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Wavenet ability assessment in comparison to ANN for predicting the maximum surface settlement caused by tunneling

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ABSTRACT

An alternative method of maximum ground surface settlement prediction, which is based on integration between wavelet theory and Artificial Neural Network (ANN), or wavelet network (wavenet), is presented. In order to minimize the risk of tunneling, a tunnel engineer needs to be able to make reliable prediction of ground deformations induced by tunneling. Any prediction from numerical analysis was highly dependent on the model adopted for modeling the soil behavior. However, setting up a realistic model that would be able to calculate tunneling-induced settlement profiles is rather difficult. Most of the researches show that the capability (i.e. pattern recognition and memorization) of an ANN is suitable for inherent uncertainties and imperfections found in geotechnical engineering problems considering its successful application without any restriction. Wavenet is a single hidden layer feedforward neural network, which uses wavelets as its activation functions. In this study different wavelets are applied as activation functions to predict the maximum surface settlement due to tunneling. Wavenet parameters such as dilation and translation are fixed and only the weights of the network are optimized during its learning process, which is performed by a back-propagation algorithm. The efficacy of this type of network in function learning and estimation is demonstrated through measurements extracted from EPB shield tunneling. The simulation results indicate decrease in estimation error values that depicts its ability to enhance the function approximation capability and consequently exhibits excellent learning ability compared to the conventional back-propagation neural network with sigmoid or other activation functions.

1. Introduction

Ground settlements induced by tunnel construction may cause serious damage to adjacent structures, so an analytical estimation of the settlements is often conducted before the construction. Any tunnel and underground excavation inevitably disturbs the original stress field, which causes ground movement leading to ground settlement. The ground movements can be large enough to disrupt the function of adjacent structures and utilities. Particularly, in urban areas, the freedom of alignment choice and tunnel depth is rather limited. Furthermore, it is essential to protect existing adjacent structures and underground facilities from damage due to tunneling. In the last decades, some attempts have been made to develop analytical solutions for tunneling-induced ground settlements. Bobet (2001) presented an elastic solution for ground deformations of a shallow tunnel in a saturated ground by expanding the solution suggested by Einstein and Schwartz (1979) for a deep tunnel in dry ground. However, Chou and Bobet (2002) pointed that the estimation of the gap parameter was the most difficult task in these methods, because it depended on the quality of the construction and might vary from section to section with varying layer patterns. A displacement controlled model (DCM) was proposed to predict accurate tunneling induced ground movement, and it was applied to tunnel–soil–pile interaction problems (Cheng et al., 2008). On the other hand, with the development of computer hardware and numerical algorithms for the solution of large systems, the finite element method (FEM) becomes a popular numerical method to investigate this study (Augarde and Burd, 2001; Gioda and Swoboda, 1999; Karakus, 2007). In fact, simulation of tunneling using 2D or 3D FEM can often calculate any deformations and stress redistributions due to tunneling operations without constructing real trial tunnels. It takes account of the characteristics of both construction and ground conditions (geometry, initial stresses, ground behavior, excavation stages, etc.) with sophisticated constitutive models (ITA, 2007). Since the available information about the soil properties is scarce in many cases and does not justify the use of a complex constitutive soil model or a refined numerical method,

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the excavation process is also hard to simulate. Furthermore, the numerical model results always differ from field measurements and case histories. An infinite element has been developed for problems with an infinite domain (Beer and Meek, 1981; Beer and Young, 1983), and it is recommended for practical use in the subsidence estimation of grounds with a shallow depth. Karakus and Fowell (2003) concluded that any prediction from numerical analysis was highly dependent on the model adopted for modeling the soil behavior. However, setting up a realistic model that would be able to calculate tunneling-induced settlement profiles is rather difficult. The development of an analytical technique which can deal with the weight of the ground removed is a very important research theme. In order to minimize the risk, a tunnel engineer needs to be able to make reliable prediction of ground deformations induced by tunneling. Numerous investigations have been conducted in recent years to predict the settlement associated with tunneling; the selection of appropriate method depends on the complexity of the problems. In addition, numerical representation of excavation sequence, lining installation procedure, grouting and reinforcement, scale and time effects are also often-mentioned difficulties especially in the case of New Austrian Tunneling Method (NATM) (Jing, 2003). The magnitude of the settlements is affected by the weight of the ground which is removed at the tunnel excavation (Hisatake et al., 2009). Peck (1969) presented three basic requirements for the satisfactory design of a tunnel in soft ground. The first is that the construction method should be compatible with the nature of the ground and the ground water conditions. The second states that the tunnel should not excessively damage any adjacent structures. The third requires that the tunnel should withstand all the influences to which it may be subjected during its lifetime. It must be noted that this study is concerned primarily with the third stage of the problem. Obviously ground movements during tunnel excavation vary in magnitude and distribution depending on several factors related to tunnel geometry, ground conditions and so on. The basic effects of settlement are cracking causing structural damage or leakage and misalignment of the tunnel. These tunnels can take a surprising amount of differential settlement before a serious structural failure occurs, but long before that, leakage can become a severe problem that can shorten the life of a tunnel.

There are several empirical or semi-empirical formulae (Hong, 1984; Sagaseta, 1987, 1998; Bae, 1989) available for predicting ground movement. These empirical or semi-empirical approaches are based on the accumulated experiences over the years. Many environmental factors associated with tunneling have recently led to a considerable research effort being devoted to the study of settlements caused by tunneling through soft ground. Progress has been made in recent years in the ability to predict ground movement, but the state-of-the-art is deficient in many ways. On the basis of detailed investigation, a viable approach for ground movement prediction is necessary, and digital computers come in handy to fulfill this approach regarding to the increase in power and availability of them. There have been several applications of Artificial Neural Network (ANN) in geotechnical and rock engineering problems (Shi et al., 1998; Ghaboussi and Sidarta, 1998; Shin and Pande 2000). Most of the researches show that an ANN can be applied successfully to engineering problems without any restriction. It has also been seen that the capability (i.e. pattern recognition and memorization) of an ANN is suitable for inherent uncertainties and imperfections found in geotechnical engineering problems. Kim et al. (2001) concluded that the instrumentation data should be the best 'text book' for understanding the tunneling-induced ground settlement. However, most of the cases reported in the literature focused on the maximum ground settlement or the settlement distribution in space. The settlement trough produced by these analysis is always much shallower and wider than measured data (Karakus, 2007).

The combination of wavelet transformation ability with learning ability and general approximation properties of neural network causes a powerful method for revealing the property of function in localize region. Hence, different types of wavelet neural network (WNN) have been proposed in engineering problems (Boubez and Peskin, 1993; Yamakawa et al., 1994; Wang and Sugai, 2000a,b; Chen et al., 2006a,b; Zhang, 1992; Zhang et al., 1995). As an illustration, Boubez and Peskin (1993), used orthonormal set of wavelet basis functions. Moreover Yamakawa et al. (1994) applied non-orthogonal wavelet function as an activation function in single layer feedforward neural network. They have used a simple cosine wavelet activation function. Zhang (1997) has already shown that neural network with sigmoidal activation function can carry out large dimensional problem very well. WNN instigates a superior system model for complex and seismic application in comparison to neural network with sigmoidal activation function. The application of wavelet is limited to small dimension (Benveniste et al., 1994), though WNN can handle large dimensional problems (Zhang, 1997).

Motivated by the above considerations, this paper's main objective is to demonstrate how to utilize the accumulated database to evaluate particular tunnel sites. Thus, an intelligent neurons assemblage model with generalized wavelet basis function network namely a wavelet-based neural network is incorporated with the database leading to the prediction of ground settlement based on past tunnel records. This type of network, called wavelet network and Wavenet is another term to describe wavelet networks inspired by both the back-propagation neural networks and wavelet decompositions. The efficacy of these networks in function learning and estimation is demonstrated through measurements of settlement and ground movements recorded in an EPB shield tunneling project. The data from this case study were used to train and test the developed neural network and wavenet model to enable the prediction of the magnitude of settlements and ground movements with the help of input variables that have direct physical significance. Considering wavelets excited functions, the networks experience variations of geometrical parameters at different sections of the tunnels, geotechnical properties, ground conditioning, and construction procedures. Observations by comparing the model responses with the actual output measurements revealed that satisfactory model matching was obtained. For minimizing the mean square error between model outputs and its observation, an iterative minimization method of gradient steepest descent is applied. In the experiments, the wavelet network performed well and compared favorably to the back-propagation neural network. The simulation results indicate its ability to enhance the function approximation capability and exhibits excellent learning ability compared to the back-propagation neural network with conventional activation functions. It is shown that not only the wavelet neural networks convergence rate is much faster and its nonlinear approach capability is much better but also its intelligent characteristics, such as the variable-scale adaptive adjustment of structure and the generalized information storage, make it reflect much more accurately the biological original. It has been shown that the wavelet network has universal approximation properties and is a consistent function estimator.

The paper is organized as follows: Section 2 deals with empirical and conventional methods for predicting the maximum settlements of ground surface due to tunneling. Section 3 briefly describes ANN accompanied by its literature review for tunnel projects and consequently explains the measurements that are used in this study. Section 4 introduces the wavelet analysis and outlines a general WNN and wavenet with their applications. An optimal wavenet is then chosen in Section 5 and numerical examples are presented. Finally, in Section 6 conclusions of this study are presented.