Design service life of geogrids in mechanically stabilized earth walls

La durée de vie des murs en terre mécaniquement stabilisée par geógrilles

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ABSTRACT

Geosynthetic-reinforced mechanically stabilized earth (MSE) walls have been used since the 1970s in a variety of applications where steepened embankments are needed. MSE walls have been generally designed for a service life of 75 to 100 years. However, in some applications, a service live in excess of 100 years is desired. Geogrids are among the most widely used geosynthetic reinforcement in MSE walls, and this paper concentrates on the design service life of geogrid-reinforced MSE walls. The durability of geogrids is a function of damage that may occur during their installation, tensile stresses to which they are subjected during their service life, and degradation experienced during exposure to the in-soil environment. The current design approach used to account for strength losses due to installation damage, creep, and long-term degradation is to apply reduction factors to the ultimate tensile strength of the reinforcement. Reduction factors commonly used in design were developed for road embankment applications and generally reflect a 100-year service life. This paper presents the factors affecting durability and service life of geogrid reinforcement used in MSE walls, and a method to account for the design service life of the geogrid reinforcement. The conclusion of the paper is that MSE walls can be designed for a service life greater than 100 years using total combined reduction factors.

RÉSUMÉ

Les murs en terre mécaniquement stabilisée (MSE) par géosynthétiques sont utilisés depuis les années 1970 dans une variété d'applications où des pentes raides sont nécessaires. Les murs MSE sont généralement conçus pour servir de 75 à 100 ans. Cependant, dans certaines applications, une durée de vie de plus de 100 ans est souhaitée. Les geógrilles sont parmi les géosynthétiques les plus utilisés dans les murs MSE, et cette communication traite de la durée de vie des murs MSE avec geógrilles. La durabilité des geógrilles est fonction des dommages subis lors de l'installation, des contraintes de traction auxquelle elles sont soumises dans l'ouvrage, et de la dégradation au contact du sol. La méthode actuelle utilisée pour tenir compte de la diminution de résistance due aux dommages en cours d'installation, le fluage, et de dégradation à long terme consiste à appliquer des coefficients de réduction sur la résistance à la traction de l'armature. Les coefficients de réduction habituels ont été développés pour des remblais routiers et correspondent généralement à 100 ans de durée de vie. Cette communication présente les facteurs qui affectent la durabilité et la durée de vie de renforcement de geógrilles utilisées dans les murs MSE, et une méthode pour tenir compte de la durée de vie des geógrilles dans le dimensionnement des murs MSE. La conclusion de la communication est que les murs MSE peuvent être conçus avec pour une durée de vie de plus de 100 ans en utilisant un total combiné de coefficients de réduction.

Keywords : MSE Walls, Geogrids, Service Life, Polyethylene, Polyester

1 INTRODUCTION

This paper addresses the durability of geosynthetic reinforcement used to construct MSE walls with extended design service life. In particular, this paper concentrates on the use of MSE walls in landfill applications. The most common type of geosynthetic reinforcement used to construct MSE walls at landfills is geogrid. Geogrids used in MSE walls are typically made of either punched and drawn sheets of high density polyethylene (HDPE) or woven polyester (PET) yarns coated with polyvinyl chloride (PVC) or acrylic polymers. The durability (resistance to installation damage and aging) of geogrids is a function of polymer type, stress level, and the surrounding environment during their service life. An overview of the factors affecting geogrid durability and a method of accounting for geogrid durability in the design of MSE walls at landfills is presented herein.

2 BACKGROUND

Polymers have been used for many years in engineering applications, such as insulation on cables and by the plastic pipe industry. In landfill applications, polymer products (e.g., geomembrane liners, geonets, geotextiles, geogrids, etc) are used in a variety of components such as liner and cover system barriers, filters, drainage layers, and soil reinforcement. Geogrids have been used at landfills to enhance the slope stability of liner system and cover system veneers, to support liner systems over soft or potentially unstable foundations, and to construct MSE walls around the landfill perimeter. The industry has engineered such components for long service lives (hundreds of years).

The durability of geogrids is a function of damage that may occur during installation (i.e., construction damage), the tensile stresses to which they are subjected during their service life, and degradation experienced during exposure to the in-soil environment during the service life. The current design approach used to account for strength losses due to construction damage, creep, and long-term degradation is to apply reduction factors to the ultimate tensile strength (T_{ult}) of the reinforcement. The allowable strength (T_{al}) is then calculated using the equation shown below:

$$T_{al} = \frac{T_{ult}}{RF_{CR} \times RF_{ID} \times RF_{D}} = \frac{T_{ult}}{RF} \qquad \text{(Eqn. 1)}$$

where: RF_{CR} = creep reduction factor; RF_{ID} = installation damage reduction factor; RF_{D} = degradation reduction factor; and RF = product of all applicable reduction factors. This design approach assumes that all reduction factors are independent, which may not be the case and which may result in over-conservative RF values (Koerner and Koerner, 2007).

The effects of construction damage, creep, and long-term degradation on the allowable strength of geogrids are discussed in the following sections.

3 GEOGRID REDUCTION FACTORS

3.1 *Construction Damage*

Geogrid can be damaged during backfill placement and compaction operations, thereby reducing the tensile strength of

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the reinforcement. Assessment of construction damage can be made by conducting field installation damage testing (e.g., ASTM D 5818). Damage during construction is a function of reinforcement type, backfill material, and compaction conditions. Based on a number of studies on construction damage of geosynthetics, the highest loss is reported when coarse angular backfills are spread in relatively thin lifts with heavy compaction equipment (Elias, 2000). From construction damage testing conducted on HDPE geogrids, the following conclusions were drawn (Elias, 2000): damage and resulting loss of initial strength increased with decreasing geogrid thickness and weight; damage and resulting loss of initial strength increased logarithmically with increasing maximum backfill size as denoted by the D_{50} size (D_{50} sizes greater than 25 mm (1 in.) significantly increased the level of damage with correspondingly greater losses of strength); varying compacted lift thicknesses between 150 and 230 mm (6 in. to 9 in.) had very little effect on the loss of strength; and varying compactive effort from four to more than eight passes with a heavy vibratory compactor had only a minor effect on the resulting damage and loss of strength.

In the absence of project-specific data, conservative values of installation damage reduction factors can be used. Examples of product specific reduction factors compared to conservative values recommended by Elias (2000) are presented in Table 1.

Table 1. Installation Damage Reduction Factors for Geogrid (Elias, 2000).

Geogrid Type	Reduction Factor, RD_{ID}	
	Type 1 Backfill $D_{100} \leq 100$ mm and $D_{50} \approx 30$ mm	Type 2 Backfill $D_{100} \leq 20$ mm and $D_{50} \approx 0.7$ mm
HDPE Uniaxial Geogrid		
Elias (2000)[1]	1.20-1.45	1.10-1.20
UX1400MSE[2]	1.08	1.02
UX1600MSE[2]	1.12	1.09
PVC-Coated PET Geogrid		
Elias (2000)[1]	1.30-1.85	1.10-1.30
SG200[3]	1.34	1.1
SG500[3]	1.29	1.1
Acrylic-Coated PET Geogrid (Elias, 2000)[1]	1.30-2.05	1.20-1.40

[1] Default installation damage RDs – used when project-specific or product- specific data are not available.
[2] Product-specific data provided by manufacturer.
[3] Product specific data provided by manufacturer.

3.2 *Creep*

Under sustained loading, geogrids lose strength over time due to creep. The loss of strength is a function of the polymer, applied loads, and temperature. A creep reduction factor is applied to limit the load in the geogrids so creep rupture will not occur over the service life of the structure.

Creep reduction factors are developed from laboratory creep tests (e.g., ASTM D 5262) performed for each type of geogrid and extrapolated to the service life of the structure. A constant load is applied to a geogrid sample at a specified temperature (e.g., the assumed in-service temperature of the geogrids) and the elongation over time is measured. Some geogrid manufacturers now have creep test data that extend more than one to two decades. It is generally accepted to extrapolate creep data by one order of magnitude for HDPE geogrids and two orders of magnitude for PET geogrids (Elias et al., 2001). Thus, geogrid creep tests at the in-service temperature can be used to predict geogrid creep after more than 200 years of service.

Accelerated creep tests conducted at elevated temperatures allow geogrid creep to be inferred for an additional order of magnitude using time-temperature superposition principles (Wrigley, 1987; GGI-GG4(a),(b); GRI-GS10). Deformation versus log time curves from creep tests performed at elevated temperatures tests at up to 60°C (140°F) may be overlain upon the creep curves at the in-service temperature with an offset in the log-time direction to construct a continuous creep curve. Using this technique, creep reduction factors for some geogrids can be estimated for time periods in excess of 500 years.

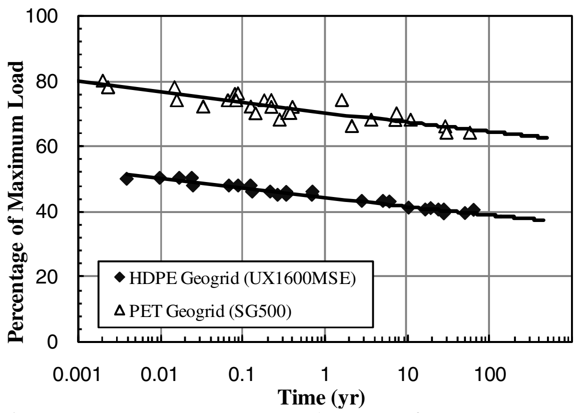

Figure 1. Stress-Rupture Test Results at a Reference Temperature of 20°C for an HDPE and a PET geogrid.

Published creep reduction factors for geogrid, such as those proposed by Elias et al. (2001) (Table 2), are considered applicable to a design service life of up to about 100 years. While a service life for an MSE wall on the order of 75 to 100 years is typical for many applications, a longer service life may be needed when an MSE wall is constructed adjacent to a landfill that has an operating life that exceeds 100 years. Product-specific creep reduction factors for longer time periods can be obtained by extrapolating data from geogrid manufacturers (Table 2). It is noted that creep tests are currently performed with geogrids clamped at both ends and unconfined between clamps. This method of testing tends to over predict creep strains as compared to the actual creep strains anticipated when geogrids are confined in soil.

Table 2. Creep Reduction Factors for Geogrid.

Polymer Type	Design Service Life (years)	Reduction Factor, RD_{CR}
HDPE	100	2.6-5.0[1]
	100	2.57[2]
	200	2.62[2]
	500	2.69[2]
PET	100	1.6-2.5[1]
	100	1.61[3]
	200	1.64[3]
	500	1.68[3]

Notes: [1]Elais et al. (2001) default value.
[2]Provided by manufacturer for UX1600MSE.
[3] Provided by manufacturer for SG500.

The long term creep reduction factors were evaluated for an HDPE geogrid (UX1600MSE) and a PET geogrid (SG500). Data from creep tests on the HDPE geogrid (Anderson, 2006), at temperatures ranging from 20°C to 40°C and time shifted to a reference temperature of 20°C are presented in Figure 1. In addition, data from creep tests on the PET geogrid at temperatures ranging from 20°C to 60°C and time shifted to a reference temperature of 20°C are presented in Figure 1. The creep reduction factors were back-calculated from Figure 1 for service lives of 100, 200, and 500 years as presented in Table 2.

As evident from Table 2, HDPE geogrids are more susceptible to creep rupture than PET geogrids. However, creep of geogrids occurs slowly over a long period of time and creep rupture of HDPE geogrids requires relatively large strains [e.g., 15 to 20% (Wrigley, 1987)] in the geogrids. The creep reduction factors increase only slightly when extending the design life from 100 years to 500 years (5% increase for HDPE geogrids and 4% increase for PET geogrids). Periodic monitoring of the facing of MSE walls constructed with geogrids for outward movements provides one means of identifying potential creep problems well in advance of creep rupture.

3.3 *Long-Term Degradation*

Polymers consist of long chains of carbon atoms, with various branches and side groups. The structure of the polymer can be attacked by oxidation promoted thermally, catalytically, by ultraviolet light, by other forms of chemical attack including hydrolysis, by the combined effect of chemicals and mechanical load, or by microorganisms (Elias, 2000). As results of molecular-chain scission, the molecular weight and tensile properties of the geogrids are reduced. Additives and stabilizers are often added to improve the resistance of the polymer to degradation. However, the additives and stabilizers themselves can leach or degrade. The predominant degradation mechanism(s) is polymer specific. Considering that reinforcement geogrids, once installed, are protected from high temperatures and ultraviolet light, the primary degradation mechanism for HDPE geogrids is oxidation and the primary degradation mechanism for PET geogrids is hydrolysis.

3.3.1 *HDPE Geogrids*

Oxidation of HDPE geogrids is caused when the material reacts with oxygen, causing a polymeric reaction that reduces the length of the HDPE polymer chain. Oxidation reactions are initiated by heat, ultraviolet radiation, mechanical stress or other mechanisms and proceed slowly throughout the service life of HDPE geogrids. The rate of oxidation is temperature dependent, with lower oxidation rates occurring at lower temperatures (Hsuan and Koerner, 1998; Koerner and Hsuan, 2002; Rowe and Sangam, 2002). Oxidation can be accelerated by the presence of high levels of soluble transition metals (e.g., iron, manganese, copper, cobalt, and chromium) in the soil (Elias et al., 1997). Burial or submersion of HDPE geogrids can diminish the rate of oxidation by limiting the exposure of the geogrids to oxygen and isolating the geogrids from high temperatures and ultraviolet radiation. Antioxidants are added to HDPE geogrids to prevent polymer degradation during processing and the initial stage of the service life.

Given that the projected service life of geosynthetics is typically many hundreds of years, measuring the actual service life under site-specific field conditions has not been possible. Therefore, laboratory-accelerated aging tests using elevated temperatures are used to assess the service life of geosynthetics (Hsuan and Koerner, 1998). The service life of the geosynthetics at normal ambient temperature can be estimated using the relationship between chemical reaction rate and temperature expressed by the Arrhenius equation (Hsuan and Koerner, 1998).

The long-term degradation of HDPE geogrids can be inferred from studies on the long-term degradation of HDPE geomembranes. Hsuan and Koerner (1998) studied the degradation process of HDPE geomembranes and observed that the chemical aging process of HDPE appears to proceed in three relatively distinct stages: (A) depletion time of antioxidants; (B) induction time to the onset of measurable material degradation; and (C) time to reach a specified reduction in the value of a significant engineering property, e.g., elongation, strength, modulus. During the first stage, antioxidants are depleted due to chemical reactions with the oxygen diffusing into the geomembrane and the physical loss of the antioxidants. Oxidation progresses extremely slow at the beginning of the second stage, with negligible degradation during the induction stage. As oxidation continues, however, a critical point in the reaction is reached and the reaction rate significantly accelerates, marking the end of the induction stage. During the third stage, oxidation causes a reduction in the molecular weight of the polymer and a decrease in tensile stress and strain at break. Tensile modulus and tensile stress and strain at yield also decrease, but to a lesser extent (Koerner and Hsuan, 2002). Eventually the HDPE material becomes brittle to an extent that it has reached the end of its service life. Koerner and Hsuan (2002) selected this point as the 50% reduction in a specific design property, such as tensile stress at break. They note that even with this reduction in design property, the material can still function, albeit at a decreased performance level. By summing their estimated duration of each stage of aging (200 years to deplete antioxidants, 20 years for onset of measurable degradation, and 750 years for 50% reduction of tensile strength at break), they concluded that the overall service life of HDPE geomembranes at 20°C is on the order of 1,000 years.

A recent study by Hsuan and Li (2005) found that the expected time for depletion of antioxidants (Stage A) in two HDPE geogrids with different additives was approximately 120 and 170 years at 20°C (68°F). Based on the rate of antioxidant loss, the former geogrid appeared to have an antioxidant package that was similar to that for HDPE pipes and the latter geogrid appeared to have an antioxidant package that was similar to that for HDPE geomembranes. It may take another 20 years after antioxidant depletion for polymer degradation to be observed in HDPE geogrids (Stage B). After this time, HDPE geogrids will begin to exhibit strength loss due to oxidation. For HDPE geogrids presently available, a degradation reduction factor, RF_D, of 1.1 is typically used for a 100-year service life at an in-place temperature of 20°C (Elias, 2000). Considering the results of the Hsuan and Li (2005) study, this degradation reduction factor may actually be applicable to a 140 to 190-year service life. After this time the reduction factor would increase in proportion to the loss of geogrid strength due to oxidation. If the half life of HDPE geogrids is similar to that for HDPE geomembranes (750 years after the end of Stage B for 50% reduction of tensile strength at break), then the degradation reduction factor for HDPE geogrids would be approximately 2.0 and the tensile strength would be about half the original strength after approximately 890 to 940 years of service at an in-place temperature of 20°C (68°F). Conservatively assuming that the rate of strength loss over time for Stage C is a linear function (rather than an exponential function), with a degradation reduction factor of $RF_D = 1.1$ at 140 to 190 years and $RF_D = 2.0$ at 890 to 940 years, the calculated RF_D at 500 years is 1.5.

3.3.2 *Polyester (PET) Geogrids*

Hydrolysis is the reverse of the reaction that forms PET in the presence of water, which can cause decrease in molecular weight leading to decrease in strength. This reaction is more rapid in alkaline environments with pH > 9, in highly acidic environments with pH < 3, and at higher temperatures. Because of this, PET should not be used in these environments without product-specific test data to document suitability (Elias, 2000).

The rate of hydrolysis is primarily affected by the concentration of carboxyl end groups (CEGs) in the PET chain. PET products with low concentrations of CEGs have a higher density and are less susceptible to strength loss due to hydrolytic degradation than PET products with high concentrations of CEGs (Elias et al., 1998). Stabilizers are used in manufacturing PET geogrids to impede hydrolysis by converting the CEGs to another compound. For hydrolysis to occur in the in-service environment as modeled in immersion tests, the soil would have to either be saturated or contain sufficient water to maintain high humidity throughout the service life of the geogrid. This condition is not expected to occur in MSE walls around landfills because the embankments are usually constructed above the ground surface (and therefore do not typically encounter groundwater in the reinforced zone), and backfill material used in constructing the wall is typically specified to be freely draining material that does not hold large amounts of moisture. Such measures reduce the potential for hydrolysis.

Naughton and Kempton (2006) reported data from testing of PET reinforcement exhumed from a test embankment and indicated no reduction in strength after 28 years in service. In their discussion, Naughton and Kempton argued that creep generally governs the long-term design strength of PET reinforcement, while degradation due to hydrolysis is not significant in most cases.

For coated PET geogrids, a degradation reduction factor, RF_D, of 1.15 is typically used for a 100-year service life at a temperature of 20°C and pH of 5 to 8 (Elias, 2000). For pH of 3 to 5 or 8 to 9, a higher reduction factor of $RF_D = 1.3$ is used. Based on immersion tests on SG500, a degradation reduction factor of $RF_D = 1.1$ is appropriate for a 100-year service life at a temperature of 20°C. Risseeuw and Schmidt (1990) reviewed published data on hydrolysis of high tenacity PET yarns and reported a representative curve for time-dependant loss of strength due to hydrolysis. Using their curve, degradation reduction factors (RF_D) of 1.15 and 1.3 are appropriate to design PET reinforcement for 200-year and 500-year service life, respectively, at an in-place temperature of 20°C.

4 ALLOWABLE STRENGTH OF GEOGRIDS

The strength reduction factors for HDPE and PET geogrids presented in Sections 3.1 to 3.3 and the resulting overall reduction factors calculated using Equation 1 are summarized in Table 3. Interestingly, the overall reduction factors calculated for specific HDPE and PET products at service lives up to 500 years fall within the range of reduction factors for geogrids proposed by Elias et al. (2001) for a 100-year service life.

Table 3. Strength Reduction Factors for Geogrid.

Geogrid	Design Service Life (years)	Installation Damage Red. Factor RD_{ID}	Creep Red. Factor RD_{CR}	Degradation Red. Factor RD_D	Overall Red. Factor RF
HDPE Uniaxial Geogrid	100	1.1-1.45[1]	2.65-5.0[1]	1.1[1]	3.2-8.0
	100	1.12[2]	2.57[2]	1.1[2]	3.2
	200	1.12[2]	2.62[2]	1.1[2]	3.2
	500	1.12[2]	2.69[2]	1.5[2]	4.5
PVC Coated PET Geogrid	100	1.1-1.85[1]	1.6-2.5[1]	1.15-1.3[1]	2.0-6.0
	100	1.29[3]	1.61[3]	1.1[3]	2.3
	200	1.29[3]	1.64[3]	1.15[4]	2.4
	500	1.29[3]	1.68[3]	1.3[4]	2.8
Acrylic Coated PET Geogrid	100	1.2-2.05[1]	1.6-2.5[1]	1.15-1.3[1]	2.2-6.7[1]

Notes: [1] Elias et al. (2001)
[2] For UX1600MSE
[3] For SG500.
[4] Durability reduction factor for PET (Risseeuw and Schmidt, 1990).

5 SUMMARY AND CONCUSIONS

Durability of geogrid reinforcement is a function of installation damage, creep, and material degradation. Reduction factors are used to assess the effect of each of these factors on the long-term tensile strength of geogrid reinforcement. Installation damage occurs during construction of an MSE wall is and therefore is not a function of the design service life. Degradation and creep reduction factors increase with increase in the design service life of the MSE wall. Testing at elevated temperatures can be used to determine the creep and degradation reduction factors of geogrids designed for service lives in excess of 100 years. Two examples were presented for calculating the overall reduction factors for HDPE and PET geogrids for design service lives ranging from 100 to 500 years.

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