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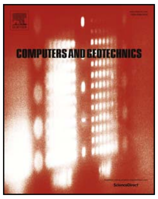

Research Paper

Effects of vertical spatial variability on supported excavations in sands considering multiple geotechnical and structural failure modes

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ABSTRACT

In this paper, a probabilistic assessment of supported excavations in spatially varied sands is presented. Random finite element modelling (RFEM) is performed to simulate excavation-induced responses. A procedure for automating the Monte Carlo simulation is developed to facilitate the RFEM. The effects of soil vertical spatial variability on several major geotechnical and structural failure modes, including geotechnical ultimate failure, geotechnical serviceability failure, wall bending failure, wall shear failure, and strut buckling failure, are explicitly investigated. This study demonstrates the importance of addressing the spatial variation of soil properties by considering multiple failure modes for complicated soil-structural interaction problems.

1. Introduction

Supported excavations are complicated soil-structure interaction problems in engineering practices. The retaining system of supported excavations typically consists of retaining walls (e.g., soldier piles, sheet piles, column piles, and diaphragm walls) and strut components (e.g., wood, steel or reinforced concrete struts). Excavations can be conducted in multiple stages, and during each stage, one or more levels of struts are installed. The strut components provide additional resistance against lateral earth pressure and can more effectively control the excavation-induced wall and ground responses in an urban setting, compared to cantilever retaining or tie-back walls [32].

The engineering design of supported excavations mainly includes geotechnical and structural designs. The geotechnical design can be subdivided into ultimate limit state (ULS) design and serviceability limit state (SLS) design. The ULS design can also be referred to as the strength limit design, in which the stability of the foundation pit (e.g., wall push-in failure and basal-heave failure) is evaluated using a defined safety factor. The SLS design is generally used to assess the excavation-induced maximum lateral wall deflection and maximum ground surface settlement, which are positively correlated (e.g., [22]). The designed maximum wall and ground responses need to satisfy the limiting values specified by the local regulatory agency. For the structural design, the excavation-induced diagrams of the bending moment and shear force with depth, as well as the strut axial force, are evaluated. The structural design needs to ensure that no failures will occur due to excessive bending moment, shear force in walls or excessive axial force in struts. As a systematic soil-structure interaction problem, all major geotechnical and structural failure modes need to be examined when designing a supported excavation. For supported excavation projects in urban areas, the geotechnical and structural failures may have considerable and adverse social, political, environmental and economic impacts [1].

In previous decades, several methods were developed to understand the soil-structure interactions in supported excavations, and these methods can be categorized as follows: (1) analytical or empirical methods (e.g., [6,37]), (2) field observations [5] or model tests [24], (3) semi-empirical methods [22] and (4) numerical methods. Among the numerical methods, the finite element method (FEM) and the finite difference method are commonly used to analyse these soil-structure interaction problems (e.g., [3,7,13,14,23,28,29,33–35,43,47]).

In the numerical analysis of supported excavations, the soil parameters are usually obtained from a limited number of tests that often do not reflect the actual field conditions. In this regard, reliability-based methods are used in the geotechnical ultimate analysis [16] and geotechnical serviceability analysis (e.g., [27,28]) of supported excavations to address uncertainty in the soil parameters. In those studies, the soil parameters are modelled as random variables that are spatially constant. Nevertheless, the soil property has inherent spatial variability, which should be properly addressed using random field theory in the reliability-based design [46]. Recent research in various fields has highlighted the importance of soil spatial variability, e.g., the influence of spatial variability in the shear strength and friction angle on slope reliability [25] and the effect of spatial variability in penetration

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resistances or cone tip resistances on liquefaction-triggered settlement and lateral spreading of an infinite slope [30,42]. For excavations, existing research reveals that soil spatial variability has a significant impact on the design of supported or unsupported excavations [28,36,40,48]. However, supported excavations are complicated soil-structure interaction problems that involve multiple critical failure types. There is still a lack of research on the probabilistic modelling of supported excavations, which consider multiple geotechnical and structural failure modes.

In this paper, the effects of spatial variability of soil parameters on the geotechnical and structural assessments of supported excavations are investigated, with consideration of multiple failure modes. A two-stage, supported excavation in sands with one level of strut is studied. This soil-structure interaction problem is modelled with a two-dimensional finite element method, and the one-dimensional spatial variability of the soil parameters is simulated using random field theory. Random finite element modelling is combined with a Monte Carlo simulation. The resulting distributions of maximum lateral wall deflection, factor of safety against foundation pit instability, maximum bending moment, maximum shear force in walls and axial force in struts are analysed statistically, and the probability of failure is assessed against each failure mode. This study can provide a reference for this missing element in the field of reliability-based design of supported excavations, with consideration of multiple geotechnical and structural failure modes. This research also indicates the importance of modelling the spatial variability of soil parameters in complex soil-structure interaction problems of supported excavations.

2. Finite element model of supported excavations

In this study, supported excavations in sands are modelled by the computer programme *PLAXIS*. Fig. 1 shows the geometry of the meshed two-dimensional (2-D) finite element model (FEM) for supported excavations under plane-strain conditions. Due to the symmetry of the excavation cross-section, only half of the excavation is modelled, as shown in Fig. 1. The horizontal and vertical lengths of the model are 35 m and 20 m, respectively. The geometry of this model follows the requirements for minimizing the boundary effect [4]. The groundwater table is located at 3.5 m below the ground surface. The final excavation depth is 6 m and the half-width of the excavation is 7 m. The supporting system includes 10-m deep AU14 sheet pile walls and one level of struts of W16 × 40 steel, which is installed at 1.5 m below the ground surface. The surcharge includes a permanent load (PL) of 10 kPa and a variable load (VL) of 60 kPa, as shown in Fig. 1.

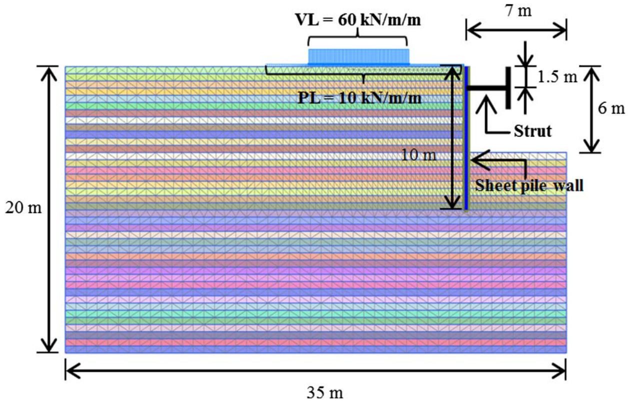

Fig. 1. Layout of the two-dimensional finite element model of braced excavations.

Table 1
Soil parameters adopted in finite element modelling.

Parameter	Notation	Value	Unit
Unsaturated unit weight	γ_{unsat}	18	kN/m^3
Saturated unit weight	γ_{sat}	20	kN/m^3
Initial void ratio	e_0	0.6	–
Secant stiffness	E_{50}^{ref}	11,782	kPa
Tangent oedometer stiffness	E_{oed}^{ref}	11,782	kPa
Unloading/reloading stiffness	E_{ur}^{ref}	35,346	kPa
Power for stress depend stiffness	m	0.5	–
Cohesion	c'	0.1	kPa
Friction angle	φ'	33	°
Dilatancy angle	ψ	3	°
Poisson's ratio	υ'_{ur}	0.2	–
Reference stress	p^{ref}	100	kPa
Lateral stress coefficient	K_0^{nc}	0.4554	–
Over consolidation ratio	OCR	1.0	–
Interface reduction factor	R_{int}	0.67	–
Reference pressure	P_{ref}	100	kPa
Failure ratio (q_f/q_a)	R_f	0.9	–
Permeability	k_x, k_y	0.6	m/day

In this study, the hardening soil model (HS) is selected to represent the constitutive relationship of sands. Table 1 shows the soil parameters used in the FEM analysis. The dependent parameter $K_0{}^{nc}$ is estimated with Jaky's empirical equation [18]:

$$K_0^{nc} = 1{-}\sin\varphi' \tag{1}$$

The sheet pile walls are modelled as linear elastic materials. The parameters for sheet pile walls are listed in Table 2. In the FEM simulation, the struts are modelled as spring elements with a normal stiffness (*EA*) of 15,00,000 kN/m. The triangular elements for soils have an average size of 0.594 m with a refined mesh around the sheet pile walls and surcharge. The interface elements between walls and soils are used to simulate the reduced wall friction compared to that of the adjacent soils. The reduction ratio for interface elements is 0.67. The total number of elements and the total number of nodes in this FEM model are 5150 and 41,958, respectively. The bottom flow boundary is set to be impermeable, while the left and right flow boundaries are permeable. The vertical and horizontal coefficients of permeability for sands are listed in Table 1. The excavations are simulated in the following steps:

1. Generate the initial stresses due to soil gravity and surcharge loads;
2. Activate the sheet pile walls and interface elements between the walls and soils;
3. Excavate the soils in the foundation pit to a depth of 2 m below ground surface (BGS);
4. Activate the struts and excavate soils to a depth of 3.5 m BGS; and
5. Excavate the soils to a final depth of 6 m BGS and dewater in the excavation zone to 6 m BGS; meanwhile, lower the water level near the excavation zone linearly from a depth of 3.5 m to 6 m BGS.

In this study, using the FEM model in Fig. 1 and the soil and structural parameters in Tables 1 and 2 as nominal inputs, a deterministic analysis following the aforementioned steps was performed. Fig. 2 shows the excavation-induced responses of the sheet pile walls, including the variation of lateral wall deflection, bending moment and shear force with depth. In addition, the compressive strut force is

Table 2
Parameters of sheet pile walls (AU14) adopted in finite element modelling.

Parameter	Notation	Value	Unit
Normal stiffness	EA_1	27,78,000	kN/m
Stiffness in the out of plane direction	EA_2	1,38,900	kN/m
Flexural rigidity	EI	60,230	kN·m^2/m
Width	d	0.51	–
Weight	w	1.04	kN/m/m
Poisson's ratio	ν	0.0	–