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HEIGHT RELIABILITY-BASED ANALYSIS OF WOVEN BAMBOO MAT REINFORCED MECHANICALLY STABILIZED EARTH WALL IN TEMPORARY RAILWAY EMBANKMENT

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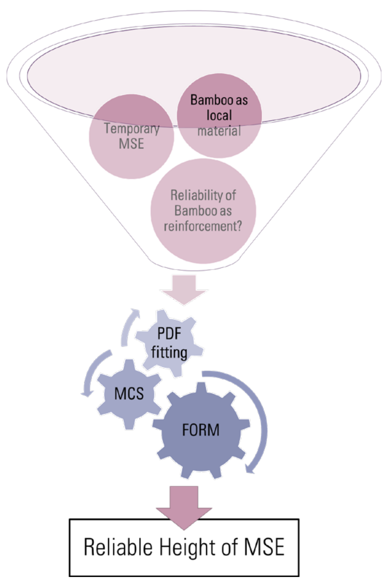
Graphical abstract



Abstract

Railway is a main transportation to sustain the fast-growing population and economy in many countries. Developing railway infrastructures, such as additional tracks, without disturbing daily operations often requires temporary mechanically stabilized earth as embankment construction. This paper discussed woven bamboo mat (WBM) as a highly potential local material that can be used in mechanically stabilized earth construction in such condition. Considering that WBM has a wide variation in tensile strength, this study determined the reliable railway embankment height through reliability-based analysis. First-order reliability method (FORM) was adopted to estimate the probability of failure (p_F). The results of FORM were compared with the results of Monte Carlo simulation (MCS). The results showed positive trends in p_F against increasing height, and the effective tensile capacity factor R negatively affected p_F. The theoretically undegradable tensile strength in the design (R = 1.00) could increase the reliable height up to 12 m when s_v = 0.2 m. Comparison between the FORM and MCS results showed that the p_F calculated by FORM conformed with those computed by MCS. This study provided some insights and opened the opportunity for further research on other potential local materials as geomechanics reinforcement.

Keywords: Breakage, local material, mechanically stabilized earth wall, reliability analysis, woven bamboo mat

1.0 INTRODUCTION

As a densely populated country, Indonesia needs reliable transportation to support its economic activity. Railway is a main transportation required by the country. It has advantages in transferring large volumes per unit square kilometers on land and has a better safety level than driving on the highway. Despite the annual positive increase of users, regulators should continuously improve services, especially infrastructure and safety [1]. Building new tracks parallel to an existing track by placing a new track adjacent to an existing track increases the capacity of railways. However, the new track is sometimes higher than the existing track, as witnessed in the Purwokerto-Kroya railway double track project in Central Java Province, Indonesia (Figure 1). During construction, the operation of the existing track was not halted. Hence, a staged construction was conducted by elevating the right embankment with a vertical inner slope. The project's vertical slope was constructed using mechanically stabilized earth (MSE) with geosynthetic reinforcement. After completing the right embankment, the left embankment was constructed on top of the existing railway while the train operation was interchanged on the right MSE reinforced embankment. Finally, the left was completed, and the right MSE inner slope was left buried. However, using geosynthetic-reinforced MSE as temporary construction was deemed inefficient and negatively impacted the environment because of its high carbon emission from manufacturing and delivery transportation.

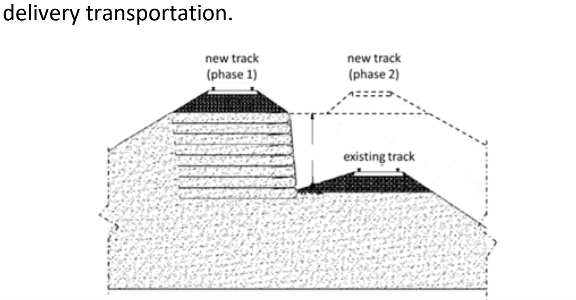


Figure 1 The construction phase of Purwokerto-Kroya double track

One method to reduce carbon emission significantly during construction is to maximize the use of local materials and resources that are energy-efficient, sustainable, and environment friendly [2,3]. Bamboo is a popular local material found worldwide, particularly in Asia, Africa, and America. Bamboo has been used for millennia in various applications, including construction, and it is proven to be a sustainable material that is environmentally and economically friendly [4,5].

In the construction sector, traditionally manufactured bamboo ranges from temporary to permanent with various forms. This paper discussed WBM as a highly potential temporary reinforcement material in MSE construction. Reference [6] concluded that substituting the geosynthetic with WBM in the Purwokerto-Kroya railway double track project would reduce the construction cost up to 38% and the carbon emission from the transportation and the manufacturing. Therefore, the utilization of bamboo for similar cases is deemed cost-efficient and environmentally friendly.

Nevertheless, considering that WBM is a natural material, one should be concerned about its wide variety of mechanical properties [7]. The uncertainty of its nature to ensure construction safety should be considered before applying it as a load-bearing material. Some questions may arise regarding its uncertain properties about how high a railway embankment can be built with WBM. Therefore, this study investigated the reliable railway embankment height, considering the wide variation in tensile strength of WBM and the possible risk of failure, through stochastic analysis.

2.0 LITERATURE REVIEW

In general, the performance of bamboo as a construction material has been examined by many researchers for decades. However, few studies characterized the mechanical properties of traditional WBM because it is usually used as a non-structural material, such as in lightweight walls. Reference [8] found through model footing that WBM as reinforcement in sand bed improves bearing capacity, increasing the bearing capacity up to 150% when the reinforcement was placed at a certain depth. Previous studies [6,9] also examined the performance of WBM as temporary reinforcement of MSE through pull-out test and tensile strength test. The test results showed the effectiveness of WBM as temporary reinforcement in both sandy and clayey soils. It emphasized the applicability of the reinforcement on a wide variety of soils. Deterministic analysis was also performed under the applicability of WBM as a replacement of geosynthetic in MSE construction.

In geotechnical engineering, the probabilistic method is usually applied to accommodate the uncertain nature of soil properties to address safety and reliability [10,11]. The probabilistic approach was implemented comprehensively in the geotechnical field through various technics and adaptations [11]. The extensive works to develop reliability analysis in geotechnical problems have been conducted by building spreadsheet software algorithms [11,12,13]. In MSE wall design, Reference [12] developed a reliability procedure to optimize MSE design that used geosynthetic as its primary reinforcement. However, such an approach always considers reinforcement properties as deterministic because it uses well-manufactured geosynthetic. The present study analyzed the reliable WBM MSE wall height through a stochastic approach by considering the probabilistic properties of WBM tensile strength as the controlling factor of maximum possible height. In this study, the reliability analysis adopted first-order reliability method (FORM) to estimate the p_F. This approach is essential, considering that moderately processed WBM naturally has a wide range of strength value. The possible risk of its application on railway infrastructure was also considered in providing the reliable height of MSE wall reinforced by WBM. FORM required minimal computational effort to yield P_f. Rigorous Monte Carlo simulation (MCS) was used for comparison.

3.0 RESEARCH METHOD

Data regarding the WBM were obtained from [6]. WBM was purchased from Cebongan Village, Godean District, Yogyakarta Special Province, Indonesia. The WBM stripes were taken and slivered from the inner side of *Gigantochloa apus*, with widths between 20 and 35 mm and thickness between 1.5 and 2.5 mm (Figure 2). The tensile strength tests of WBM were conducted per ASTM D 4595-09, which is the Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method. The specimen size was 200 mm × 200 mm. In this study, the tests on 32 specimens were performed using a universal testing machine with a capacity of 10 tons. The test specimens were clamped, and the loads were applied with a predetermined speed until the specimen was broken. The strain rate was 2.5 mm/min (10 ± 3%/min as required).

Figure 2 Specimen of woven bamboo mat (WBM)

3.1 FORM Procedure for Reliability-Based Design

Spreadsheet-based reliability calculation was performed to deal with the uncertain nature of the material and to measure the reliable height of WBM reinforced MSE wall. The Hasofer-Lind index and FORM were adopted to compromise the uncertainty of soil and the WBM reinforcement. The method is widely used in geotechnical engineering that deals with the uncertain behavior of geo-material and loading conditions [10,11]. References [13,14] demonstrated the method through object-oriented constrained optimization utilizing Microsoft Excel. They showed that FORM could handle various probability distributions between parameters by transforming the distribution to equivalent normal before the calculation. The procedure can accommodate different natures of probability function between contrasting materials, such as soil and reinforcement. Moreover, Reference [15] offered an easy technique to deal with correlated and uncorrelated variables. The procedure is suitable regarding the assumed uncorrelated behavior of soil strength and reinforcement tensile strength.

The applications of probability theory to the geo-mechanical analysis have stated the uncertainties in the form of a reliability index, which is expressed by Hasofer-Lind index β as [13]

$$\beta = \min_{x \in F_b} \sqrt{\left[\frac{x_i-\mu_i}{\sigma_i}\right]^T \left[\underline{R}\right]^{-1} \left[\frac{x_i-\mu_i}{\sigma_i}\right]} \quad (1)$$

where x_i is the i^{th} random variables, μ_i is the equivalent normal mean of the i^{th} random variable, σ_i is the equivalent normal standard deviation of the i^{th} random variable, R is the correlation matrix between standard normal variables, and F_b is the failure domain. The index is the minimum distance from the mean value point to the limit state surface in the area of reduced variables. The reliability index of Equation (1) was calculated using iterative optimization in Microsoft Excel. Once the index has been determined, the probability of failure p_F easily can be expressed as

$$p_F = 1 - \Phi(\beta) \quad (2)$$

where $\phi(\beta)$ is the cumulative standard normal distribution function evaluated at point β. The result of p_F depends on the probability density function (PDF) of the random variables [16]. In this paper, WBM MSE reliability analysis was considered three-variate non-correlated random variables: internal friction angle of fill material, unit weight of fill material, and tensile strength of WBM. The PDF of random variables related to filling material was considered as lognormal as suggested by [17], whereas that of the tensile strength of WBM was later determined after it had been examined using Kolmogorov-Smirnov normality test.

3.2 Stability Calculation of MSE Wall and Assumptions

MSE wall is a structure of soil reinforcement that retains lateral working loads. In design practice, the MSE wall should consider the external and internal aspects of stability. External stability analysis treats the reinforcement as homogenous stiff soil mass, evaluated according to the conventional failure mode of gravity wall comprising stability analysis on sliding, overturning, bearing capacity, and deep-seated stability. Meanwhile, internal stability analysis evaluates internal failure through a pull-out test, where the working tensile forces become larger than pull-out resistance and failure by breakage of the reinforcement due to excessive tensile forces [18].

All the analyses mentioned above are essential in the design detail of MSE wall. However, the latter is focuses on the strength of the reinforcement material, which is the most relevant analysis to evaluate WBM performance. Hence, the limit state function of the stability analysis was restricted only to the internal stability considering reinforcement breakage, and the other analysis of MSE wall was assumed to be satisfied.

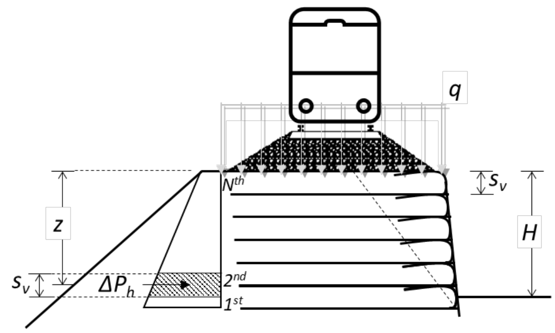


Figure 3 Design section of MSE wall for temporary railway embankment

The governing limit state equation of internal stability concerning the breakage of reinforcing material of MSE is defined by the safety factor:

$$F_b = \frac{T_a}{\Delta P_h} \quad (3)$$

where T_a is the allowable tension force per unit width of the reinforcement, and ΔP_h is the horizontal force (kN) depicted on Figure 3. The maximum value of ΔP_h occurs on the second layer of the reinforcement stack. The horizontal force follows the equation

$$\Delta P_h = K_a(\gamma z + q)s_v \quad (4)$$

where K_a is the active lateral pressure coefficient, γ is the fill unit weight, z is the distance from the crest, q is the surcharge load, and s_v is the vertical distance between layers. The surcharge load was set as a deterministic value as class I railway with a ballast thickness of 73 cm and the railway with a uniform load of 65.8 kN/m^2 [6]. When the horizontal load bore by the second layer is considered, z follows the equation

$$z = H - 0.5s_v \quad (5)$$

K_a was determined by using the Rankine equation, assuming the absence of wall friction and horizontal wall crest. For vertical wall, the coefficient of earth pressure follows the equation:

$$K_a = \tan^2(45 - \frac{\phi'}{2}) \quad (6)$$

The allowed tension force per unit width of the reinforcement, T_a was derived from the following equation:

$$T_a = \frac{T_u}{R_t} \quad (7)$$

where T_u is the ultimate tension strength per unit width of reinforcement (kN/m) and R_t is the reduction factor regarding tensile strength degradation. In the design of MSE wall using geosynthetic, R_t includes three main factors, namely, creep, durability, and installation damage [18], [20]. To simplify, R was introduced as factor of effective tensile capacity which is the inversed reduction factor for tensile strength degradation ($1/R_t$). The theoretical value of R = 1 indicates the unchanging tensile strength until the end of design life. The possible value would fall between 0 and 1. Effective tensile capacity factor R depicts the remaining tensile capacity at the end of its design life after degradation caused by the factors as mentioned earlier. Good preservation of WBM corresponds to a high value of R factor, and vice versa. However, the effective tensile capacity factor of WBM remains unclear and needs further examination in the future. Kaminski et al. [21] suggested that the main factor controlling the durability of the WBM is the treatment and the exposed environment. Nevertheless, few quantitative studies focused on the tensile strength degradation of WBM. Therefore, we suggest using the varying deterministic R values of 0.25, 0.50, 0.75, and 1.00 to accommodate the application of WBM as temporary construction in future material treatment, field installation, environmental condition, and operational duration. Further study on the tensile strength degradation of WBM and its uncertainty is warranted.

Substituting Equation (4) up to Equation (7), Equation (3) yields the following equation:

$$F_b = \frac{T_u}{\tan^2(45 - \frac{\phi'}{2})(\gamma(H - 0.5s_v) + q)s_v R_t} \quad (8)$$

Equation (8) is the explicit form of the performance function involving the tensile strength of WBM, internal friction angle, surcharge and overburden loads, reinforcement's vertical spacing, and tensile strength reduction factor. While the other parameters were kept deterministic, T_u, γ, and ϕ' were considered as random variables with specific PDF respectively denoted as x_1, x_2, and x_3. The random variables had equivalent normal mean (μ_1, μ_2, and μ_3) and equivalent normal standard deviation (σ_1, σ_2, and σ_3) with the corresponding subscript to be fit in Equation (1). The characteristics of the variables in the design are summarized in Table 1.

Table 1 Characteristic of variable in the design of MSE walls against breakage

Input Parameters	Notation	Mean	Unit	COV
Unit Weight of Backfill	γ	18	kN/m^2	0.05
Friction Angle of Backfill	ϕ'	32	°	0.10
Ultimate Tensile Strength of WBM	T_u	70	kN/m	0.24
Train and Ballast Load	q	65.8	kN/m^2	(deterministic)

3.3 FORM-Based Framework for Estimating Reliable MSE Height

The framework of reliability-based assessment on this research is presented in Figure 4. The 32 data of WBM tensile test were acquired from Reference [6] and then statistically analyzed to test the normality of the distribution to determine the most suitable PDF. In a non-normal PDF, the statistical parameters were transformed to fit Equation (1). The transformation procedures were described in detail by Low and Tang [14]. In each particular parameter value of H, s_v, and R, Excel's add-in optimization program Solver was used to minimize the cell value containing β formula by changing the values of random variables x_1 and x_2, bound by the limit state equation in Equation (7). The values that yield the minimum β were denoted as the design points of x_1*, x_2*, and x_3*. The procedure was repeated until the final designated height value was reached. In this research, the final height (H_{final}) was limited to 15 m. Iteration was performed by using the simple code in Excel's VBA. The results obtained by FORM were compared with MCS.

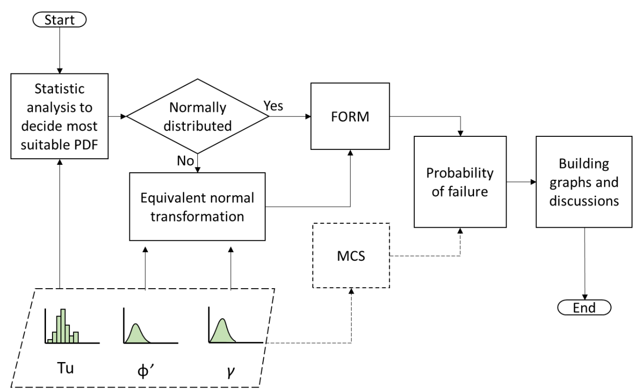


Figure 4 Framework of reliability-based assessment of WBM MSE

4.0 RESULTS AND DISCUSSION

4.1 WBM Tensile Test and Statistical Analysis

The tensile test results of 32 specimens of WBM are depicted in Figure 5. The figure shows the dispersed results of tensile strength. The data were analyzed by using the goodness-of-fit statistic of Kolmogorov-Smirnov method to test the normality. The test results are provided in Table 2, and the histogram is shown in Figure 6. The null hypothesis of normal distribution can be accepted because the computed p-value is greater than the significance level α = 0.05. Therefore, the normal distribution was chosen as the best fit PDF function for WBM tensile strength.

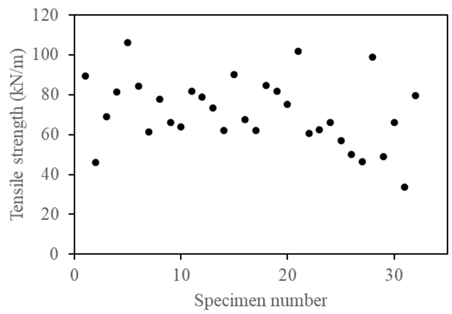


Figure 5 Plot of specimen number vs. the tensile strength [6]

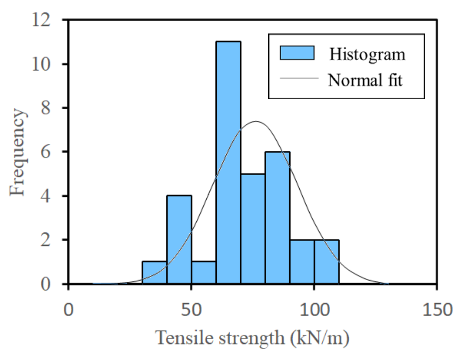


Figure 6 Histogram and normal distribution fitting

Table 2 Kolmogorov-Smirnov test results

D	0.084
P-value (Two-tailed)	0.962
α	0.05

Reference [6] performed a detailed causative study on the factors contributing to the wide variation in tensile strength of WBM. This study used the observational method to score each factor regarding ultimate tensile strength. These factors included nodes, weathering, thickness, age, and sliver integrity.

As shown in Table 3, the weathering factor was highly influential on the tensile strength with a frequency of 32.77%. Weathering is closely related to the density level of sclerenchyma tissue that could be reduced due to physical factors (i.e., sun radiation, acidity, and humidity) and biological factors (i.e., pests and molds). The existence of nodes also affects the tensile strength of bamboo mats. It is in line with the findings of [22] that the tensile strength on nodes is lower than that on the internode part.

Table 3 Frequency of ascribed factors on tensile strength (summarized from [6])

Tensile Strength Ascribing Factors	Frequency (%)
Weathering	32.77
Node	26.28
Age	18.35
Thickness	14.58
Sliver integrity	8.01

4.2 Sensitivity Analysis

The sensitivity analysis of p_F was conducted regarding the statistics of the random parameters. In general, information from the sensitivity analysis is valuable for design consideration. In the perspective of reliability analysis, the sensitivity also determines the most significant statistical components of the parameter. Consequently, a large amount of data needs to be collected to designate the best statistical inference for the most influential variables. The reliability sensitivity analysis fundamentally refers to mean and standard deviation that can be expressed by Equation (9) and Equation (10) as the changing p_F over the changing mean and standard deviation, respectively:

$$\frac{\delta p_F}{\delta \mu_i} \tag{9}$$

$$\frac{\delta p_F}{\delta \sigma_i} \tag{10}$$

The one-factor-at-a-time technique, a simple approach that involves varying one examined factor and retaining the other factors at their baseline values [23], was used in the sensitivity analysis. Any changes observed can be ascribed to the alteration of a single parameter. The baseline parameters used in the analyses are the same as those summarized in Table 1. This approach is suitable for uncorrelated parameters, as assumed in this study.

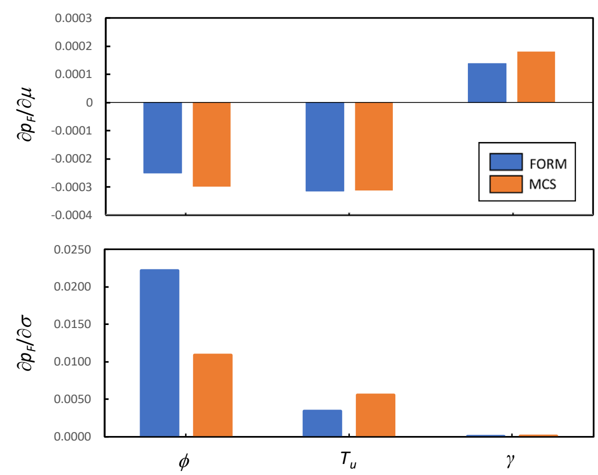


Figure 7 Comparison of reliability-based sensitivities calculated with FORM and Monte Carlo simulation (MCS) for MSE wall height H = 2.5 m, layer spacing s_v = 0.2 m, and effective tensile capacity factor R = 0.75

Figure 7 compares the sensitivity generated with FORM and MCS for a particular height and vertical distance between layers (s_v). The sensitivities were computed using FORM and MCS by addressing the analytical limit state function of Equation (7). The probability of failure p_F in the MCS was calculated as the ratio of total cases with F_b < 1.0 over the total number of runs. The minimum number of MCS runs was the number of random variables multiplied by 10 times the target p_F as per Reference [24]. Hence, the performed number of the simulation was 5.0 × 10^5 for each scenario. The comparisons between the MCS and the FORM sensitivity are shown in Figure 7 for a height and vertical distance between layers (s_v). It suggests that the FORM performed reasonably under the studied conditions. Some minor discrepancies were noticed, but overall trends were consistent for both analyses.

As shown in Figure 7, the change in the mean of internal friction angle and WBM tensile strength was negatively correlated with the p_F. It was shown by the negative value of $\partial p_F/\partial \mu$ for both parameters. This result indicates the importance of having high-strength fill material and good-quality WBM. Meanwhile, the unit weight of fill material positively correlated with the p_F because it contributes to the soil lateral pressure according to Equation (4). Although it is not as significant as material strength, utilizing lightweight fill material could be a good practice.

The change in p_F with the change in standard deviation $\partial p_F/\partial \sigma$ is depicted in Figure 7. Thus, a wide variety of the internal friction angle of the fill material could severely increase the p_F, whereas the material fill unit weight was not significant for the case. The results indicate that the p_F can be reduced by choosing homogeneous selected fill and conducting strict monitoring on compaction work. In the case of WBM, the change in standard deviation over p_F also correlated positively. Gaining a standardized WBM product is difficult, considering it is a traditionally manufactured nature-derived material. Therefore, the reliability of WBM as an alternative construction material must be evaluated, given its wide variety.

Reliability Analysis

Utilizing WBM as an alternative material for MSE wall reinforcement needs particular concern regarding the relatively high uncertainty of the tensile strength. A reliability-based analysis using FORM was conducted by involving other uncertainties from the fill material, such as friction angle and unit weight. The analysis considered a series of effective tensile capacity factor assumptions R (as described in section 2.2) and applicable values of s_v to examine the reliable height of MSE.

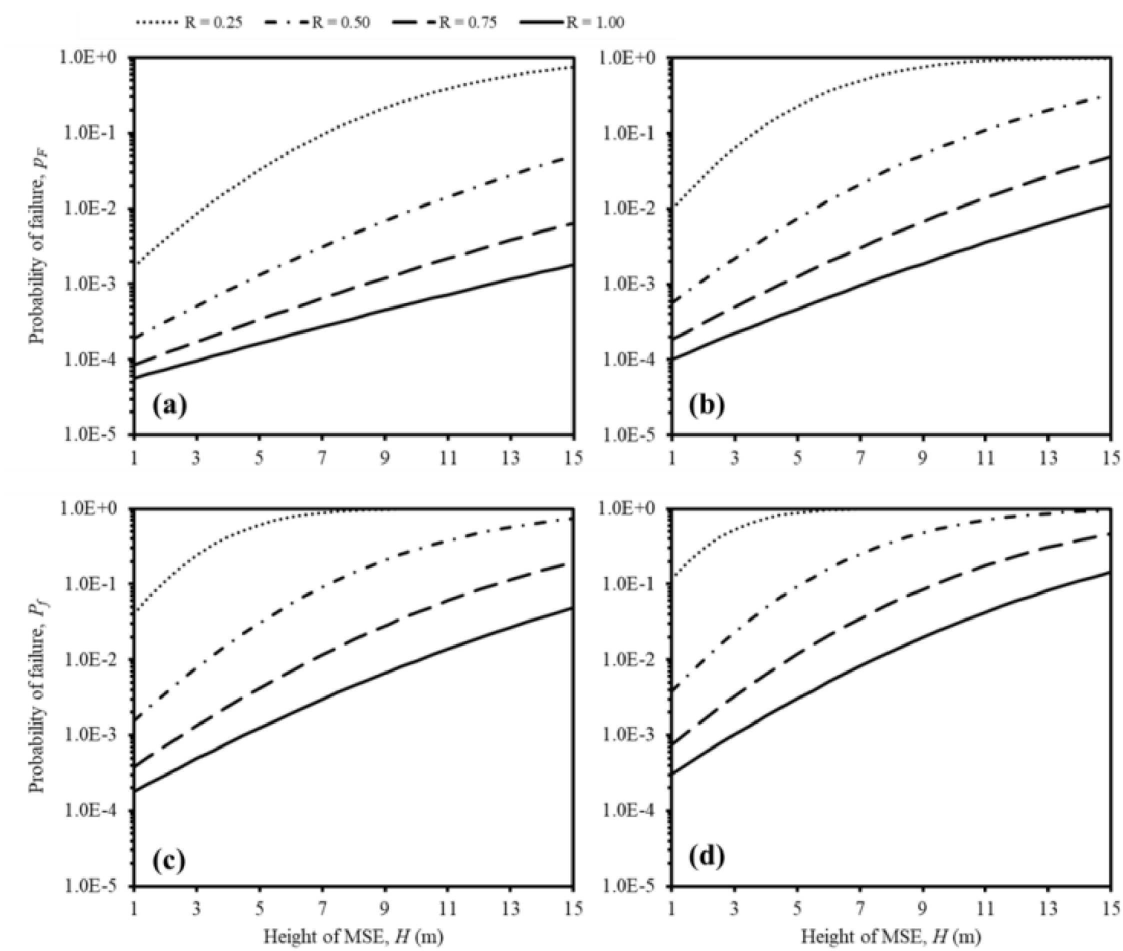


Figure 8 Plot of height of MSE, H against probability of failure, p_F. (a) s_v = 0.2 m; (b) s_v = 0.3 m; (c) s_v = 0.4 m; (d) s_v = 0.5 m.

The reliable MSE height significantly depends on the material strength as depicted in the variation of the effective tensile capacity factor, R in the analysis. If the R is 0.25, then the WBM is inapplicable in any values of s_v; if the theoretical maximum R is 1, then the reliable height can be increased up to 12 m. Therefore, good preservation on WBM could plausibly increase the reliable height of constructed MSE. Reducing s_v could also be implemented in the design to improve the reliable height. However, this procedure increases the construction cost and makes WBM less attractive than common geosynthetic.

Either Figure 8 or Table 4 can be practically used to plan the MSE wall using WBM reinforcement. For instance, if the effective tensile capacity factor R is 0.5 and s_v equal to 0.2 m, then Figure 8a can be used by taking the horizontal line from $p_F = 1.0 \times 10^{-3}$ in the ordinate. The intersection of the horizontal to line $R = 0.5$ can be projected to the abscissa to obtain the value of H_R. Alternatively, Table 4 can also be used. From both ways, the suggested reliable height of MSE would be less than 4.00 m. If the height is more than H_R, then further engineering measurement should be conducted. The measurements can either conducting preservation techniques to increase the effective tensile capacity factor R, decreasing s_v (if still possible), or combining the MSE wall reinforcement by geosynthetic at the bottom layers. Further studies about the effective preservation technique to increase effective tensile capacity at the end of the design life of WBM are essential.

Table 4 Maximum reliable height (H_R) of MSE based on $p_{Fmax} = 1.0 \times 10^{-3}$

s_v	H_R (m)			
	R = 0.25	**R = 0.50**	**R = 0.75**	**R = 1.00**
0.20	N/A	4.00	8.00	12.00
0.30	N/A	1.50	4.00	7.00
0.40	N/A	N/A	2.50	4.50
0.50	N/A	N/A	1.00	2.50

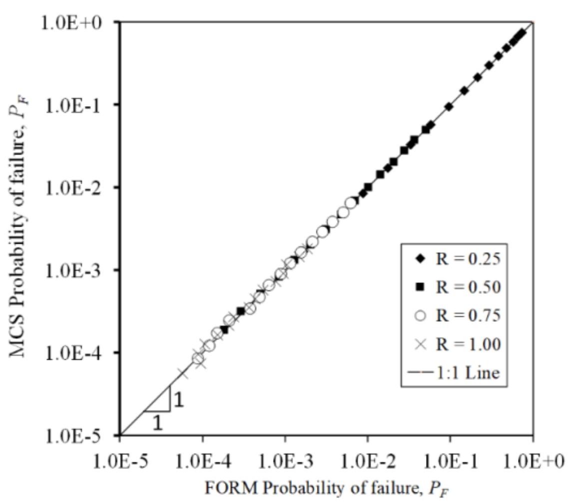


Figure 9 Plots of p_F calculated with FORM against Monte Carlo simulation (MCS) for various MSE wall heights and effective tensile capacity factors

5.0 CONCLUSION

This paper presents a reliability-based analysis of WBM reinforced MSE walls for temporary railway embankment, focusing on the breakage failure of WBM as a natural material. The uncertainties in the material property of the backfill and the reinforcement tensile strength were quantified. The reliable maximum height of the MSE wall was determined considering the system failure probability bounds. Based on the research results, the following conclusions are drawn:

1. Sensitivity analysis revealed that the mean of the internal friction angle of the fill material and WBM negatively correlated with the probability of failure p_F that is believable, whereas the unit weight of the fill material positively correlated with the p_F. Regarding the standard deviation, the change in the standard deviation of material strength could increase the p_F, whereas the material unit weight was nearly insignificant for the case.
2. Reliability-based analysis by FORM showed believable positive trends of the p_F against increasing height, whereas the effective tensile capacity factor R negatively affected the p_F. When the R was 0.25, the WBM was inapplicable in any values of layer vertical distance. The theoretically undegradable tensile strength in the design (R = 1.00) could increase the reliable height up to 12 m when s_v = 0.2 m.
3. Comparison between the results of FORM and MCS showed that the results of FORM agree with those of MCS, whereas less computational effort is required by FORM than MCS.

The system reliability assessment in this study focused on the reliable height of MSE while considering the uncertainty feature of manufactured WBM as a conventional geosynthetic replacement. This study provided some insights and opened the opportunity for further research on other potential local materials as geomechanics reinforcement.

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