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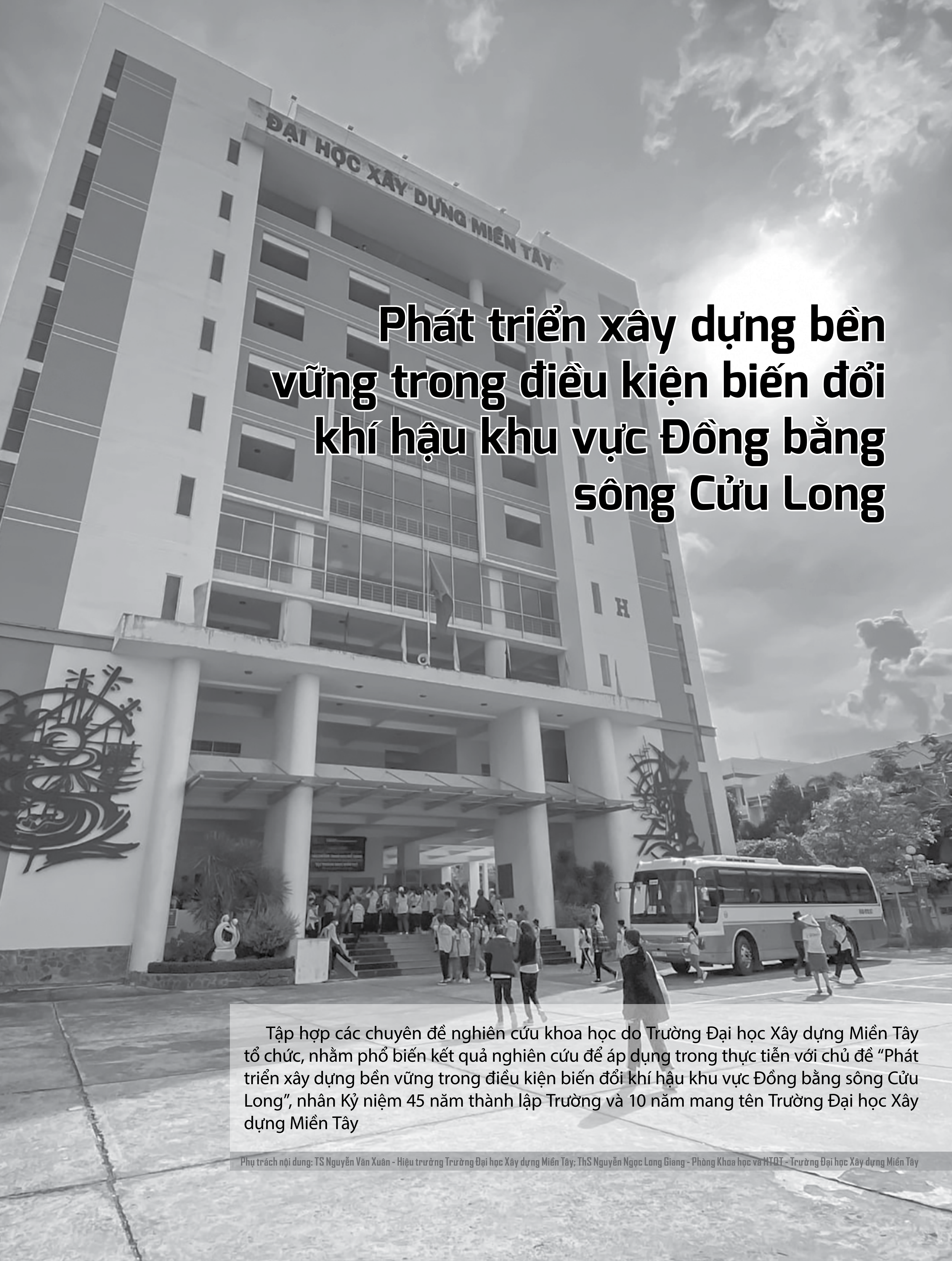

Phát triển xây dựng bền vững trong điều kiện biến đổi khí hậu khu vực Đồng bằng sông Cửu Long

Tập hợp các chuyên đề nghiên cứu khoa học do Trường Đại học Xây dựng Miền Tây tổ chức, nhằm phổ biến kết quả nghiên cứu để áp dụng trong thực tiễn với chủ đề “Phát triển xây dựng bền vững trong điều kiện biến đổi khí hậu khu vực Đồng bằng sông Cửu Long”, nhân Kỷ niệm 45 năm thành lập Trường và 10 năm mang tên Trường Đại học Xây dựng Miền Tây

Phụ trách nội dung: TS Nguyễn Văn Xuân - Hiệu trưởng Trường Đại học Xây dựng Miền Tây; ThS Nguyễn Ngọc Long Giang - Phòng Khoa học và HTQT - Trường Đại học Xây dựng Miền Tây

MỤC LỤC

Three-dimensional numerical analysis of geosynthetic-reinforced pile supported embankments

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ABSTRACT:

In many areas, poor ground conditions are a common hindrance to the construction of structures over soft ground. To deal with that problem, the geosynthetic reinforced pile-supported embankment has been widely used over recent years to support infrastructure due to the benefits for construction such as low cost and time reduction. Unfortunately, there is uncertainty concerning the applicability of the design methods due to the complicated mechanisms of the solution. In order to gain a better understanding of the method, 3D numerical modeling has been built for the geosynthetic reinforced pile-supported embankment. The load on the pile, the soft soil, and the geosynthetic are clearly illustrated. They are validated by several analytical methods. Additionally, the influence of geosynthetic stiffness and surcharge on the soil arching is investigated.

Keywords: Soil arching; numerical simulatio; geosynthetics, piled embankment

1. INTRODUCTION

In many countries, the need for economic development leads to an increase in the construction of infrastructure. However, many projects are built in areas with poor conditions. Embankment construction over soft soils is a real challenge for geotechnical engineers due to the unfavorable characteristics of the soil. Over a few decades, geosynthetic reinforced pile supported (GRPS) embankments have become a gradually common design solution for embankment construction over soft soil. Geosynthetic is installed in the supported system as one or multiple layers to increase the load transfer from the embankment to piles and to decrease the load applied on the subsoil. Based on various studies, several standards have been developed for the design of GRPS embankments, such as EBGEO (2011), BS8006 (2010), and CUR226 (2016). However, the mechanisms of load transfer from the embankment to piles and the subsoil are still not clearly understood.

Firstly proposed by Terzaghi (1943), the load transfer mechanisms caused by the soil arching phenomenon are commonly defined into three load parts: Load part A, part B, and part C. As seen in Fig. 1, the first load, including the soil weight and the traffic load, is directly transferred to the pile's head by arching, this is load part A. Geosynthetic used on the top of the pile is to redirect the residual load (load part B) to the pile head. The rest of the applied load is carried by the subsoil (load part C). There are two effects for using geosynthetic: to increase the load transfer to piles by improving the arching effect for the piles and the surrounding soil, and to transfer the load to the pile along with the geosynthetic sheet.

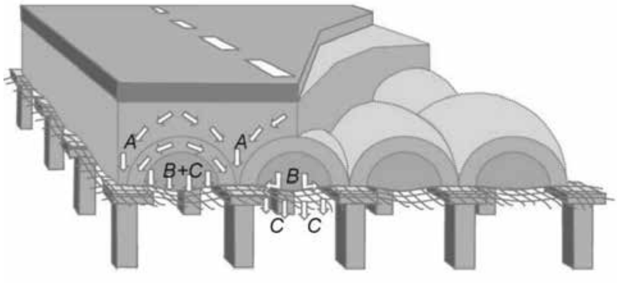


Figure 1. Load distribution in piled embankment supported by geosynthetic (Van Eekelen and Han, 2020)

In fact, the true problem of the piled embankment is in three dimensions. The two dimensions may not represent the realistic behaviors of the piles due to the fact that piles behave as walls. However, working with two-dimensional finite element modeling may not require too large computer resources and analysis time like the three-dimensional models. In this study, three-dimensional numerical modeling is used to investigate the problem then the parametric study is analyzed.

2. EXISTING DESIGN METHODS FOR GEOSYNTHETIC-REINFORCED PILED EMBANKMENTS

The technology of pile-supported embankment combined with geosynthetic reinforcement may be named in different terminologies: geosynthetic-reinforced pile-supported embankments, rigid inclusion ground improvement, geosynthetic-reinforced pile-supported embankments, basal reinforced piled embankments, or geosynthetic-reinforced piled embankments. Generally, this technology includes single or multiple layers of geosynthetic reinforcement in order to increase the load transfer to the piles for several approaches, such as bridge approaches, storage containers, the widening of present infrastructures, retaining walls, and embankments. The vertical load distribution over pile-supported embankments can be predicted by several methods. Currently, the soil arching mechanism proposed by Terzaghi (1943) is still used as the assumption for existing design methods as the embankment load is transferred to the piles. Hewlett and Randolph (1988) developed three-dimensional model tests to investigate the arching within the soil by a semi-spherical model. However, the effect of geosynthetic reinforcement on the load transfer mechanism was not considered in these early methods.

The German standard EBGEO (2011) is based on the work carried out by Zaeske (2001) and Kempfert et al. (2004). Based on scale model laboratory tests and numerical calculations, Zaeske (2001) assumed arches appear as the semi-circular formation and the vertical load on soft soil is equal over the geosynthetic reinforcement. Another method that is used in many countries is BS 8006 (2010) based on the simplified analysis method proposed by Hewlett and Randolph (1988). Van Eekelen et al. (2011) proposed some changes to improve the British standard by considering the three-dimensional modeling of piles. Following the German Standard (EBGEO, 2011), the Dutch Design Guideline (CUR 226, 2010) was published in 2010 with some modifications to adapt to the Dutch circumstances.

Recently, new studies have been performed to validate and to improve the current design methods. As presented above, the main problem to investigate is the arching phenomenon acting within the fill material of the embankment. In order to determine the arching degree, the amount of arching is considered as a ratio of the load applied on the pile head with the total load. That can be presented as a percentage of the total load, A% which corresponds to the efficiency of load transfer E, where E = A% = A/(A+B+C) (with the load parts A, B, C given in kN/pile). Note that in many studies, geosynthetic is not used in the piled embankment to measure load types A and B, as presented by Zaeske (2001), Hewlett and Randolph (1988). Recently, in a series of studies conducted by Van Eekelen et al. (2012 a, b and c), geosynthetic is considered in field tests or experimental investigations.

Numerical methods are being widely used to simulate geosynthetic behavior as it may save time and cost to perform simulation. A variety of studies has been conducted based on the Finite Element Method (FEM) to analyze the arching phenomenon acting on embankments supported by geosynthetic-reinforced piles. Among many essential studies that use the PLAXIS program, Girout et al. (2014) and Pham (2019) have successfully simulated the behavior of geosynthetic concerning the load distribution on both 2D and 3D models. As well as these studies, the model of piled embankment supported by geosynthetic analyzed by another FEM program, ABAQUS has been succeeded to validate the experimental tests. The arching degree is considered by van der Peet (2014) as the calculated results are conducted to clarify various existing analytical methods. However, even though the study has presented the similarity of the arching shape with analytic methods, the procedure to compute the arching forces is needed to verify.

3. NUMERICAL MODELING

3.1. Model descriptions

A case study of an embankment supported by piles and geogrid reinforcement is learned from several studies: a new design model provided by Van Eekelen et al. (2013), observation obtained by Van Eekelen et al. (2012a and 2012b), and full-scale field tests conducted by Van Eekelen et al. (2012c). The height of the embankment is 2.0 m, its span 4.5 m in the adopted case 2.5 m in the direction perpendicular to its cross-section. The subsoil height, H_{sub} is 1.0 m. The embankment is supported by piles, the width of piles, b = 0.75m, the distance between two piles is 2.25 m. Geosynthetic reinforcement is used on the top of the piles. The geosynthetic reinforcement is placed on the top of the piles. Realistically, a sand layer is often placed between the piles and the geosynthetic reinforcement. However, the layer was removed in the field test, due to punching failure, which may occur in this layer at the edges of the piles.

In this study, three-dimensional (3D) modeling is used to simulate the behavior of the geosynthetic-supported piled embankment using the software PLAXIS 3D version 2020. The 3D numerical modeling consisted of the piles, embankment, geosynthetic, and subsoil. Due to the symmetric condition of the embankment, a typical part of the embankment is modeled as presented in Fig. 2.

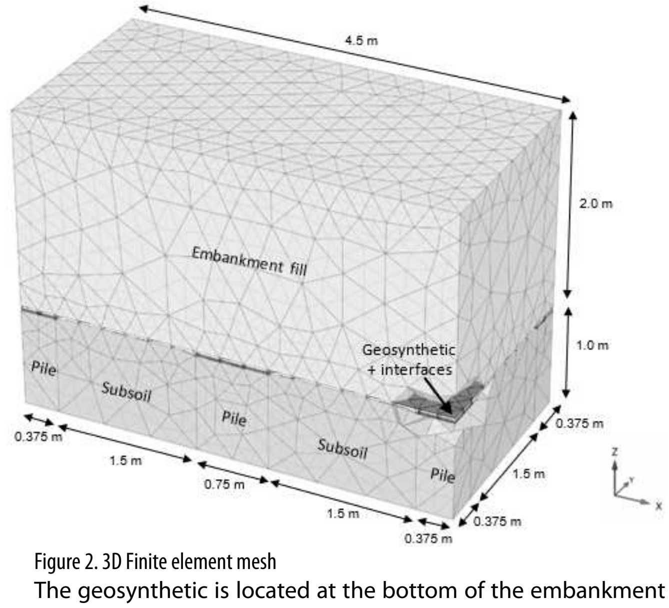


Figure 2. 3D Finite element mesh

The geosynthetic is located at the bottom of the embankment fill and is simulated by the geogrid element. Geosynthetic used in the study is only characterized by one secant stiffness with a linear elastic constitutive model $T = J \times \varepsilon$. The axial stiffnesses of the reinforcement material are set as J = EA1 = EA2, and the stiffness is fixed to anisotropic and the value in shear loading, is used as zero to simulate the material as the biaxial material behavior. In the study, J is set as 0, 1500, and 300 kN/m. The mesh is updated for each calculation phase in order to consider deformation due to the previous incremental displacement. All boundary conditions are

Table 1. Material properties used in the finite element simulations

Parameters	Symbol (unit)	Embankment fill	Subsoil	Pile	Interface Geosynthetic/Pile	Interface Geosynthetic/Fill
		Hardening soil	Mohr-Coulomb	Linear elastic	Mohr-Coulomb	Hardening soil
Unit weight	γ (kN/m^3)	17	18	15	15	17
Young's modulus	E (kN/m^2)	-	500	25×10^6	25×10^6	-
	E^{50}	80×10^3	-	-	-	80×10^3
Young's modulus for oedometric loading	E_{oed}	60×10^3	-	-	-	60×10^3
Young's modulus for un/reloading	E_{ur}	210×10^3	-	-	-	210×10^3
Power in hardening soil model	m	0.5	-	-	-	0.5
Poisson ratio	ν	0.2	0.2	0.0	0.0	0.2
Cohesion	c' (kN/m^2)	1	5	-	1	1
Friction angle	φ' (°)	45	10	-	10	36
Dilatancy angle	ψ (°)	15	0	-	0	15

standard conditions (bottom fixed in all directions, sides fixed in lateral direction). At the bottom boundary, z = 0 plane, the displacements are restricted in the three directions x, y, and z. The coefficient of lateral earth pressure K_0 is defined using the coefficient: $K_0 = 1 - \sin(\varphi)$. In the basic model, the surcharge, p = 5.0 kN/m^2 is applied homogeneously on the top of the embankment fill.

Construction was modeled in three phases aside from the initial phase. The first phase is to install the piles in the subsoil and to place geosynthetic reinforcement on the pile's top. In the second phase, the embankment fill is constructed by activating the structure above the geosynthetic and the displacement is set as zero. In the last phase, the surcharge is turned on to investigate its effect on the platform. In the study the effect consolidation is not focused, thus, the calculation phases use a plastic drained analysis. A parametric study was incorporated to highlight the influences. The model was altered one parameter at a time, while the others are kept at the baseline case values during the parameter difference study. The parameters included in this study were the geosynthetic stiffness and the surcharge.

3.2. Material models and parameters

The behavior of the subsoil layer is modeled by the Mohr-Coulomb (MC) model. The parameters used for this model are effective friction angle φ', effective cohesion c', dilatancy angle ψ, Young's modulus E, and Poisson's ratio ν. Meanwhile, the granular material of embankment fill is modeled by the hardening soil (HS) model, an advanced model for simulating the behavior of different types of stiff soils (Schanz et al. (1999). The HS model utilizes four basic parameters: the secant stiffness in standard drained triaxial tests E_{50}, the tangential stiffness for primary odometer loading E_{oed}, the unloading and reloading stiffness E_{ur}, and the power of the stress-level dependency of the stiffness m and shear strength (c', φ and ψ). The drainage type of both soils is used as drained.

The piles are modeled using a linear elastic. Interactions between piles and geosynthetic; and geosynthetic and filling material are simulated using interface elements, in which the friction is determined by a shearing box or inclined plane between granular material and the geosynthetic used. The constitutive models and the input parameters are given in Table 1.

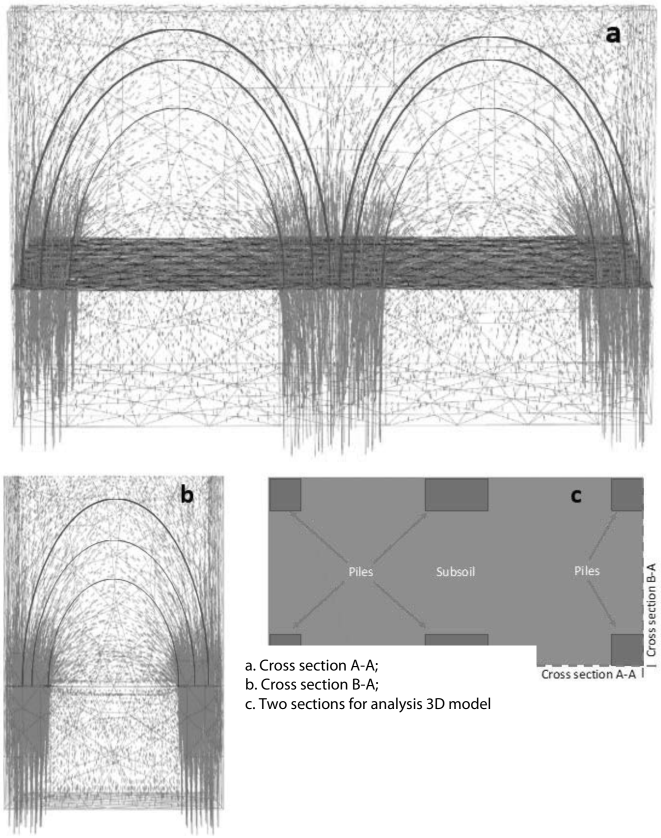
4. NUMERICAL RESULTS

4.1. Load distribution within embankment

The principal stress directions output of PLAXIS was used to determine the arch shape. Fig. 3 presents the arches formed between piles in two different cross-sections A-A (Fig. 3a) and B-A (Fig. 3b), which considers two sides of the model (Fig. 3c). As can be seen, the arches seem to be neither completely circular nor concentric as the shape is closer to oval-shaped form. This finding is close to the assumptions presented by Zaeske (2001) and in the method published by van Eekelen et al. (2013) as the Concentric Arches model. In fact, in the older study, the arches developed within the embankment are described as non-concentricity with non-uniform thickness, as well as, the arches do not form in the same size in the model of van Eekelen et al. (2013).

Fig. 4 presents the vertical stress distribution within the embankment and the subsoil. It can be noted that the 3D FEM represented the working of piles to support subsoil under the above load. The appearance of arching can be noticed as the stresses increase significantly in the areas above the piles, while the residual load (B+C) is distributed on the geosynthetic as the lower stresses can be obtained. However, the effect of geosynthetic reinforcement is not clearly provided in these typical results, even extreme stresses develop at the edge of the piles.

The load distribution over pile (A), GR (B), and subsoil (C) from the PLAXIS numerical model cannot be obtained directly due to the fact that total forces are not given in the output program. However, the stresses may be used to determine the load applied on the surfaces. If the stress points within the materials are used, the accuracy of calculated loads is not prevented because the impacted surface and the level of stress points are not alike. Nevertheless, the forces are possible to be achieved by using vertical stress applied on the interface over geosynthetic. Meanwhile, the total normal stresses above the top surface of the piles give the arching forces A, the rest provide the residual load over geosynthetic reinforcement (B+C). Even the loads B and C are not determined directly, the method should closely approximate the exact result as the arching degree can be calculated by forces type A and the combined forces B+ C. Thereby, the amount of arching is determined by the 3D numerical models and then compared with the results of the analytical methods. Fig. 5 compares the load distribution between the 3D numerical calculations and the analytical arching models presented in Van der Peet (2014) including Hewlett and Randolph (1988), Zaeske (2001), and Van Eekelen et al. (2012). As can be seen, load type A and the combination of B+C calculated by the 3D FEM are close to the Zaeske (2001) and Concentric Arches models (Van Eekelen et al., 2012), while the Hewlett and Randolph (1988) model underrated the arching degree. Note that the total load (A+B+C) calculated in numerical modes is slightly lower than in the analytical methods as it can be explained as the areas of each node providing the stress are not uniform, however, the difference of 7% is negligible. Besides the difference shown in the arching degree, the load distribution from the total load to piles is confirmed clearly in the 3D models and three analytical methods as the force type A is larger than the residual forces (B+C).



a. Cross section A-A;
b. Cross section B-A;
c. Two sections for analysis 3D model

Figure 3. Principal stress directions within embankment

4.2. Influence of geosynthetic stiffness and surcharge

In order to clarify impacts on the soil arching, some parameters were varied in the numerical, including geosynthetic's stiffness and the surcharge. The properties of the geosynthetic are not taken into account in analytical methods, which means the influences are not considered on the amount of arching. In the study, the use of geosynthetic over piles is modeled in three cases: without geosynthetic (J = 0 kN/m) and with geosynthetic (J = 1500 and 3000 kN/m). Fig. 6 presents the effect of the geosynthetic stiffness and the uniform loading on the arching in the embankment. In fact, the stiffness does not influence the amount of arching in the case of non-surcharge. Since the load increases with the variation of geosynthetic stiffnesses, the arching degrees change, but the trend is not uniform.

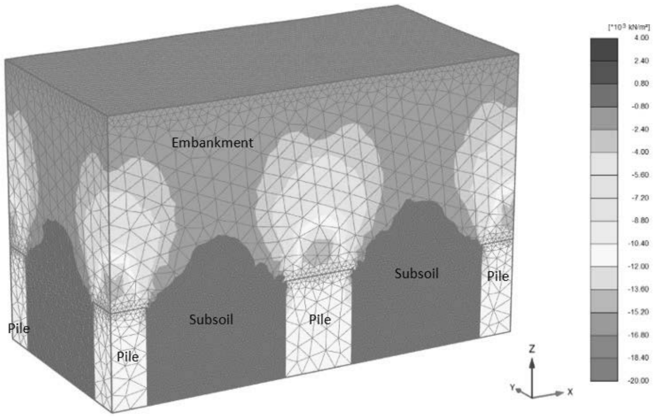


Figure 4. Vertical stress distribution

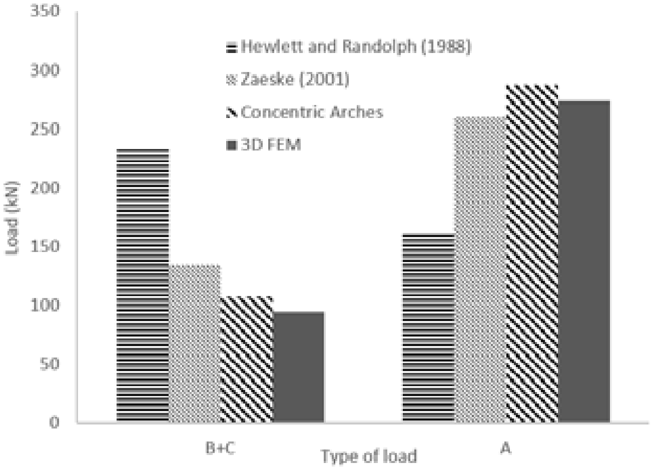


Figure 5. Comparison of load distribution between analytical and numerical methods

Another influence of the amount of arching can be seen in Fig. 6 concerning the effect of top load within the embankment for a given geosynthetic stiffness. The top load is varied as 0 kPa, 5 kPa,100 kPa, and 1300 kPa for each case of used geosynthetics. The last value of surcharge is selected in order to provide the ultimate limit state for the soil arching. As can be seen in the results, it is noticed that when the top load increases, the amount of arches increases as well, except one case of low loads (0 kPa and 5 kPa) is tested without geosynthetic support. As mentioned by van der Peet (2014), this relevance is not considered by analytical methods; however, by the finding of the numerical methods, the appearance of a high surcharge above embankment may affect the piles as a larger part of the total load may transfer directly to the piles. In addition, the increase in volumetric weight of the embankment fill and top load may affect differently on the arching.

Fig. 7 describes the effect of geosynthetic stiffness on the total settlement in the numerical models. The use of geosynthetic is changed as the stiffness varies between 1500 kN/m and 3000 kN/m, and no geosynthetic is used in the last case. Generally, the geosynthetic reinforcement reduces the total settlement of the embankment. The normalized settlements for the cases with geosynthetic are lower than 1.0 (settlement without using geosynthetic reinforcement). Additionally, using stiffer geosynthetic can decrease the settlement, but the effect is limited. The amount of top load affects differently on the relation between geosynthetic stiffness and settlement.

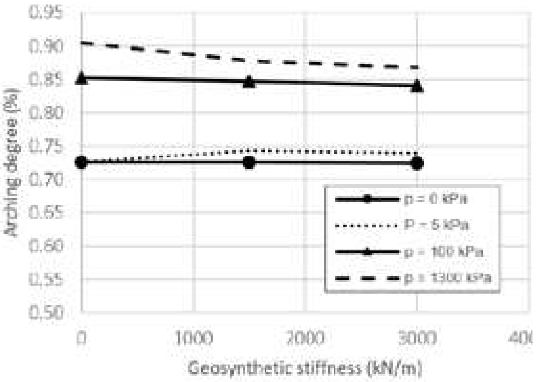


Figure 6. Effect of geosynthetic stiffness and surface load on arching

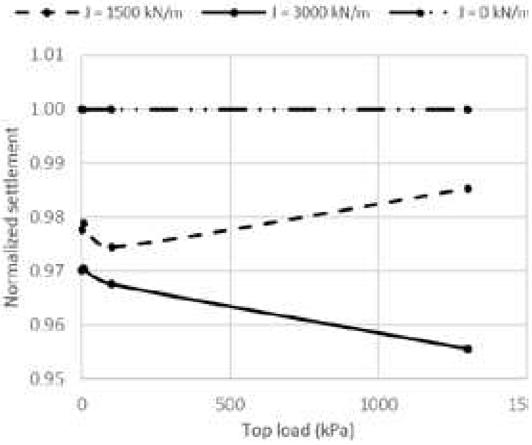


Figure 7. Effect of geosynthetic stiffness on settlement

5. CONCLUSIONS

Three-dimensional numerical modeling has successfully analyzed the model of the geosynthetic-reinforced pile-supported embankments in order to investigate the arching within the embankment. The formation of stress arches has been modeled through the principal stress directions in the numerical model and the similarities to the Concentric Arches model (van Eekelen et al. 2013) and the model proposed by Zaeske (2001) are presented. Moreover, the arching degree has been calculated by the numerical models; thereby, the load distribution has been clarified for piles and subsoil reinforced by geosynthetic. Compared to the existing analytical methods, the numerical calculation shows the similarity, and it seems to validate clearly the Concentric Arches model.

The influence of most of the varied model parameters has been identified such as the geosynthetic stiffness and the surcharge. For the effect of geosynthetics, the numerical calculation agrees with the predictions of the existing analytical method, which is specifically presented by van der Peet (2014). In contrast to analytic methods, 3D modeling has shown that the top load may increase the arching degree. The settlement of soil layers is not focused significantly in the present study, however, based on a parametric study, the effectiveness of using geosynthetic to reduce settlement is presented as a stiffer material that may limit the total settlement.

For further studies, numerical studies can be used continuously to validate other studies on arching formation, which show different shapes by using image techniques in physical experiments. Although the Concentric Arches model has been validated by 3D numerical simulation, the results can be improved by considering new interfaces affecting the reinforced system. Furthermore, the interface behaviors may be considered the interaction between subsoil and pile material through the length of the piles. Moreover, the parameters for surface interaction between geosynthetic and soil; and piles and subsoil should be identified based on some laboratory tests.

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