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Simulation of Root-Reinforcement Effect in Natural Slopes Based on Progressive Failure in Soil-Root Interaction

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ABSTRACT: A new numerical scheme in Finite Element Method (FEM) along with Mesh Free Method (MFM) and suitable convergence criterion is used to simulate the progressive nature of failure in soil-root matrix continuum. With the consideration of homogenizing approach, the complex behavior of soil-root interaction can reliably be captured of any natural slopes. Root-reinforcement effect has significant role in modifying stress anisotropy and displacement behavior of the slope. Result shows that stability factor first increases with RAR, after attaining certain stability factor further increment of RAR within certain limit does not impart on stability factor of slopes. After certain RAR say more than 0.5%, there is no any change on stability factor. Results show that vegetation has significant influences on safety factor in certain effective RAR-range, which further illustrates the necessities of vegetation cover in slopes; however, it requires more realistic model parameters and boundary conditions to perform more relevant simulations.

Keywords: Finite element method (FEM), Mesh free method (MFM), Progressive failure, Soil-root interaction, Natural slopes

1. INTRODUCTION

Numerical simulation considering the progressive failure and the soil-root matrix interaction certainly provides reliable information regarding stability factor of natural slope. Such information can effectively be used to assess the hazard for potentially landslide prone soil slope, and design the structurally safe and economic slopes. However, it is difficult to treat both progressive nature of failure and the interaction of soil-root matrix analytically and numerically. However, in practice, progressive failure patterns and effects of vegetation are not considered in routine slope stability computation. This is mainly due to complex behavior of soil-root interaction. With the consideration of natural slope, in addition to vegetation effect, different underlying soil profiles under partially saturation condition add more complexity to the problem domain. In this regard, the linear behavior of problem domain will no longer perform linear behavior therefore, nonlinear analysis is needed that can address some form of nonlinear behavior of a problem domain. Progressive failure phenomenon shows complex constitutive relations supersede the simple linear elasticity assumptions. In linear problems, the solution is always unique, however there is no longer the case in many nonlinear situations and involves huge iterations. The basic iteration process should be selected in such a way that the solution will remain unchanged. There are, of course, the simulation under nonlinear analysis exhibits high computational cost. Nonlinear FEM with MFM is adopted, which dramatically reduces the processing time so that it is easier to accommodate complex problem. The nonlinear FEM is ideally suited to handle the slope stability analysis because there is no need to make any assumptions regarding the shape and geometry of failure surface as well as its searching procedures. Both material nonlinearity and geometrical nonlinearity are existed in natural slopes (large deformation and includes power terms of the series). Numerical computation based on nonlinear FEM with mesh technique will no longer work in ordinary computers [13]. Progressive failure demands increased number of iterations and huge number of meshes are necessary for the convergence of the result. As we have seen memory problem in ordinary computers, we might have two possibilities. One possibility is to seek super computer and go for parallel processing and other possibility is to apply mesh free strategy in existing programs. This strategy drastically reduces the storage memory of computers and accelerates the computational speed. In this regard, new numerical scheme in non linear FEM along with MFM and suitable convergence criteria is used to simulate both the progressive nature of failure and interaction of the soil-root matrix continuum. A simple numerical formulation for the progressive failure with the consideration of homogenizing approach to treat the soil-root interaction reliably simulated the complex behavior of natural slopes. Slope model geometry with the consideration of water profile, surcharge effect and different soil profiles, vegetation types and its root depths (maturity periods) and RAR can be simulated effectively. Soil bioengineering technique that uses vegetation as a structural element gained popularity in natural and manmade slope stabilization [1]. The effect of root reinforcement caused by vegetation is modeled as additional cohesion to the soil as root cohesion. The root zone by certain depth as per maturity period of particular species is incorporated in the model. The role of vegetation in stability factor of the soil slope, as expected, becomes significant after certain maturity period when roots have pervaded the certain depths, nevertheless resistant to erosion even at the earlier period cannot be neglected. In this paper, the factor of safety (FS) of natural soil slopes is examined using elastic-plastic (Mohr–Coulomb) FEM program for $c-\phi$ soils and thus concluding the slope is safe enough or not for the certain considered case. Even the most widely used numerical method, FEM is capable of solving the wide range of boundary value problems [2]; however, the computation of failure path is quite cumbersome. Use of continuous displacement function makes it difficult to treat the rupture process, which is inherently discontinuous in nature. In this case, new approach in ordinary FEM platform is proposed to address the different problems in soil-engineering (Fig. 1). Thus the simulation of soil-root interaction, consideration of the progressive fracture in the soil-root networked continuum, and evaluation of the factor of safety based on the strengths and the fracture phenomena using new numerical scheme is effective way of evaluating the stability of soil slope. Simulation of the slope failure in 3-dimensional domain will be a cumbersome task with reference to the computational cost, special 3-dimensional case of plane condition is used in this paper. It should be noted, however that, more accurate result can be achieved with the simulation in 3-dimensional domain. This numerical scheme can handle material heterogeneity and complex topography. Either simple or complex water table profile may be used to access effects of hydrostatic pressure. Both surface loading and pseudo-static seismic loading are well implemented.

2. NUMERICAL PROCEDURE

2.1 Mathematical formulation

In this approach, a numerical method is used to compute the displacement field to simulate stress-deformation behavior of the slope adopting homogenizing or continuum modeling. Continuum modeling describes the model as a continuous body. Therefore, this method is applicable to slopes whose behavior may be realistically reproduced under the continuum assumption, e.g. soils, massive rocks, heavily jointed rocks, etc. FEM with some modifications is applied here as continuum based modeling. It solves a weak (Variational) form of the governing equation on an unstructured mesh, descretization and the solution procedure are generally relatively complex, but unstructured meshing is well suited for complex geometries. In this numerical procedure, we add vegetation root to the model, which is simply honored by the different sized meshes. Honoring the root reinforcement makes it easier to identify root-reinforcement part nodes during the calculation of root-cohesion. Same procedure is also applied to identify the submerged nodes during the calculation of hydrostatic pressure.

Progressive failure itself is a very complex phenomenon in space-time (Fig. 1). A simple FEM based analysis is not sufficient for getting the more reliable results especially in natural slopes. Iterative, trial and error, solutions may not converge in large domain. The governing equation in case of soil slope with vegetative cover (natural slopes) considering the progressive fracture can be represented as:

$$\begin{aligned} &\left(\bar{C}_{ijkl} u_{kl}(X,t)\right)_{,j} + f_i(X,t) = \bar{\rho}\ddot{u}_i(X,t) \text{ in } \Omega \\ &u_i(X,t) = \hat{u}_i(X,t) \text{ on } \partial\Omega(t) \\ &\sigma_{ij}(X,t) n_j(X,t) = \hat{t}_i(X,t) \text{ on } \partial\Omega(t) \end{aligned} \tag{1}$$

Where $\bar{C}_{ijkl} = \sum_m W_m (C_{ijkl})_n = W_r (C_{ijkl})_r + W_s (C_{ijkl})_s = r(C_{ijkl})_r + (1-r)(C_{ijkl})$ represents the average elasticity tensor, and $\bar{\rho} = \sum_i W_i \rho_i = W_r \rho_r + W_s \rho_s = r\rho_r + (1-r)\rho_s$ represents the average mass density of the material including roots for linearly elastic isotropic material. Similarly, W_r denotes the weight function of roots; W_s denotes the weight function of soil; ρ_r for the density of roots; ρ_s for the density of soils, and r for the root area ratio. Similarly, $\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$ (Generalized Hook's Law) and $\varepsilon_{ij} = 0.5(u_{i,j} + u_{j,i})$ (for infinitesimal deformation), where n_j represents the unit normal in the direction of j. The nonlinearity of the problem can be addressed with the evolution of C^{ep}_{ijkl}, which can be expressed as:

$$C^{ep}_{ijkl} = C_{ijmn}\left(I_{mnkl} - \frac{(C_{mnpq}\,\delta f_{pq})(C_{klrs}\,\delta f_{rs})}{\delta f_{pq}\, C_{pqrs}\,\delta f_{rs}} \right) \tag{2}$$

Where C^{ep}_{ijkl} represents the stochastic instantaneous (or elastic-plastic) moduli; f represents the yield function depending on the stochastic stress state and the past stress history, and δf_{ij} represents the gradient of f with respect to the stress component σ_{ij}. In this mathematical formulation, we consider the body in dynamic state with body force f_i in Ω and the traction $\hat{t}$ and the displacement $\hat{u}$ on $\delta\Omega(t)$. Both indicial notation and summation convention are followed. The indices i, j, k and l run from 1 to 2 for 2-D case. Indices after comma (,) represents the partial derivative of corresponding variable with respect to index. Time evolution of the domain boundary is the key point of this numerical approach. The boundary of the domain is dependent on the time. As the fracture propagate with respect to time the boundary of the domain is also evolving, which may either be traction free or with the specified traction. The governing equation set in the Eq. 1 can be solved by variational formulation. Energy functional corresponding to the governing Eq. 1 can be represented as:

$$I(u) = \int_{\Omega} \left(\sigma_{ij}\varepsilon_{ij} + \bar{\rho}\ddot{u}_i u_i\right) dV - \oint_{\Omega} f_i u_i dV - \oint_{\partial\Omega(t)} \hat{t} u_i dS \tag{3}$$

Where σ_{ij} represents the stress tensor and ε_{ih} represents the strain tensor. The first variation of the functional $I(u)$ with respect to infinitesimal variation of displacement is given by:

$$\delta I(u) = \int_{\Omega} \left(\sigma_{ij}\delta\varepsilon_{ij} + \bar{\rho}\ddot{u}_i \delta u_i\right) dV - \oint_{\Omega} f_i \delta u_i dV - \oint_{\partial\Omega(t)} \hat{t}_i \delta u_i dS \tag{4}$$

Refer to Eq. 4, it is discretized in terms of the displacement field with the approximation of:

$$u_i(X) = \sum_{\alpha} u_i^{\alpha} \phi^{\alpha} \tag{5}$$

Where ϕ^{α} satisfies the orthonormal condition.

$$\phi^{\alpha}(X^{\beta}) = \delta^{\alpha\beta} \tag{6}$$

Where $\delta^{\alpha\beta}$ represents the Kronecker's delta. The functional $I(u)$ can be minimized equating δI to zero. Thus together with the Eq. 6, the final finite element equation can be obtained as:

$$\sum_{\beta} M^{\alpha\beta} \ddot{u}_i^{\beta}(X,t) + \sum_{\beta,j} K_{ij}^{\alpha\beta} u_j^{\beta}(X,t) = F_i^{\alpha}(X,t) \tag{7}$$

Where $M^{\alpha\beta} = \int_{\Omega} \bar{\rho}\phi^{\alpha}\phi^{\beta} dV$, $K_{ij}^{\alpha\beta} = \int_{\Omega} \sum_{k,l} \bar{C}_{ijkl} \phi^{\alpha}_{,k} \phi^{\beta}_{,l} dV$ and $F_i^{\alpha} = \int_{\Omega} \phi^{\alpha} f_i dV + \oint_{\partial\Omega(t)} \phi^{\alpha} \hat{t} dS$ respectively represents the mass matrix, stiffness matrix and force matrix.

2.2 Conjugate gradient iteration and Mesh Free Method (MFM)

Many algorithms of this type can be found in the literature [8] and [13], the most popular and commonly used method is conjugate gradient iteration method. A simple mathematical relationship of the general equation, and its residual, functional and minimization can be expressed as:

$$Ku = B; \quad R = B - Ku; \quad f(u) = \frac{1}{2}u^T Ku - u^T B; \quad \delta f\,(u) = 0 \qquad (8)$$

Conjugate gradient iteration checks in conjugate direction and follows the gradient so that it will reach the require point in few computation from bowl shape problem. It helps to reduce heavy computation for global matrix solution.

In MFM, the use of pre-defined mesh is avoided removing the problems associated with mesh distortion. MFM does not require a structured mesh (Fig. 1(b)), but use a set of nodes distributed within the material domain and elemental sum can be carried out using the relation (K_i is the element stiffness matrix of the i^{th} element):

$$u = \sum_{elements} K_i R_i \qquad (9)$$

2.3 Vegetation effect

An enhanced cohesion due to the presence of roots can be calculated by two major characteristics of root systems T_R and RAR. Both T_R and RAR are influenced by species and site factors such as local climate; soil type; season; root type and size as well as root architecture [5] and [6]. The fiber reinforcement (perpendicular root reinforcement model) in terms of root cohesion C_r can be written as:

$$C_r = t_r(\sin\theta + \cos\theta * \tan\phi) \qquad (10)$$

Where t_r represents the mobilized tensile stress of root fibers per unit area of soil; θ represents the angle of shear distortion in shear zone, and ϕ is for the angle of internal friction of the soil. A shear strength increase from full mobilization of root fiber tensile strength requires calculation of the average tensile strength of the root fibers, and the fraction of soil cross section occupied by roots (A_R / A). The mobilized tensile stress per unit area of soil t_r in this case is given by: $t_r = T_R(A_R / A)$ and $k' = (\sin\theta + \cos\theta * \tan\phi)$. The common value of k' can be taken as 1.15 [11] or 1.2 [12]. Then the Eq. 10 can be further written as:

$$c_r = k' t_r \qquad (11)$$

To account the variability of root diameter Eq. 11 can be further written as:

$$c_r = k' \sum_{i=1}^{N} (T_r a_r) * i \qquad (12)$$

Where T_R denotes the tensile strength and a_r denotes the RAR (both specified per diameter class i , and the number of class N). RAR refers to the fraction of the total cross sectional area of a soil that is occupied by roots. Regardless of plant types and conditions, the common value of root area ratio is ranging from 0:01 to 0:00001, but if the value assigns greater than 0.005 then there will be the chances of overestimating root cohesion [14]. Root tensile strength usually decreases with increasing diameter or root depth. It depends on plants species, root diameter, age, site conditions (e.g. moisture), and season. A decrease in root diameter from 5mm to 2 mm results in a doubling or even tripling of tensile strength [10]. Finer roots have the advantage of not only higher tensile strengths but also superior pullout resistance because they have higher specific surface areas than larger roots at equivalent area ratios [10]. Ranges of tensile strength (kN/m^2) for different groups of plants can be categorized as: Grass (5-10); Herbs (3-60) and Woody plants (10-70).

2.4 Fracture treatment

Consideration of the fracture is quite natural in this approach. Fracture is considered to be evolved along the element edge. As the precise physical formalism is not known for the fracture phenomena, consideration of the fracture process is somehow empirical. Nature of the fracture evolution is determined by the edge (surface) stress $(\sigma_{ij})_{edge(surface)}$ and nodal stresses $(\sigma_{ij})_{node}$ of the corresponding edge (surface) simultaneously. Any of the existing fracture criteria can be applied with equal ease. Continuous displacement functions are used until the occurrence of fracture. After the fracture, fractured edge (surface) is changed into the traction free or specified traction boundaries, thus introducing the elegant way of consideration of discontinuous displacement functions.

There are three possible ways of fractures depending on the location of failed node. When the failed node lies on the boundary, crack will be initiated at the boundary node and will propagate to the inner intact node. In this process a new node and a new edge will be generated as shown in Fig. 3(a). When the failed node lies near the boundary, then all the conditions will be similar with the case when the failed node lies in the domain, except that the boundary node will also get failed. Therefore, there will be generation of two failed edges and two failed nodes as shown in Fig. 3(b). Another possible way of fracture will be when the failure node lies in the domain of the continuum. In this case separation of only one edge is incompatible; hence, crack will be initiated from an edge which exceeds the yield criteria starting from a node of higher stress and accompanied with a next edge with highest stress among the remaining edges meeting at the failed node. Thus, in this case one new node and two new edges are generated as shown in Fig. 3(c).

3. MODEL AND MATERIAL

3.1 Slope model

For the computation the natural slope, authors present realistic problem domain (Fig. 4). Slope is then discretized including all the complexities of soil; water and root related effects. For this particular case, fixed boundary at the bottom and vertical movable boundary at the left, and partially fixed and movable at the right are appropriate to the slope. Problem domain mainly concerns partially saturation state of soil which resembles the natural slope. Natural slope might be both types of slopes: slope with vegetation cover and slope without vegetation cover.

3.2 Material model

The theoretical soil parameter used to compute stability factor are presented on Table 1 [3]. This model does not mean that fully saturated soil may have zero cohesion value. On the other hand, these model material properties do not concern about the corresponding changes on angle of internal friction ϕ ; Poisson's ratio υ ; dilation angle ψ , and young's modulus of soil E and many other factors with changes on degree of saturation and presence of root, however corresponding changes due to saturation on unit weight of soil γ and soil cohesion c , are considered. For the finite element modeling, the soil is modeled as a elasto–plastic material. The elastic part was governed by modulus of elasticity E and Poisson’s ratio υ of the soil. Root material is considered as a linear-elastic material with a modulus of elasticity of (1.5 E^5) kN/m^2, a Poisson’s ratio of

0.3, and a maximum yield stress of 107 kN/m^2 as a sample. The dilation angle ψ affects the volume change of the soil during yielding. As a frictional material, it will exhibit high dilation near the peak, leading eventually to a residual state under a constant volume condition $(\psi = 0)$ and the selection of soil dilation angle is comparatively less important [7]. The exact values of different parameters can be obtained from site specific and species specific tests. However for the rough estimation, one may use: enhanced unit weight of root γ_R=1.5 kN/m^3; young's modulus of elasticity of root $E_R = 0.1\ E^5$ kN/m^2; cohesion due to evapo-transpiration c_e =0 to 10 kN/m^2, and angle of internal friction due to root $\phi =$ 0 to 5 degrees; surcharge loading due to weight of vegetation = 0 to 5 kN/m; wind loading force parallel to the slope per tree = 0 to 3.5 kN/m. Mean tensile strength of root T_R , generally varies from 5 to 80 kN/m^2 along with wide range of RAR, generally varies from 0.00001 to 0.01 in fraction [4] and [10].

3.3 Computational procedure

The response of the slope is numerically computed with the programs in FORTRAN 90. Basic steps of the program are outlined as follows. In the preprocess section, nodal data, element connectivity, boundary conditions, geometries, material properties are taken from input files. After reading the input data, elemental matrices and local nodal forces are generated and assembled in to global stiffness matrix and global load vector which are modified by incorporating boundary conditions. Matrix is solved using the preconditioned conjugate gradient method for efficient storage and fast computation of the nodal displacements and stresses. Then checks for fracture criteria are carried out. If there is no failure at any node or edge, given loading is increased by a specified amount which can be adjusted depending upon the requirements, and solution are repeated for the next iteration. If any edge is failed, then the number of edges and nodes are increased by one or two depending upon the location of the failed node, and restructuring is carried out creating a traction free surface and then analysis is carried on the same load and checked for further fracture. This process is repeated up to the desired cycles of iterations. The stresses, factor of safety with progression of fracture and failure path are computed with this simulation. A complete flow chat of the numerical procedure is shown in Fig. 5.

4. RESULT AND DISCUSSION

In this numerical procedure, both displacement fields and stress fields are computed in partially saturated soil slope condition with and without vegetation. The numerical computation has been carried out under pseudo-static seismic condition of coefficient 0.1*g. Numerical analysis can account for the correct reproduction of the stress distribution between root and surroundings soil. Weights of the building structures are taken as 100 kN/m^2. Useful conclusions of soil-root interaction effect can be drawn from Table 2 and 3. Table 2, shows the comparison of FS for LEM and FEM, and Table 3 shows, changes on stability factor of slope with respect to RAR if other variables remain constant. Table 3 indicates that stability factor first increases with RAR, after attaining certain stability factor further increment of RAR within certain limit does not strengthen stability factor. Maturity period of root has expected influences on the RAR and hence the stability factor of the soil slopes.

The simulation result for the slope clearly indicates that the stresses are very high near the mid part of the domain as shown in Fig. 6. Thus, a high degree of stress anisotropy existed along the slope geometry. This stress anisotropy probably caused considerable displacement. This highly anisotropic stress condition and the large displacements are believed to have great influence on the stability of the slope geometry as shown in Fig. 6(a) to Fig. 6(c). In particular, the simulation results obtained from such analysis may provide valuable input for predicting the potential progressive development of failure which may ultimately lead to failure. As shown in displacement contours in Fig. 7(a) to Fig. 7(c), lateral displacement mainly appears at the slope surface. The maximum lateral displacement appears at the foot of the slope where the contours are denser. There is obvious change in lateral displacement incorporating with vegetation cover. Vertical displacement distributes widely and the maximal value appears at the top of the slope. The magnitude of horizontal displacement is the important measurement of slope stability analysis. The decrease in horizontal displacement corresponding to the increase in slope stability. One notable characteristic of lateral and vertical displacement is that gradient variation of displacement occurs directly at the superficial layer of slope and the visible slope is prone to superficial layer failure. Visualization of the failure mechanism can be accomplished through a combination of both total displacement contours and deformed outline of boundaries. The maximal lateral and vertical displacement appear at the foot and the top of the slope respectively. One of notable characteristics in these two displacements is that the change region of displacement is mainly at the superficial layer, and not at the deep layer.

The effect of reinforcement on the slope is not only in the FS, but also in displacement; pore-pressure; stress level, and so on. The reinforcement reduces displacement, pore pressure, and stress level while it increases the FS. The FEM method with the elastic-plastic constitutive model can analyze all these factors. Synthesis of all these factors shows that the effect of reinforcement in natural slopes is obvious.

The numerical analysis of natural slope has demonstrated that if reliable, good quality input data are available, valuable analysis of stresses and displacements as well as evaluation of possible slope failure can be achieved. In particular, the simulation results obtained from such analysis may provide valuable input for predicting the potential progressive development of failure which may ultimately lead to failure.

5. CONCLUSION

A new numerical scheme in Finite element method (FEM) along with Mesh free method (MFM) and suitable convergence criteria is implemented to simulate the progressive nature of failure in soil-root matrix continuum. With the consideration of homogenizing approach, the complex behavior of soil-root interaction can reliably be captured of any natural slopes. In this numerical scheme, both displacement fields and stress fields of each failure stages are computed in partially saturated soil slope condition with and without vegetation cover. Root-reinforcement effect has significant role in modifying stress anisotropy and displacement behavior of the slope. We estimated the value of FS in between 1.20 and 1.35 on the basis of different possible RAR. We also compared the results with LEM for the preliminary judgment of the result. Result shows that stability factor first increases with RAR, after attaining certain stability factor further increment of RAR within certain limit does not impart on stability factor of slopes. After certain RAR say more than 0.5%, there is no any change on stability factor. Results show that vegetation has significant influences on safety factor in certain effective RAR-range, which further illustrates the potential applications of soil-bioengineering techniques in slopes or the necessities of vegetation cover in slopes; however, it requires more realistic model parameters and boundary conditions to perform more relevant simulations.

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