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Plane strain evaluation of stress paths for supported excavations under lateral loading and unloading

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Abstract

Excavations are generally analyzed as plane strain problems. The shear strength parameters determined from the triaxial conditions are not representative of the real field conditions. Therefore, plane strain tests on reconstructed silty clay were performed using a modified apparatus to measure the stress-strain curves directly. Three stress paths were tested, where the lower shear strength and the failure strain were measured for tests with unloading in the minor principal stress direction and compared to tests with loading. A set of hyperbolic constitutive models was developed to fit the experimental data at different stress paths. The stress-strain-strength characteristics and the deformation parameters were determined for these tests. A displacement-dependent earth pressure model was then proposed for retaining walls due to excavations, and then it was calibrated against the measured soil response. In the end, a case history of bored pile walls subjected to excavations was illustrated. Calculations using the proposed approach and the standard Mohr-Coulomb model were compared. The analysis using the standard Mohr-Coulomb model was found to underestimate the maximum wall deflection by 15%.

Keywords: Plane strain tests; Excavation; Hyperbolic stress-strain model; Loading and unloading; S-shaped earth pressure curve; Numerical analysis

1. Introduction

A deep excavation is a crucial segment of foundations for supporting the weight of infrastructures. Any unfavourable outcomes induced by construction should be avoided, such as excessive diaphragm wall deflections, ground and wall settlements, friction mobilized along propping struts, uplifts of the interior columns, variations in the groundwater table, and damage to adjacent roads, bridges, tunnels, and pipelines. It should be emphasized that new projects cannot solely rely on the past experiences of supported excavations, since the size of excavations and the geological conditions vary from site to site. As the scale of these projects becomes much deeper and much larger, stricter requirements are being proposed for excavations in order to provide underground spaces for usage as a result of urbanization (Ou, 2006). Construction on difficult soils is sometimes inevitable, such as the soft soils on the east coast of China, the frozen soils on the Tibetan Plateau and northeast of China, the loess on the Loess Plateau of China, and expansive soils (Shi et al., 2002).

Field evidence of the performance of supported walls can provide guidance for the analysis of deep excavations. For example, Ou et al. (1998) reported a field testing program on an excavation performed with the top-down technique. Different instruments were installed to monitor the

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changes in strut loads, wall displacements, wall bending strains, ground surface settlements, pore pressures, and basal heaves. An inward movement of the supported wall was observed, so that the earth pressure was in an intermediate active state (i.e., smaller than the at-rest pressure). Long (2001) compiled a database containing 300 case histories of retaining walls and ground movements induced by deep excavations. He compared the field measurements with the theoretical derivations of Clough and Duncan (1991), and found that the current practice could provide reasonable evaluations of wall movement at stiff soil sites, but that it underestimates the movement where soft ground exists. Excavations of metro stations often require careful monitoring measurements. Some recent cases of deep excavations (Tan and Li, 2011; Tan and Wei, 2011) feature examples where the responses of diaphragm walls, propping struts, ground settlements, and the behaviour of nearby infrastructures were extensively monitored. These studies confirmed that the struts could effectively reduce the inward movements of the retaining walls. Over-excavation and a long duration without bracings were found to be detrimental to the structural integrity of diaphragm walls. In addition, the excavations were also influenced by the space effects (e.g., relatively long shape).

Some alternative approaches have been developed to facilitate the design of deep excavations. Briaud and Lim (1999) modeled the soil-wall interaction in a finite element analysis, where the soil response due to unloading was taken into account using a modified hyperbolic model. The complete sequence of construction was simulated to investigate the influence of tendon bonding, anchor forces, pile embedment, and stiffness. Finno et al. (2007) compared the maximum basal heaves calculated from three-dimensional finite element analyses and plane strain simulations. They found that the plane strain assumption could provide more consistent results than three-dimensional analyses only when the excavated length was six times larger than the excavated depth. Semi-empirical models were proposed based on numerical data to predict ground surface settlements induced by excavations, and these models were then evaluated against field measurements, such as the simplified model of Kung et al. (2007). Briaud and Kim (1998) compared the efficacy of three analysis methods, and claimed that the beam-on-elastic-foundation method could calculate more consistent bending results for retaining walls than the numerical analyses, which was better than the pressure diagram method. However, the beam-on-elastic-foundation method requires the input of a set of springs for the soil model and its application should be implemented with caution, since empirically derived soil springs are not appropriate for analyzing flexible buried structures, such as pipelines (Saiyar et al., 2016).

Pastor et al. (1990) indicated that the soil behaviour is highly dependent on the stress path and the stress history. Earth pressure acts on the supported walls, which is a function of lateral displacement (Mei et al., 2009; Ni et al., 2017c). At present, the calculation of earth pressure is still largely based on the conventional Rankine or Coulomb theory or empirical earth pressure equations (Peck, 1969; Tschebotarioff, 1973). In reality, excavations introduce the movement of supported walls in both vertical and lateral directions, and the soil response behind the walls corresponds to an unloading process. Once the bracing system is applied, the retaining walls may also experience lateral loading. The complexity involved with the nonlinear stress-strain response of soils subjected to different stress path needs to be further understood. The stress path method has been applied to investigate the constitutive properties of soils using different experimental approaches, such as pressuremeter tests (Silvestri and Diab, 2001), triaxial compression and extension tests (Nagaraj et al., 1981; Lo and Lee, 1990), constant-shear-stress-drained (CSD) tests, and anisotropic-consolidation-undrained (ACU) tests (Zhu and Anderson, 1998).

The stress-strain response of soils is significantly different under the plane strain and triaxial test conditions. For deep excavations, soil responds more closely to the plane strain conditions. Although soil parameters for the plane strain conditions could be derived from triaxial testing data (Nanda and Patra, 2015), the complexity of the calculation may prevent its application. In addition, the influence of intermediate principal stress on Mohr-Coulomb plasticity under plane strain conditions cannot be interpreted from triaxial testing data explicitly (Coombs et al., 2012). Plane strain tests should be conducted directly to evaluate the constitutive behaviour of soils during excavation. Some earlier attempts to develop plane strain apparatus include the works of Vaid (1968), Oda et al. (1978), Tatsuoka et al. (1986), and Mokni and Desrues (1999). Different considerations have been taken into account during the design of plane stain testing facilities, such as flexible specimen sizes and the restrained lateral movement of the bottom end platen (Alshibli et al., 2004), reversed axial loading devise (Ma et al., 2006), measurable intermediate principal stress (Wanatowski and Chu, 2006), a double-wall biaxial device for testing unsaturated soil (Alabdullah, 2010), and a horizontal plane stain apparatus (Luo and Shao, 2015).

This paper presents a series of consolidated undrained tests on silty clay using a plane strain test cell. Soil specimens were reconstructed under different k_0 conditions with a controlled water content. Three stress paths were considered, in terms of loading in the major principal stress direction, and loading and unloading in the minor principal stress direction, to model the behaviour of soils during excavations. The Duncan and Chang (1970) constitutive model that was initially developed for the triaxial compression conditions has been further modified to account for the plane strain conditions under different stress paths. Comparisons between experimental measurements and calculations using the proposed approach were conducted. In the end, an illustrative example was presented numerically

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