Geosynthetics Conference

Monitoring and warning system including a bi-modulus geosynthetic for the reinforcement of cohesive soil on cavities

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ABSTRACT

The use of reinforcement geosynthetics to prevent localized collapses such as cavities is common today. Numerous experimental and numerical studies allow a precise understanding of the geosynthetics behavior related to these applications. Within the REGIC (reinforcement by intelligent geosynthetics on natural or anthropic cavities) research project, an innovative solution has been developed and patented by the Afitexinov company. This solution includes a specific reinforcement geosynthetic coupled with an autonomous and remote warning device to detect a localized collapse or sinkhole. This innovative geosynthetic is an inverted bi-modulus reinforcement geosynthetic equipped with optical fibers. The first modulus at lower strength allows detecting possible deformations before transmitting the load to the second modulus with higher strength. This two-stages reinforcement system guarantees a high degree of safety from the start of the failure.

The new geosynthetic solution presented in this article aims to reduce the costs and time related to the installation of a monitoring system on a construction site. This solution's installation and set-up do not require an expert on-site, thanks to a standalone monitoring box. This Preditect® system is able to monitor large critical areas for ground deformations and detect potential underground failures. In case of any unexpected event, it will launch an automatic alert.

INTRODUCTION

Compressible soils are characterized by low shear strength that increases with consolidation, high compressibility, and delayed behavior under loading over time. Any construction on soft soils will face stability and settlement issues. One of the solutions used for the construction of embankments on compressible soils is the use of high modulus geosynthetics. This is a cost-effective solution that permits to save natural resources and reduce the time of work.

Geosynthetics significantly increase the safety factor and the maximum allowed height of the embankment by reducing displacements during construction and uniformizing settlements after construction. In conjunction with other geotechnical ground improvement methods, like rigid inclusions or aggregates piers, high modulus geosynthetics are also used as a distribution mattress to transfer the loads to the pile heads.

Implementing a high modulus geosynthetic makes it possible to secure civil engineering structures built on areas at risk of underground cavities (e.g., karstic zones). It will retain the soil in case of collapse and limit the settlements of the surrounding layer within the acceptable limit for the stability of the structure and the safety of the users (Figure 1). It also provides the time needed to implement a definitive treatment corresponding to voids filling in areas where collapses have occurred.

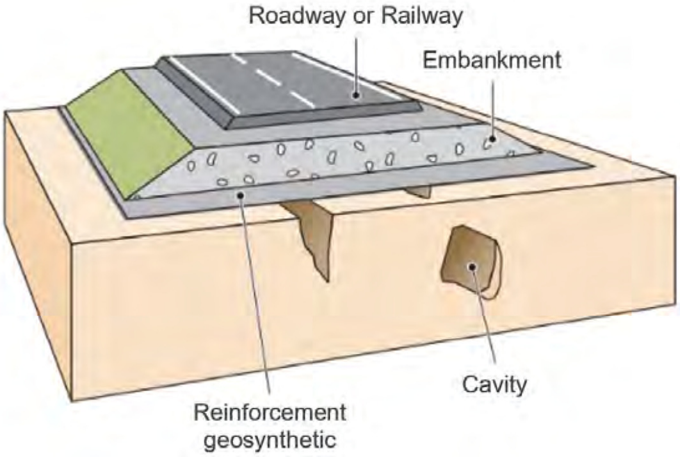


Figure 1. Reinforcement geosynthetic over cavity (credit CFG – Le Moniteur, 2015)

The high modulus geosynthetic material needs to have at least the following characteristics:

- High tensile strength (as per the design considerations),
- High stiffness (immediate tension of the technical yards, raw material used),
- Ability to effectively retain the soil (even if cohesive soil, separation function).

All reinforcement geosynthetic solutions, no matter how well dimensioned they are (Villard et al. 2000), have one main limitation: the monitoring of the reinforced structure over time. This is even more important for Mechanically Stabilized Earth (MSE) walls or reinforced structures on areas at risk of underground cavities. The possibility of having real-time monitoring of the stress-strain distribution in the reinforcement geosynthetics is a real contribution to any of these solutions, especially for the reinforcement of areas at risk of cavities. While the design of high modulus geosynthetics in areas at risk of cavities is currently limited to cavities with a diameter of 5 m, the use of an instrumented geosynthetic in conjunction with the appropriate monitoring system is a solution to detect and monitor the risk of large diameter cavities.

NEW GEOSYNTHETIC DEVELOPMENT

Inverted bi-modulus reinforcement geosynthetic. A new type of reinforcement geosynthetics has been developed to ease the detection of small settlements even for structures that require a product with very high stiffness, like structures with low or no settlement allowed on cavities with large diameters. The strength between the two moduli is well identified. The first modulus with lower strength allows deformation to be measured at low elongations (up to 2%) and prevents the onset of failure; when the second modulus is designed to retain the structure at high deformations (up to 10%), its stiffness will be the same as that of a mono-modulus reinforcing geosynthetic designed for the same reinforcement purpose (Delli Carpini and al. 2021).

The reinforcement geosynthetic is a high-modulus woven-knitted geotextile made with high tenacity yarns, manufactured by a double warp knitting process, GEOTER FPET (Figure 2).

The woven geotextile provides the separation function, whereas the high-tenacity yarns give the high strength capacity to the overall product. It allows tensile strength up to 2,000 kN/m.

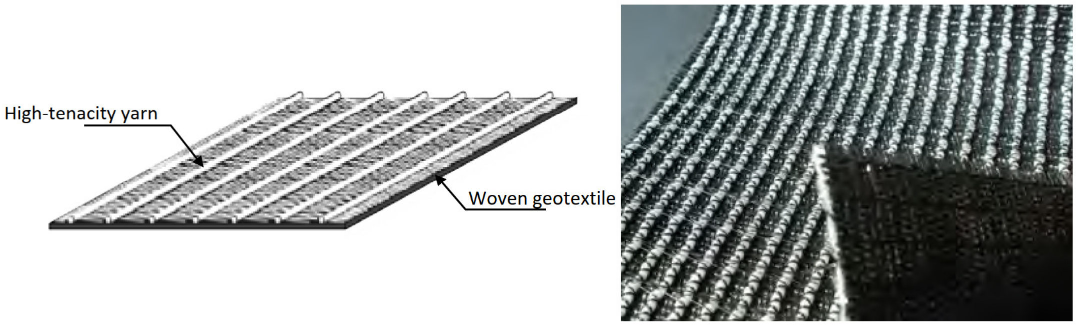


Figure 2. Description of the reinforcement geosynthetic

A numerical model using a Discrete Element Method (DEM) coupled with a Finite Element Method (FEM) has been used to analyze the interaction of the inverted bi-modulus reinforcement geosynthetic with the cohesive soil at the different stages of the collapse. This numerical model has already been tested and validated in the case of mono-modulus reinforcement (Delli Carpini et al., 2020).

Numerical model. The numerical model is based on the Spherical Discrete Element Code (SDEC) calculation code (Donzé, 1997). It uses the DEM to model the soil and the FEM to model the reinforcement geosynthetic. The DEM considers particles interacting at the points of contact, which allows it to describe the soil's behavior under large deformations and the failure in a block as observed for cohesive soils ruptures. The reinforcement geosynthetic is modeled by connected deformable planar elements interacting with the soil at the contact points.

The geometry and main characteristics of the numerical model are shown in Figure 3. The particles are bounded together at their points of contact by a cohesive bound (normal and tangential adhesion) with a Mohr-Coulomb type criterion to simulate the cohesive soil (Delli Carpini, 2021).

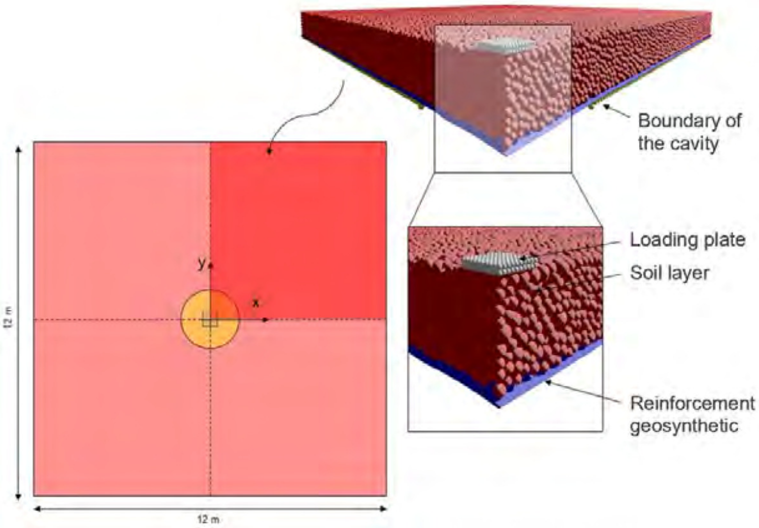


Figure 3. The geometry of the numerical model

The two types of reinforcement geosynthetics (mono-modulus and inverted bi-modulus) are modeled with the products' stiffness from tensile strength laboratory tests. Figure 4 shows the good correlation between the model and the experimental values for the inverted bi-modulus reinforcement geosynthetic. The two stiffness modulus are visible in Figure 4: the lower stiffness modulus for small elongations (inferior to 1.75%), then the high stiffness modulus for larger elongations.

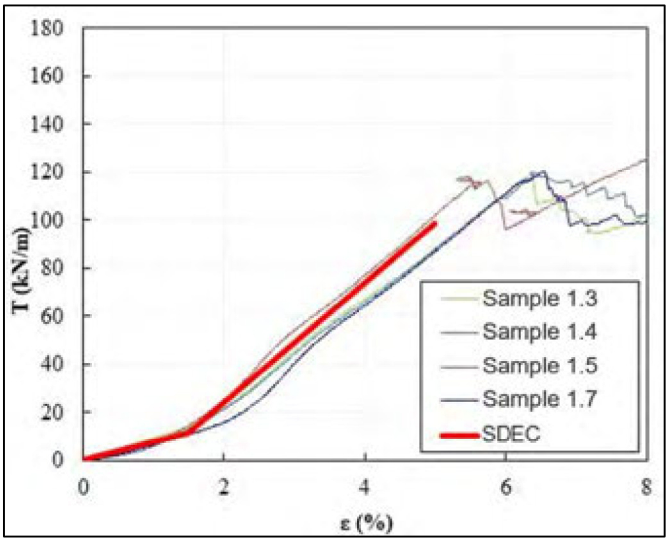


Figure 4. Strength-strain curve from laboratory test and numerical model

Experimental device. An experimental apparatus has been constructed to validate and calibrate the numerical model. Laboratory models have already been implemented (Hassoun et al. 2017), but no in situ model has been carried out. It reproduces a 2 m (80 in) diameter cavity with a trapdoor mechanism to simulate the cavity's opening under the reinforcement geosynthetic. The trapdoor is placed in a concrete sump and allows for draining (when open) the aggregates from the upper chamber to the lower chamber (Figure 5). The trapdoor is divided into several zones to control the opening factor of the cavity and permit to create first a 1 m (40 in) diameter cavity and extend it to 2 m (80 in).

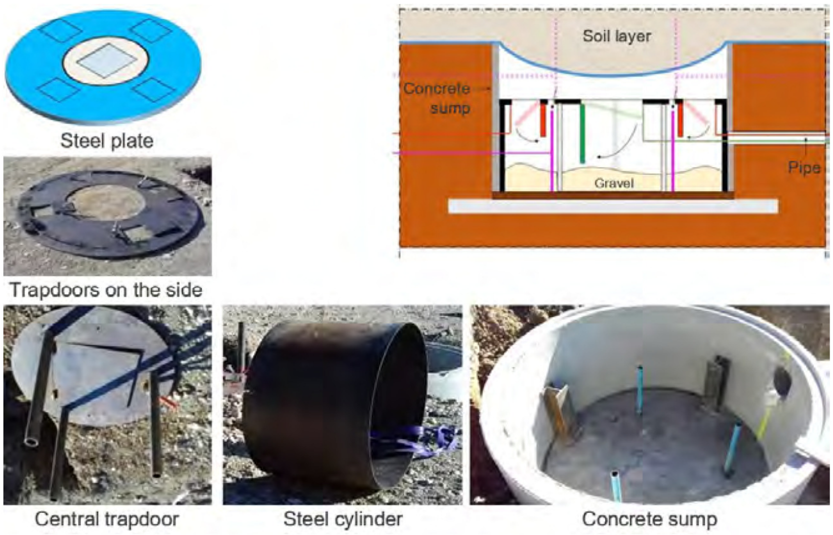


Figure 5. Trapdoor mechanism in the concrete well

The reinforcement geosynthetic is first put in place with the sensors. The Bragg grating sensors used to measure strain within the geosynthetic are placed every 0.5 m (20 in) from the side of the cavity along its diagonal, as shown in Figure 6.

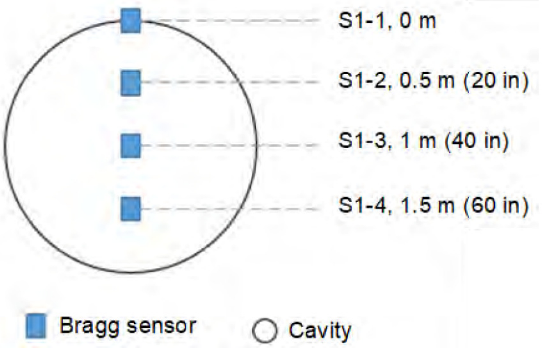


Figure 6. Bragg sensors placement over the cavity

The 0.50 m (20 in) thick layer of cohesive soil is then placed on the reinforcement geosynthetic and compacted. Its main geotechnical characteristics are shown in Table 1.

Table 1. Soil characteristics

	γ_d (kN/m^3)	w (%)	c_{uu} (kPa)	φ_{uu} (°)	σ_t (kPa)
Cohesive soil	15	16-18	18,93	34,9	~15

The experimental device is left in place for 15 days before opening the cavity. It is first opened to 1 m (40 in) diameter; a slight deformation takes place, as shown in Figure 7. Then the cavity is opened to 2 m (80 in) diameter.

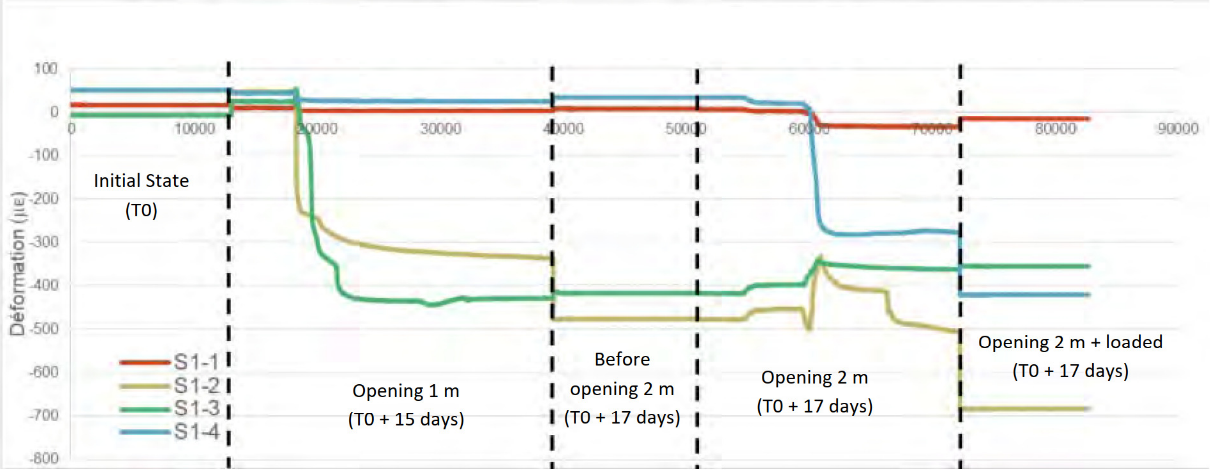


Figure 7. Deformation recorded by the sensors during the test for one iteration

Following the opening of the cavity, the soil layer is loaded with successive steel plates 80 kg (176 lbs), each placed on a steel cube 0.50 m (20 in) wide and 30 kg (66 lbs) in weight (Figure 8). The aim is to produce the collapse of the cavity.

Figure 8. Steel plates on the steel cube

Results. The numerical model has been performed to give the vertical displacement of the two types of reinforcement geosynthetics (mono-modulus and inverted bi-modulus) function of the loading until the failure of the soil layer. Several steps are presented:

- I: Opening of the cavity,
- R: First failure of the cohesive soil layer,
- E: Collapse of the soil bloc on the geosynthetic.

The two products have the same behavior at each step of the loading (Figure 9). The value of 16 kN for the load to reach the soil collapse in the numerical model is higher than the values measured with the experimental device that were not superior to 12 kN. It is explained by the non-homogenous compaction of the soil layer (that has been observed on the experimental device) and its geotechnical characterization.

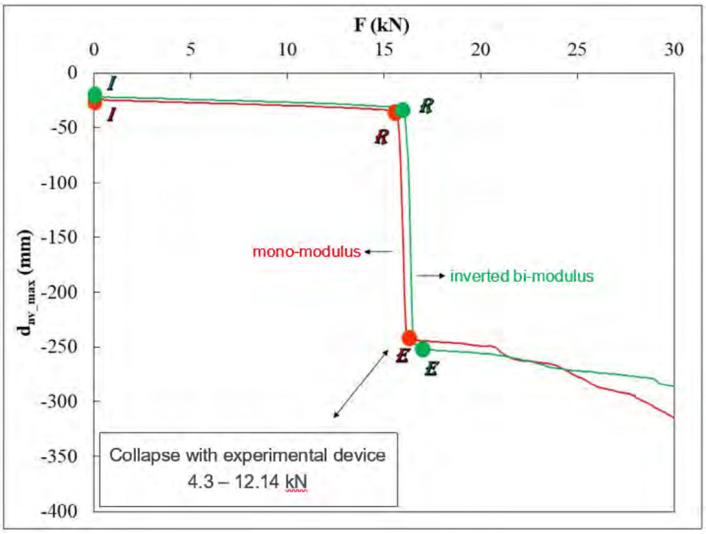


Figure 9. Vertical displacements of the reinforcement geosynthetics function of the loading

The elongation of the reinforcement geosynthetics function of the distance to the center of the cavity has also been modeled for the 3 steps I, R, and E (Figure 9). The total length is 12 m (39 ft), which corresponds to the 2 m (80 in) diameter of the cavity and the anchoring. The maximum elongation in the inverted bi-modulus reinforcement geosynthetic reaches 2.07 % with the numerical model when the experimental value measured is 1.96 %. For the mono-modulus reinforcement geosynthetic, the maximum elongation is 1.5 % with the numerical model compared to 1.46 % with the experimental model.

The numerical model is accurate to characterize the deformations in the geosynthetics. Moreover, it clearly shows the different behavior of the two types of reinforcement geosynthetics, especially in the anchorage zone, which leads to higher deformation values in the center of the cavity for the inverted bi-modulus reinforcement geosynthetic, even though the vertical displacements obtained for both products are the same at 250 mm (Figure 10).

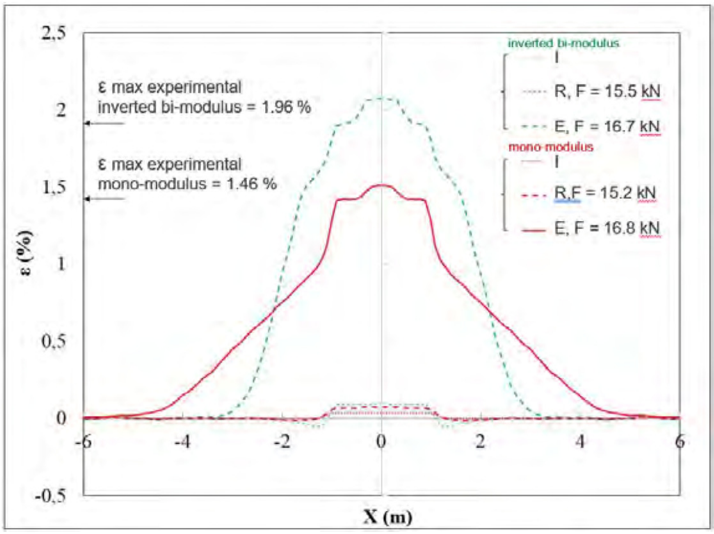


Figure 10. Elongation of the reinforcement geosynthetics at each step (I, R, E)

During the loading step, after the soil collapse on the geosynthetic, the inverted bi-modulus reinforcement geosynthetic leads to lower displacements. This result confirms that the inverted bi-modulus reinforcement geosynthetic fulfills its function: the large initial deformations enable the warning signal transmitted by the optical fibers inserted in the product to be activated at the early stage of the failure. The high stiffness mobilized, later on, ensures surface settlements as it would have been expected with an equivalent in strength mono-modulus reinforcement geosynthetic.

REMOTE MONITORING SOLUTION

Preditect® system. The development of the inverted bi-modulus reinforcement geosynthetic and its specific mechanical behavior allows the use of a monitoring system within the product to detect the soil failure at the early stage. This monitoring system is composed of optical fibers regularly inserted and positioned in the product during the manufacturing process (Figure 11). They are connected on both sides together during the manufacturing process to have a redundancy of the signal. The coverage of the optical fibers is sized according to the required resolution of the system and the sensitivity of the monitored structure.

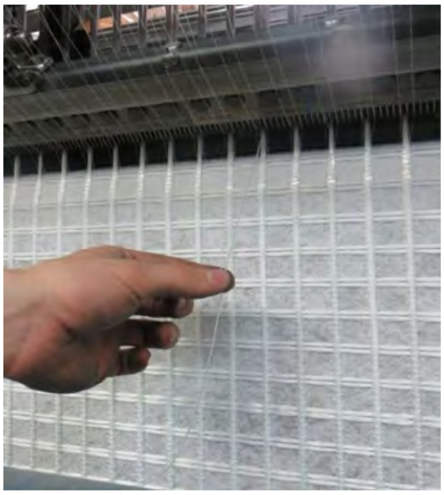


Figure 11. Insertion of the optical fibers in the product

Preditect® system uses the Fiber Bragg Grating (FBG) technology that allows temperature and strain measurements. The optical fibers used in the product can measure deformations up to 6% elongation before breakage and have a range of 50 km. The accuracy is about 1 µdef, the measurement acquisition time is of the order of milliseconds, with a spatial resolution of 8 mm.

The optical fibers are connected on-site to a self-sufficient data logger, powered by a solar panel (Figure 12). The data logger monitors the deformations in the reinforcement geosynthetic on the overall covered area. It generates a detailed report at given intervals through dedicated software and sends an alert to the selected persons in case of an unexpected event (if the deformations exceed the limit values fixed by the user).

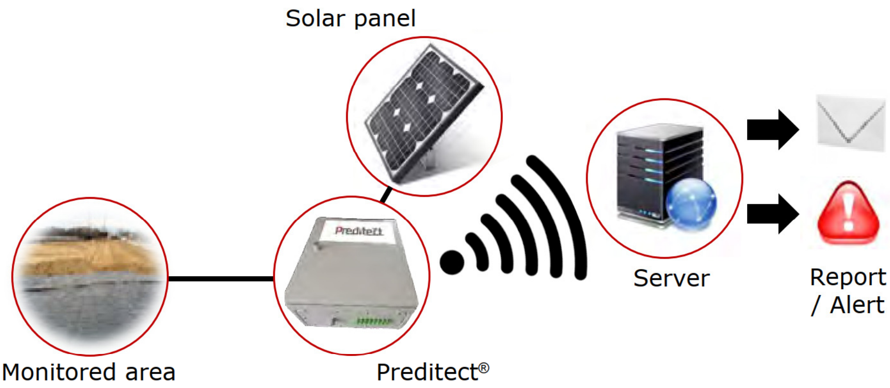
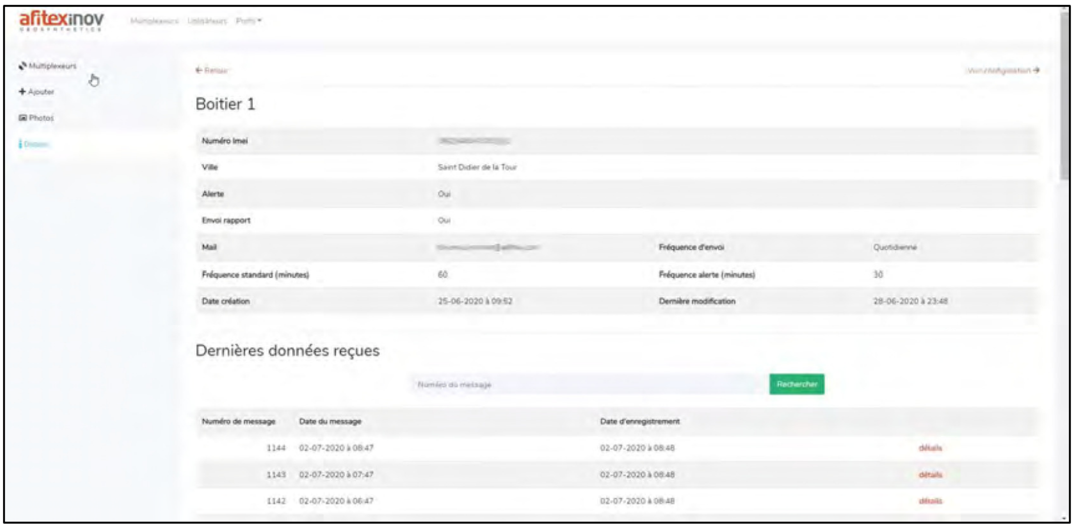


Figure 12. Description of the monitoring system

The Preditect® software allows customizing the acceptable deformations limit in the reinforcement geosynthetic per zones, the generation frequency of the report, the emergency contacts, etc. (Figure 13).



Boitier 1

Numéro Imei	[redacted]		
Ville	Saint Didier de la Tour		
Alerte	Oui		
Envoi rapport	Oui		
Mail	[redacted]	Fréquence d'envoi	Quotidienne
Fréquence standard (minutes)	60	Fréquence alerte (minutes)	30
Date création	25-06-2020 à 09:52	Dernière modification	28-06-2020 à 23:48

Dernières données reçues

Numéro du message

Numéro de message	Date du message	Date d'enregistrement	
1144	02-07-2020 à 08:47	02-07-2020 à 08:48	détails
1143	02-07-2020 à 07:47	02-07-2020 à 08:48	détails
1142	02-07-2020 à 06:47	02-07-2020 à 08:48	détails

Figure 13. Preditect® software screen view

CONCLUSION

The use of inverted bi-modulus reinforcement geosynthetics increases the elongation in the geosynthetic for small displacements of the surrounding soil compared to a mono-modulus geosynthetic, keeping the same mobilized strength in the geosynthetics and the same behavior of the reinforced structure.

A numerical model has been developed to predict the behavior of the geosynthetic and the failure mechanism of the structure in case of reinforcement of cavities on cohesive soils. This model has been compared to experimental instrumentations, and both confirmed the differences mentioned above between the two types of reinforcement geosynthetics. Therefore, the numerical model seems relevant and could be used for parametric studies (influence of the soil layer's thickness, the geometry, and size of the loading plate or even on the soil model).

The use of the inverted bi-modulus reinforcement geosynthetic equipped with optic fibers and connected on-site to the Preditect® system allows the continuous monitoring of the reinforced structure. It allows, among other things, to monitor the settlements of the structure and send an alert if they exceed a value previously set by the user. This technology, being able to detect a failure at the early stage, gives more time to put in place possible measures to secure the structure and protect people's health.

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