Prediction of ground settlement during tunnelling in water bearing ground

La prédiction de règlement de terre pendant tunnelling dans l'eau portant la terre

C. Yoo
Sungkyunkwan University, Suwon, Korea
S. B. Kim
Sungkyunkwan University, Suwon, Korea
H. S. Jung
Sungkyunkwan University, Suwon, Korea

ABSTRACT
This paper presents an artificial neural network approach for prediction of tunnelling-induced ground groundwater drawdown and associated settlement during tunneling in water bearing ground. A parametric study using a calibrated 2D stress-pore pressure coupled finite element analysis was conducted to form a database concerning the settlement and groundwater drawdown during tunneling in groundwater drawdown environment. An artificial neural network (ANN) was then developed based on the database to establish underlying relationships between tunneling and its consequence. The developed ANN exhibited excellent performance in predicting the magnitude of settlement and groundwater drawdown for tunneling conditions considered in this study, confirming that a generalized ANN can be deployed in practical use. Also examined the relative importance of influencing factors on the settlement and groundwater drawdown during tunneling based on the ANN results.

RÉSUMÉ

Ce papier présente une approche de réseau neuronale artificielle pour la prediction de nappe phréatique de terre tunneling-incitée drawdown et de règlement associé pendant tunneling dans l'eau portant la terre. Une etude paramétrique en utilisant un 2ème caliber étudie soigneusement tension la pression s'est accouplée l'analyse d'élément finie a été accomplice pour former une base de données concernant le règlement et la nappe phréatique drawdown pendant tunneling dans la nappe phréatique drawdown l'environnement. Un réseau neuronal artificial (ANN) a été alors développé base sur la base de données pour établir des rapport sous-tendants entre tunneling et sa consequence. ANN développée a exposé la performance excellente dans la prediction de l'étendue de règlement et de nappe phréatique drawdown pour les conditions tunneling considérées dans cette étude, en confirmant qu'ANN généralisée peut être déployée dans l'utilisation pratique. Aussi examine l'importance relative d'influencer les facteurs sur le règlement et la nappe phréatique drawdown pendant tunneling base sur les resultants d'ANN.

Keywords : tunnelling, settlement, groundwater drawdown, finite element anlaysis, artificial neural network

1 INTRODUCTION

It is well known that a groundwater drawdown caused by construction activities or pumping from a well accompanies ground settlements. Such a groundwater drawdown related ground settlements, or subsidence, problems can raise both environmental and technical issues (NSREA 1995), especially true in urban settings.

Tunnelling activities under the groundwater table inevitably result in groundwater inflow into excavated areas, the consequences of which is a groundwater drawdown in the surrounding aquifer and the related ground settlement, or subsidence, occurring as a result of the reduction in water pressures in the soil layers can damage nearby structures and utilities (Yoo 2005). Magnitudes of the groundwater drawdown-induced ground settlements are often excessive as they are additive to the settlements caused by tunnel excavation (Yoo 2005; Yoo and Kim 2006). It is therefore impetrative that such unwanted groundwater drawdown-related ground settlements during tunnelling should be controlled by appropriate control measures.

In this study, an ANN-based prediction method for groundwater drawdown and associated settlements during conventional tunneling in water-bearing ground is presented. The method is based on the results of a series of stress-pore pressure coupled finite element analyses on tunnelling cases with groundwater drawdown conditions frequently encountered the Seoul metropolitan area. Also discussed are the relative importance of influencing factors on the settlement and groundwater drawdown. This paper presents tunnelling cases considered, finite element modeling strategy including verification, finally development and implementation of the prediction method.

2 TUNNELLING CASES CONSIDERED

A typical tunnelling condition encountered in the Seoul metropolitan area is considered in this study (Figure 1). The ground is a multi-layered ground including a fill, alluvium, and a weathered zone as shown in this figure. The miscellaneous fill material is typical gravelly silty sand in nature. Underlying the fill layer is an alluvial deposit of clayey sand having the standard penetration blow count of N=30~35 followed by a decomposed granitic soil layer. The decomposed soil layer is underlain by a weathered granitic rock layer having N value greater than 50, followed by a soft to hard granitic rock layer.

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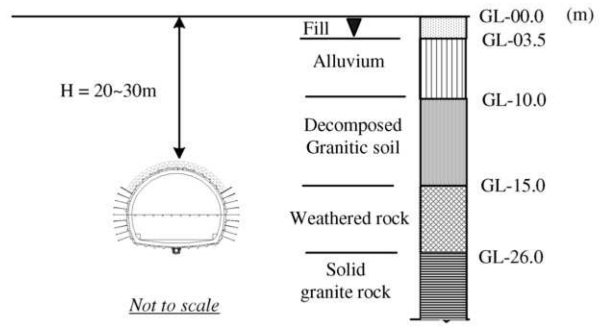


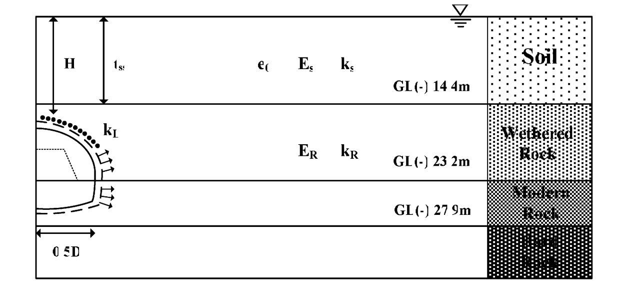
Figure 1. Typical tunnel section considered.

In order to cover a broad range of urban tunnelling situations, the ground profile including the location of groundwater table and the mechanical as well as hydraulic properties of the soil above the tunnel as well as the rock layer at the face were varied with due consideration of the results of survey on tunnel design reports conducted as part of this study. Variable considered include the thickness of the soil layers, the location of ground water table, the void ratio of the soil layer, and the elastic moduli and permeabilities of the soil and rock layers. It should be noted that the elastic moduli of the soil and rock layers were varied with fixed shear strength properties to reduce the number of variables.

Although a trumpet shaped circumferential pregrouting is usually adopted in tunnelling cases with high groundwater table, no pregrouting was considered in this study to represent rather worst case scenarios in terms of groundwater control. The variables and the ranges of variables considered in this study are summarized in Table 1 and 2, respectively. A total of 140 cases were considered in this study.

Table 1. Variables considered.

Variabl es	Description	Range
D (m)	Tunnel diameter	10 ~ 18.985 (m)
H (m)	Tunnel cover depth	15.610 ~ 70 (m)
t_{ss} (m)	Thickness of soil layer	0 ~ 30 (m)
e_s	Void ratio of soil layer	0.7 ~ 1.4
k_l (m/s)	Permeability of shotcrete	2×10^{-10} ~ 2×10^{-7}(m/s)
E_s (kPa)	Elastic modulus of soil layer	20 ~ 70 (MPa)
k_s (m/s)	Permeability of soil layer	2.7×10^{-6} ~ 5.8×10^{-5}(m/s)
E_r (kPa)	Elastic modulus of rock layer	100 ~ 10250 (MPa)
k_r (m/s)	Permeability of rock layer	3×10^{-10} ~ 6.2×10^{-6}(m/s)



3 PARAMETRIC STUDY

The commercially available multi-purpose finite element package Abaqus (2007) was used for analysis of aforementioned cases to form a database for use in the development of the prediction method. A fully coupled stress-pore pressure formulation was adopted in order to realistically capture the mechanical and hydrological interaction between the tunnelling and groundwater. Details of the coupled formulation can be found in Abaqus (2007).

3.1 *Finite element model*

Figure 2 shows the finite element model adopted in this study. Due to the symmetry about the tunnel centerline only half of the tunnel section was modeled. To account for the importance of far-field boundary conditions in a stress-pore pressure coupled analysis, hence the size of the model, the far-field boundary was placed at a distance of 18 diameters from the tunnel with the bottom boundary at the solid rock layer. At the vertical boundaries, displacements perpendicular to the boundaries are restrained whereas pin supports were applied to the bottom boundary. With regard to the hydraulic boundary conditions and with reference to Figure 2, a no-flow condition was assigned to the left vertical boundary, i.e., the line of symmetry, while a constant hydraulic water pressure assuming the groundwater level at the surface was assumed throughout the analysis. The location of the far-field boundary was selected so that the presence of the artificial boundary does not significantly influence the stress-strain-pore pressure field in the domain. Free drainage after excavation was allowed at the excavated surface by assigning zero pore pressure flow boundary condition to allow for the water inflow to occur during tunnel excavation.

In discretizing the model, 8-node displacement and pore pressure elements with reduced integration (CPE8RP) were used for the soil/rock layers and the shotcrete lining assuming full saturation as part of initial condition. The soil and rock layers were assumed to be an elasto-plastic material conforming to the Mohr-Coulomb failure criterion together with the non-associated flow rule proposed by Davis (1968), while the shotcrete lining was assumed to behave in a linear elastic manner. The time dependency of the strength and stiffness of the shotcrete lining after installation was not modelled in the analysis, but rather an average value of Young's modulus of 10 GPa representing green and hard shotcrete conditions reported in literature (Queiroz et al. 2006) was employed. Geotechnical properties of the soil and rock layers for the baseline case are given in Table 2.

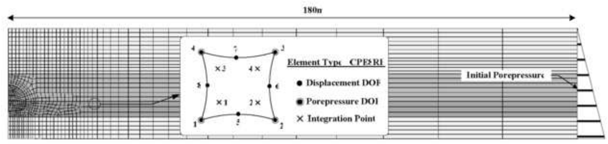


Figure 2. A typical finite element model adopted.

Table 2. Geotechnical properties of soil/rock layers

Type	γ (kN/m³)	c' (kPa)	ϕ' (deg)	E (MPa)	ν	K (m/sec)
Fill/alluvial	18	20	30	20	0.30	2.7×10^{-5}
weathered rock	22	70	32	120	0.30	6.2×10^{-6}
hard rock	25	1000	40	4000	0.25	1.4×10^{-7}

Note) γ =unit weight, c' =cohesion, ϕ' =internal friction angle, E =young's modulus, ν =poisson's ratio, k_s =coefficient of permeability

The 3D effects of advancing a tunnel heading was accounted for by using the "stress relaxation method" in which the boundary stresses arising from the removal of excavated elements are progressively applied to simulate the progressive release of the excavation forces as the tunnel heading advances. Modeling the 3D effects using a 2D model for a tunneling problem is beyond the scope of study and can be found elsewhere (Bernat and Cambou 1995; Yoo et al. 2007). For simplicity, it was assumed that 30% of the unbalanced excavation forces are released as unsupported while the remaining 70% are released after shotcrete lining installation. The tunnelling process was assumed to be done in a 30 day period until a steady state in terms of hydraulic head field can be achieved.

3.2 *Validation*

The finite element modeling approach described in the previous section was validated using a case history reported by Yoo et al. (2008) in which considerable groundwater drawdown-induced ground settlements during tunneling occurred. The ground at the site was a multi-layered ground including a fill, alluvium, and a weathered zone, similar to the one described earlier. The tunnel was a 10.5 m wide, 8.7 m high double track tunnel a cover depth of approximately 25 m. Excessive settlements, as great as 160 mm, were reported with a maximum drawdown of 25 m.

Figure 3 shows the measured and the computed surface settlement data for one of the monitoring points. As shown, the transient nature of the measured settlement is well described by the computed data, although the maximum value in the computed results is slightly less than the measured. Nevertheless, the computed results are considered to be in good agreement with the measured data, allowing the finite element model be deployed for the parametric study.

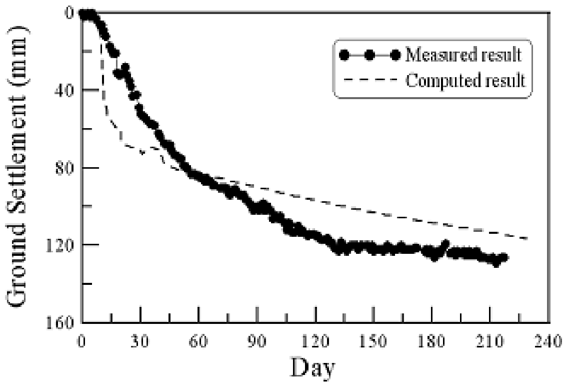


Figure 3. Measured versus computed settlement.

4 DEVELOPEMET OF PREDICTION TOOL

4.1 *Artificial neural network (ANN) based prediction*

There are a number of factors affecting magnitude and extent of tunneling-induced ground settlement such as ground condition including mechanical and hydraulic properties, tunnel geometry and location, and excavation sequence. The magnitude and extent of immediate settlement during tunneling in particular, recognized as the plastic deformation or relaxation of the ground towards the tunnel face, can be predicted using the semi empirical error function approach by Peck (1969), given the volume loss expressed as a percentage of the notional excavated volume of the tunnel. When a groundwater drawdown occurs during the tunneling, the magnitude and extent of the settlement are governed by additional factors, making the prediction even more difficult.

In this study, an ANN approach was utilized for prediction of magnitude of maximum ground settlement and groundwater drawdown considering the complexity of inter-relationships between the influencing factors and the consequence of tunneling when a groundwater drawdown is involved. The ANN technique was chosen in this study as a number of studies demonstrated that a generalized ANN can be effectively used in establishing underlying relationships between tunneling and its consequence, i.e., settlement, when sufficient data are available (Shi et al. 1998; Yoo and Kim 2005). Details of the ANN technique can be found in Hecht-Nielsen (1990).

4.2 *ANN development*

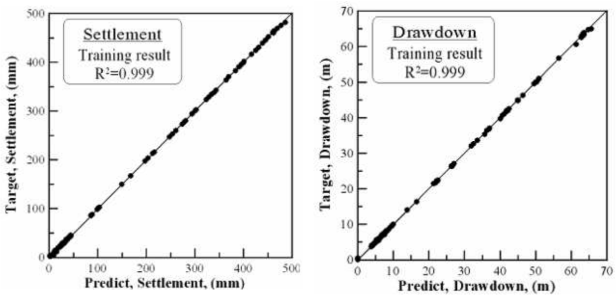
The results of the finite element analyses on the cases considered were synthesized to establish underlying relationships between the influencing factors and the consequence of tunneling, i.e., settlement and groundwater drawdown. The established relationships were then used as data sets for ANN development.

Input variables for the ANN include previously mentioned influencing factors such as the tunnel the cover depth, the thickness of soil layer, and the mechanical and hydraulic properties of the soil and rock layers as summarized in Table 1. The outputs from the ANN include the maximum ground surface settlement ($S_{v,\max}$) and the maximum groundwater drawdown level ($H_{D,\max}$). For the development of the ANNs, a commercial software package MATLAB® (MathWorks Inc. 2004) was used to simulate ANN operation.

For ANN development the data sets were divided into three subsets: a training set, testing set, and validation set, in order to avoid model overfitting when dividing the data into only two subsets of training and validation sets, as pointed out by Shahin et al. (2002). In total, 80% of the data were used for training and 20% were used for validation. The training data were further divided into 70% for the training set and 30% for the testing set.

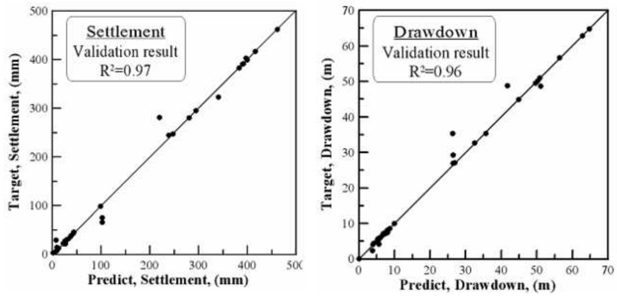
In terms of the ANN structure, the ANN has seven and two nodes, respectively, in the input and output layers, with one hidden layer. Note that one hidden layer can approximate any continuous function provided with sufficient connection weights (Hornik et al. 1989). Based on the sensitivity study, the optimum number of hidden layer nodes, the momentum term, and the learning rate values were chosen as 20, 0.8 and 0.2, respectively.

Figures 4 and 5 show the performance of the ANN for the training and validation sets. As seen in Figure 4 and 5, excellent correlations between the ANN predictions and the target values can be observed. In terms of the statistical parameters, the R^2 values for the output variables are over 97% for the validations sets. The consistency in statistical parameters between the training and validation sets indicates that the predictive capability of the ANN models for the validation sets is consistent with that of the training set. The statistical parameters representing excellent prediction capability of the developed ANN in fact suggest successful generalization of the relationships between the input and output variables.



(a) settlement (b) drawdown

Figure 4. Predicted vs. target settlement (training)



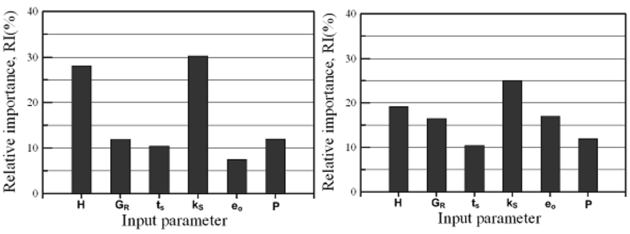
(a) settlement (b) drawdown

Figure 5. Predicted vs. target settlement (validation)

4.3 *Relative importance of influencing factors*

The relative importance of the influencing factors on the settlement and the groundwater drawdown during tunneling was examined using the results of ANN development. Garson (1991) proposed a systematic way for interpretation of the relative importance of the input variables by examining the connection weights of the trained ANNs. The results are given in Table 4, in which the relative importance (RI) for each parameter is given in terms of a percentage value. These values in fact represent the degrees to which each variable affect the settlement and groundwater drawdown development.

As shown in Figure 6, the tunnel cover depth, thus the height of hydraulic head, and the permeability of soil layer have more pronounced effect on the settlement as well as the groundwater drawdown. Also of interest trend is that the void ratio of the soil layer has not as significant effect on the settlement, only 15%, as it first seems, suggesting that the settlements related to the groundwater drawdown are more or less due to increases in effective stresses rather than the volume change. Although further study is still warranted, the sensitivity analysis presented provides valuable information as to the underlying mechanisms governing the settlement development.



(a) settlement (b) drawdown

Figure 6. Relative importance of variables

5 CONCLUSIONS

An ANN-based prediction method for groundwater drawdown and associated settlements during conventional tunneling in water-bearing ground is developed in this study. The results of a series of stress-pore pressure coupled finite element analyses on tunnelling cases with groundwater drawdown conditions frequently encountered the Seoul metropolitan area were used to form a database for ANN development. The developed ANN exhibited excellent statistical performance, thus confirming its applicability for tunneling cases similar to those considered in this study. The developed ANN was also used to study the relative importance of influencing factors on the settlement and groundwater drawdown. It is shown that the tunnel cover depth and the permeability of the soil layer have more pronounced effect on the settlement and the groundwater drawdown.

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