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Research Paper

Underground excavation behaviour in Bangkok using three-dimensional finite element method

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ABSTRACT

This study provides evidence that three-dimensional finite element modelling can be effectively applied for deep excavation analysis in Bangkok. The Bangkok subsoils were modelled using the hardening soil model and their parameters were calibrated against the results of laboratory and field tests. A study of a MRT station excavation was initially used to validate the model. The predicted wall movements and surface settlements were compared with the instrument data and two-dimensional analysis from a previous study. Another deep excavation project was selected as an independent study. The result shows that the model can be confidently used for deep excavation analysis.

1. Introduction

Bangkok, the capital city of Thailand, is a densely conglomerated metropolitan centre with a rapidly growing population resulting in limited space for residential and transportation infrastructure development. Hence, developing underground space to fulfil people's needs is a current trend. Importantly, Bangkok metropolis is also located on a large river deposit which consists of a thick soft clay layer deposited on the top [1]. Excavations in soft soils are usually associated with substantial difficulties. Since these types of soils are sensitive to deformations and possess low shear strength, they may lead to structural damage during the construction as well as throughout the life of projects [2]. In particular, deep excavations in soft clays, which could induce soil movements, need to be assessed thoroughly. Due to advancement of computational tools, most of the complex geotechnical problems including deep excavation employ finite element analysis. However, the results of finite element analysis are influenced by many input factors such as simplified geometry and boundary conditions, mesh generation, choice of constitutive soil model and its parameters, modelling of construction sequences, and structural modelling.

Ou et al. [3] employed non-linear three-dimensional finite element analysis (3D FEA) to evaluate the wall performance of an irregular excavation site of the Hai-Hua Building in Guangzhou, China. Similarly, Hou et al. [4] successfully modelled the excavation of the north square underground shopping centre in the Shanghai South Railway Station using 3D FEA. Those studies show that 3D FEA provided better results that were closer to the instrument data than predicted from 2D FEA for modelling wall deformation. Hsieh et al. [5] utilised 3D numerical analysis to study the deformation of a D-wall with and without cross wall. The results show that the cross wall effectively reduced lateral wall movement. Recently, Dong et al. [6] modelled the highly irregular geometry of the North Square shopping centre of the Shanghai South Railway Station with a 3D finite element model. The 12.5 m deep excavation was adjacent to a metro line, a metro underground station and other surrounding public infrastructure. Numerical analysis can be reasonably used to predict the wall deformation and ground surface settlement of the complex excavation. Dong et al. [7] also studied several effects on diaphragm deflection of deep excavation in Shanghai using 3D FEA. They concluded that much care must be taken in the FEA. For one, the corner effect was inherent in the 3D analysis of diaphragm wall deflection. Furthermore, Hsiung et al. [8] modelled deep excavation in Taiwan with 3D finite element modelling. They emphasised the corner effect and the results showed good agreement with the measured lateral wall deformation. Hence, the 3D effect shares much with ground movement analysis in deep excavation. Nowadays, the shape of excavation becomes more complicated and it leads to be very far from the assumptions used in 2D FEM as in Dong et al. [6] and Lin et al. [9].

In Bangkok, the numerical studies of deep excavation are often conducted using two-dimensional finite element analysis with the Mohr-Coulomb model. Many researchers [10–12] concentrated their work on back-calculating the ratio of undrained elastic modulus and undrained shear strength (E_u/s_u). Recently, Likitlersuang et al. [13] conducted a 2D FEA of a Bangkok MRT station considering the

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influence of constitutive soil models. The results revealed that the advanced soil models, the Hardening Soil Model (HSM) and Hardening Soil Model with small strain (HSS), provided better results compared to instrument data on the long side of the excavation. Due to the simplified assumptions of the 2D FEA, the effect of 3D cannot be included, such as wall movement predictions at the short side or near corner of an excavation. Moreover, the study was extended to predict ground surface settlements due to tunnel excavations in Bangkok [14]. This study was an extension of previous studies [13,14] but employing the 3D finite element method to model deep excavation problems in soft ground in Bangkok. The 3D finite element model was initially validated with the case study of a MRT station excavation by comparing the results with the instrument data and 2D analysis from the previous study [13,14]. In addition, an independent underground excavation was selected to make predictions. This study aims to provide necessary information to model the deep excavation problem using 3D FEA.

2. Challenges in deep excavation

2.1. Wall deformation

The most challenging issue in deep excavation is inward movement of retaining walls. Wall deformation can lead to catastrophic consequences when the deformation is excessive and has not been controlled effectively. Hence, this is a problem drawing much attention from geotechnical engineers. The finite element method is capable of modelling and predicting such stresses on retaining walls. Wall deflection results from lateral earth pressure and surcharge adjacent to the wall. Clough and O'Rourke [15] demonstrated the behaviour of wall deformation in response to excavation stages, as shown in Fig. 1. They concluded there are two types of deformation: cantilever and deep inward. Cantilever type appears at the early stages of excavation when struts or slabs have yet to be installed. In contrast, the deep inward pattern is usually exhibited after bracing systems have been installed and the excavation has advanced to deeper depths. These two types of deformation lead to the different ground settlement profiles as depicted in Fig. 1. Similar findings were presented by Ou et al. [16]. They also added that maximum lateral wall movement (δ_{hm}) often occurs near the surface of an excavation and falls within the range of 0.002–0.005 of excavation depth.

2.2. Ground surface settlement

In general, wall deformation is associated with surface ground settlement. The larger the wall deformation, the more ground surface settlement. Substantial degrees of settlement can be harmful to surrounding structures or public facilities. Ou et al. [16] conclude that there are two types of ground surface settlement: spandrel and concave type, as illustrated in Fig. 1. Spandrel type corresponds to cantilever type retaining wall deformation while concave type corresponds to the deep inward wall deformation pattern. Mana and Clough [17] and Hsieh and Ou [18] showed that maximum ground surface settlement (δ_{vm}) fell in the envelope of (0.5–1) of δ_{hm}. Hsieh and Ou [18] proposed an empirical trilinear relationship to estimate a ground surface settlement pattern as a function of distance from the wall, as shown in Fig. 2. It is noted that the maximum ground surface settlement (δ_{vm}) must be known. However, Ou and Hsieh [19] have suggested a new ground surface settlement pattern which takes the width of the excavation and depth to hard stratum into account.

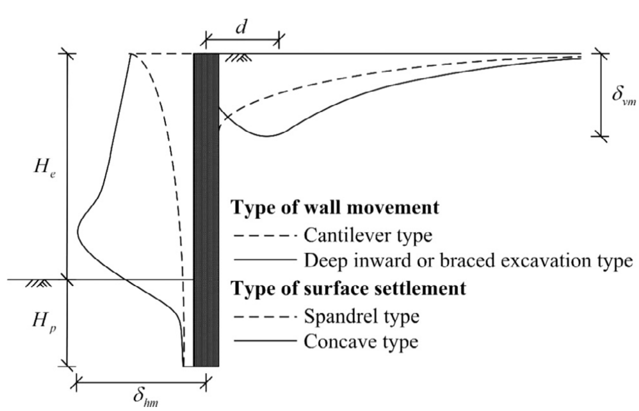

Fig. 1. Types of wall movement and ground surface settlement [13,18].

3. Finite element modelling

The numerical method has become a very powerful tool in geotechnical engineering in recent years. At present however, only two-dimensional (2D) finite element analysis (FEA) has been extensively employed in practice. Simplified assumptions are made in 2D FEA, for instance, plane strain or axisymmetry. In fact, only a few cases of deep excavation can be reasonably simplified as in 2D FEA. For example, the 3D effect could be neglected only in excavations whose length-to-width ratio is larger than 6 [20]. Furthermore, some features cannot be modelled in 2D FEA such as corner effects, complex conditions, and irregular shapes of excavation. Ou et al. [3] indicated that the degree of accuracy of 2D plane strain FEA was affected by the presence of corners. The existing corners can reduce the deformation of the wall especially on the short side. Therefore, this study focuses on utilisation of 3D finite element modelling in deep excavation analysis and evaluates its performance. Commercial software PLAXIS 3D AE (Anniversary Edition) was used in this study. A 10-noded tetrahedron element with a quadratic displacement function was selected to discretise soil volume. In 3D FEA, many parameters must be considered carefully including geological conditions, the constitutive soil model and its parameters, soil-structure interface modelling, and boundary conditions as well as construction sequences.

3.1. Bangkok subsoils

Bangkok is situated on a thick soft layer of clay consisting of marine deposits formed during the Quaternary period. Most deep excavation projects in Bangkok have been constructed in this layer. The soft layer

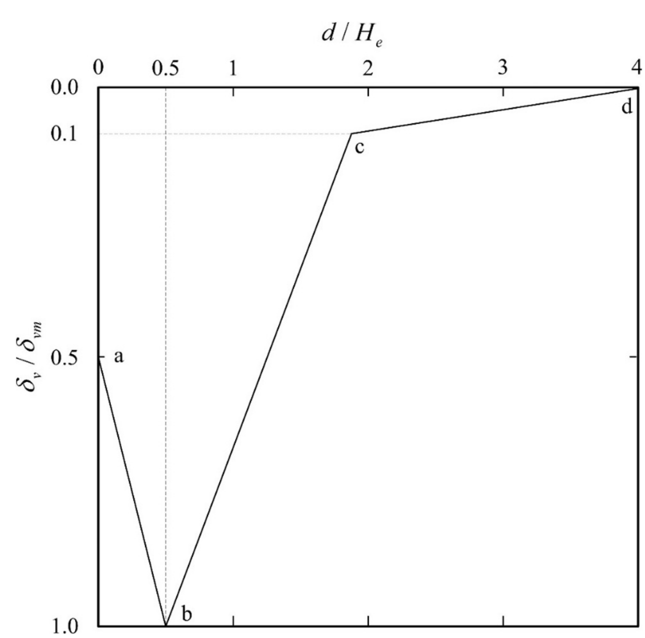

Fig. 2. Estimation of ground concave surface settlement [18].

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