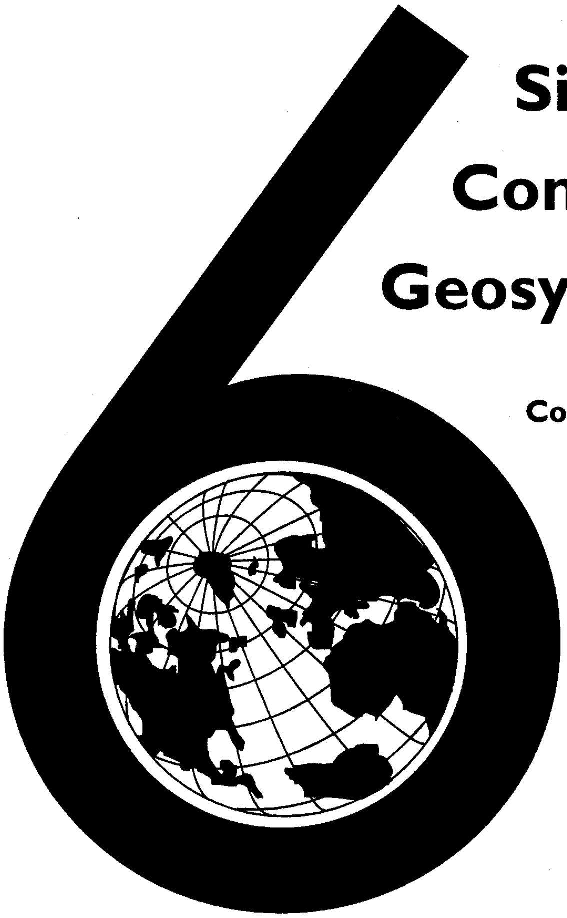

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A Rational Design for the Protection of Landfill Geomembrane Liners

Krishna R. Reddy
Assistant Professor, Department of Civil & Materials Engineering, University of Illinois, Chicago, Illinois, USA

Richard E. Saichek
Graduate Research Assistant, Department of Civil & Materials Engineering, University of Illinois, Chicago, Illinois, USA

ABSTRACT: An adequate protective cover system is essential for preventing damage to the landfill geomembrane liner from impact, over-stressing, tearing, or puncturing during and after construction. The current method for ensuring protection of the geomembrane liner usually employs a soil layer that is 0.3 m thick, and in some cases uses a nonwoven geotextile between the soil and geomembrane for increased protection. The soil layer must possess a minimum hydraulic conductivity of 1×10^{-3} cm/s so that it also functions as a drainage layer. The optimal thickness and appropriate gradation of the soil to use in the protective cover and drainage layer have not been established. Furthermore, the optimal weight (or mass per unit area) of the geotextile has not been determined. In order to address these issues, field and laboratory tests were performed to determine the effects of soil gradation, presence of a geotextile, construction loading, and long-term waste loading on the geomembrane protection. The results of this testing demonstrated that a 0.3 m thick soil layer consisting of particles with D_{50} less than 30 mm and sphericity greater than 0.8 overlain on a 270 g/m^2 nonwoven geotextile serves as an efficient protective cover system for a 1.5 mm thick HDPE geomembrane liner when it is constructed using construction equipment which exerts a ground pressure less than 30 kPa. This protective cover system was also found to be effective even under long-term waste loading up to a maximum pressure of 1400 kPa. However, a rational design approach taking into account site-specific conditions will provide the most optimal protective cover system for the geomembrane liners.

KEYWORDS: Geomembranes, Geotextiles, Landfills, Liner, Soils, Protective Cushioning, Installation Damage, Survivability

1 INTRODUCTION

An adequate protective cover system is essential for preventing damage to the landfill geomembrane liners from impact, overstressing, tearing, or puncturing during and after construction. Currently, specific USEPA regulations on protective cover systems do not exist other than the stipulation that the leachate drainage layer which overlies directly above the geomembrane liner should be selected such that leachate head does not exceed 0.3 m. Some state landfill regulations additionally stipulate that the drainage layer material must possess a minimum hydraulic conductivity of 1×10^{-3} cm/s and a minimum thickness of 0.3 m. Many materials meet these requirements to be suitable for use in the drainage layer. These materials include soils, geosynthetics, recycled materials (e.g., shredded scrap tires), or a combination of these materials. Soils have been conventionally used; however, geosynthetics and recycled materials have also gained wide acceptance.

In addition to the efficient drainage of leachate, the designer must also assess the potential damage to the geomembrane liner during and after the construction of the drainage layer. Intuitively, there is a greater potential for geomembrane damage if a soil consisting of large size angular particles is used. Thus, the drainage layer material must be selected such that it serves a dual purpose, both as an efficient drainage medium and as an adequate geomembrane protective cover.

The common design practice is to use a soil layer to serve as a protective cover as well as a drainage layer. Optionally, a geotextile is placed above the geomembrane prior to the placement of the soil. The current approach to the selection of the soil type is mainly based on the minimum hydraulic conductivity requirement; however, a wide range of soils can possess hydraulic conductivities equal to or greater than the required 1×10^{-3} cm/s. Therefore, an additional requirement which ensures maximum protection to the geomembrane liner is needed. In addition, the adequacy of using a 0.3 m thickness for the leachate drainage layer to serve as a protective cover is unknown. Furthermore, the necessity of using a geotextile above the geomembrane and, if necessary, the type of geotextile needed is unknown. Generally, protective cover systems are designed based on an empirical approach or the personal judgement of the designer. In order to develop a rational design approach, several researchers have performed both theoretical and experimental studies.

In this paper, an overview of previous studies performed on protective cover systems is provided first. Then, a summary of findings from a research study performed at the University of Illinois at Chicago (UIC) which involved both field and laboratory testing on protective cover systems is presented. Finally, a rational approach to the design of protective cover systems is outlined.

2 PREVIOUS STUDIES ON PROTECTIVE COVERS

Giroud (1992) evaluated the effects of placing a geotextile on the top, the bottom, or on both sides of the geomembrane on properties of the geomembrane. Puncture and impact tests were performed using a variety of 0.75 mm-thick geomembranes and 200, 400 and 600 g/m^2 nonwoven needle punched geotextiles. These test results showed that using a geotextile either on top, bottom or on both sides increases the puncture and impact resistance over the geomembrane by itself. However, the combined effects of using a geotextile with soils over the geomembrane were not investigated in this study.

Motan et al. (1993) performed laboratory testing using a pressure chamber in which a layer of angular gravel was formed by mounting particles with epoxy onto a plywood base, a geotextile was then placed, and finally a 1.5 mm thick smooth geomembrane was placed over the geotextile. Air pressure was applied in increments up to 815 kPa and then released. The geomembrane sample was removed and multi-axial tension tests were performed. This testing was repeated with geotextiles with four different weights of three different brands. Although beneficial effects of using a geotextile were observed, there was no consistent trend observed to conclude if one geotextile was better than the other. The testing conditions used in this study simulated protrusions from the subgrade. Only one particular soil was used and the soil particles were not allowed to move or reorient during the loading.

Koerner and his co-investigators reported a comprehensive investigation performed at Drexel University in order to determine the puncture protection of 1.5 mm thick HDPE geomembranes under different conditions and the results have been published in a three part comprehensive paper (Wilson-Fahmy et al., 1996; Narejo et al., 1996; Koerner et al., 1996). This investigation included a theoretical approach, an extensive laboratory experimental program, and a simplified design procedure. The theoretical approach is based on tensioned membrane theory and assumes axi-symmetric conditions on a geomembrane overlain on a single isolated protruding object rising above a firm subgrade. The effects of the height and top shape of the protrusion on the puncture resistance of geomembrane under the application of hydrostatic pressure were studied. The effects of the presence of geotextile between the geomembrane and the protrusion was also analyzed. Based on the comparison of pressures required for the initiation of yield conditions for a 1.5 mm thick HDPE geomembrane, it was concluded that an increase in the protrusion height, which is correlated to soil particle size, reduced the puncture resistance of the geomembrane. However, an increase in the radius of the protrusion shape, which reflects rounded or subrounded compared to angularly shaped particles, resulted in higher puncture resistance. In addition, it was determined that the effect of increasing the mass per unit area of the protection geotextile proved to significantly increase the puncture resistance of the geomembrane.

The above theoretical study was augmented with a laboratory testing program which involved: (1) hydrostatic pressure truncated cone puncture tests as per the standard test method ASTM D 5514, (2) similar tests except with cones substituted with isolated stones, (3) hydrostatic tests with geomembranes overlain on a bed of stones, and (4) geostatic tests which involved one truncated cone overlain by a geomembrane which in turn was overlain by a layer of sand and then was subjected to loading through the use of a rigid plate. The loading was gradually increased until failure of the geomembrane occurred. Some long-term tests were also conducted which involved loading to the fraction of its failure load and maintaining it for a long duration or until failure occurred. The different test variables considered in this testing program included different cone heights, different thicknesses of HDPE geomembrane, and a 1.5 mm thick HDPE geomembrane with different protective geotextiles. The tests with isolated truncated cones or stones revealed that the geomembrane puncture resistance increases when: (1) the mass per unit area of the protective geotextile is greater, (2) protrusion heights are smaller, and (3) protrusion shapes are rounded as compared to angular. The arching and creep effects are also found to influence the geomembrane puncture resistance. All of these results are very useful in evaluating the geomembrane protection against isolated protrusions from the subgrade. In tests with a layer of packed stones, geomembrane failure could not be achieved; therefore, the signs of yield conditions were visually observed.

Using the puncture test data obtained using the isolated truncated cones and isolated stones, an empirical equation was suggested to calculate an allowable stress for a 1.5 mm thick HDPE geomembrane. This equation involves mass per unit area of the protective geotextile, protrusion height, and a series of modifying factors and partial factors of safety to account for the field conditions such as stone shape, packing density, soil arching, creep and chemical/biological degradation as well as a global factor of safety to account for uncertainties in the formulation.

The above study by Koerner and his co-investigators clearly documents the beneficial effects of using a geotextile to protect the geomembrane from damage due to isolated protrusions in the subgrade. The tests performed with a layer of stone closely simulated the protective cover and drainage layer over a geomembrane. However, the damage to the geomembrane in these tests was only assessed visually; therefore, quantification of the extent of physical changes that occurred for different stone types was subjective. The proposed design procedure is conservative because it is mainly based on the test results using isolated truncated cones or stones rather than test results using a bed of stone. Also, the values of different modification factors and partial factors of safety are required in using this procedure. In addition, the effects of construction loading are not addressed in this methodology.

Richardson (1996) investigated damage induced to a geomembrane when it is subjected to construction loading. A variety of geosynthetic cushions were evaluated to protect the geomembrane under two types of construction equipment loading conditions. A particular soil was employed with two different thicknesses 0.3 m and 0.6 m. It was found that even the lightest of geotextiles offered increased protection from scratches and dents. From laboratory wide width tensile testing, it was concluded that the recommended weight for a nonwoven geotextile, based on a factor of safety of three, was a 405 g/m^2 for a normal pressure of 345 kPa and linearly increased to approximately 1519 g/m^2 for a pressure of 2068 kPa. In this study, the yield strain and load correlated well with the visual damage to the geomembrane. However, other studies have found that physical changes to the geomembrane do not affect the yield strain and load, but the ultimate strain and load are affected (Reddy et al., 1996).

Among other countries, German regulations specify more stringent requirements on protective cover systems for the geomembrane liners (Brummermann et al., 1994). According to these regulations, if a strain as small as 0.25% is induced due to local deformation of the geomembrane, the protective cover system is deemed unsuitable (Seeger and Muller, 1996). The yield stress of a 1.5 mm smooth geomembrane liner as determined by a wide strip tension test is approximately 18%. Even a third of this strain to reflect a factor of safety of 3 would be significantly higher than that of the German regulatory limit of 0.25%. Due to the strict regulations on the allowable strain in the geomembrane, the protective cover layer is constructed as a separate layer underneath the drainage layer. Three types of materials are commonly used for these protective cover layers: (1) nonwoven geotextiles with masses per unit area that are greater than 2000 g/m^2, (2) sandfilled geotextiles or woven mattresses, and (3) nonwoven geotextiles with masses per unit area greater than 1200 g/m^2 that are covered with a coarse (0-8 mm) particle layer with a thickness of 15 cm or greater. Additionally, German systems use a geomembrane that has a 2.5 to 3 mm thickness and a drainage layer that employs a very coarse gravel that is graded from 16 to 32 mm (Seeger and Muller, 1996). Thus, it appears that the protective cover systems used in Germany are overly conservative.

3 RESEARCH ON PROTECTIVE COVERS AT UIC

Research conducted on protective covers for landfill geomembrane liners at UIC involved both field and laboratory testing to asses the performance of different protective cover conditions and to develop a rational design approach. An overview of the field and laboratory testing is provided in this section and the recommended rational design approach based on these test results is provided in the next section.

The procedures and results of field testing performed to evaluate different protective cover systems under construction loading have been described in detail by Reddy et al. (1996). This testing included seven test pads in order to determine the soil type, geotextile, and construction equipment that best protected the 1.5 mm thick smooth HDPE geomembrane liner. Two soils, a fine gravel and a medium gravel, were tested both with and without a 270 g/m^2 nonwoven geotextile. Two types of dozers, a light and a heavy dozer, were used for construction and reflected the typical field loading conditions. After the application of repetitive construction loading, geomembrane samples were exhumed, visually observed, and tested in the laboratory to assess the effects of physical changes on the properties of the tested geomembranes as compared to the virgin geomembrane. The laboratory tests performed on the exhumed geomembrane samples included wide strip tension, multi-axial tension, and water vapor transmission (WVT) tests. Typical results of multi-axial tension tests are presented in Figure 1.

These results showed that the physical changes in the geomembrane are reflected in the differences in the elongation at burst from multi-axial test and the ultimate strain and ultimate stress from wide strip tensile tests as compared to the values for the virgin geomembrane. The physical changes were significant for coarser soil and for heavy construction loading conditions. It was concluded from this study that a 270 g/m^2 nonwoven geotextile can significantly protect the geomembrane from construction loading even when using construction equipment exerting a pressure of 46 kPa is used.

The field testing was complemented with a laboratory testing program in order to assess the protective cover systems under simulated long-term waste loading conditions. These tests were performed in a specially constructed simulation test setup. The details of the test setup and testing procedures have been given by Reddy and Saichek (1997). For these tests, an elastomer, which possessed compressibility similar to that measured for a typical compacted clay, was laid at the bottom of the test setup, and then a geomembrane was laid on the top of the elastomer. Different protective systems were installed over the geomembrane with different soils both with and without a geotextile. The soils used ranged from sand to gravel corresponding to D_{50} values of 0.65 to 30 mm, respectively. The sphericity values ranged from 0.798 for the crushed gravel to 0.846 for the fine gravel. A rigid plate was placed on the cover system and incremental loading up to 1400 kPa was applied. The load was maintained constant for 48 hours and then gradually released. The geomembrane was then carefully exhumed and visually observed. Multi-axial tension, wide strip tension and WVT tests were performed similar to the field testing program in order to characterize the physical changes that the geomembrane had undergone due to loading. These test results also revealed that physical changes were reflected in the elongation at burst from multi-axial tests, and the ultimate stress and strain from wide strip tension tests. Overall, these long-term simulation testing results showed a similar trend in that a 270 g/m^2 geotextile adequately protected the geomembrane even when it was subjected to a high pressure of 1400 kPa. For long-term testing performed without a geotextile, the geomembrane elongation at burst and, generally, the stress and strain at break also decreased as the soil particle size increased. Figure 2 shows the changes in the elongation at burst observed as a function of mean particle size. The results for the tests incorporating a 270 g/m^2 geotextile are also shown in this figure. These results demonstrate that larger size particles cause more extensive physical changes as compared to smaller size particles, and the beneficial effects of incorporating a geotextile weighing 270 g/m^2 is clearly evident.

It should be noted that although valuable information has been obtained from this study, additional field and laboratory testing using distinctly different soils, types of geotextiles, and loading conditions is essential in order to create an extensive database which can then be utilized to develop design charts.

4 RATIONAL DESIGN APPROACH

In order to construct a protective cover system which will perform the functions of efficient drainage and adequate protection of the geomembrane, a rational design approach is outlined below:

Step 1: Obtain information on the subgrade and the liner components. Particularly, the type and thickness of the geomembrane must be known before the protective cover design can proceed.

Step 2: Select the type of material which will serve as both the protective cover and drainage layer. Potential materials can be

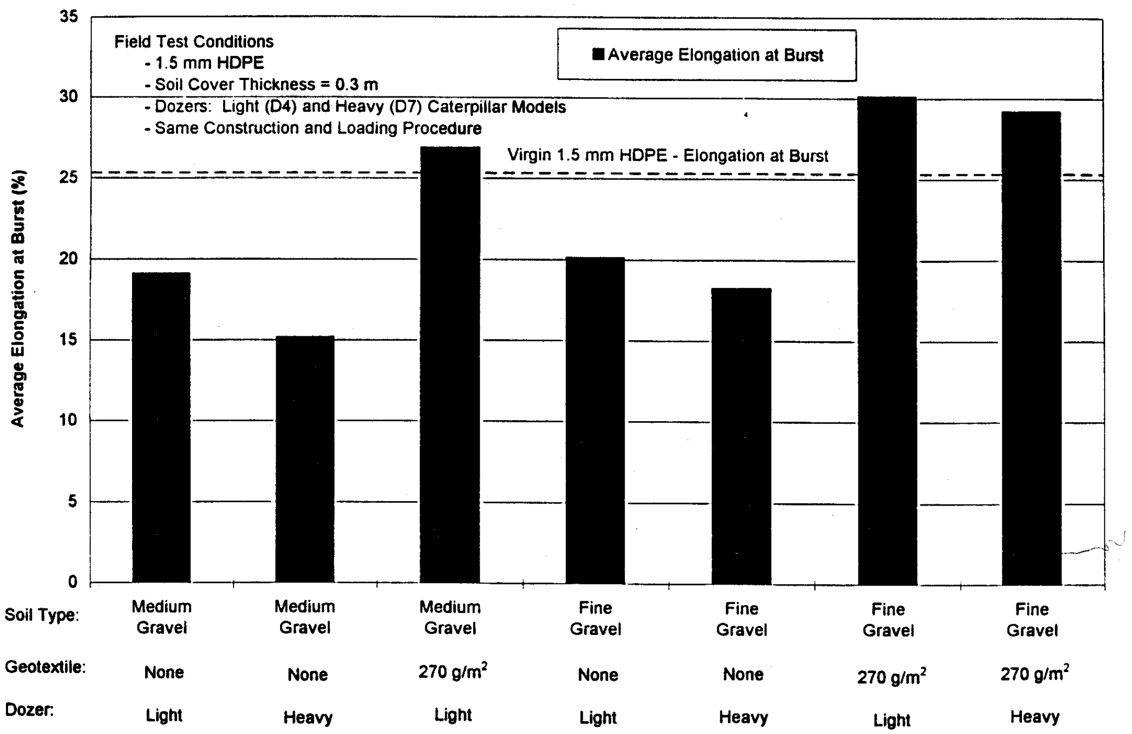

Figure 1. Evaluation of Field Performance of Protective Cover Systems Under Construction Loading

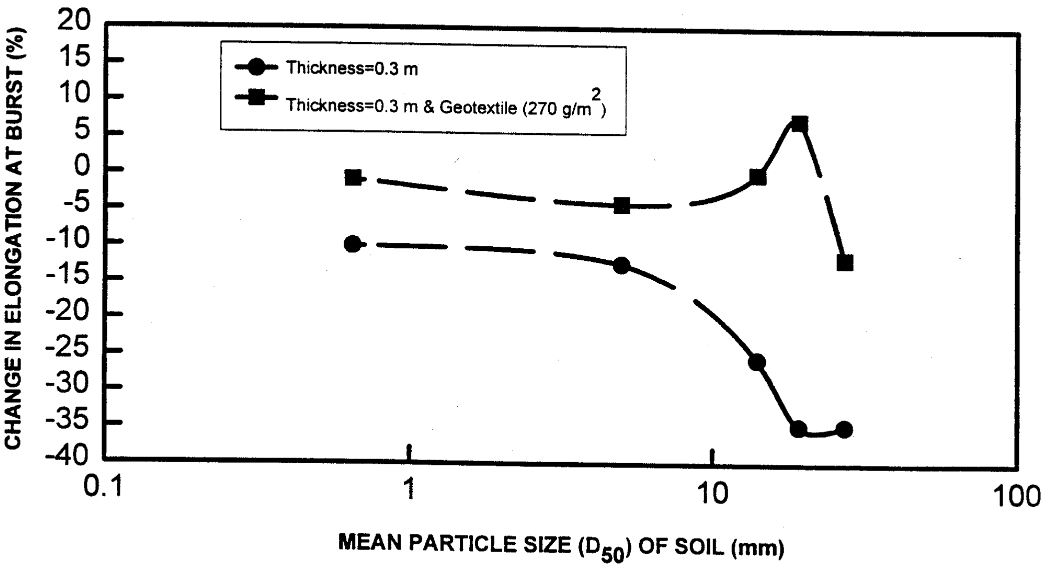

Figure 2. Evaluation of Protective Cover Systems Under Long-Term Waste Loading Conditions

either soils, geosynthetics, recycled materials, or a combination of these materials. For this paper, soils are considered as the suitable choice of materials. The different soil sources in the vicinity of the project site should be identified, and costs associated with procuring soils from these sources should also be obtained.

Step 3: Characterize the soils which have potential for use as protective and drainage materials as well as being cost-effective. The characterization must include particle shape, grain size distribution, density, hydraulic conductivity, durability, and shear strength. The soil must possess a minimum hydraulic conductivity of 1×10^{-3} cm/s and be compatible with the leachate characteristics of the expected waste material in order to be further considered.

Step 4: Determine the clogging potential of the soil. Standard filtration, retention, and clogging procedures can be followed as detailed by Koerner (1994). In addition to investigating physical clogging, biological activity should also be studied. Logically, soils containing relatively large voids and a high permeability are less likely to become clogged by finer particles or biological growth.

Step 5: Perform a protective performance evaluation of the potential soils under both construction and long-term loading conditions. This evaluation provides the necessary thickness of the soil and the necessity of using a geotextile. The UIC research results showed that a 0.3 m thick soil layer consisting particles with D_{50} in the range of 0.65 to 13 mm and sphericity greater than 0.8 placed over a 270 g/m^2 nonwoven geotextile will provide adequate protection against low ground pressure (<30 kPa) construction equipment as well as long-term waste loading pressures up to 1400 kPa. These results may be used as an initial guidance for the selection of soil gradation; however, a site-specific testing program using the procedures developed at UIC (Reddy et al., 1996; Reddy and Saichek, 1997) is highly desirable.

Step 6: Evaluate the selected system for stability on the slopes to ensure that no sliding will take place within any material layer or along any interface.

Step 7: Stipulate QC and QA procedures in order to ensure that the materials, equipment, and construction procedures meet the specifications. The composition and placement of the first few lifts of waste should also be monitored to ensure that possibly damaging waste products, such as old concrete reinforcement bars, are not located directly on top of the protective cover soil.

5 SUMMARY

The current practice for geomembrane protection is to use a 0.3 m thick soil layer with or without an underlying geotextile. The protective soil layer also serves as the leachate drainage layer and must possess a hydraulic conductivity greater than 1×10^{-3} cm/s. Employing an excessively thick layer of protective cover soil is uneconomical, and using a layer that is too thin increases the susceptibility of the geomembrane to damage. The type of soil, particularly the shape and size of the particles, also influences the degree of protection offered to the geomembrane. In addition, the beneficial effects of the geotextile below the soil layer have not been well quantified.

Comprehensive field and laboratory testing undertaken at UIC was aimed at determining the adequacy of different cover systems during construction and under long-term waste loading conditions to protect a smooth 1.5 mm high density polyethylene (HDPE) geomembrane. The field investigation involved the testing of cover systems that were comprised of different soils with or without a geotextile and were subjected to various construction loads. The laboratory investigation involved the development of a simulation test apparatus and testing of various protective cover systems under incremental loads to simulate increasing waste heights. The laboratory simulated protective cover systems were comprised of a soil layer with varied soil type both with and without a geotextile. Damage to the geomembrane liner was quantified by performing water vapor transmission (WVT), multi-axial tension, and wide strip tension tests on the geomembrane samples exhumed after both field and laboratory simulation testing. These test results allowed the evaluation of the relative protective performance of different protective cover systems tested in this study.

The protective performance was found to depend on the soil type, incorporation of a geotextile, construction loading, and long-term waste loading. The geomembrane protection was found to be significantly dependent on the soil particle size. A 0.3 m thick layer of soil consisting of particles with D_{50} less than 30 mm and sphericity greater than 0.8 provided greater protection. Incorporation of a 270 g/m^2 nonwoven geotextile significantly enhanced geomembrane protection. Additionally, the use of construction equipment with ground pressure less than 30 kPa caused less damage to the geomembrane. Protective cover systems meeting these criteria are found to perform satisfactorily under long-term waste loading up to 1400 kPa. Finally, a site-specific testing should be conducted, where possible, to determine the most efficient and economical protective cover system.

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