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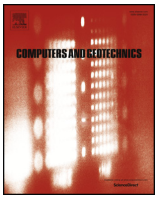

Research Paper

Life-cycle reliability-based assessment of internal stability for mechanically stabilized earth walls in a heavy haul railway

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ABSTRACT

This paper presents an efficient system reliability approach for the internal instability of mechanically stabilized earth walls in a heavy haul railway. The first-order reliability method is adopted to assess the wall failures due to rupture and pullout. The effects of uncertainties in the backfill unit weight, the friction angle of backfill and the friction along the soil-reinforcement interface, as well as the width, thickness and tensile strength of steel strips are explicitly explored. Moreover, the system reliability analysis clearly demonstrates the impact of steel corrosion on the life-cycle retaining wall stability.

1. Introduction

Mechanically stabilized earth (MSE) walls have been widely used as an economical infrastructure for earth retention and load support in various engineering projects [33]. Compared with other retaining structures, the advantages of this technology mainly include that it is low-cost, has a rapid construction, is space saving and has a high tolerance for differential settlements [32]. In the light of the widespread use and significance of MSE walls, several design manuals are developed based on the factor of safety (*FS*). For example, under static loading, the minimum *FS* against sliding and overturning required by American Association of State Highway and Transportation officials (AASHTO) [1] are 1.5 and 2.0, respectively. The Second Survey and Design Institute [23] recommends that the minimum *FS* against pullout is 2.0. It is irrational that the same *FS* is applied to various design scenarios without quantifying the design uncertainty. Hence, the reliability-based design approaches are adopted to address the effects of uncertainties. Several efforts have been dedicated to the reliability-based design and assessment on the external stability (e.g., [6,7,11,37,40]) and internal stability (e.g., [8,27]) of MSE walls.

The reinforcement durability is a major consideration in MSE wall design and maintenance. The metallic reinforcement corrosion can result in premature failure of MSE walls [5]. It was reported by the National Association of Corrosion Engineers International that the repair and maintenance of reinforced structures cost $276 billion annually in the US, while 25–30% of that could be saved with new corrosion management practices [25]. The AASHTO model for estimating the reinforcement corrosion is considered unnecessarily conservative [19,20]. In this regard, MSE wall reinforcement corrosion was explored in depth by several researchers. For example, key corrosion parameters were considered to develop numerical models that can calculate the corrosion rate of galvanized steel [33,34]. The corrosion effects on the geotechnical behaviour of MSE walls were evaluated by considering the corrosion-induced stiffness and strength loss of steel strips [13,14].

In this paper, an efficient system reliability-based approach for assessing MSE wall internal stability of a heavy haul railway is developed. In practice, the axle load for a heavy haul railway typically ranges from 28.0 ton to 32.5 ton and can even reach 39.0 ton, which is significantly larger than that for a traditional railway. Thus, the retaining walls for a heavy haul railway are subjected to challenging loads and design uncertainty, which requires a reliability-based design approach to ensure the various stability requirements. In this study, the first-order reliability method (FORM) is adopted for estimating the probability of failure (P_f). The effects of uncertainties in the unit weight and friction angle of backfill as well as the friction along the soil-reinforcement interface are investigated explicitly. In addition, the effects of corrosion-induced metal loss and steel tensile strength reduction on the internal stability of the retaining wall are quantified in the system reliability analysis. This FORM-based system reliability method, which requires much less computational effort and has the potential for application in other aspects of railway engineering, is compared with Monte Carlo simulation (MCS).

2. Design for MSE wall stability

There are multiple failure modes involved in the stability design of MSE walls, including but not limited to (I) overturning failure, (II) sliding failure, (III) slip circle failure of the embankment, (IV) bearing

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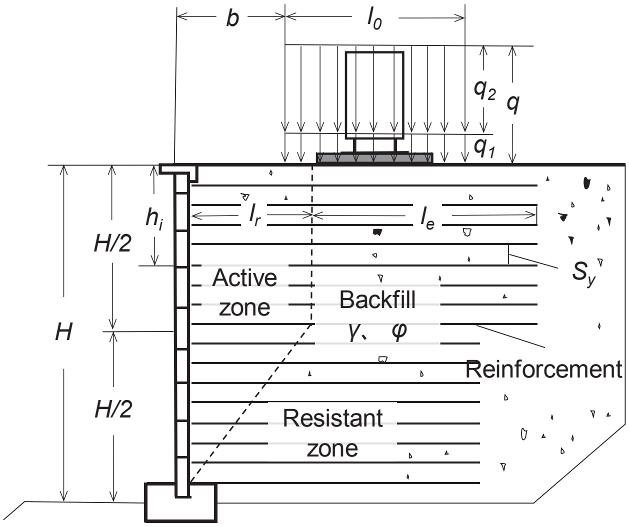

Fig. 1. Example design section of MSE walls for heavy haul railway.

capacity failure, (V) excessive settlement, (VI) pullout failure, and (VII) rupture failure [22]. These individual failure modes can be grouped into external failure modes [(I)–(V)] and internal failure modes [(VI)–(VII)]. Due to the scope limit, this paper emphatically explores the effects of uncertainties in the material property of backfill, the friction between the soil-reinforcement interface and steel corrosion on the internal stability of MSE walls for a heavy haul railway. Thus, the internal stability against pullout failure and rupture failure is investigated, rather than covering the external failure modes.

Fig. 1 illustrates the example section of an MSE wall subjected to heavy haul railway loads. This example wall is located in DK283 + 523.70 ~ DK283 + 628.24, Tianlin Station, Nanning-Kunming Railway Section, China. The parameters used in the design example are shown in Tables 1 and 2.

The *FS* for the retaining walls against local pullout, overall pullout and rupture can be determined with Eqs. (1)–(3) [23]

$$FS_{Local\ pullout} = \min\left(\frac{S_{f_i}}{E_{x_i}}\right) = \min\left(\frac{2\sigma_{vi} a L_b f}{\sigma_{hi} S_x S_y}\right) \tag{1}$$

$$FS_{Overall\ pullout} = \frac{\sum S_{f_i}}{\sum E_{x_i}} = \frac{\sum 2\sigma_{vi} a L_b f}{\sum \sigma_{hi} S_x S_y} \tag{2}$$

$$FS_{Rupture} = \min\left(\frac{[\sigma]}{T_i}\right) = \min\left(\frac{[\sigma]}{K\sigma_{h_i} S_x S_y}\right) \tag{3}$$

where $FS_{\ Local\ pullout}$ = factor of safety for a single block against pullout, $FS_{\ Overall\ pullout}$ = factor of safety against overall pullout, $FS_{\ Rupture}$ = factor of safety for single steel strip against rupture, S_{f_i} = total friction force along both top and bottom surfaces of the steel strips, E_{x_i} = lateral earth force on the block, σ_{v_i} = vertical pressure on the steel strips at the plate i, a = width of the steel strips, f = coefficient of friction for the soil-reinforcement interface, σ_{h_i} = horizontal pressure on the plate i, S_x and S_y = horizontal and vertical spacing between the steel strips, $[\sigma]$ = tensile strength of the steel strips, T_i = tensile force on the steel strips, K = amplification factor of tensile force of reinforcement and L_b = effective reinforcement length, which can be categorized with Eq. (4)

Table 1
Parameters as random variables in the design of MSE walls against rupture and pullout.

Input parameters	Notation	Mean	Unit	COV
Unit weight of backfill	γ	19	kN/m^3	10% [17]
Friction angle of backfill	φ	35	°	20% [35]
Coefficient of friction for soil-reinforcement interface	f	0.3 [23]	–	10%
Tensile strength of steel strips	$[\sigma]$	200	MPa	10%
Width of steel strips	a	0.05	m	5%
Thickness of steel strips	e	0.0044	m	5%

Table 2
Constant parameters in the design of MSE walls against rupture and pullout.

Basic calculation parameters	Notation	Value	Unit
Foundation load	q_1	13.91 [38]	kN/m^2
Train load	q_2	54.11 [38]	kN/m^2
Total load	q	68.02 [38]	kN/m^2
Load distribution width	l_0	3.3 [38]	m
The distance from the inner edge of the load to the panel	b	1.9	m
Overall height of retaining wall	H	5.56	m
Initial zinc coating thickness	e_i	86	μm
Amplification factor of tensile force of reinforcement	K	1.5 [23]	–
Horizontal spacing between steel strips	S_x	0.4	m
Vertical spacing between steel strips	S_y	0.4	m
Length of reinforcement	L	6	m

$$L_b = \begin{cases} 0.7H & \text{for } h_i \leqslant H/2 \\ 0.4H + 0.6h_i & \text{for } h_i > H/2 \end{cases} \tag{4}$$

where H = overall height of the retaining wall, and h_i = depth of the steel strips.

2.1. *Horizontal pressure on wall-facing blocks*

The horizontal pressure caused by backfill materials and surcharge loads can be computed with

$$\sigma_{h_i} = \sigma_{h_{1i}} + \sigma_{h_{2i}} = \lambda_i \gamma h_i + \frac{q_1 + q_2}{\pi}\left(\frac{bh_i}{b^2 + h_i^2} - \frac{h_i(b + l_0)}{h_i^2 + (b + l_0)^2} + \arctan\frac{b + l_0}{h_i} - \arctan\frac{b}{h_i}\right) \tag{5}$$

in which $\sigma_{h_{1i}}$ = horizontal earth pressure at the depth of h_i, $\sigma_{h_{2i}}$ = horizontal pressure caused by surcharge loads at the depth of h_i, γ = unit weight of backfill, q_1 = track load, q_2 = train load, b = distance from the inner edge of the load to the panel, l_0 = surface load distribution width, and λ_i = coefficient of earth pressure at the depth of h_i, which can be categorized as follows:

$$\lambda_i = \begin{cases} (1-\sin\varphi)(1-h_i/6) + \tan^2(45°-\varphi/2)(h_i/6) & \text{for } h_i \leqslant 6m \\ \tan^2(45°-\varphi/2) & \text{for } h_i > 6m \end{cases} \tag{6}$$

where φ = internal friction angle of backfill.

2.2. *Vertical pressure on the steel strips*

The vertical pressure induced by backfill materials and surcharge loads can be determined with

$$\sigma_{vi} = \gamma h_i + \frac{\gamma h_0}{\pi}\left(\arctan X_1 - \arctan X_2 + \frac{X_1}{1 + X_1^2} - \frac{X_2}{1 + X_2^2}\right) \tag{7}$$

where $X_1 = \frac{2x + l_0}{2h_i}$, $X_2 = \frac{2x - l_0}{2h_i}$, and x = distance between the calculation point and the load centreline.

3. Conventional FORM procedure for reliability-based design considering a single failure mode

Fig. 2 illustrates the uncertainty propagation in the probabilistic design of retaining walls. In this study, six major parameters are