Design of Reinforcement Geosynthetics in Landfill Piggyback Expansion

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ABSTRACT

The construction of a vertical expansion of existing waste disposal facilities (piggyback landfills) involves the use of reinforcement geosynthetics to address differential settlements and stability issues that will be reactivated under the load of the new cell. The challenge is to guarantee the integrity of the new liner system. This paper presents the extension project of an old landfill and the design method used to evaluate the tensile strength of the required reinforcement geosynthetic. The methodology used in this project is a calculation method for the design of geosynthetics in the case of soil subsidence and sinkholes. This reference method, usually used with granular backfill, has been adapted and optimized to consider waste material-specific properties.

PROJECT OVERVIEW

To extend the life of its Non-hazardous Waste Storage Facility (NWSF), an operator proposed to continue operating its site, within the perimeter already authorized, by a vertical expansion of the cells already in operation to a maximum thickness of waste of about 16 m (52 ft). This project is based on non-hazardous waste storage cells about 15 m (50 ft) thick, some of which are more than 20 years old and, therefore, at different degradation stages.

The vertical expansion requires the new cell to be hydraulically independent of those already in place underneath. The overall leachate barrier system must comply with the current regulation and must remain functional in the long term. The design included the installation of a soil layer rein-forced with geosynthetics over the old final cover system. This layer is becoming the subgrade soil for the new leachate barrier system. A typical section is shown in Figure 1. As the site also operates as a valorization and disposal site for incinerator bottom ash, it has been decided to use this material to construct the soil-reinforced layer.

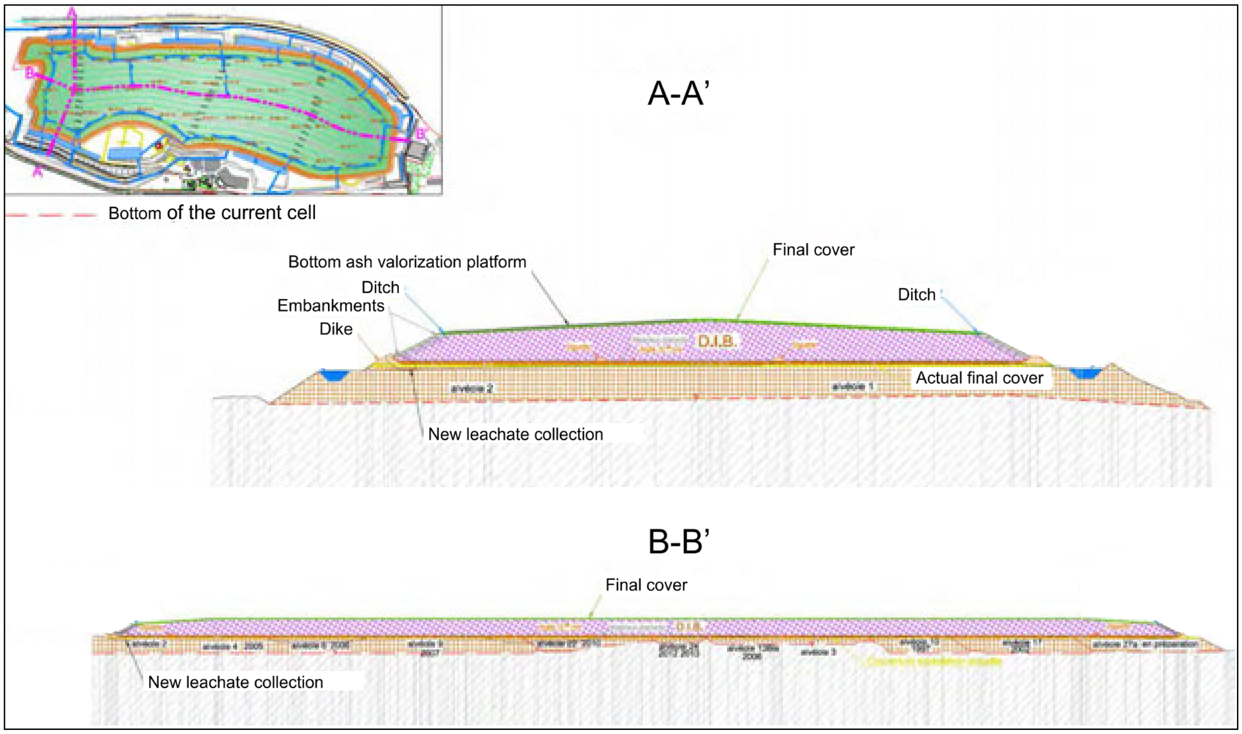

Figure 1. Typical cross-sections

GEOTECHNICAL DESIGN

In addition to the slope stability considerations and design, the vertical expansion of the cell requires a specific analysis to estimate the overall settlements that will occur.

Global settlements. Global settlements in waste result from complex phenomena that occur over time. They can be determined by adding up:

- Primary settlements caused by the weight of the new waste (short term);
- Residual secondary settlements due to the non-homogeneous degradation of the old waste (long term).

The guide "Recommandations pour la conception des extensions d'ISDND en appui sur des casiers anciens" (BRGM, 2020) recommends the application of the "Modèle Incrémental de Prédiction des Tassements" (Olivier, 2003 and ADEME, 2005), also called ISPM model. This model, developed from field experience in France and abroad, allows the prediction of the evolution of the primary (short-term) and secondary (long-term) settlements of a waste mass in the case of a vertical expansion over it. It is recommended to apply this model by retro-analysis (or calibration) to improve accuracy, which has been done on that project.

The estimation of the primary settlements was carried out from the field data by applying the pressiometric method from modulus values measured on-site (average Pressuremeter Modulus E_{PMT} = 9.2 MPa) and the ISPM method from data collected in the literature. The estimation of the secondary settlements was achieved by applying the ISPM method with data resulting from a retro-analysis carried out using the topographic survey on the post-operation settlements of the site. In the worst-case scenario, the global settlements were estimated at 1.20 m (4 ft): 0.90 m (3 ft) of primary settlements and 0.30 m (1 ft) of secondary settlements.

Structural differential settlements. Structural differential settlements develop in areas where there are significant variations in the geometric parameters and the nature of the support, such as:

- Variations in the thickness and nature (age, composition) of the compressible support or even the presence of geotechnics structures (dikes, etc.);
- Variations of the load on the compressible support (thickness and unit weight of the material).

The consideration of the structural differential settlements led to specific constructive measures:

- Modification of the landfill gas collection network, including the vertical wells, to avoid the development of localized hardpoints;
- Specific layout with the installation of two monodirectional reinforcement geosynthetic layers orthogonally crossed to have a homogeneous reinforced soil structure at any point under the new cell.

Localized differential settlements. Localized differential settlements are difficult to anticipate. The BRGM guide suggests taking them into account by considering a cavity with a diameter of about 1.0 to 2.0 m (3 to 6 ft) within the waste mass, as explained in Figure 2. It illustrates the main geometric definitions and notations that will be used. The value n = 3 is to be considered for household waste.

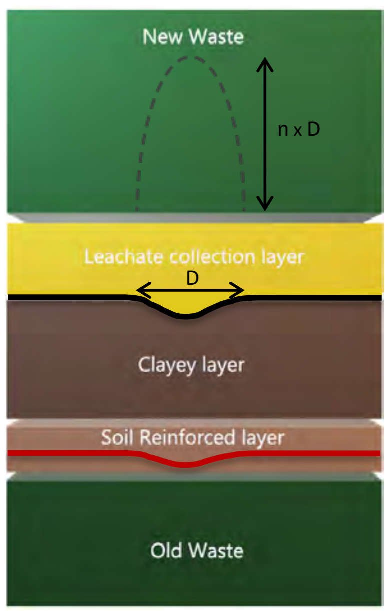

Figure 2. Illustration of the behavior of a homogeneous waste mass under loading

The following limit state designs are to be considered:

- Serviceability limit state (SLS) to address the failure of the reinforced soil layer, either by insufficient geosynthetic tensile strength or low interaction properties between the geosynthetic and the soil;

- Ultimate Limit State (ELU), to verify that the maximum allowable deformation in the leachate barrier system is not exceeded. It ensures that the system will continue to perform appropriately even after localized and global settlements.

It must be verified that none of these limit states are to be reached either during construction or during the expected service life of the cell.

Serviceability limit state (SLS). The maximum admissible deflection for the lining system is first determined. A value of 3% is used in the literature for a 2 mm (80 mil) HDPE geomembrane used as a primary lining system (Seeger et al., 1996). The other components of the leachate barrier system may influence this value.

The stress distribution on the reinforcement geosynthetic is considered uniform and vertical without considering any contribution from the circumference of the soil cylinder:

$$\sigma = FS_{Gsup} \times \left(\gamma_{waste} \times n \times D + \gamma_{pb} \times H_{pb} + \gamma_{sb} \times H_{sb} + \gamma_{ll} \times H_{ll} + P\right) + FS_{Qsup} \times Q \quad (1)$$

where:
σ: Stress on the reinforcement geosynthetic
FS_{Gsup}, FS_{Qsup}: Factors of safety
γ_{waste}: Unit weight of the waste
n: arching effect factor (n=3 for municipal solid waste)
D: diameter of the cavity
γ_{pb}: Unit weight of the primary leachate barrier system
H_{pb}: Thickness of the primary leachate barrier system
γ_{sb}: Unit weight of the secondary leachate barrier system
H_{sb}: Thickness of the secondary leachate barrier system
γ_{ll}: Unit weight of the leveling layer (above the reinforcement geosynthetic layer)
H_{ll}: Thickness of the leveling layer (above the geosynthetic layer)
P: Permanent loads
Q: Temporary loads

The residual stiffness of the reinforcement geosynthetic during the service life of the structure must be greater than:

$$J_{min} = \frac{\sigma \times D}{2 \times \varepsilon_{max}} \times \sqrt{1 + \frac{1}{6 \times \varepsilon_{max}}} \quad (2)$$

where:
ε_{max}: maximum allowable elongation in the reinforcement geosynthetic to ensure that the barrier system remains fully functional.

The strength increase in the reinforcement geosynthetic will cause the geosynthetic deformation in the anchoring zones and increase the deflection in the cavity. The stiffness of the reinforcement geosynthetic must then be overdesigned to take it into account and remain within the allowed deformations.

Ultimate Limit State (ULS). The ultimate limit state design regarding the minimum required strength of the reinforcement geosynthetic shall consider the long-term behavior of the product and its installation. This will be covered in the "Geosynthetic Design" paragraph. The ULS verification is then:

$$T_{ELU} \leq \frac{T_{ult}}{RFs} \tag{3}$$

where:
T_{ult}: Ultimate tensile resistance of the reinforced geosynthetics
RFs: Reduction factors specific to the product, the environment, and the installation

GEOSYNTHETIC DESIGN

Product description. The selected reinforcement geosynthetic is a high-modulus woven geotextile made with high tenacity yarns, manufactured by a warp knitting process (Figure 3). 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.

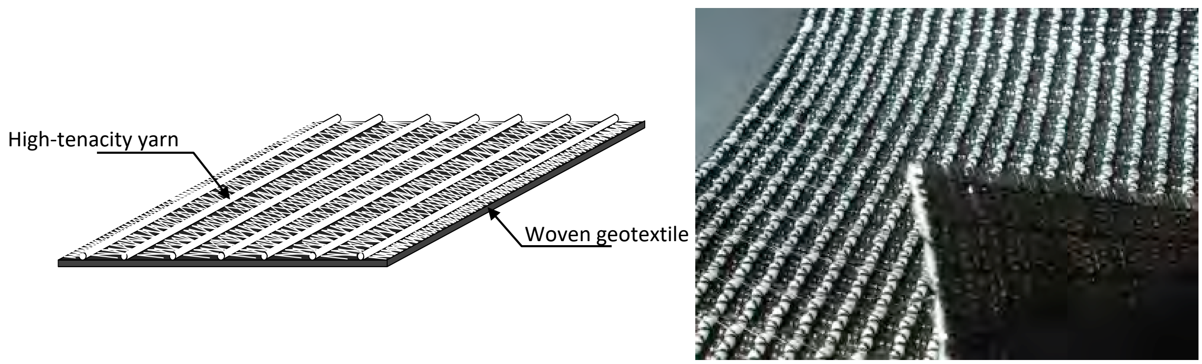

Figure 3. Description of the reinforcement geosynthetic

The process guarantees a high level of reinforcement with reduced elongation as the cables are inserted without undulation during the knitting process. It also allows dissociating the separation and reinforcement functions. Indeed, because the high-tenacity polymer yarns provide the reinforcement capability of the product, the woven geotextile keeps its filtration opening size constant regardless of the tensile strength of the geosynthetic. The composition of the high-tenacity yarns (PET, PVA, etc.) is selected according to the type of structure and the nature of the surrounding soils.

The reinforcement geosynthetic selected for this project is GEOTER F PVA 450. It is made with PVA high-tenacity yarns and has an ultimate tensile strength of 450 kN/m. The sizing of the geosynthetic is described in the following paragraphs.

Product sizing. The minimum required long term tensile strength and elongation for the reinforcement geosynthetic has been calculated by the project engineer with a geotechnical design. Then, a study has been performed by the geosynthetic manufacturer to select the appropriate product. As for any project using geosynthetics, this study took into account:

- Tensile creep of the high-tenacity cables,
- Damages on the geosynthetic during the installation,
- Chemical resistance of the geosynthetic.

The ultimate tensile resistance T_{ult} of the reinforced geosynthetics is then given using the following formula:

$$T_{design} = \frac{T_{ult}}{RF_{CR} \times RF_{ID} \times RF_{D} \times RF_{global}} \tag{4}$$

where
T_{design}: allowable tensile strength (kN/m)
RF_{CR}: reduction factor for creep to account for long term behavior,
RF_{ID}: reduction factor for installation Damage, determined form construction damage tests,
RF_{D}: reduction factor for durability, chemical resistance of the polymer in the specific environment under consideration
RF_{global}: safety coefficient on the geosynthetic material, equal to 1,25 for every application.

Creep behavior. The creep behavior was determined by an independent expert laboratory using ASTM D6992 standard. The isochronous curves were obtained according to this test, which was performed during several months at several strains on a creep bench.

The reduction factor for creep is obtained from the isochronous curves, getting the remaining fraction of the initial ultimate strength (Load UTS) at the allowed elongation (determined by the geotechnical design), as written in the following formula:

$$RF_{CR} = \frac{100}{Load\ UTS\ (maximum\ elongation\ (\%))} \tag{5}$$

Installation Damage. The installation damage reduction factor has been determined by doing in-situ tests (as described in NF G38-064 and ISO/TR 20432 standards). Strips of the product have been backfilled with several soil types, from fine soils to gravel 0-12in (Figure 4).

Figure 4. In-situ tests with several types of soil over the geosynthetic

After exhuming the product, a visual inspection was carried out (Figures 5 and 6). The woven geotextile on one side of the GEOTER F reinforcement geosynthetic protects the high-tenacity yarns. Therefore, the product presents less degradation than most uncoated geosynthetics on the market.


Figures 5 and 6. Visual inspection on the geosynthetic after exhumation

Tensile strength tests have been carried out on the exhumed product by an independent laboratory to determine the installation damage reduction factor function of the tested soils (Table 1).

Table 1. RF_{ID} for several types of soil in contact with the reinforcement geosynthetic

	Fine material	Sand < 2mm	Gravel 0/100mm	Gravel 0/300mm
RF_{ID}	1.05	1.19	1.15	1.26

Durability. The high-tenacity yarns of the selected reinforcement geosynthetic are made in Polyvinyl Alcohol (PVA). Oxidation has been identified to be the significant degradation mechanism of PVA. Tests on PVA yarns in wet and dry cycles for the use in reinforced earth structures (Nait-Ali et al., 2009) results in a reduction factor for durability of 1.20.

Applying the reduction factors to the allowable tensile strength determined by the geotechnical design led to the selection of the reinforcement geosynthetic with PVA high-tenacity yarns and ultimate tensile strength of 450 kN/m: GEOTER F PVA 450.

FINAL CROSS-SECTION AND LAYOUTS

The final cross-section for the vertical expansion of the cell is presented in Figure 7.

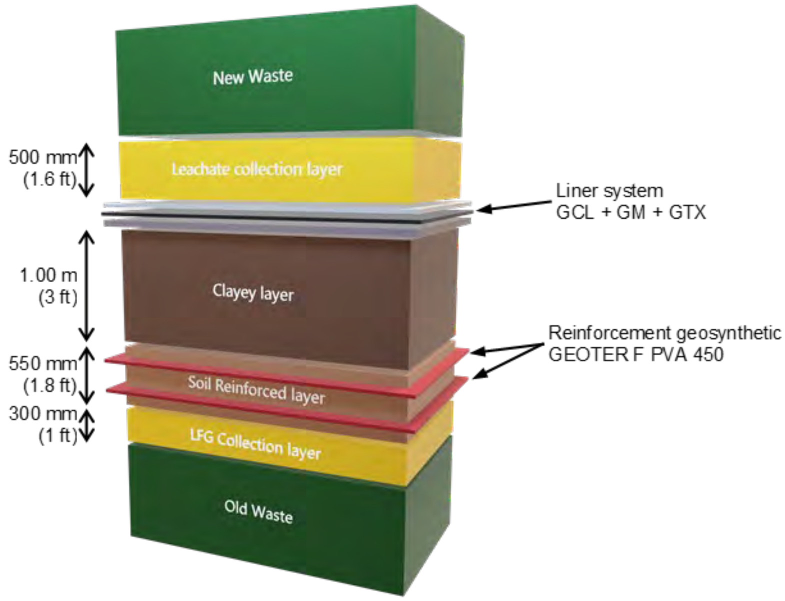

Figure 7. Final cross-section of the new cell

Landfill gas management. To ensure the collection of landfill gas from the existing waste and to avoid the development of hardpoints under the embankment, the following improvements have been proposed:

- Old wells are modified to ensure a safe distance from the soil-reinforced layer. This distance is equivalent to the estimated maximum settlement under the future cell;
- Old wells are not connected to the horizontal collector pipes; the gas flows through a 300 mm (1 foot) gravel drainage layer between the old waste and the soil-reinforced layer.

Soil-reinforced layer. A 550 mm (1.8 ft) thick soil-reinforced layer is required to have a uniform load distribution over the old waste mass and limit the differential settlements. It is composed of:

- Two layers of PVA reinforcement geosynthetic with an ultimate tensile strength of 450 kN/m and a maximum elongation of 6% installed perpendicularly at two different levels to fully mobilize the interface friction angles; the overlaps are calculated to ensure continuity of the reinforcement;
- Incinerator bottom ash material available on site.

Numerous analyses have been carried out on the bottom ash material to characterize its physical, mechanical, and chemical properties (Table 2). It has been found suitable as a backfill material. The pH, which may exceed 10, has been considered when selecting the reinforcement geosynthetic. PVA material has been proven to be more adapted for that range of pH.

Table 2. Bottom ash material characterization

Bottom ash material				
Test	Symbol	Unit	Value	Comment
Natural water content	W_n	%	12.1	0.8 W_{opn} < W < 1.1 W_{opn}
Dry unit weight	ρd	T/m³	1.28	
Particule size distribution	D_{max}	mm	23	PSD 0/20mm
	<50mm	%	100	
	<2mm	%	39.7	
	<80µm	%	4.7	
Methylene blue	MBV	%	0.04	
Sand equivalent	SE	-	67.8	
Organic content by loss on ignition	LOI	%	7	
GTR class			F_{61}	Similar to D_2
Proctor test	$ρd_{OPN}$	%	14	
		T/m³	1.75	
Immediate bearing capacity factor	IPI		40.3 46.2 34.3 7.1 2.2	IBC > 20 (average and for 3 values over 5)
Fragmentability	FR		1.9	High fragmentability
Consolidated drained triaxial	c'	kPa	42	
	ϕ'	°	37	

Leachate barrier system. The leachate barrier system required by the French regulation is implemented on top of the soil-reinforced layer. It is composed of (from bottom to top):

- A clayey layer 1 meter (3 feet) thick with a hydraulic conductivity inferior to $1x10^{-9}$ m/s, and a geosynthetic clay liner (GCL);
- A 2 mm (80 mil) HDPE geomembrane protected by a non-woven geotextile;
- A gravel drainage layer 0.50 m (1.6 ft) thick.

The barrier system allows the leachate generated in the new cell to be collected separately with dedicated collection wells. The slope of the bottom cell has been increased to 3% in the drainage direction to ensure a remaining long-term slope of 1% after the maximum expected settlements.

GEOSYNTHETIC INSTALLATION

To limit overlaps, simplify the installation, and ensure the continuity of the reinforcement, rolls with specific lengths have been produced. The length of the product was 120 m (395 ft). Handling was achieved using mechanical shovels.

Roll placement. GEOTER F PVA is unrolled on a base that has been graded and compacted (Figures 8 and 9).

Figure 8. Installation of reinforcement geosynthetic

Figure 9. Continued installation of reinforcement geosynthetic

The product is placed with the woven geotextile on top to protect the high-tenacity yarns during the backfilling. Two layers of geosynthetics were installed, perpendicular to each other, with a soil layer in between.

Overlaps. Side by side (longitudinal) connections are achieved with a minimum overlap of 300 mm (12 in.) following the direction of the backfill placement (Figure 10).

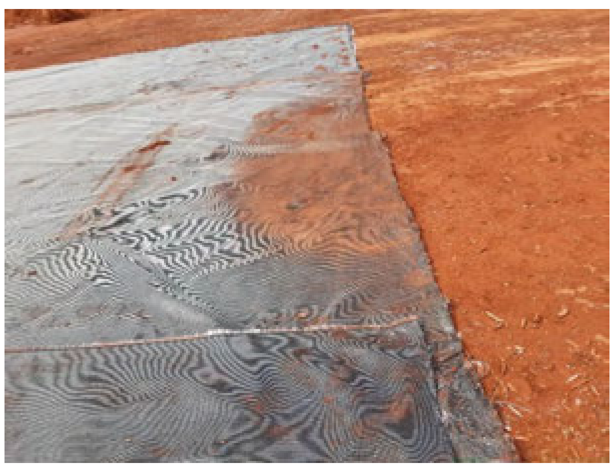

Figure 10. Longitudinal overlap of the reinforcement geosynthetic

Bottom ash material placement. The incinerator bottom ash material is free of foreign matter that could damage the geosynthetic. A 300 mm (1 ft) thick layer has been placed between the two geosynthetic layers to improve the interface friction properties (Figures 11 and 12).

Figure 11. Placement of bottom ash soil over geosynthetic

Figure 12. Continued placement of bottom ash soil over geosynthetic

MONITORING

The implementation of a monitoring system to record the settlements of the reinforcement geosynthetic aims to validate and refine the calculation and assumptions taken into account in the geotechnical model, and to better understand the reality and dynamics of the settlements.

The settlement monitoring system includes hydraulic settlement gauges connected to a reference tank. They are arranged as required, in line every 30 m (100 ft). Each gauge has been placed on the reinforcement geosynthetic on a rectangular plate and protected with sand to limit unexpected settlements (Figures 13 and 14).

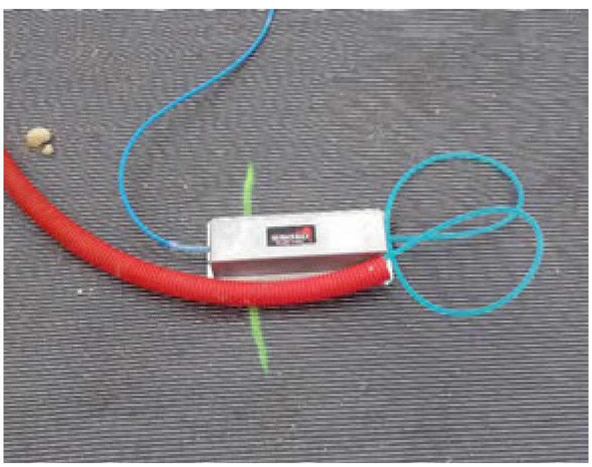

Figure 13. Hydraulic settlement gauge

Figure 14. Backfilling of the gauges

The gauges are connected to a reference tank, and a data logger is mounted on a concrete base outside the cell (Figures 15 and 16). The concrete base must not settle and is under a topographical survey. The data acquisition is made manually by connecting a reading device to the datalogger.

Figure 15. Reference tank

Figure 16. Datalogger

CONCLUSION

The use of a soil-reinforced layer as a subgrade for a piggyback landfill ensures that the leachate barrier system of the new cell will remain functional over the long-term. The designed and selected GEOTER F PVA reinforcement geosynthetic is a high-modulus woven geotextile made with high tenacity yarns that exhibits a tensile strength of 450 kN/m at 6% strain. It creates a uniform repartition of the load on the old waste and controls the differential settlements.

The high tenacity yarns made in PVA permit to re-use the bottom ash material (available on site) as backfill material on the product.

The methodology followed for the design of the reinforcement is already in use and described in several guides; however, the implementation of a monitoring system permits to refine the calculation and assumptions taken into account in the geotechnical model and confirm the expected behavior of the structure.

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