Use of geosynthetics in piggy-back landfills : development of an iterative methodology for the design of the lining system over old unlined waste

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ABSTRACT: Given the difficulties in identifying suitable sites for the establishment of new sanitary landfills, the extension of existing sites is considered more and more often as a solution. This increasing interest is also linked to the possibility of increasing the waste storage capacity and using the operating infrastructures over a longer period, thus allowing savings. Beyond the benefits associated to this rather new landfill concept, it is necessary to carefully consider the integrity of the liner system considering the important settlements (reactivated under the new cell load) that can develop. Indeed, the settlements can alter the sealing and the drainage functions of the liner system. An iterative method inspired mainly from the Incremental Settlement Prediction Model (Olivier, 2003) was developed to look deeper into this issue. Applicable to various geometric configurations, this method helps designing the barrier reinforcement using high-performance geogrids. In addition to this aspect, the proposed methodology also helps designing bottom liner system slopes to guarantee free drainage and avoid leachate accumulation.

Keywords: landfill expansion, settlements, liner system, geosynthetics, stability

1 INTRODUCTION

Landfill sites are becoming increasingly technical works in which various materials interact: natural materials (clay, sand, gravel), synthetics materials (geosynthetics) and waste, whose behavior can be variable both in time and space. The technical nature of these facilities has increased in recent years with new landfills being built over older cells. This new “piggy-backing” design was implemented for the first time in 1987 on a landfill site close to New York City (Bouthot et al., 2003) before being taken up and developed during the last two decades in North America, China and more recently in Europe and in France, where there are now a dozen such sites.

With the increasing difficulty in identifying suitable sites for the establishment of new landfills, the implementation of these piggy-back landfills is considered more and more often: a simple review of recent landfill projects confirms an increase in the number of such projects and their number is expected to remain high in the medium term, regardless of their governance (public or private). Indeed, although the quantities of waste sent to landfill sites are slightly decreasing as a result of public policies for the reduction and the recycling of waste, the stabilization of waste treated through valorization processes (biogas production, composting, ...) often remains incomplete while other processes lead to waste residues requiring a final disposal. For all these reasons, landfill sites will remain necessary, being the last treatment process for waste residues.

From the perspective of real estate, piggy-back landfills have the advantage of limiting the spreading of existing facilities, hence favoring the preservation of agricultural land as well as simplifying site opening procedures for site operators (since the acquisition of new land is not necessary or very limited) and rationalizing equipment and structure expenditure (economy of scale). Moreover, when a landfill site operator has developed a good relationship with the local residents, it goes without saying that it will be easier to promote an extension on the same site rather than in an area where he doesn’t have any connection yet.

However, storage of waste over older waste leads to the reactivation of their settlement, which may result, without the implementation of appropriate reinforcement structures, to large deformations within mineral and synthetic impervious barriers. In addition, in the case of piggy-back landfill projects partly established on side slopes, large-scale instabilities can also appear, favored by the presence of geosynthetic interfaces, which can easily become sliding surfaces. Therefore, it is crucial to integrate all the components of the geotechnical analysis, in order to ensure not only the overall stability of the sites but also the long-term performance (impermeability, drainage) of their bottom passive and active liner system.

2 CHARACTERISTICS OF PIGGY-BACK LANDFILL PROJECTS AND RELATED ISSUES

As discussed above, piggy-backing or landfill expansion consists in creating one or more new landfill cells partly or completely supported on older closed cells. Beyond this definition, landfill expansion encompasses a wide range of configurations and associated issues, particularly regarding (Olivier and Tano, 2013):

- Geometry of the older cell and of the newer one (see Figure 1):
- Raise of the landfill in a valley or a quarry and supported on the side slope
- Raise of the landfill in tumulus and entirely supported on the old waste cell
- Raise of the landfill supported totally or partially on the side slope of the old cell

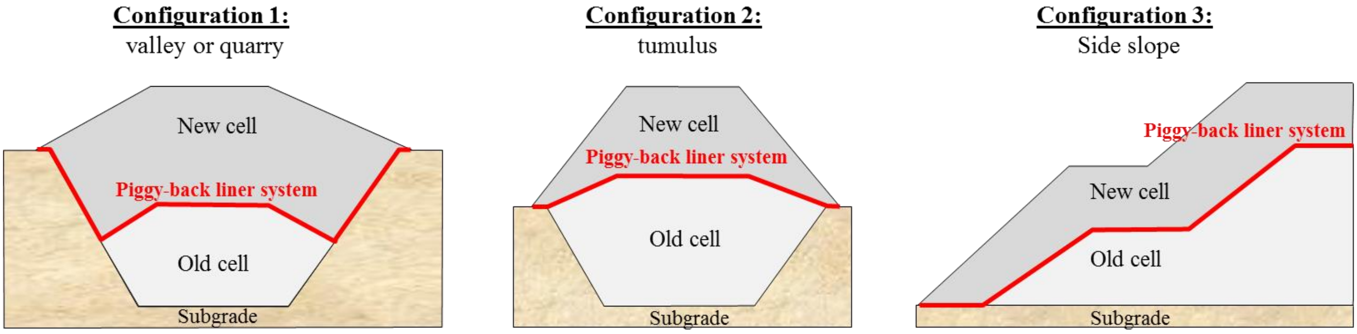

Figure 1. Example of the main configurations of piggy-back landfill (possibly in combination).

- Characteristics of older waste:
- Nature of the waste (household waste, industrial waste, bulky waste, organic waste, etc.)
- Height of the waste (usually between 5 and 50 m)
- Age of the waste (0 to 30 years)
- Water content of the waste

- Type of safety equipment of older cells:
- No passive and active liner system (such as in old landfills)
- Existing liner system but not strictly in conformity with the current regulations (especially in terms of hydraulic equivalence)
- Liner system meeting all current regulations

- Possible retaining and reinforcement structures related to the landfill expansion:
- Soil improvement / reinforcement of the foundation (PVD, jet grouting, soil mixing)
- Reinforced wall (reinforced earth, gabions, etc.)
- Heavy retaining wall

By the possible combination of the above factors, piggy-back landfill projects present various characteristics, which should be approached with method. Under these conditions, it is more important to develop a general analysis approach than turnkey design solutions. In addition, special attention is necessary in terms of design, dimensioning and implementation of the piggy-back liner system (Table 1) which is of crucial importance with regard firstly to its role for containing leachate and secondly to its mechanical properties (rather medium or low interface friction that make it a preferential sliding surface).

Table 1. Constitution of safety barriers on existing waste

Containment	Cell bottom		Cell side slopes	
	Function	Material	Function	Material
Active liner system	Drainage	Granular materials (+ drainage geocomposites : optional)	Drainage	Geosynthetic[1]
	Active permeability	Geomembrane[1]	Active permeability	Geomembrane[1]
Passive liner system	Passive permeability	Clay only (thickness : 1 m) or clay associated with GCL[2] or treated soil (SBP[3] for example)	Passive permeability	GSB[2] or treated soil and 0,5 m of clay on the lower 2 m from cell bottom
	Mechanical reinforcement	Reinforcement geogrid or geosynthetic[4]	Mechanical reinforcement	Reinforcement geogrid or geosynthetic[4]
	Attenuation + subgrade layer	Local materials	Attenuation + subgrade layer	Natural materials existing on the site

[1] Geotextile necessary on the upper face of the GMB for protection
[2] GCL: Geosynthetic Clay Liner
[3] SBP: Sand-Bentonite-Polymer
[4] Structural element not yet routinely part of piggy-back landfill projects

3 PROPOSED METHOD FOR THE DESIGN OF A LANDFILL EXPANSION

3.1 *Basis of the method: settlement of the existing waste under the new waste*

3.1.1 *Settlement of waste: what are we talking about?*

The proposed method (Figure 2) primarily consists in taking into account the settlement of waste which may cause disturbances for the piggy-back cell following the surcharge load. To anticipate at best the predictable distortions in the waste in place (under the piggy-back liner system) but also at the top of the piggy-back cell, both structural and localized settlements which may appear in the waste mass must be considered.

Structural (or "large-scale") settlements arise primarily from:

- Mechanical actions (mainly related to the application of surcharges causing distortion and rearrangement of waste components)
- Biochemical actions (due to the decomposition of the organic part of the waste)
- Physicochemical actions (corrosion of ferrous materials, oxidation phenomena , etc.)
- Sieving of degraded particles through macro-pores of the waste

These mechanisms interact, overlapping one another in a complex way over time. Their association may nevertheless be represented on the basis of two distinct components (Olivier, 2003):

- Primary (short-term) settlements resulting from the surcharge induced by the overlying waste and the cap cover. This short-term component (a few days to a few weeks) is generally assumed to be independent of time
- Secondary (long-term) settlements assumed to be independent of the surcharge and possibly continuing over several decades

The amplitude of these settlements can reach cumulative levels of several meters after 30 years. Also, taking into account the inevitable spatial variations depending on the type, height and age of the buried waste, significant differences in settlement (differential settlements) may occur from one area to another in the same cell. In a piggy-back context, these settlements may result in a potential loss of integrity of the intermediate barrier and in the breaking of gravity water channels.

Unlike structural settlements, localized settlements result from collapses that can sometimes occur in a waste mass. Indeed, although composed mainly of a fine matrix of moderately variable mechanical behavior (for a given age and level of compression), municipal solid wastes can be very heterogeneous due to the presence of large items (mattresses, scrap metal, etc.) which can act as hard spots within the material structure or, on the contrary, as softer pockets in the presence of highly degradable waste and/or waste of malleable consistency (sludge, putrescible waste, etc.). In the case of bioreactor landfills (with leachate reinjection), these phenomena can be amplified in case of a non-homogeneous distribution of moisture in the waste.

3.1.2 *Evaluation of the effects of landfill expansion on settlements*

In order to anticipate future (structural) movements of piggy-back liner system, it is proposed to use the Incremental Model Prediction of Settlements (ISPM model) [Olivier (2003), ADEME (2005)]. Indeed, compared to traditional models, this model has advantages both fundamental (determination of compression coefficients inherent to the waste) and practical (increased reliability of predictions). In addition, its incremental nature (analysis by elemental waste layer) gives it a great flexibility of use, predestining it to the study of waste bodies whose height and age often vary in space. Finally, this model presents the advantage of having been calibrated on fifty or so landfill sites in France and abroad, giving it a reliability that other models do not have.

Moreover, in addition to the traditional study of structural (large scale) settlements, it is appropriate, in order to anticipate (conservatively) the maximum deformations that can occur within a waste mass, to also take into account the risk of occurrence of localized settlements. In the absence of a mathematical model, this risk is estimated on the basis of feedback acquired on several landfill sites around the world.

3.2 *Process and main steps of the proposed method*

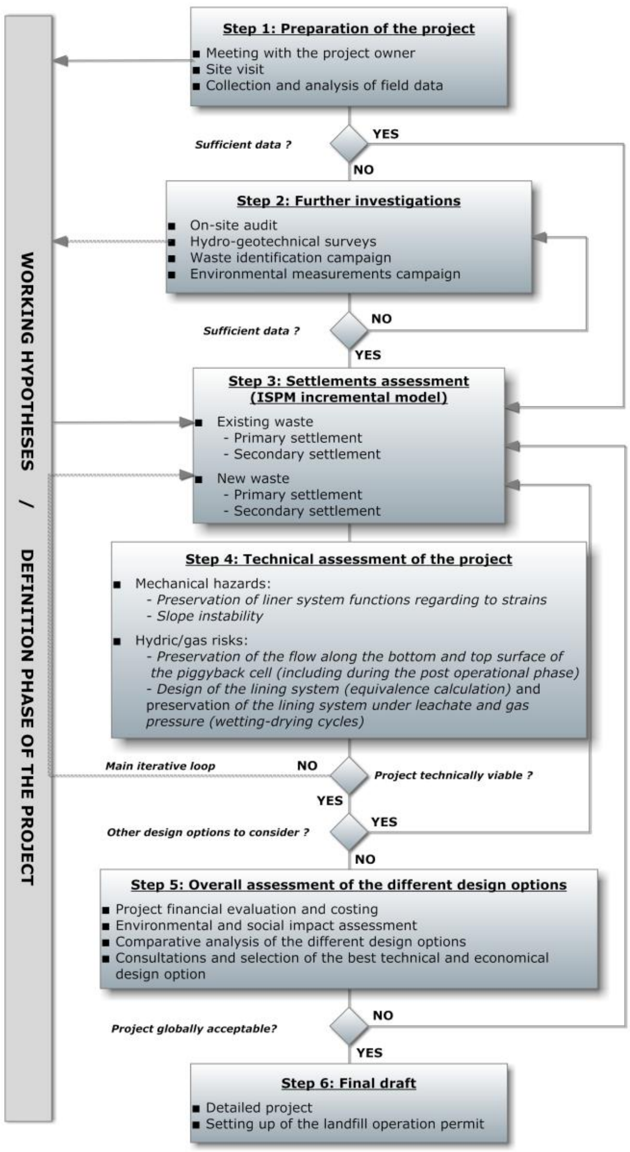

Figure 2. General methodology proposed for designing a piggy-back cell.

Figure 2 summarizes the successive steps of the suggested method. Following the preparation of the study (step 1), further investigations (step 2) may be required depending on the quality of available data. Once the data is considered sufficient, it is used to complete the working hypotheses that must be fixed before proceeding to step 3 (calculating settlements). Based on the first set of hypotheses considered, settlements of both the old waste and the new waste are estimated over the entire hold of the studied cell, with a mesh sufficiently narrow to allow the assessment of maximum differential settlements. The time scale taken into account in these calculations naturally differs depending on whether are only taken into account the settlement of the waste at passive and active liner system or the settlement of the whole waste column (old + new waste) at the cover of the new cell. In any case, the most unfavorable conditions for the project shall be taken into account, generally at the end of the post-operation period of the site. Once all the calculations are made, step 4 can begin, consisting primarily in verifying the continuity of flow streamlines along the liner system as well as the cap cover of the new cell (in order to avoid the formation of rainwater stagnation zones).

After these verifications, the initial hypotheses, generally revealing to be perfectible, will require several adaptations to ultimately lead to a satisfactory technical solution. It is therefore necessary to go back to the previous step (3) as many times as necessary until approaching (with successive approximations) the optimal technical solution. For each iterative loop, an exchange with the project owner or his representative is desirable in order to refine the working hypotheses in a way that remains consistent with future operating constraints of the site. As shown in Figure 3, this especially necessitates spatial adaptation:

- Of the thickness of the subgrade layer (variable thickness at all points of the cell)
- Of piggy-back liner slopes $\Rightarrow \alpha(x, y)$
- Of the cap cover of the new cell $\Rightarrow \beta(x, y)$

Given the reliability of the settlement prediction method (which guarantees a minimal uncertainty regarding the magnitudes and distribution of post-operation settlements), it is also possible within the framework of the proposed design (Figure 3):

- To reduce cover slopes $\beta(x, y)$ of the piggy-back cell.
- And possibly to raise the maximum upper level of the waste of δH height (Figure 3) in anticipation of post- operation settlements, while ensuring the top cover elevation to be back under a certain level at a given date (determined on a case by case basis).

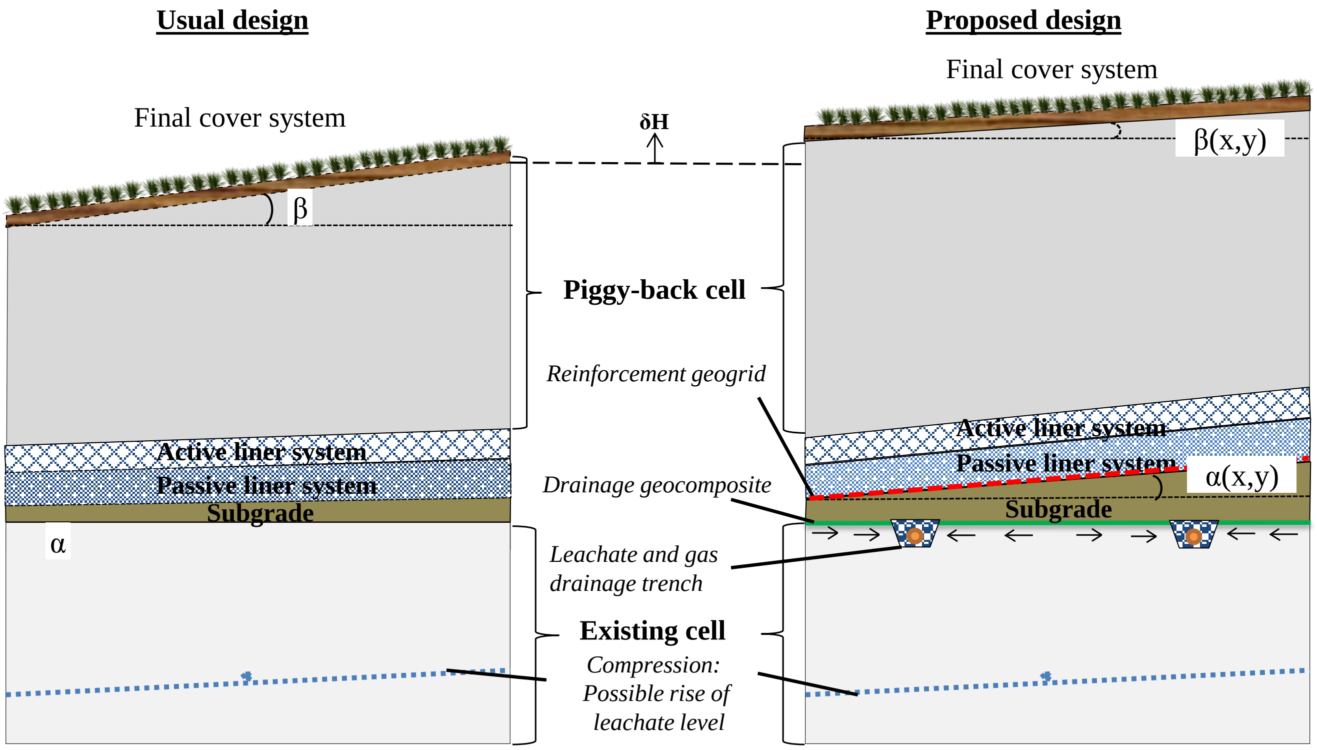

Figure 3. Proposed design vs. usual design for a landfill expansion.

In addition to the previous issues, other technical questions are raised within the framework of step 4 (geogrid reinforcement, leachate and biogas drainage …). These are detailed below (§ 3.3 and 3.4). Once the project is considered viable, and possible alternatives exhausted, we can finally move to the overall project evaluation (step 5) followed by the detailed project (step 6) if it is considered acceptable.

3.3 *Design of geosynthetic reinforcement to maintain the functions and the integrity of the piggy-back liner system*

In order to avoid any loss of integrity (by cracking or breakage) of the active and passive piggy-back liner system as a result of the differential settlements that will inevitably occur under the new cell, a mechanical reinforcement ought to be provided, including a reinforcement geosynthetic that can withstand significant tensions while deforming as little as possible both on short and long term (material nit hardly sensitive to creep). The geosynthetic shall be placed between the passive mineral barrier and the attenuation layer in order to fully play its role.

3.3.1 *Design of the geosynthetic reinforcementabove a cavity*

The geosynthetic reinforcementmust be able to withstand both the occurrence of significant (and spatially and highly variable) overall settlements and the potential formation of localized collapse zones. This second phenomenon is here discussed in more detail.

Giroud et al. (1990) were the first to propose, in the presence of a cavity under a bottom barrier system, an analytical method for the evaluation of the required tensile strength, taking into account the induced membrane effect. This method was adapted to allow consideration of the barrier slope by means of a successive approximation method. This design method includes six steps (a to f) from the definition of calculation hypotheses to a performance evaluation of preselected geosynthetic (Figure 4).

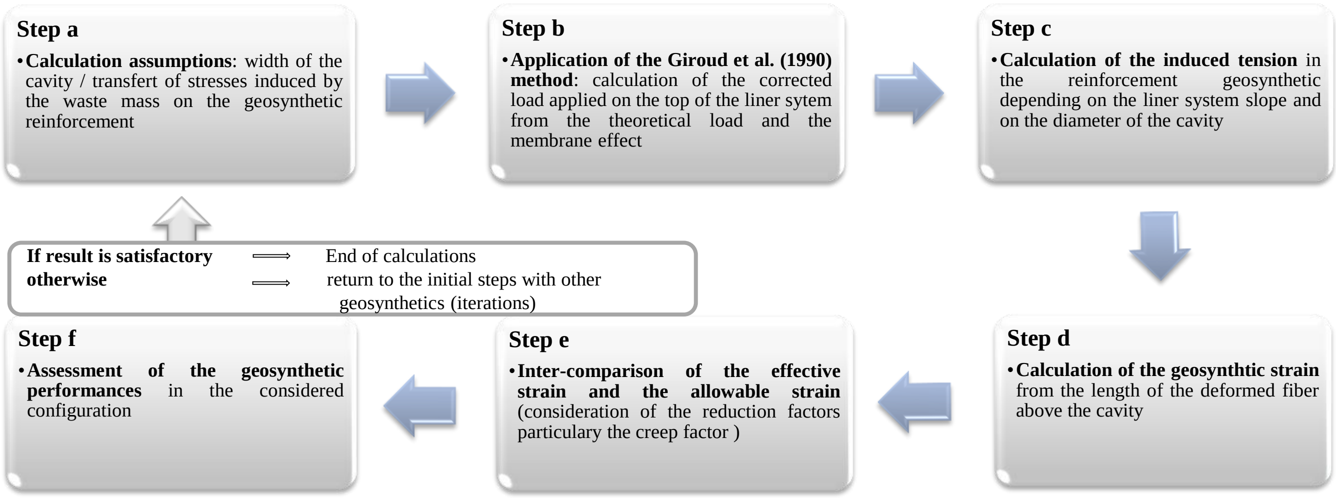

Figure 4. Steps of the iterative process for the design of geosynthetic reinforcement (above a cavity).

3.3.2 *Design calibration based on real cases*

As part of the calculation process illustrated on Figure 4, it is first necessary to establish an acceptable strain corresponding to the nominal tensile strength of the geomembrane and of the geosynthetic reinforcement tested. Regarding the vertical surcharge, taking into account the entire height of the piggy-back waste would be quite unrealistic, due to "fiber cohesion" (entanglement) and friction phenomena that have the effect of retaining waste elements one to another, which reduces the surcharge load at the base of the column where the collapse occurred. A calculation taking into account the thickness of the bottom liner system, the earth pressure coefficient and the internal friction angle of waste can determine this load.

Besides, caution leading to consider the most potentially penalizing conditions, a series of correction coefficients is applied for the design of the geosynthetic, including a weighting factor (consistent with Eurocodes), a series of reduction coefficients linked to risks of mechanical damage (during installation), environmental risks (mainly related to the chemical inertness of the geosynthetic) and creep risks (depending on the nature of the geosynthetic, of the duration considered for the service life of the construction and of the eventual certification of envisaged geosynthetic) and at last, a general safety factor. Finally, the value of nominal strain considered for the product is generally assessed for 20°C. If a medium temperature of 40 to 50°C is considered at the heart of the waste as well as an increase of the ultimate strain depending on temperature, it is necessary to proportionally reduce the nominal strain of the product so as not to exceed its ultimate value.

The ultimate strain of GCL and treated soils (corresponding to the passive barrier) are generally sufficient to withstand effective deformations. As for clays, their resistance to deformation in unconfined conditions is generally quite low as attested by several laboratory and field tests. However, the work carried out by Jessberger and Stone (1991), Viswanadham and Jessberger (2001) and more recently Camp (2008), in confined conditions, largely put in perspective the risks of tensioning because when pressure increases due to overload, tension mechanisms are gradually replaced by shear phenomena comparatively less penalizing (especially in the presence of geosynthetic reinforcement).

3.4 *Other technical considerations*

In addition to the previous issues, other problems may arise during the design of a piggy-back cell, such as the question of the installation of geosynthetics. All these issues cannot be discussed here in detail. However, two specific points may for instance be briefly mentioned:

- <u>Drainage of leachate and biogas from older waste under the piggy-back liner system:</u> in some cases, waste degradation coupled with rainwater infiltration in old cells is likely to result in an important humidification of the waste in place, which can be accentuated by the surcharge applied on the older waste (due to the decrease of the pore size of the waste). Also, in the presence of initially very wet waste (possibly with presence of perched leachate table) and/or biogas insufficiently drained, our approach calls for the establishment of drainage trenches possibly coupled with drainage geocomposites (Figure 3) under the subgrade layer as is also done under the concrete slabs of buildings built on contaminated soil in order to avoid any risk of leachate / biogas rise in contact with the passive barrier. Indeed, clay and GCL even more are materials sensitive to humidification / desiccation cycles and, as such, must be maintained in a water conditions as stable as possible. If required, the previous equipment can thus be designed as single or mixed (leachate / biogas) networks.
- <u>Stability on slopes:</u> in the presence of steep slopes, it is important to carefully consider the interface (residual) properties of synthetic and mineral materials. Indeed, the interface friction angles between the materials most commonly used generally vary within a range of 6 to 20°, depending on the surface condition of geosynthetics considered, their surface moisture, their deformation, etc. (Bergado et al., 2006; Eid, 2011). Moreover, according to the surface state (more or less smooth or rough) of each geosynthetic, the transfer of lateral loads (in case of slight slope deformation) may occur along different interfaces. Therefore, it is important before installing the piggy-back barrier to conduct a study of interface or block stability in order to avoid any risk of instability.

4 FROM DESIGN TO IMPLEMENTATION: FIELD FEEDBACK

To date, the authors have worked on seven vertical expansion projects such as the Crépy-en-Valois landfill site (Figure 5) located 60 km from Paris. An assessment of the project design and the work carried out has been made.

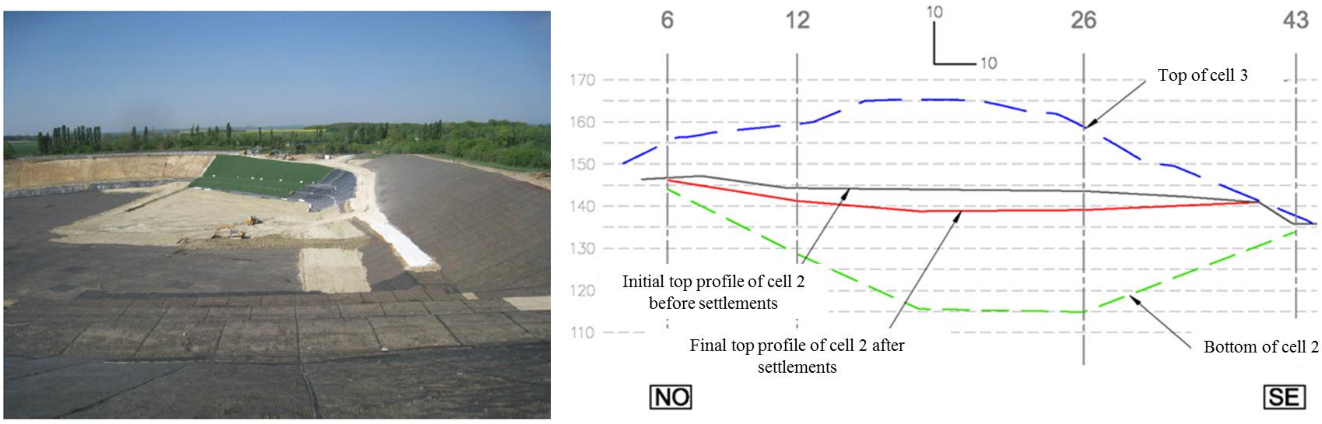

Figure 5. Crépy-en-Valois landfill expansion site. (a) Implementation of geogrid reinforcement under the passive barrier. (b) Cross section of the existing cell and of the piggy-back cell showing the expected evolution of the geometry of the piggy-back lining system after settlements.

Despite a somewhat complex site configuration (combination of configurations 1 to 3 shown in Figure 1) and a relatively significant height of waste in place (up to 45 m), maintaining the long-term flow streamlines at the bottom of new cells did not raise any particular difficulty, given the direction of the initial slopes which settlements were only going to accentuate over time. It thus was not necessary to specifically increase the subgrade layer. Given the height of old and new waste (up to 35 m locally), primary settlements between 0.5 and 2 m and secondary settlements between 1 and 3.5 m were predicted 30 years after the end of the site operation. As a direct consequence of these settlements, a general stretching of the barrier with an average order of magnitude of 0.2 to 0.5% was estimated. Based on the detailed results of the study, it was decided to install a Fortrac® R MPT type, made of polyvinyl alcohol (PVA) fibers with polyamide coating. Presenting a very low creep deformation compared to polyester or HDPE fibers, PVA fibers have been selected for optimum long-term performance of the product. In this regard, the dimensioning of the geogrid was made on the basis of a 100 year creep. Given the cost of geogrid reinforcement, special attention was given to the layout plan of the geogrid in order to limit the longitudinal overlaps (and thus product "loss"). Retrospectively, this proved to be all the more important that the cell showed irregular shapes (Figure 5). Finally, given the high stiffness of the geogrid, it appeared that longitudinal overlaps were more fitting than conventional anchor trenches. A first attempt of double anchor trench made on a trial section confirmed that such implementation was likely to lead to the weakening of anchor trenches but also to the tension of GCL. Thereafter, the geogrid strips were therefore systematically laid flat. When the slope geometry allows it, a temporary anchorage solution using big-bags or concrete blocks can also prove to be interesting.

5 CONCLUSIONS

Facing the difficulties of identifying suitable sites for the implementation of new landfill sites, it was reminded that the current trend was to focus on the expansion of existing sites (piggy-backing). Beyond the benefits that this type of installation represents, carefully taking account the settlement phenomena (reactivated as a result of surcharge loads) however proves to be necessary so as to ensure the long-term drainage and sealing functions of the active and passive barrier systems (as well as the cap cover of the new cell). An iterative design method inspired by the ISPM model was developed, adapted to different site configurations. In addition to setting the slopes of the piggy-back liner system, this method also contributes to the design of the geosynthetic reinforcement required under the mineral (passive) sealing layer. Applied to date to seven landfill sites in France and abroad, the proposed approach has proven to be reliable and helps rationalizing the construction of piggy-back cells. Without doubt, improvements are however still possible. Given the importance of the issue, a research project was launched in 2013, in collaboration with two major French public laboratories, a geosynthetic producer and landfill operators.

6 AKNOWLEDGEMENTS

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