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Reliability-based analysis of combined installation damage and creep for the tensile rupture limit state of geogrid reinforcement in Japan

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Abstract

The paper uses statistical data for the prediction of installation damage and creep-reduced strength collected by the writers in earlier investigations to estimate the probability of failure of tensile rupture of geogrid reinforcement products. The original data were compiled from Public Works Research Center (PWRC) geogrid product certification reports issued in Japan. The paper develops the formulation for the ultimate tensile rupture limit state equation and links it to allowable stress design (ASD) practice currently used in Japan and reliability theory-based load and resistance factor design (LRFD) used in North America. The paper shows that variability in the prediction of creep-reduced strength is largely captured by the inherent variability in strength of the materials at the time of manufacture. Combined variability due to creep and installation damage is typically dominated by variability in the prediction of strength after installation damage. Where this is not the case the combined variability is very low (less than 5%). The variability in the estimate of strength reduction due to combined installation damage and creep is demonstrated to be less than the variability in the estimates of reinforcement load even for the case of a load model judged to give relatively accurate load predictions. For poorer load models the under-prediction of reinforcement loads provides an additional margin of safety. The paper provides a framework for future rigorous reliability theory-based LRFD calibration for the ultimate tensile rupture of geogrid reinforcement in reinforced soil applications in Japan and elsewhere, and provides the necessary bias statistics for the resistance side in the ultimate tensile rupture limit state equation.

Keywords: Geogrid; Installation damage; Creep; Reliability; Load and resistance factor design; LRFD; Factor of safety; Tensile rupture; Limit state

1. Introduction

An allowable stress design (ASD) approach is currently used in Japan to calculate the long-term design strength of geosynthetic reinforcement layers in reinforced soil walls, slopes and embankments (Public Works Research Center – PWRC, 2013). The design tensile load is calculated as $T_{des} = FT_{max}$ where the maximum tensile load in a layer (T_{max}) is multiplied by a minimum specified factor of safety (F) for each limit state (e.g. $F=1$ and 1.5 for tensile rupture in walls and embankments, respectively, and $F=2$ for pullout). The design tensile

Abbreviations: AASHTO, American Association of State Highway and Transportation Officials (USA); ASD, allowable stress design; ASTM, American Society for Testing and Materials (USA); COV, coefficient of variation (=standard deviation/mean); HDPE, high-density polyethylene; PWRC, Public Works Research Center (Japan); LRFD, load and resistance factor design; PET, polyester; POM, polyoxymethylene; PP, polypropylene

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load is assumed to act for the life of the structure and cannot exceed the long-term allowable strength of the reinforcement (T_{al}). Hence, in ASD practice the ultimate tensile rupture limit state of a reinforcement layer is

$$T_{al} \geq FT_{max} \tag{1}$$

An alternative method for design against rupture in reinforced soil wall structures is the load and resistance factor design (LRFD) framework used in North America (AASHTO, 2012; CSA, 2006). The equivalent design equation for the ultimate (tensile) rupture limit state of a reinforcement layer subjected to a single load term (e.g. load due to soil self-weight in a reinforced soil wall application) can be expressed as

$$\varphi T_{al} \geq \gamma_Q T_{max} \tag{2}$$

Here φ is the resistance factor and γ_Q is the load factor. The expectation is that design outcomes will have a probability of failure that is acceptable (i.e. small) when the inequality is satisfied. An important constraint on the factors in Eq. (2) is that $\varphi \leq 1$ and $\gamma_Q \geq 1$ to be consistent with LRFD practice.

Regardless of the design approach (ASD or LRFD), the computation of the (nominal) long-term allowable strength available at the end of design life is computed as

$$T_{al} = \frac{T_{ult}}{\mathrm{RF}} = \frac{T_{ult}}{\mathrm{RF_{CR}} \times \mathrm{RF_{ID}} \times \mathrm{RF_D} \times \mathrm{RF_J}} \tag{3}$$

Here, T_{ult} is the in-isolation ultimate tensile (reference) strength of the reinforcing geosynthetic expressed in units of force per unit width of material. RF is the product of reduction factors to account for potential strength loss over the design life of the structure due to installation damage ($\mathrm{RF_{ID}}$), creep ($\mathrm{RF_{CR}}$), chemical/biological degradation processes (i.e. durability) ($\mathrm{RF_D}$), and connections (junctions) ($\mathrm{RF_J}$).

The focus of this paper is the influence of variability in the prediction of installation damage and creep-reduced strength of geogrid reinforcement products on the probability of failure for the ultimate tensile rupture limit state. The limit state is expressed in a load and resistance factor design (LRFD) format. The data for the current study have been taken from two complementary investigations by the writers (Miyata et al., 2014; Miyata and Bathurst, 2015). They reviewed PWRC product certification reports to calculate statistical variations in the predictions of strength loss due to installation damage and creep for geogrid products used in Japan. The general approach used in this paper to estimate probability of failure of the ultimate tensile rupture limit state follows that described by Bathurst et al. (2011c). However, in this prior work, creep bias statistics were not available and bias values for installation damage were computed using data from western installation damage testing protocols which are different from the Japanese methodology (Miyata and Bathurst, 2015). Another unique feature of the current investigation is a quantitative assessment of the influence of under-estimation of the reference tensile strength (T_{ult}) of a geogrid reinforcement material on probability of failure of the tensile rupture limit state.

2. LRFD tensile rupture limit state equation incorporating variability in strength reduction contributions

The limit state equation (performance function) for the long-term tensile rupture of a reinforcement layer is expressed as

$$g = T_{al,meas} - T_{max,meas} \tag{4}$$

where $T_{al,meas}$ is a random variable representing the measured long-term tensile strength of a reinforcement layer and $T_{max,meas}$ is a random variable representing the maximum measured tensile load in the same layer. As examples, the layer could be a reinforcement layer in a geosynthetic reinforced soil wall or embankment. The probability that this limit state is less than zero, denoting failure due to long-term rupture (i.e. random variable $g < 0$), can be equated to variability in measured load and measured resistance (strength) values. In the developments to follow this variability is quantified by the mean and spread of bias values, where bias is defined as the ratio of measured value to predicted (nominal) value (Allen et al., 2005; Bathurst et al., 2008, 2011a, 2011b, 2011c; Bathurst, 2014). In this paper the following nomenclature is used for the load bias:

$$X_Q = T_{max,meas} / T_{max} \tag{5}$$

In the context of geotechnical soil-structure design, the magnitude of load bias values will depend on model accuracy (the intrinsic accuracy of the deterministic theoretical, semi-empirical or empirical model representing the mechanics of the limit state under investigation), random variation in input parameter values, spatial variation in input values, quality of data and, consistency in interpretation of data when data are gathered from multiple sources, which is the typical case (Allen et al., 2005).

The resistance bias is expressed as

$$X_R = T_{al,meas} / T_{al} \tag{6}$$

Here $T_{al,meas}$ is measured tensile rupture strength and T_{al} is the predicted value using Eq. (3).

In the context of reinforced soil structures, resistance bias is a measure of the variability of actual available strength with respect to the nominal value used in the limit state design equation (i.e. Eqs. (1) and (2)).

Substituting bias terms into Eq. (4) gives

$$g = T_{al} X_R - T_{max} X_Q \tag{7}$$

An important condition to allow this substitution to be made is that bias ratios and predicted (nominal) values in the denominator are independent (uncorrelated) (e.g. Bathurst et al., 2008, 2011a; Bathurst, 2014). Strategies to remove hidden dependences (correlations) include assigning different load or resistance factors to different ranges of bias values or to modify the underlying load or resistance model to ensure that bias values do not vary with magnitude of the nominal value to an acceptable significance level (Bathurst et al., 2008, 2012b; Huang and Bathurst, 2009).