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Modeling tunneling-induced ground surface settlement development using a wavelet smooth relevance vector machine

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ABSTRACT

Accurate prediction of ground surface settlement is necessary for effectively controlling the settlement that develops during tunneling. Many models have been established for this purpose by extracting the relationship between the settlement and the factors that influence it. However, most of the models focused on the maximum ground surface settlement and do not involve dynamic and real-time predictions. This paper investigated how tunneling-induced ground surface settlement developed using a smooth relevance vector machine with a wavelet kernel (wsRVM). Various factors that affect this settlement, including geometrical, geological and shield operational parameters were considered. The model was applied to earth pressure balance (EPB) shield-driven tunnels. The results indicate that the prediction model performs well and that the distribution of the predictions can provide a measure of the prediction uncertainty. Unlike conventional methods that requireadditional efforts to determine relevant model parameters, the proposed method can optimize the parameters in the training process. The results of the parametric study conducted show that the model performance can be improved by the optimization and that the method can serve as a simple tool for practitioners to use in estimating ground surface settlement development during tunneling.

1. Introduction

Ground surface settlement is an important field measurement for identifying the potential damage incurred to adjacent structures or facilities due to tunneling. Thus, analyzing and predicting settlement development are essential to avoid excessive settlement by taking appropriate countermeasures. Although empirical methods and analytical methods are available for settlement prediction, some researchers question the accuracy of these methods, pointing out that these methods fail to consider all the relevant factors which jointly affected the settlement [1–3].

During the past decade, artificial neural networks (ANNs) have been used as an alternative method for solving the problem. Most of the ANN-based analyses were implemented by extracting the relationships between influencing factors, such as the tunnel depth and soil properties, and the induced settlement. For example, Kim et al. [1] used artificial neural networks to predict the maximum settlement and inflection point that needed to generate the transverse settlement trough caused by tunneling. A total of 47 factors were considered as input variables for the network. Suwansawat and Einstein [4] established a neural network model to predict the maximum settlement induced by earth pressure balance (EPB) tunneling. Shield operational parameters, as well as tunnel geometries and geological conditions, were incorporated to establish the predictive relations. Santosand Celestino [5] also developed ANN-based models to analyze the influence of relevant factors on settlement and concluded that the complete adoption of factors would improve the prediction capacity of these models.

Support vector machines (SVMs), which are based on statistical learning [6], have also been successfully applied in highly nonlinear geotechnical areas. Samui [7] applied an SVM to the prediction of the settlement of shallow foundations on cohesionless soil and concluded that the use of SVMs could be very advantageous because the machines can perform nonlinear regression efficiently for high-dimensional datasets. Zhao and Yin [8] used an SVM in a back analysis to identify geomechanical parameters. Feng et al. [9] illustrated the potential of SVMs for modeling displacement time series. They proposed a model that incorporated an SVM to predict the deformations of high rock slopes and landslides and obtained satisfactory results. SVMs typically have goodgeneralization abilities because they adopt a structural risk minimization (SRM) induction principle instead of an empirical risk minimization (ERM) induction principle, which minimizes the error in both the training and testing data.

However, when using ANNs, it is difficult to determine the network architecture because no direction or analytical method is

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available, and ANNs often suffer the problem of poor generalization performance. SVMs also have some drawbacks, such as the determination of model parameters (e.g., the penalty weight C and the insensitivity parameter ε), relatively high model complexity and kernel function restrictions (i.e., the kernel function must satisfy Mercer's condition) [10].

The relevance vector machine (RVM) has recently emerged as a viable SVM competitor, due to its model sparsity, good generalization performance, free choice of kernel function and distributive prediction [11]. Because of these advantages, the results obtained from an RVM are often superior to those obtained from an SVM for the same inputs [12,13]. RVMs have been successfully applied to fault diagnosis [14], canal flow prediction [15] and monitoring network analysis [16]. Smooth relevance vector machines (sRVMs) are an extension of RVMs, to some extent [17]. To avoid overfitting or underfitting problems, sRVMs incorporate a sparsitycontroller called "smoothness prior" to directly control the model complexity. Due to the need for accurate real-time prediction capability, the potential for use of sRVMs with wavelet kernel functions (wsRVMs) to model ground surface settlement development induced by EPB shield tunneling was investigated in this paper. The instrumentation data and continuous observation of shield operational factors in two tunnel sections of the Wuhan metro project provide a good opportunity to study how settlements develop during shield passing. To this end, the model was trained and validated using the collected data. The performance of the wsRVM model was compared to that of other models (e.g., RVM, SVM and ANN), and the results indicated that the wsRVM model has good predictive ability.

2. Ground surface settlement development

The International Association of Engineering Insurers (IAEA) has reported that most failures, including excessive deformation, in tunneling projects occur during the construction phase [18]. However, most of the aforementioned studies focused on the maximum ground surface settlement. These static results do not fulfill the dynamic and real-time requirements of predicting ground surface settlement during tunnel construction [19]. Fig. 1 shows a typical longitudinal settlement profile obtained by connecting the instrumentation readings. The appropriate preventive measures have to be designed and implemented before a large settlement occurs, so predicting the settlement of each excavation step is critical for achieving the goal.

Nevertheless, settlement data are typically nonlinear and noisy, and shield–ground interaction is complex, implying that the modeling of settlement development could be challenging. Yeh [20] used the actual soil pressure, coupled with other factors, to predict the soil pressure of the next excavation step. In this paper, a similar method is adopted. The present settlement at a specific settlement marker s and affecting factors $\mathbf{F}$ are used as inputs to the model to predict the next settlement s', and the actual measurement of the next settlement is then taken as the present settlement for the next prediction (see Fig. 2). That is,

$$s' = f(s, \mathbf{F}) \tag{1}$$

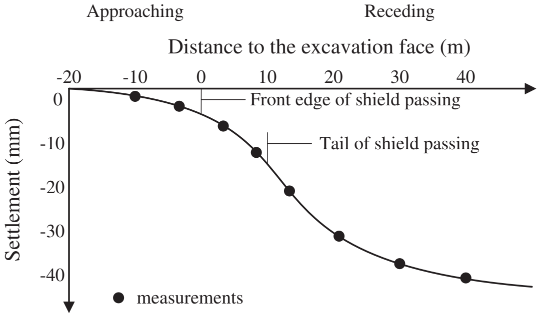

Fig. 1. A typical ground surface settlement development.

3. Factors affecting ground surface settlement

The factors that affect ground surface settlement can be classified into three groups: tunnel geometry (e.g., tunnel diameter, cover depth, excavation face height, etc.), geological conditions (e.g., Young's modulus, Poisson's ratio, permeability, shear strength parameters, etc.) and construction parameters (e.g., excavation method, support method, support time, etc.) [1,5]. Because the proposed method is applied to EPB shield-driven tunnels, the construction parameters are specifically the shield operational parameters.

3.1. Geometrical characteristics

Tunnel depth (Z) and tunnel diameter ($2R$) are usually considered important geometrical parameters that affect the settlements [21] and excavation face stability of shield-driven tunnels [22]. An analysis carried out by Norgrove et al. [23] indicated that the ratio of the depth to the diameter ($Z/2R$) should be taken as a combined factor of influence. However because the diameter of the tunnels was designed as a constant of 6 m, the effect of tunnel diameter is negligible in the present model. Therefore, the first geometric factor is the tunnel depth. Another important factor is the distance from the excavation face to the settlement markers. As summarized in the longitudinal development ofsettlement, the effect of tunneling increases as the shield approaches and decreases as the shield recedes [24]. To distinguish the directions, we define the distance value as negative in the case of approaching and positive in the case of receding.

3.2. Geological conditions

Some previous works have taken soil properties such as Young's modulus and shear strength as geological factors [25,26]. However, detailed geological investigation of the soil properties at each instrumentation section is practically impossible, making it difficult to obtain the values of the soil properties. Other researchers, such as Kim et al. [1] and Suwansawat and Einstein [4], used soil type to represent the soil properties because the differences in properties among soils of different types are generally greater than those among soils of the same type. Thus, the use of soil type can, to some extent, solve the problem of the values of soil properties being unavailable. In the model presented in this paper, the soil types at the tunnel crown and at the tunnel invert are considered

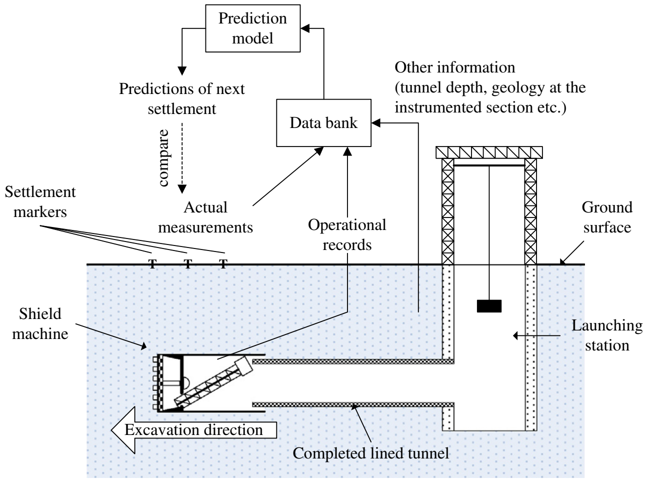

Fig. 2. Schematic diagram for predicting settlement development.