Finite difference modelling of the deformation and slippage processes of multi-layered geosynthetic lining systems.

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ABSTRACT: In landfills, geosynthetics (GSYs) are implemented on the bottom and side slopes of the waste cells to prevent the leachate infiltration into groundwater, as a lining system. In piggy-back landfill expansions (PBLE) where a new landfill is built over an older one, this lining system can be subject to high tensile forces (tear) and interface shear stresses (interface failure) due to the overlying waste mass. Certainly, the GSY tensile behaviour and their interface shear strength have been widely studied, but very little attention has been paid to the deformation and slippage processes. Understanding these mechanisms in order to improve the design of GSY lining system remains an outstanding challenge and this is the focus of our work. Using the finite difference code FLAC 2D, numerical modelling was conducted on a typical PBLE based on realistic conditions. The model includes a multi-layered GSY system and takes into consideration the interface strain softening at interfaces, the nonlinear stiffness of GSYs and the differentiation between their compressive and tensile behaviour. A new parameter named stability ratio is proposed to better understand the failure mechanisms at the various interfaces and their evolution as backfilling progresses. This parameter calculated for each individual portion of the interfaces allows for the location of the local instability. The numerical results showed that the interface failure mainly begins at the rightmost part of the lower flat area of PBLE and near the corner of the inner slope. The numerical results also indicated that when the GTX/GMB interface exhibits a low shear strength, the significant relative shear displacements calculated for this interface leads to a great tensile deformation of the GTX.

Keywords: interface failure, shear stress, strains, geosynthetics mechanical behaviour, numerical modelling

1 INTRODUCTION

For over half a century, engineers have used geosynthetics (GSYs) in engineering constructions for various applications because GSYs often allow for the reduction of time and cost construction and greenhouse gas emission. In landfills, several GSYs are typically installed at the bottom and side slopes of the landfill as a barrier to prevent the groundwater from leachate infiltration. Particularly, in piggy-back landfill expansions (PBLE) where a new landfill is built over an older one, the lining system implemented between old and new wastes, is subject to high tensile forces and interface shear stresses. It should be noted that most of the reported landfill failures as Kettleman hills landfill (Stark and Poeppel, 1994, Filz et al., 2001), Cincinnati and Ohio landfills (Huvaj-Sarihan and Stark, 2008), involve the lining system. These cases concern the failure at the interface between separated GSYs (stability) and the deformation (integrity) of the GSYs.

Admittedly, the interface shear strength that controls the stability and the integrity of GSYs, has been extensively discussed by numerous authors (Tanchaisawat, 2013, Girard et al., 1990, Stark et al., 1996, Izgin and Wasti, 1998, Dixon et al., 2006, Fleming et al., 2006, Fowmes, 2007, Le Hello, 2007, Fowmes et al., 2008, Palmeira, 2009, Eid, 2011), but very little attention has been paid to the mechanisms that govern the interface failure and the deformation of GSYs. Understanding these processes remains a challenge to improve the current design practices.

Byrne et al. (1992) and Byrne (1994) discussed the interface failure of Kettleman hills landfill but the authors modelled the multiple interfaces as a single interface without any GSY. Hence, axial forces and strains within the lining system could not be calculated and the lining system integrity could not be assessed. Moreover, for the same landfill case, Filz et al. (2001) have modelled the whole lining system (geotextile, geomembrane and clay) as a single simplistic bar element and hence neglecting the multiple interactions between GSYs. For this case, this simplification could influence the simulated shear displacements and the calculated axial forces and strains could not be representative.

In this study, numerical modelling simulations are performed on a typical PBLE for the understanding of the deformation and slippage processes of GSYs within the lining system. The lining system consist of a subgrade layer and 4 GSY (geotextile, geomembrane, geosynthetic clay liner and geogrid) interacting via six interfaces. For a more rigorous assessment of the processes, this study considers the strain softening behaviour of interfaces, the nonlinear stiffness of GSYs and the differentiation between their compressive and tensile behaviour. The analyses are performed using a two-dimensional (2D) finite different code.

After the presentation of the numerical model configuration and properties, we discuss the shear stresses and displacements along interfaces and the axial tensile strains and forces within the lining system. A parameter named stability ratio is proposed to better understand the progressive shear displacements and instability along the interfaces. We also highlight how the backfilling influences the distribution and the evolution of the shear stresses and displacements at the interfaces and of the forces and strains within the GSYs.

2 NUMERICAL MODEL

The numerical simulations were performed on a section trough a typical mixed PBLE in which the new waste cell is supported on both side slopes and top of the old waste cell (Figure 1). The model has a total length of 400 m and a total height of 60 m. This model includes two waste materials (new waste and old waste) considered as municipal solid waste, three mineral materials (clay substratum, sand subgrade and a mechanical stabilized earth: MSE) and four GSY (geogrid: GGR, geosynthetic clay liner: GCL, geomembrane: GMB and protective geotextile: GTX). The materials and the four GSY interact via six interfaces (I1 to I6) defined as follows:

- Interface I1: the contact between a drainage gravel layer (not modelled) under the new waste and the protective GTX,
- Interface I2: the contact between the above GTX and the GMB,
- Interface I3: the contact between the above GMB and the GCL,
- Interface I4: the contact between the above GCL and a subgrade layer on top of the existing cell, and
- Interfaces I5 and I6: Respectively the upper and lower contacts of the GGR with the sand layer in which it is located.

Furthermore, the two-dimensional (2D) finite different software Fast Lagrangian Analysis of Continua (FLAC 2D) has been used for the numerical modelling in order to consider multi-layered GSY interactions while modelling materials, structural elements and interfaces in a non-linear stress-strain law. This software is widely used for this application (e.g. Byrne (1994), Jones et al. (2000), Connell (2002), Jones et Dixon (2005), Fowmes et al. (2005), Chen et al. (2009), Zhu et al. (2009), Arab et al. (2011), Zamara et al. (2014)). Moreover, 6400 volume elements (mesh zones) which size ranges between 1 m × 1 m and 2 m × 2 m each form the model materials. The GTX, GMB and GCL have been modelled by linearly elastic structural beam elements while strip elements have been used for the GGR. Strip elements are specifically designed for thin flat reinforcing structures, like a GGR, installed within a soil embankment.
Concerning the boundary conditions, fixed nodal horizontal displacements were assigned to the left and right sides of the model while both nodal horizontal and vertical displacements were set at the lower side of the model. Fixities (perfect anchorage) were also imposed for all the GSYs except the GGR, at the top of the old waste cell 2 meters away from the crest slope. The GGR has been modelled without specific condition to materialize a flat anchorage.
Furthermore, this study considers the strain softening behaviour of GSY interfaces (as progressive failure), the differentiation between the compressive and the tensile behaviours of GSY and the nonlinearity of the GSY axial stiffness. These considerations follow a previous work (Tano et al., 2016, submitted for publication) that shows a rational methodology for the modelling of multi-layered GSY system interactions. For taking into account such considerations, it was necessary to model all the GSY and the interfaces with a concatenation of several elements. Depending on the GSY strain level or interface displacement, this provision allows for the variation of the properties of each individual part of GSYs and of interfaces. To take into consideration the previous aspects, four functions (FISH codes) were developed in the programming language compiled by the software inbuilt subroutine compiler.

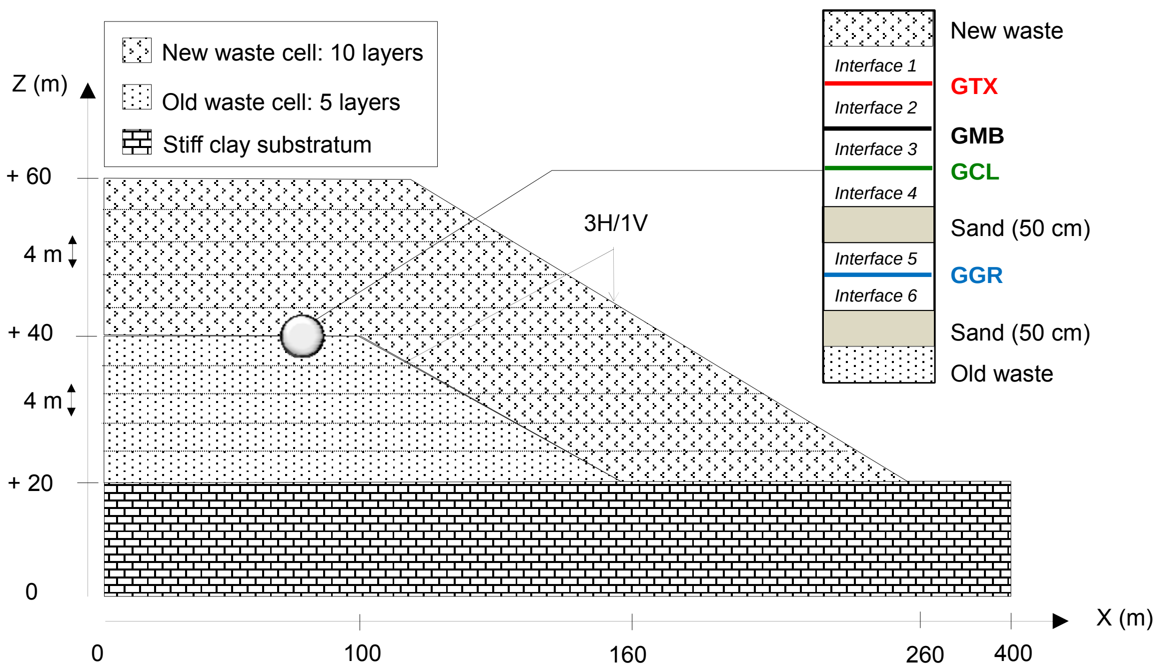

Figure 1: Simplified diagram of the piggy-back landfill expansion case studies

3 MATERIALS, GEOSYNTHETICS AND INTERFACE PROPERTIES

For this study, the well-known elastic-plastic Mohr-Coulomb (MC) constitutive model has been used for the soil, waste materials and interfaces. MC is likely the most used model for the study of waste and GSY interactions (e.g. Villard et al., 1999, Jones and Dixon, 2005).
The waste properties were defined following an in-depth review of literature (Tano et al., 2016, submitted for publication). For example, the hyperbolic law of Zekkos et al. (2006) with typical compaction efforts has been used to set the evolution of the waste unit weight with depth. Moreover, based on a comprehensive literature data base, typical values have been chosen for the soil and interface parameters. The GSY parameters were derived from uniaxial tensile tests (NF EN ISO 10319 for the GTX, GCL and GGR and NF EN 12311-2 for the GMB). The various GSY correspond to the four following products:
- GTX (1200 g/m²): 8 mm thick non–woven Polypropylene (PP) product with a tensile strength Rt = 52.5 kN/m at 100 % strain.
- GMB: 2 mm thick high density polyethylene (HDPE) product with a tensile strength Rt = 33 kN/m at 12 % strain.
- GCL (5000 g/m²): 7 mm thick sodium of with a tensile strength Rt = 32 kN/m at 38 % strain.
- GGR: 2.5 mm thick uniaxial product in polyvinyl alcohol (PVA) with a tensile strength Rt = 200 kN/m at 8 % strain.
The various parameters assigned to all the soils, GSY and interfaces are summarized in Table 1.

Table 1. Summary of the material, geosynthetics and interfaces properties used in this study

<table>
<tr><th colspan="6">MATERIALS PROPERTIES</th></tr>
<tr><th>Type</th><th>γ
(kN/m^3)</th><th>E
(MPa)</th><th>υ</th><th>c
(kPa)</th><th>ϕ
(°)</th></tr>
<tr><td>New waste</td><td>9.0 to 12.6</td><td>0.5 to 1.0</td><td>0.2 to 0.3</td><td>10.0 to 5.0</td><td>30.0 to 25.0</td></tr>
<tr><td>Old waste</td><td>10.0 to 12.8</td><td>1.0 to 1.2</td><td>0.3 to 0.4</td><td>5.0 to 3.0</td><td>24.0 to 22.0</td></tr>
<tr><td>Subgrade layer</td><td>18</td><td>20</td><td rowspan="3">0.3</td><td>0</td><td>35</td></tr>
<tr><td>Clay substratum</td><td>18</td><td>50</td><td>5</td><td>28</td></tr>
<tr><td>Mechanical stabilized earth</td><td>20</td><td>50</td><td>5</td><td>40</td></tr>
</table>

<table>
<tr><th colspan="4">GEOSYNTHETICS PROPERTIES</th></tr>
<tr><th>Type</th><th>e
(mm)</th><th>E at 1 % of strain
(MPa)</th><th>E at 10 % of strain
(MPa)</th></tr>
<tr><td>GTX</td><td>8</td><td>15.6</td><td>8.4</td></tr>
<tr><td>GMB</td><td>2</td><td>541.2</td><td>166.0</td></tr>
<tr><td>GCL</td><td>7</td><td>10.0</td><td>15.4</td></tr>
<tr><td>GGR</td><td>2.5</td><td>1280.0</td><td>870.0</td></tr>
</table>

<table>
<tr><th colspan="6">INTERFACES PROPERTIES</th></tr>
<tr><th>Type</th><th>K_s
(MPa/m)</th><th>K_n
(MPa/m)</th><th>c
(kPa)</th><th>ϕ_{peak}
(°)</th><th>ϕ_{res}
(°)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>I1: Drainage gravel - GTX</td><td rowspan="5">10</td><td rowspan="5">100</td><td rowspan="5">0</td><td>28</td><td>23</td></tr>
<tr><td>I2: GTX - GMB</td><td>12</td><td>7</td></tr>
<tr><td>I3: GMB - GCL</td><td>13</td><td>8</td></tr>
<tr><td>I4: GCL – Subgrade layer</td><td>28</td><td>23</td></tr>
<tr><td>I5 and I6: GGR- Subgrade layer</td><td>29</td><td>24</td></tr>
</table>

γ is the unit weight;
E is the elastic modulus
υ is the Poisson ratio;
c and ϕ are the cohesion and Friction angle respectively;

e is the thickness of the geosynthetic
ϕ_{peak} and ϕ_{res} are the peak and residual friction angles of interfaces respectively;
K_s and K_n *are the* shear and normal stiffness of interfaces respectively.

4 RESULTS AND DISCUSSIONS

4.1 *Identification of the slippage processes along interfaces*

4.1.1 *Shear stresses and total displacements along interfaces*

Figure 2 shows the shear stresses and total shear displacements at interfaces I1 to I6 at a height of backfilling H = 20 m. Shear stresses at interface I5 and I6 are not represented in Figure 2a because it is not possible to extract theses values when strip elements are used. The profiles of the shear stresses provided by the overlying waste weight are quite similar for interfaces I1 through I4. A gradually increase in the shear stresses is observed along the slope downwards the foot until 30.2 kPa. However, a peak (stress concentration) larger than 50 kPa is calculated at the slope corner. This stress concentration is likely due to the transfer of the shear stress surplus which is not mobilized at the interface I2 (low shear strength, ϕ_{res} = 7°) along the upper part of the slope. After this peak, there is a decrease to 8.1 kPa between 60 and 200 m before an increase up to 24.1 kPa. This increase in the shear stresses highlights a potential zone of interface slippage at the rightmost part of the lower flat area (between 220 and 260 m). Focusing on Figure 2b, it appears that the shear displacements at interfaces I3, I4, I5 and I6 are very limited under 0.1 m. However, significant shear displacements around 1.5 m are simulated for the less resistant interface I2 along the slope. Logically, because the GTX slips along the GMB, significant total shear displacements are also calculated for interface I1. Moreover, the increase in the shear strength at the rightmost part of the lower flat area leads to an increase in the shear displacements up to 0.5 m at interfaces I1 and I2.

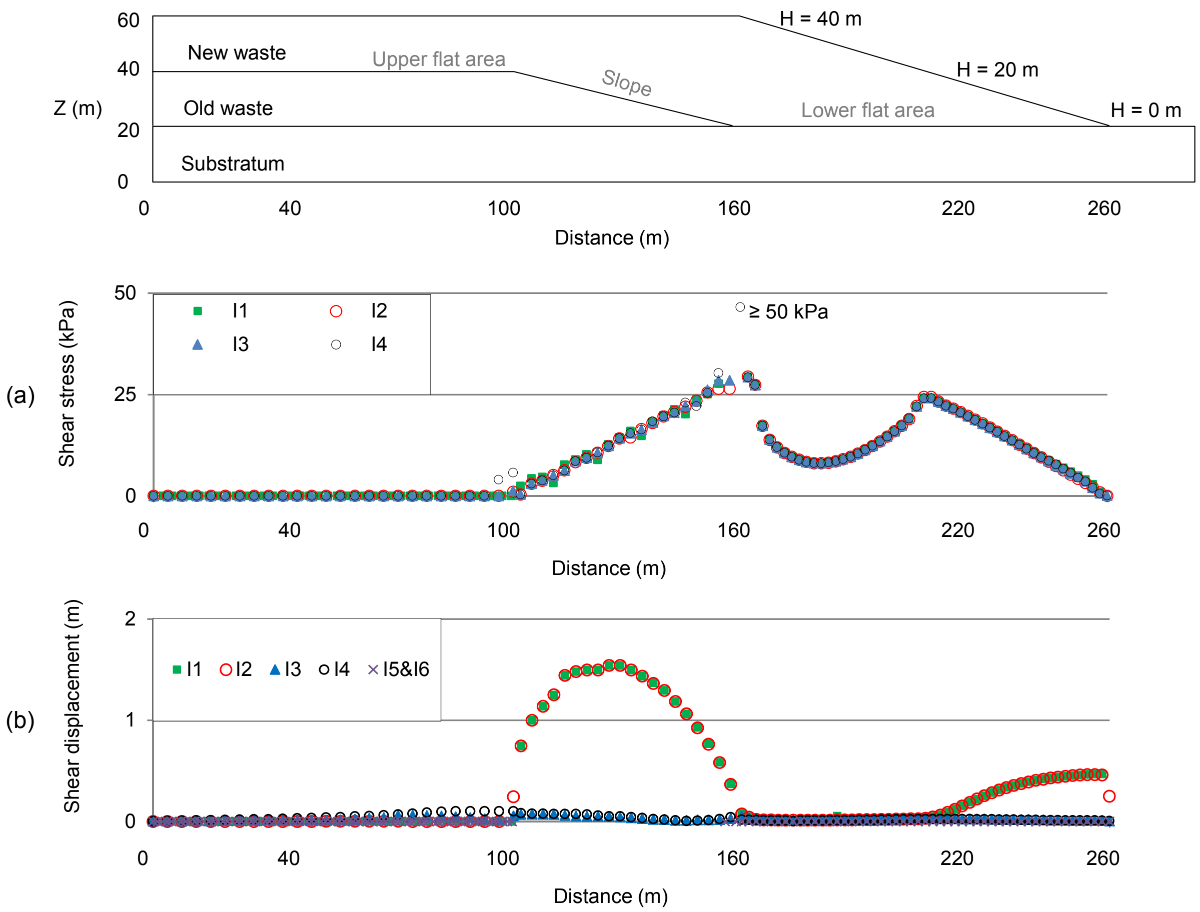

Figure 2: Interfaces I1 trough I6 at a backfill height H = 20 m. (a) Shear stresses. (b) Total shear displacements

4.1.2 *Relative shear displacements between the geosynthetics*

To analyze the displacements of each GSY in relation to the material in contact within the lining system, the relative shear displacements of interfaces I1 through I4 have been represented in Figure 3.

Even if the total shear displacements of I1 are significant (1.5 m), its relative shear displacements are limited to only 0.3 m. This means that the overlying waste is driven by the downslope slippage of the GTX on the underlying GMB. This is due to the fact that the high friction angle (23° at residual) of I1 leads to a good contact between the GTX and the overlying waste, so that the displacement of the GTX systematically induces the displacements of the overlying waste. Here, it is the GTX (material underneath) which slips under the overlying waste (upper material).

On the contrary due to a low shear strength of I2, Figure 3b shows that the GTX significantly slips along the GMB with a maximum relative shear displacement of 1.5 m. Moreover, the relative displacements of the GMB in relation to the underlying GCL and those of the GCL in relation to the underlying subgrade are very limited and close to zero (Figure 3c and d). The direction of the relative displacements is the same as for I2 (upper material slips along the material underneath).

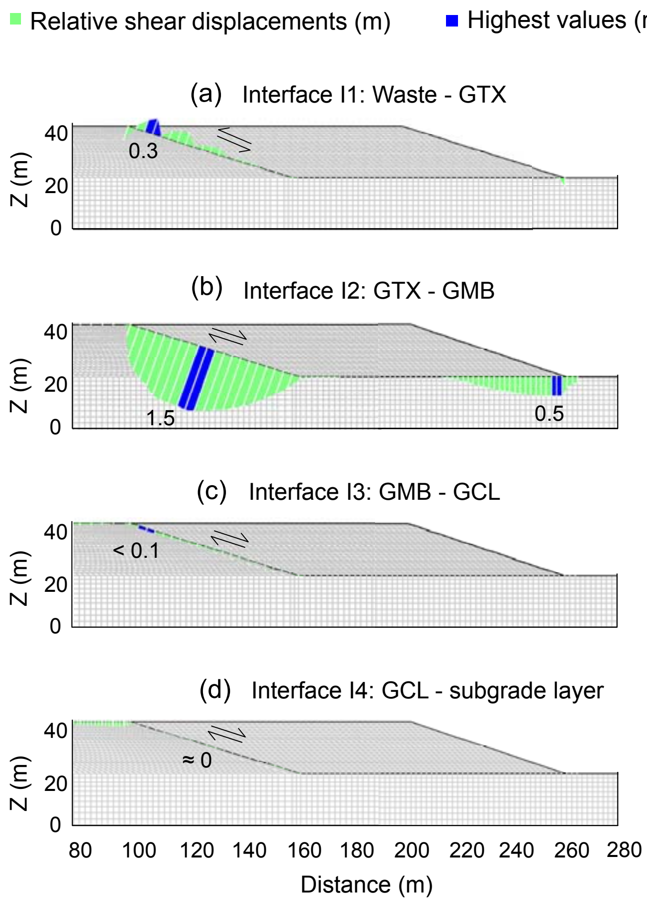

Figure 3: Relative shear displacements at interfaces I1 through I4 at a backfill height H = 20 m

4.1.3 *Evolution of the slippage along the geotextile/geomembrane interface with backfilling*

Since I2 is the less stable interface (highest relative shear displacements), a further analysis of the behaviour of this interface is performed here. The evolution of the shear stresses and displacements at I2 as backfilling progresses is shown in Figure 4.

The increase of the height of backfilling H logically leads to the increase of both shear stresses and displacements. Generally, the shear stresses and displacements respectively remain below 25 kPa and 0.5 m for $H \leq 12$ m. But there is a sharp increase from H = 20 m with shear stresses and displacements respectively greater than 50 kPa and 3 m at H = 40 m. This high shear displacement highlights a strong tensile deformation of the GTX due to its slippage of the GTX along the GMB. This point will be further discussed.

Moreover, Figure 4 shows that the increase in the shear stresses and displacements is progressive and there is also a laterally spread of the zones subject to these shear stresses and displacements. The interface movement seems to begin simultaneously at the rightmost parts of the inner slope and of the lower flat area.

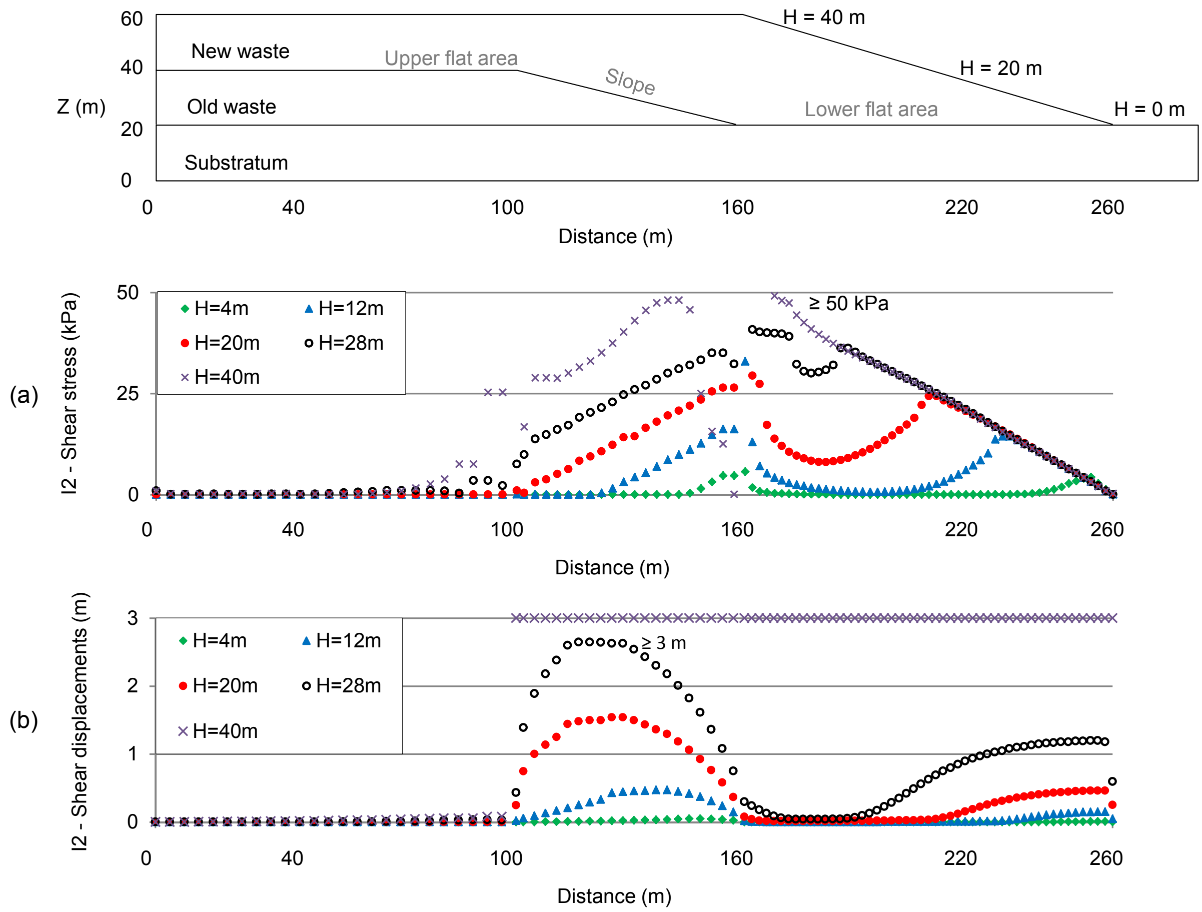

Figure 4: Effect of the backfill height on interface I2 GTX/GMB behaviour (a) Shear stresses versus distance. (b) Shear displacements versus distance

4.1.4 *Proposition of a parameter to analyze the progressive instability of interfaces*

For the analysis of the progressive instability at the various interfaces within the lining system, a new parameter named stability ratio R_S is proposed herein. This parameter calculated for each individual portion of the interfaces, is the ratio between the interface shear strength τ and the mobilized shear stress T (Equation 1). τ is calculated using Equation 2. R_S allows for a better understanding of the failure mechanisms at the various interfaces and their evolution as backfilling progresses. This is because the FISH codes developed and implemented in the software allow us to get access to σ_n, Φ and T for each portion of the interfaces I1 to I4 and at each stage of the construction.
With R_S, it is possible to localize the local instability at interfaces and hence zones where shear stresses are in equilibrium with the interface shear strength in the numerical simulations. A value of R_S close to 1 reveals a weak interface area while a high value of R_S means a good mechanical stability of the interface portion for which R_S was calculated.

$$R_S = \frac{\tau}{T} \tag{1}$$

$$\tau = \sigma_n . \tan\Phi \tag{2}$$

Where R_S = stability ratio, τ = interface shear strength, T = mobilized shear stress at the interface, σ_n = normal stress at the interface and Φ = interface friction angle.
Figure 5a shows the R_S values calculated for interfaces I1 through I4 at H = 20 m. At this stage of backfilling, R_S of I1 and I4 are generally higher than 3 along all the construction from 0 to 260 m of distance. This demonstrates that these interfaces are still stable at this lev-

el of backfilling. On the contrary, R_S of I2 and I3 have reached 1 along the slope and the latter half of the lower flat area. This is due to the fact that I2 and I3 exhibit the lowest shear mechanical properties. Because the shear stresses are equal to the shear strength along the slope and along the latter half of the lower flat area, these zones can be considered as unstable. To identify the beginning of the instability, the evolution of R_S along I2 with the height of backfilling H has been represented in Figure 5b. At H = 4 m, the most part of I2 are stable except the rightmost part of the lower flat area and near the corner of the inner slope where R_S = 1. As H increases, the instability zone with R_S = 1 is laterally extended to the left. At H = 40 m, it can be seen that I2 is completely unstable along the slope and the lower flat area. This reveals a translational failure of the PBLE.

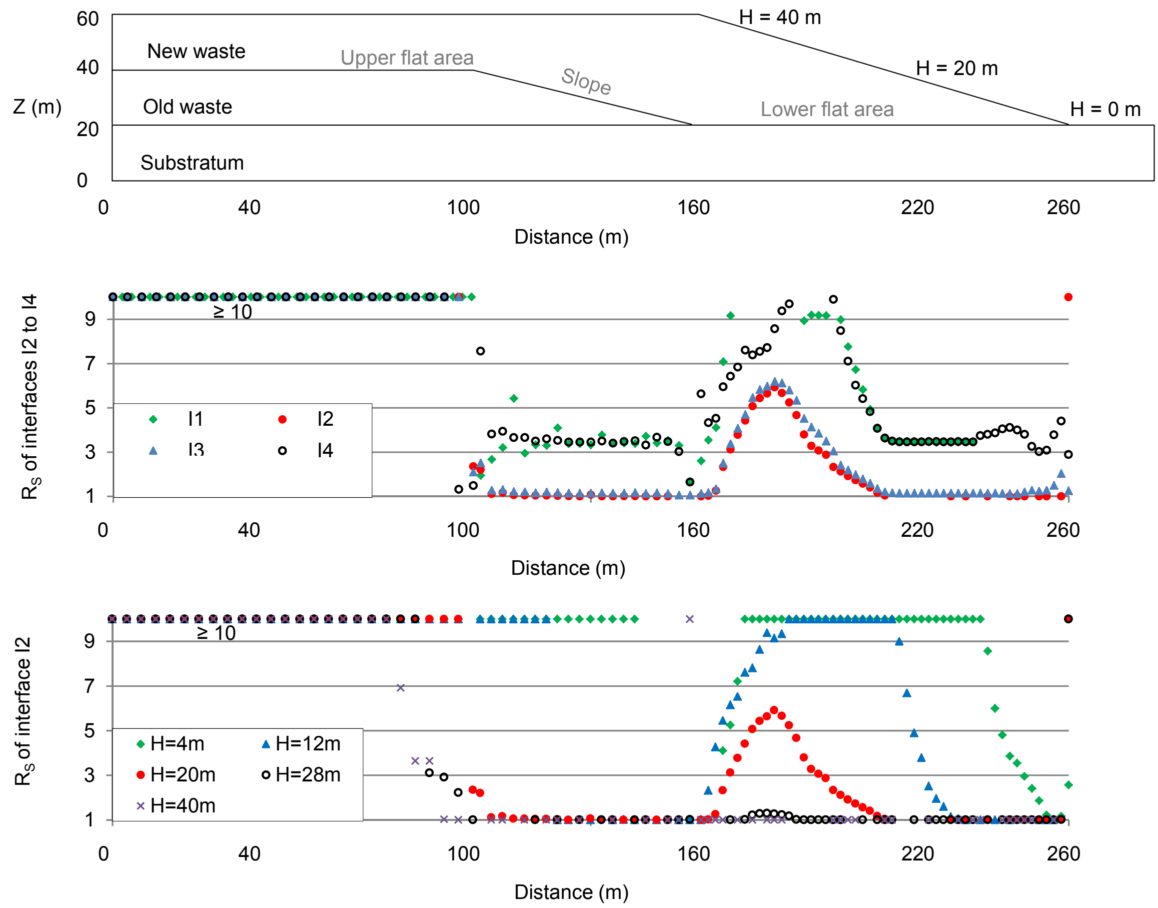

Figure 5: Stability ratio R_S (a) along interfaces I1, I2, I3 and I4 at H = 20 m (b) along interface the interface I2 from H = 4 m to H = 40 m

4.2 *Identification of the deformation processes of the geosynthetics within the lining system*

4.2.1 *Axial tensile strains and forces within the lining system*

The strains within the four layers of GSY (GTX, GMB, GCL and GGR) calculated at H = 20 m are presented in Figure 6. At this stage, the strains within the GSY do not exceed 1 % except for the GTX for which significant strains of 16 % are calculated near the anchorage point. These observations are consistent with the total and relative shear displacements of interfaces presented in Figure 2b and Figure 3. Indeed, the more the relative shear displacements of an interface are calculated, the more the tensile strains within the upper GSY are observed. As interface I2 exhibits the higher relative shear displacements, significant strains are calculated within the GTX. The GTX which is anchored at the slope top slips along the smooth GMB and is elongated mainly near the anchorage point. The strains within the other GSY are limited because total and relative shear displacements of the interfaces (I3 and I4) beneath them are low. Furthermore, the low friction angle of I2 (7° at residual) does not allow a high transmission of the tensile forces taken by the GTX to the underlying GSY.

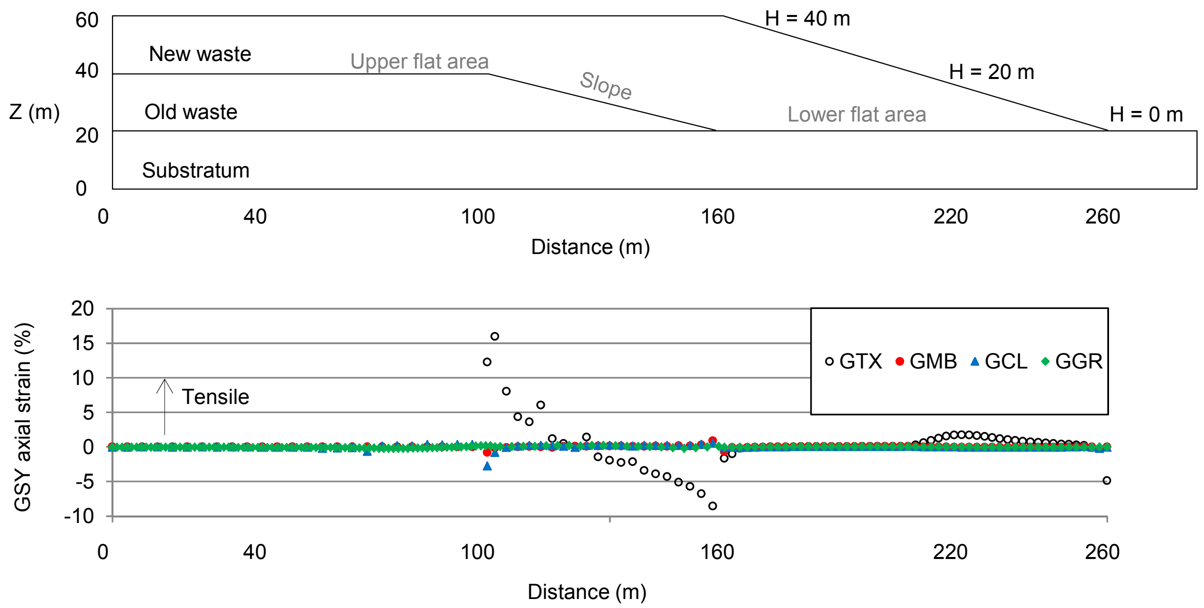

Figure 6: Axial strain within the four geosynthetics GTX, GMB, GCL and GGR at a backfill height H = 20 m

4.2.2 *Evolution of the deformation of the geotextile and the geomembrane with backfilling*

Figure 7a and 7b show the evolution of the strain respectively within the GTX and the GMB as backfilling progresses. As previously mentioned, the GTX is the GSY the most subject to tensile strains. The strains within the GTX gradually increase until H = 12 m. Beyond this level, the strains considerably increase until more than 100 %, thereby exceeding the ultimate allowable strain of the GTX. At H = 40 m, the strains within the GTX higher than 100 % highlight a tear of the GTX and an instability. This tear appeared both along the slope and the lower flat area. This is consistent with the instability evidenced in Figure 5a with the stability ratio R_S. Therefore, particular attention must be paid to the GTX behaviour for the design of the PBLE lining system.

On the contrary, limited strains up to 2.9 % at H = 40 m, are calculated within the GMB. As discussed above, since the shear displacement of interface I3 is very low, the GMB does not significantly slip along the underlying GCL and hence it does not considerably stretch out.

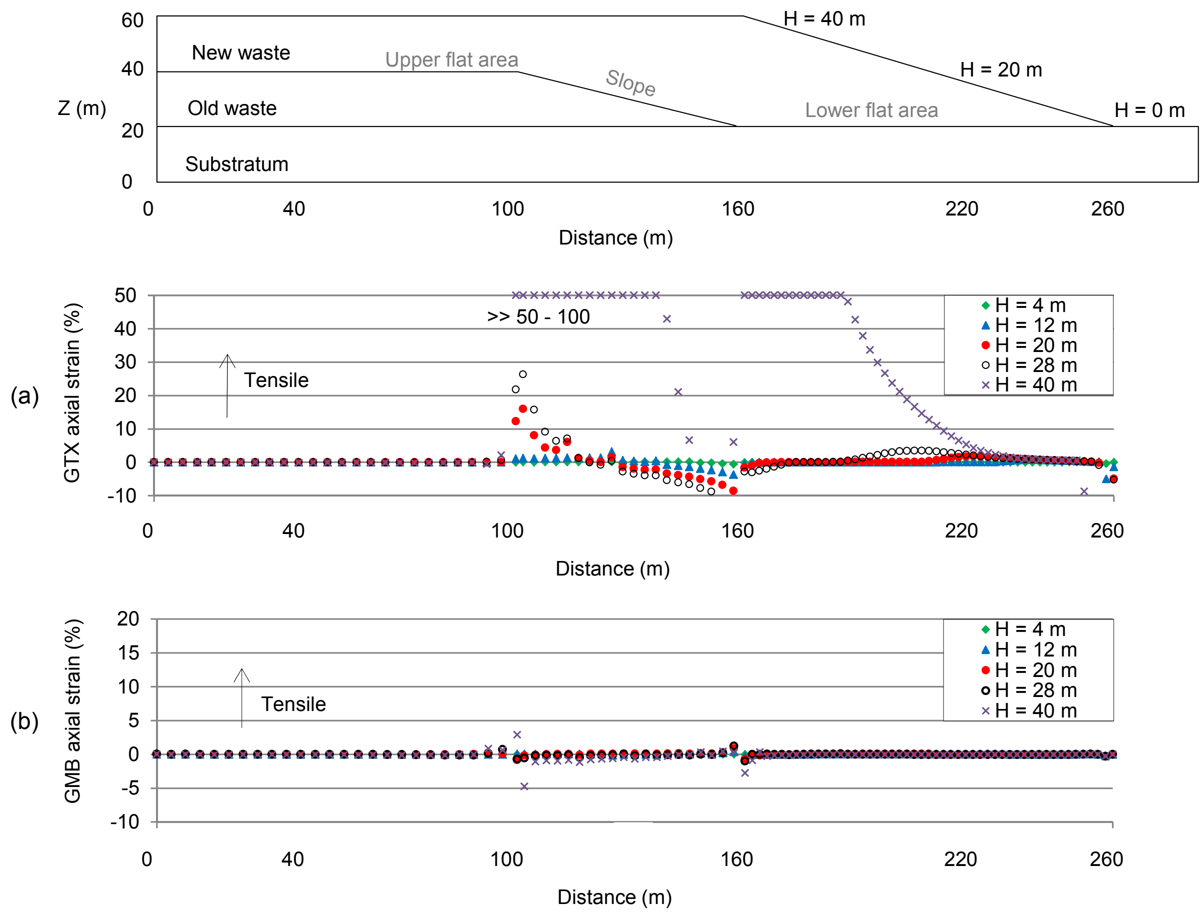

Figure 7. Effect of the backfilling on the axial strain (a) within the geotextile (d) within the geomembrane

5 SUMMARY AND CONCLUSIONS

Geosynthetics (GSY) have been increasingly used in engineered constructions for various applications (sealing, reinforcement, drainage, etc.) as they can reduce the time and cost construction and greenhouse gas emission. This is typically the case of landfills where several layers of GSY are implemented on the bottom and side slopes of the waste cells to prevent the leachate infiltration into groundwater, as a lining system. Particularly in piggy-back landfill expansions (PBLE) where a new landfill is built over an older one, four layer of GSY are often implemented between old and new waste. In such configurations, the various GSYs within the lining system can be subject to high tensile forces resulting from significant shear displacements of the interfaces between the various layers of GSY. The integrity and interface stability of the lining system is thus a key criterion for the design of a PBLE. Certainly, the tensile strength of GSYs and their interface shear strength have been widely studied, but very little attention has been paid to the processes of the slippage and deformation of a multilayered GSY system. Understanding these processes remains a challenge to improve the current design practices and that is the focus of this work.
For this purpose, numerical model techniques can be used as they allow for a more precise analysis. However, most of the previous studies which focussed on geosynthetic and waste interaction did not take into consideration several key aspects such as strain softening behaviour of interfaces, the nonlinear stiffness of GSYs and the differentiation between their compressive and tensile behaviour. In these previous studies, axial forces and strains within the

lining system could not be always calculated and thus the integrity of the various GSYs could not be assessed. Here in this study, considering all the above key aspects for a more rigorous assessment of the deformation and slippage processes, several numerical were conducted. The numerical modelling were performed on a typical PBLE based on realistic conditions using the finite difference code FLAC 2D. The model included a multi-layered GSY system composed of, from top to bottom, a geotextile (GTX), a geomembrane (GMB), a geosynthetic clay liner (GCL) and a geogrid (GGR). Several results were drawn from the numerical simulations.

First of all, the shear stresses induced by the downward load of the overlying waste appeared to be quite similar at all interfaces. Hence, at equal shear stresses, the highest relative shear displacements occurred at the interface I2 between the GTX and GMB which is the least resistant. For a height of backfilling H = 40 m, an instability (interface failure) was evidenced with shear displacements much higher than 3 m at I2. These excessive slippages of the GTX along the GMB are associated with strains within the GTX more than 100 % (tear of the GTX) near the anchorage point. From this observation, it can be pointed out that when an interface exhibits low shear strength, significant relative shear displacements will occur at this interface and a high tensile strain will develop within the upper GSY. Thus, proper friction of all interfaces within the lining system of PBLE should be selected for its design.

Moreover, the effect of the backfilling process on the distribution and on the evolution of shear stresses and displacements at the various interfaces and of strains within the various GSYs was investigated. The numerical results showed that, as backfilling progresses, the shear stresses and displacements progressively increase and the zones subject to these shear stresses and displacements are laterally extended.

Furthermore, in order to better understand the failure mechanisms at the various interfaces and their evolution as backfilling progresses, a new parameter named stability ratio was proposed. This parameter calculated for each individual portion of the interfaces allows for the detection of local instabilities and for the understanding of the evolution of such instabilities along the whole interface. Using this parameter, it appeared that the interface failure begins simultaneously at the rightmost part of the lower flat area of PBLE and near the corner of the inner slope.

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