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ICA-ANN, ANN and multiple regression models for prediction of surface settlement caused by tunneling

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ABSTRACT

Nowadays, with increasing urbanization and population of cities, the amount of internal transportations enlarged. To facilitate these movements, need for subway tunnels has been considerably increased. In urban areas, subway tunnels are excavated in shallow depth under thick populated areas and soft ground. Its associated hazards include poor ground condition, presence of water table above the tunnel, shallow overburden and surface settlement induced by tunneling. To avoid damage to surface structures and environmental problems, Maximum surface settlement (MSS) and its accurate prediction is one of the serious challenges during this procedure. In this paper, a new hybrid model of artificial neural network (ANN) optimized by Imperialist competitive algorithm (ICA), called ICA-ANN, has been presented for the prediction of MSS. For this purpose, a total number of 143 datasets including, horizontal to vertical stress ratio, cohesion and Young's modulus considered as input parameters and their corresponding MSS considered as an output parameter, were inquired from the line No. 2 of Karaj subway, in Iran. This datasets used in order to construct the MSS predictive models. To show the capability of the ICA-ANN model in predicting MSS, an ANN model and traditional statistical model of multiple regression (MR) was also employed. In order to assess the prediction performance of mentioned models, performance indices including, correlation coefficient (R^2), root mean square error (RMSE) and variance account for (VAF) were calculated. Results of comparing reveals that the proposed ICA-ANN model is capable to predict MSS with higher reliability than the ANN and MR models.

1. Introduction

There is a great demand for infrastructures in cities and crowded urbanized areas due to rapid growth in urban development. In many cases, the best choice for much of this infrastructure will be a tunnel. Sewage disposal, water supply and transportation systems urged us to construct the underground tunnels. Tunneling operations unavoidably disturbs the original stress field, and consequently in response, ground settlement is induced (Wang et al., 2016). Most common metro tunnels characteristics are that they are very shallow tunnels which is widely excavated in urban areas with high population density and soft ground, which induce both lateral and vertical surface movements (Boscardin and Cording, 1989). Both surfaces (Melis et al., 2002) and subsurface facilities (Vorster et al., 2005) are threatened by Ground settlement (surface vertical movement) especially in urban areas (Liao et al., 2009). Therefore, reliable estimation and analysis of MSS induced by tunneling is one of the major concerns in tunneling constructions, particularly in congested urban areas. Peck (1969) demonstrated that the surface settlement trough can be approximated by the Gaussian curve.

$$S = S_{\max}\exp\left(-\frac{x^2}{2i^2}\right) \tag{1}$$

In the above equation, S is ground settlement, S_{max} is the maximum surface settlement (MSS) above the tunnel centerline, x is the horizontal distance from the tunnel centerline in the transverse direction, and i is the distance from the tunnel centerline to the inflexion point of the curve and is called settlement trough width, which determines the shape of the curve, as shown in Fig. 1. The MSS accurate prediction plays a vital role in order to avoid potential damage to both surface and subsurface facilities. The MSS is depending on many parameters including excavation method and its parameters such as NATM, TBM or cut and cover, support method such as shotcrete, lining, etc., geological conditions such as unit weight, poison's ratio, friction angle, Young's modulus, cohesion, geometrical shape of the tunnel, including tunnel diameter and depth, number and distance between the tunnels and geotechnical parameters such as groundwater and permeability. There are several methods for prediction of tunneling induced MSS which is investigate the effects of the mentioned parameters on MSS. MSS prediction methods can be divided into empirical, analytical, numerical

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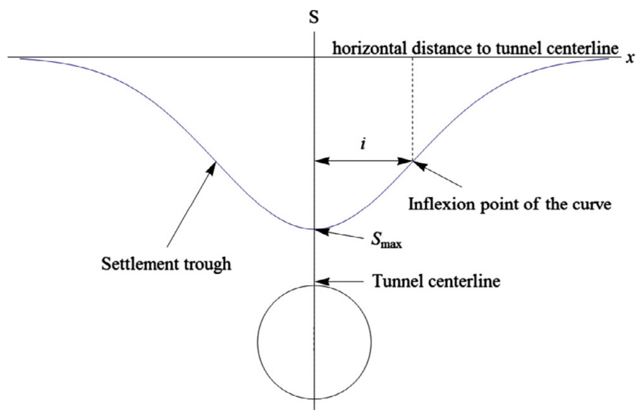

Fig. 1. Ground settlement trough induced by a single tunnel (Ma et al., 2014).

and artificial intelligence methods.

Empirical models propose simple mathematical formulae based on data gathered from extensive field in situ observation and a large number of measurements during tunnel excavation. These models can approximate settlement trough in a specific area and settlement can be calculated at any point of the area. Martos (1958) first showed that the Gaussian or normal distribution curve could be well represent the settlement trough above the mining excavation. Peck (1969) first fitted the Gaussian curves and established a relationship between the relative depth of a tunnel and the inflection point of the transverse settlement trough for various soil types. He showed that settlement curve is approximately symmetrical above the vertical axis of the tunnel. various researchers attempt to estimate the MSS and form an empirical relationship based on different input parameters such as depth and diameter of tunnels, elastic modulus, the distance between the tunnel and the underlying rigid base stratum, plastic failure, initial stresses, ground loss (including the annular void), injection of clay grout into the tail-piece void and inflection point (O'reilly and New, 1982).

The analytical methods for estimation of MSS divides into four main categories, namely virtual image technique (Sagaseta, 1987), the general series form stress function in polar coordinate (Bobet, 2001), stochastic medium theory (Yang et al., 2004) and the complex variable method (Verruijt, 1997).

In recent decade, Computer technology and numerical algorithms are rapidly developed and make the opportunities to employ these methods in broad tunneling projects. The MSS estimation by the finite element method (FEM) and finite difference method (FDM) is interested by various researchers (Melis et al., 2002; Sun and Liu, 2002; De Farias et al., 2004). Kasper and Meschke (2004), investigated the surface settlement in shield-driven tunnels by finite element method (FEM). Chakeri et al. (2013) studied the effects of tunnel depth, overburden pressure, tunnel dimension and face pressure on surface settlement in the EPB tunneling method by empirical, analytical and numerical (FDM) methods. Yasitli (2013) modeled the surface settlement of the transition zone of Istanbul metro, which is excavated by New Austrian Tunneling Method (NATM) and Umbrella Arch Method (UAM) using a 3D FDM method called FLAC^{3D}.

Beside other methods mentioned above, in recent years many artificial intelligence (AI) methods are employed to estimate the surface settlement due to tunneling excavation. Many studies indicate the application of Artificial neural network (ANN) to develop surface settlement predictive models caused by EPB shield tunneling (Suwansawat and Einstein, 2006; Ocak and Seker, 2013). Also other researchers employed the ANN method for other type of tunneling such as NATM or sequential excavation (Neaupane and Adhikari, 2006; Pourtaghi and Lotfollahi-Yaghin, 2012). support vector machines (SVM) (Samui, 2008), combination of ANN and heuristic algorithms called Hybrid methods (Jiang et al., 2011; Ding et al., 2012; Hasanipanah et al., 2016) has been used by many researchers for prediction of MSS. It is recognized that the empirical and analytical methods fail to take into account all the relevant parameters on MSS and limited only to the region that have been developed for. These methods have many simplifications such as soil isotropy (Franzius et al., 2005) and elastic behavior (Park, 2004; Pinto and Whittle, 2013). Numerical methods will give approximate solution, but not the exact solution. These methods are time consuming due to incorporating many details, especially in large problems that entire volume must be discretized in FEM or FDM methods. Analyzing of results obtained by numerical methods requires the basic understanding of the mechanisms involved in the physical process being modeled and more experience are needed. In this research, a combination of the ICA and ANN was proposed to develop the tunneling induced MSS predictive model along line No. 2 of Karaj subway. In point of fact, the ICA was employed for optimization of the ANN predictive model.

2. Theory and methods of modeling

2.1. Multiple linear regression

Regression analysis is a statistical technique for estimating the relationship between variables. It can predict the behavior of the dependent variables, based on the set of independent variables. Regression-based prediction is most effective when dealing with smaller numbers of variables, and large amounts of the reliable and valid data (Armstrong et al., 2015). It frequently makes useful forecasts (Allen and Fildes, 2001). It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables (or 'predictors') it is called simple regression and multiple regression, respectively. Multiple linear regression (MLR) is a method of finding a linear model of the relationship between the dependent variable (output parameters) and a set of independent variables (input parameters). In this technique, we wish to find a linear combination (line of best fit) of independent variables that will determine the dependent variable and minimizes error in predicting the dependent variable. The mathematical form of this model is

$$y = b_1x_1 + b_2x_2 + \ \dots + b_nx_n + c. \tag{2}$$

where the b values are the regression coefficients representing the change of dependent variable (y) when the corresponding independent variables (x) changes by 1 unit. c is constant, called the intercept as it is the value of the dependent variable when all independent variables are zero and the regression line intercepts the y-axis.

2.2. Artificial neural network

McCulloch and Pitts proposed the first prototype of neural network in 1943 (McCulloch and Pitts, 1943). Frank Rosenblatt created a perceptron network in 1958 that used for pattern recognition (Rosenblatt, 1958). Paul Werbos created the back-propagation algorithm in 1975 that increase the efficiency of the perceptron networks (Werbos, 1974). An artificial neural network (ANN) is a mathematical model inspired by the biological behavior of neurons and by the structure of the brain, which is used in order to solve a wide range of problems. The ANNs consist of basic processing elements called artificial neurons (AN) or nodes, which are a model of biological neurons and highly interconnected with each other. Each AN receives incoming signals from ANs in the previous layer. Associated with all incoming signals, there is a negative or a positive numerical weight that indicates an inhibitory or excitatory connection to the AN respectively. To produce the AN input, all the incoming signals are summed together and modified by the weights (linear combination). The output of each AN is a function of the AN inputs called an activation function that controls the amplitude of the output. An acceptable range of output values may be between [0