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TECHNICAL PAPER

Numerical Analysis of Load Transfer Mechanisms Within Embankment Reinforced by Geosynthetic Above Cavity

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Abstract

Geosynthetics have been widely used as a specific reinforcement to support embankments constructed in areas subject to localized sinkholes. The solution works based on several mechanisms such as soil expansion, effect of membrane, friction, and load transfer. However, the load transfer mechanisms have been underestimated due to simple assumptions used in the common existing design methods. The study develops a numerical model to approve the presence of arching within the embankment reinforced by geosynthetics over the cavity. Based on a referenced study that combined experimental and numerical works, the finite element method (FEM) has been used to develop a model of cavity problems. Thereby, the performance of different numerical methods and the ability to reproduce a full-scale experiment have been illustrated according to the analysis of displacement and load distribution acting within the embankment platform over the cavity. The influences on the expansion and the load transfer mechanisms acting inside the reinforcement system have been clarified by a parametric study considering surcharge, embankment height, and friction angle of the embankment.

Keywords FEM · Geosynthetics · Load transfer · Cavity

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1 Introduction

Currently, the need for economic development and infrastructure has led to an increase in construction projects including urban roads and highways. However, the stability of structures faces risks from geological hazards. One of them, a sinkhole or cavity can appear in the subsoil and affect the structure's safety. The phenomenon can be caused by the effect of groundwater such as underground erosion, groundwater extraction, or the collapse of underground works. When sinkholes appear, the road subsides; sinks can be destroyed due to the collapse of the embankment. Therefore, it is very necessary to prevent the appearance and limit the influence of sinkholes. Among many technical solutions, geosynthetics can be used to protect the structure or to limit deformation and settlement of the road surface.

As a sinkhole appears and affects the structures (Fig. 1), it is very difficult to solve the problem due to the complication of the phenomenon. Usually, the cavity is needed to be refilled. The materials used to fill the cavity can be crushed stone, compacted sand, cement mortar, or a combination of them. Then, the drainage ditches are created with the construction of a new road surface; after that, load testing and monitoring are needed to conduct as engineering requirements. The main difficulties that the solutions need to handle are technical requirements, construction time, and especially construction costs. Therefore, geosynthetic solutions applied in the construction process can limit the effect of sinkholes on the structures, and provide economic and technical efficiencies.

Many studies have focused on the load transfer mechanisms within the embankment reinforced by the geosynthetic for the areas where the cavities can appear.

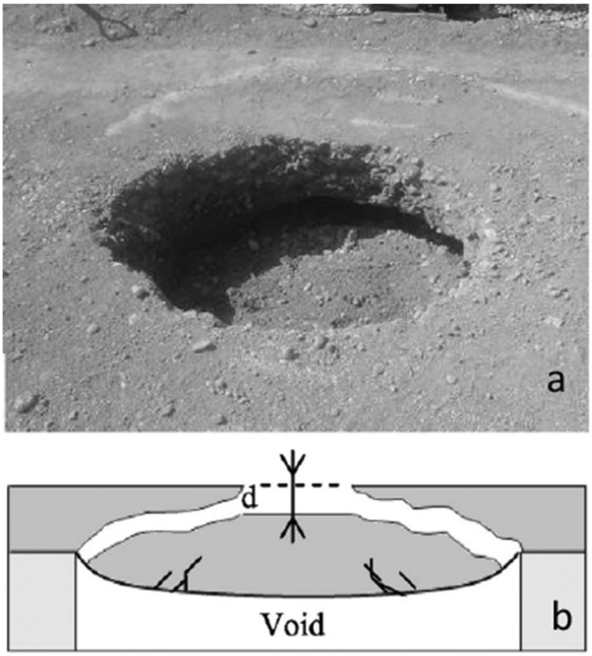

Fig. 1 Behavior of the surface soil overlying breaking cavity (Huckert et al. 2016). **a** Surface view. **b** Collapse mechanism

Recently, Huckert et al. (2016), Villard et al. (2016), Pham et al. (2018), and Pham (2019) have improved the understanding of the complicated mechanisms as the soil expansion and the load distribution acting within the granular embankment. In these studies, various research methods have been used, such as full-scale experiments, physical experiments, and numerical solutions. Due to the benefits of the numerical methods as saving time and requesting reasonable cost for testing, the modeling results have provided important improvements to better understand the geotechnical problems, compared to the experimental works. Many studies have used numerical methods to investigate the problem; Villard et al. (2016) validated a full-scale experiment by a combination of the finite element method (FEM) and the discrete element method (DEM) (FEM & DEM) and then developed several models to investigate the load distribution. In which, DEM and FEM are used to reproduce the behavior of soil and geosynthetic, respectively. Furthermore, the finite element method has been used by Girout et al. (2014) to study the arching effect and by Pham (2019) to successfully simulate the load transfer mechanisms compared to physical experiments. However, there are not many comparisons between numerical methods that have been conducted in order to evaluate the capability to reproduce the geotechnical problems and the performance to investigate the complex mechanisms. Therefore, the present study has been conducted using FEM to reproduce a considerable study performed by Villard et al. (2016). The comparisons between results of FEM and the coupling of DEM and FEM have been illustrated by considering the displacements and load distribution acting within the embankment; then, the arching effect has been analyzed by FEM to improve the knowledge for the phenomenon.

2 Embankment Reinforced by Geosynthetic Above Cavities

2.1 Mechanisms

Geosynthetic materials have been widely used to reinforce and protect the stability of structures, and this solution can completely prevent the risks associated with deep sinkholes (Blivet et al. 2002). Acting as a "hammock," geosynthetic reinforcement such as geotextiles or geogrids can minimize surface settlement (Ziegler 2017), a problem caused by the appearance of a sinkhole. The effect of geosynthetic materials on the embankment is highly dependent on the mechanisms developed during the formation of the cavity. Complicated mechanisms include the membrane effect, the friction between the material and surrounding soils, the soil expansion within the embankment, and the load transfer mechanisms. At present, the mechanisms in the system of the geosynthetic-reinforced embankment have not been fully investigated due to the wide range of influences related to the formation of a cavity, geological kinematic, and properties of filling soil.

During the opening of a sinkhole or cavity, various mechanisms may occur within a geosynthetic-reinforced embankment. In fact, the complex mechanisms have been taken into account in many studies:

- The membrane effect of the geosynthetic material over cavity;

– The friction effect between the geosynthetic and the upper and lower soils in the anchorage areas around the cavity;
– The soil expansion of the granular material inside the embankment;
– The load transfer acting within the embankment overlying cavity.

Concerning realistic problems, the main challenge for designing the solution is to estimate the surface settlement on the top of the embankment as geosynthetics are used below as reinforcement. For a granular soil layer, during the collapse, the movement of particles allows for an increase in the volume of the soil above the cavity. In fact, the expansion coefficient Ce has been defined by the ratio between the final and the initial volume of soil located above the cavity (Villard et al. (2000)). The soil expansion could appear in truncated or cylinder-shaped soil collapse, leading to a considerable decrease in the soil surface settlement. Currently, a global expansion factor has been taken into account, and this can lead to an overestimate of the expansion mechanisms. In order to determine this coefficient, it is necessary to handle the volume of deformed shapes of both the soil surface and the geosynthetic deflection. Many previous research works concluded a parabolic fit (BS8006 (2010), EBGEO (2010), and Giroud et al. (Giroud 1995)), and hence, it is possible to obtain the Ce value as the ratio between the maximum deflection of geosynthetics (Dg) and the surface settlement (Ds). Based on a simplifying assumption as the shape of the deformed zone is as paraboloid (Blivet et al. 2002), a relation between surface settlement (Ds), the geosynthetic deflection (Dg), the embankment height (H), and the expansion coefficient (Ce) can be demonstrated as:

$$\mathrm{Ds} = \mathrm{Dg} + 2\mathrm{H} \times (1 - \mathrm{Ce}) \tag{1}$$

Several shortcomings are still appearing due to the simple assumptions that had been adopted by Briançon and Villard (2008) and have been continuously investigated by a full-scale experiment conducted by Huckert et al. (2016) and numerical works performed by Villard et al. (2016). Nevertheless, this assumption is not approved because the shape of both surface soil and geosynthetic are not exactly parabolic (Villard et al. (2016) and Pham et al. (2018)). Using a precise method to evaluate the volume of the deformation zone, Pham et al. (2018) presented exact values of Ce with more complicated assumptions used to fit the deformed surfaces; however, the difference is not significant compared to the result computed considering simple assumptions as shown in Eq. 1. Furthermore, Feng et al. (2017) proposed a formula to determine the expansion coefficient Ce, considering the relation between the maximum and the initial void ratios; however, it is necessary to validate the method by experiment. Then, up to now, no method can give a precise relation between the expansion coefficient and the geometrical parameters of the problem such as friction angle and dilatancy of filling soil.

Another complicated mechanism, the arching effect, is defined by the ability of load transfer between different locations by considering a relative displacement (Briançon and Villard 2008). Within an embankment fill, soil arching is typically defined as load transfer between a yielding portion (collapsed soil) and adjoining stationary portions. Taking the cavity presence into account, the volume of collapsed soil should be considered, and it could be defined by different assumptions: the shape of subsidence soil over the cavity is widely assumed as a truncated or a cylindrical shape. Additionally, if shearing mechanisms occur, an arch could appear within the embankment over the cavity. Even if such design methods recommend evaluating the arching effect from simplified assumptions, the soil arching is not well identified due to the effect of parameters such as the cavity opening process, the geometrical conditions, geosynthetics, and the soil physical characteristics. Villard et al. (2016) presented the efficiency ratio (*E*) which can be defined by the ratio between the load determined on the sides of the cavity and the weight W_s of the cylindrical part of the soil sited over the cavity in order to analyze the load transfer acting within the granular embankment. From the load applied on the geosynthetic placed above the cavity F_g, the efficiency of the load transfer inside the granular embankment can be identified as:

$$E = \left(W_s - F_g\right)/W_s \tag{2}$$

Even the two first mechanisms have been studied completely for a long time, these two last complex mechanisms acting within the embankment are still being considered in many research studies. In fact, the presence of these mechanisms has been also ignored in the common design methods, BS 8006 (BS8006 2010), or underestimated in the German standard, EBGEO (2010), as Ce is a uniform factor.

2.2 Experiments in this Field

In order to investigate the arching effect, Costa et al. (2009), Zhu et al. (2012), and Pardo and Sáez (2014) reproduced the trapdoor test that is first developed by Terzaghi (1936). Costa et al. (2009) examined failure mechanisms utilizing an active movement of a deep trapdoor under a granular soil; meanwhile, Pardo and Sáez (2014) illustrated an increment in stress in the area that is far from the trapdoor. Zhu et al. (2012) tried to illustrate the influence of the arching effect within overburden sand and the interaction between soil and geosynthetic over the localized cavity. However, the image acquisition system used to analyze the stress has affected the accuracy of these studies. Then, Huang et al. (2015) developed a 2D experimental testing and numerical simulation based on the discrete element method to model a platform of geosynthetic-reinforced soil over a channel. Nevertheless, the use of aluminum bars to simulate soil particles leads to many shortcomings concerning realistic conditions. It is concluded that the trapdoor test which causes the gradual movement of the cavity opening has got significant considerations from many authors; however, a different opening method, the progressive opening of the cavity, is also necessary to be studied.

Currently, numerical methods are very useful in studying the load transfer mechanisms and the soil expansion within the soil reinforcement system by using geosynthetic materials above the cavity. The finite element modeling method has been successfully used to simulate the vertical load distribution (Cui et al. (2007) and Potts (2007)), reinforcing the reinforced earth retaining wall (Yu et al. 2015) and load transfer mechanisms in geosynthetic soil reinforcement (Girout et al. (2014) and Pham (2019)).

In a recent study on a cavity, Pham et al. (2018) used a physical experiment to simulate underground sinkholes. The study focused on the method to open the cavity in two different modes, the first one is named the trapdoor process: the cavity is formed suddenly, quickly, and the second one is the progressive opening: the cavity develops by increasing diameter. In this study, several accurate devices were used to measure ground settlement and deformation of geosynthetic materials. A tactile pressure sensor is placed in a few places on the geosynthetic to monitor the change in stress acting along with the reinforcement during the cavity opening. The soil expansion and the mechanism of load transfer within the embankment were analyzed when the conditions of the model are changed, such as geosynthetic stiffness and embankment height and fill materials. Then, the research results of Pham et al. (2018) were simulated and verified by Chalak et al. (2019). Thereby, the study shows the heterogeneity of the expansion coefficient within the embankment and the important influence of the ratio between the embankment height and the cavity diameter on the load transfer mechanism.

2.3 FEM & DEM Numerical Study of Villard et al. (2016)

Considering the influence of the cavity formation process on the load distribution, Villard et al. (2016) compared the experimental results with the calculations obtained by the numerical models combining the finite element method and the discrete element method (FEM & DEM), to simulate the behaviors of geosynthetic and granular material, respectively. Two processes to open the cavity were considered as a progressive opening and a gradual downward process, in order to understand the influence on the load distribution. The simulation has succeeded to reproduce the geosynthetic behavior as presenting the difference in the shape of the geosynthetic deflection between both opening procedures. Moreover, considering Terzaghi's formulation (Terzaghi (1943)) for the calculation of the load acting on the geosynthetic sheet, the numerical results showed that the values of the soil pressure ratio could reach 1.3 when considering ratios between embankment height and cavity diameter (H/D) between 0.25 and 2, and the use of the active earth pressure ratio K_a is not well adapted. Moreover, the non-uniform shape of load distribution above the cavities was noted, and it is influenced by the opening process: a conical shape for the progressive opening and constant for the gradual downward process. Taking into account the change in local porosities within the granular embankment, the authors also confirmed the difference in the expansion coefficients and the dependence with two opening processes. A value of 1.037 was found as the expansion factor for the gradual downward opening, and values of 1.048 and 1.036 were obtained for the progressive process.

3 Numerical Model

The numerical calculations are done using the finite element code PLAXIS (2020). Due to the symmetric conditions, the experimental tests are modeled using a two-dimensional (2D) axisymmetric condition in the drained condition. The configuration is used following the referenced study performed by Villard et al. (2016). The cavity area is located from the origin coordinates and has a radius of 1.1 m. In numerical models, the dimensions and the number of elements are related to the experimental height of overlying soils and cavity width. The mesh is made considering 15-node triangular elements. And it is refined near the cavity area and is updated at the beginning of each phase to consider the deformation from the previous incremental displacement. The used element size and dimension of the mesh are respectively set equal to 1.0 and 0.143 mm. Horizontal movements are blocked along the vertical boundaries. The bottom of the numerical model is fixed in the horizontal and vertical directions.

Although in the study of Villard et al. (2016), two processes for cavity opening are considered; however, in the present study, only a progressive opening of the cavity by an increase of the cavity diameter is modeled. In fact, not only presented in the referenced study, in an experimental study conducted by Pham et al. (2018), the effect of the progressive opening of the cavity on the deformation of the platform was stronger than the other, a gradual movement process. Thus, the considered opening method is modeled in several steps, 5 polygons are deactivated step by step (the polygons closing to the opening center are deactivated first). Thereby, this increased diameter process allows reproduction in a simplified way of the cavity opening. The geosynthetic sheet located between the overlying soil and the foundation soil is modeled using a geogrid element as an anisotropic condition. The behavior of geosynthetic is assumed as a linear-elastic behavior and follows the equation $T = J \times \varepsilon$, and the tensile stiffness is equal to 3000 kN/m and 250 kN/m in the longitudinal direction and the transversal direction, respectively.

Figure 2 presents the geometrical configuration of the model, the height of the overlying soil layer is set as 1.0 m, the width of the model is 3.0 m, and the radius of the cavity in a half-model is 1.1 m. Following the procedure to simulate the cavity opening, the foundation soil, which is located at the base of the model, is separated into 12 components, including 11 parts used to simulate the cavity components.

As can be seen in Fig. 2, two different interface elements are used to model the interaction surface between soils and the geosynthetic. The first one is the interface between the geosynthetic (GSY) and overlying soil. This interface is named Overlying soil/GSY. The second one, Foundation soil/GSY, is the interface between the foundation and the geosynthetic. In fact, the interface friction angles between geosynthetic and soil or metallic material were obtained from inclined tests or determined by the relevance with the friction angle of the soil as $0.8 \times \varphi$ (Villard et al. (2016)). The other parameters of these interfaces are used following the soil properties. The MC model has been used to successfully simulate the soil behavior in many studies such as Cui et al. (2007), Potts (2007), and Pham (2019), especially no significant difference in the results has been found between the use of Mohr–Coulomb (MC) model and the complicated ones. The MC model was suggested for the soils. The constitutive models' parameters were used as those presented in the article Villard et al. (2016), as presented in Table 1. In addition, the lateral earth pressure coefficient at rest K_0 is defined using the coefficient at rest $K_0 = 1 - \sin\varphi$.

For each numerical calculation, several steps are adopted to model the opening. The first phase consists of applying the initial stress conditions. After this initial phase, a large deformation analysis is used. The calculation steps are defined due to the consideration of two opening modes. A series of continuous phases consist of a deactivation process to model the increasing cavity diameter.

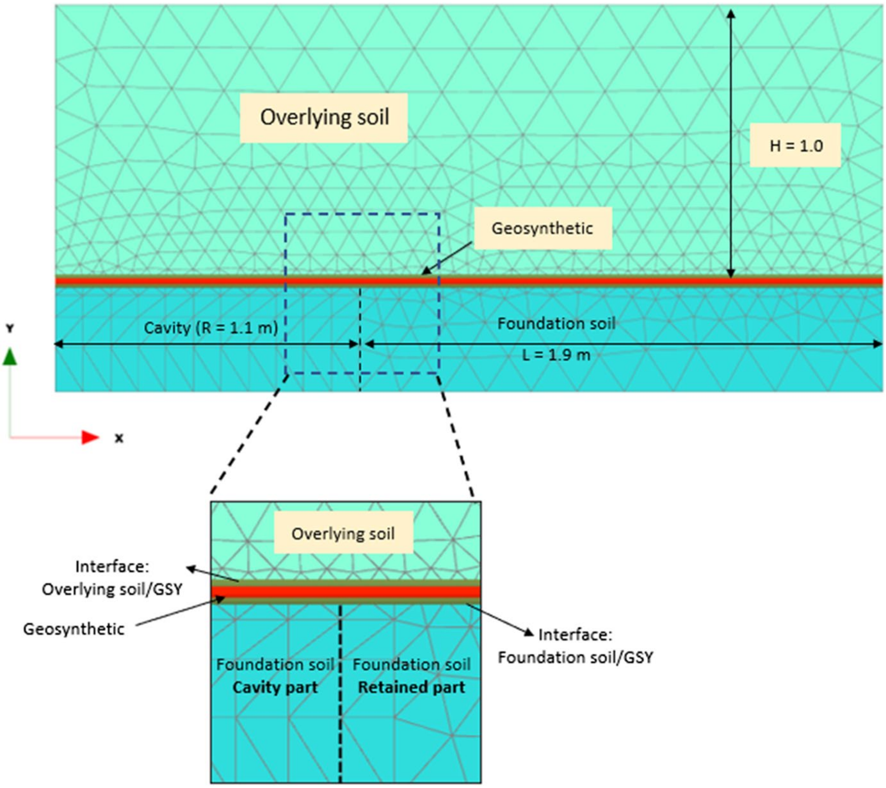

Fig. 2 Geometrical configuration for the numerical calculation

Table 1 Material properties used in the finite element simulations

Parameters	Symbol (unit)	Overlying soil	Foundation soil	Interface geosynthetic/ overlying soil	Interface geosynthetic/foundation soil
Constitutive model		MC	MC	MC	MC
Unit weight	γ (kN/m^3)	15.65	17	15.65	17
Young's modulus	E' (kN/m^2)	19×10^3	22×10^3	19×10^3	22×10^3
Poisson's ratio	ν	0.3	0.3	0.3	0.3
Cohesion	c (kN/m^2)	0	10	0	10
Friction angle	φ (°)	36	50	23	40
Dilatancy angle	ψ (°)	6	20	0	10
Initial void ratio	e	0.74	0.6	0.74	0.6

4 Results and Discussion

4.1 Displacements Within Embankment Above Cavity

The surface settlement of the overlying soil layer and the geosynthetic deflection are computed by FEM simulations and then compared with the results obtained by FEM & DEM (Villard et al. (2016)). As can be seen in Fig. 3, FEM results are in accordance with the results obtained based on a combination of FEM & DEM. The two numerical methods match well the experimental observations. Especially, the shape of the surface settlement modeled by FEM near the cavity center is very similar to the findings achieved by the experimental and FEM & DEM works. The great agreement between the experimental and the two numerical results allows to well describe the soil expansion acting within the filling embankment. According to the values of surface settlement and geosynthetic deflection obtained by FEM, 0.15 m and 0.18 m respectively, the volume of the soil expansion within the overlying soil may not change significantly.

Due to many essential studies such as Pham et al. (2018) and Villard et al. (2016), the cavity opening following a process of increasing diameter, the displacements on surface settlement, and geosynthetic is larger than those in gradual movement on the

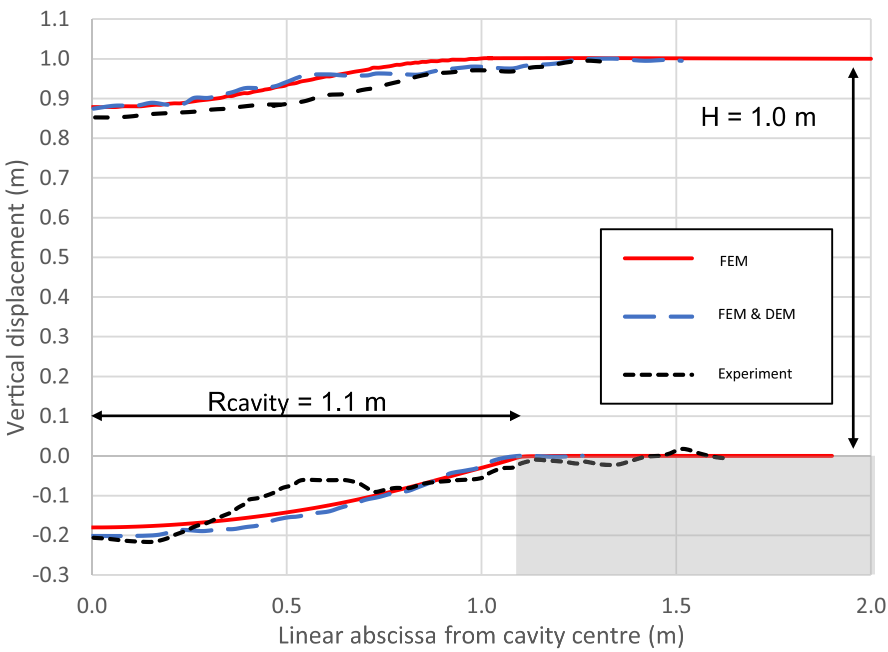

Fig. 3 Surface settlement and geosynthetic deflection comparison between numerical and experimental results

cavity opening. This can be explained by the changes in porosity or void ratio during the cavity-forming as presented in Fig. 4. It can be noted that the porosity computed by FEM & DEM or the void ratio obtained by FEM is changed after the cavity opening. Compared to the initial values for the anchorage areas, in the cavity areas, the void ratio increases to approximately 1.0 (Fig. 4b), and the porosity of soil reaches 1.25 (Fig. 4a). Moreover, another agreement between the two numerical methods can be noticed as the significant increment occurs along the geosynthetic as it may identify the shearing areas of soil. This finding can lead to the reason for the greater displacements in cases of cavity opening by a progressive process. However, the differences between FEM & DEM results can be seen as the maximal changes in porosity are shown near the area between the cavity and anchorage areas; meanwhile, the rise in the void ratio is seen on the top of the overlying soil (see Fig. 4). Due to the presented results, the change in volume of the deformed zone inside the embankment over the cavity has been clarified following the variation of voids of the deformed soil.

4.2 Load Distribution in the Granular Embankment

The change in orientation of the principal stresses may show the shape of the arching effect, which causes the load transfer within the granular embankments. Figure 5 presents the principal stresses obtained by FEM & DEM (Villard et al. (2016)) and FEM. Both numerical methods, with an a-half model, show clearly the arching effect with a curved shape formed between the deformed zone over cavity and anchorage areas. Especially, the appearance of full arches located above the geosynthetic can be seen in the results of FEM; meanwhile, for the results obtained by FEM & DEM, that is not clear. The appearance of arches within the granular embankment is to demonstrate the load transfer mechanisms acting within the soil.

The load distribution is investigated by considering the ratio between the final stresses and initial stresses (σ_f/σ_i) acting on the upper face of the geosynthetic during the cavity opening (Fig. 6). In the FEM models, the varied stresses are calculated based on the vertical stresses applied on the interface between geosynthetic and overlying soil. The results of FEM & DEM (Villard et al. (2016)) are in accordance as the stresses in the anchorage areas seem to increase as the ratio is higher than 1.0; meanwhile, an opposite trend is found in the cavity areas. Moreover, the shape of the load distribution seems to be conical.

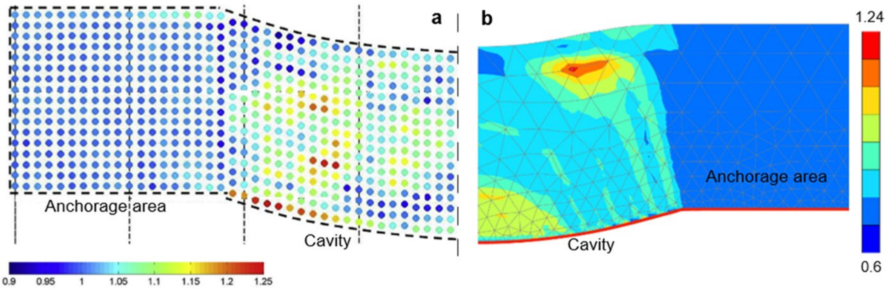

Fig. 4 Changes in porosity of soil obtained by FEM & DEM (Villard et al. 2016) (**a**) and void ratio in FEM models (**b**)

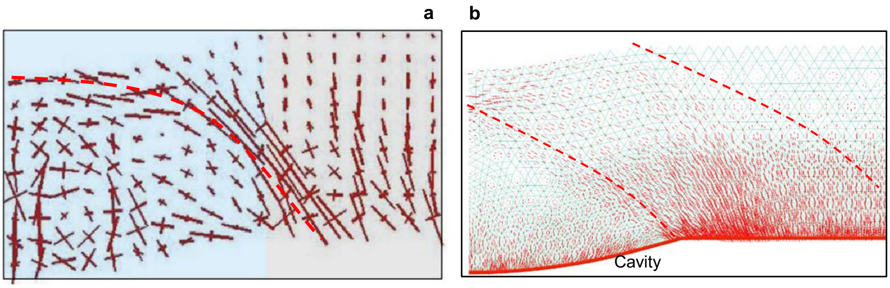

Fig. 5 Principal stresses within overlying soil observed by FEM & DEM (**a**) and FEM (**b**)

Thus, it can be noted that the load distribution is well reproduced by FEM as the stresses reduce in the cavity area, but increase in the anchorage area during the cavity opening.

The efficiency of load distribution is computed by Eq. 2 considering the increasing diameter process of the cavity opening (Fig. 7). Moreover, the responses of the surface settlement (Ds), the geosynthetic deflection (Dg), and the relevant expansion coefficient (Ce) are also determined following the opening of the cavity; thus, the effect of the displacement of embankment fill on the load distribution is estimated. Note that during that process, the diameter of the cavity varies from 0.2 to 2.2 m, corresponding to the variation of cavity radius from 0.1 to 1.1 m; hence, the cavity and anchorage areas are altered accordingly. As can be seen in Fig. 7a, a significant influence of the cavity-forming as increasing diameter on the load distribution is noted as the efficiency decreases following the evolution of the cavity width after it remains the completed form. In fact, the efficiency of load transfer remains around

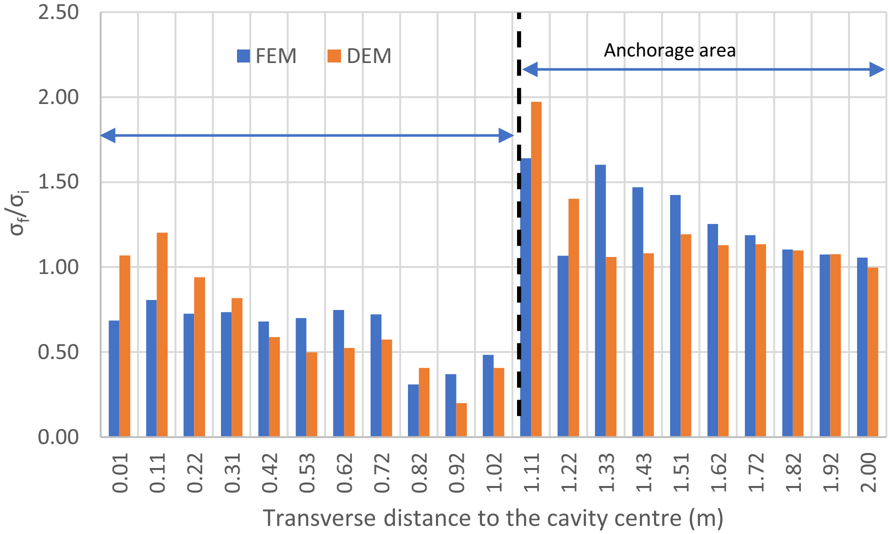

Fig. 6 Variation of the vertical stresses acting on the geosynthetic

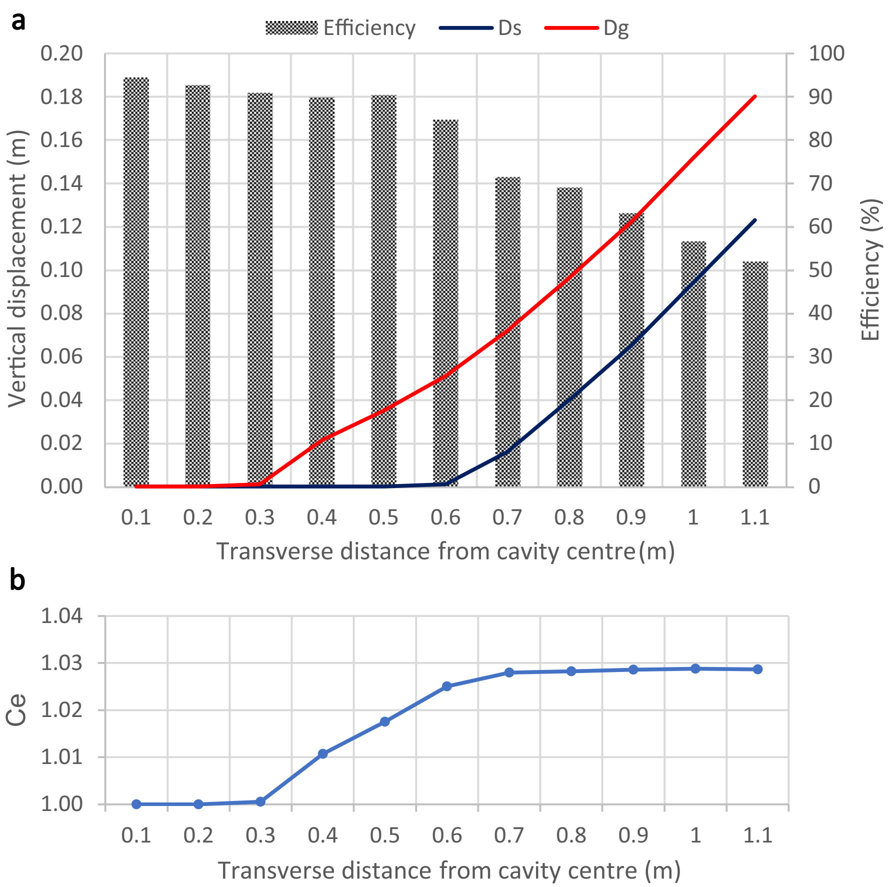

Fig. 7 Responses of efficiency of load transfer & displacements (**a**) and expansion coefficient (**b**) on the increasing diameter process of cavity

90% in the first stages of cavity opening; then, it begins to decrease since the cavity radius is 0.6 m, before achieving the minimal value of 52%.

Concerning the vertical displacements of surface soil and geosynthetic, when the cavity begins to open, the overlying zone above the cavity seems not to be deformed. Then, both surface settlement and geosynthetic deflection increase with the development of cavity diameter. The relevance between the arching effect, which allows the load transfer from the cavity to anchorage areas, and the displacement is clarified due to the fact that the load applied on geosynthetic responses correspondingly during the evolution of the cavity diameter. This result is essential for realistic conditions; indeed, even the cavity appears under the existing embankment; if the ratio between embankment height and cavity diameter is large enough or the cavity appears at a deep level, the above structure may be protected. Additionally, the expansion coefficient of filling soil (Ce) is estimated by Eq. 1 as it is relevant to the insignificant displacements in the three first steps of the cavity opening. In the four next stages, Ce increases after reaching the maximal value, 1.029 (see Fig. 7b), a close value to the FEM & DEM results presented in Villard et al. (2016).

4.3 Parametric Analysis

In this section, a series of parametric finite element analyses were performed in order to investigate the effect of influencing parameters on the performance of the geosynthetic-reinforced soil above cavities. These parameters consist of the surcharge, the embankment height, and the friction angle of the embankment. The numerical analysis was conducted considering displacement for both surface filling soil and geosynthetic; thus, the influences on Ce are also illustrated. In addition, the arching effect reflected by the efficiency of load transfer is also examined. For each parameter study, the other parameters of the problem analyzed in the above sections were kept to be constant.

In the basic model, no top load was applied on the embankment. In the parametric study, the top load was varied upward up to 120 kPa, including a value of 15.65 kPa which equals the load of a 1-m-height embankment, to investigate its effect on the displacement and load distribution. The results can be found in Fig. 8. The numerical results show the independence of the efficiency of load transfer on the top load. When the top load increases or even no top load is applied on the embankment, the efficiency changes a negligible quantity as it varies from 52 to 56%. Regarding the displacements, a clear trend can be seen for both surface settlement and geosynthetic deflection as the vertical deformations of fill and reinforcement develop when the top load increases. It is clear to notice that a minor difference in the load transfer efficiency causes an increment on the remaining load on geosynthetic at the cavity area, while the top load increases. Therefore, this allows the rise of geosynthetic deflections.

In the next strategy of the parametric study, the embankment height is changed to 0.5 and 2.0 m, involving the value of 1.0 m of the basic model. It is evident to see the clear trend of the efficiency of load transfer considering the effect of embankment height. Since the height of the granular embankment increases 4 times from 0.5 m, the amount of efficiency raises approximately 3.5 times, from 20 to 70%. This means the load acting on the geosynthetic seems to be kept unchanged, and hence, the geosynthetic deflections are nearly the same during the variation of the embankment heights. On the contrary, the surface settlement reduces significantly since the embankment is thicker. This agrees with a finding presented in Fig. 7 as with higher embankments or deeper underground cavities, the effect on the surface soil is limited. This point demonstrates that an equal settlement plane may exist.

Moreover, the total amount of a load of 2-m-height embankment equals the case 1-m-height embankment plus 15.65 kPa as analyzed in Fig. 9. It can be noted that the load forming by granular materials permits much higher efficiency than the uniform load as the results are 76% and 56%, respectively. This can be explained as in the lower embankments, the top of soil arching, which permits the load transfer, is slighter than the higher embankments; this explains the efficiency increases

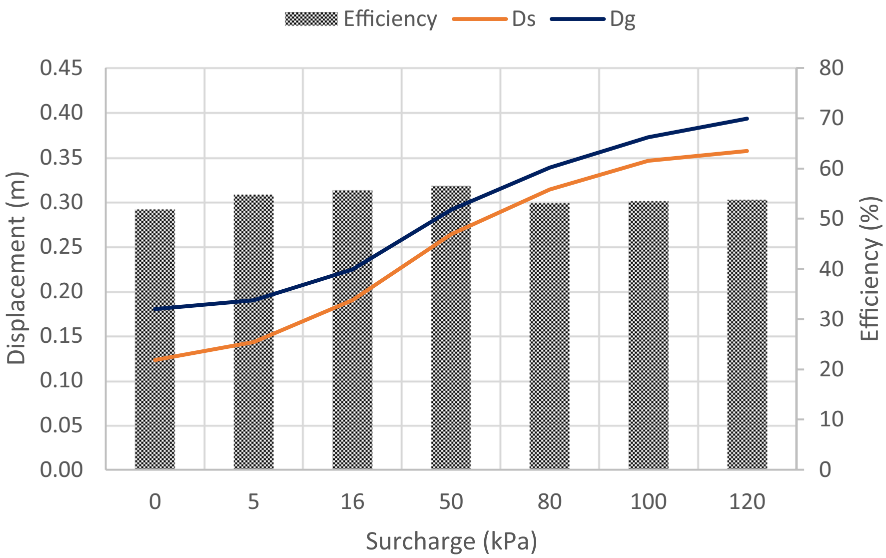

Fig. 8 Effect of surcharge on displacement and efficiency of load transfer within embankment

following the higher embankment. Thus, if the top load appears over the lower arches, it is transferred less effectively to the anchorage areas.

Concerning the last approach of the parametric study, numerical results were determined for friction angles between 25 and 45 degrees, in regular intervals of 5 degrees. The other material parameters were not changed, but note that due to the use of default values for the advanced parameters, the value of K_0 changes also. As presented in Fig. 10, an approximately linear relation between the friction angle of the fill φ and the efficiency of load transfer can be seen as the load may transfer more effectively in the cases of the embankment filled by higher friction

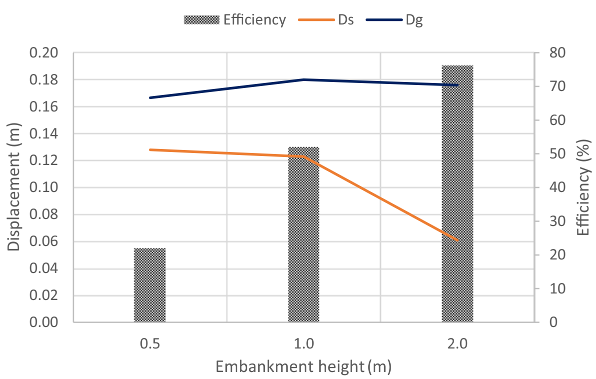

Fig. 9 Effect of embankment height on displacement and efficiency of load transfer within embankment

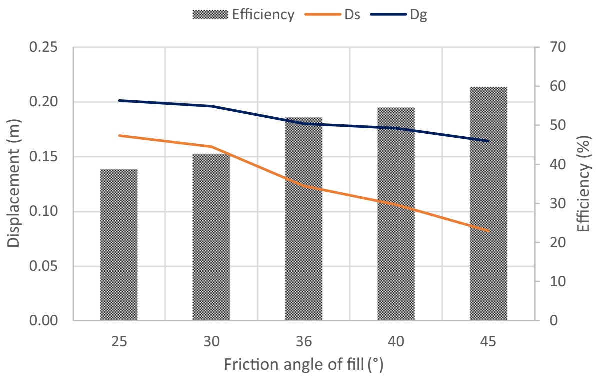

Fig. 10 Effect of friction angle of embankment on displacement and efficiency of load transfer within embankment

angle materials. This is related to the displacements of the surface soil and the reinforcement materials as both factors reduce when the efficiency improves.

The value of Ce in the existing design method is assumed as a uniform factor. However, due to many tests performed in the experimental of Pham (2019) and Pham et al. (2018) as well as in the numerical modeling of Villard et al. (2016), Ce may be influenced by many impacts such as the method to open the cavity, embankment height, or type of filling materials. Figure 11 presents more influences on the complex coefficient as top load, friction angle of the fill, and embankment height as well. Regarding the effect of top load, the response of Ce seems not homogeneous as it increases with a range of low loads but reduces since the surcharge develops from 80 to 120 kPa. This can be relevant to the change in the efficiency of load transfer for the high range of load as presented above. For the effect of the friction angle of the fill, a clear trend can be seen. In fact, through 5 regular intervals of 5 degrees of friction angle, Ce rises from 1.105 to over than 1.040. This finding seems to agree with the values presented by Villard et al. (2016), and to match the range proposed in Pham et al. (2018), even the tested soil and geosynthetic are not the same. Concerning the effect of embankment height, the relevance is not really clear as it can be assumed that the height of the fill seems to affect insignificantly the soil expansion. In fact, this result is similar to the conclusions of Pham et al. (2018). According to these newly considered impacts, it is evident to conclude that the expansion coefficient is not uniform and may be affected by various parameters.

5 Conclusions

A numerical program based on the finite element method is used to study the behavior of embankments reinforced by geosynthetic beneath a localized sinkhole. It has shown that the 2D numerical simulation results represent a good

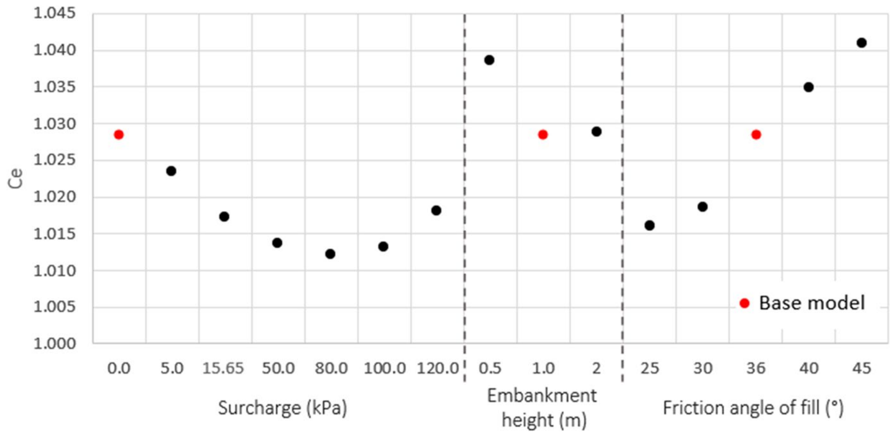

Fig. 11 Influences of surcharge, embankment height, and friction angle of embankment on the expansion coefficient (Ce)

description of the displacement and the evolution of the load transfer within the embankment by considering the increasing-diameter process of the cavity opening. By comparing with the experimental and FEM & DEM numerical results, the proposed FEM results show good accordance in terms of the surface settlement, the geosynthetic deflection, and the shape of the load distribution acting on the geosynthetic. Furthermore, the significant improvements to better understand the complicated mechanisms are illustrated, as follows:

- The displacements are not uniform in the vertical and horizontal directions. The relevance between the displacements and soil arching causing the load transfer is confirmed and reproduced in numerical models.
- Granular material is expanded during the cavity opening process, reflected by the change in void ratio. A complex mechanism, the expansion coefficient, is not a uniform factor as it is affected by several impacts such as top load, embankment height, and friction angle of the embankment.
- The presence of soil arching is provided as it allows the load transfer from the cavity area to the anchorage areas. The height of arches acting within the granular material affects the efficiency of load transfer and it develops corresponding to the height of the embankment.
- The shape of the load distribution is an approximate cone as considering if the cavity opens in a progressive process when considering a progressive cavity diameter opening process.
- The efficiency of the load transfer determined by FEM is affected by the evolution of cavity opening as it declines following the increment of cavity diameter. The top load applied on the embankment has a minor effect on the efficiency. However, the properties of the granular embankment have a significant effect on the load transfer as higher embankment and larger friction angle of soil cause greater efficiency.

An extension of the parameter variation could focus on further research related to filling material, especially with different kinds of soil types. Moreover, the behavior of new materials to change the fill weight may be considered as a new point of view to improve the performance of the solution geosynthetic-reinforced embankment over the cavity. Likewise, the conduct of reinforcement materials is needed to study the effect of the physical properties including different types of geosynthetics or the application of multiple layers. Furthermore, the numerical model could be improved to simulate the cyclic or dynamic loading, thereby illustrating the effect on the reinforced system.

List of Symbol 2D: Two-dimensional; c : Cohesion (kN/m^2); Ce: Expansion coefficient; D: Cavity diameter (m); DEM: Discrete element method; Dg: Geosynthetic deflection (m); Ds: Surface soil settlement (m); E: Efficiency of load transfer (%); e: Initial void ratio; E' : Young's modulus (kN/m^2); FEM: Finite element method; Fg: Load acting above geosynthetic after opening (kN/m); GSY: Geosynthetic reinforcement; H: Embankment height (m); J: Geosynthetic stiffness (kN/m); K_0: Lateral earth pressure coefficient at rest; L: Length of foundation soil (m); R: Cavity radius (m); T: Tensile force per unit width of the geosynthetic fabric (kN/m); W: Weight of soil above cavity before opening (kN/m); ε: Geosynthetic strain (%); φ : Friction angle (°); ψ: Dilatancy angle of filling soil (°); ν: Poisson's ratio; γ: Unit weight (kN/m^3

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Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

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