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Estimation of factor of safety of rooted slope using an evolutionary approach

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ABSTRACT

Use of roots as one of slope stabilization technique via mechanical reinforcement has received considerable attention in the past few decades. Several mathematical models have been developed to estimate the additional cohesion due to roots, which is useful for the calculation of factor of safety (FOS) of the rooted slopes using finite element method (FEM) or finite difference method. It is well understood from the literature that the root properties such as root area ratio (RAR) and root depth affects the mobilized tensile stress per unit area of soil consequently affecting the FOS of the rooted slope. In addition, a fracture phenomenon also influences the FOS of the rooted slope and should also be considered. In the present work, a new evolutionary approach, namely, multi-gene genetic programming (MGGP) is presented, and, applied to formulate the mathematical relationship between FOS and input variables such as slope angles, root depth and RAR of the rooted slope. The performance of MGGP is compared to those of artificial neural network and support vector regression. Based on the evaluation of the performance of the models, the proposed MGGP model outperformed the two other models and is proved able to capture the characteristics of the FEM model by unveiling important parameters and hidden non-linear relationships.

1. Introduction

Soil bioengineering technique that uses vegetation as a reinforcement have got significant attention in the field of natural and manmade slope stabilization (Stokes and Mattheck, 1996; Waldron, 1977; Simon and Collison, 2002; Pollen and Simon, 2005; Rees and Ali, 2006; Norris et al., 2008; Stokes et al., 2009; Ali, 2010; Rees and Ali, 2012; Ali et al., 2012; Garg et al., 2012; Stokes et al., 2012a, 2012b; Mao et al., 2013a, 2013b; Ghestem et al., 2013). Roots with typical tensile strengths of 5–50 MPa (Mickovski et al., 2009) have comparable strengths to some materials used in engineering and therefore, its reinforcement effect on slope stability is not surprising.

Various models based on experimental analysis and numerical modeling have been developed to account for mechanical reinforcement by roots in the engineering design of new slopes (Wu et al., 1979; Waldron and Dakessian, 1981; Gray and Sotir, 1996; Operstein and Frydman, 2000; Bibalani et al., 2007; Wu, 2007; Schwarz et al., 2010; Tiwari et al., 2012). These design takes into account detrimental effects of roots, e.g., serviceability, wind throw, slope loading, cracking and (or) desiccation near the surface etc. (Greenway, 1987; Gray and Sotir, 1996). Recently, a model developed Tiwari et al. (2012) considered fracture phenomenon by considering progressive failure of rooted slope while computing FOS of rooted slope. In their study, fracture treatment takes into account the sudden transition of continuous displacement function to the discontinuous displacement function and is able to treat complex nature of fracture phenomena in a more reliable manner. This type of progressive failure is more close to reality as it considers both material and geometrical non-linearity in natural slopes (Tiwari et al., 2012). It is useful as it can effectively be used to assess the hazard for potentially landslide prone soil slope, and design the structurally safe and economic slopes. Therefore, it is more reasonable to consider progressive failure into account while estimating FOS of rooted slopes. Several equilibrium equations are solved using Finite element method (FEM) in order to compute factor of safety for rooted slopes.

Other modeling methods, namely statistical methods such as regression analysis, and, soft computing methods such as multi-gene genetic programming (MGGP), support vector regression (SVR) and artificial neural network (ANN), are becoming increasingly popular in formulation of the models in field of geotechnical engineering (Shahin et al., 2008). Statistical methods are based on assumptions such as the structure of the model, the normality

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of residuals, and, are generally not preferred, whereas, the soft computing methods being void of statistical assumptions are best known for capturing the dynamics of the system involving multiple input parameters. Gandomi and Alavi (2011, 2012, 2013a) in his work demonstrated the usefulness of MGGP approach in designing the non-linear models based on the data obtained from the complex geotechnical and earthquake systems. Studies reveal that MGGP method provides a fast and cost-effective explicit formulation of a mathematical model based on multiple variables with no existing analytical models. Apart from MGGP, several ANN models have been developed to estimate FOS of slopes with different slope geometry and soil conditions (Li and Liu, 2004; Cho, 2009; Lin et al., 2009; Choobbasti et al., 2009; Li and Wang, 2010; Abdalla et al., 2012). However, these models did not take into account any effect of root properties on FOS of the slopes. Since, Tiwari et al. (2012) showed that FOS of rooted slope is greatly affected by its slope angle and root properties such as root area ratio (RAR) and root depth. These parameters along with the observed fracture phenomenon in rooted soils must be taken into account while developing any models using soft computing methods.

The present study explores the ability of three soft computing methods: MGGP, SVR and ANN in the formulation of explicit mathematical models for the prediction of FOS of the rooted slope under different input conditions. For the comparison of three methods, statistical analysis is conducted to identify the best prediction method. Further, the parametric and sensitivity analysis is conducted on the best model to reveals insights about the mechanism of estimation of FOS.

2. Finite element method for estimating FOS

For the model development, FOS data for the rooted slopes was taken from a comprehensive study conducted by Tiwari et al. (2012). A realistic problem domain was considered with slope being discretized to include the complexities of soil; water and root related effects. Slope angle was varied in the range 30–50°. A fixed boundary at the bottom and vertical movable boundary at the left, and, partially fixed and movable boundary at the right, were imposed. Problem domain mainly concerns partially saturation state of soil, which resembles the natural slope. Vegetation roots effect was considered by considering mobilized tensile stress of the root fibers per unit area of soil and RAR. RAR was used as an input to a model of root-reinforcement which takes into account the additional cohesion to the stability factor. Root material is considered as a linear-elastic material with a modulus of elasticity of 1.5×10^{-5} kN/m^2, a Poisson's ratio of 0.3, and a maximum yield stress of 107 kN/m^2 as a sample. Based on field investigation, enhanced unit weight of the root was assumed as 1.5 kN/m^3 and Young's modulus of elasticity as 0.15×10^{-5} kN/m^2. Other factors such as cohesion due to evapo-transpiration were varied from 0 to 10 kN/m^2; angle of internal friction due to root from 0 to 5°; surcharge loading due to weight of vegetation from 0 to 5 kN/m; wind loading force parallel to the slope per tree from 0 to 3.5 kN/m; Mean tensile strength of root from 5 to 80 kN/m^2 and RAR from 0.00001 to 0.01. The soil is modeled as an elasto-plastic material with Mohr–Coulomb failure criteria. A new numerical scheme in FEM along with Mesh Free Method and a suitable convergence criterion is used to simulate the progressive nature of failure including fracture phenomenon in soil-root matrix continuum. A parametric study was conducted to investigate FOS using different combinations of slope angle, root depth and RAR. FOS was computed for different combinations of slope angle, root depth and RAR using FEM analysis. Further details on slope geometry, root properties, soil properties and modeling procedures are described in Tiwari et al. (2012).

Table 1
Descriptive statistics of the input and output process variables collected from experimental study.

Parameter	Root area ratio (x_1)	Root depth (x_2)	Slope angle (x_3)	Factor of safety (y)
Mean	0.21	0.51	40.59	1.12
Standard error	0.01	0.03	0.50	0.01
Median	0.2	0.6	40	1.08
Standard deviation	0.14	0.44	6.84	0.13
Variance	0.02	0.19	46.90	0.01
Kurtosis	−0.75	−1.22	−1.22	−0.42
Skewness	0.36	0.53	−0.07	0.80
Minimum	0	0.1	30	1
Maximum	0.5	1.2	50	1.47

Data obtained from the FEM modeling comprise of three input process variables such as RAR (x_1), root depth (x_2) and slope angle (x_3) and the output process variable, namely, FOS (y). Total of 184 set of data samples were obtained from the FEM analysis. Nature of the data set collected is shown by descriptive statistics in Table 1. The formulation of problem of modeling the FOS is shown in Fig. 1. Selection of training and testing data set affect the learning capability of the methods. In this work, Kennard-and-Stone algorithm is used to select the appropriate training and testing data set. The algorithm selects the training data samples in such a way, that the data is distributed uniformly throughout the domain. Several applications of this algorithm have been reported in literature (Garg and Tai, 2013; Garg et al., 2013a,b,c,d). 147 samples was chosen as the set of training data with the remainder as the set of test samples. The training data was used for formulating the models while the test data samples were used for testing the generalization ability of the models.

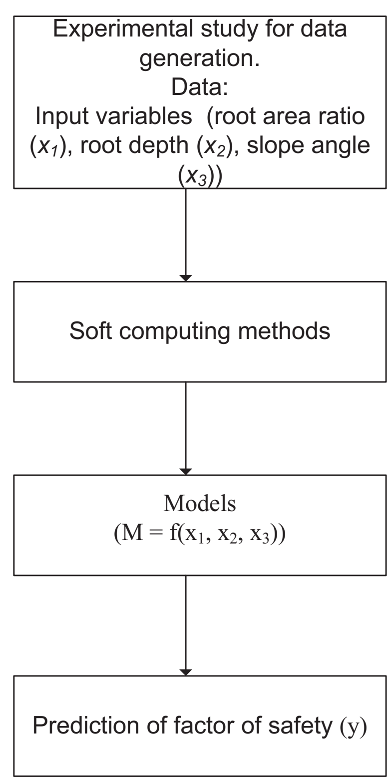

Fig. 1. Problem formulation of modeling factor of safety.