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NUMERICAL ANALYSIS OF PILED EMBANKMENTS ON SOFT SOILS

Wisam Al-Ani[1], Dariusz Wanatowski[2] MASCE and Swee Huat Chan[3]

[1]PhD student, The University of Nottingham, United Kingdom
[2]Associate Professor, The University of Nottingham Ningbo China
[3]Assistant Professor, The University of Nottingham Malaysia Campus,

ABSTRACT: The construction of embankments on soft soils is a common problem. Soft soil cannot sustain external loads without having large deformations. Piled embankments system provides a possible solution for the construction of roads and rail over soft soils. Until now the system behaviour can only be described by analytical models such as those included in British or German Codes. This paper describes research undertaken to investigate the effects of pile embankment construction in soft soils. Experimental results are used to help investigate arching effect developed due to differential settlement between pile and surrounding soft soil. Numerical parametric study was carried out to examine impact of various soil parameters on the pile-embankment system behaviour. The outcome of parametric study implemented using numerical analysis has been investigated and discussed throughout this paper. Based on the numerical analysis carried out in this research, it was found that the earth pressure coefficient normalized by the passive earth pressure K_p plotted on a vertical profile at the midpoint between piles gave a good illustrations of arching behaviour. The findings presented in this paper can be considered as guides for numerical analysis and design criteria of soil arching for embankments constructed over piles.

1. INTRODUCTION

Geometry, load transfer mechanism (arching) and embankment stability are the main factors to consider in piled embankment system design. Embankment stability can be checked using most common slope stability methods such as Bishop's method and Fellenius's method. Construction requirements, system stability and soil arching phenomenon are the main factors which dictates embankment geometry. Both embankment stability and geometry are well defined, however uncertainties lie with load transfer mechanism through soil arching. Therefore, any improvement in piled embankment system design should address to soil arching and how to measure this aspect of design.

Arching action has been recognised by many published standards and papers in civil engineering. As stated by Handy (1987), in civil engineering is defined as the transfer of stress from a yielding part of soil mass to adjoining less-yielding or restrained parts of mass. Lack of a standard design has led to the development of many design theories and methods (Love and Milligan, 2003; Van Eekelen et al, 2003 and many others). Additionally, soil-structure interaction is complex and the precise mechanism by which load transfers occur remains unknown. Current procedures such as BS8006 and German method EBGEO 2004 section 6.9 gives significant difference in the design results. However, it is both on safe side compared to measurements. The piles that support embankment are generally assumed as rigid piles. For the design of embankment on floating piles further studies of the floating piled embankment is required, although some studies on floating piled embankment exist (Poulos, 2007 and Satibi et al, 2008).

Construction of embankments over soft soils for highways and rail embankments impose a significant load over wide area. The soft soils and other compressible soils are quite challengeable subject normally face geotechnical engineers. Several challenges include potential bearing failure, intolerable settlement, large lateral pressure and movement, global or local instability and soil arching (Han and Jabr, 2002). Geotextile reinforcement stabilise arching effect by which called membrane effect. Structures settlement may be minimised considerably with shorter piles installed in soft soils.

In 1943, Terzaghi was one of the first researchers to define soil arching in his text "Theoretical Soil Mechanics". He describes the arching effects based on his experiment from which came the 'trapdoor' theory. Although arching effect has been acknowledged for decades, it still needs to be investigated due to various design uncertainties.

As shown in FIG. 1, Terzaghi initially proposed vertical shear planes at either side of a 'trapdoor'. Hewlett and Randolph (1988) derived theoretical solution based on observations from experimental tests of arching in a granular soil attempting to investigate arching in cohesionless soil. Semicircular arch proposed by Hewlett and Randolph for piled embankments.

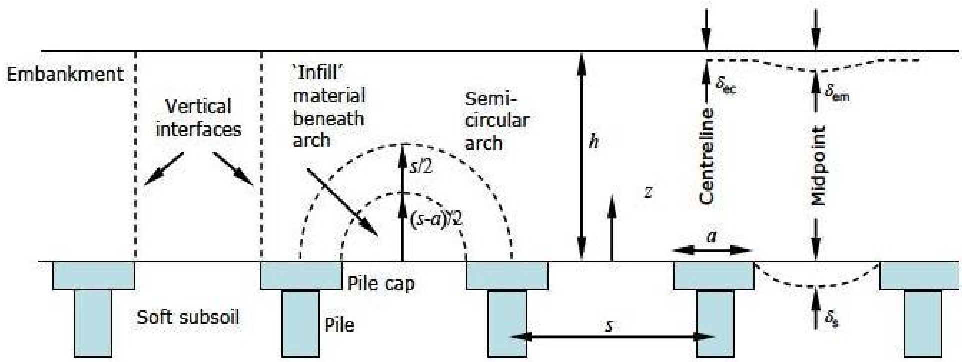


FIG. 1. Piled embankment showing potential arching mechanisms

(Zhuang, 2009).

2. PLAXIS SOIL PARAMETERS

A very useful set of laboratory model tests were performed at University of Kassel. As described by Zaeske (2001) and Kempfert et al. (2004), four piles placed in a square grid in a 40 cm thickness of soft soil are arranged in a 1.1m x 1.1m box as shown in FIG. 2. Pile size was 16cm and centre to centre spacing of 50cm, which correspond to an area of replacement ratio of 10%.

In separate experiments, sand was placed on top of the piles to represent embankment in two thicknesses: 35cm and 70cm. However, 70cm test is chosen to verify numerical analysis. All simulations are performed with the finite element code Plaxis 2D.

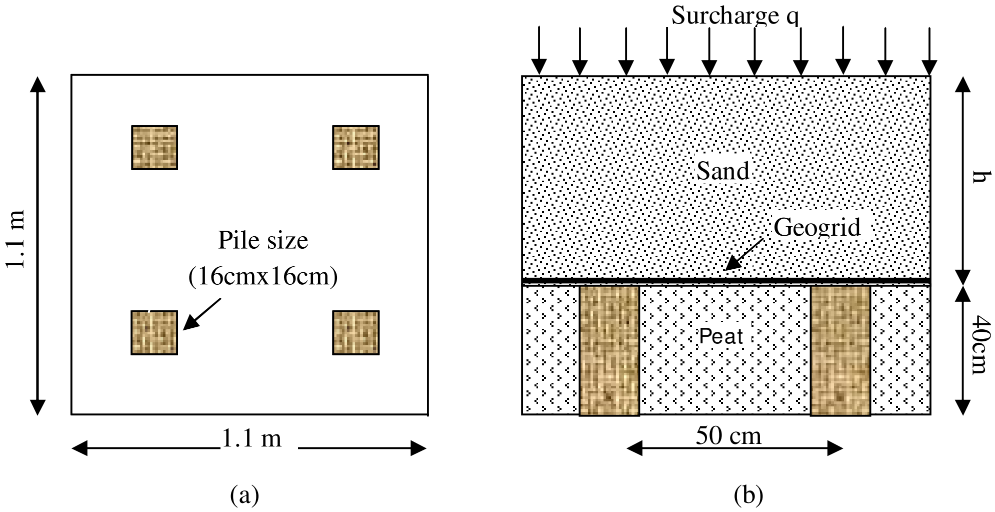


FIG. 2. Zaeske (2001) Model test dimensions and configuration: (a) plan view of piles; (b) Section view.

The advanced elastic-plastic Hardening soil (HS) model in Plaxis was chosen to simulate the behaviour of the sand and peat. The HS model is an extension of the hyperbilc model developed by Duncan and Chang (1970). The sand and peat properties used in the soil model as described by Zaeske (2001) and Kempfert et al. (2004) are presented in Table 1.

Table 1. Soil parameters for Hardening Soil model

	Properties	Sand	Peat
Φ'	[°]	**38**	**24**
c′	**[kPa]**	**0.1**	**8.5**
Ψ'	[°]	**11**	**0**
γ'	[kN/m³]	**18**	**8**
E^{ref}	[MPa]	**23**	**1.7**
E^{ref}	[MPa]	**28**	**0.85**
E^{ref}	[MPa]	**112**	**12.75**
v_{ur}	[-]	**0.2**	**0.2**
m	[-]	**0.5**	**1**
R_{inter}	[-]	**1**	**0.35**

The system has been simulated as axisymmetric and 3D models. Half of the geometry is selected to reflect the effect of symmetry. The nodes on the lateral boundaries have been restrained in the x-direction only but the nodes on the bottom boundary have restrained in both x and y-directions. The finite element mesh was generated automatically with six- node elements for axisymmetric model.

3. FINITE ELEMENT ANALYSIS

3.1 Soil Primary Compression

The soil stress increase within a normally consolidated soil during the sedimentation process (Lambe and Whitman 1969). The ratio of the lateral effective stress to the vertical effective stress is known as the coefficient of the lateral earth pressure K_o, is given by

$$K_o = \frac{\acute{\sigma}_h}{\acute{\sigma}_v} \tag{1}$$

$$\acute{\sigma}_v = \sigma_v - u \text{ and } \acute{\sigma}_h = \sigma_h - u \tag{2}$$

where $\acute{\sigma}_h$ and $\acute{\sigma}_v$ represent effective lateral and vertical stresses respectively, σ_h and σ_v represent lateral and vertical stresses respectively. There are two ways to obtain K_o which is either from laboratory test carried out on undisturbed sample or field tests. However, in absence of tests or for simplicity K_o value can be readily estimated from the well known Jaky 1944 empirical formula:

$$K_o = 1 - \sin \acute{\varphi} \tag{3}$$

where φ' is soil effective angle of internal friction. However, there are also empirical equations to estimate the K_0 in soft soils in particular. The Jaky's formula which is widely accepted among engineers and researchers is underestimating the K_o value. In order to find out the right approach to calculate accurate figure for K_o, measured K_0 values from Scherzinger 1991 and published work by Alphan 1967, Lee and Jin 1979 and Sherif and Koch 1970 (FIG. 3) compared with Jaki formula. Jaki formula k_o value lies far away from the range of measured K_0 by Scherzinger hence K_0 calculated based on Scherzinger is recommended in this research.

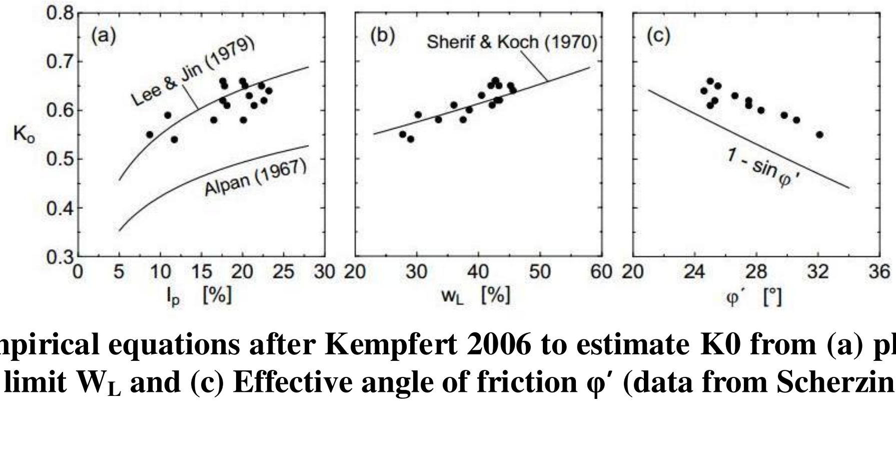


FIG. 3. Empirical equations after Kempfert 2006 to estimate K0 from (a) plasticity index I_p, (b) Liquid limit W_L and (c) Effective angle of friction φ' (data from Scherzinger 1991)

3.2 Validation of Soil Model

A well- documented set of laboratory model tests were performed by Zaeske (2001) was simulated using Plaxis in order to substantiate the use of parameters in Table 1. Firstly, the initial stresses were generated under K_o conditions. Then, pile sector was activated to represent pile installation (wish in place). The embankment fill was then added to simulate embankment's construction on the top of the piles. If embankment was reinforced with basal geotextile, it was applied simultaneously with the embankment construction. Last stage in computation procedure was placing an external surcharge on to top of the embankment. Finite element mesh of various stages of analysis is shown in FIG. 4.

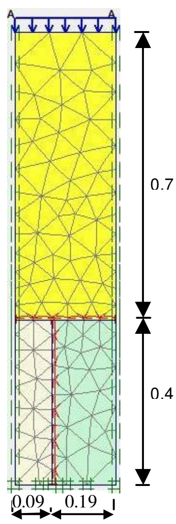


FIG. 4. FE- Axi-symmetric model mesh used for the calculations

The pile load and geogrid tensile force versus embankment load responses of the model test recorded by Zaeske (2001) are shown in FIG. 5 together with the Plaxis 2D prediction.

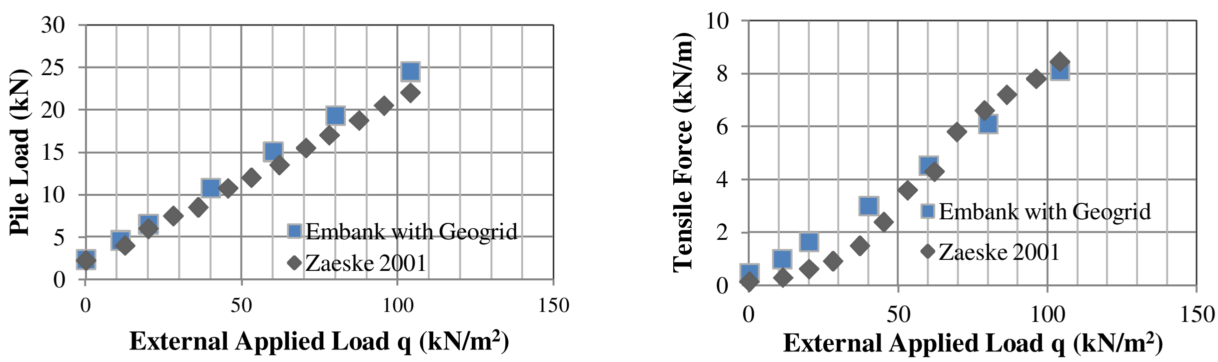


FIG. 5. Validation of soil profile and parameters for Zaeske (2001) model test.

It is clear that both curves are in good agreement with Zaeske (2001) model test, affirming the selection of the adopted soil profile and material parameters.

4. MIDPOINT OF EARTH PRESSURE COEFFICIENT

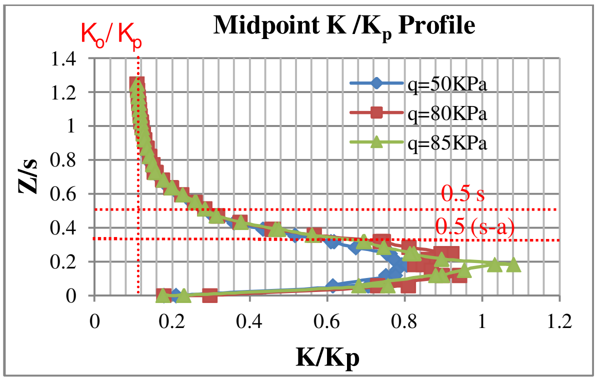
It is found the earth pressure coefficient ($K= \frac{\sigma'_h h}{\sigma'_v}$) plotted on a vertical profile at the midpoint between piles (the right-hand boundary of the mesh in FIG.4) gave a good 'illustration' of arching behaviour (Zhuang, 2009). Earth pressure coefficient (K) midpoint profile has been used to investigate embankment material arching and compare it with a semi-circular arch in shown in FIG.1 developed by Terzaghi (1943). In this research, K profile has been normalized by passive earth pressure K_p (taking the standard Rankine value and ignoring the small cohesive element of strength $K_p = (1+\sin\varphi)/(1-\sin\varphi)$) plotted upward from the base of embankment normalised by spacing (s). This approach will provide direct results whether the soil is in plastic state comparing this with FIG. 1.

5.0 RESULTS

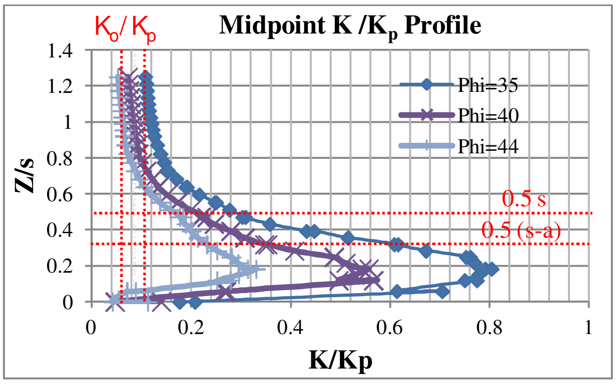
Zaeske (2001) model test shown in Fig. 2 is revisited, which shows the influence of key parameters variation upon the normalized K value. Fig. 6 shows the profiles plotted with z – vertical distance upwards from the base of the embankment normalized by s. The profile as plotted do extend to the top of the embankment, values of 0.5(s-a) and 0.5s are highlighted on the z/s axis. Subplot (a) shows the effect of increased embankment surcharge (q) keeping angle of friction (φ'), embankment height (h) and dilatation angle (ψ) constant. Subplots (b) and (c) again show variation of embankment angle of friction whilst keeping other soil properties constant. In order to measure embankment surcharge affects, surcharge in subplots (c) increased to 85kPa.

Referring to FIG. 6 (a) for (z/s) >1.0, $K= K_0$, and thus has not been modified by the formation of the arch. Embankment where h/s= 1.25, K increases with depth for z/s< 1.0, reaching K_p just below $z \approx 0.5(s-a)$ for the higher surcharge of 85kPa. Comparing this with a semicircular arch in FIG. 1, the upper limit of the effect of arching is about 2.0 times higher, but the passive limit is only reached (q= 85kPa) below the inner radius of the arch, where the 'infill material is evidently in a plastic state. Subplot (e) where h/s=2.3 suggests for (z/s) >0.9, $K= K_0$, and thus has not been modified by the formation of the arch. Comparing this with a semicircular arch in FIG. 1, the upper limit of the effect of arching is about 1.8 times higher, but the passive limit is only reached (q= 85kPa) below the inner radius of the arch, where the 'infill material is evidently in a plastic state. Therefore, even the data show similar trends to lower embankment however embankment modified by arching at lower level than for the lower embankments.

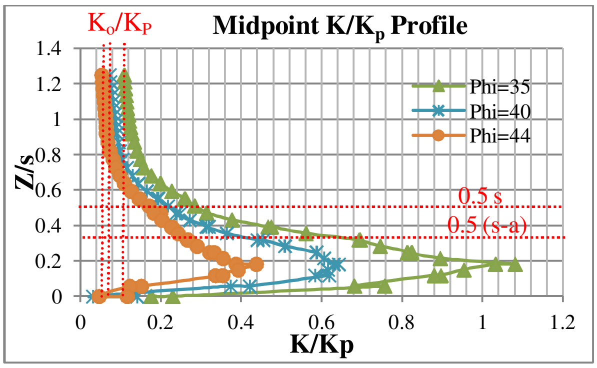
Effective cohesion can be assumed zero for granular embankment. Hence, evaluation is focused on the variation of φ' and ψ to investigate the influence of shear parameters. In order to assess the influence of φ', all other parameter are kept constant. Moreover, dilation angle ψ has been taken as zero and 8° to assess its influence on piled embankment system behaviour. φ' has an influence on subsoil surface settlement as illustrated in FIG.7 (a). The higher the angle of friction is the less subsoil surface settlement. FIG. 7 (b) shows that pile loads have a proportional relationship with the embankment angle of internal friction and the portion of external loads transferring to pile. Therefore, φ' has significant influence on embankment soil arching. FIG.6 (subplots b to e) shows the effect of increased friction angle.



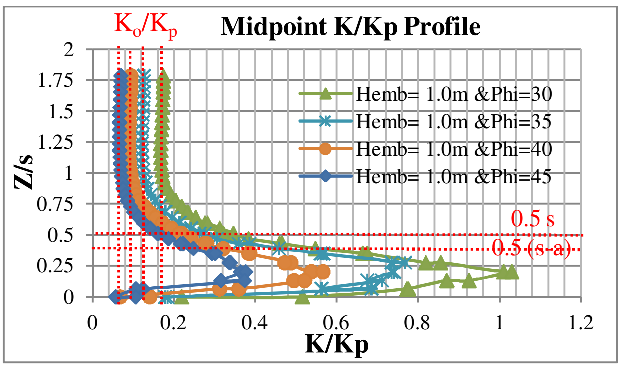
(a) h=0.7m, Ψ=0° and Φ= 35°



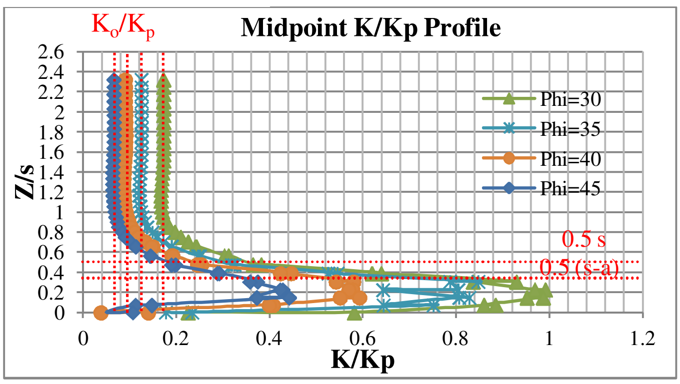
(b) h= 0.7m, Ψ=0° and q= 50 kPa



(c) h= 0.7m, Ψ=0° and q=85KPa



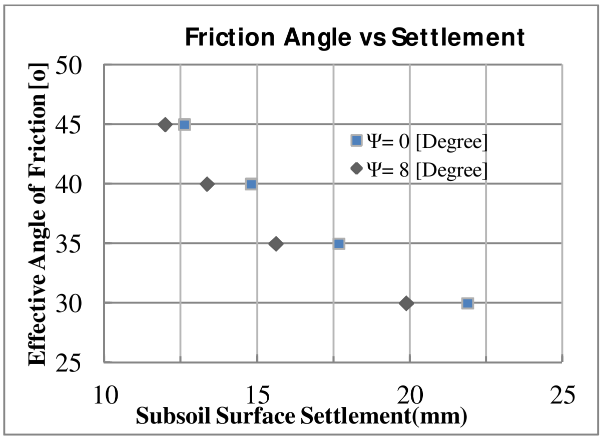
(d) h= 1.0m, Ψ=0° and q= 100KPa



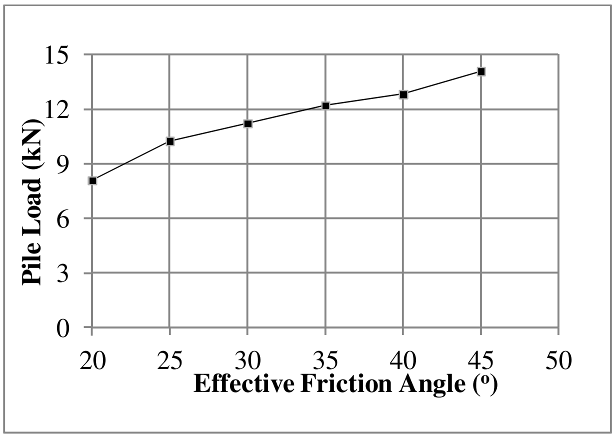
(e) h= 1.3m, Ψ=0° and q= 135KPa

FIG.6. Profiles of normalized earth pressure coefficient (K/Kp) on a vertical profile at the midpoint between piles.

The same results can be observed in FIG.6 (subplots b to e) where the higher φ' the stronger the arching action in the embankment. The higher φ' leads to less K at the same height. The influence of ψ on Subsoil surface settlement is less significant than φ' as shown in FIG. 7(a). However, similar trends to increasing φ' is observed when increasing ψ. The higher subsoil surface settlement is for reduced ψ angle.



(a)



(b)

FIG. 7 Shear strength parameters influence

FIG.7. (subplots b and c) demonstrate the effect of external embankment surcharge on piled embankment system. Increasing q value from 50kN to 85kN leads to an increase in K value for φ'= 35° at the same level.

6. CONCLUSION

A parametric finite element study with an advanced soil model was carried out to assess the effect a number of key design variables on the arching of a granular embankment supported by pile caps over a soft soil. The results of a series of hardening soil constitutive relation using axi-symmetric finite element analysis to investigate piled embankment performance. The following conclusions may be drawn, which are based on modelling Zaeske 2001 laboratory model test:

- There is virtually no effect of arching above z/s= 1.0 for h/s= 1.25 embankment and above z/s= 0.9 for h/s= 2.3 embankment therefore embankment height is ine of key parameters when assessing embankment soil arching.

  K value increases with depth reaching Kp below z ≈ 0.5(s-a). Comparing this with a semicircular arch in FIG. 1, the upper limit of the effect of arching is about 1.8 to 2.0 for h/s between 1.25 to 2.3 times higher, but the passive limit is reached for lower angle of friction (FIG.6 (c-e)) below the inner radius of the arch, where the 'infill material is evidently in a plastic state.

- The higher φ' the stronger the arching action in the embankment. The higher φ' leads to less K at the same height.
- The influence of ψ on Subsoil surface settlement is less significant than φ' as shown in FIG. 7(a). However, similar trends to increasing φ' is observed when increasing ψ. The higher subsoil surface settlement is for reduced ψ angle.

It is found the earth pressure coefficient (K= $\frac{\sigma'_h}{\sigma'_v}$) normalized by passive earth pressure coefficient plotted on a vertical profile at the midpoint between piles gave a good 'illustration' of arching behaviour and can be used to perform a sensitivity analysis to measure the affect of number of key design variables on the arching of the piled embankment system.

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