Technical Note

Puncture resistance of PVC geomembranes using the truncated cone test

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ABSTRACT: This paper presents an experimental study to develop a design procedure for the puncture behavior of polyvinyl chloride (PVC) geomembranes. The puncture resistance was measured using the truncated cone test, in which truncated cones are used as puncture points. The heights of the truncated cones are varied to determine the critical cone height, which is the height at which geomembrane puncture occurs for a given pressure. A cushion geotextile is not used in any test to enhance puncture resistance because of the large cone heights required to puncture PVC geomembranes. Critical cone heights are presented for 0.5 mm, 0.75 mm and 1.0 mm thick PVC geomembranes. The results of these tests show that as the thickness of the PVC geomembrane increases, the critical cone height increases. This indicates an increased puncture resistance with increasing geomembrane thickness. The results of the puncture tests on PVC geomembranes are compared with other types of geomembrane, e.g. smooth and textured 1.5 mm thick high-density polyethylene and 1.0 mm thick linear low-density polyethylene. This comparison shows that the puncture resistance of PVC geomembranes used in this investigation exceeds that of polyethylene geomembranes, even though the PVC geomembranes are thinner.

KEYWORDS: Geosynthetics, PVC geomembrane, Puncture resistance, Truncated cone test, Durability

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1. INTRODUCTION

Geomembranes are used for many applications because of their advantageous physical and mechanical properties. Several geomembrane materials are available, and the appropriate material for a given application varies with the properties required, which may include strength, flexibility, chemical resistance, temperature resistance, and puncture resistance.

In particular, geomembrane puncture resistance is important in containment applications because small punctures can reduce the effectiveness of installed geomembranes and thus that of the containment system. Information is available on the puncture resistance of some geomembranes, such as high-density polyethylene (HDPE) (Badu-Tweneboah *et al.* 1998; Frobel *et al.* 1998; Zanzinger and Gartung 1998), but there is only a small amount of information available on polyvinyl chloride (PVC) geomembranes. This is especially perplexing because of the extensive anecdotal information about the excellent puncture resistance of PVC geomembranes, especially in mining applications, and the information available on other properties of PVC geomembranes. For example, methane migration through PVC geomembranes is reported on by Stark and Choi (2005), wedge welding by Stark *et al.* (2004), plasticizer molecular weight and long-term durability of PVC geomembranes by Stark *et al.* (2005), and interface shear strength by Frobel *et al.* (1998) and Amaya *et al.* (2006). Because of the lack of data on the puncture resistance of PVC geomembranes, there is also no meaningful comparison of the puncture resistance of PVC geomembranes with other types of geomembrane.

To evaluate the puncture resistance of PVC geomembranes, a truncated cone test is used herein, because it was difficult to find a representative subgrade stone that caused puncture of 0.5 mm, 0.75 mm and 1.0 mm thick PVC geomembranes. The results of the truncated cone tests are used to develop a puncture design procedure for PVC geomembranes.

2. TESTING MATERIALS AND METHODS

2.1. Geosynthetics involved in test program

Three different types of geomembrane were tested in the truncated cone tests to capture the range of geomembranes typically used in practice: 0.5 mm, 0.75 mm and 1.0 mm thick PVC geomembranes, and 1.5 mm thick textured HDPE. The HDPE geomembrane was tested by Hullings (1990) and reported by Hullings and Koerner (1991). The PVC geomembrane was manufactured by Canadian General-Tower Ltd of Cambridge, Ontario, Canada.

The puncture resistances of other types of geomembrane, e.g. 0.91 mm chlorosulfonated polyethylene (CSPE-R) and 1.0 mm thick smooth, very-low-density polyethylene (VLDPE), are also included from data published by Hullings (1990) and Hullings and Koerner (1991). No geotextiles were used in the truncated cone testing to increase the puncture resistance of the geomembranes used in the testing.

2.2. Short-term puncture testing

2.2.1. *Puncture test procedure and apparatus*

The truncated cone test procedure used to measure the puncture resistance of PVC geomembranes is similar to ASTM D5514. Other testing methods besides truncated cone tests have been used to evaluate the puncture resistance of geomembranes. These test methods can be grouped into three main categories:

- index puncture tests;
- quasi-performance puncture tests; and
- performance puncture tests (Narejo *et al.* 1996).

The truncated cone test falls into the quasi-performance puncture test category. Other researchers have developed tests that are closer to performance puncture tests than the truncated cone test. For example, the pyramid cone test and the geostatic or cylinder test are widely used in Europe as performance tests. The standard German puncture test uses a hydraulic loading ram and a container similar to a Proctor compaction mold for geomembrane and subgrade material (Zanzinger and Gartung 1998). The truncated cone test was used for the testing herein so that data reported by Hullings and Koerner (1991) could be used. In addition, truncated cone data were developed by Narejo *et al.* (1996) and used by Koerner *et al.* (1996) to develop the puncture resistance design method for geomembranes discussed subsequently. Thus, to develop consistent puncture resistance data and design methods, the truncated cone test was used for the various thicknesses of PVC and HDPE geomembrane tested herein.

The test apparatus used for the puncture testing described herein is shown in Figure 1. The equipment consists of a 0.56 m inside diameter pressure vessel that can accommodate significant pressure. The top of the pressure vessel is clamped to the bottom using 16 clamps, as shown in Figure 2, to resist the high applied pressure.

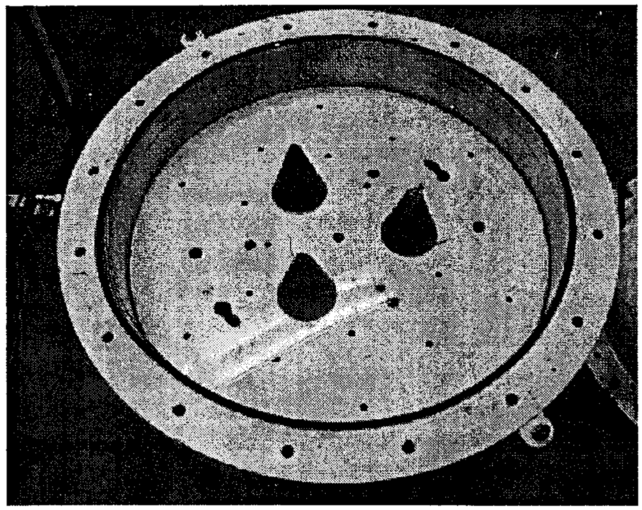

Figure 1. Photograph of hydrostatic pressure test device used in testing program

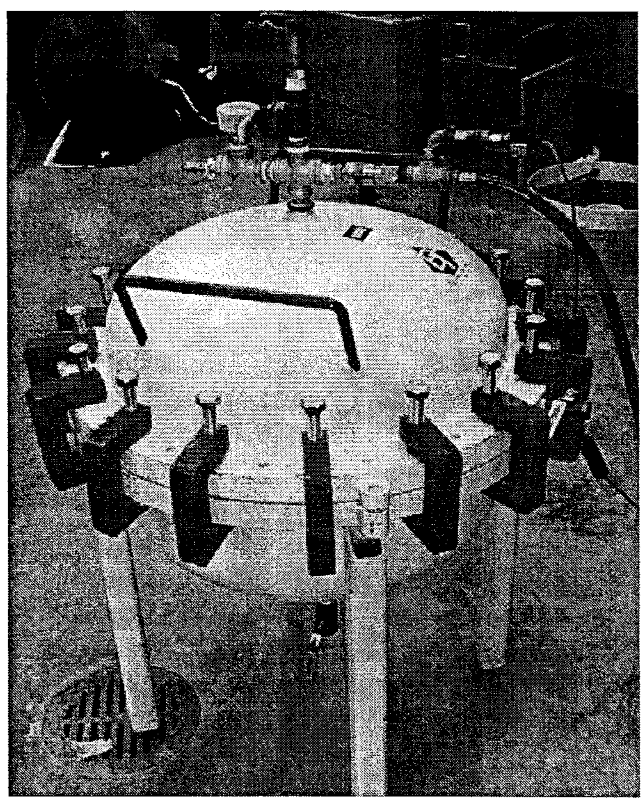

Figure 2. Photograph of assembled hydrostatic pressure test device

The pressure vessel is quite heavy and made of a strong metal frame. The frame supports a thick steel plate, which fits inside the vessel. The truncated cones are bolted to this steel plate, as shown in Figure 1. The height of the truncated cones can be varied by placing various Plexiglas plates over the truncated cones to reduce the exposed height of the cones. The Plexiglas plates rest on the thick steel plate and decrease the exposed height of the truncated cones. The geomembrane is then placed over the exposed height of the truncated cones. After securing the geomembrane and the top of the pressure vessel with the 16 clamps, the area above the geomembrane is filled with water and pressurized to force the geomembrane over the truncated cones. Air pressure or water pressure can be used to compress the geomembrane over the truncated cones.

During this study it was found that it is easier to detect a puncture if pressurized water is used. The thick steel plate has holes in it, so that after the geomembrane punctures, water flows through the plate and out the bottom of the vessel. When water appears out of the bottom of the pressure vessel, puncture is deemed to have occurred. The truncated cones also have a sensor on the top of each cone. When water flows through the punctured geomembrane, the sensor on the top of the truncated cone comes into contact with water, and terminates the test by reducing the applied pressure.

The geosynthetic specimen is placed on top of the lower half of the vessel, as indicated by ASTM D5514, so that it just touches the truncated cones prior to testing. The top part of the vessel is then positioned on the test specimen and secured to the lower part by clamps that fasten the geomembrane in place. The top position of the vessel has a water intake valve, an air bleed valve, and a pressure gauge. Water is introduced into the top of the vessel, displacing the air until the entire top piece of the vessel is filled with water. After the air is released from the air bleed valve, the water and air valves are closed. After valve closure, the pressure is increased until the geomembrane fails, or the limit of the system (520 kPa) is reached. If the test is terminated by one of the cone sensors contacting water, the failure pressure is taken as the last pressure measured before the pressure was reduced.

In accordance with ASTM D 5514, the representative subgrade is the truncated cones shown in Figure 3. Three equally spaced truncated cones are used to achieve the requirements of ASTM D5514. The cones are bolted into place by nuts. The truncated cones are 10.4 cm tall with a 8.3 cm base, and are truncated at 45° from horizontal. The critical cone height simulates the maximum protrusion size that the geomembrane can experience in the field without puncture. Thus truncated cones represent a worst-case scenario of large, highly angular particles in the geomembrane subgrade.

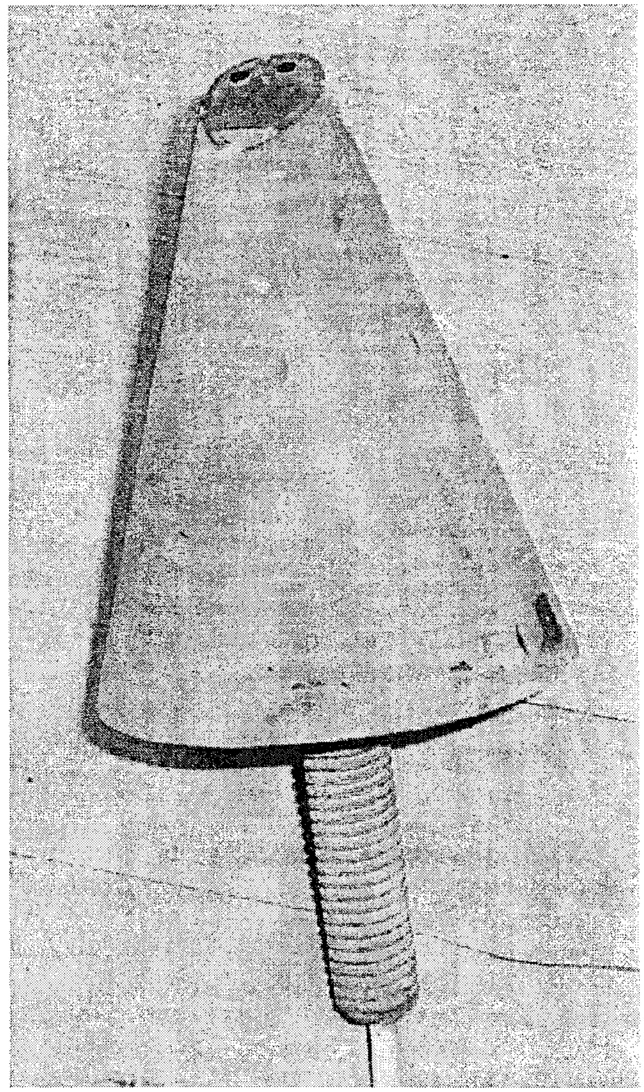

Figure 3. Truncated cone with electrical cord extending from the cone

2.2.2. *Short-term puncture resistance test results*

ASTM D 5514 requires the hydrostatic pressure in the truncated cone test be increased by about 7 kPa every 30 min. In general, the maximum pressure applied in a test on a particular geomembrane is between 400 and 500 kPa (see Figure 4). Thus a pressure increase of 7 kPa every 30 min results in a test time of about 36 h for a failure pressure of 500 kPa. To accelerate the testing, a pressure increase of 7 kPa every minute was also used, which results in a test duration of 1 h 12 min, compared with the previous experimental time of 36 h. The test results show little to no difference in the measured failure pressures for the two loading rates of 7 kPa every 30 min and every minute for both the 0.75 mm PVC and the smooth 1.5 mm thick HDPE geomembranes. Because no significant difference was found for the two pressure increase rates, the majority of the testing was conducted using a pressure increase of 7 kPa every minute. The faster loading rate probably resulted in a conservative puncture resistance for the PVC geomembranes, because a slower rate allows the PVC to deform around the cones, as discussed subsequently.

Figure 4 presents the relationships of cone height to failure pressure for the geomembranes tested herein as well as some published data (Hullings and Koerner 1991). All of the materials tested had similar minimum failure pressures of 25 to 75 kPa. However, the PVC and smooth

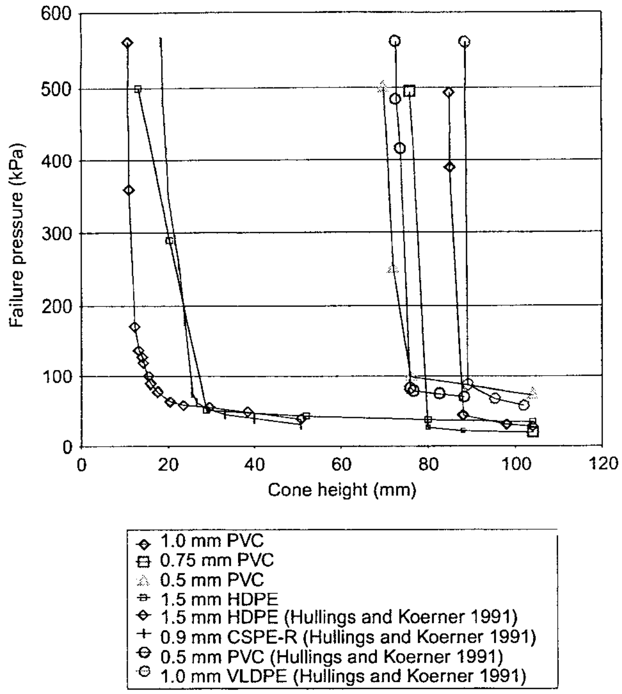

Figure 4. Puncture pressure against truncated cone height for various geomembranes

VLDPE geomembranes show greater critical cone heights for the failure pressure. The critical cone height is the cone height at which there is a dramatic decrease in the pressure to cause failure. For example, the critical cone height for the 0.75 mm thick PVC geomembrane is about 80 mm (see Figure 4). This means that at a truncated cone height of 80 mm the 0.75 mm thick geomembrane is not readily susceptible to puncture, because it can accommodate pressures greater than the maximum of the testing apparatus (500 kPa). The less flexible geomembranes, e.g. HDPE, exhibit smaller critical cone heights, which means the subgrade must be smoother than for flexible materials, otherwise the geomembrane can puncture. The less flexible materials also develop a gradual transition from critical cone height to failure, whereas the more flexible materials (PVC and VLDPE) exhibit a sharp transition.

For the three thicknesses of PVC geomembrane tested, the critical cone height increases as the thickness of the material increases. The increase in critical cone height for the 0.75 and 1.00 mm thick PVC geomembranes is almost twice that for the 0.5 and 0.75 mm thick PVC geomembranes. The minimum failure pressure for the 0.75 mm thick PVC geomembrane is slightly less than for the 1.00 mm thick material. It is even more interesting that the 0.5 mm thick PVC geomembrane exhibits a minimum failure pressure that is greater than those for the 0.75 and 1.0 thick PVC geomembranes, which may indicate a greater flexibility and ductility of the 0.5 mm thick PVC geomembrane.

2.3. Long-term puncture testing

The testing described so far herein consists of short-term tests, because the loading rate is 7 kPa/min, which results in a test duration of about one hour. It is anticipated that flexible geomembranes, such as PVC, exhibit better puncture resistance at slower loading rates than rigid geomembranes such as HDPE. It is also anticipated that the better puncture resistance of flexible geomembranes is due to additional time allowed for the flexible material to deform to the protrusion instead of puncturing. As a result, data were sought on the long-term puncture resistance of geomembranes.

2.3.1. *Puncture test procedure and apparatus*

Long-term puncture resistance data were obtained from Laine *et al.* (1988, 1989), which summarize a US Environmental Protection Agency study of puncture resistance. This study uses a truncated cone testing configuration similar to the one used in this study. However, a static pressure of 17.9 kPa was applied on the specimen and held for 365 days. After 365 days the pressure was increased to 60 kPa for an additional 30 days. This process was preformed for HDPE, CSPE-R and PVC geomembranes at temperatures of 23°C and 50°C. Samples were tested at truncated cone heights of 9.5 mm, 19 mm, and 25.4 mm. No cushion geotextile was used for any geomembrane in these tests.

2.3.2. *Long-term puncture resistance test results*

Results from the long-term puncture resistance tests are presented in Tables 1 and 2. Each entry in Tables 1 and 2 corresponds to a specimen that failed under the given loading. Table 1 shows the failures during the first year of low-pressure testing; Table 2 shows the failures after a year of low-pressure loading and subsequent high-pressure testing.

The PVC and CSPE-R geomembranes are not listed in Tables 1 and 2 because they did not fail in either the low-pressure or high-pressure testing. These materials were able to stretch over the protrusions in the subgrade and still withstand the one year of low-pressure testing and the subsequent 30 days of high-pressure testing without puncture.

The 1.5 mm thick smooth HDPE geomembrane failed in the long-term testing at pressures and cone heights that it was able to endure in the short-term testing conducted herein. Thus the slow application of pressure did not help the rigid HDPE geomembrane, but did help the puncture resistance of the PVC and CSPE-R geomembranes. Three HDPE samples failed during the first year of low pressure-testing in the testing reported by Laine *et al.* (1988, 1989). In addition, four HDPE failures occurred after one year of low pressure testing at 17.9 kPa, and during the high-pressure (60 kPa) portion of the test.

3. PUNCTURE RESISTANCE DESIGN METHOD PVC GEOMEMBRANES

Based on the data presented herein and the design equation for HDPE presented by Koerner *et al.* (1996) and Koerner (1997), an empirical relationship for the allowable pressure for 0.75 mm thick PVC geomembranes to resist puncture was obtained:

Table 1. Failed geomembranes under a pressure of 17.9 kPa material after various durations (Laine *et al.* 1988)

Material		Sample no.	Temperature (°C)	Pressure (kPa)	Time (days)	Load height (mm)
Type	mm					
HDPE	1.5	24	23	17.94	60	25.40
HDPE	1.5	15	23	17.94	148	25.40
HDPE	1.5	13	50	17.94	148	25.40

Table 2. Failed geomembranes after one year of pressure at 17.9 kPa and after 30 days of 60 kPa pressure (Laine *et al.* 1988)

Material		Sample no.	Temperature (°C)	Pressure (kPa)	Time (days)	Load height (mm)
Type	mm					
HDPE	1.5	6	23	60.03	30	19.00
HDPE	1.5	17	50	60.03	30	19.00
HDPE	2.5	39	50	60.03	30	19.00
HDPE	2.5	32	23	60.03	30	25.40

$$P'_{\text{allow}} = \left(450\frac{M_A}{H^2}\right)\left(\frac{1}{\text{MF}_S \times \text{MF}_{PD} \times \text{MF}_A \times \text{MF}_{CCH}}\right) \times \left(\frac{1}{\text{FS}_{CR} \times \text{FS}_{CBD}}\right) \quad (1)$$

where the MFs are modification factors (protrusion shape, MF_S; packing density, MF_{PD}; soil arching, MF_A; and critical cone height, MF_{CCH}) and the FSs are partial factors of safety for creep (FS_{CR}, which is a function of M_A) and chemical and biological degradation ($\text{FS}_{CBD} = 1.5$).

The results of the long-term puncture tests described previously show that a creep-related modification factor is not needed for PVC geomembranes when used without a geotextile. This is because the PVC geomembrane shows no long-term creep-related puncture without the use of a cushion geotextile. When a PVC geomembrane is used with a cushion geotextile, it is recommended that a creep-related modification factor be used.

This equation uses modification factors on a base puncture resistance of the material to calculate the amount of geotextile protection that is necessary to prevent puncture. Values of the modification factors are presented in Koerner (1997), and are shown in Table 3. One modification factor for critical cone height is not included in Table 3 because data on PVC geomembranes were not available prior to this study. Based on the ASTM D5514 puncture tests conducted herein, the PVC gains significant puncture resistance after the cone height has fallen below the critical cone height. Thus a conservative estimate of the puncture resistance gained is reflected with an MF_{CCH} factor of 0.1 when the maximum particle size is less than the critical cone height. When the maximum particle size is greater than or equal to the critical cone height, MF_{CCH} is equal to unity (1.0). If a cushion geotextile is used, the value of MF_{CCH} should be set to unity,regardless of the protrusion height in the field. Depending on the cushion geotextile chosen, the geotextile may not allow the PVC to stretch/deform enough to take advantage of the increase in puncture resistance due to deforming around the protrusion.

A base puncture resistance of 30 kPa is used to represent the strength of unreinforced PVC geomembranes such that the allowable pressure that can be applied without puncturing a 0.75 mm PVC geomembrane is given by

$$P_{\text{allow}} = 450\frac{M_A}{H^2} \geqslant 30 \text{ kPa} \quad (2)$$

3.1. Puncture resistance design example

This example is based on an example presented in Koerner (1997). Given a 0.75 mm thick PVC geomembrane under a layer of AASHTO No. 57 angular drainage stone (maximum size of 25 to 38 mm) and 50 m of solid waste (unit weight of 11.8 kN/m^3), determine the required mass per unit area of a protection geotextile that will provide a global factor of safety of 3.0. Assume that the subgrade, e.g. compacted low-permeability soil, was prepared such that the effect of any isolated protrusion underneath the geomembrane is insignificant in comparison with the effect of the overlying drainage stone.

Using Table 3, and assuming that the effective protrusion height (16 mm) is equal to half the maximum stone size (32 mm), the following data ARE used for the puncture evaluation for the 0.75 mm thick PVC geomembrane:

- effective protrusion height $H = 19$ mm $= 0.019$ m
- modification factors (see Table 3):
  protrusion shape, $\text{MF}_S = 1.0$
  packing density, $\text{MF}_{PD} = 0.5$

Table 3. Modification and reduction factors for geomembrane protection design using nonwoven needle-punched geotextiles (Koerner 1997)

<table>
<tr><td colspan="8">Modification factors</td></tr>
<tr><td colspan="2">MF_S</td><td colspan="2">MF_{PD}</td><td colspan="4">MF_A</td></tr>
<tr><td>Angular
Subrounded
Rounded</td><td>1.0
0.5
0.25</td><td>Isolated
Dense, 38 mm
Dense, 25 mm
Dense, 12 mm</td><td>1.0
0.83
0.67
0.50</td><td colspan="3">Hydrostatic
Geostatic, shallow
Geostatic, mod.
Geostatic, deep</td><td>1.0
0.75
0.50
0.25</td></tr>
<tr><td colspan="8">Reduction factors</td></tr>
<tr><td colspan="2" rowspan="3">RF_{CBD}</td><td colspan="6">RF_{CR}</td></tr>
<tr><td colspan="2" rowspan="2">Mass per unit area (g/m^2)</td><td colspan="4">Protrusion (mm)</td></tr>
<tr><td>38</td><td colspan="2">25</td><td>12</td></tr>
<tr><td>Mild leachate
Moderate leachate
Harsh leachate</td><td>1.1
1.3
1.5</td><td colspan="2">Geomembrane alone
270
550
1100
>1100</td><td>N/R
N/R
N/R
1.3
≈ 1.2</td><td colspan="2">N/R
N/R
1.5
1.2
≈ 1.1</td><td>N/R
>1.5
1.3
1.1
≈ 1.0</td></tr>
</table>

N/R = Not recommended

soil arching, $MF_A = 1.0$
critical cone height, $MF_{CCH} = 0.1$ when critical cone height is greater than the maximum particle size, otherwise $MF_{CCH} = 1.0$

- partial factors of safety (see Table 3):
  creep, FS_{CR} = a function of $M_A = 1.3$
  chemical and biological degradation, $FS_{CBD} = 1.5$
- global factor of safety = 3
- mass per unit area of the available geotextiles varies between 130 AND 1500 g/m^2.

The allowable pressure on the geomembrane can be computed as

$$P'_{allow} = FS \times P_{reqd} = 3 \times 50\ m \times 11.8\ kN/m^3 = 1062\ kPa \quad (3)$$

This value is expressed in terms of the unknown mass per unit area of the geotextile and partial factor of safety against creep in Equation 1. Rearranging and substituting,

$$M_A = \frac{(P'_{allow})(H^2)(MF_S \times MF_{PD} \times MF_A \times MF_{CCH}) \times (FS_{CR} \times FS_{CBD})}{450} \quad (4)$$

$$M_A = \frac{(1770\ kPa)(0.019\ m)^2 \times (1.0 \times 0.5 \times 1.0 \times 1.0)(FS_{CR} \times 1.5)}{450} \quad (5)$$

Note that M_{CCH} is set to 1 because a geotextile is used.

$$M_A = 0.001 \times FS_{CR} \quad (6)$$

It is clear that a geotextile with a mass per unit area greater than 450 g/m^2 is required. Using a creep factor of safety of 1.3 from Table 3, the resulting required mass per unit area of the geotextile is

$$M_A = 0.001 \times 1.3 = 0.001\ g/m^2$$

No cushion geotextile is required for 50 m of solid waste (unit weight of 11.8 kN/m^3) being placed on top of the angular drainage stone. For comparison purposes, a 500 g/m^2 nonwoven geotextile is required for a 1.5 mm thick HDPE geomembrane (Koerner 1997).

4. CONCLUSIONS

The purpose of this paper is to present a design procedure for the puncture resistance of PVC geomembranes. The following conclusions can be discerned from the information presented in this paper.

- Flexible geomembranes (PVC and smooth VLDPE) in this study exhibited better puncture resistance than rigid geomembranes (i.e. HDPE, CSPE-R) and thus are a better choice for subgrades that contain large or angular particles, or applications where large or angular particles will be placed on the geomembrane.
- In the short-term truncated cone testing conducted herein, the flexible geomembranes exhibited a greater critical cone height than the less flexible geomembranes (HPDE and CSPE-R) by about four times. All of the geomembranes tested have a minimum failure pressure in the range 20 to 75 kPa. Thus there is little difference in the failure pressure, but a large difference in the critical cone height or allowable particle size for the geomembranes tested.
- For PVC geomembranes, as the thickness of the

geomembrane increases, the critical cone height increases. This is intuitive, as the thicker material provides more cross-sectional area of material as well as more cushioning over the sharp edges of the truncated cone. However, this behavior does not hold for the minimum failure pressures, because the 0.5 mm thick PVC has a greater minimum failure pressure than either the 0.75 or 1.0 mm thick PVC geomembrane.

- PVC and CSPE-R geomembranes investigated in this study are able to withstand long-term pressures better than more rigid geomembranes because the flexible material is able to deform to the truncated cone. This is important for a geomembrane because field loading is usually much slower than laboratory loading, especially in landfill and heap leach pad applications. The HDPE geomembrane used by Laine *et al.* (1988, 1989) in the long-term tests failed at pressures and cone heights at which it did not fail at in the short-term test, because of the reduced flexibility. Thus HDPE geomembranes may not be suitable for applications with a rough subgrade in which a pressure will be applied for a long period of time.

NOTATIONS

Basic SI units are given in parentheses.

FS	factor of safety (dimensionless)
FS_{CR}	factor of safety for creep (dimensionless)
FS_{CBD}	factor of safety for chemical and biological degradation (dimensionless)
H	protrusion height (m)
M_A	mass per unit area (kg/m^2)
MF_A	modification factor for soil arching (dimensionless)
MF_{CCH}	modification factor for critical cone height (dimensionless)
MF_{PD}	modification factor for packing density (dimensionless)
MF_S	modification factor for protrusion shape (dimensionless)
P_{allow}	allowable pressure (Pa)

ABBREVIATIONS

PVC	polyvinyl chloride
CCH	critical cone height
HDPE	high-density polyethylene
CSPE-R	chlorosulfonated polyethylene
VLDPE	very low-density polyethylene

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