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Kinematical limit analysis approach for the design of nailed soil retaining structures

Ilan Juran, Baudrand George & Farag Khalid
Louisiana State University, Baton Rouge, La., USA

Victor Elias
V. Elias and Associates, P.A., Bethesda, Md., USA

ABSTRACT: Soil nailing is an in-situ soil reinforcement technique which has been used during the last two decades mainly in France and Germany to retain excavations or stabilize slopes. Design of nailed soil systems has been traditionally done using slope stability analysis methods. These methods have been modified to incorporate the effect of the available tension and shear forces in the passive reinforcements on the slope stability. However, they provide only a global safety factor. This paper presents a limit analysis design approach which provides estimation of maximum tension and shear forces mobilized in each reinforcement. To verify the applicability of the method, the predicted forces are compared with those measured in both laboratory models and full scale structures.

1 INTRODUCTION

The fundamental concept of soil nailing consists of placing in the ground passive inclusions, closely spaced, to restrain its displacements and limit its decompression during and after excavation.

The currently used approach in the design of nailed soil structures is based on rather conventional slope stability analysis procedures that have been adapted to evaluate the safety factor of the nailed-soil mass and the surrounding ground with respect to failure along potential circular or wedge shaped sliding surfaces. When such a method is used for the design of a nailed-soil structure, the conventional slope stability analysis procedure is modified to account for the available limit shearing, tension, and pullout resistance of the inclusions crossing the failure surfaces.

Available design methods that are derived from this approach (Stocker, et al., 1979; Shen, et al., 1981; Schlosser, 1983) involve different assumptions with regard to the definition of the safety factors, the shape of the failure surface, the type of soil-reinforcement interaction and the resisting forces in the inclusions. Stocker and coworkers proposed a force equilibrium method that assumes a bilinear sliding surface, whereas Shen, et al. proposed a similar design method with a parabolic sliding surface. Both methods consider only the tension capacity of the inclusions.

A more general solution, including the two fundamental mechanisms of soil-inclusion interaction (lateral friction and passive normal soil reaction), has been developed by Schlosser (1983). This solution involves a slices method (e.g., Bishop's modified method or Fellinius' method) with a multicriteria analysis procedure. This method takes into account both the pullout tension and the shear resistances of the nails as well as the effect of their bending stiffness.

These design methods can only be used to evaluate the global safety factor with respect to the shear strength characteristics of the soil and the soil-inclusion lateral friction. They do not allow for the evaluation of the local stability of the reinforced soil-mass at each reinforcement level. In nailed-soil retaining structures the local stability at the level of a sliding nail can be more critical than the global stability with respect to general sliding in the structure and/or its environment. Therefore, it appears necessary to develop design methods, which provide an estimation of nail forces under the expected working loads.

This paper presents a kinematical limit analysis design approach which allows for the evaluation of the effect of the main design parameters (i.e., structure geometry, inclination, spacings, and bending stiffness of the nails) on the tension and shear forces generated in the nails during construction. To verify the applicability of the method, the predicted forces are compared with those measured in both laboratory models and full scale structures.

2 KINEMATICAL LIMIT ANALYSIS DESIGN METHOD

This design method is based on a limit analysis solution associating a kinematically admissible displacement/failure mode, as observed on model walls, with a statically admissible limit equilibrium solution. The main design assumptions, shown in Figure 1, are that: (a) failure occurs by a quasi-rigid body rotation of the active zone which is limited by a log-spiral failure surface; (b) at failure, the locus of maximum tension and shear forces coincides with the failure surface developed in the soil; (c) the quasi-rigid active and resistant zones are separated by a thin layer of soil at a limit state of rigid plastic flow; (d) the shearing resistance of the soil, as defined by Coulomb's failure criterion is entirely mobilized all along the failure surface; (e) the horizontal components of the interslice forces acting on both sides of a slice comprising a nail (Figure 1) are equal; and (f) the effect of a slope (or horizontal surcharge) at the upper surface of the nailed-soil mass on the forces in the inclusions is linearly decreasing along the failure surface.

The effect of the bending stiffness is analyzed considering available elastic solutions for laterally loaded long (semi-infinite) piles, illustrated in Figure 1. This solution implies that at the failure surface, the moment (M_o) is zero whereas the tension and shear forces generated in the nails are maximum. It is assumed that the maximum shear stress in the nail (S) is mobilized in the direction (α) of the failure surface in the soil. Hence, the shear stress (τ_n) and the normal stress (σ_n) acting on the normal plane of the nail are related by:

$$\tau_N = \frac{1}{2} \cot \left[2 \; (\alpha - \beta_{mod})\right] \cdot \sigma_N;$$

$$\beta_{mod} = \beta - d\beta \qquad (1)$$

$$d\beta = \frac{2}{\left(\frac{K_s \cdot \beta}{\gamma \cdot H}\right) \times \left(\frac{\ell_0^2}{S_v \cdot S_h}\right)} \cdot TS; \qquad (2)$$

where, $d\beta$ is the maximum nail deformation attained at the failure surface, α is the inclination of the failure surface with respect to the vertical; β is the nail inclination.

$TS = T_c/(\gamma \cdot H \cdot S_v \cdot S_h)$ is the normalized maximum shear force; K_s is the lateral soil reaction modulus.

$\ell_0 = [4EI/K_s D]^{1/4}$ is the transfer length which characterizes the relative rigidity of the inclusion to the soil.

E and I are the elastic modulus and the moment of inertia, respectively, of the nail; D is the nail diameter; γ is the unit weight of the soil; H is the wall height; and S_h and S_v are the horizontal and vertical spacings, respectively, between two nails.

In this non-dimensional solution, the effect of nail bending stiffness depends on both the relative rigidity of the nail to the soil and the structure geometry. It can be defined by the rigidity parameter

$$N = [(K_s D/\gamma H)/(S_v S_h/\ell_0^2)]$$

This elastic solution is derived for the relatively flexible nails encountered in practice (i.e., length of the nail: $L > 3\ \ell_0$). For more rigid nails, a solution considering the limit case of perfectly rigid nails, has been derived.

A unique failure surface which verifies all of the equilibrium conditions of the active zone can be defined. In order to establish the geometry of this failure surface, it is necessary to determine the two geometrical parameters: A_0 - inclination of the failure surface at the upper ground surface, and A_f - inclination of the failure surface at the toe of the reinforced soil-mass. Observations on nailed-soil model walls suggest that for flexible nails the failure surface is practically vertical at the upper part of the structure ($A_0 = 0$). The angle A_0 depends upon the nail bending stiffness and the

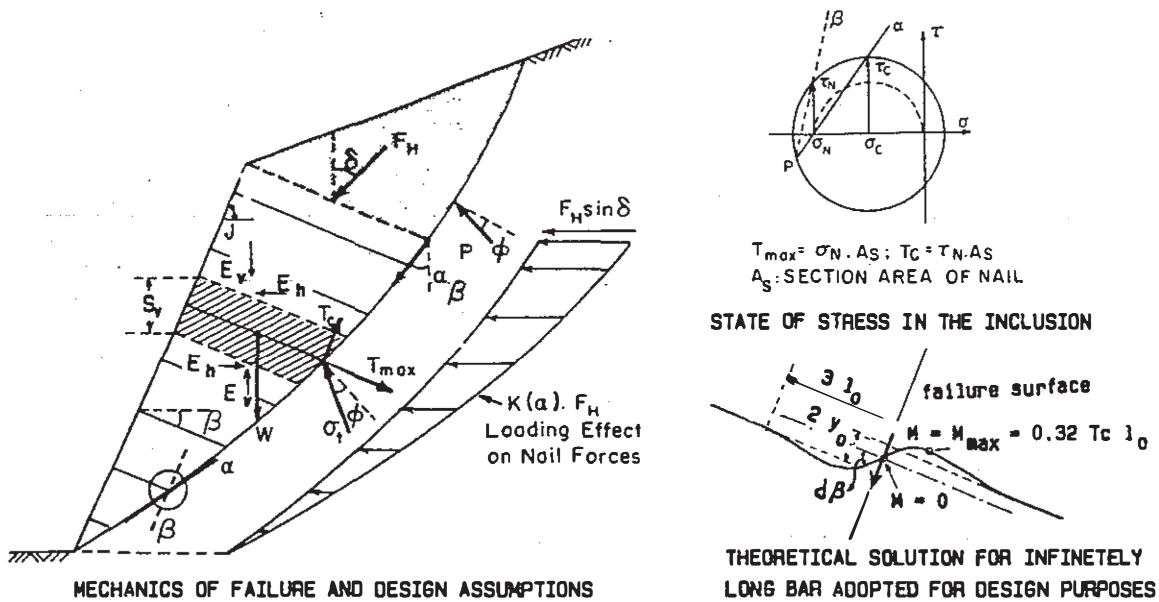

Figure 1. Kinematical limit analysis approach.

failure surface is practically perpendicular to perfectly rigid nails. The parameter A_f is determined from the moment equilibrium of the active zone.

The normal soil stress along the failure surface is determined using Kotter's equation. The maximum tension force in each reinforcement is calculated from the horizontal force equilibrium of the slice comprising the inclusion and the maximum shear force is calculated from Eq. 1. The normalized width of the active zone (S/H) and the values of the normalized maximum tension forces (TN) and shear forces (TS) are represented as non-dimensional parameters: $[TN = (T_{max})/(\gamma \cdot H \cdot S_v \cdot S_h)]$ and $[TS = (T_c)/(\gamma \cdot H \cdot S_v \cdot S_h)]$ at the relative depth (Z/H). Figure 2 illustrates the output variation of the normalized tension and shear force obtained for a typical nailed-soil wall with a vertical facing (J = 90°), a horizontal ground surface (V = 0°), soil strength characteristics of $\phi = 35°$ and $(c/\gamma \cdot H) = 0.05$, nail inclination β of 15° and different values of the rigidity parameter N (perfectly flexible; N = 1, 10; perfectly rigid).

3 DESIGN OF NAILED-SOIL CUT SLOPES

Design with the kinematical limit analysis is based on the evaluation of the local stability of each reinforcement with respect to failure by pull out, breakage and excessive bending.

Detailed analysis with relevant parameters at each depth (Z/H) requires an appropriate computer code for design optimization. However, for structures in homogeneous soils with uniform nail lengths, simplified, yet conservative, design charts can be prepared considering the maximum values of S/H, TN and TS. Design charts for perfectly flexible nails and for #8 rebars which are frequently used in practice are shown in Figure 3. The design charts for #8 rebar are established for N = 0.33 corresponding to a wall height of 12 m in a silty sand with a K_s of 50,000 kN/m^3. With these charts the following iterative design procedure can be used:

(1) Select the nail type (bending stiffness - EI, allowable tension stress - F_{all}, diameter - D, and spacing - S_v, S_H).

(2) For the specified soil properties (γ, K_s, c, ϕ), selected nail type (EI, F_{all}), nail inclination (β) and the structure height (H), determine the ratios S/H, TN and TS. The soil strength properties should be factored considering an acceptable safety factor.

(3) Verify that the selected reinforcement satisfies the breakage/excessive bending failure criteria.

(4) Select the limit interface lateral shear stress, f_ℓ, from field pullout data or available correlations with in-situ tests.

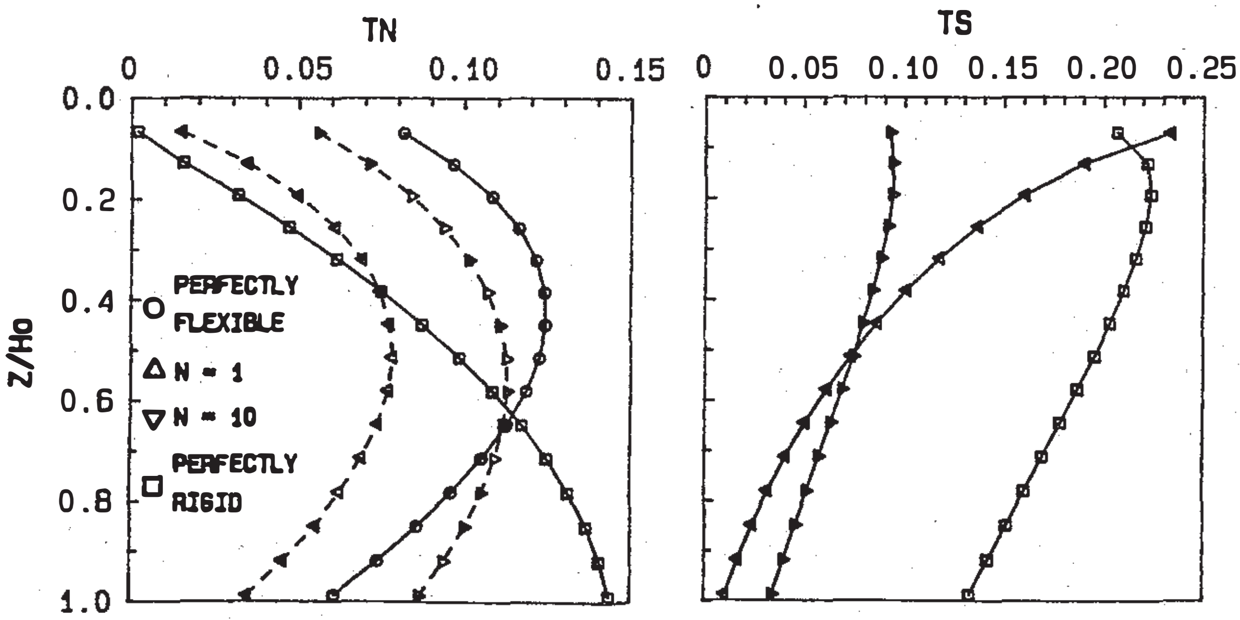

Figure 2. Variation of TN and TS for different relative nail rigidities.

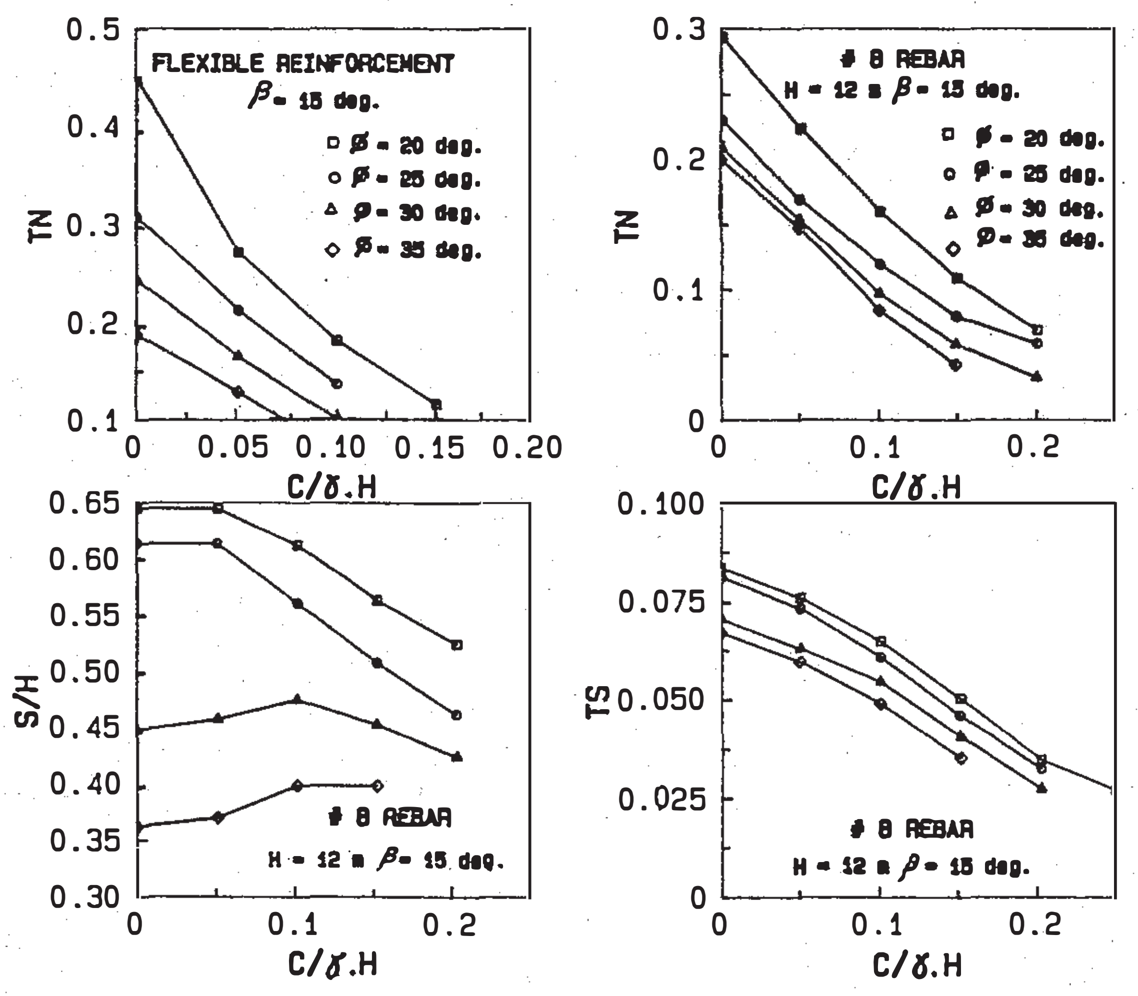

Figure 3. Nail forces and geometry of the active zone (Elias and Juran, 1988)

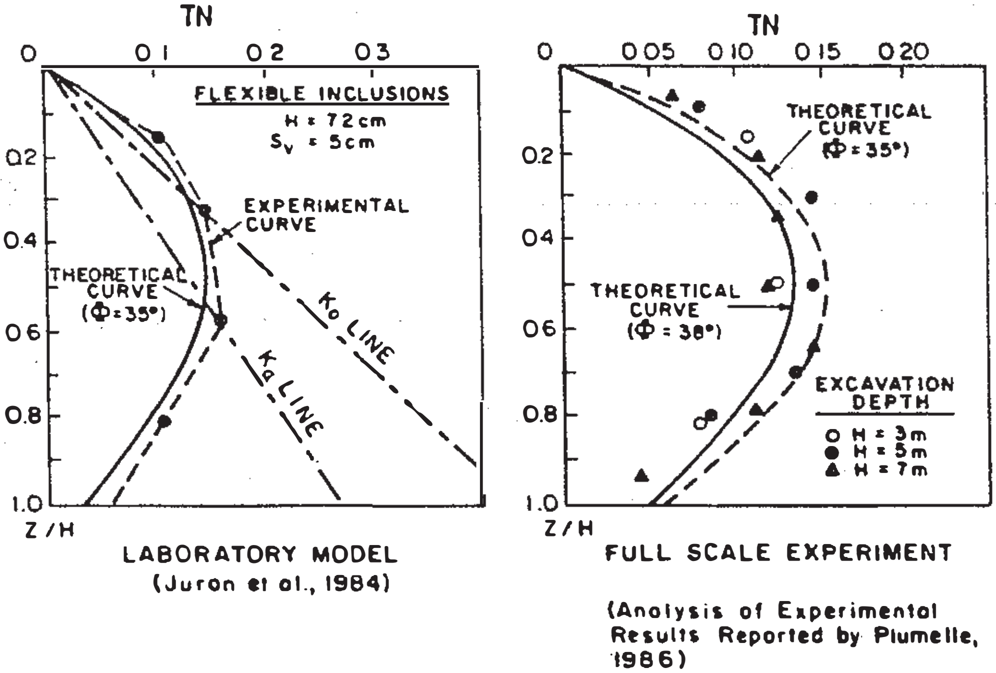

Figure 4. Comparison between predicted and measured nail forces.

(5) Establish structure geometry (L/H) to satisfy the pullout failure criteria with the required value of the safety factor, F_L.

4 THEORETICAL PREDICTIONS VS. EXPERIMENTAL RESULTS

In order to evaluate the proposed kinematical analysis design method, laboratory tests on nailed-soil model walls (Juran, et al., 1984) and full scale experiments on instrumented structures (Plumelle, 1986) have been analyzed and measured nail forces have been compared with predicted values. The use of this limit analysis method to predict at working stress structure behavior assumes that during construction, the soil resistance to shearing is entirely mobilized along the potential slip surface.

Figure 4 shows a comparison between predicted and measured values of maximum tension forces in a model wall and in a 7 m deep experimental nailed soil wall in granular ground (field data reported by Plumelle, 1986). The results obtained on this experimental wall are reported for successive excavation depths of 3, 5 and 7 m. They illustrate that the total excavation depth has only a negligible effect on the variation of the normalized tension force (TN) with the relative depth (Z/H) and on the geometry (S/H) of the potential sliding surface. The comparison between predicted and measured values of the maximum tension forces indicates that the proposed design approach provides a reasonable estimate of nail forces.

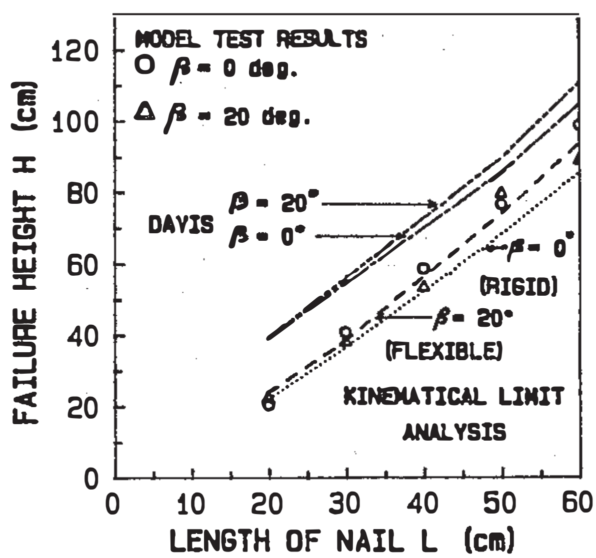

Figure 5. Predicted and measured failure heights of reduced scale model walls (Elias and Juran, 1988).

Most failures of nailed-soil retaining structures that have been reported in the literature occurred as the result of nail pullout. It is therefore essential to evaluate the proposed design method through the analysis of observed pullout failures on laboratory model walls. For this purpose a series of laboratory model tests has been conducted (Elias and Juran, 1988). Pullout tests on the 6 mm diameter rigid steel nails, used in this study, provided the pullout resistance for the laboratory test conditions. Figure 5 shows the comparison between predicted and measured failure heights of the model walls. The heights are calculated using both the "Davis" slope stability design method, developed by Shen, et al. (1981), and the kinematical limit analysis. With the "Davis" method the failure height is attained when the safety factor reaches 1. For the kinematical limit analysis, the failure height is defined as the structure height that will generate sliding ($F_L = 1$) of the upper two nails. The failure heights were calculated considering perfectly rigid horizontal nails ($\beta = 0°$) and perfectly flexible inclined nails ($\beta = 20°$). Predicted failure heights correspond fairly well to the experimental results.

The "Davis" method was found to overestimate the critical height at pullout failure. The differences between the predicted and measured failure heights suggest that the definition of an overall "global" value of the factor of safety is not consistent with the observed progressive pullout failure due to sliding of the upper nails. The calculated global safety factor can be significantly higher than the local safety factor at the critical level of a sliding nail. Therefore, for safe engineering design local nail stability has to be investigated.

5 CONCLUSIONS

The kinematical limit analysis, presented in this paper provides a new engineering approach for the design of nailed-soil retaining structures. It allows for the evaluation of the effect of the main design parameters (inclination and bending stiffness of the nails, embankment slope, facing inclination, soil strength characteristics) on the magnitude and location of the maximum nail forces and on the structure stability. This design method enables the engineer to evaluate the local stability at the level of each reinforcement and therefore provides rational predictions of progressive pullout failure. The local factor of safety at the critical level of a sliding nail can be significantly smaller than the overall "global" safety factor predicted by the conventional slope stability design methods.

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