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Evaluation of Geosynthetic Reinforcement Strength in Reinforced Wall With *c–ϕ* Soil Backfill Using Horizontal Slice Method

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Abstract. Reinforced earth walls are widely recognized for their adaptability, cost efficiency, and ease of construction. While geosynthetic reinforced earth walls are typically recommended to use cohesionless soil, cohesive-frictional soil has commonly employed worldwide for economic feasibility. The study assessed numerous factors, including the internal friction angle, K_h, soil cohesion, and surcharge influence on backfill. It was discovered that the stability of the reinforced soil wall is affected by the horizontal seismic coefficient, and the tension force generated in the reinforcement to uphold the wall's stability increases with a rise in horizontal seismic coefficients and surcharge, while it decreases as the cohesion of the soil increases.

1 Introduction

The seismic stability of reinforced earth (RE) walls has been a subject of extensive research. Early investigations provided foundational analytical frameworks for seismic design and introduced the horizontal slice method (HSM) of analysis [1, 2]. Following these works, evaluations were conducted on the stability check for earth walls subjected to external surcharges [3], which were later expanded upon by incorporating the combined effects of oblique displacement and pseudo-static acceleration [4, 5]. To improve prediction accuracy, several simplified and kinematic procedures for evaluating seismic behavior were subsequently developed. These included analytical models tailored for cohesive–frictional backfills [6, 7] alongside alternative simplified kinematic approaches [8].

More recently, the horizontal slice method was extended to accommodate comprehensive parametric assessments [9], and a kinematics-based analysis was introduced to evaluate resistance against transverse pullout [10]. The specific influences of backfill soil characteristics and reinforcement types have also been a major focal point. Experimental evaluations have been conducted on geotextile-reinforced clay [11], alongside comprehensive studies detailing the response of geosynthetic walls utilizing cohesive soils [12]. Further advancements in the horizontal slice method for reinforced structures soon followed.

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From a material standpoint, a higher internal friction angle (ϕ) significantly enhances the bonding between soil particles, which in turn reduces the lateral pressure exerted on retaining structures. This stabilizing effect becomes particularly pronounced when ϕ exceeds 30°. Conversely, when the horizontal seismic coefficient (K_h) exceeds 0.20 and poor-quality backfill (ϕ less than 30°) is utilized, significantly higher resistance forces—such as longer reinforcement lengths—are mandatory to maintain global structural stability [9]. The proposed study builds directly upon these established methodologies, extending the horizontal slice analytical framework to evaluate the coupled effects of backfill cohesion, surface surcharge, horizontal seismic coefficients, internal friction angles, and backfill stiffness [9].

1.1 Method of analysis

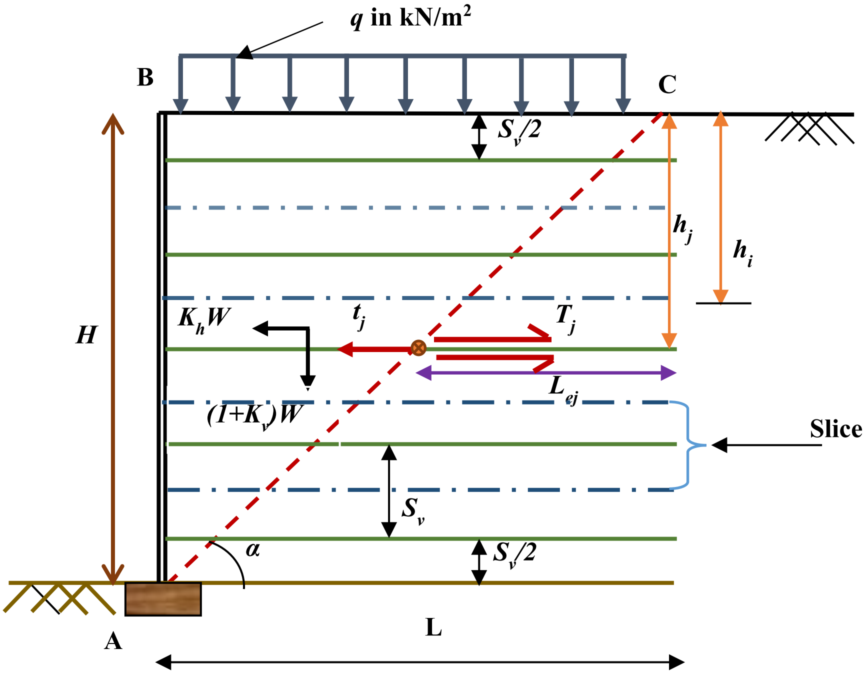

Fig. 1. Parametric model study

Fig. 1 gives a RE wall with sheet reinforcements of elongation (L). The material considered to be homogeneous and cohesive-frictional, characterized by γ, c, and ϕ. The wall supports a uniform surcharge load of intensity q per unit area, and the sheet is subjected to oblique displacement was shown in **Fig. 2**. The failure wedge divided into several horizontal slices, with failure surfaces assumed to be linear. The following assumptions have been made in this analysis:

1. The failure surface is restricted from passing below the toe of the wall due to the presence of a strong material layer beneath the toe. This inherent strength effectively prevents the propagation of the failure surface into the underlying stratum.
2. The FOS was considered to be uniform across and is taken as unity for the analysis.

3. The component of the vertical force within the failure zone is considered to be equal to the overburden stress.
4. The cohesive backfill was finalized same on the backfill.

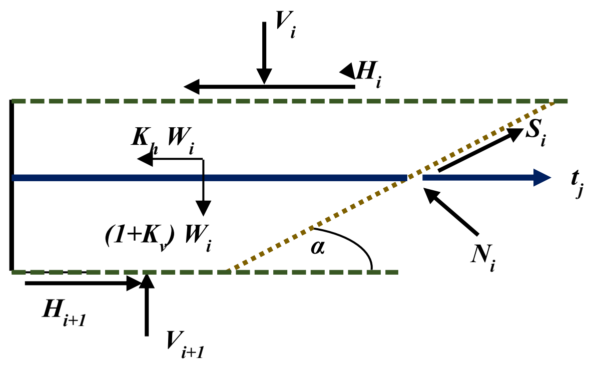

Fig. 2. Tensile and other forces showing on a horizontal slice

2 Proposed evaluation of the model

The equilibrium equations maintain balance for both the individual slices and the entire sliding wedge. The tension developed in the reinforcement is significant, resulting from not only the typical vertical and horizontal forces but also the transverse forces. The equilibrium condition of the one part expressed as:

$$\sum F_y = 0;$$
$$V_{i+1} - V_i - [1 + K_v]W_i + S_i sin \propto + N_i cos \propto = 0 \quad (1)$$

$$S_i = \frac{Cb_i + N_i tan\phi}{FS_{sr}} \quad (2)$$

$$N_i = \frac{V_i - V_{i+1} + (1+k_v)W_i - \frac{C.b_i sin\alpha}{FS_{sr}}}{\frac{tan\emptyset}{FS_{sr}}.sin\propto + cos\propto} \quad (3)$$

The balance of horizontal forces for the entire sliding mass is considered with respect to the mobilized transverse forces. $\sum F_x = 0$

$$\sum_{j=1}^{m} \bar{t}_j = \sum_{i=1}^{n} \bar{N}_i \, sin \propto - \sum_{i=1}^{n} \bar{S}_i cos \propto + \sum_{i=1}^{n} \bar{W}_i K_h + \bar{H}_i - \bar{H}_{i+1} \quad (4)$$

$$\sum_{j=1}^{m} \bar{T}_{Tj} = \left[\frac{tan\emptyset_r}{n}\left[\frac{L}{H}\right] - \frac{tan\emptyset_r}{n} tan[90-\propto]\right] \sum_{j=1}^{m}[2 + P_j^*]\left[j - \frac{1}{2}\right] + \left[\frac{2\, tan\emptyset_r}{n^2} tan[90-\propto]\right] \sum_{j=1}^{m}[2 + P_j^*]\left[j - \frac{1}{2}\right]^2 \quad (5)$$

$$\sum_{i=1}^{n} \bar{W}_i K_h = \sum_{i=1}^{n} \frac{K_h}{2n}[\bar{L}_i + \bar{L}_i]$$

$$P^* = \mu_j \frac{W_L}{L_{ej}} \frac{1}{n_e} \left[\frac{W_{i+1}}{2} + \sum_{k=2}^{n} W_k \right] \quad (6)$$

$$W_k = \frac{T_i^* n_e^2 [W_{k-1} + W_{k+1}]}{\left[2n_e^2 T_k^* + \frac{\mu_j}{2 tan\emptyset_r} \right]} \quad (7)$$

$$T_{k+1}^* = \frac{1}{2n_e} \left[\mu_j W_k \frac{W_L}{L_{ej}} + 2 \right] + T_k^* \quad (8)$$

$$\mu_j = \mu \frac{\left[{L_{ej}}/{L} \right]}{\left[{h_j}/{H} \right]} \quad (9)$$

$$\frac{w_L}{L_{ej}} = \frac{w_l}{L} \frac{1}{\left[{L_{ej}}/{L} \right]} \quad (10)$$

$$FS_T = \frac{\sum_{j=1}^{m} \bar{T}_{Tj}}{\sum_{j=1}^{m} \bar{t}_j} \quad (11)$$

3 Current Findings

3.1 Variation of FS_T Versus ϕ

For the given parameters—angle of shear resistance, FS_T. The variation of FS_T is shown in **Fig. 3**. For horizontal seismic coefficients. The range of FS_T to gain stability increases with ϕ. In the case of the vertically reinforced soil wall, the required reinforcement strength to ensure stability is lower under static conditions compared to extra loading. To finalize the effect of the internal friction on the stability of the vertical wall is marginal in K_h=0, but becomes higher importance in seismic.

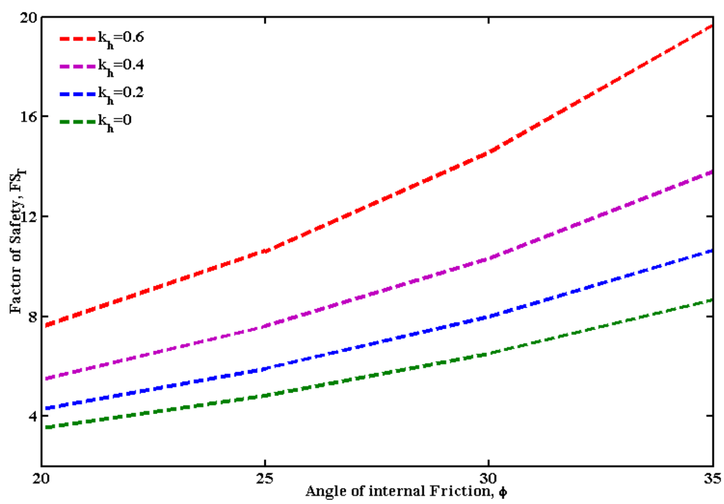

Fig. 3. Effect of FS_T with ϕ - K_h

3.2 Variation of FS_T versus c

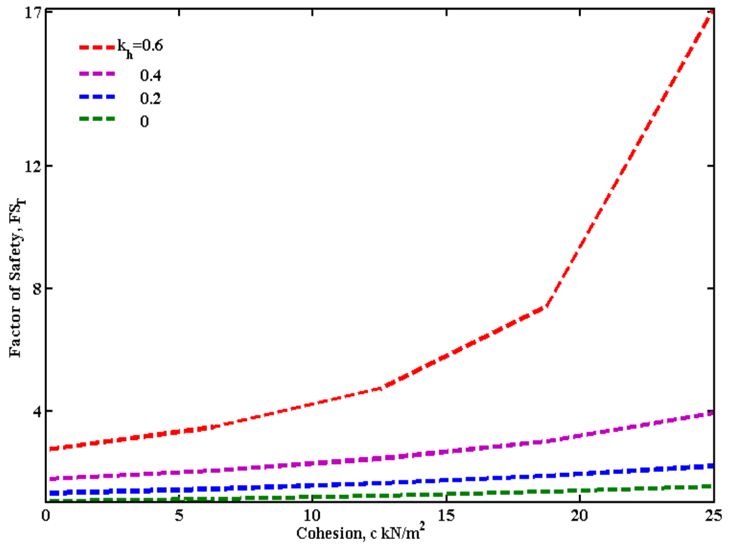

Fig. 4. Effect of FS_T with cohesion

The value safety factor and c for various values of K_h is presented with **Fig. 4**. It can be observed, for cohesion values ranging from c=0 to 20 kN/m^2, q=50kN/m^2, and W_L=0.01, the FS_T increases as the cohesion improved. This is attributed to the additional bond resistance developed between the soil and the sheet reinforcement. Therefore, to conclude that the consideration of the angle of internal friction on the stability of the vertical wall is for cohesive soils compared to cohesionless backfills.

3.3 Variation of FS_T versus μ

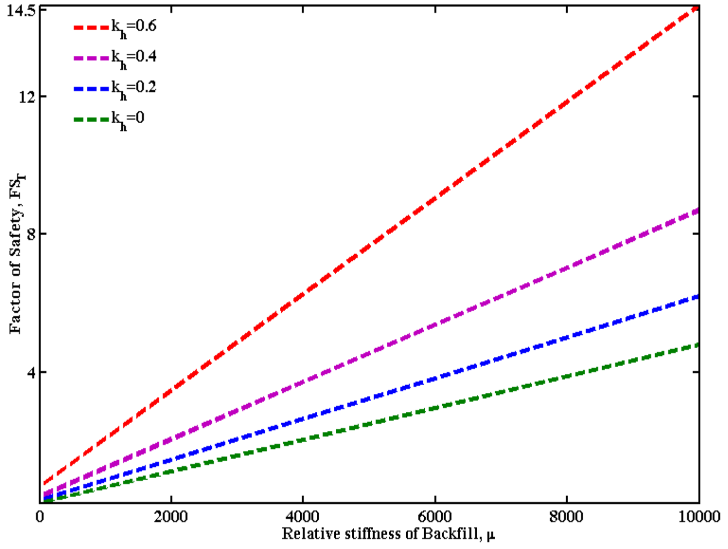

Fig. 5. Effect of FS_T with μ: c = 5 kN/m^2

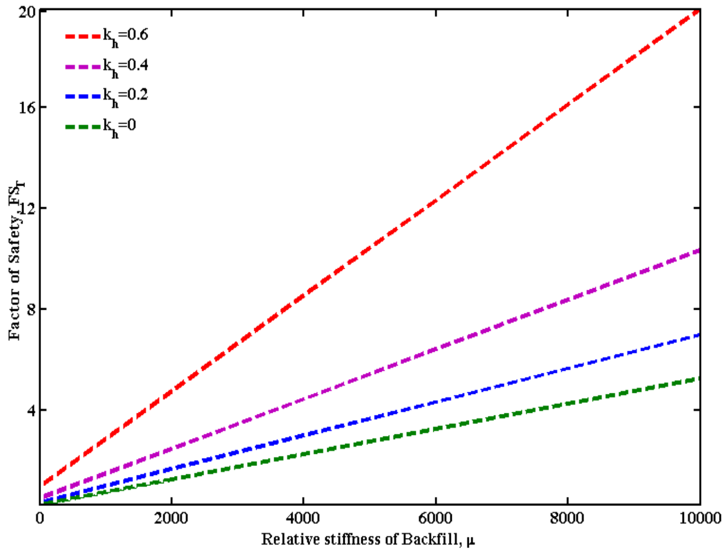

Fig. 6. Effect of FS_T with μ: c = 10 kN/m^2

The variation of safety factor, considering subgrade stiffness (μ), different K_h, is shown in **Fig. 5** and **Fig. 6**. The results show that FS_T increases considerably with an increase in the relative soil stiffness of the backfill for low values of K_h. However, the effect of relative stiffness becomes marginal for higher values of K_h due to the increase in the horizontal seismic coefficient. As K_h increases, the angle of the failure surface with the horizontal decreases, resulting in a reduction in bond resistance because of the decreased effective length of the reinforcement. Consequently, the increase in FS_T due tension with stiffness is more pronounced for lower values of K_h. For example, FS_T increases by 75% for K_h=0 as μ increases from 50 to 10,000. At K_h=0.6, the increase in FS_T is 93% for the corresponding increase in μ. additionally, for a cohesion of c=10 kN/m^2, the transverse pullout from 14.5 to 20 due to the enhanced bond resistance.

4 Comparison of Proposed Model with Previously Developed Model

To confirm the present numerical study, results of present study have been compared with that of previous numerical analyses conducted with the same parameters. Numerical modelling yields generally dependable and satisfactory results for parametric investigations, and there are minor disagreements, but overall, there is good agreement regarding the variation of total reinforcement force is given in **Table. 1**.

Table 1. Comparison of the current results by Shahgholi et al. (2001) and Reddy et al. (2009)

K_h	ϕ=20^0			ϕ=25^0		
	Shahgholi et al. (2001)	Reddy et al. (2008)	Present study	Shahgholi et al. (2001)	Reddy et al. (2008)	Present study
0	108	109	109	90	91	92
0.05	118	117	116	106	107	106
0.1	141	140	139	125	127	126
0.15	176	175	174	151	153	150

5 Conclusion and Recommendations

The stability of a reinforced soil retaining wall subjected to earthquake loading is primarily governed by the backfill properties (c and ϕ), surcharge loading, and the horizontal seismic coefficient. The analysis indicates that increasing ϕ enhances the overall stability of the wall under both static and seismic conditions. As a result, the tensile force required in the reinforcement to achieve a specified factor of safety decreases with higher values of ϕ. Similarly, an increase in the cohesion contributes to greater wall stability by improving the shear strength. In contrast, higher horizontal seismic coefficients generate larger inertial forces, thereby increasing the tensile force that must be resisted by the reinforcement to ensure stability during seismic events. Likewise, increasing the surcharge load imposes additional stresses on the reinforced soil system, leading to a corresponding increase in the tensile force required in the reinforcement to maintain a safe and stable wall.

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