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Finite element parametric study of the performance of a deep excavation

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Abstract

Deep excavations are widely used for the development of underground space. The structural performance of any deep excavation is influenced by details of the soil behaviour, the form of the retaining and support structures that are employed and also the sequence of construction. Finite element analysis is potentially an effective tool for considering both the geotechnical and structural aspects of the design of deep excavations. To capture the main features of the excavation behaviour, a finite element model is required that is able to represent the principal deformation and structural mechanisms at an appropriate level of detail. The current paper explores the various modelling assumptions that need to be considered when developing detailed 3D finite element models for the design of deep excavations. A parametric study is described, based on an idealised square excavation, to investigate the influence that certain key features of the model can have on the quality of the computed results. The study includes the choice of element type to model the structural components, the selection of appropriate material parameters, the choice of procedures to model post-cure shrinkage of the concrete elements and the choice of procedure to model the soil/structure interfaces. The results of this parametric study provide guidance for the development of finite element models for practical design purposes.

Keywords: Finite element analysis; Deep excavations; Shrinkage; Discontinuities; Soil/structure contact

1. Introduction

Deep excavations are widely used in urban areas for the development of underground space. However, the excavation process inevitably alters the stress state in the ground and may cause significant local ground movements to occur. When the excavation is close to existing infrastructure (e.g. buildings, tunnels and buried pipelines), any excavation-induced ground movements must be carefully monitored and controlled to ensure that damage is minimised.

The performance of a deep excavation is influenced by a number of issues relating to details of the local soil behaviour, the structural form of the retaining structures and the sequence of construction. Finite element analysis has the potential to be an effective design tool for deep excavations. For the results of any finite element model to be useful, however, careful attention needs to be paid to the choice of constitutive models for the soil and structural elements, the approach used to simulate the construction procedure and modelling procedures for the soil/structure interfaces (e.g. Potts and Zdravkovic, 2001).

Previous research on this topic has demonstrated the importance of several aspects of the modelling process such as: (i) the advantages of 3D analyses over 2D analysis (Gourvenec et al., 2002; Zdravkovic et al., 2005; Lee et al., 2011), (ii) small-strain stiffness nonlinearity of the soil (Simpson, 1992; Hashash, 1992; Potts and Zdravkovic, 2001; Dong et al., 2016), (iii) thermal and shrinkage effects

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in the concrete floor slabs (St. John et al., 1993; Whittle et al., 1993; Dong et al., 2016), (iv) wall installation effects (Ng et al., 1995; Gourvenec and Powrie, 1999; Ng and Yan, 1999; Schäfer and Triantafyllidis, 2004; Schäfer and Triantafyllidis, 2006), (v) soil/structure interface behaviour (Day and Potts, 1998; Dong, 2014), (vi) joints in the retaining wall (Zdravkovic et al., 2005; Dong et al., 2016), (vii) stiffness reductions in the concrete structural components (St. John et al., 1993; Ou et al., 1998; Dong, 2014), (viii) initial stress distribution in the ground (Potts and Fourie, 1984; Dong et al., 2016). Neglecting some of these aspects is likely to reduce the accuracy of the analysis. In practice, however, it is difficult to consider all of these aspects in a single analysis, due to the level of complexity which would be required in the model. It is, therefore, relevant to understand the influence of these aspects individually in a parametric study. The current paper describes a set of parametric studies conducted on an idealised excavation. The purpose is to provide experience that may be used to support the development of finite element modelling procedures that are effective and useful for practical design purposes.

Constitutive data are required for the soil, the structural components and the soil/structure interfaces. In practice, uncertainties will exist in the most appropriate parameters for use in the analysis. Parameter selection is therefore also addressed in the current paper.

The particular issues addressed in the current paper are:

(1) appropriate choice of element type to model the retaining wall (solid elements or shell elements) and the piles (solid elements or beam elements),
(2) selection of appropriate values of operational stiffness for the concrete structural components,
(3) choice of method to model thermal effects and post-cure shrinkage in the concrete elements,
(4) choice of appropriate modelling procedure for the soil/structure interface behaviour,
(5) development of appropriate procedures to model the presence of construction joints or other discontinuities in the retaining walls,
(6) investigation of the sensitivity of the computed results to the stiffness and strength properties of the soil.

Various other issues also need to be addressed in the development of finite element models of the behaviour of deep excavations. The issues listed above have been prioritised, however, in the current paper. All calculations described in this paper have been conducted using Abaqus v6.11.

2. Idealised square excavation

2.1. Excavation geometry and construction sequence

The parametric study is based on an idealised square basement excavation (40 m × 40 m in plan, 12 m deep) constructed using a top-down method as illustrated in Fig. 1. The excavation is retained by a diaphragm wall (1 m thick, 30 m deep) which is supported by three levels of horizontal floor slabs (150 mm thick) and beams (400 mm × 600 mm in section). The floor slabs and beams are, in turn, supported by circular piles (800 mm in diameter, 30 m deep). The vertical distance between the floor slabs is 4 m and the horizontal span of the beams is 8 m. Openings are normally designed in the floor slabs for the purpose of lighting, ventilation, and transport of excavated soils, but these details are excluded in the current model. The construction sequence follows the top-down construction method specified in Fig. 2. This excavation configuration is broadly typical of modern urban developments.

2.2. Finite element modelling procedure (basic analysis)

Initially, a finite element model of the deep excavation specified in Figs. 1 and 2 is developed, based on modelling assumptions that are regarded as being broadly appropriate. This model is referred to as the 'basic analysis', meaning that it includes basic features of an excavation analysis, but that additional features could be added to refine the model. A parametric study is then conducted in which selected aspects of the basic analysis are adjusted individually. The basic analysis is specified below.

The mesh for the soil and the retaining system is shown in Fig. 3. The soil is modelled using hexahedral solid elements C3D8R (linear elements with reduced integration). The beams and piles are modelled using beam elements B31 (linear elements). The floor slabs are modelled with

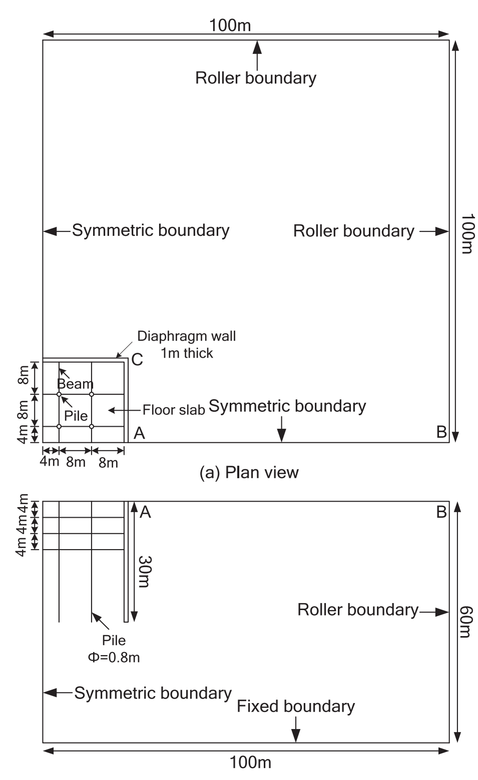

Fig. 1. Geometric model of the supported deep excavation that is adopted for the parametric study.

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