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Use of bi-modulus geosynthetics for the reinforcement of cohesive backfill on cavities

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ABSTRACT: The results of an experimental campaign of reinforcement of thin cohesive soil embankments in the case of cavity collapse are presented. In particular, the aim is to test the effectiveness of a new type of bi-stiffness geosynthetic. A coupled DEM-FEM numerical model is validated based on these results and allows a better understanding of the soil-geosynthetic interaction phenomena mobilized during the collapse. Comparison between the numerical and experimental results obtained with the two types of reinforcement (mono-stiffness and reversed bi-modulus) make it possible to underline the interest of the innovative product developed.

1 INTRODUCTION

The collapse of an underground cavity represents a major potential risk of ground movements, affecting the safety of the concerned infrastructures as well as people.

In order to limit the risks associated with a collapse of the embankment, a solution of reinforcement of embankments above a cavity by a geosynthetic sheet is generally adopted. During the collapse of the soil surface, the geosynthetic reinforcement is able, by deforming, to transfer the vertical load related to the weight of the collapsed soil and the overloads towards the edges of the cavity, by limiting the surface deflections to acceptable values. Numerous experimental works such as the RAFAEL project (Villard et al. 2022), the GeoInov project (Huckert 2015) and numerical studies (Le Hello 2007; Potts 2007; Pham et al. 2018; Villard et al. 2009) have led to an understanding of the load transfer mechanisms that develop within reinforced granular layers in particular when the tensile behavior of the geosynthetic reinforcement is assumed to be linear elastic and characterized by a single stiffness. On the other hand, knowledge on the load transfer mechanism for cohesive soils is still limited. Based on full-scale experiments, an analytical design formulation has

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been proposed for such cohesive soils by Huckert (2015) and has been evaluated and partially validated by Hassoun (2019) through an experimental campaign on a small-scale laboratory setup.

To fill the existing gaps and to complete the current knowledge on the behavior of reinforced embankments made of cohesive soil, an experimental campaign has been conducted in the framework of the REGIC (Reinforcement by Intelligent Geosynthetics over Cavities) research project. The objective is to test innovative reinforcement solutions in the specific case of the reinforcement of a cohesive soil layer. This innovative reinforcement process, patented by the company Afitexinov under the name of "reversed bi-modulus" geosynthetics, ensures that the reinforcement layer has two tensile stiffnesses which are activated one after the other, the first being weaker than the second (unlike the "bi-modulus" for which the first is higher than the second). This new type of "reversed bi-modulus" reinforcement makes it possible to detect the beginning of a rupture of the soil layer (by means of an integrated optic fiber and thanks to the first low stiffness of the geosynthetics) while guaranteeing the same level of safety as a geosynthetic with only one stiffness (thanks to the second high stiffness mobilized after the threshold of deformation necessary to the detection of the movements related to the cavity).

The experiments carried out allowed the analysis of the behavior of the reinforced embankments during the opening of cavities 1 and 2 m in diameter, then during a progressive loading phase until the final collapse of the soil layer on the geosynthetic reinforcement.

In order to analyze the interaction behavior of the geosynthetic sheet (single- or bi-modulus) with the cohesive soil, during the opening of the cavity, the collapse of the soil on the sheet, and the loading phase, a numerical study, complementary to the experiments, using a coupled DEM-FEM numerical model has been conducted. This numerical model has been tested and validated in the case of a classical reinforcement (Delli Carpini et al. 2020).

The aim of this paper is to highlight, through the numerical study, the interest and specificities of the new "reversed bi-modulus" technology and to compare it to the classical solution of the single-stiffness geosynthetic.

2 THE EXPERIMENTAL CAMPAIGN

The experimental campaign, carried out in La Tour-du-Pin (France), consisted in the realization of 3 full scale tests for which backfills 0.5 or 0.75 m thick were implemented. For each test, three cavity openings were tested with a size of 1 m then 2 m in diameter and when the backfill did not reach failure under its own weight, an incremental loading was applied until collapse.

For this type of experimentation, different void generation mechanisms have been used for granular soils. One of the most commonly used techniques is the emptying of a cavity filled with materials. For example, Bridle and Jenner (1997) adopted emptying by sand suction, while in the RAFAEL project (Villard et al. 2002) clay balls were used. Another alternative is to implement inflatable pads or air chambers (Huckert 2015).

In this campaign, the cavity was filled with washed rolled gravel. A trap door device between two chambers allows to drain the aggregates from the upper chamber to the lower chamber and thus to create a cavity under the geosynthetic. In order to obtain a progressive opening, an inner cylinder was also placed in the upper chamber, in order to obtain a first cavity of 1 m in diameter when the central trap door is opened. The cylinder falls into the lower chamber when the four outer hatches are opened to create a cavity of 2 m in diameter.

After the installation of the opening device, the geosynthetic sheet was placed, equipped with backscattering fiber optic sensors that allows a distributed measurement of the deformation on the length of the optical fiber. After the placement of the cohesive soil and before the opening of the cavity, the compaction of the backfill (in 2 layers of 0.25 m) is controlled with a light dynamic penetrometer which allowed to conclude that the compaction is not homogeneous on the backfill depth H = 0.50 m. Indeed, the surface layer of 0.10 m appeared denser than the rest of the backfill and this for both layers. After the opening of the cavities, the backfill was overloaded with steel plates of 80 kg each, placed on a steel cube 0.5 m in width and 38 kg in weight. The deformations obtained with the optical fiber will be presented when comparing with the numerical results.

2.1 *The materials*

Two coherent soils were used for the realization of the test plots: a sand treated with 1% of lime and a silty soil. Only the tests carried out on the 0.5 m thick treated sand will be presented here.

Preliminary Proctor compaction tests showed that the Proctor Normal optimum is obtained for the following conditions: an optimum water content equal to 16.7% and an optimum dry density γd_OPN of 16.3 kN/m3. In order to complete the characterization of this material which is in unsaturated condition and is loaded in a quick way, three triaxial Unconsolidated - Undrained tests (UU tests) as well as flexural tests were carried out on, following the same procedure as for the preliminary tests. The parameters are summarized in Table 1. These characteristics will be taken into account for the numerical back analysis of the full-scale tests.

Table 1. Treated sand main mechanical properties measured in laboratory tests.

	γ_d (kN/m^3)	*w (%)*	c_{uu} (kPa)	φ_{uu} (°)	σ_t (kPa)
Limed sand	15	16-18	18.93	34.9	~ 15

Two cavities were opened for each of the two full scale tests using the lime treated sand: cavity N°1 concerns a reinforcement sheet with reversed bi-modulus behavior, cavity N°2 was opened under a conventional reinforcement sheet (monostiffness). The monostiffness geosynthetic is composed of PVA cords with a breaking strength T = 165 kN/m and a stiffness Jsp = 2395 kN/m in the X direction (production), the non-woven support brings a low stiffness in the perpendicular Y direction (estimated at 30 kN/m). The reversed bi-modulus geosynthetic consists of PVA cords with a breaking strength of 45 kN/m in the weft direction and a breaking strength of 131 kN/m in the production direction. From standardized tensile tests performed on this product, it was determined that, in the reinforcement direction, the reversed bi-modulus geosynthetic has an initial stiffness Jsp_1=750 kN/m up to a threshold strain value of 1.5% (a strain value that allows the detection of cavity-related movements and remains well above the minimum strains that can be detected by fiber optics), and beyond that, a second stiffness Jsp_2= 2500 kN/m up to failure. An anchoring by simple covering of the sheet by the backfill allows the tensioning of the sheet above the cavity.

3 NUMERICAL MODEL

The numerical modelling (Figure 1) is based on the SDEC numerical code (Donzé 1997) that is coupling the Discrete Element Method (DEM) to model the soil and the Finite Element Method (FEM) to represent the reinforcement layer simultaneously. The DEM considers a set of particles interacting at the contact points, which makes it possible to describe the behaviour of soils under large deformations (shear, overturning or global rotation) and their failure by blocks, such as those observed for cohesive soils during the collapse of the soil

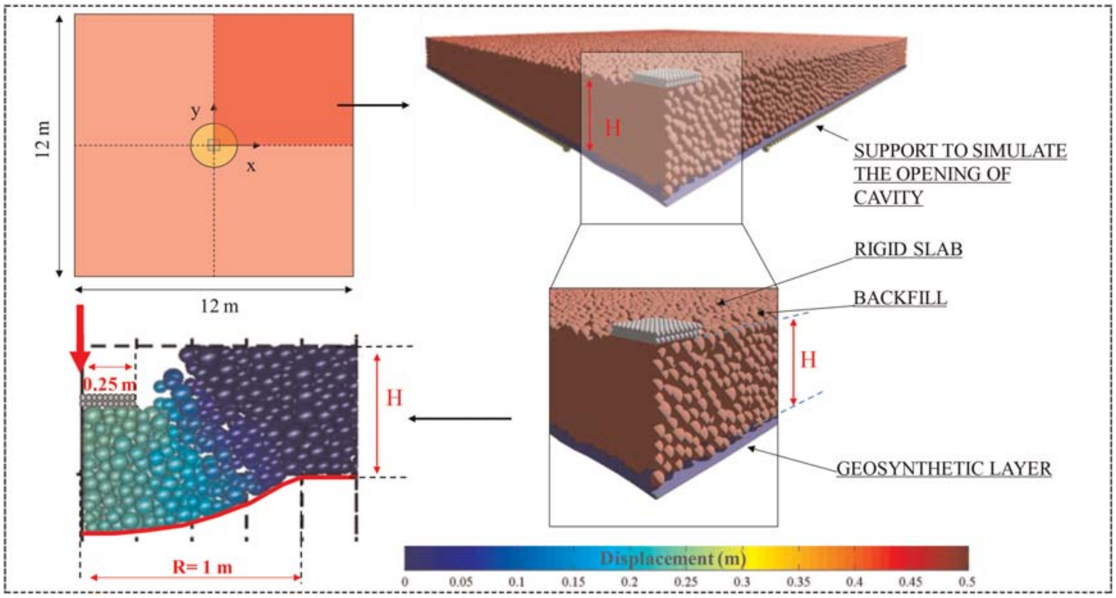

Figure 1. Geometry of the numerical model.

layer on the geosynthetics sheet. The embankment consists of several spheres of different diameters placed in a volume of 6 m x 6 m (boundary conditions with a minimum impact on the behaviour of the part of the backfill close to the cavity) x 0.5 m, corresponding to a quarter of the model for symmetry reasons. To represent the cohesive soil, the soil particles are linked together at their contact points by cohesive bonds (normal and tangential adhesion). The forces between particles are subjected to a Mohr-Coulomb type criterion (Delli Carpini 2021).

The contact micro-parameters that allow to reproduce the macroscopic behavior of the cohesive granular material (cohesion of 19 kPa, internal friction angle of 35° and tensile strength of 15 kPa, as identified by triaxial UU tests and bending tests) are: c = Tn = 60 kPa and ϕ= 40° (c is the microscopic contact shear resistance, Tn the microscopic contact resistance to traction and ϕ the microscopic contact friction angle). A thin geosynthetic layer, modelled by deformable 3-nodes triangular finite elements and which are assembled together to form a continuous sheet, is positioned below the embankment. The elements of the sheet interact with the soil particles by contact forces defined at the point of contact. The behaviour of the fibre's system is described in details by Delli Carpini (2021).

Some of the spheres in the support are moved downwards at a constant speed to create the void under the backfill and to simulate the opening of the cavity. After the cavity is fully opened, a loading procedure is applied by means of a rigid slab consisting of two layers of bounded spheres. Once the slab is in contact with the backfill surface, the actual loading test begins. A uniformly distributed load is progressively applied to the slab until the backfill breaks.

For the geosynthetic, the values of the numerical parameters retained are deduced from the average stiffnesses obtained during tensile tests. Figure 2 shows the good match between the experimental results and the numerical modelling of the tensile tests carried out in the production direction on the single-stiffness geosynthetic sheet (a) and the reversed bi-modulus geosynthetic sheet (b). A tensile stiffness in the perpendicular direction of 30 kN/m was considered for both products. In the absence of experimental friction test results, a friction angle of 30° was used to numerically characterize the soil/geosynthetic interface.

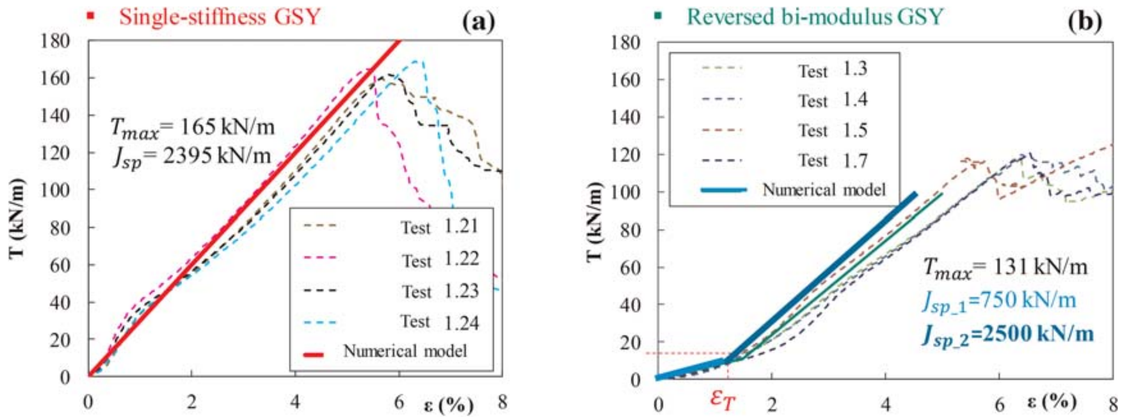

Figure 2. Stress-strain curve of tensile tests performed on single-stiffness (a) and reversed bi-modulus (b) geosynthetic sheets. Comparison with numerical modeling.

4 RESULTS OF COMPARISONS WITH EXPERIMENTAL MEASUREMENTS

A comparison with experimental results available for the 0.5 m backfill made of treated sand is used to test the validity of the numerical model (single-stiffness geosynthetic and reversed bi-modulus geosynthetics).

Several main phases can be highlighted during the test: opening of the cavity, rupture of the soil layer, collapse and stabilization of the cohesive block on the sheet, deformation of the sheet during loading. In this article, we would like to focus our attention on the failure of the cavity to better understand the different behaviour from a single stiffness and a reversed bi-modulus geosynthetics. The analysis of the shape of the collapsed block and the deformations of the geosynthetic layer are important elements that allow the evaluation of the relevance of the numerical model.

For the numerical model, the cohesive soil layer collapses for a loading force of 16 kN for the single-stiffness reinforcement and a loading force of 16.7 kN for the reversed bi-modulus reinforcement. The numerical values obtained for both types of reinforcement are higher than the failure force obtained during the full scale tests: F = 4.30 kN and 12.14 kN for the two tests done. The difference between the values can be attributed to the uncertainties on the real experimental mechanical characteristics of the backfill, related to the non-homogeneous compaction in depth of the soil layer for both tests. However, the shape of the collapsing rigid block of soil is similar between the experimental observation and numerical result, as Figure 3 shows. As it can be seen in Figure 4a, in both cases tested (mono-modulus or reversed bi-modulus geotextiles), the maximal vertical displacements of the reinforcement after collapse of the cohesive soil are rather similar (dn,v = 250 mm approximately).

Figures 4b and c show the deformations of the geosynthetic along the entire length of the model (12 m), during stabilization of the cohesive block on the sheet, after its collapse. The comparison shows in particular that the reversed bi-modulus geosynthetic undergoes a greater maximum deformation than the single-stiffness one, but that it is less stressed in the anchorage zones due to its low initial stiffness. On the other hand, the results obtained at the collapse of the soil layer are very comparable to the experimental measurements. For the single-stiffness reinforcement, the maximum numerical strain value $\varepsilon = 1.5\%$ is close to the experimental value $\varepsilon = 1.46\%$. Similarly, for the reversed bi-modulus reinforcement, the numerical value of deformation ($\varepsilon = 2.07\%$) is comparable to the experimental value ($\varepsilon = 1.96\%$).

Nevertheless, in the anchorage zone, the experimental measurements are bigger than the numerical results. This difference is due to the slippage of the measuring device from the geosynthetics.

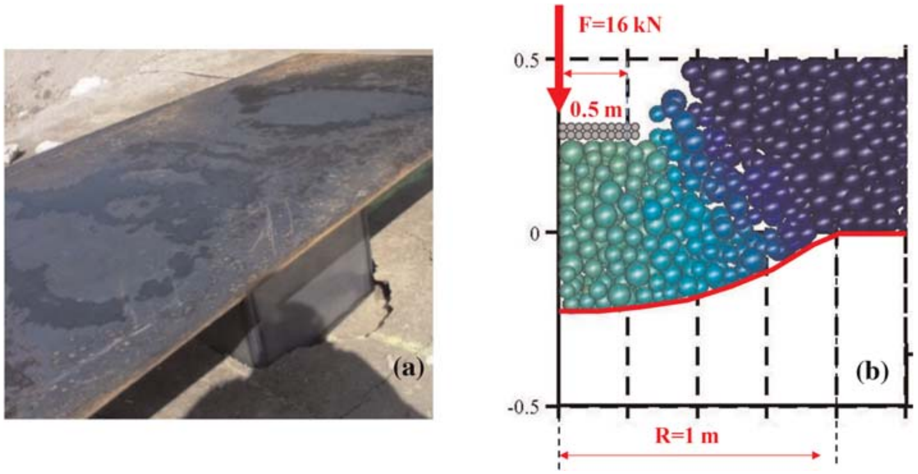

Figure 3. Shape of the collapse soil. Comparison between experimental observation (a) and numerical model (b).

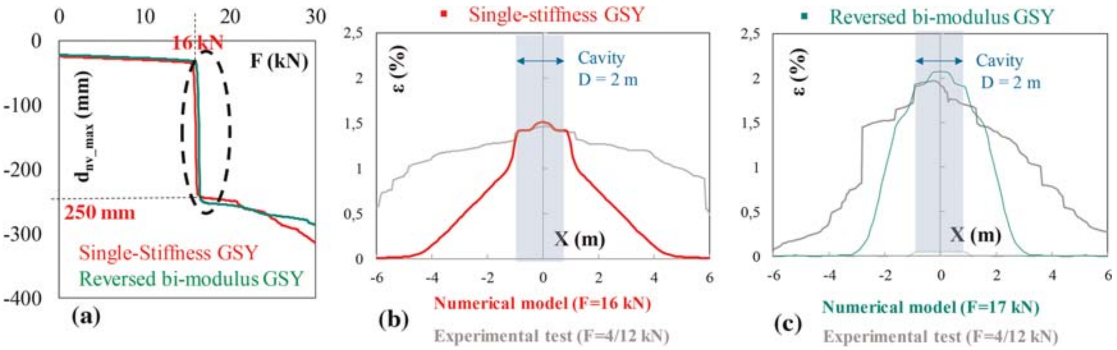

Figure 4. Displacement vs loading force (a), deformation of the geosynthetic at the collapse : (b) single-stiffness model (red curve) and (c) reversed bi-modulus model (green curve).

The numerical model clearly shows the different behaviour of the two types of reinforcement, especially in the anchorage zone, which leads to higher deformation values at the center of the cavity for the reversed bi-modulus geosynthetic, even though similar vertical displacements are obtained for the two products. After collapse of the soil on the sheet, the reversed bi-modulus geosynthetic leads to lower deformation of the sheet. This result confirms that the reversed bi-modulus reinforcement fulfils its function: the large initial deformations activate the warning signal transmitted by the optical fibres inserted in the product, while the high stiffness mobilised later ensures global deflections of the sheet.

5 CONCLUSIONS

The presence of a cavity in the subsoil represents a risk of collapse of the overlying soil that can be reduced by the installation of geosynthetic layer. In this context, different geosynthetic reinforcement products (single stiffness or reversed bi-modulus) associated with cohesive backfills were tested in the framework of the REGIC project. The instrumented reversed bi-modulus geosynthetic allows, in a first step, to activate the warning system based on deformation measurements by optical fibers installed on the sheet as soon as a threshold movement of the ground can be recorded. The second stiffness, much larger than the first one, allows to contain the deformations and to limit the displacements of the sheet and the soil surface. In spite of the inherent limitations of the experiments and the numerical model used, it can be concluded that qualitatively the numerical model correctly represents the behavior of reinforced cohesive embankments (conventional geosynthetic, single stiffness and reversed bi-modulus geosynthetic). The difference between the two types of reinforcement highlighted during the experimental campaign is also confirmed by the numerical results, i.e. larger deformation values at the center of the cavity for the reversed bi-modulus sheet despite similar vertical displacements for the two products. As expected, the large initial deformations activate the warning signal while the high stiffness mobilized later limits the surface settlements during loading.

On the basis of the observations made, the numerical model, used also by Delli Carpini (2021) for parametric studies, will lead to an improvement of the existing design methods.

REFERENCES

Bridle, R. J., Jenner C. G. 1997. Polymer Geogrids for Bridging Mining Voids. *Geosynthetics International*. ICE Publishing, 4(1), 33–50.

Delli Carpini M., Emeriault F., Briançon L., Villard P., Mengue E., Leguernevel G. 2020. Etude du Comportement des Remblais Cohesifs Renforcés par Géosynthétique. *Journées Nationales de Géotechniques de l'Ingénieur*, 1–8.

Donzé F. V. 1997. Spherical Discrete Element Code. *Discrete E. Universite du Quebec a Montreal*.

Hassoun M. 2019. *Modélisation Physique du Renforcement par Géosynthétique des Remblais Granulaires et Cohésifs sur Cavités*. Thèse de Doctorat. Communité Université Grenoble Alpes.

Huckert A. 2015 *Approche Expérimentale du Dimensionnement d'une Couche de Sol Traité Renforcée Par Géosynthétique sur Cavités Potentielles*. Thèse de Doctorat. Université Grenoble Alpes.

Le Hello B. 2007 *Embankment on Piles Reinforced by Geosynthetic Sheet - True Scale Experimental Study and Numerical Analysis*. Thèse de Doctorat. Université Joseph-Fourier - Grenoble I.

Pham M. T., Briançon L., Dias D., Abdelkader A. 2018. Investigation of Load Transfer Mechanisms in Granular Platforms Reinforced by Geosynthetics Above Cavities. *Geotextiles and Geomembranes*. Elsevier, 46(5), 611–624.

Potts V. 2007 *Geosynthetic Reinforced Fill as a Load Transfer Platform to Bridge Voids*. University of London.

Villard P., Chevalier B., Le Hello B., Combe G. 2009. Coupling between Finite and Discrete Element Methods for the Modelling of Earth Structures Reinforced by Geosynthetic. *Computers and Geotechnics*, 36(5), 709–717.

Villard P., Gourc, J.-P., Blivet J.-C., 2002. Prévention des Risques d'effondrement de Surface Liés à la Présence de Cavités Souterraines: Une Solution de Renforcement par Géosynthétique des Remblais Routiers et Ferroviaires, *Rev. Fr. Geotech.*, 99, 23–34.