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Research Paper

A study of failure mechanisms of deep excavations in soft clay using the finite element method

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ABSTRACT

In this study, four failure mechanisms of excavations were investigated using the finite element method (FEM) with reduced shear strength. Center posts were considered in this finite element model. Both the elastic and elastoplastic support systems were used for comparison. The results showed that when the elastoplastic support system was used, reasonable stability of the excavations was estimated by the FEM. The yielding of the support system caused failures of the excavations. When the elastic support system was used, the FEM overestimated the stability of the excavations. The failures of these excavations were due to a large soil heave present at the excavation bottoms. For the two excavations in thick clay, the horizontal struts were bent until yield due to an upward movement of the center posts and a downward sinking of the wall. The yielding of the struts was followed by the yielding of the wall and failures of the excavations. For the remaining two excavations, which had either a shallow hard stratum or an insufficient support system, the failure was caused by the yielding of the wall due to an inward movement of the soil and the yielding of the struts because of the transfer of a large axial load from the wall.

1. Introduction

The stability of deep excavations is a main concern for practical engineers. The failure of excavations is often characterized by a collapse of the support system and the large inward movement of the surrounding soil. Therefore, the failure of excavations would result in not only economic losses (e.g., destruction of neighboring facilities) but also casualties. Hsieh et al. [1] reported two case histories (the 13.45-m-deep Taipei Rebar Broadway and 9.3-m-deep Taipei Shi-Pai excavations) detailing the failure of excavations carried out in Taipei clay (see Fig. 1a and b) that occurred because of the overestimation of their stability. A large inward deformation of the wall, an upward movement of center posts, and a bending deformation of struts were observed in these cases. The collapse of a 33.3-m-deep excavation near Nicoll Highway, Singapore, resulted in four casualties and subsidence of the highway pavement (see Fig. 1c). For this case, the Committee of Inquiry (COI) [2] reported a poor design of the wall-wale connections. Very recently in Hangzhou, China, a 15.7-m-deep excavation collapsed because the lowest strut level was not installed at the right time and this resulted in twenty-one casualties (see Fig. 1d). Based on the results of an intensive investigation, the failure surface of the soil has been identified by Chen et al. [3] by analyzing the disturbance of the surrounding soil.

The stability of excavations has been studied by many researchers using the finite element method (FEM) with reduced shear strength. The results of a parametric study by Goh [4] showed that the stability of excavations increases with an increase of the embedded depth and the stiffness of the wall but decreases with the increase of the clay layer thickness below the excavation bottom. Faheem et al. [5] also conducted a parametric study, whose results agreed well with those by Goh. [4]. Furthermore, closed-form equations considering the wall embedded depth were developed to estimate the bearing capacity of soil (N_c). Based on the results of case studies, Do et al. [6] showed that the strength reduction (SR) ratio of soil, which corresponds to the onset of rapid development of nodal displacement, is able to represent the factor of safety of excavations. The methods proposed by Wang et al. [7] and Huang et al. [8] can be considered as both cost-effective and safe. However, for convenience, most of the previous studies used the elastic support system and did not model the existence of center posts that are employed to support the horizontal struts, such that the FEM might not sufficiently simulate the behaviors of excavations in the site. In addition, few researchers have studied the failure mechanism of excavations in soft clay, which is significantly affected by the subsoil profile (e.g., the existence of hard stratum)

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Nomenclature

M	bending moment
M_p	maximum (plastic) bending moment
N	axial force
N_p	maximum (plastic) axial force
SR	strength reduction ratio applied to reduce soil strength during strength reduction procedure in stability analysis
SR_{max}	maximum strength reduction ratio or factor of safety estimated by FEM with reduced shear strength
ΣM_{stage}	unloading ratio of the unloading applied successfully in calculation to the total one caused by excavation at a stage
$\Sigma M_{stage\ max}$	maximum unloading ratio indicating the successful level of calculation of an excavation stage

and the stiffness of the support system. Therefore, this problem remains to be resolved.

In this study, the FEM with reduced shear strength was used to investigate the failure mechanisms of four case histories: the Taipei Rebar Broadway, Taipei Shi-Pai, Hangzhou, and Nicoll Highway excavations. Details of the strength reduction technique can be obtained elsewhere (e.g., Do et al. [6]), and the center posts were considered in the finite element model. For comparison, both the elastic and elastoplastic support systems were employed. Finally, the failure mechanism for excavations in soft clay was proposed.

2. FEM with reduced shear strength

The following assumptions were made: (1) there was no influence by the reduction in shear strength parameters of soil (c, ϕ) on the deformation parameters, such as Young's modulus (E) and Poisson's ratio (ν); (2) there were equal contributions of c and $\tan\phi$ to the shear strength of the soil. Therefore, in stability analysis of an excavation, the strength reduction procedure will be performed by simultaneously applying the same SR to both c and $\tan\phi$ as follows:

$$c_{input} = \frac{c_{original}}{SR} \tag{1}$$

$$\phi_{input} = \tan^{-1}\left(\frac{\tan\phi_{original}}{SR}\right), \tag{2}$$

where c_{input} and ϕ_{input} are input strength parameters of the soil, and $c_{original}$ and $\phi_{original}$ are original strength parameters of soil.

The value of SR will be increased constantly to reduce the soil strength until a divergence of the numerical solutions occurs, which is also defined as the failure of excavations. The maximum SR value (SR_{max}) achieved before failure will be considered as the factor of safety of the excavation. In this study, the following convergence criteria are adopted: (1) the global error is lower than the tolerated error of 0.01, and (2) the number of inaccurate soil (interface) points is <3 plus 10% of the number of plastic soil (interface) points.

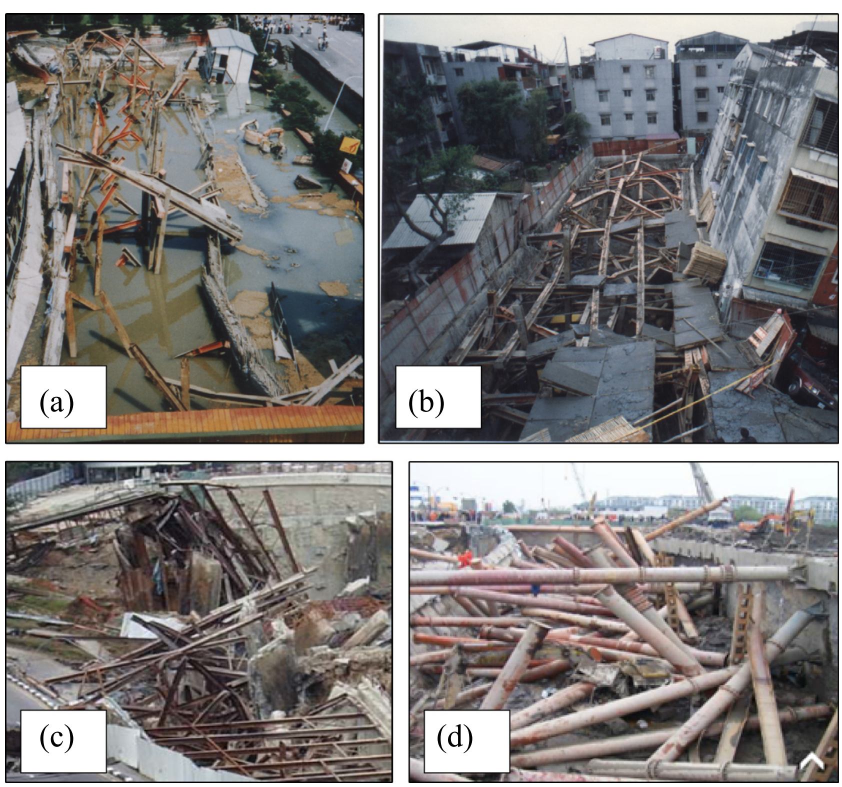

Fig. 1. Failure cases of excavations: (a) Taipei Rebar Broadway case (private document); (b) Taipei Shi-Pai case (private document); (c) Nicoll highway case (COI [2]) and (d) Hangzhou case. *Source:* www.pmdoudou.com.