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Research Paper

Effect of spatial variability of soft clays on geotechnical design of braced excavations: A case study of Formosa excavation

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ABSTRACT

This case study presents the effect of spatial variability of soft clays on the geotechnical serviceability assessment of braced excavations. Finite element modeling is performed to predict the excavation-induced wall and ground movement. The spatial variations in two key soil parameters are modeled as two correlated lognormal random fields. The system reliability-based serviceability assessment conducted in this case study shows that the system probability of serviceability failure is greater than or equal to that for each single failure mode, indicating that serviceability assessment considering an individual failure mode can result in unsafe predictions.

1. Introduction

Braced excavations are commonly used in urban areas for constructing foundation systems of multi-story buildings and underground railway systems, providing space at various elevations. The support system of a braced excavation typically consists of retaining walls such as diaphragm walls and bracing components such as struts or tie-backs. The braced excavations are a complicated soil–structural interaction problem. In the geotechnical design of a braced excavation, two requirements must be satisfied: (1) the ultimate limit state (ULS) requirement and (2) the serviceability limit state (SLS) requirement. For ULS assessment, excavation stability is ensured by meeting a minimum required the factor of safety (FS): for excavations at sites with clay-dominant soils, this stability factor is referred to FS against basal heave; for excavations in sands, FS against piping is used. In the SLS assessment, control factors such as excavation-induced lateral wall deflection, ground surface settlement, uneven settlement and angular distortion of adjacent buildings are examined to ensure that no failures due to excessive wall and soil movement will occur [18].

In a typical excavation project, either the owners or a local regulatory agency will establish the design criteria, such as the PSCG [20], a specification used in Shanghai, China. In PSCG, depending on the importance of the project, the minimum acceptable FS, maximum acceptable lateral wall deflection, and maximum acceptable ground surface settlement are specified. Traditionally, the deterministic geotechnical designs for braced excavations are realized by meeting the limiting criteria in a code or specification, such as PSCG [20]. However, due to the uncertainties in soil properties and design models, the predictions in the design phase are often inconsistent with field observations. It is rational to model these uncertainties quantitatively in the geotechnical design by meeting an acceptable reliability or probability of failure.

Compared with the parameters for structural components, it is challenging to determine the soil parameters involved in braced excavations, since uncertainty in soil properties stems from the their inherent spatial variability [25]. To deal with the spatial variation in soils, random field theory [25] has been developed and applied in various geotechnical designs: e.g., shallow foundations [4], piles [13], drilled shafts [15], slope stability [10], conventional retaining walls [6], supported excavations [16,24], and basal heave stability of braced excavations [14]. In random field modeling, a spatially varied soil parameter is described by its mean value, coefficient of variation (COV) and scale of fluctuation (θ) under the assumption of a normal or lognormal distribution [25]. Some investigators have implemented random field theory using finite element method, referred to as random finite element modeling (RFEM), which serves as a powerful tool to address more complicated geotechnical problems [5]. It is noted that most existing research using RFEM has focused on simple and hypothetical design examples. There is very limited research on the effect of soil spatial variability on the actual geotechnical design case history of braced excavations.

In addition to the aforementioned soil spatial variability, the selected design model can also dominate the design of braced excavations. In previous decades, a few models for excavation design were developed, including empirical models [3,8,22,33], semi-empirical models [2,12,30,31], field observational methods [7,27,29,32] and

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numerical models [23]. Other researchers dedicated their efforts in developing a database of excavation case histories [11,19,26] or conducting back-analysis using field observations [9,21,27]. It should be noted that although an advanced method such as numerical modeling can be adopted, it is important to calibrate the adopted model to fit the local experience and consider various scenarios in the modeling. For instance, a lesson learned from the April 2004 failure of the Nicoll highway deep excavation in Singapore is that modeling using effective strength parameters yields an unsafe design, compared with models that use the total strength parameters [17].

In this paper, the effect of soil spatial variability in soft clays on the geotechnical design of a braced excavation is investigated through a case study. A well-documented excavation case, the Formosa excavation case in Taipei, Taiwan [19] is adopted in this study. The excavation-induced wall and ground responses are modeled by using finite element code. Based on the FEM model calibrated using field observations, the soil spatial variability is modeled using RFEM combined with Monte Carlo simulations. The effect of the spatial variability in soil properties on the geotechnical serviceability assessment is systematically investigated. This research also points to the importance of considering multiple serviceability failure modes and the system reliability assessment of braced excavations.

2. Case history of Formosa excavations

In this study, a well-documented excavation case, the Formosa excavation in Taipei, Taiwan [19], is adopted in this case study of the soil spatial effect on the geotechnical design of a braced excavation. This excavation project was conducted using the bottom-up method. The rectangular cross section of the excavation has an excavation width of 33.4 m and final excavation depth of 18.45 m. The excavations were performed in seven stages, and struts were installed at the end of each excavation stage. The detailed excavation depths for the seven stages, the strut locations, and the strut stiffness are shown in Table 1 and Fig. 1.

The Formosa excavation is situated in a site with clay-dominated soils. Fig. 1 depicts the soil profile in the field for this project. In Fig. 1, it can be clearly seen that the majority of the excavations were conducted in soft clays with a thickness of 20 m, classified as CL by the Unified Soil Classification System. A few previous case studies have demonstrated that the soil parameters of this soft clay layer dominate the predictions of wall and ground responses [11,12,19]. As shown in Fig. 1, underneath the soft clays are a 3-m thick layer of clayey slits, a 5-m thick gravel layer, a 3-m thick layer of mudstone, and a 10-m layer of sand shale stone, followed by a layer of fresh sandstone. The diaphragm walls have a thickness of 0.8 m and a length of 31 m. The structural parameters for diaphragm walls are listed in Table 2.

Fig. 2 shows the reported profiles of excavation-induced lateral wall deflection and the ground surface settlement, respectively, for all seven stages of the Formosa case. The maximum lateral wall deflection and the maximum ground surface settlement at the end of Stage 7 are 62 mm and 47 mm, respectively. Unlike other similar excavation case histories with comparable structural and geotechnical designs, the Formosa case has a soil profile with hard layers of considerable thickness below the excavations, and the diaphragm walls were extended into the hard layers, indicating that basal heave stability can be guaranteed. By comparison, the excavation case of the Taipei National Enterprise Center (TNEC) has a nearly identical structural and geotechnical design for its excavation as the Formosa case [11]. However, due to the hard stratum buried more than 10 m below the bottom of the diaphragm walls, the observed maximum lateral wall deflection (106 mm) and maximum ground surface settlement (76 mm) at TNEC are much larger than those in the Formosa case, indicating that basal heave instability was a major concern in the design of the TNEC. In this regard, this study selects the Formosa excavation case to explicitly investigate the effect of spatially varied soil properties on the serviceability assessment of a geotechnical design.

Table 1
Excavation depth and struts depth and stiffness in Formosa case (data from [19]).

Stage	H (m)	H_p (m)	E (GPa)	A(cm^2·cm^{-1})
1	1.6	1.0	200	0.28
2	4.3	3.7	200	0.28
3	6.9	6.2	200	0.28
4	10.15	9.5	200	0.28
5	13.2	12.5	200	0.46
6	16.2	15.5	200	0.46
7	18.45	nil	nil	nil

Note: H = final excavation depths; H_p = depth of struts; E = modulus of struts; A = cross-section area of struts

3. Random finite element modeling of braced excavations

3.1. Development of the finite element model

In this study, the finite element code PLAXIS [1] is adopted to model the braced excavations. Fig. 1 shows the two-dimensional plane strain finite element model (FEM). Since the cross section of an excavation is symmetrical, only the left half of the excavation is modeled, as shown in Fig. 1. The horizontal length and vertical height of the model are set at 107.5 m and 62.0 m, respectively. The groundwater table is located at 1.0 m below the ground surface. In the FEM simulation, the struts are modeled as spring elements, and the diaphragm walls are modeled as linear elastic materials. The parameters for the retaining structural system are shown in Tables 1 and 2.

In reference to the soil profile in Fig. 1, Table 3 shows the detailed soil parameter profile based on a systematic literature review. In this study, the hardening soil model with small-strain stiffness ("HS small model") is used to simulate the constitutive relationships of silty clay and clayey silt layers. As mentioned previously, in this case study since all excavation activities were performed in the soft silty clay layer, the soil parameters of this silty clay layer dominate the geotechnical design and should be properly determined in the FEM analysis. In practice, the use of total stress parameters (such as the undrained shear strength s_u) can be more common due to the limitations in project budgets, time and available soil testing equipment. When using total strength parameters, s_u are converted from the normalized undrained shear strength (s_u/σ'_v) for each silty clay layer and clayey silt layer, where σ'_v indicates the vertical effective stress. For the Formosa case, s_u/σ'_v is reported to be 0.31 [12]. As for the stiffness parameters, both sets of parameters use the stiffness converted from normalized secant modulus (E_{50}/σ'_v). The E_{50}/σ'_v is 500 for silty clay and 800 for clayey silt.

Using the FEM model as in Fig. 1, the seven-stage excavation activities are simulated by deactivating the corresponding soil elements involved in a specific excavation stage. The water levels inside the foundation pit were lowered stage by stage as the excavation proceed, and the seepage from outside the diaphragm walls into the excavation area through the permeable soil layer below the walls was also considered in the analysis. The simulated seven-stage wall deflection and ground surface settlement profiles obtained by FEM are shown in Fig. 2. It is revealed that the predictions using FEM match well with the field observations (predicted maximum lateral wall deflection = 63 mm and predicted maximum ground surface settlement = 45 mm).

3.2. Generation of two correlated random fields

For the Formosa excavation, two key soil parameters, s_u/σ'_v and E_{50}/σ'_v were identified in previous studies [12]. To this end, this study models s_u/σ'_v and E_{50}/σ'_v as two positively correlated lognormal random fields, while the correlated soil parameters in HS small model