PORE PRESSURE AND STRESS CHANGES DURING EXCAVATION

by

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SYNOPSIS

This paper presents the application of non-linear finite element analysis for predicting excavation performance in Taipei. The analysis uses the finite element program ABAQUS incorporating a generalized effective stress model referred as MIT-E3. The predictions are in very good agreement with the measurements of soil deformations, groundwater conditions, earth pressures and wall deflections. This paper concentrates on discussion of pore pressure and stress changes on the diaphragm wall. It indicates that significant wall adhesion developed during excavation. The predicted total vertical stress is very different from the overburden pressure that commonly assumed in design.

INTRODUCTION

Braced excavations are frequently used in building construction and infrastructure projects. This paper presents the results of an advanced finite element analysis that was conducted in order to have a thorough understanding of the excavation behavior of Taipei soil deposits (Whittle et al., 1993). The study site is the International Convention Center of the Taipei World Trade Center (WTC). The analysis uses the finite element program, ABAQUS, incorporating a generalized constitutive model MIT-E3 to carry out the staged excavation analysis. It gives consistent results including deflection of the wall, ground settlement in adjacent area, and pore pressure and lateral stress changes at each stage of excavation. Predictions are in very good agreement with field measurements. This paper summarizes some of the major findings of the study with emphasis on the change of stress fields around the wall.

SITE AND PROJECT DESCRIPTION

The WTC Convention Center is located in the eastern part of the Taipei basin. It is a 10-story steel frame building with a 2-story basement. It occupies a plan area of 14,750 m^2. The soil stratigraphy is relatively uniform across the site and is generally typical of conditions elsewhere in the K1 zone of the Sungshan formation in the Taipei basin (MAA, 1987):

1. The top fill layer comprises a heterogeneous mixture of sand, sandy gravel and construction debris with a thickness of about 1.5 m.

2. Underlying the fill is a deep layer of low plasticity (I_p=8-25%,I_L ~1.0) , soft silty clay which extends to an average depth of 30 m. The clay is intermixed with shell and organic material.

3. The lower 'stiff' silty clay interbedded with fine sand lenses extends from 30 to 45 m. The transition to the lower clay is also marked by a reduction in water content (25-30% compared to 35-45% in the upper layer) and corresponding increase in total unit weight.

4. Below the cohesive soil deposits at a depth of about 45 m are very dense silty sand and very stiff silty clay layers.

Excavation was carried out within 0.9 m thick diaphragm walls extending to a depth of 28m. The walls were supported by three levels of prestressed H-section steel struts spaced horizontally at intervals of 5.5 m. The first two levels of struts spanned the full width of the site, while the third level of struts were braced against the inner wall of the basement. The excavation is further stabilized by soil berms which were left in place until the third level struts were installed. The bottom of excavation was at a depth of 12.1 m. Various instruments were installed to monitor the performance of the excavation (Fig. 1).

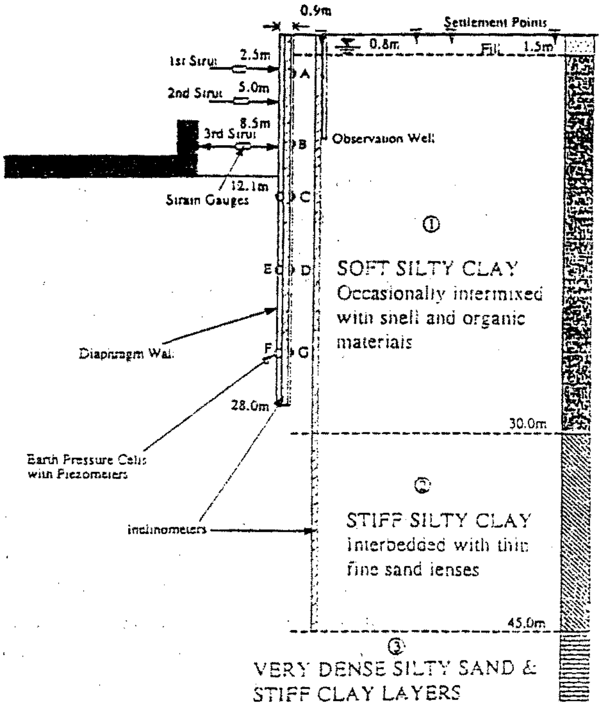

Fig.1 Composite Cross-Section of Field Instrumentation on West and South Walls of Convention Center

In this analysis, a total of 12 stages was used to simulate the excavation sequence. Time duration of each stage was specified according to the construction record.

FINITE ELEMENT MODEL

Hashash (1992) describes in detail the finite element procedures used to perform numerically accurate, effective stress analysis of excavation in non-linear soils using ABAQUS. Coupled analysis of fluid flow and deformation in the soil is performed using mixed isoparametric elements with 8-displacement nodes and 4-corner pore pressure nodes. Partial drainage effect during excavation is simulated. The two principal clay strata are modeled using the MIT-E3 model. The fill is described by a much simpler elastic perfectly plastic model with a Drucker-Prager failure criterion and non-associated flow rule.

The MIT-E3 model (Whittle, 1987) is a generalized effective stress soil model for describing the rate independent behavior of normally to moderately overconsolidated clays (OCR $\leqq$ 8) which exhibits normalized behavior. The model formulation comprises three components: 1) an elasto-plastic model for normally consolidated clays, which describes anisotropic properties and strain softening behavior; 2) equations for the small strain non-linearity and hystertic stress-strain response in unload-reload cycles; and 3) bounding surface plasticity for irrecoverable, anisotropic and path dependent behavior of overconsolidated clays.

COMPARISONS OF PREDICTIONS AND MEASUREMENTS

Moh and Chin (1991) have summarized the extensive program of field monitoring which was carried out in conjunction with the excavation for the WTC Convention Center. The focus of this paper is pore water and lateral earth pressure measurements.

Measurements of pore water pressures (u) and total lateral stresses (σ_h), using piezometers and earth pressure cells mounted on both the inside and outside faces of the diaphragm wall, are a relatively unique feature of the instrumentation used at the WTC Convention Center site. Figures 2 and 3 compare the distributions of u and σ_h

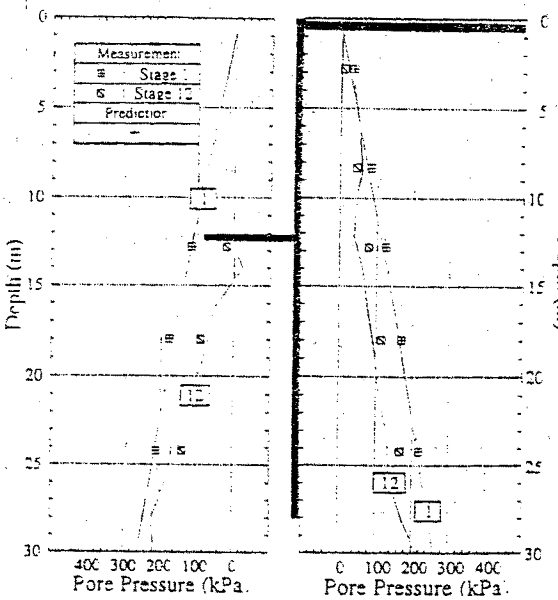

Fig.2 Comparison of Predicted and Measured Pore Water Pressures acting on Diaphragm Wall Before and After Excavation

acting on the two sides of the perimeter wall with the measured data prior to construction and at the end of excavations (Stages 1 and 12, respectively). There is excellent agreement between the measurements and the initial conditions imposed in the finite element model (i.e., both the pore water pressures and total lateral stresses). These results confirm the interpretation of initial pore pressures at the site and also show that the in-situ K_0 stress conditions $(=\sigma'_{h0}/\sigma'_{v0})$ in the upper clay are well modeled in the analysis. There is a net reduction in both the measured pore water pressures and total lateral stresses acting on both sides of the wall at the end of excavation (Stage 12). The predictions match closely with these measurements.

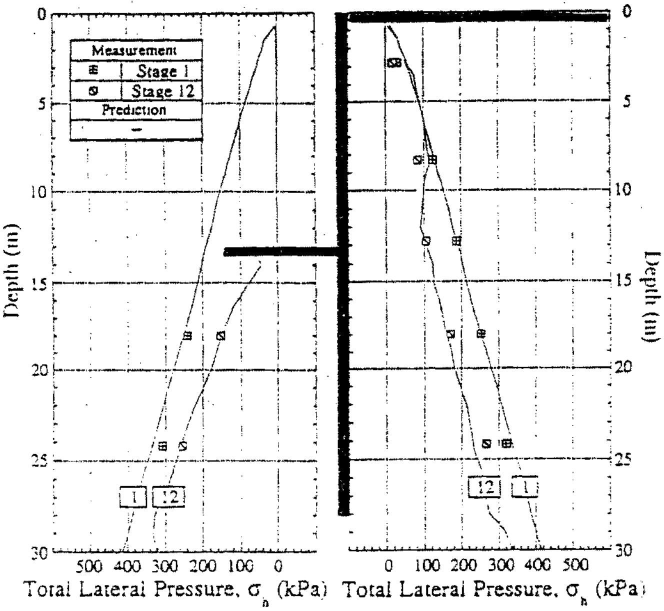

Fig.3 Comparison of Predicted and Measured Lateral Earth Pressures acting at Diaphragm Wall Before and After Excavation

TOTAL VERTICAL STRESS CHANGE AND SHEAR STRESS DEVELOPMENT

Complete interpretation of the mechanisms controlling the stress changes in the soil can only be developed through detailed study of the stress paths of individual soil elements around the excavation. Figure 4 compares the normalized total and effective stress paths of interpreted monitoring results at depth of 18m, with behavior predicted by the finite element analysis. The response is characterized by shear stress component, $q = (\sigma_v - \sigma_h) / 2$, and the average total and effective stress, $p = (\sigma_v + \sigma_h) / 2$, $p' = (\sigma'_v + \sigma'_h) / 2$, respectively. Case 1 presents the results of finite element analysis. Case 2 plots stress paths using predicted u and σ_h but assumed σ_v (= γ_t z, where z is the height of retained soil within excavation or the depth below ground level outside excavation). Case 3 presents stress paths based on the of u and σ_h while assuming σ_v equals to overburden pressure. The comparisons indicate the following:

1. By assuming σ_v equals overburden pressure, as in Cases 2 and 3, total stress path of soil element outside excavation (Element D in Fig.1) is similar to that of plane strain active (or triaxial compression) mode of shearing. For the soil element within excavation (Element E), total stress path is similar to that of plane strain passive (or triaxial extension) mode of shearing. These two modes of shearing are commonly assumed in design analysis as well as in the interpretation of monitoring results.

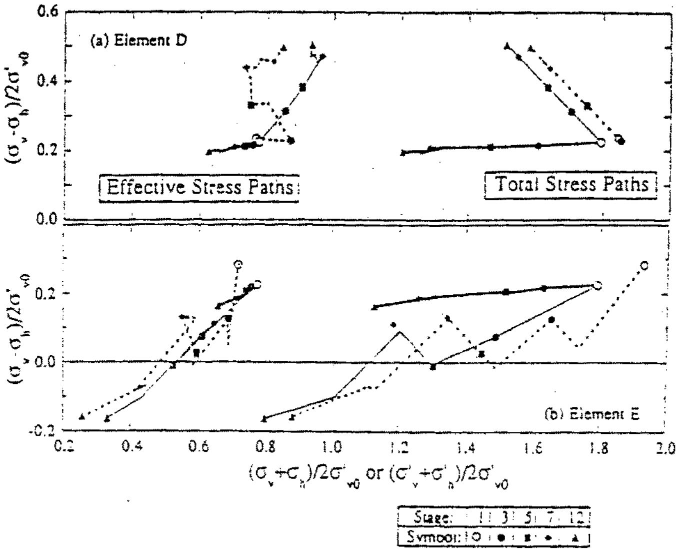

Fig.4 Comparison of Predicted and Measured Stress Paths

2. As Figs. 2 and 3 indicated, the analysis give very good prediction of lateral earth pressure and pore pressure. It is not surprising that Case 2 and Case 3 have very good agreement with the directions and magnitudes of total and effective stress paths.

3. Comparisons between Case 1 and Case 3 show very large differences between predictions and measurements. This behavior reflects, in large part, by the assumed vertical stress condition. It implies that actual stress path of soil element outside excavation is not similar to conventional triaxial compression mode of shearing, and the stress path of soil element within excavation is not similar to conventional triaxial extension mode of shearing. Soil elements on both sides of the wall involve major principal stress rotations during excavation.

4. This comparison demonstrates that extreme caution should be used in interpreting the stress paths for soil elements adjacent to the diaphragm wall, where shear stress must be considered in the equilibrium calculations.

Figure 5 presents the complete, normalized total and effective stress paths predicted for Elements B, D and E (Fig. 1). Wall adhesion is characterized by the shear stress, τ. Element B is located in the retained soil at a depth z = 8.3 m with initial OCR~2 ; while Elements D and E are at a depth z = 18 m, which is below the finial excavation level, and have an initial OCR~1.2. The results show the following:

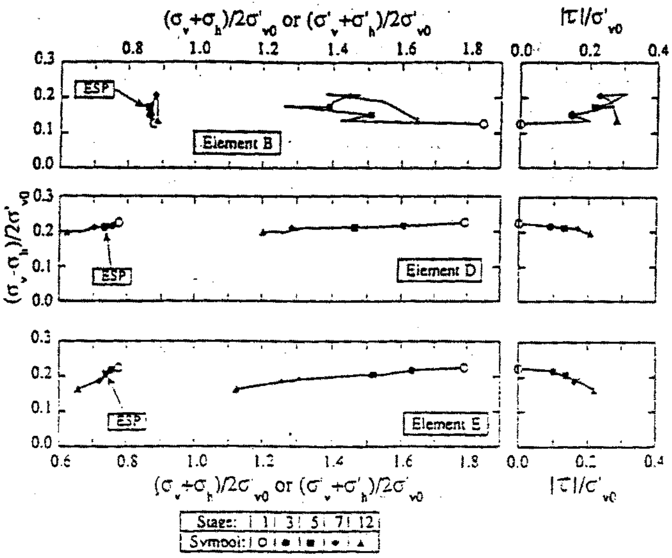

Fig.5 Predictions of Stress Paths for Selected Soil Elements

1. Significant wall adhesion develops on both sides of the wall. Comparing with the interpreted SHANSEP compression strength for Taipei K1 clay (Whittle et al.,1993), the maximum wall adhesion for soil Element B is about 50% of the SHANSEP compression strength. For soil Elements D and E, wall adhesions can be as large as 2/3 of their corresponding SHANSEP strengths.

2. Element B experience an important reversal in shear directions (q and τ) which occurs when the excavation progress below this elevation in the soil (i.e., after Stage 7). There is very little net change in the effective stress (p') during the shearing as the soil is initially overconsolidated at this depth. The total stress path shows a large decrease in both σ_v and σ_h during the initial phases of excavation (Stage 1 through 7), after which there is an increase in σ_h associated with deep seated movements in the retained soil.

3. Elements D and E experience very similar stress path in which there is a small reduction in the effective stress p', and shear stress component q, but large rotations of stress directions associated with shearing on vertical planes (τ). In the retained soil (Element D), the shear stress directions can be related to the settlement trough, while the response at Element E is controlled by the surface heave inside the excavation.

Overall, the results in Fig. 5 indicate the importance of the shear stress, τ , which is generated by friction between the soil and the diaphragm wall. In principle, these shear stresses can be measured by surface stress transducers which are capable of measuring σ_h and τ concurrently.

CONCLUSIONS

This paper presents the results of an advanced non-linear finite element analysis for predicting excavation performance in Taipei K1 clay. With a reasonable simulation of the clay behavior by MIT-E3 model, this analysis gives excellent agreement with measurements of pore water pressures and lateral earth pressures. This study also provides insightful information of the development of wall adhesion and its associated total vertical stress change. The predicted wall adhesion and vertical stress are very different from those commonly assumed in design practice. It indicates that induced shear stress between wall and soil should be properly considered in the equilibrium calculation. It is also suggested that surface stress transducers be used in future major research and construction projects.

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