
FIGURE 1 Installation of reinforcement geosynthetic

Case Study

Design of reinforcement geosynthetics in landfill piggyback expansion

By Jean-Baptiste Duquet, Cédric Sarbach and Stephan Fourmont

An operator at a nonhazardous waste storage facility proposed extending the facility's life, within the existing perimeter, by vertically expanding the cells in operation to a maximum thickness of waste of 52.5 feet (16 m). This project is based on nonhazardous waste storage cells 49.2-feet (15-m) thick, some of which are more than 20 years old and, therefore, are at different degradation stages.

The vertical expansion requires the new cell to be hydraulically independent of those in place underneath. The overall leachate barrier system must comply with current regulations and must remain functional in the long term. The design included the installation of a soil layer reinforced with geosynthetics over the old final cover system (**Figure 1**). This layer is becoming the subgrade soil for the new leachate barrier system. Two typical sections are shown in **Figure 2**. As the site also operates as a valorization and disposal site for incinerator bottom ash, it was decided to use this material to construct the soil-reinforced layer.

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 nonhomogeneous degradation of the old waste (long term)

PROJECT HIGHLIGHTS

REINFORCEMENT IN LANDFILL PIGGYBACK EXPANSION

LOCATION
France

DESIGN ENGINEER
Antea Group

GEOSYNTHETICS PRODUCT
GEOTER F PVA 450

GEOSYNTHETICS MANUFACTURER
Afitexinov

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All figures courtesy of the authors.

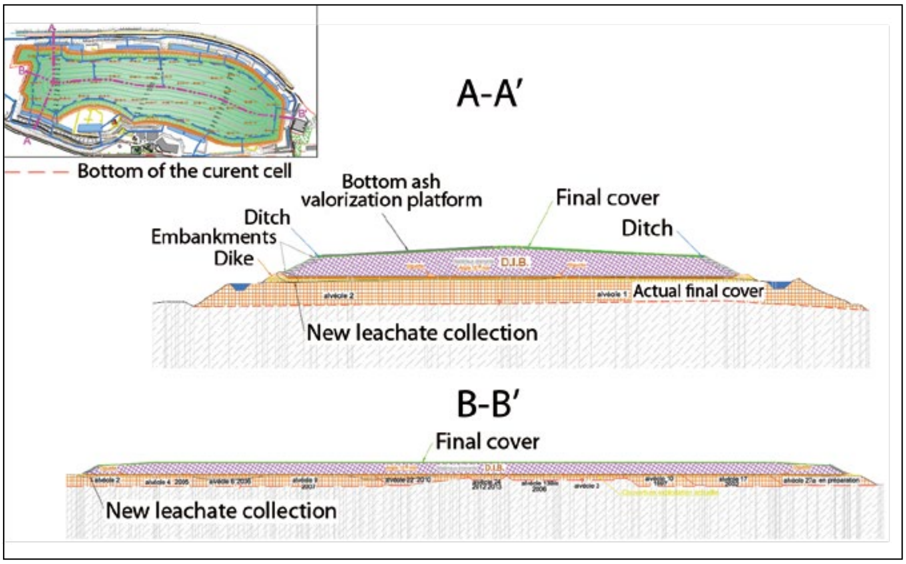

FIGURE 2 Typical cross sections

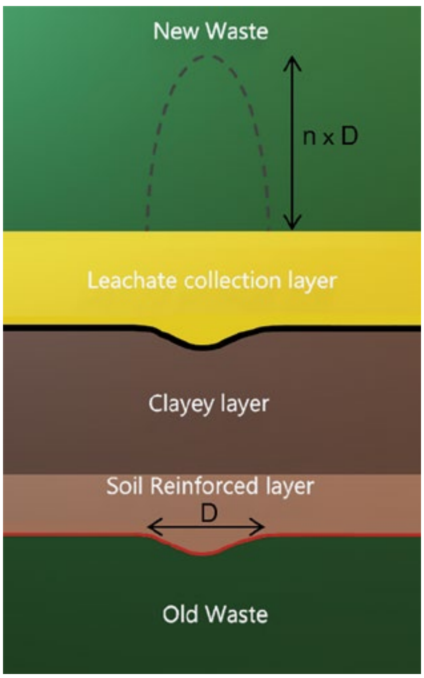

FIGURE 3 Illustration of the behavior of a homogeneous waste mass under loading

The guide "Recommandations pour la conception des extensions d'ISDND en appui sur des casiers anciens" ("Recommendations for the design of nonhazardous waste landfill extensions based on old cells") from the Bureau de Recherches Géologiques et Minières (BRGM) (Geological and Mining Research Bureau) (2020) recommends the application of the "Modèle Incrémental de Prédiction des Tassements" ("Incremental Settlement Prediction Model") (ISPM) (Olivier 2003 and Agency for Environment and Energy Management [ADEME] 2005). 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 retroanalysis (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 [EPMT=1,334 psi {9.2 MPa}]) and the ISPM from data collected in the literature. The estimation of the secondary settlements was achieved by applying the ISPM method with data resulting from a retroanalysis carried out using the topographic survey on the postoperation settlements of the site. In the worst-case scenario, the global settlements were estimated at 4 feet (1.2 m): 3 feet (0.9 m) of primary settlements and 1 foot (0.3 m) 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 geotechnical 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 3–6 feet (1–2 m) within the waste mass, as shown in **Figure 3**. It illustrates the main geometric definitions and notations that will be used. The value n=3 is to be considered for household waste.

The following limit state designs are to be considered:

- Serviceability limit state (SLS) 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.
- Ultimate limit state (ULS) 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.

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.

SLS

The maximum admissible deflection for the lining system is first determined. A value of 3% is used in the literature for an 80-mil (2-mm) high-density polyethylene (HDPE) geomembrane used as a primary lining system (Seeger and Müller 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, as shown in **Equation 1**.

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

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 (**Equation 2**) 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 will 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.

ULS

The ULS design regarding the minimum required strength of the reinforcement geosynthetic shall consider the long-term behavior of the product and its

Localized differential settlements are difficult to anticipate. The BRGM guide suggests taking them into account by considering a cavity with a diameter of 3–6 feet (1–2 m) within the waste mass.

The selected reinforcement geosynthetic is a high-modulus woven geotextile made with high-tenacity yarns, manufactured by a warp-knitting process. The woven geotextile provides the separation function, whereas the high-tenacity yarns give the high strength capacity to the overall product.

installation. This will be covered in the following "Geosynthetic design" section. The ULS verification (**Equation 3**) is then:

$$T_{ULS} \leq \frac{T_{ult}}{RF_s} \tag{3}$$

where:

T_{ult}: Ultimate tensile resistance of the reinforced geosynthetics

RF_s: 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 4**). 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 11,420 pounds-force per inch (2,000 kN/m).

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 (polyester [PET], polyvinyl alcohol [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 2,570 pounds-force per inch (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 considered (**Equation 4**):

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

where:

T_{design}: allowable tensile strength (pounds-force per inch [kN/m])

RF_{CR}: reduction factor for creep to account for long-term behavior

RF_{ID}: reduction factor for installation damage, determined from 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

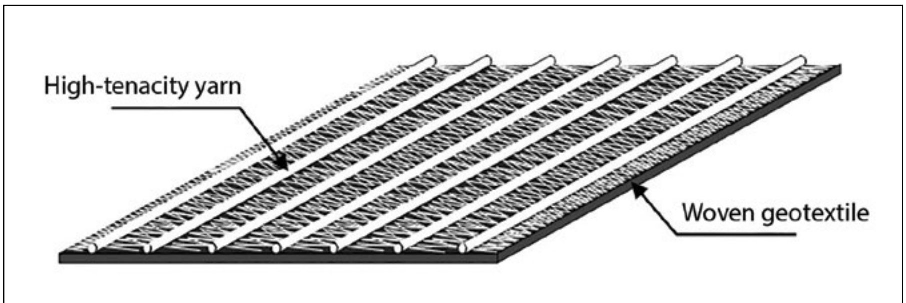

FIGURE 4 Description of the reinforcement geosynthetic

Creep behavior

The creep behavior was determined by an independent expert laboratory using the 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 tensile strength (load UTS) at the allowed elongation (determined by the geotechnical design), as written in the following formula (**Equation 5**):

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

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 0–12 inches (0–300 mm) (**Figure 5**).

After exhuming the product, a visual inspection was carried out. 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.

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**).

Durability

The high-tenacity yarns of the selected reinforcement geosynthetic are made of 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 and Freitag 2009) results in a reduction factor for durability of 1.2.

Applying the reduction factor to the allowable tensile strength determined by the geotechnical design led to the selection of the reinforcement geosynthetic with PVA high-tenacity yarns and UTS of 2,570 pounds-force per inch (450 kN/m): GEOTER F PVA 450.

FIGURE 5 In situ tests with several types of soil over the geosynthetic

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

TABLE 1 Reduction factor for installation damage (RF_{ID}) for several types of soil in contact with the reinforcement geosynthetic

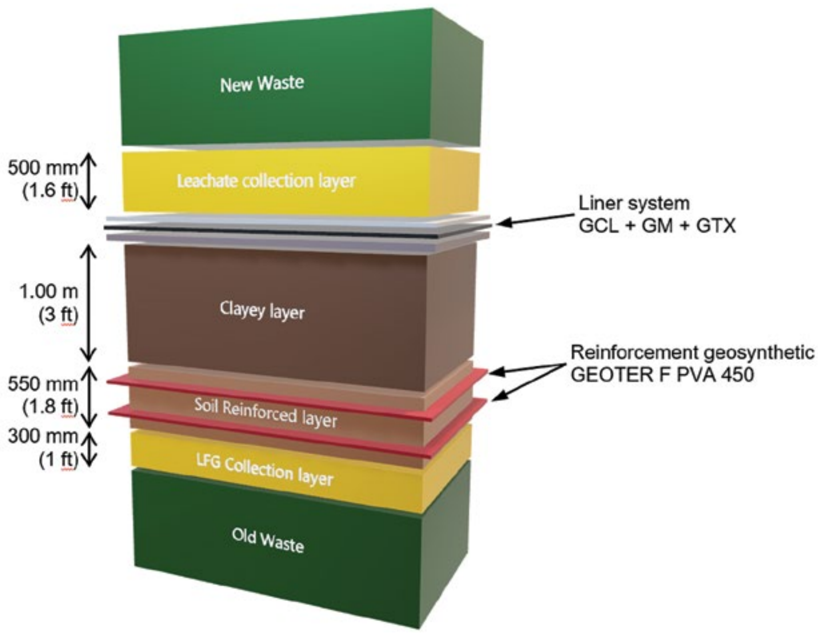

FIGURE 6 Final cross section of the new cell

Final cross section and layouts

The final cross section for the vertical expansion of the cell is presented in **Figure 6**.

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

Test	Symbol	Unit	Value	Comment
Natural water content	Wn	%	12.1	0.8 Wopn < W < 1.1 Wopn
Dry unit weight	ρd	T/m^3	1.28	
Particle size distribution	Dmax	mm	23	PSD 0/20 mm
	< 50 mm	%	100	
	< 2 mm	%	39.7	
	< 80 μm	%	4.7	
Methylene blue	MBV	%	0.04	
Sand equivalent	SE	-	67.8	
Organic content by loss on ignition	LOI	%	7	
GTR class			F61	Similar to D2
Proctor test	ρdOPN	%	14	
		T/m^3	1.75	
Immediate bearing capacity factor	IPI		40.3	IBC > 20 (average and for 3 values over 5)
			46.2	
			34.3	
			7.1	
			2.2	
Fragmentability	FR		1.9	High fragmentability
Consolidated drained triaxial	c′	kPa	42	
	φ′	°	37	

TABLE 2 Bottom ash material characterization

flows through a 1-foot (300-mm) gravel drainage layer between the old waste and the soil-reinforced layer.

Soil-reinforced layer

A 1.8-foot (550-mm) 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 2,570 pounds-force per inch (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.

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 3-foot (0.9-m) thick with a hydraulic conductivity inferior to 1×10^{-9} m/s, and a geosynthetic clay liner (GCL)
- An 80-mil (2-mm) HDPE geomembrane protected by a nonwoven geotextile
- A gravel drainage layer 1.6-feet (0.5-m) 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 395 feet (120 m). Handling was achieved using mechanical shovels.

FIGURE 7 Installation of reinforcement geosynthetic

Roll placement

The PVA reinforcement geosynthetic is unrolled on a base that has been graded and compacted (**Figure 7**).

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 12 inches (300 mm) following the direction of the backfill placement.

Bottom ash material placement

The incinerator bottom ash material is free of foreign matter that could damage the geosynthetic. A 1-foot (300-mm) thick layer has been placed between the two geosynthetic layers to improve the interface friction properties (**Figure 8**).

FIGURE 8 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 considered 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 98 feet (30 m). Each gauge has been placed on the reinforcement geosynthetic on a rectangular plate and protected with sand to limit unexpected settlements (**Figure 9**).

The gauges are connected to a reference tank, and a data logger is mounted on a concrete base outside the cell. 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 data logger.

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 PVA reinforcement geosynthetic is a high-modulus woven geotextile made with high-tenacity yarns that exhibit a tensile strength of 2,570 pounds-force per inch (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 of PVA permit the reuse of 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 refining of the calculation and assumptions considered in the geotechnical model and confirm the expected behavior of the structure.

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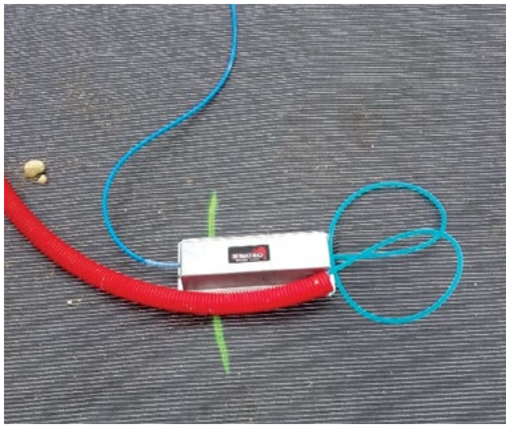

FIGURE 9 Hydraulic settlement gauge