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## ABSTRACT

Geosynthetic reinforced soil walls have been widely used for earth retention and stabilization in many geotechnical applications. In the traditional design of geosynthetic reinforced soil walls, Allowable Stress Design (ASD) is used to address the uncertainties. However, it cannot explicitly consider the uncertainties in a systematic way in the design process; especially geotechnical uncertainties are typically at high levels and problem-specific. Traditional methods usually result in over-conservativeness, inconsistence, and empiricism in the design practice. Recently there has been a trend of the application of reliability methods for design of geosynthetic reinforced soil walls to explicitly address uncertainties in the design process and account for the actual safety and reliability level of a given design. In this paper, a series of reliability analyses of geosynthetic reinforced soil walls are performed, results from which can provide a useful decision making tool for selection of suitable design of geosynthetic reinforced soil walls based on target reliability levels. A case study is presented to demonstrate the significance of the proposed framework.

## INTRODUCTION

Geosynthetic reinforced earth structures are implemented in geotechnical engineering projects all around the world due to their internally supported systems and their ductile performance against various loading and foundation deformation. The "geosynthetics" is a generic term that includes most flexible polymeric materials in geotechnical engineering, such as geotextiles, geogrids, geomembranes, geofoam and geocells (Elias et al. 2001). This type of structures has been increasingly used for many geotechnical applications such as highway mechanical stabilized earth walls, bridge abutments, ramps, overpasses, column-supported embankment, and roadway subgrade stabilization (Allen et al. 2002; Sayed et al. 2008; Huang et al. 2011; Wu et al. 2013; Liu 2016). While geosynthetic reinforced soil walls are widely employed in geotechnical engineering, the performance prediction from a model for geosynthetic reinforced soil wall design can be highly uncertain because of the difficulties in accurately determining geotechnical and loading parameters in the design. Failure to consider these uncertainties could lead to either expensive over-design or under-design, which may prolong the construction period and fail to meet the performance requirements.

In the traditional design of geosynthetic reinforced soil walls, Allowable Stress Design (ASD) is used to address the uncertainties, which adopts an experienced calibrated factor of safety in the design process. However, the deterministic method relies significantly on engineering judgment and does not explicitly considered uncertainties; especially the geotechnical uncertainties are typically at high level and site-specific. ASD method usually results in over-conservativeness, inconsistence, and empiricism in the design process. In recent years, reliability-based methods have been shown as an effective approach for design of geosynthetic reinforced soil structures under various failure modes and loading conditions using probabilistic methods (Sayed et al. 2008; Yang et al. 2010; Miyata and Bathurst 2012; Basha and Babu 2014; Chen et al. 2016). In this paper, the effects of uncertainties associated with geotechnical and loading parameters on the performance of geosynthetic reinforced retaining walls are evaluated using the advanced reliability method for assessing failure probabilities under various failure modes. This reliability approach accounts for the stochastic nature of geotechnical parameters and provides useful information on the level of design performance under uncertainty. A case study for geosynthetic reinforced soil walls is presented to demonstrate the effectiveness of the proposed framework. The proposed reliability approach provides a useful tool for the engineer to make a more informed design decision based on the target reliability levels.

## DETERMINISTIC MODEL OF GEOSYNTHETIC REINFORCED SOIL WALLS

There are mainly two types of stability requirements for the deterministic analysis of geosynthetic reinforced soil walls, including the external stability and internal stability. External stability concerns about the stability of the entire rereinforced soil walls, including the checking for the possible failure modes such as sliding, overturning/capsizing, and bearing capacity failures. The internal stability concerns about the stability of the reinforced materials, including the checking for the possible failure modes due to pullout and rupture. The limit state function $g_i(X)$ can be derived to evaluate the performance of geosynthetic reinforced retaining walls against each failure modes for external and internal stability. These limit functions are for the design of geosynthetic reinforced soil walls in uniform granular soil with zero effective cohesion. They are summarized in the Eq. (1) to Eq. (5) based on the resisting forces and driving forces for each failure modes (Sayed et al. 2008; Das 2014; Chen et al. 2016).

### Sliding Failure

Sliding occurs when the friction between the subgrade and the retaining wall is not sufficient enough to compensate for the external load, which causes the retaining wall to slide. The limit state function against the sliding failure is represented as:

$$g_1(X) = \mu L(\gamma H + q_0) - k_a(\gamma H + 2q_0)H/2 \tag{1}$$

where μ is the coefficient of friction, L represents the reinforced length of the geosynthetic strip, the unit weights of the backfill, reinforced fill and foundation soil are assumed to be the same value and represented by γ, H is the height of the reinforced soil wall, $q_0$ represents the surcharge for the backfill, $k_a$ represents the active coefficient of the earth pressure for the reinforcement fill based on the Rankine's theory, and $N_\gamma$ is the bearing capacity factor.

**Overturning Failure**

Overturning or capsizing occurs when the soil pressures behind the wall are great enough to offset the retaining wall based on the wall toe (Chen et al. 2016). The limit state function for overturning is represented as:

$$g_2(X) = \frac{L^2}{2}(\gamma H + q_0) - \left(\frac{\gamma H}{3} + q_0\right)k_a\frac{H^2}{2} \tag{2}$$

**Bearing Capacity Failure**

Bearing capacity failure occurs when the subgrade soil beneath the reinforced soil wall fails under shear due to overloading or insufficiently constructed subgrades (Das 2014). The limit state function for bearing capacity is represented as:

$$g_3(X) = 0.5\gamma L N_\gamma - (\gamma H + q_0) \tag{3}$$

**Pullout Failure**

Pullout or uplift failure occurs when the reinforced materials do not have sufficient length or do not contain the proper amount of friction, which causes failure by surface fractures. The limit state function for pullout/anti-uplift is represented as:

$$g_4(X) = 2\tan\delta(\gamma z_i + q_0)L - (\sigma_{vi}k_a V_i) \tag{4}$$

where δ is the friction angle for soil reinforcement interface, which is equal to 2/3 of the soil friction angle φ (Das 2014), $z_i$ represents the depth of the *i*th reinforcement level from the top of the wall, $\sigma_{vi}$ is the vertical soil stress at the *i*th reinforcement level, and $V_i$ is the effective height of the soil resisted by the *i*th reinforcement strip.

### Rupture Failure

Rupturing occurs when the strength of the reinforcement material is not enough for the developed tensile stress, which causes failure by surface fractures and the reinforcement strips to be torn apart (Chen et al. 2016). The limit state function for rupture is represented as:

$$g_5(X) = T - (\sigma_{vi} k_a V_i) \tag{5}$$

where T is the tensile strength of the reinforcement strip.

## EXAMPLE APPLICATION

A design example is presented for the reliability analysis of geosynthetic reinforced soil walls. In this paper, the first order reliability method (FORM) is used for the reliability analysis, which is an effective method and provides accurate failure probability results comparable to Monte Carlo simulations for either explicit or implicit limit state functions (Ang and Tang 1984; Phoon 2004; Low and Tang 2007). The geosynthetic reinforced retaining wall in the granular soil used in this analysis is shown schematically in Figure 1. The height of reinforced soil wall (H) varies from 6 to 10 m and the reinforced length of the geosynthetic strip (L) varies from 5 to 10 m. The backfill, foundation, and reinforced soil are assumed with the same geotechnical properties with zero cohesion, and the mean values for friction angle and unit weight are $\varphi = 35$, and $\gamma = 18$ kN/m$^3$ respectively. The tensile strength of the reinforcement (T) has a mean value of 50 kN/m$^2$. The vertical spacing between the reinforcement level is set as 0.5 m. Surcharge is a uniform load applied along the horizontal surface of the backfill with a mean value of 20 kPa.

In this analysis, four parameters are modeled as random variables including geotechnical and loading parameters. The mean value and coefficient of variations (COV) for these parameters are summarized in Table 1. The COV for the friction angle ($\varphi$) of soils is assumed as 10% (Phoon and Kulhawy 1999). The COV for unit weight ($\gamma$) of soils is assumed as 7% (Goh and Kulhawy 2005; Zevgolis et al. 2010). The COV for the tensile strength of the reinforcement (T) is assumed as 10% considering the chemical and biological degradation, installation damage and creep effects (Sayed et al. 2008) and the COV of surcharge ($q_0$) applied at the surface of the backfill is assumed as 15%. Based on the statistics of uncertain parameters presented in Table 1, FORM is used as a means to compute the failure probability for a given set of combination of H and L. Results from the reliability analysis can be observed in Figure 2 to Figure 6 for each of the five failure modes, including sliding, overturning, bearing capacity, pullout and rupture. Each of these figures presents the probability of failure for each failure mode versus two parameters in the design, the height of the retaining wall H and the length of the reinforcement strip L. In this analysis, the height of the wall varies from 6 to 10 m with 1 m increment and reinforcement length L varies from 5 to 10 m with 1 m increment.

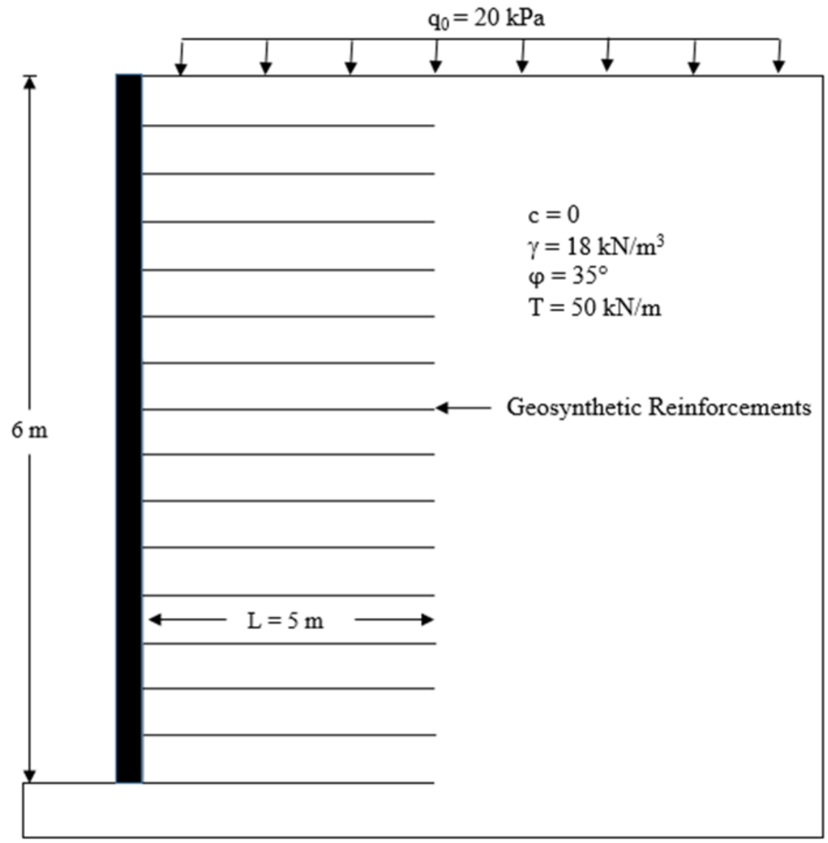


**Figure 1. Schematic of Geotextile Reinforced Soil Wall**

**Table 1. Statistics of uncertain parameters**

| Parameter | Mean | COV (%) |
|---|---|---|
| Friction Angle (φ) | 35° | 10 |
| Unit Weight (γ) | 18 kN/m$^3$ | 7 |
| Tensile Strength of Reinforcement (T) | 50 kN/m | 10 |
| Surcharge ($q_0$) | 20 kPa | 15 |

Figure 2 depicts the relationship of retaining wall height H and reinforcement length L versus the probability of failure for sliding. As can be observed, the failure probability decreases with lessening wall heights and increasing reinforcement lengths. The greater reinforcement lengths and reduced wall heights produce a higher level of stability and thus lower the probability of failure. The probability of failure for overturning or capsizing can be viewed in Figure 3. As can be observed, the failure probability for the overturning generally decreases with increasing reinforcement lengths and decreasing retaining wall heights. However, the effect of increasing the reinforcement length has the most significant improvement for the wall height of 10 m. With the deceasing wall height, the effect becomes less significant. For the height of 6 m, the effect of increasing the reinforcement length is negligible since the failure probability is already very small. Also it can be observed, for a given height, when the length of the reinforcement reaches certain length (e.g., 8 m for H = 10 m), the failure probability somewhat stabilizes, which also indicates the effects of increasing too much reinforcement length has very limited effects on the failure probability. Therefore, any design based on reliability analysis could limit the length of the reinforcement strip to save on material costs.

Figure 4 represents the probability of failure for bearing capacity. The failure probability decreases with the increased reinforcement lengths and decreased wall heights. This is due to the fact that increased reinforcement length strengthens the soil, making it less prone to bearing capacity failure. Greater height also increases the loads acting on bearing soil, making a structure more prone to bearing capacity failure.

Pullout or anti-uplift failure depends on the effective height of the soil resisted by the reinforcement layer ($V_i$) which is set as 0.5 m based on the vertical spacing between reinforcement levels. It should be noted that for the given combination of wall height and reinforcement length, the failure probability is calculated for all the reinforcement levels and the maximum failure probability is presented in Figure 5. As can be observed in Figure 5, for the same reinforcement length, the greater height indicates more failure probability. However, for the same wall height, failure probabilities all reach maximum when the reinforcement length L = 6 m. For the failure probability against rupture, since the reinforcement length is not considered in the limit state equation for rupture failure, the failure probability is consistent with different reinforcement lengths. In contrast, as the height of the reinforced soil wall is reduced, the probability of rupture decreases. The soil friction angle has significant effects on the rupture failure probabilities. Reducing the soil friction angle can significantly increase the probability for the rupture failure while increasing the soil friction angle can help stabilize against the rupture.

By comparison of the failure probabilities for different failure modes, it can be found that the sliding controls the external stability requirements while the rupture controls the internal stability requirements. The reduced wall height and increased reinforcement length generally indicate a more safety with smaller failure probability for every failure modes other than rupture. Based on

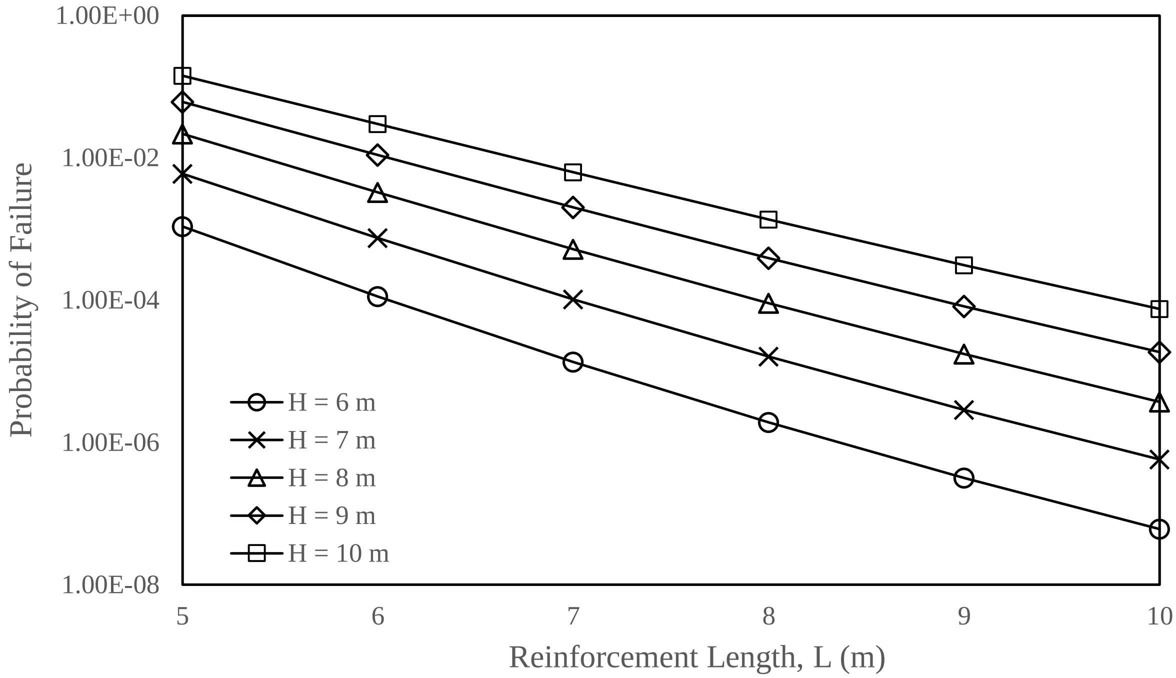


**Figure 2. Probability of failure versus differing wall heights and reinforcement lengths for sliding failure**

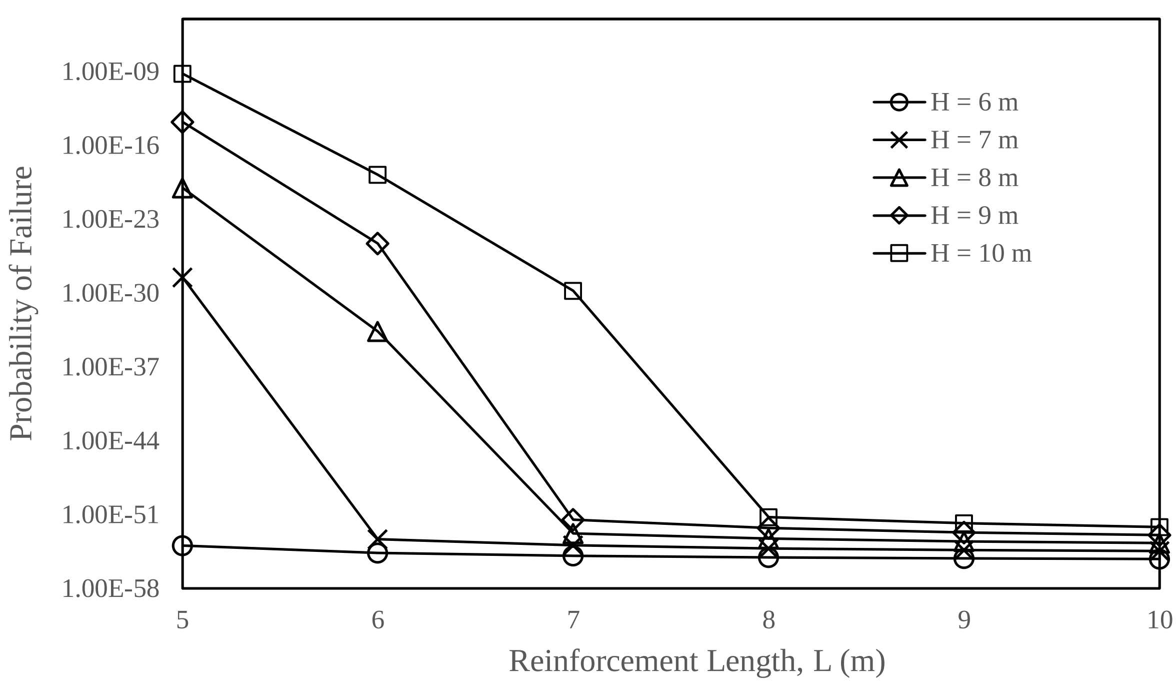


**Figure 3. Probability of failure versus differing wall heights and reinforcement lengths for overturning failure**

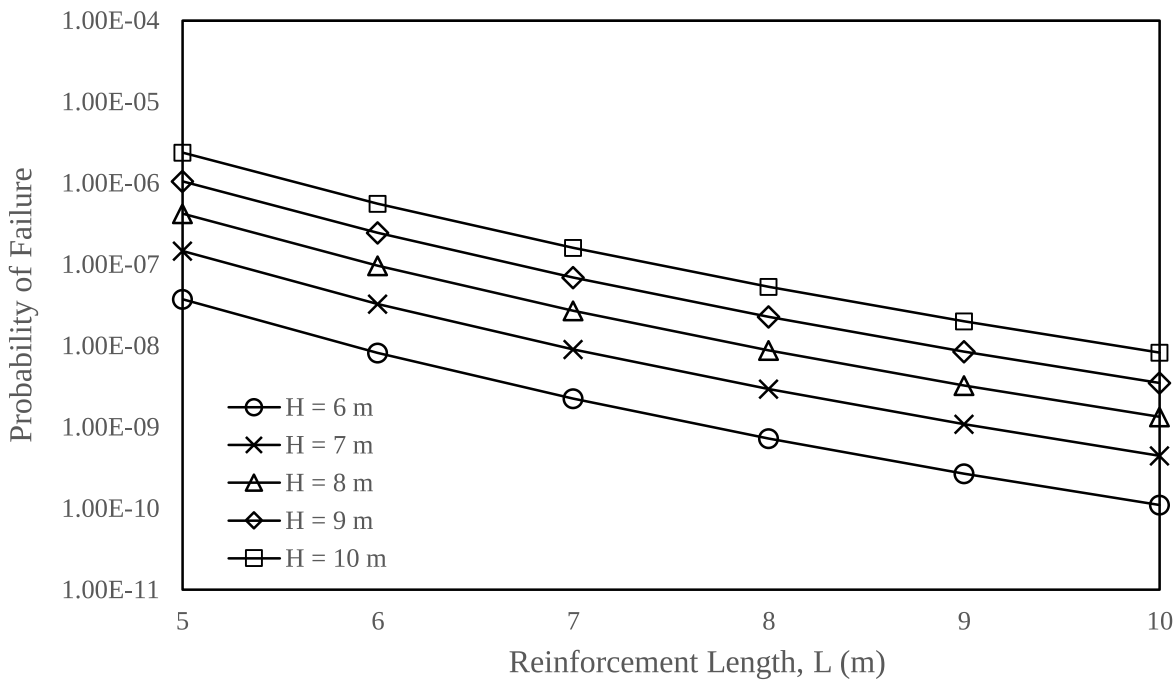


**Figure 4. Probability of failure versus differing wall heights and reinforcement lengths for bearing capacity failure**

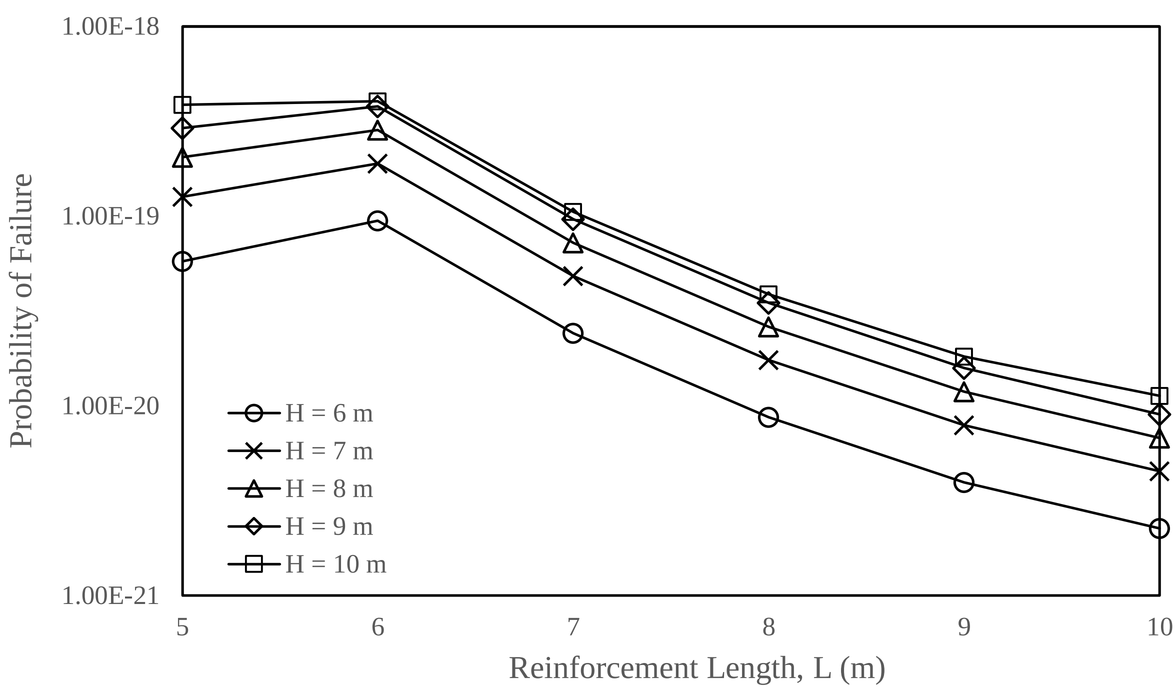


**Figure 5. Probability of failure versus differing wall heights and reinforcement lengths for pullout failure**

the results from this paper, a more informed design decision can be made by incorporating the target reliability requirements.

## CONCLUSION

Uncertainties in the geotechnical and loading parameters have significant effects on the design of geosynthetic reinforced soil walls. In this paper, a series of reliability analyses are performed for geosynthetic reinforced soil wall considering various uncertainties in the design process. An example application is conducted for a geosynthetic reinforced retaining wall with granular fills to demonstrate the efficiency and effectiveness of the proposed reliability method considering various internal and external failure modes. Results show that the probability of failure decreases with reduced wall heights and increased reinforcement lengths for every scenario other than rupture. This is due to the fact that more stability is induced with greater reinforcement length throughout the structure and less load imposed from the reinforced backfill. The results from this study can be helpful for the engineers to make a more informed design decision based on target reliability requirements.

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