GEOTEXTILE DEFORMATION ANALYSIS OF GEOSYNTHETIC CLAY LINERS WITH FEM

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Summary: This paper provides information on placing geosynthetic clay liner (GCL) as a lining material over coarse-grained soils in cover systems or irrigation ponds. The effects of the hydraulic head acting over the GCL and the void size of the subgrade material on deformation behavior of the GCL were analyzed by using finite element method (FEM) and a relation between the deformations and failure of the GCL was established by comparing the results with those obtained from an experimental study. Based upon these results, recommendations for the use of GCL as a barrier over coarse materials are given.

1 INTRODUCTION

Geosynthetic clay liner (GCL) is a barrier material that is manufactured by a thin layer of bentonite (5-15 mm) sandwiched between two geotextiles as shown in Figure 1. GCLs are preferred as lining materials instead of compacted clay soils, concrete or asphalt due to their low hydraulic conductivity (<10⁻¹⁰ m/s), low cost and ease of installation in cover systems, irrigation ponds and composite bottom liners¹,². GCLs are used either as part of composite liners at the bottom of landfills or storage tanks to control the migration of liquids³,⁴ or alone as the barrier material in irrigation pond liners or for decorative applications (pond liners at golf courses or amusement parks)⁵.

Figure 1: GCL specimen with bentonite sandwiched between woven and nonwoven geotextiles⁶
The geotextile components of a GCL could be either woven or nonwoven. The GCL shown in Figure 2 is placed with its woven geotextile over the soil and the cover geotextile component is nonwoven as can be seen in Figure 2.

![Figure 2: GCL specimen placed over a soil with its nonwoven geotextile component up](image)

The soil, over which a GCL is placed, could range from clay to gravel. When the water level over the GCL increases, the bentonite in the GCL might extrude out through the carrier geotextile which may also cause the hydraulic conductivity of the GCL to increase significantly. This interaction which might cause hydraulic failure of the GCL is named as internal erosion. When a GCL is placed over a coarse-grained soil, the carrier geotextile component of the GCL is in contact with the voids of the subsoil. Under high hydraulic heads, there is the possibility of the geotextile to be pushed into these voids which causes deformation on the geotextile. Most of the bentonite extrusion occurs through these deformed geotextile zones.

Considering that base pedestals made of Plexiglas with uniform voids simulated rounded uniform coarse-grained gravel successfully in terms of internal erosion, these base pedestals were used as the subgrade beneath the GCLs in a previous experimental study. In the present work, deformations of the woven geotextile component of a GCL that was placed over base pedestals with different uniform void sizes were analyzed by using Finite Element Method (FEM) with the software program PLAXIS. In this work, one of the same GCLs used in the previous experimental study was modelled as a barrier over two different Plexiglas bases with 20-mm and 10-mm diameter voids that represented coarse-grained gravel under hydraulic heads of 30 m and 10 m. The main objective of this work was to establish a relation between deformations of the geotextile and internal erosion.

2 NUMERICAL MODELLING BY USING FEM

In order to investigate the relation between geotextile deformation and internal erosion, a numerical analysis was performed by using software PLAXIS® 2D 2012. The numerical
modelling that was based on FEM, involved analysis to investigate the effect of void size of the subbase material placed beneath GCL and hydraulic head collected over GCL on deformation of geotextile component of GCL.

2.1 Materials

For this numerical analysis, the GCL was designed identically with that was used in the previous experimental study. The GCL was composed of sodium bentonite sandwiched between a nonwoven cover geotextile and a woven carrier geotextile. The woven geotextile component was in contact with the Plexiglas base pedestal with uniform circular voids that represented uniform coarse gravel.

In this study that was performed by using PLAXIS®, four different cases were analyzed. For the first case, the GCL was in contact with a base with 10-mm diameter voids under a hydraulic head of 30 m; for the second case, the GCL was in contact with a base with 10-mm diameter voids under a hydraulic head of 10 m; for the third case, the GCL was in contact with a base with 20-mm diameter voids under a hydraulic head of 30 m; and for the fourth case, the GCL was in contact with a base with 20-mm diameter voids under a hydraulic head of 10 m. The engineering properties of the components of the GCL and the Plexiglas base pedestal that were used in PLAXIS® are listed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>BENTONITE</th>
<th>NONWOVEN GEOTEXTILE</th>
<th>WOVEN GEOTEXTILE</th>
<th>BASE PEDESTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsaturated unit weight, ( \gamma_{\text{unsat}} ) (N/mm³)</td>
<td>0,015x10⁻³</td>
<td>-</td>
<td>-</td>
<td>0,0117x10⁻³</td>
</tr>
<tr>
<td>Saturated unit weight, ( \gamma_{\text{sat}} ) (N/mm³)</td>
<td>0,018x10⁻³</td>
<td>-</td>
<td>-</td>
<td>0,0117x10⁻³</td>
</tr>
<tr>
<td>Cohesion, ( c ) (N/mm²)</td>
<td>9x10⁻³</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internal friction angle, ( \phi ) (°)</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Permeability, ( k ) (mm/day)</td>
<td>0,01</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Elasticity modulus, ( E ) (N/mm²)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3300</td>
</tr>
<tr>
<td>Poisson’s ratio, ( \nu )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,37</td>
</tr>
<tr>
<td>Tension stiffness x Cross-section area, ( EA ) (N/mm)</td>
<td>-</td>
<td>34,2</td>
<td>122</td>
<td>-</td>
</tr>
<tr>
<td>Maximum tension force per unit length, ( N_y ) (N/mm)</td>
<td>-</td>
<td>15,4</td>
<td>12,2</td>
<td>-</td>
</tr>
</tbody>
</table>
2.2 Method

The GCL placed over a Plexiglas base with uniform voids in a flexible-wall permeameter was simulated by using FEM. In the experimental study, hydraulic conductivity tests were conducted on various GCLs under high hydraulic heads to compare the GCL behavior against internal erosion\(^5\). 100-mm diameter GCL specimens as outlined in ASTM D 5887, were placed over bases having 100-mm diameter. The thickness of the bentonite and the base was taken as 10 mm, the same as that was used in the experimental study. The cross-section of this experimental setup was simulated in PLAXIS\(^\text{®}\) as shown in Figure 3. From top to bottom, the test setup was composed of the nonwoven geotextile, bentonite and woven geotextile components of the GCL and the Plexiglas base with 10-mm diameter void. The loads exerted on the GCL were also taken as the same as those used in the experimental study\(^1\). During saturation and consolidation, cell pressure that was exerted on the GCL was shown with distributed load A in Figure 3 and was taken as 550 kPa. The difference in distributed load B at the top and bottom of the GCL was equal to the hydraulic gradient. In Figure 3, load B at the top and bottom of the GCL was 530 kPa and 235.7 kPa respectively. This difference caused a hydraulic head of 30 m over the GCL.

![Modelled GCL over a base with 10-mm voids in PLAXIS®](image)

The calculation phases of the analysis are listed in Figure 4. In the “initial phase”, the external loads A and B were excluded from the geometry and only the initial condition was taken into account. In the experimental study, the GCL placed over the base in the permeameter filled with water was the equivalent condition to the initial condition of this numerical analysis. Then, “phase 1” with consolidation analysis was performed. In this phase, consolidation of the GCL specimen was maintained by applying cell pressure of 550 kPa with load A all around the specimen and vertical pressure of 515 kPa with load B to the top and bottom of the specimen for 2 days\(^1\). After the specimen was consolidated, permeation of water from top to bottom of the specimen was initiated in “phase 2”. In this phase, the
difference between load A and B provided the hydraulic head acting on the specimen\textsuperscript{11}. For a hydraulic head of 30 m, a load difference of 294.3 kPa was applied whereas for a hydraulic head of 10 m, 98.1 kPa load difference was used\textsuperscript{5}. For this phase, the calculation type was chosen as “plastic”, because the permanent deformation of the geotextile component of the GCL had to be calculated in order to investigate the relation between deformation of geotextile and internal erosion. Maximum elapsed time for plastic calculation was taken as 12 days because failure occurred in maximum 12 days for all of the GCLs that experienced internal erosion\textsuperscript{12}. Therefore, test period of 12 days was satisfactory for comparing the results.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Calculation steps for the numerical analysis with GCL in PLAXIS®}
\end{figure}

In this analysis, two different void diameters for the base placed beneath the GCL were chosen. GCL was placed over a base with 10-mm diameter voids and a base with 20-mm diameter voids in order to compare the effect of void size on geotextile deformation. Apart from the void size, the other parameter that was taken into account was the hydraulic head acting over the GCL. Hydraulic heads of 10 m and 30 m were applied in the analysis. In fresh water reservoirs where GCLs are placed as barrier materials, the water depths might increase even up to 30 m\textsuperscript{13}. This is the reason why hydraulic heads as high as 30 m were used in this numerical study.

3 RESULTS AND DISCUSSION

After performing the calculation phases, outputs showing the displacements of the GCL were obtained in PLAXIS\textsuperscript{®}. For the GCL placed over the base with uniform voids of 10 mm under a hydraulic head of 30 m, the total deformation of the GCL was calculated as 0.97 mm as shown in Figure 5.
Maximum deformation occurred around the lower, carrier geotextile that was in contact with the void of the base. Red zones around the carrier geotextile shown in Figure 6, were significant indications that showed that the maximum deformation occurred in the lower geotextile. Red zones were the locations where highest deformations took place whereas orange zones were the locations for smaller deformations and light blue locations were the locations for smallest deformations. As can be seen in Figure 6, lower deformations occurred in the upper, cover geotextile and lowest deformations took place in the geotextile zones away from the void of the base. This behavior was also obtained for the other analyses with the GCL placed over a base with different void size and under a different hydraulic head.

Similar with the first case, maximum deformations were calculated in the lower, carrier geotextile where the GCL was in contact with the void of the base for the other cases. As can be seen in Figures 7, 8 and 9, the total deformation of the GCL placed over the base with
uniform voids of 10 mm under a hydraulic head of 10 m was 0.61 mm, over the base with uniform voids of 20 mm under a hydraulic head of 30 m was 2.60 mm and over the base with uniform voids of 20 mm under a hydraulic head of 10 m was 2.22 mm respectively.

According to these results, the zones of the lower geotextile component of the GCL that were in contact with the void, deformed more than those of the upper geotextile. Deformations were more severe in the zones of the geotextile around the void. As can be seen in Figure 6, deformations diminished slowly in the zones vertically and horizontally away from the void. These deformations occurred both in the geotextiles and the bentonite, however, the most severe displacements took place in the lower geotextile.

As the void size of the base increased, greater deformations were calculated in the GCL. This result was due to the increased surface area of the void, causing the zones of the lower geotextile pushed into the void.

Figure 7: Deformation of the geotextile components of the GCL placed over the base with a 10-mm void under a hydraulic head of 10 m in PLAXIS®

Figure 8: Deformation of the geotextile components of the GCL placed over the base with a 20-mm void under a hydraulic head of 30 m in PLAXIS®
The results also indicated that as the hydraulic head acting on the GCL increased, the GCL and the lower geotextile deformed more. This behavior was attributed to the increased stress on the GCL due to a higher hydraulic head causing the lower geotextile to be pushed more into the void of the base.

![Figure 9: Deformation of the geotextile components of the GCL placed over the base with a 20-mm void under a hydraulic head of 10 m in PLAXIS®](image)

The results of the numerical analysis with FEM were compared with those of the experimental study and according to this comparison, similar parameters affected the failure of the GCL. The results of both of these studies indicated that higher void size of the base material and higher hydraulic head caused greater deformation in the GCL and failure could occur easier as shown in Table 2.

### Table 2: Comparison of results between parametric analysis in PLAXIS® and experimental study

<table>
<thead>
<tr>
<th>GCL over the base with</th>
<th>Maximum geotextile deformation in PLAXIS®</th>
<th>Elapsed time for failure of GCL in PLAXIS®</th>
<th>Hydraulic head at failure of GCL in experimental study</th>
<th>Elapsed time for failure of GCL in experimental study</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-mm diameter voids</td>
<td>0,97 mm</td>
<td>0,81 day</td>
<td>30 m</td>
<td>9-10 days</td>
</tr>
<tr>
<td>under a hydraulic head</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of 30 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-mm diameter voids</td>
<td>0,61 mm</td>
<td>2,41 days</td>
<td>No Failure</td>
<td>No Failure in 12 days</td>
</tr>
<tr>
<td>under a hydraulic head</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of 10 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-mm diameter voids</td>
<td>2,60 mm</td>
<td>0,39 day</td>
<td>Not Tested (Failure occurred even under lower hydraulic head)</td>
<td>Not Tested (Failure occurred even under lower hydraulic head)</td>
</tr>
<tr>
<td>under a hydraulic head</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of 30 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-mm diameter voids</td>
<td>2,22 mm</td>
<td>0,58 day</td>
<td>10 m</td>
<td>8-9 days</td>
</tr>
<tr>
<td>under a hydraulic head</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of 10 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Although the parameters that affected the failure mechanism of the GCL were almost the same for the numerical analysis and the experimental study, there were some differences between the elapsed time for the failure and the exact hydraulic head level that caused failure for these two different methods as can be seen in Table 2. According to the experimental study, failure that was the result of internal erosion occurred in at least 8 days after permeation. However, the result of the numerical analysis indicated that failure occurred in less than 1 day for the three cases and in 2.41 days for the case where the GCL was tested over the base with 10-mm void under a hydraulic head of 10 m. Moreover, the GCL placed over the base with 10-mm void did not experience failure under 10-m hydraulic head in the experimental study whereas it experienced failure in the analysis performed with FEM by PLAXIS®.

Bentonite loss through the deformed lower geotextile was the main reason for internal erosion. When a significant amount of bentonite extruded out from the GCL, permeability of the GCL increased at least 3-4 order of magnitudes which resulted in hydraulic failure. Based upon the results of the experimental study, bentonite loss occurred slightly just after the lower geotextile over the void began to deform. As a result of more bentonite loss, the GCL experienced further deformation which caused failure of the geotextile. However, all of the GCLs failed in the numerical analysis performed by PLAXIS®. Only geotextile deformation seemed to be the main reason for failure for the numerical analysis. Practically, not only deformation of the geotextile components of the GCL but also the bentonite-geotextile interaction affects hydraulic failure of the GCL. The effect of the opening size of the geotextiles on internal erosion also supports this statement. Internal erosion or failure of the GCL was affected by the amount of bentonite extrusion through the openings of the lower geotextile in the experimental study. However, apparent opening size of a geotextile cannot be defined as a material property; only tension stiffness parameters can be defined in PLAXIS®. Because of this, only the effect of the geotextile deformation on GCL failure could be analyzed in this numerical analysis.

4 CONCLUSIONS

Main conclusions of this numerical analysis performed with FEM can be summarized as given below:

Higher geotextile deformations were obtained for the GCL placed over a base with a greater void size.

Higher geotextile deformations were obtained under higher hydraulic heads.

Higher deformation of the geotextile component of the GCL placed over a base material with voids caused faster failure of the GCL.

Based upon comparison between the results of this numerical analysis and a previous experimental study, it might be concluded that internal erosion is not only related to the strength parameters of the geotextile, but also to the opening size of the geotextile and the bentonite-geotextile interaction.
ACKNOWLEDGEMENTS

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REFERENCES


