van Eekelen et al. 2013b). The paper gives a graphical presentation of the models and summarizes and discusses them.

RÉSUMÉ : Plusieurs modèles analytiques sont disponibles pour décrire la distribution en arcs des forces dans une l'amélioration des sols de fondation par inclusions rigides et géosynthétique. Parmi eux, il y a des modèles d'équilibre aux états-limites. Deux d'entre eux sont fréquemment appliquées en Europe : le modèle de Zaeske (2001), le modèle de Hewlett et Randolph (1988, mais les deux modèles ont seulement été décrits très brièvement dans la langue anglaise. Le présent article examine ces deux modèles et les compare avec notre nouveau modèle: le Modèle Arches Concentriques (Van Eekelen et al. 2013b). L'article donne une représentation graphique des modèles qui sont résumés et discutés.

KEYWORDS: arching, piled embankments, geosynthetic reinforcement, basal reinforced load transfer platforms

MOTS-CLES: effet voutes, inclusion rigide, renforcement géosynthétique, plateforme de transfert de charge

1 DESIGN OF BASAL REINFORCED PILED EMBANKMENTS

Many analytical design models for the design of piled embankments distinguish two calculation steps. Step 1 is the arching behaviour in the fill. This "arching step" divides the total vertical load into two parts: load part A, and the 'rest load' (B+C in Figure 1). Load part A, also called the 'arching', is the part of the load that is transferred to the piles directly.

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

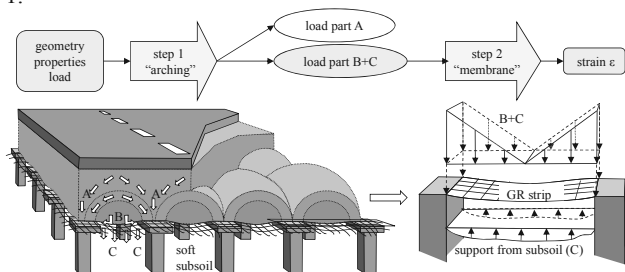


Figure 1. Calculating the geosynthetic reinforcement (GR) strain comprises two calculation steps.

This paper focuses on calculation step 1 only and thus on the determination of the load distribution in the load transfer platform. The two most interesting results of the arching step are:

1. The calculated value for the arching A (kN/pile)
2. The load distribution of B+C (kN/pile)

Van Eekelen et al. (2012a, b and 2013a) showed with experiments, numerical calculations and field measurements that load B+C is concentrated on the GR strips between each two adjacent piles, and that the load distribution on these strips approaches the inverted triangular shape, as shown in Figure 1 (right hand side of the figure). The two most applied models in Europe (Zaeske 2001 and Hewlett and Randolph 1988) are summarized, analysed and discussed in this paper.

Zaeske (2001), between several other researchers, showed the great influence of the application of a sufficient stiff GR in a piled embankment. The concentration of load on GR strips is only found for GR basal reinforced piled embankments, not for piled embankments without GR. Therefore, it is necessary to make a distinction between arching models for piled embankment with and without GR. This paper focuses on GR reinforced piled embankments only.

2 EQUILIBRIUM MODELS DESCRIBING ARCHING

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

The model of Hewlett and Randolph (1988, see Figure 2) is adopted in the French ASIRI guideline (2012) and suggested in BS8006 (2010) as an alternative for the originally first empirical model in BS8006. The other frequently applied equilibrium model is the model of Zaeske (2001, also described in Kempfert, 2004). See Figure 3. This model is adopted in the German EBGEO (2010) and the Dutch CUR226 (2010), and is hereafter called EBGEO. These two models are of great importance.

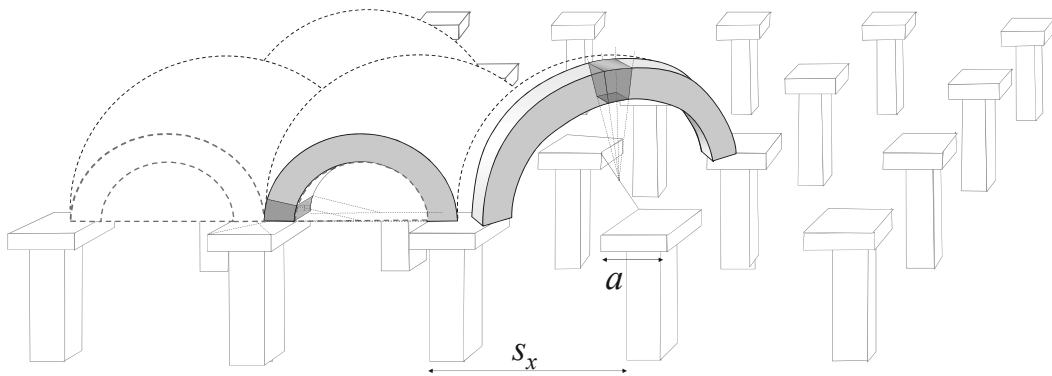


Figure 2. Hewlett & Randolph (1988) consider the ‘crown’ element of the diagonal arch and the ‘toe’ element (just above the pile cap) of the plane strain arch as indicated in this figure.

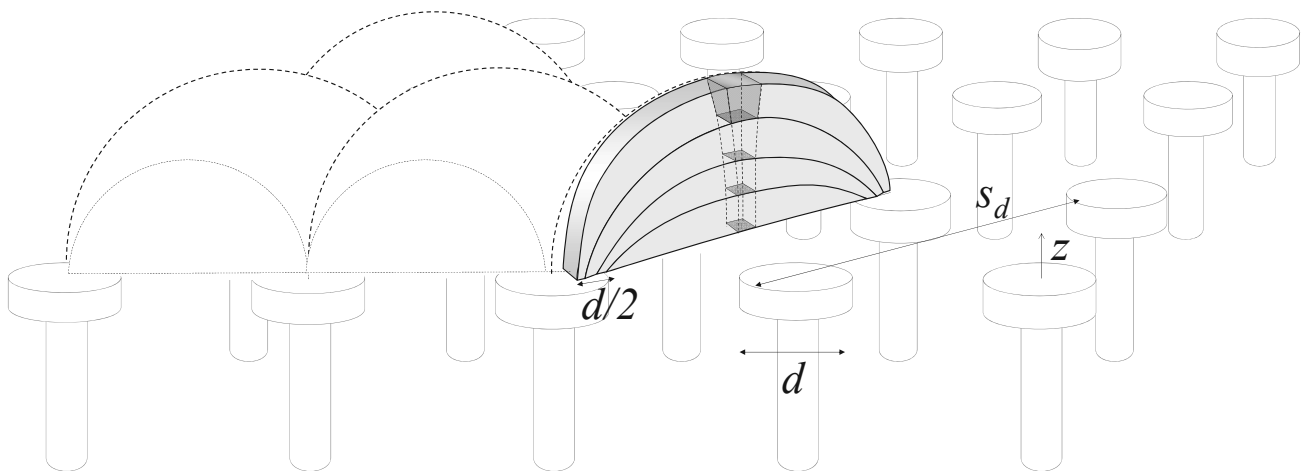


Figure 3. Zaeske (2001) considers the equilibrium of the crown elements of the diagonal arches

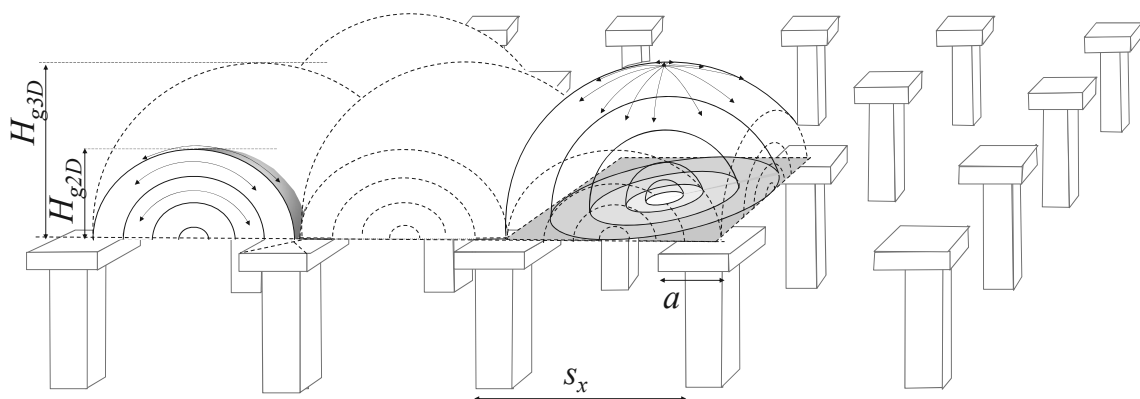


Figure 4. Van Eekelen et al. (2013b), the Concentric Arches Model. The load is transferred along the 3D hemispheres (right hand side) towards the GR strips and then via the 2D arches (left hand side) towards the pile caps

A third model is the concentric model presented by Van Eekelen et al. (2013b). Figures 2 to 4 present these three models and are presented in the following sections.

3 HEWLETT AND RANDOLPH (1988)

Hewlett & Randolph (1988) based their model on 3D door trap tests, without geosynthetic reinforcement. Their analytical model consists of a series of thick-walled 3D-shells, or arches, in the embankment. They consider two arch elements separately: a ‘crown element’ and an element just above the pile cap, the ‘toe’ element, as shown in Figure 2 and Figure 5. For the toe element, the pile load (A) is calculated by assuming

radial equilibrium of the crown element in the plane strain arch (left in Figure 2) and assuming that the principal stresses follow the arches with σ_θ the major principal stress and σ_r the minor principal stress and that the arches are in a nearly-plastic situation:

$$\sigma_\theta = K_p \cdot \sigma_r = \frac{1 + \sin \varphi}{1 - \sin \varphi} \cdot \sigma_r \quad (1)$$

Where σ_θ (kPa) is the tangential stress, σ_r (kPa) is the radial stress, K_p (-) is the Rankine passive earth pressure coefficient and φ ($^\circ$) is the friction angle. The pile load (A) is obtained by integrating σ_θ over the pile area, indicated in Figure 5. For the crown element, the vertical stress $\sigma_{r,i}$ below the crown is calculated using equilibrium of the crown element in the 3D

(diagonal) arch right in Figure 2 and the limit state of equation (1). Note that this is different from figure 78 in BS8006, where the crown element is the crown of the plane strain arch (but the equations in BS8006 are correct and thus derived for the diagonal arch). The soil weight below the arch is added to calculate the pressure on the subsurface $\sigma_{v,GR}$:

$$\sigma_{v,GR} = \sigma_i + \gamma \cdot \frac{s-a}{\sqrt{2}} \quad (2)$$

It is supposed that the entire area between the piles is loaded by this load $\sigma_{v,GR}$. This load is thus assumed to be equally distributed. The remaining load is assumed to be the pile load (A). This pile load is calculated for both the crown and the foot element. The minimum pile load of Acrown and Atoe is considered to be normative.

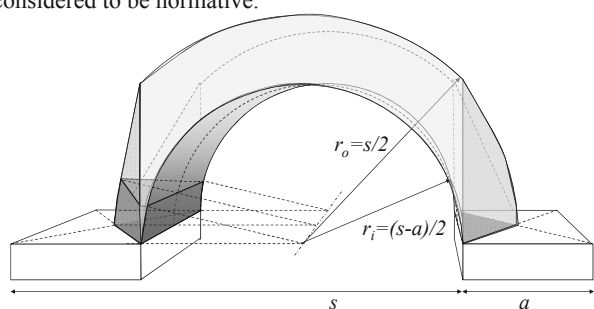


Figure 5. Hewlett & Randolph (1988) detail of the 'toe' element

4 ZAESKE (1988)

De model of Zaeske (2001) exists of a set of scales. The crown of each scale is thicker than the feet of the scales as indicated in Figure 3. Only the diagonal of the arches is considered, and this diagonal rests on the pile caps. Zaeske derived the vertical (radial) stress σ_z in the central line between 4 piles by considering the vertical (radial) equilibrium of the set of crown elements of the arches, as indicated in Figure 3. He assumed that:

- The stress situation in the feet of the arches, thus just on top of the pile cap, is in a nearly-plastic situation. Thus the earth pressure coefficient is maximal: $K = K_p$ (equation (1)).
- The total tangential force just above the top of the pile cap equals the total tangential force along the vertical line of crown elements. Thus the passive earth pressure coefficient K at the top of the arch is less than the K at the toe of the arch, according to the ratio of the scale width at the toe and the crown (d/s_d).

This way, Zaeske determined the radial stress in the crown element of each scale and extended this downwards for the entire vertical line through the crown elements. For $z=0$, he finally obtained the value for the vertical pressure on the GR in the mid of 4 piles ($\sigma_{z0} = \sigma_z(z=0)$). Zaeske assumes that this pressure σ_{z0} is constant for the entire GR area between the piles.

5 CONCENTRIC ARCHES (VAN EEKELLEN ET AL. 2013B)

In the concentric arches model, 3D concentric arches (hemispheres) occur above the square between each four piles (Figure 4). These hemispheres exert part of the load to their subsurface, the square between the four piles. The rest of load is transported laterally in the direction of the GR strips. The load is then further transported along the 2D arches, in the direction of the pile caps. The 2D arches also exert part of the load to the subsurface (the GR). Thus, both the 3D hemispheres and the 2D arches exert a load on its GR subsurface, and this exerted force increases towards the exterior. The part of the load not resting on the GR is the load on the piles (arching A).

Following Hewlett and Randolph (1988), the radial stress σ_r and tangential stress σ_θ in the 2D and 3D arches is calculated by assuming radial equilibrium of the crown element and assuming that:

- The principal stresses follow the arches with σ_θ the major principal stress and σ_r the minor principal stress. These concentric hemispherical stress paths were observed in several numerical studies, like Vermeer (2010) and Nadukuru and Michalowski (2012).
- The arches are in a nearly-plastic situation (equation (1)).

The forces exerted on the subsurface (the GR) are calculated by integrating the tangential stress over the GR area. This is fully elaborated and presented in Van Eekelen et al. (2013b). Figure 6 presents the resulting load distribution on the GR subsurface. The figure shows that the load is indeed concentrated on the GR strips, and the load distribution on the GR strips indeed approaches the inverted triangular load distribution found earlier in model tests, numerical analysis and field measurements (Van Eekelen et al., 2012a, b and 2013a).

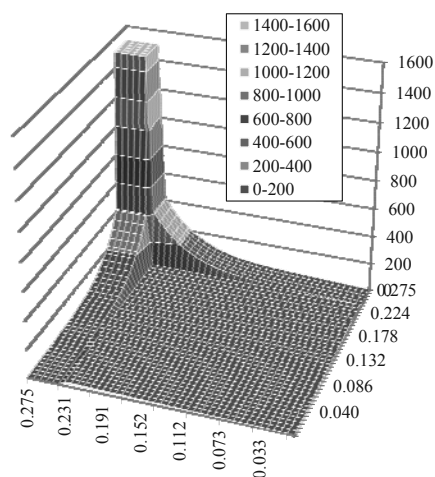


Figure 6. Pressure exerted on the GR subsurface by the arches and hemispheres of the concentric arches model.

6 DISCUSSION

Both Hewlett and Randolph (1988) and Zaeske (2001) determine the pressure exerted on the GR at the central point between four piles only. They continue with assuming that the entire GR area is loaded with this pressure, thus resulting in an equally distributed load on the GR. The concentric arches model, however, gives a load distribution that resembles the observed load distribution: a concentration on the GR strips between adjacent piles, and approximately an inverted triangular load distribution on the GR strips.

All three considered models obtained the load distribution (Efficacy E , which is the ratio pile load (A in kN/pile) / total load ($A+B+C$ in kN/pile), thus $E = A/(A+B+C)$) while assuming that the surcharge load $p = 0$. Afterwards, the resulting $A_{p=0}$ and $(B+C)_{p=0}$ are multiplied with $(\gamma H + p)/(\gamma H)$ to obtain the A and $B+C$ for surcharge load $p > 0$. This results in robust calculation models.

Hewlett and Randolph (1988) as well as Zaeske (2001) compared their analytical model with measurements in scaled model tests without GR. As discussed before, it would be better to compare with measurements in situations with GR.

Van Eekelen et al. (2013b) give many comparisons between the three models and results of scaled model tests, field measurements and numerical calculations. All with GR. Figure 7 shows a comparison with numerical calculations of Le Hello et al. (2009), Figure 8 with field measurements in a high way exit in Woerden (Van Eekelen et al. 2012c). In these figures is H (m) the embankment height, a (m) the (equivalent) width square pile cap, d (m) the (equivalent) diameter of circular pile

cap, s_x and s_y (m) the centre-to-centre distance piles along and across the road, s_d (m) the diagonal centre-to-centre distance piles, γ (kN/m³) the unit fill weight, p (kPa) the surcharge load and φ (°) the friction angle. Figure 7 also gives the minimum embankment height as required in respectively EBGEO (2010) and CUR226 (2010).

The figures, as well as most other comparisons in Van Eekelen et al. (2013b), show that the concentric arch model agrees best with the numerical calculations, and most measurements in the scaled model tests. For the considered field test, the model of Zaeske and the concentric arches model give comparable good results.

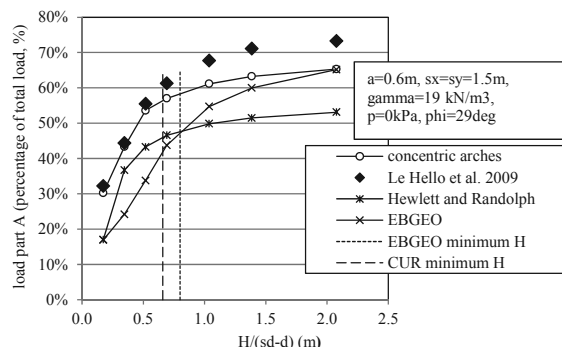


Figure 7. Variation of embankment height H , comparison analytical models with numerical calculations of Le Hello et al. (2009).

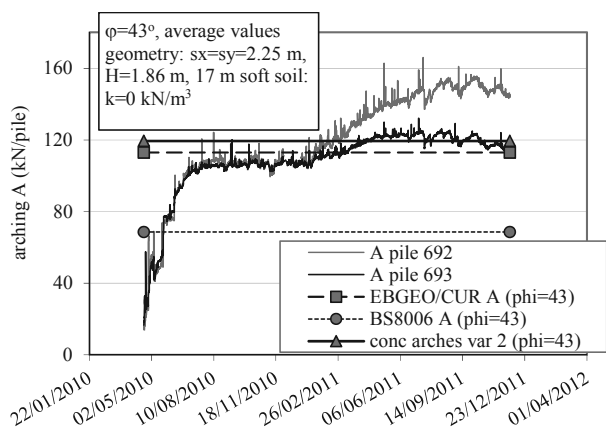


Figure 8. Comparison measured and calculated arching A in highway exit Woerden, the Netherlands, described in Van Eekelen et al., 2012c

7 CONCLUSIONS

It is important to make a distinction between models for piled embankments with or without geosynthetic basal reinforced (GR). In the case with GR, the load is concentrated on the GR strips between the piles (and the piles), and the load on the GR strips is inverted triangular distributed. This paper deals with the situation with GR.

The paper summarizes three equilibrium models describing arching in GR basal reinforced piled embankments, namely the models of Hewlett and Randolph (1988), Zaeske (2001) and the concentric arches model of Van Eekelen (2013b).

It is shown how the three models obtain their load distribution. Hewlett and Randolph (1988) as well as Zaeske (2001) find an equally distribution load on the GR between the piles. The concentric arches model (Van Eekelen et al. 2013b) finds a load concentration on the GR strips, and approximately an inversed triangular load distribution on those GR strips. This is more in accordance with observations in scaled model tests, numerical analysis and field measurements. The considered numerical calculations agree best with the concentric arches model. Measurements in the field agree equally well with the concentric arches model and the model of Zaeske (2001).

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