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GRI White Paper #14

Modification to the "GRI-Method" for the RF_{CR}-Factor Used in the Design of Geotextiles for Puncture Protection of Geomembranes

by

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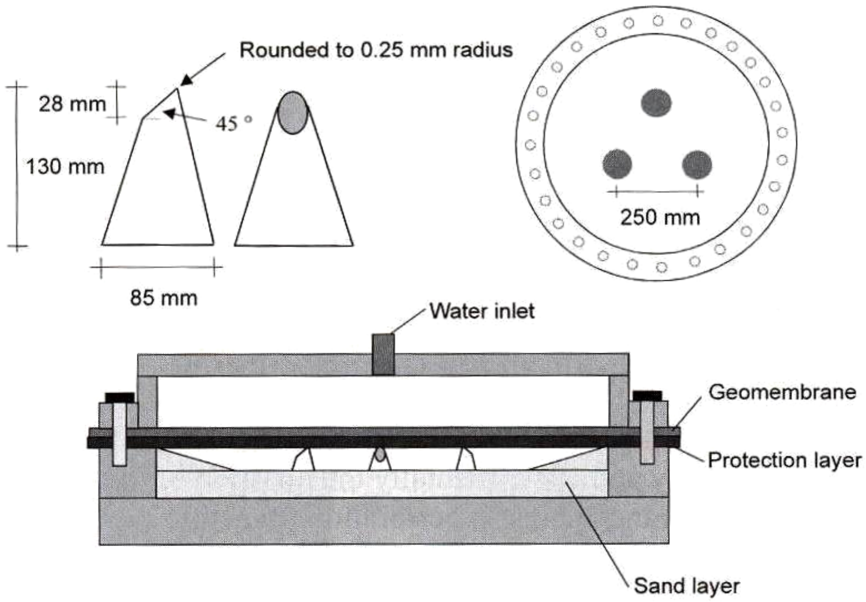
1.0 Background

In 1991, we published our first paper eventually leading to a geotextile design method for protecting geomembranes against puncture. Through the work of a number of colleagues (George Koerner, Grace Hsuan, Ragui Wilson-Fahmy) and graduate students (Don Hullings, Dhani Narejo, Mike Montelone, Bao-Lin Hwu) this method has been used worldwide for such geotextile design for about twelve-years.

The data from which the method was developed, however, was based on short-term laboratory testing. To extend it into a long-term prediction, tables for biological/chemical degradation and long-term creep were presented largely on the basis of intuition rather than by experiments. Of these two mechanisms, creep is by far the more important. Now, after ten-years of creep puncture testing we are in a position of verifying, or not, the originally proposed table. This verification issue is the focus of this White Paper.

2.0 The "GRI-Method" for Designing Geotextiles to Prevent Geomembrane Puncture

Figure 1 shows details of the truncated plastic cones used as worst-case puncturing objects to a geomembrane. The containment vessels are used to apply hydrostatic pressure to the geomembrane test specimen (1.5 mm smooth HDPE was used throughout the various studies), in turn to the protection geotextile (the "variable" in all tests), and then onto the stationary array of three cones. A well graded concrete sand was used to backfill portions of the cones allowing for a known height-of-cone to be evaluated.



(a) Sketches of truncated cones, their arrangement, and test vessel cross section

(b) Single pressure vessel

(c) Two of four identical pressure vessels with readout boxes

Fig. 1. Geosynthetic Research Institute (GRI) test vessel(s) used to evaluate geotextile protection materials; one vessel was used in the short-term tests, four were used for the long-term tests.

While many theses and technical papers have been written using this experimental test setup, a series of three papers captures the entire program; Wilson-Fahmy, et al. (1997), Narejo, et al. (1997) and Koerner, et al. (1997). The resulting design formula uses a conventional factor of safety as follows:

$$FS = p_{allow} / p_{act} \tag{1}$$

where

FS = factor of safety (against geomembrane puncture),

p_{act} = actual pressure due to the applied normal stress, e.g., landfill contents or surface impoundments, and

p_{allow} = allowable pressure using different types of geotextiles and site-specific conditions

Based on the experimental test results an empirical relationship for "p_{allow}" was obtained. It is given as Equation 2. Its use, however, requires the use of modification factors and reduction factors as given in Table 1. Note that in this table, all MF values ≤ 1.0 and all RF values ≥ 1.0.

$$p_{allow} = \left(50 + 0.00045\frac{M}{H^2}\right)\left[\frac{1}{MF_s \times MF_{PD} \times MF_A}\right]\left[\frac{1}{RF_{CBD} \times RF_{CR}}\right] \tag{2}$$

where

p_{allow} = allowable pressure (kPa),

M = geotextile mass per unit area (g/m^2),

H = protrusion height (m),

MF_S = modification factor for protrusion shape,

MF_{PD} = modification factor for packing density,

MF_A = modification factor for arching in solids,

RF_{CBD} = reduction factor for long-term chemical/biological degradation, and

RF_{CR} = reduction factor for long-term creep.

Table 1. Modification factors and reduction factors for geotextile protection material design using Equation 2, i.e., the "GRI-Method".

(a) Modification factors (all ≤ 1.0)

MF_s		MF_{PD}		MF_A	
Angular	1.0	Isolated	1.0	Hydrostatic	1.0
Subrounded	0.5	Dense, 38 mm	0.83	Geostatic, shallow	0.75
Rounded	0.25	Dense, 25 mm	0.67	Geostatic, mod.	0.50
		Dense, 12 mm	0.50	Geostatic, deep	0.25

(b) Reduction factors (all ≥ 1.0)

RF_{CBD}		RF_{CR}			
		Mass per unit area (gm/m^2)	Protrusion height (mm) 38	25	12
Mild leachate	1.1	Geomembrane alone	N/R	N/R	N/R
Moderate leachate	1.3	270	N/R	N/R	>1.5
Harsh leachate	1.5	550	N/R	1.5	1.3
		1100	1.3	1.2	1.1
		>1100	≅ 1.2	≅ 1.1	≅ 1.0

Abbreviation: N/R = Not recommended

The design situation can be approached by using a given mass per unit area geotextile to determine the unknown FS-value, or from using a given FS-value to determine the unknown mass per unit area geotextile. Koerner (2005) gives numeric examples, and Valero and Austin (1999) present design charts for the many variables contained in the design equation. It might be noted that this method is the only design method that allows for direct selection of a geotextile protection material without the need for large scale trail-and-error experimental testing.

In Equation 2 the two terms "RF_{CBD}" and "RF_{CR}" are intended to extend the short term test results into a simulated long term performance behavior. Since HDPE is quite resistant to chemical and biological degradation, the term RF_{CBD} is comparatively small. The term RF_{CR}, however, is not small and in many cases a "not recommended" decision is suggested. Due to its importance in the overall design, a series of long term creep tests using this same methodology, i.e,. truncated cones, has been undertaken for the past ten years. This White Paper presents these new results which will be seen to lead to a revised table for the RF_{CR}-values.

3.0 Creep Puncture Results After Ten-Years

There are four identical test vessels used in this creep study, each containing three identical truncated cones shaped and configured as shown in Figure 1. In all cases the geomembranes being evaluated are 1.5 mm nominal thickness smooth HDPE which conform to the GRI-GM13 specification insofar as their physical, mechanical, and endurance properties are concerned. Also common to all four setups is the geotextile cushioning materials. They consisted of three layers of 200 g/m^2 needle-punched nonwoven (continuous filament) polyester geotextiles. They will be collectively referred to as 600 g/m^2 protection materials.

The differences in the four test vessels are the heights of the truncated cones causing the puncture to occur and the applied hydrostatic pressures.

Regarding the cone heights, sand is placed and compacted in the vessels leaving a protrusion height rising above the sand level; see Figure 2. As placed, two vessels had initial cone heights of 12 mm and the other two had initial cone heights of 38 mm. It was recognized that 38 mm was unacceptable, e.g., in Table 1b, “not recommended” is listed, but this limit was in need of being verified. Regarding the 12 mm cone heights, Table 1b indicates that it should be acceptable providing a FS_{CR} = 1.3 is used in the design procedure of Equation 2. This, of course, had to be verified as well.

(a) Array of three cones rising above sand level   (b) An individual cone height of 38 mm

Fig 2. Photographs indicating the truncated cone protrusions producing the puncturing action.

Regarding the applied hydrostatic pressure, there was considerable uncertainty. The design procedure using Eqs. 1 and 2 does not address a maximum pressure. As a result high hydrostatic pressures were used for the two 12 mm cone heights (430 and 580 kPa) and low hydrostatic pressures were used for the two 38 mm cone heights (52 and 34 kPa). It is worth mentioning that hydrostatic pressure represents surface impoundment (liquid) stresses but overestimates solid waste stresses due to the arching that occurs within the solid waste as deformation occurs. The MF_A-term in Table 1a attempts to take such geostatic stresses into account.

Table 2 presents the results of this creep puncture study. Note that the cone heights varied somewhat due to shifting sand as pressure was applied and maintained. It should also be mentioned that the applied hydrostatic pressure represent 10 to 28% of the short-term failure stresses. As noted, all twelve of the truncated cones experienced yield in the geomembranes, with one having an actual break. The thickness reductions in the yield regions are also noted with the 38 mm cone heights resulting in the greatest reductions.

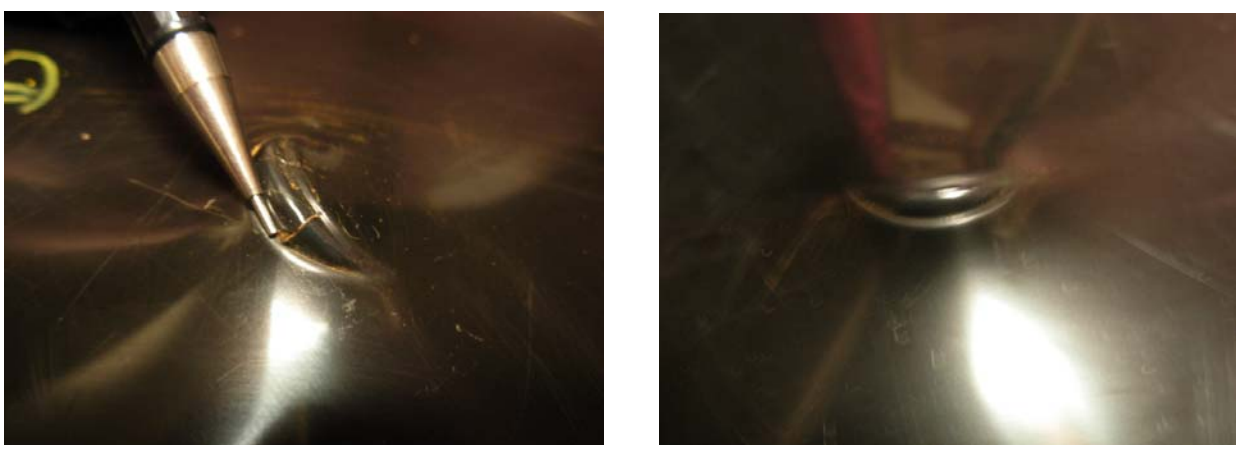
Table 2. Results of Truncated Cone Ten-Year Creep Puncture Tests
(600 g/m^2 NP-NW-PET geotextile protecting a 1.5 mm smooth HDPE geomembrane)

Vessel	Vertical Cone Heights[1]		Applied Puncture Stress[3]		Final Description of Geomembrane[5]	
No.	Initial (mm)	Final (mm)[2]	(kPa)	(%)[4]	Visual	Thickness (mm)[6]
1	12	12.1	430	23	3-subtile yields – no breaks	1.16 (30% reduction)
2	12	11.5	580	28	3-subtile yields – no breaks	0.80 (52% reduction)
3	38	29.7	52	15	3-pronounced yields; one break	0.32 (80% reduction)
4	38	31.1	34	10	3-pronounced yields; no breaks	0.34 (78% reduction)

1. Each test apparatus had three identical truncated cones beneath the geomembrane; see Figure 4.
2. The cone heights changed during, or after, pressurization due to movement of the initially placed sand layers. i.e, the sand was essentially pushed up around the stationary cones.
3. Hydrostatic stress applied to geomembrane; beneath which is the geotextile and then the three puncturing cones.
4. Percentage of short-term failure stress using Equation 2 for the calculations.
5. Refers to geomembrane response after ten-years of hydrostatic stress.
6. Results are average minimum geomembrane thickness above the cone tips.

Regarding the type and amount of yield it was very subtle for the 12 mm cone heights and very pronounced for the 38 mm cone heights (there was a small break in the yield zone for one of the six cones); see Figure 3. An analytic analyses of the resulting geomembrane strains in the yield regions was attempted but the crescent moon shape of the yield regions was not amendable to standard tensile strain calculations. On the other hand thickness strains were tractable and Table 2 gives these results; see Koerner, et al. (2009) for complete details.

(a) Deformations from 12 mm cone heights; Vessels No. 1 and 2



(b) Deformation from 38 mm cone heights; Vessels No. 3 and 4

Fig. 3. Photographs of several of the yield zones caused by truncated cone deformations of geomembrane test specimens.

4.0 Summary and Conclusions

The need for geomembrane protection against puncture by objects such as stones and gravel has been apparent for many years. Commonly used for this purpose are relatively thick needle-punched nonwoven geotextiles. In essence, such geotextiles provide a cushion in blunting the inherent aggressiveness of the puncturing object against the geomembrane. Even further, geomembranes used as liner materials beneath solid waste landfills are commonplace and for large landfills the normal stresses on such geomembranes are very high, i.e., the puncture situation is greatly exacerbated.

The type of geomembrane is also an issue. By virtue of its good chemical resistance and long anticipated lifetime, HDPE geomembranes are routinely used to line solid waste landfills. Many countries even sole source this type of geomembrane. That said, HDPE is (other than scrim reinforced geomembranes) the most sensitive geomembrane type to out-of-plane deformation, as is the situation arising from a puncturing stone located above or below the geomembrane; Nosko and Touze-Folz (2000).

As a result of the above issues, several approaches toward selecting a proper geotextile protection material are in the literature. This White Paper has focused on the "GRI-Method" which was the result of a large short-term testing project that has been published and widely used for about twelve-years. Needed, however, is the projection of the short-term testing results into long-term behavior. This was done in the past using empirical tables for both degradation (RF_{CBD}) and creep (RF_{CR}) reduction factors; recall Equation 2. The degradation by chemical and biological agents is the lesser of the two reduction factors and, as a result, this present effort is focused entirely on the validity of the RF_{CR}-values. The original values are given in Table 1b. To verify or refute the given values, this ten-year creep study of HDPE geomembranes and their associated geotextile protection materials against puncture has been concluded and this White Paper presents the results.

The same type of pressure vessel and truncated puncturing cones as used in the short-term tests were used for these long-term tests. In all cases, 1.5 mm thick smooth HDPE geomembranes were used and protected by 600 g/m^2 needle-punched nonwoven PET geotextiles. Three truncated cones were used in each of four pressure vessels, the differences being the protruding cone heights (six at $\simeq$ 12 mm and six at $\simeq$ 38 mm) and applied hydrostatic pressures (varying from 34 to 580 kPa).

After ten-years of pressurization the vessels were dismantled and it was found that all six of the high cone heights ($\simeq$ 38 mm) had pronounced yield zones in the geomembranes and one of the six had a small break within its yield zone. Clearly, such high cone heights with this type of geotextile are unacceptable. *The entry in Table 1b in this regard mentions "not recommended" and this comment is hereby substantiated.*

However, the creep test results at low cone heights ($\simeq$ 12 mm) provide a different conclusion. Table 1b indicates that a 12 mm cone height with a 550 g/m^2 protection geotextile is acceptable with a RF_{CR} = 1.3. Since all six of these cases resulted in geomembrane yield (albeit small yields in comparison to the higher cone heights), *the Table 1b values must be changed and made more conservative in their design guidance.*

To be noted in Table 1b for RF_{CR}, a not recommended (N/R) comment exists for the various protrusion heights in descending order as the cone heights decrease and the protection geotextile mass increases. By virtue of these long-term creep test results, the N/R comments must be extended. Thus, our conclusion as a result of this creep testing program is to replace the existing RF_{CR}-values with Table 3 following:

Table 3. Revised values for "RF_{CR}" to be used in Equation 2 for geotextile protection materials design.

Mass per unit area (g/m^2)	"RF_{CR}"-Values Protrusion Height (mm)		
	38	25	12
Geomembrane alone	N/R	N/R	N/R
270	N/R	N/R	N/R
550	N/R	N/R	>1.5
1100	N/R	1.5	1.3
>1100	1.3	1.2	1.1

Abbreviation: N/R = Not recommended

Lastly, the entry of ">1.5" for a 12 mm cone height associated with a 550 g/m^2 geotextile is felt to be appropriate considering the following items.

- The geotextiles used at present are made from polypropylene fibers versus the tested geotextiles which were made from polyester fibers. Since the specific gravity of PP is 0.91 and that of PET is between 1.22 and 1.38, one has from 25% to 34% more filaments in an equivalent mass per unit area geotextile using polypropylene fibers. This provides for considerably greater protection capability.
- The area of yield for the six $\underset{\sim}{}$ 12 mm cone heights was extremely small and the thicknesses of the remaining geomembrane was such that considerable deformation could still be sustained before break is even close to occurring.
- The ">1.5" recommendation is precisely for additional conservatism and safety and if a designer wishes to be more conservative than the new recommended table suggests he/she is free to do so.

5.0 References

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