State-of-the-art of piggy-back landfills worldwide: comparison of containment barrier technical designs and performance analysis in terms of geosynthetics stability

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ABSTRACT
Nowadays, it is becoming a challenge to identify suitable sites for the establishment of new sanitary landfills. As an alternative solution, landfill expansion has become an attractive option because it offers many advantages such as the increase of waste storage capacity while using the existing operating infrastructures over a longer period, thus allowing savings. Beyond these benefits, it is necessary to ensure the integrity of the liner system considering the related issues. In order to look deeper into these issues and identify current practices, a comprehensive state-of-the-art has been performed based on some twenty case studies around the world. This work has highlighted important design differences, confirming the need for additional research works on this topic to achieve an international best practice standard. The analysis is completed in the light of the authors' experiences who have been involved in the design of several piggy-back landfills in France and abroad.

1. INTRODUCTION

Landfilling constitutes the last stage in the municipal solid waste (MSW) treatment operations. Although significant efforts are carried out for the ultimate waste reduction, landfills will surely stay for a long time to come a major step in the MSW treatment process. However, for nearly 30 years, it has been more and more difficult to find suitable sites for the construction of new MSW landfills in several countries. This is mainly due to the scarcity of suitable ground (low permeability, etc.), social pressure (nearby residents) as well as the long permitting and approval process of MSW landfill construction.
In this context, in order to maximize landfill airspace with limited footprint, designers often choose to build new cells over older cells. Indeed, this specific mode of storage commonly known as piggy-back landfill is an interesting way to continue storing the waste with significant cost-benefits while using the existing infrastructure and facilities.
However, the success of such a project requires careful assessment of several issues especially integrity and stability of the piggy-back liner system (PBLS) intercalated between the old and the new waste. Moreover, there is a lack of state and international standardization in the design of such PBLSs; hence, this barrier is not always properly designed with regard to the related issues.
Thus, by providing an overview of 22 piggy-back landfill projects, the purpose of this study is to show the current state of practice around the world in the design of PBLSs. It intends to identify unsuitable features in the design of landfill PBLS. To the authors' knowledge, it is the first time PBLS structures worldwide are compared each over. This attempt aims to provide some guidance on acceptable practices in the designing of landfill expansion projects.

2. PIGGY-BACK LANDFILLS AND REGULATORY FRAMEWORK

2.1 Main configurations of piggy-back landfills

Piggy-back landfills also termed landfill expansions present three main configurations depending on the site context:

- **Vertical expansion (V)**: the piggy-back cell is built over the top surface of the old (existing) cell. In this context, the landfill is expanded vertically by a rise of its vertical height in order to reach the design capacity (Figure 1a).
- **Lateral expansion (L)**: when it is possible to extend laterally the footprint of the landfill, the piggy-back cell can be established over the old cell side slopes (Figure 1b).
- **Mixt expansion (M)**: more often, landfill expansion is achieved in a combination of the 2 previous configurations. The lateral and vertical airspace is filled, thereby providing a more important MSW volume to store (Figure 1c).

Furthermore, piggy-back landfills are often associated with the construction of a perimeter berm on the toe of the slopes in order to improve the slope stability and/or to increase the landfill airspace. This perimeter berm can be a simple retaining wall without reinforcement or a mechanically stabilized earth (MSE). Additionally, the geometry of piggy-back landfills depends on the configuration of the existing cell which can be in a valley (or a quarry) or supported on the side slope of the ground surface making a tumulus configuration.

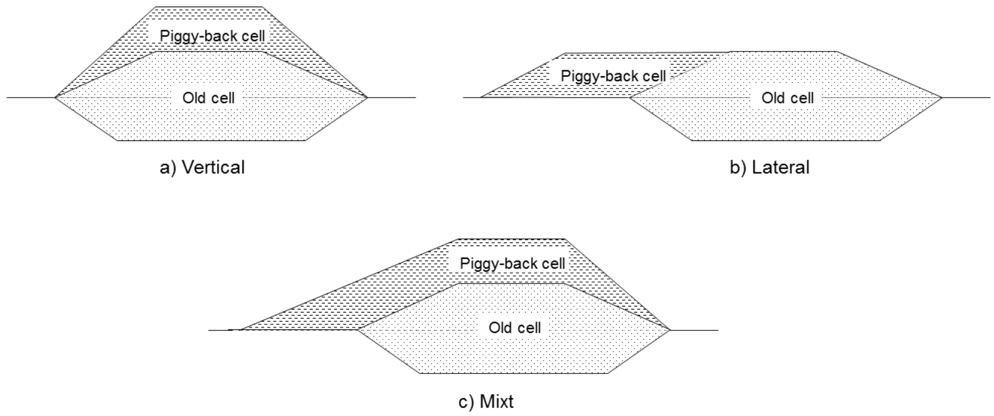

Figure 1. Main types of piggy-back landfills.

2.2 Piggy-back liner system regulatory framework

Modern MSW landfills commonly use proper veneered liner systems placed at the bottom and in part on slopes of the cells to protect the groundwater from leachate percolation and to keep a safe sanitary environment.
Unlike most countries and states has design regulatory concerning the base or cover liner system of standard landfills, there is a deep lack of regulatory concerning the PBLS. In fact, to the authors' knowledge, there are no regulations or guidelines specific to the piggy-back landfill context.
Indeed, none of the modified ministerial order 1997 and Geosynthetics French Committee (CFG) recommendations in France, the subtitle D of the Resource Conservation and Recovery Act (RCRA) for USA and the Best Practice Environmental Management (BPEM) in Australia for example, deals with the PBLS design.
Hence, most designers use the existing regulations concerning standard landfills as the design criteria although they are not always appropriate for piggy-back landfill projects. A good illustration of that is the Maine landfill PBLS design. Grillo et al. (2001) relied on the state of Maine regulations through its Department of Environmental Protection (MEDEP) that requires a double liner with a leak detection system and geogrid (GGR) reinforcement when landfills are established on weathered or fractured (unstable) bedrock. Indeed, in piggy-back landfill context, the old waste is assimilated to that unstable bedrock; these MEDEP regulations were therefore used (Figure 2a).
In the following section, the PBLS structure of the 22 case studies around 6 countries is presented and then discussed.

3. PRESENTATION OF THE CASE STUDIES

3.1 The first landfill expansion and its piggy-back liner system

In 1987, the first landfill expansion around the world has been installed in New-York state (USA) at the Blydenburgh landfill in operation since the 1950's. This construction was made prior to the development of any federal regulation in this state concerning this mode of landfilling (Tieman et al. 1990).
The PBLS presented in Figure 2b comprised the following components from top to bottom: a 30 cm thick drainage sand layer, a filter fabric, a drainage net, a 2 mm high-density polyethylene (HDPE) geomembrane (GMB) and two polyethylene (PE) uniaxial GGR reinforcement placed in a 60 cm thick select fill in order to provide multidirectional support for non-symmetrical depressions (Tieman et al. 1990). This was probably the first time a GGR was used in a landfill for this application (Berg 1987, Whelton and Wrigley 1987). The design of the GGR was based on conservative assumptions assuming a 2.4 m circular void beneath the PBLS.
The structure of the 22 PBLSs reviewed for this paper is further discussed below and summarized in Table 1.

3.2 Description of the piggy-back liner system case studies

This section aims to show the current state of practice in the design of PBLSs. For this purpose, the similarities and differences between the various designs are highlighted for each function of the piggy-pack liner system (i.e. sealing, drainage, protection and reinforcement functions). However, because limited information from the case studies is available on the puncture-protection layer, this point is not discussed in details in this section but will be considered in Section 4.

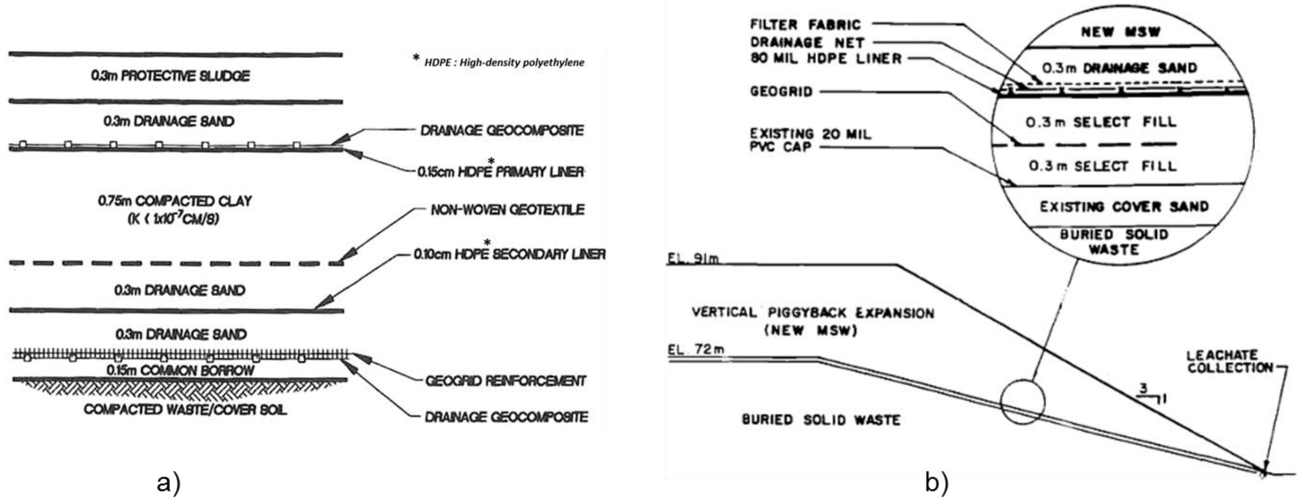

Figure 2. Cross-section of piggy-back liner systems. (a) State of Maine regulatory for fractured bedrock assimilated to waste (adapted from Grillo et al., 2001). (b) 1st landfill expansion: Blydenburgh (from Tieman et al. 1990).

3.2.1 Sealing function

3.2.1.1 Active containment barrier: geomembrane

- **Nature: high-density polyethylene or linear low-density polyethylene?**

The analysis of Table 1 reveals that all the GMB used in the piggy-back landfill liners are made of PE. Moreover, as can be seen from Figure 3, almost 80% of the GMB used are made of HDPE, presumably for its excellent chemical inertness (Frobel and Sadlier 1997).

However, it is not unusual to use linear low-density polyethylene (LLDPE) GMBs in some countries like Australia, China or USA. Its use is always motivated by its higher flexibility, more suitable when differential settlements hazard is high. For the sites identified in France only HDPE GMBs were used. Indeed, LLDPE GMBs are still uncommon in France (Benneton and Girard 2004) while abroad, some designers opt for a low density GMB, such as for the Peabody site, in Johnston County, USA, and the MLRMC site in Australia. On the Peabody site, the designers had even chosen very low density PE (VLDPE) GMB but this one was not available and could not be installed. According to Stulgis et al. (1996), polypropylene (PP) or flexible PVC have properties similar to VLDPE and LLDPE GMB in terms of flexibility (similar multiaxial behavior) which would be required to set up a flexible liner system in order to withstand waste settlement. But PP and PVC GMB have some drawbacks that are discussed in section 4.

- **Type: smooth or textured?**

Often associated with geosynthetic clay liners (GCLs) or with a clay layer, GMBs used in PBLSs are available in two types: smooth and textured. The analysis of all PBLSs described in Table 1 and Figure 3, shows that both smooth and textured GMB uses are significant. However, smooth GMB has been used in about 70% of the sites reviewed.

On the Maine, RIEDSBM and Danes Moss sites, textured GMBs were used to increase the interface shear strength. Moreover, some PBLS include both smooth and textured GMB depending on the slope gradient. This is the case for the Blydenburgh landfill (first landfill expansion), Maine landfilll and MLRMC landfill. For the first one, textured GMBs were placed on slopes steeper than 6H/1V (≈ 9.5°) while the smooth ones were implemented on the lower gradient slopes. The general trend in landfill sites in France is to use only smooth GMB except Site D where a double-sided textured GMB was used.

- **Number: single or double?**

While only one GMB is used for about 80% of the sites reviewed, some designers prefer to provide a double-liner system with GMB. Indeed, a typical PBLS variation is the addition of a second GMB and a drain between the two GMB, thus forming a leak detection system (Richardson et al. 2008). This is the case for Johnston County, Maine and RIEDSBM sites. Regarding the first and last cases, the old waste cells did not have any base liner system (Blond et al. 2005, Pieter 2010). Indeed, according to Vogt (2006) and Golder Associates (2011), when new cells are built on old cells with no sealing system or not complying with modern regulations, a double-liner GMB should be incorporated in the PBLS. In the case where the old cell has a modern base liner system, a single-liner GMB would be sufficient.

Finally, for the Maine site, the use of a double-liner system was motivated, as mentioned previously, by the Maine regulations which required a double-liner when landfills are established on weathered or fractured subgrade by assimilating this unstable base to the old waste cell (Grillo et al. 2001).

3.2.1.2 Passive containment barrier: clay, geosynthetic clay liner and sand-bentonite-polymer mix

These containment barrier materials are generally placed beneath the GMB in order to provide passive sealing in case of GMB failure (leakage). Table 1 shows that the clay layer in the PBLS is generally about 1 meter thick or slightly less. This compacted clay is implemented in order to achieve a maximum permeability of 10^{-9} m/s.
Regarding the GCL, about 45% of the case studies have used this type of sealing material. However, only one of the 22 case studies (≈ 5%) has used a sand-bentonite-polymer mix (SBP) which plays the same role as GCL and clay. There is no evidence given to explain this major difference. Nevertheless, it is well known that GCL has good resistance to stress cracking compared to mineral granular materials like clay or sand and offers generally high friction interface when it is in good operating conditions. This may be the reason why designers prefer using GCLs.
It could be also pointed out that neither GCL nor SBP has been used in several sites like those of Blydenburgh, Southern Alleghenies, South Hadley, Regina, Site A and Site C. These sites generally have either a thick clay layer or a double liner system (GMB).

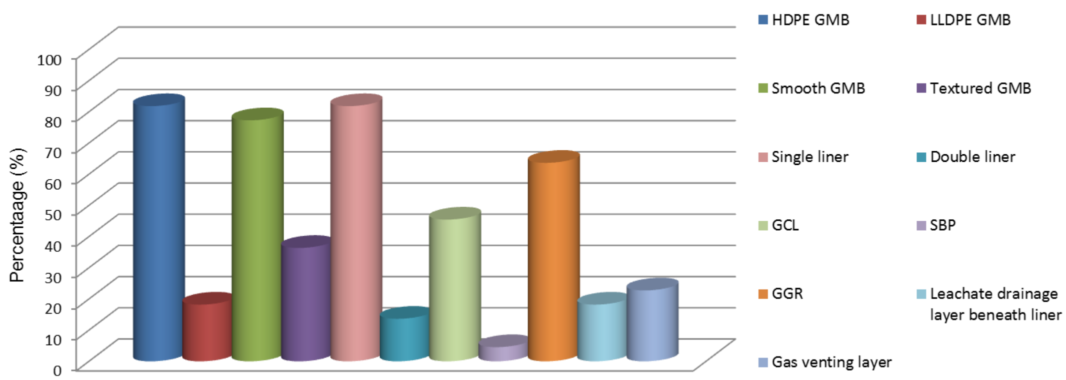

Figure 3. Distribution of the piggy-back liner system practices.

3.2.2 Drainage function

3.2.2.1 Leachate drainage system

There is no significant difference between the drainage structure of a standard base liner system and that of PBLS. For drainage, a layer of sand or permeable granular materials like gravel is often associated with drainage geosynthetic (GSY) which could be a geonet (GNT) or a geocomposite drain (GCD). The thickness of the drainage layer is quite variable depending on the site (see Table 1); indeed one can observe a thickness of only 0.15 m on the Danes Moss site in England and much more on the Maine site (0.6 m).
It should also be noted that drainage GSY is always covered by the granular layer. Indeed, the granular layer plays a second role which is the protection of the GSY drainage against Ultra-Violet radiations and mechanical actions of the construction site machinery (Golder Associates 2011).
However, as shown in Figure 3, only 18% of the case studies have a leachate drainage layer under the PBLS, anticipating an eventual rise in the leachate level under the surcharge load. These are the sites of Peabody, Maine, SENT and Site E.

3.2.2.2 Gas venting system

In the piggy-back landfill context, the waste of the underlying cell will surely also generate gas and this gas should be collected and treated even if the flow is quite small. Only 22% of the case studies a drainage layer has been implemented, often a GCD, dedicated exclusively to gas venting. These 5 cases are the piggy-back landfills of Nobles County, Qizishan, SENT, Site E and MLRMC.

3.2.3 Reinforcement function

Since the 1950s, GSY reinforcement or GGR are traditionally used for soil improvement, stabilization of slopes (Schmertmann et al. 1987, Ponterosso and Fox 1999) or in the case of foundation soil with poor mechanical properties (Tieman et al. 1990, Rowe and Skinner 2001, Sharma et al. 2009). In piggy-back landfills, GGR are mainly used to bridge the settlements or collapsed zones, in other words to support the whole PBLS (Sharma and Lewis 1994). It can be seen in Table 1 that this innovative practice of providing GGR reinforcement in PBLS, was progressively generalized since the first landfill expansion in 1987 (see Figure 2b). In addition, Figure 3 shows that GGRs are used in about 63% of

the case studies. There are even some piggy-back landfills where 2 layers of GGRs were set up at different levels of the PBLS, probably in order to increase the mechanical strength (Southern Alleghenies landfill for example).
However, despite the importance of this structural component, it should be pointed out that more than one-third of the case studies did not include it.

Table 1. Structure of the 22 piggy-back liner systems case studies.

State	Year and site	Type	GGR	HDPE[1]	Text[2]	GVL[3]	LDL[4]	References
France	2011, Site A	L						Communauté d'agglomération de Montpellier (2011)
	2011, Site B	M	×	×				Ecogeos (2011) unpublished
	2012, Site C	V	×	×				Ecogeos (2012) unpublished
	2013, Site D	M		×	×			Unpublished
	2013, Site E	M	×	×		×		Ecogeos (2011) unpublished
	2014, Site F	M	×	×				BRGM (2009) Ecogeos (2010) unpublished
USA	1987, Blydenburgh	V	×	×	×[6]			Tieman et al. (1990) Barbagallo and Druback (1997)
	1990, Frederick County	V	?	×	?	?	?	Law et al. (2013)
	1991, South. Alleghenies	M	×	×				Dayal et al. (1991)
	1995, Peabody	M		×[5]	×		×	Stulgis et al. (1996)
	1996, Colonie	M	×	×				Barbagallo et Druback (1997)
	1999, Johnston County	M		×[5]	×			Pieter (2010)
	2001, Maine	L	×	×	×[6]		×	Grillo et al. (2001)
	2004, Nobles County	M		×		×		Lynott (2004)
	2012, South Hadley	V		×				Wehler (2011), Sochovka et al. (2012)
	2013, Kekaha	M	×	×				AECOM (2013)
Canada	2003, RIEDSBM	M	×	×	×			Bouthot et al. (2003), Blond et al. (2005)
	2010, Regina	M		×				Mihial and Wright (2011)
U.K.	2005, Danes Moss	V?	×	×	×			http://www.trisoplast.fr/downloads/2005_Danes_Moss_EN.pdf
China	2009, Qizishan	M	×			×		Chen et al. (2009c), Chen et al. (2011)
	2011, SENT	M		×		×	×	http://www.epd.gov.hk/eia/register/report/eiareport/eia_1432007/html/Section3.htm
Australia	2015, MLRMC	M	×		×[6]	×		Golder associates (2011), AECOM (2012)

[1]high-density polyethylene geomembrane
[2]textured geomembrane
[3]gas venting layer
[4]Leachate drainage layer
[5]LLDPE GMBs have also been used
[6]smooth GMBs have also been used

4. IDENTIFICATION AND DISCUSSION OF SHORTCOMINGS AND RELATED ISSUES

4.1 Main issues to consider while designing a piggy-back liner system

Mainly due to a lack of technical regulations on the topic, an important diversity can be found in the design of PBLS, as shown by the analysis of the various PBLSs presented previously.
After showing current practices around the world, it is important to identify the key issues that may result from some “wrong” design practices. Table 2 summarizes the main hydric and mechanical hazards related to some practices. They are also discussed below and the related issues are illustrated on Figure 4.

Similar to the standard base liner system, the PBLS should meet certain performance criteria depending on the site condition and the related issues. This point is discussed below.

- **Overall slope instability**

Depending on the waste and subgrade mechanical properties and the gradient of the exterior slope of the piggy-back landfill, a sliding surface may occur through the waste mass. This failure surface is generally rotational and can be shallow (Figure 4 a) or deep (Figure 4 d). Thus, the instability can involve both the waste mass and the subgrade if they present low shear strength. As can be seen in Table 2, the overall slope stability is also influenced by the height of the piggy-back waste and by the leachate pressure. To improve slope stability, MSE or perimeter berms (without reinforcement) are often built on the toe of the piggy-back slope (Figure 4 k). It also allows steeper slopes thus gaining additional airspace for waste placement. Lastly, it entails a proper design of this retaining wall involving structural integrity and subgrade stability. It can sometimes be necessary to improve foundation bearing by soil improvements such as Prefabricated Vertical Drains (PVD) coupled with surcharge.

- **Interface failure** (see Figure 4 c)

Interface failure, also called veneer instability, is considered to be the primary cause of instability in landfills (Koerner and Soong 2000, Bergado et al. 2006). Indeed, liner system interfaces represent a potential sliding surface in the way that they have generally low shear strength. These interfaces can involve two GSY (GMB-GTX, GMB-GCL, etc.) or a GSY and waste, or a GSY and a mineral layer. Generally, GMB interfaces present the lowest shear strength. In any case, if an interface failure were to occur, the corresponding sliding surface would be at the interface with the lowest mechanical properties. In order to prevent slippage, adequate friction should be provided. This point is further discussed below. Like the overall stability, the veneer stability can be improved by installation of a MSE.

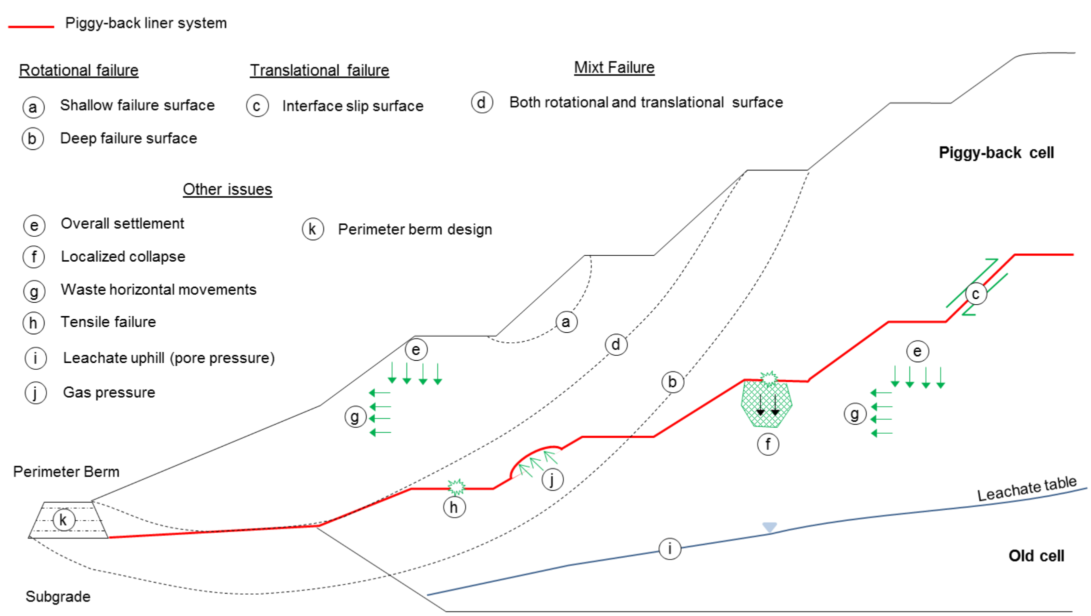

Figure 4. Overall key issues to consider for the design of a piggy-back liner system.

- **Settlement considerations**

The surcharge load provided by the piggy-back cell generates a general consolidation of the underlying waste. These settlements are intensified by waste degradation over time. These phenomena lead to a generalization of these vertical movements throughout the waste mass (Figure 4 e).

On the other hand, some smaller and more local soft or hard points due to the heterogeneity of the underlying waste can lead to localized depressions (Figure 4 f). It should be pointed out that differential settlements constitute a greater threat than overall settlements. If no GSY reinforcement or GGR is provided under the PBLS, significant strains and tensions can occur. The GGR does not reduce uniform settlements but aims to reduce differential settlements. Generally, it is designed with an analytical method based on a circular void of 1.80 - 2.40 m diameter (Stulgis et al. 1996, Tieman et al. 1990). This void is termed as “refrigerator effect”. However, if the waste disposal history (nature of waste, compaction method, etc.) is known and/or the risk of large sinkhole is low, a lower diameter (0,90 - 1.80 m) is sometimes considered.

The magnitude of these settlements and especially their impact on the integrity of each component of the PBLS must be assessed in order to demonstrate that the liner system can withstand these differential settlements.

Furthermore, the slope of the PBLS does not change significantly during settlements in order to maintain continued positive drainage. This specific point is discussed more in details in Olivier and Tano (2013) paper.

- **Tensile failure** (see Figure 4 h)

Tensile failure occurs when tension in a liner exceeds its ultimate tensile strength and can result from various situations:
- The waste downdrag on side liners cause an additional tension in the liner system. If this tension is high, tensile failure may occur;
- A very long steep side slope coupled with an important height of the overlying waste can result in tensile failure;
- If a high friction GSY such as textured GMB is used, the shear stresses can be transferred to this liner and create excess tensile stresses; an appropriate analysis should thus be performed.
- As discussed above, differential settlement may bend the liner, thus creating excess tension and tensile failure.
- In addition to these points, thermally induced stresses and stresses during waste placement can also contribute to tensile failure.

The maximum tensions and strains in the each layer should therefore be limited to acceptable levels.

- **Rise of the leachate level** (see Figure 4 e)

When the piggy-back cell is built, there may occur a “squeezing effect” resulting in an increase of the leachate level in the old cell. In case the old cell does not have an adequate drainage system, it is possible that the leachate level rise up to the PBLS underside. Therefore, pore pressure acting at the lower liner interface will reduce the effective stresses and a gradual failure mechanism will start. Additionally, the leachate from the overlying waste can also cause the same effect if the drainage system above the PBLS is ineffective. Therefore, a proper drainage system must be installed both below and above the PBLS in order to collect the leachate produced respectively in the underlying and the overlying waste.
Moreover, if the underlying cell already had vertical leachate wells, it is possible to raise them as overlying waste placement progresses. However, such a practice can be difficult to achieve, especially when the overlying cell thickness is great. Indeed, the horizontal movements of the overlying waste (Figure 4g) can generate stresses, shear and bending at the vertical wells, which can cause their failure. So if this option is chosen, a careful pipe stress analysis should be performed in order to assess the integrity of the wells in such conditions.
The other solution for leachate drainage is the provision of horizontal drains like GCD or drainage trenches beneath the PBLS. This option is most likely suitable for piggy-back landfills as there is no bending or stresses issue if the PBLS has been properly designed (provision of GGR, moderate steep slope, etc.).
In any case, since every landfill site is specific, the right leachate collector system should be customized for each of them.

- **Gas design considerations**

Landfill gas (biogas) is continuously generated in landfills as the waste decomposes. As in the case of leachate, an uplift pressure caused by the gas generated in the underlying waste can reduce the effective normal stress at the piggy-back interface (Thiel 1998). Indeed, the trapped biogas should be freed to avoid excess pressure which may cause interface failure. Therefore, a proper gas drainage system should be designed beneath the PBLS. Like for leachate, vertical gas vents could already be present in the old waste, so the same precautions should be adopted. The collector gas system should be moved toward a gas flaring or biogas production and recovery system if the gas flow is important enough.

- **Protection considerations**

Like the base GMB liner, the piggy-back GMB liner should be protected from damages, mainly due to the load induced by waste and to the construction site machinery traffic. A non-woven needle punched GTX is often used for protection. However, it is not rare that a protective GCD is used for both draining the leachate and protecting the GMB. If these two kinds of protection are used, the GSY should be covered quickly or UV-treated because of UV radiations. Additionally, a mineral layer like sand or gravel placed above the GSY could provide this UV-protection.
Furthermore, protective-GTX or GCD should be chosen depending on the applied load, the material size (crushed coarse, medium, fine) and the shape of the grain particles (angular, rounded). The subgrade layer should also be properly prepared with minimum irregularities. The design of the protective component is often based on analytical methods such as the one presented by Narejo et al. (1996).
However, even if some analytical methods are available for the protective GTX design, a real test, especially in laboratory, simulating the load and the site conditions (type of gravel and subgrade) can provide more accurate results. This kind of test is described in others papers like those of Reddy and Saichek (1998) or Budka et al. (2006).

- **GMB liner selection**

There is a wide range of GMB available witch differ in their properties such as friction shear strength, flexibility and durability. When selecting a GMB, its overall performance involving mechanical, chemical, temperature resistance and also convenient installation and cost effectiveness should be analyzed.
Concerning the GMB nature, HDPE is expected to have an excellent ability to reduce the flow of contaminants and is known for having a high chemical resistance to leachate. As discussed above, HDPE GMB was used in most of the case studies. This is due to a wide experience of their use in standard landfills: designers of PBLSs often choose the same

material without further analysis. However, in the piggy-back landfill context as much as for capping applications, attention is more focused on the ability to accept strain with limited impact on its integrity rather than on chemical compatibility and, hence, flexible GMB such as linear LLDPE can be more appropriate. Indeed, LLDPE has both excellent uniaxial and multiaxial strain behavior while HDPE has only excellent uniaxial strain resistance (BPEM, 2010). For example, the maximum allowable strain of HDPE GMB ranges from 4 to 6% while it varies from 8 to 12% for LLDPE GMB (Peggs 2003). Additionally, it is well known that HDPE has a high potential for stress-cracking.

As seen previously, only PE GMB were incorporated in PBLS even if there are other polymers like ethylene-propylene-diene-monome (EPDM), PVC and flexible Polypropylene (PP), which are easy to set up and can withstand high strain. Indeed, EPDM has limited mechanical resistance (tensile strength) while PVC has limited chemical resistance and could lose its flexibility on the long term. EPDM, PVC and PP also present generally lower tear resistance and greater permeability than HDPE or LLDPE. Each polymer has thus advantages and disadvantages and cannot be suitable for all cases. However, in view of the current knowledge on LLDPE GMB and its benefits discussed previously, this polymer seems to be more suitable for PBLS.

Moreover, even if most of the GMBs used in PBLS are smooth, high friction GMBs such as textured GMBs are also used. There are probably two main reasons why designers often choose smooth GMBs. The first one is to avoid an additional stress that could lead to tensile failure. For example, in France, regulations and recommendations tend to limit GMB use to its sealing function, avoiding, as far as possible, the mechanical solicitation of the GMB (CFG 1995, MEDDE 2007, AFNOR 2010). Going in the same direction as French recommendations, Golder Associates (2011) advocate for the possible provision of a preferential slip surface above the GMB in order to reduce strains developed in PBLS. The second reason is economic, because smooth GMBs are generally less expensive than the textured ones. But in case of steeper slopes or a high veneer instability risk, adequate friction is necessary to prevent slippage, therefore high friction GMB can be used. However, before using such GMB, a careful analysis of a tensile failure should be performed. So the designer has to find a balance between interface failure and tensile failure risks. Thus, if there is no interface failure risk, smooth GMBs should be preferred.

Table 2. Main hazards induced by current practices.

Design cases	**Overall slope failure**	**Interface failure**	**Tensile failure**	**Rise of leachate level**	**Differential settlement**
No provision of geogrid			×		×
Steep slope	×	×	×		
High piggy-back waste thickness	×	×	×	×	×
No leachate drainage layer	×	×		×	
No gas venting layer		×			
No filter fabric	×			×	
Textured GMB			×		
Smooth GMB		×			

4.2 General guidelines for the design of a piggy-back liner system

In the absence of specific regulations relating to the design of piggy-back landfills, it is important to establish minimum technical standards and guidelines for the PBLS. In this purpose, a typical section of a PBLS based on the current knowledge and safety practices discussed above is proposed on Figure 5. It should be noted that more accurate understanding of piggy-back landfill behavior and of its liner system is attained. Thus, the model presented below on Figure 5 should be considered as a starting point and could be further improved depending on research progress.

As described on Figure 5, some materials can be used instead of others depending on site conditions. In any case, the use of a material should be justified and provide at least an equivalent performance to the replaced material. For example, GCLs are often selected instead of clay layers because they provide equivalent sealing and they can withstand more tensile strains (under confinement). Incorporating GGR reinforcement may also be better than a thick soil bedding layer for the reduction of differential settlement effects because allowable strains of soils are generally low. When GGR is used, it should be installed in a select fill with high friction in order to improve the shear resistance.

Furthermore, a double composite liner system with a leak detection (discussed previously) offers an additional sealing protection and this option can also be implemented. It involves higher costs but is a kind of monitoring system that can detect leakage through the GMB primary liner.

At last, the anchor issue that is scarcely discussed in piggy-back landfills bibliography should also be considered. According to Thiel (2013), there has been very little change in the design of anchor trenches in landfills over the past 25

years. According to the author, a good design should be simple and keep the anchor trench flexible with a proper backfilling. For double-liner systems, it may be better to seam the two liners together in the anchor trench. For high-strength GSYs (GGR), critical anchor trenches with a more detailed engineering analysis are required. The most recent available methods for the design of anchor trenches are provided by Villard and Chareyre (2004) and Thiel (2010).
Beyond all these aspects, it should be noted all the issues considered previously should be carefully analyzed (on a case by case basis) while designing a safety piggy-back system.

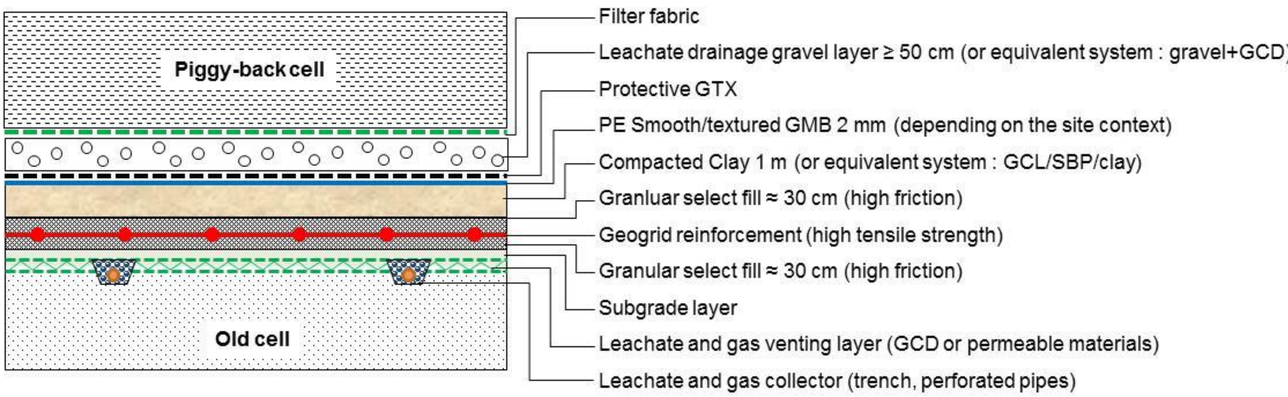

Figure 5. Proposed typical section of piggy-back liner system.

5. CONCLUSION

The objective of this paper is to provide the current state of practice in the design of piggy-back liner systems (PBLS), for which an overview of 22 PBLSs has been performed. Indeed, while piggy-back landfills are increasingly established around the world because of their advantages (airspace gaining, cost-benefits, etc.), there are some key issues to consider for a safe design. These technical considerations involve both mechanical issues such as settlement assessment, veneer system stability and gas/hydric issues.
However, given the lack of national and international standards specific to piggy-back landfills design, it is not rare to find cases with unsafe design. For example, GGR reinforcement or leachate/gas drainage systems beneath the PBLS are not always set up even if they are potentially required in the PBLS.
It was also shown that the various PBLSs studied in this paper are quite different as the type, the nature and the thickness of the materials used vary. Additionally, it should be pointed out that piggy-back combinations are unique; therefore, it is important for the design to be site-specific.
Furthermore, a typical section of PBLS has been defined based on the current safety practices and the experience authors.
Nevertheless, despite the numerous piggy-back landfills built over the last 28 years, new understandings and field experiences are needed in order to provide best compliance regulations and a more efficient design. For this purpose, the authors are currently undertaking additional research works involving field instrumentation and numerical modeling.

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