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Simplified approach to analyse global stability of reinforced soil walls

A. Pineda, A. Moncada & S. Olivella
Department of Civil and Enviromental Engineering, Universitat Politècnica de Catalunya·BarcelonaTech (UPC), and International Centre for Numerical Methods in Engineering (CIMNE), Barcelona, Spain

I.P. Damians
International Centre for Numerical Methods in Engineering (CIMNE), Universitat Politècnica de Catalunya·BarcelonaTech (UPC), and VSL International, Barcelona, Spain

R.J. Bathurst
GeoEngineering Centre at Queen's-RMC, Royal Military College of Canada, Kingston, Ontario, Canada

ABSTRACT: Reinforced soil walls (RSW) are a proven alternative to conventional earth retaining structures due to their rapid construction, smaller environmental impact, lower cost, as well as more sustainable social/functional features. Design methods for RSW appear in international codes and guidelines. However, they often do not provide detailed calculations for global stability assessment. Global stability can significantly affect RSW design for specific geometric cases and/or site-specific boundary conditions. Traditional limit equilibrium (LE) methods have the disadvantage of not considering reinforcements and/or require iterations to achieve a safety factor (SF) value. Alternatively, numerical methods can be time consuming for both model generation, particularly for complex geometries, and during calculations. The present study discusses different analytical strategies using limit equilibrium formulations and a numerical finite element method, and proposes a simplified analytical method for global stability analysis based on a three-part wedge failure mechanism, and simple wall conditions.

1 INTRODUCTION

Reinforced soil walls (RSW) offer a more sustainable solution to perform the earth retaining wall function compared to conventional gravity structures (Damians *et al*. 2016).

Design practice for RSWs often focus on internal stability modes of failure, which include failure due to connection rupture, reinforcement rupture, and pullout of the reinforcement layers. However, similar to conventional earth retaining structures, RSWs must be externally stable against sliding, overturning, and bearing capacity failure.

Global stability failures of RSWs are characterized by a failure surface beginning in the vicinity of the toe of the wall, extending beyond the reinforced soil and into the retained soil zone. The propagation of the failure surface can be assumed as a circular surface (e.g., FHWA-NHI-10-024 2009) or as a non-circular surface with various segments (e.g., AFNOR 2020). A commonly used methodology to design earth retaining structures is the limit equilibrium (LE) approach together with the method of slices. Variations of the slice method are available, which make different assumptions to satisfy equilibrium between the interacting slices (e.g., Fellenius method, Simplified Bishop method, Janbu method, among others). More recently, the use of numerical tools has allowed the deformational behaviour of RSWs to be included in stability assessment. Numerical techniques such as the finite element (FE) method allow for simulation of construction stages, interfaces between materials, and include the in-soil behaviour of reinforcement layers in the analysis.

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The present study focuses on comparing the calculated safety factor for a 6-meter high RSW with polymeric reinforcement layers obtained using LE formulations, numerical tools, and a novel simplified analytical methodology. Different surcharge conditions and geometries are included in the analysis, as well as a parametric analysis using different soil properties.

2 GLOBAL STABILITY ASSESSMENT

2.1 *Problem definition*

An idealized H = 6 m high RSW with segmental facing panels was studied. Wall dimensions include a front toe embedment of 0.50 m, segmental panels of 1.5 m height and 0.15 m thickness, and polymeric reinforcement lengths of 4.2 m (0.7H) placed at a spacing of 0.75 m (Figure 1a). Foundation, retained, and reinforced soil properties are given in Table 1. Stiffness and weight parameters for the facing panels and polymeric reinforcement are shown in Table 2.

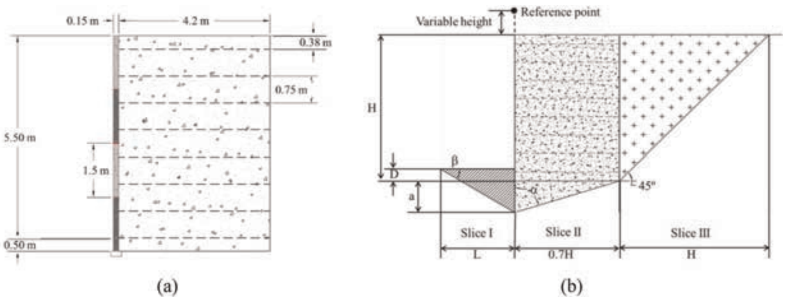

Figure 1. (a) RSW geometry, and (b) failure mechanism for the proposed simplified method.

Table 1. RSW model properties.

Parameter	Foundation and retained soil	Reinforced soil
Unit weight, γ	20 [kN/m^3]	20 [kN/m^3]
Cohesion, c	5 [kPa]	0.1 [kPa]
Friction angle, ϕ	28 [º]	34 [º]
Elastic modulus, E	100 [MPa]	80 [MPa]
Poisson's ratio, ν	0.3 [-]	0.3 [-]

Table 2. Parameters for structures components used in the numerical model.

Parameter	Precast facing panels	Polymeric reinforcement
Axial stiffness, EA	4.5×10^6 [kN/m]	1500 [kN/m]
Flexural stiffness, EI	8440 [kNm^2/m]	–
Self-weight, w	3.75 [kN/m/m]	–

2.2 *Limit equilibrium method*

LE methods are commonly used to compute the global stability of earth retaining structures, particularly in combination with the method of slices. The slope or structure is divided into discrete slices, each is considered as a rigid body that must satisfy equilibrium conditions. The slice methods result in a statically indeterminate problem. Hence, results may vary depending on the assumptions adopted to satisfy equilibrium (Fredlund & Krahn 1977). The present study uses the ordinary or Fellenius method, which assumes no forces between slices.

Shear resistance for each slice is determined using the Mohr-Coulomb failure criterion (MC). Using the Fellenius method, the global stability of the structure is quantified using safety factor (SF) and considering the driving and resisting forces in Equation 1:

$$SF = \left(\sum c_i l_i + [W_i \cos\alpha_i]\tan\phi\right) / \left(\sum W_i \sin\alpha\right) \tag{1}$$

Here c_i is the cohesion of slice i acting over a failure surface of length Δl_i, W_i is the weight of slice i, ϕ is the internal friction angle of the soil, and α is the inclination of the bottom of the slice i with respect to the horizontal. LE analyses were conducted using the software package SLIDE (Rocscience 2017) with the Fellenius method option.

2.3 *Numerical method*

The numerical method to assess global stability was the strength reduction method (Marek-Cala 2003) available in the FE software package PLAXIS (Plaxis 2004). In the strength reduction approach, c-ϕ properties of the soil are continuously reduced until failure is achieved. The SF value is then calculated as the ratio original strength parameters (ϕ_{input}, c_{input}) divided by the reduced strength parameter ($\phi_{failure}$, $c_{failure}$), as shown in Equation 2.

$$SF = \tan(\phi_{input}) / \tan(\phi_{failure}) = c_{input} / c_{failure} \tag{2}$$

Mesh geometry included all relevant structural components with their respective stiffness values (discrete facing panels, reinforcement layers). The FE constitutive model was the MC failure criterion. A soil-reinforcement interface reduction factor of $R_i = 1$ was used. Soil-facing interfaces considered an equivalent material with $\phi_{interface} = (2/3)\phi_{reinforced\text{-}soil}$. An initial sensitivity analysis was made to determine the optimum combination of mesh refinement, computation time and amount of output. There were no practical advantages with respect to numerical outcomes for mesh refinement with more than 15,000 nodes. The placement and compaction of the soil was carried out using 4 and 8 rows of elements; no practical differences in model results were detectable using each number of rows.

2.4 *Simplified method*

The objective of the proposed simplified method is to compute global stability SF in a straightforward manner. Figure 1b shows the proposed failure mechanism. The structure is divided into three zones or slices: the front embedment slice (I), the reinforced soil slice (II), and the retained soil slice (III). LE conditions are then applied, using the Fellenius method and slice boundary conditions adopted using this method. The three-slice failure mechanism resembles that proposed in design standards (AFNOR 2020, BSI 2010), and the failure surfaces often observed from numerical analyses. Slice dimensions are based on wall height (H), depth of wedge III (D), and soil frictional strength (ϕ), as shown in Equations 3–5:

$$\beta = (45 - \phi/2) \tag{3}$$

$$L = H/2 \tag{4}$$

$$\alpha = \tan^{-1}(0.7H/(a/\tan(\beta) - D)) \tag{5}$$

in which *a* is the relative depth (m) of slice II based on slice I geometry.

To determine the inclination of each slice (θ_i), a reference point must be selected. Past studies have shown that the rotation point of a RSW is usually located above and in line with the vertical facing of the wall (Brand & Shen 1984; Petterson 1955). For a base wall height of 6 m, the reference point was located at a height of 2.5 m above the vertical wall facing. The reference point can be adjusted based on computed SF values from numerical or analytical results. For simplification, the weight of slice II acts in the middle of the reinforced soil

(0.45H). SF is obtained by imposing equilibrium conditions between the acting moment (M_A) and resisting moment (M_R) considering each slice (Eq. 6):

$$SF = M_A/M_R = \left(\sum c_i l + [W_i \cos(\theta_i)] \tan\phi\right) / \left(\sum W_i \sin\theta_i\right) \tag{6}$$

in which θ_i is the angle between the vertical projection of each slice self-weight and the reference point.

3 RESULTS AND DISCUSSION

3.1 *Base case and variable surcharges*

Figure 2a shows SF values for the base case and different load scenarios using the analytical` Fellenius method, numerical PLAXIS model and the simplified method proposed here. Surcharge cases consider an equivalent 12 kPa load. For cases 1 and 2, which include surcharge over the toe of the wall, length L is reduced to H/3, angle β is increased to 45-ϕ/10, and the reference point is relocated to 3.5 m above the vertical wall.

The largest SF values were consistently obtained with the Fellenius method. SF values decreased with the application of a surcharge on top of the wall and increased with surcharge loading applied at the toe. Overall, the simplified method yields SF values similar to those obtained from the FE analysis. SF values for the base case were 1.46, 1.47, 1.50 and 1.37 using PLAXIS, simplified method and Fellenius method, respectively.

Figure 3a shows the variation of SF values with wall height using the three methods. Wall heights were 6, 12, and 18 m. Reinforcement length was 0.7H for each case. Increasing wall height gave lower SF values, particularly for PLAXIS solutions and the simplified method. SF values using the simplified method match those obtained using PLAXIS.

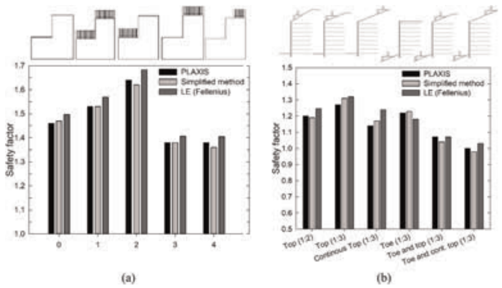

Figure 2. Safety factor (SF) for (a) the base case (no surcharge) and different surcharge load conditions, and (b) different top and toe wall geometries (H = 6 m).

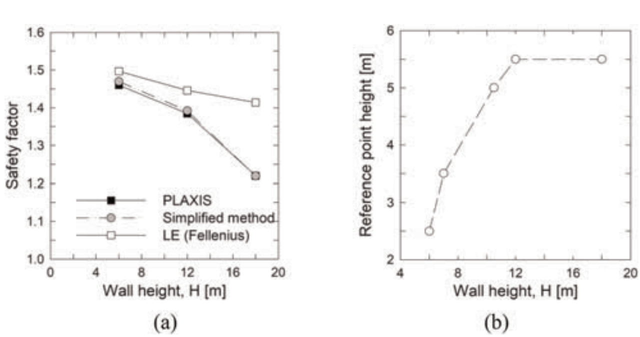

Figure 3. Variations of (a) safety factor, and (b) reference point location as a function of wall height. Base case comparison (no surcharges nor slope conditions).

Modifications of the reference point and slice I dimensions for the simplified method are required to obtain SF values in general agreement with those obtained using PLAXIS and Fellenius method. As wall height increases, the reference point must be moved higher (see Figure 3b), the length L of slice I decreases, and the angle β increases.

3.2 *Variable top and toe wall slope geometry*

Figure 2b compares SF values using the three methodologies and considering a top back-slope and/or fore-slope at the toe of the RSW. For cases with a sloped toe embedment, slice I length increases to H/1.5, and the reference point is lowered to 0.5 m above the vertical wall. When considering an inclined toe and top, the reference point was set to 1.0 m above the vertical of the wall facing.

The three approaches yield comparable results. For greater top slope length, SF is reduced progressively. Furthermore, as the resistance at the toe is reduced due to increasing fore-slope angle, SF values are further reduced. As with previous cases, results from the simplified method are in reasonable agreement with those obtained from numerical analyses.

3.3 *Soil parameter variations*

A sensitivity analysis for the influence of retained and foundation soil parameters was also conducted. Parameter variations include specific weight (γ_s), cohesion (c), and friction angle (ϕ). Parameters were varied individually.

Figure 4 shows computed SF values using the three approaches. Figure 4a shows that increasing γ_s for the retained soil reduced SF, increasing soil cohesion increased SF, as does increasing ϕ. Changing the foundation soil parameters (Figure 4b) resulted in increased SF values for larger values of γ_s, c, and ϕ. SF values obtained using the Fellenius method deviate from those obtained using PLAXIS and the simplified method when and ϕ values for the foundation soil increased. The Fellenius method gave higher SF values when varying soil parameters in all cases, with the exception of the cohesion of the retained soil. The most

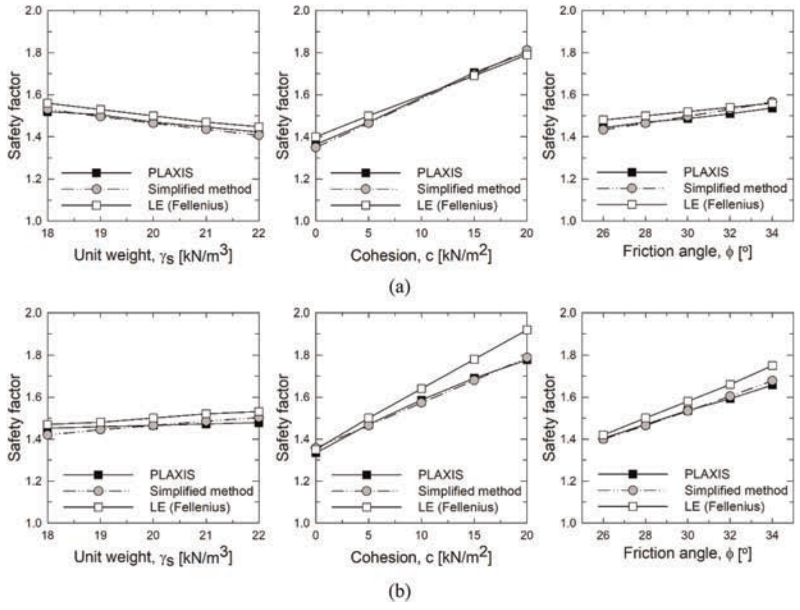

Figure 4. Safety factor (SF) parametric analysis results changing material properties for (a) retained soil, and (b) foundation soil.

sensitive parameters were c of the retained and foundation soil, and ϕ of the foundation soil. Changing the foundation soil γ_s, the self-weight of the vertical wall was included in the weight contribution of slice I, which brought the simplified method results closer to those obtained using the PLAXIS program.

Changing the interface resistance values modified the failure surface obtained using the PLAXIS c-ϕ reduction method. For a perfect bonded soil-reinforcement interface (R = 1) the failure surfaces propagate under the reinforced soil, while a sliding interface (R = 0.6) shifts the failure surface, which then intersects the lowest reinforcement layer.

4 CONCLUSIONS

The present study proposes a simplified analytical method to assess the global stability of a reinforced soil wall with simple geometry. The methodology considers a planar three-slice failure mechanism resembling the failure surface obtained in numerical simulations and described in design standards. Horizontal forces between slices are disregarded. Parameters include structure geometry and soil strength properties. The proposed simplified method provides a fast and simple procedure intended as a preliminary estimation of the global stability safety factor for these systems.

Calculated safety factors with numerical techniques using the program PLAXIS, limit equilibrium formulation using the Fellenius method, and the proposed simplified three-slice failure mechanism were compared. Overall, satisfactory agreement was found between the numerical simulation outcomes and the simplified method. The Fellenius method tended to give similar trends but higher safety factor values, mainly due to an overestimation of the resistance at the toe.

Different surcharge scenarios, geometric variations, and sensitivity analyses were performed. The simplified method results consistently showed satisfactory agreement with the results of numerical simulations. Modifications of the toe length (slice I) and the reference point height serve as calibration parameters to obtain closer safety factor values between numerical simulations and other limit equilibrium methods.

The present study analysed simple geometries with generic, static, load conditions. Further work is required to use the simplified method for real, more complex, wall configurations, such as tiered walls and back-to-back walls, among other configurations.

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