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An integrated SRM-multi-gene genetic programming approach for prediction of factor of safety of 3-D soil nailed slopes

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ABSTRACT

Soil nailing is one of the slope stabilisation techniques useful for the strengthening of existing slopes. It helps to reinforce the soil with passive inclusions that increase the overall shear strength of the soil slope and also restrains its displacements. The limit equilibrium method is usually employed to estimate factor of safety (FOS) of nailed slopes through either finite element or finite difference methods. Alternatively, soft computing methods such as multi-gene genetic programming (MGGP), support vector regression (SVR) and artificial neural network (ANN) can also be used to predict the FOS for different soil properties. Among these methods, MGGP possesses the ability to evolve the model structure and its coefficients automatically. Although widely used, the MGGP method has the limitation of producing models that perform poorly on testing data. Therefore, in this study, an integrated structural risk minimisation-multi-gene genetic programming (SRM-MGGP) method is proposed to formulate the mathematical relationship between FOS and the six input variables of cohesion, frictional angle, nail inclination angle, nail length, slope height and slope angle of 3-D nailed slope. The results indicate that the SRM-MGGP model outperforms the other three models (MGGP, SVR and ANN) and is able to generalise the FOS satisfactorily for any given input variables conditions. This would be useful for engineers in their design calculations of slopes with different soil, slope and nail conditions based on certain limitations such as ignorance of effect of pore water pressure or overburden pressure.

1. Introduction

Soil nailing is one of the economic slope stabilisation technique and is particularly useful for the strengthening of existing slopes. The principle behind soil nailing is to reinforce the soil with passive inclusions which increases the overall shear strength of the soil slope and also restrains its displacements. There are many different design methods for soil nailing, which includes limit equilibrium method (LEM), strength reduction method, several working stress design methods, the Davis method (Shen et al., 1981), the German method (Stocker et al., 1979) and the French method (Schlosser, 1982, 1991). Among them, LEM is commonly used for slope stability analysis by many researchers (Donald and Giam, 1988; Matsui and San, 1992; Griffiths and Lane, 1999; Ugai and Leshchinsky, 1995; Song, 1997; Dawson et al., 1999; Cheng et al., 2007, 2008). The LEM analysis used in nailed slope analysis is based essentially on Spencer's method, where the effect of a soil nail is considered by applying a concentrated load provided by the nail on the slip surface. FOS for slopes using LEM methods are computed using 2-D or 3-D Finite element method (FEM) or Finite difference method (FDM) is generally used to estimate FOS of nailed slopes (Shen et al., 1981; Juran and Elias, 1987; Plumelle et al., 1990; Thompson and Miller, 1990; Srinivasa Murthy et al., 2002; Sivakumar Babu et al., 2002; Wei and Cheng, 2010).

On the other hand, in recent years use of soft computing methods such as artificial neural network (ANN) is becoming increasingly important in geotechnical engineering (Shahin et al., 2008). Many 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, all those models did not take into account any effect of nails on FOS of slopes. In addition to this, most of these developed models are based on 2-D boundary conditions without incorporating 3-D effects which are more realistic in nature and is essential for soil nail problems. Since, Wei and Cheng (2010) showed that FOS of nailed slope is greatly affected by cohesion, frictional angle, nail inclination angle, nail length, slope height and slope angle of 3-D nailed slope. These parameters must be taken into account while developing any models using soft computing methods.

Other soft computing methods such as support vector regression (SVR) and genetic programming (GP) can also be used to

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predict the FOS for the different soil properties. Among these methods, GP possesses the ability to evolve models structure and its coefficients automatically (Cevik and Guzelbey, 2007; Cevik and Sonebi, 2008; Gandomi et al., 2010). Most popular variant of GP used recently is multi-gene genetic programming (MGGP) (Gandomi and Alavi, 2011; Garg and Tai, 2012, 2013; Garg et al., 2013a). Despite large applications of MGGP in field of structural and civil engineering, MGGP has limitation for producing models that over-fit on the testing data. The reason can be attributed to the large size models produced during the evolutionary stage in MGGP that captures noise along with relationships from the training data. *Over-fitting* in MGGP is the popular problem among researchers and have been paid less attention (Chan et al., 2011; Gonçalves et al., 2012; Garg et al., 2013b).

Therefore, in the present work, SRM-based-multi-gene genetic programming approach (SRM-MGGP) is proposed for predicting FOS for 3-D nailed slopes using the results from the LEM analysis. FOS under different six input parameters such as cohesion, frictional angle, nail inclination angle, nail length, slope height and slope angle of 3-D nailed slope were used to train and test newly developed SRM-MGGP model. Unlike standard GP, each model participating in SRM-MGGP approach is a set of combination of genes. Structural risk minimisation (SRM) principle is integrated to improve the generalisation ability of the models during the evolutionary stage of the method. The performance of the proposed SRM-MGGP method is compared to that of the other three potential methods: standardized MGGP, SVR and ANN.

2. Numerical method for estimating FOS

For model development, FOS data for nailed slopes was selected from a comprehensive study conducted by Wei and Cheng (2010). A parametric study was conducted to investigate FOS using LEM analysis under different combinations of cohesion, frictional angle, nail inclination angle, nail length, slope height and slope angle. In their LEM analysis, only the tensile strength and pull-out capacity of the nail were considered. The tensile forces mobilised in the nails were divided into tangential and normal components along the potential slip surface which were then added to the resistant forces to determine the FOS. The effective nail load is taken as the minimum of: (a) the tensile strength of the nail; (b) the bond strength between the grout and the nail; (c) the bond strength between grout and soil. The ultimate bond strength of a soil nail (τ_f) based on approach by Shen et al. (1981) is estimated as $\tau_f = \pi Dc' + 2c'\sigma_v' \tan\varphi'$, where D is the hole diameter, σ_v' is the effective vertical stress on the nail, $\tan\varphi'$ is the frictional coefficient between the soil and the nail, and c' is the cohesion of the soil. An additional FOS of 2.0 is given to the ultimate bond strength for design purposes for a reason that adhesion and friction between the soil and nail will be less than c' and $\tan\varphi'$, respectively. There is another soil design practice where bond strength is assumed to be independent of the confining stress. Based on laboratory and field tests in Hong Kong, both design practices may be applicable under different cases. During bond strength calculation, portion behind the failure surface is taken in the calculation for pull-out failure, while the portion in front of the failure surface is taken in the calculation for face failure. The force determined is then applied as a point load on the failure surface. Another important conclusion as determined from Wei and Cheng (2010) study is the importance of modeling of nail head. It was revealed that failure modes associated with modelling of nail head and without modelling of nail heads were found as face failure mainly and pull out failure respectively. These can be compared to the real performance of geotextiles for embankment stabilisation, where the bond loads for the two sides of geotextiles need to be checked (no anchorage to the geotextile). Apart from this, another type of failure which can be possible is nail tensile failure (Byrne, 1996). FOS values for the different combinations of cohesion, frictional angle, nail inclination angle, nail length, slope height and slope angle were estimated using 3-D FEM analysis, which was conducted using their in-house developed programme Slope2000. In general, soil nailed slope with a height of 6 m and slope angle of 45° was analysed. 8 m length nails are installed at 1.5 m centres horizontally and vertically. The diameter of the steel bar is 40 mm and the grout hole diameter is 100 mm. For describing, grout–soil–nail systems, the material properties of the grouted nail were calculated considering a combination of the stiffness of the steel bar and the cement grout. In their study, the Young's Modulus of the grouted nail was determined as 45.44 GPa. A thin layer of material with a thickness of 4.0 mm surrounding the nail was used to model the shearing zone between the nail and the soil. Cross-sectional area, compressive yield strength and tensile yield strength of the grouted nail was determined as 0.00785 m^2, 0.238 MN and 0.238 MN. Further, details on material properties of grout–soil–nail system, slope geometry, nail distribution and interpretation of results (FOS and failure mechanisms) are described in Wei and Cheng (2010). Based on rigorous study by Wei and Cheng (2010), any effects of overburden pressure on the nail from the external load is usually not considered in the bond strength calculation (appear to be the practice for all commercial programs) in LEM analysis.

Data obtained from the LEM analysis comprise of six input process variables such as cohesion (x_1), frictional angle (x_2), nail inclination angle (x_3), slope angle (x_4), nail length (x_5) and slope height (x_6) and the output process variable, namely, FOS (y) of 3-D nailed slope. It should be noted for simplicity, any effects of pore water pressure distribution on FOS are not taken into account. Comprehensive studies are required to consider effects of pore water pressure on soil–nail interaction. Total of 42 set of data samples were obtained from the LEM analysis as discussed in Section 2.1. Nature of the data set collected is shown by its descriptive statistics in Table 1. The formulation of problem of modelling the FOS is shown in Fig. 1. Selection of training and testing data set affect the prediction ability of the model. In

Table 1
Descriptive statistics of the input and output process variables used in LEM analysis.

Parameter	Cohesion (x_1)	Frictional angle (x_2)	Nail inclination angle (x_3)	Slope angle (x_4)	Nail length (x_5)	Slope height (x_6)	Factor of safety (y)
Mean	10.83	23.71	3.80	51.42	8.95	6.38	1.45
Median	9	18	0	45	8	6	1.24
Standard deviation	5.93	11.15	12.08	13.71	2.03	0.79	0.67
Variance	35.16	124.40	146.10	188.15	4.14	0.63	0.45
Kurtosis	−1.11	−0.48	12.94	2.86	−0.99	0.70	2.11
Skewness	0.27	0.37	3.55	2.02	0.65	1.63	1.23
Minimum	2	5	0	45	6	6	0.27
Maximum	20	45	60	90	12	8	3.67