Stage Excavation Analyses of CA/T Slurry Walls

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Abstract

The JE/Sverdrup Boston office is the first Section Design Consultant of the Central Artery/Tunnel project for the Massachusetts Highway Department (MHD) to use FLAC analyses for the slurry walls of a Support of Excavation (SOE) system. During the construction phases of the CA/T contract D015A1 and D015A2 projects, the Contractors submitted Value Engineering Change Proposals for SOE designs with a two-dimensional (2-D) approach, using the ANSYS finite element code, in lieu of the project defined one-dimensional (1-D) approach. Since ANSYS is a general structural engineering program, MHD was concerned about its applications to geotechnical problems. JE/Sverdrup, therefore, recommended using FLAC, a 2-D finite difference code for geotechnical applications, as an independent check of the ANSYS analysis results. This paper outlines the FLAC methodology, discusses a simplified modeling concept, describes the numerical stage excavation procedures, and compares ANSYS, FLAC, and 1-D analysis results. In conclusion, a suitable 2-D analysis generally results in a more cost-effective design for vertical members of an SOE system than that of the conventional 1-D approach.

Introduction

Traditionally, the analysis of a Support of Excavation (SOE) wall is performed by a one-dimensional (1-D) approach. Generally, the wall is simulated by a continuous beam, the bracing struts by axially loaded members, and the responses

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from the ground either by the classical earth pressure theory or by elastic-plastic springs. These types of analyses include the Equivalent Beam Analysis (Steel Sheet Piling Design Manual, United States Steel, 1972) and the Beam on Elastic Foundation Analysis methods. A special numerical technique is required for these types of approaches to simulate the stage excavation phenomenon (Chen, 1996). Wall moments and shears from these types of 1-D approaches are generally conservative, and the wall displacement is extremely sensitive to the selected subgrade reaction constants, the spring constants of the numerical model. Most of the time, the displacement results are unrealistic and greater than those obtained from field instrumentation data. To obtain a realistic displacement model, field measurement and back analysis are required. This becomes a dilemma during a design stage when an accurate prediction of wall displacement adjacent to sensitive historic buildings is crucial and field measurement data are not available.

Realizing the conservative 1-D approach by the Section Design Consultant (SDC) of the Massachusetts Highway Department (MHD) Central Artery Tunnel (CA/T) D015A1/D015A2 projects, the contractors submitted Value Engineering Change Proposals (VECPs) for SOE designs by a two-dimensional (2-D) approach, using the ANSYS finite element code. The objective of the VECPs is to revisit the original design concept and to produce an innovative and cost effective design without impairing the original design intention and the function of the structure.

However, ANSYS is a general structural engineering program; it does not have an explicit geotechnical application capacity. It could not define the in-situ stress field and the pore water pressure explicitly in a finite element model. A "pseudo" in-situ ground effective stress field is generated by the buoyant weight of the ground and the Poisson's effect, by specifying displacement boundary conditions around the boundaries of a model. A "pseudo" hydrostatic pressure is manually applied only on the wall, the continuous beam member in a numerical model, at every excavation stage. These pseudo approaches awkwardly simulate the soil-structure-hydraulic interaction phenomenon. Applying the "pseudo" hydrostatic pressure on the wall directly, this type of analysis might generate higher bending moments and shears than those anticipated. The accuracy of its displacement results is also uncertain, especially in the case of a passive pressure situation. Because the model does not build-in pore water pressure, its displacement results, lacking the pore water pressure resistance, would be higher than those anticipated in a passive pressure situation.

Recognizing that the modeling of soil-structure-hydraulic interaction phenomenon is crucial for excavation near displacement sensitive historical building sites, JE/Sverdrup, the SDC of the MHD, recommended using FLAC, a 2-D finite difference code for geotechnical applications, as an independent check of ANSYS finite element analysis results.

Table 1 identifies the ANSYS and FLAC numerical approaches.

Table 1 ANSYS and FLAC Approaches

ISSUES	ANSYS	FLAC
Numerical Scheme	Finite Element Method	Finite Difference Method, Dynamic relaxation scheme
Constitutive law/model	Cohesive soil: multi-linear isotropic hardening. Req. Tangent Young's modulus derived from hyperbolic model (Duncan and Chang, 1970). Cohesionless soil: elastic plastic. Req. Young's modulus, and Poisson's ratio.	Elastic plastic. Req. Young's modulus, and Poisson's ratio.
Yield function/failure criteria (all in terms of effective stress)	Cohesive soil: Von Mises shear strain energy criterion, independent of hydrostatic pressure. Req. parameters: undrained shear strength. Cohesionless soil: Drucker-Prager model. Req. parameters: effective friction angle, and effective cohesion.	Mohr-coulomb shear stress criterion or Drucker-Prager shear strain energy criterion. Req. parameters: effective friction angle, and effective cohesion.
Soil-structure-hydraulic interaction model	Approximate effective stress by Poisson's effect. "Pseudo" hydrostatic pressure technique; no coupling analysis capability.	Performs either total or effective stress analysis. Pore water pressure is built-in in the model.
In-situ effective stress conditions	Vertical stress, σ_v: by buoyant weights. Horizontal stress σ_h = ko . σ_v Where $k_o = (v / (1- v))$, i.e., the σ_h is by displacement boundary conditions (suitable assumption for elastic theory only).	Vertical stress, σ_v: by buoyant weights. Horizontal stress σ_h : user defined. This feature is important for over-consolidated soil/rock with a k_o value greater than 1.

General FLAC Methodology

FLAC, Fast Lagrangian Analysis of Continua (ITASCA, 1996), is a 2-D explicit finite difference program, applying the dynamic relaxation (Otter, Cassell, and Hobbs, 1966) concept, for engineering mechanics computations. This program can simulate non-linear soil/rock-structure-hydraulic interaction problems. The structural domains or material are defined in a grid pattern similar to the finite element method approach. Figure 1 shows a typical FLAC mesh model. FLAC also contains a built-in programming language, *FISH* (short for *FLACish*). With *FISH*, we can write our own functions to expand FLAC's capabilities. User defined in-situ stress conditions and constitutive models are some of the examples of these functions.

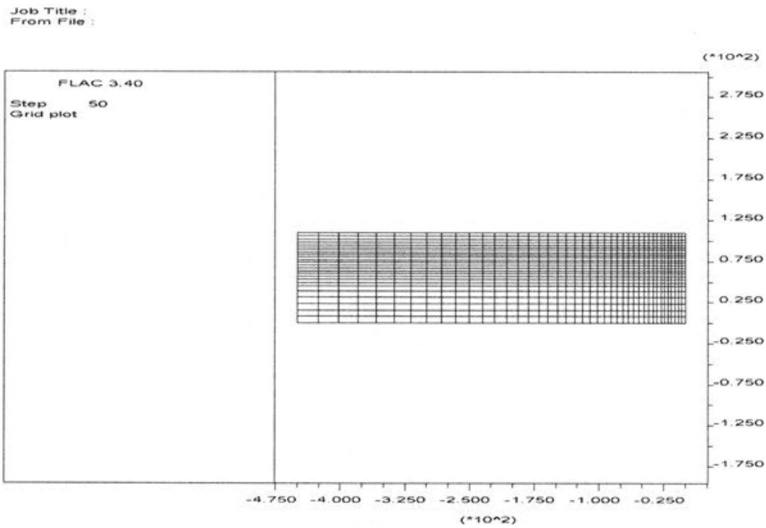

Figure 1. A typical FLAC Mesh Model

Slurry Wall Analysis

The SDC's independent analysis assumed the ground to be nonlinear elastic-plastic isotropic material with Mohr-Coulomb shear failure criterion, a common assumption for this type of application, though other failure criteria could be defined in FLAC. The groundwater is assumed to be at a fixed elevation in areas outside of the excavation. During construction, dewatering is performed inside the slurry wall; therefore, the analysis assumed the depressurized groundwater level, within the excavation, is at the top of excavation. Because of the short excavation duration, a undrained condition is assumed throughout the analyses.

We recommend the vertical and horizontal dimensions of a FLAC model should be at least two and eight times of the excavation depth and width, respectively. The purpose of this requirement is to eliminate the possible boundary effect that impacts the analysis results. The slurry wall is simulated by pile elements in FLAC. The wall connects to its adjacent ground elements with coupling springs with high normal strength and low shear strength, simulating the interfacing behavior between the wall and the ground. Struts are simulated by beam elements with null rotational displacement and moment, by "slaving" one end of the strut nodal displacements, both horizontally and vertically, to the corresponding pile element's nodal displacements, thus eliminating the strut rotational displacement and moment. The function of the FLAC "slave" command is equivalent to the moment release command in many general structural analysis programs.

Simplified Numerical Modeling Concept

A FLAC slurry wall model usually contains only one wall to take advantage of geometrical symmetry. One can achieve this simplification in a model by locating or predicting the point of zero strut horizontal movement and assuming this point the center of the excavation width. Using this concept, we only analyze half of the actual structural domain. In cases where the total excavation width is wide or more than two walls are involved, modeling the total structural domain becomes unpractical and might exceed FLAC's built-in capacity. In these cases, an equivalent strut stiffness concept could further simplify the model. Since the displacement (δ) of a strut is equal to its thrust (P) multiplied by its length (L) and divided by the product of its Young's modulus (E) and its area (A), adjusting the stiffness, EA/L, could result in a smaller numerical model without sacrificing the end results.

Numerical Stage Excavation Procedures

First, the buoyant weights of the ground, the pore water pressure, and the coefficient of earth pressure at rest, Ko, simulate an in-situ geostatic condition. At this in-situ condition, no deformations occur yet in the model. If multiple ground material layers exist with various Kos, the FLAC *FISH* language is a perfect application to generate the in-situ stress field for each material layer. After the generation of in-situ stresses, surcharges, such as construction equipment loads, are then applied to the model. The structural domain of this model would start experiencing deformation at this stage. Numerical simulations of dewatering and ground excavation cycles begin by changing the pore water pressure condition inside the excavation (to the top of present excavation level) and eliminating the elements of the model to a pre-defined excavation elevation. An axially loaded beam member, the strut, is then introduced after each excavation cycle. A complete excavation cycle begins from dewatering, excavation, to strut installation. This cycle continues until the final bottom of excavation elevation is reached. The FLAC model could also include a strut pre-jacking load during the strut installation simulation.

Numerical Example

This example is a typical rigid Soldier Pile and Tremie Concrete (SPTC) slurry wall of the CAT/D015A Project in downtown Boston, Massachusetts. This wall serves as both a SOE during excavation and the permanent wall of a roadway cut-and-cover tunnel during operation. The dual functions of this wall reduce the required construction space, which is a major cost saving for construction in urban areas. This wall is 1.07 m wide, with W-36X320 (inch-pound) soldier piles at 1.83 m on center and 28 MPa unreinforced concrete. The strut is composed of two W30X90 (inch-pound) steel at 18' spacing along the tunnel axis. Figure 2 shows the SOE numerical model geometry, geotechnical profiles, and boundary conditions. The total width of the excavation is 17.1 m and the excavation depth is 16.2 m. The SPTC wall is 21.6 m long with 3.05 m embedded in rock.

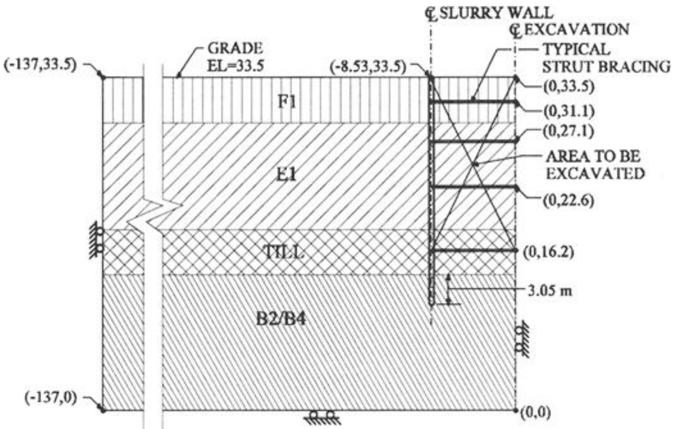

Figure 2 The SOE Numerical FLAC Model. The groundwater table is about 1.2 meter below grade before excavation.

Table 2 summarizes the material properties (GEI, 1997) of the numerical model.

Table 2 Soil Properties Used in the FLAC Analysis Example.

Material	Total Unit Weight	Dry Unit Weight (2)	Poisson's Ratio	Young's Modulus	PHI (1)	Ko
	(kg/m^3)	(kg/m^3)			(DEG'S)	
Fill (F1)	1842*	1342 (187) (3)	0.33	9.60	30	0.5
	2002*	1502 (153)				
Organic Silt (E1)	1730	1230 (125)	0.35	17.20	0	0.5
Glacial Till	2211	1711 (175)	0.30	86.20	37	1
Bedrock (B2/B4)	2643	2143 (219)	0.43	1915.00	45	0.75

1. PHI is the Friction Angle
2. Dry Unit Weight = Total Unit Weight – 1000 x n (porosity; assumed to be 0.5 here)
3. The mass densities are shown in parenthesis = Dry Unit Weight / 9.81

Note: Average values from GEI Report were used
* Use 1842 kg/m^3 for fill above groundwater level and 2002 kg/m^3 for fill below groundwater level.

Figure 3 shows the maximum strut thrust at each bracing level versus the stage of excavation from the FLAC example results.

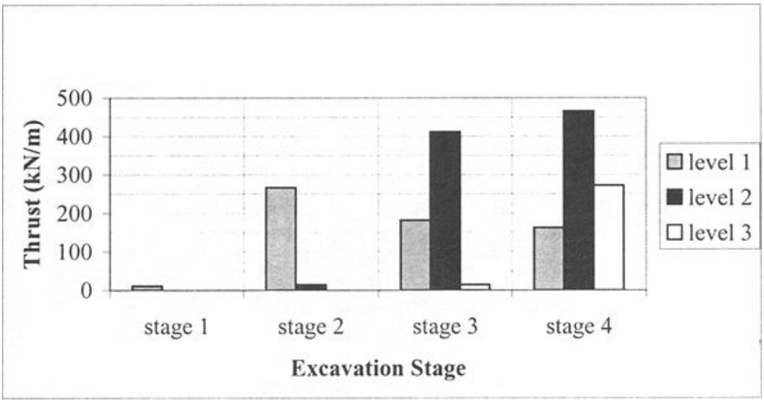

Figure 3 The maximum Strut Thrust at Each Bracing Level vs. the Excavation Stage.

Figure 4 and 5 show the wall displacement and the wall moment versus the ground elevation, respectively.

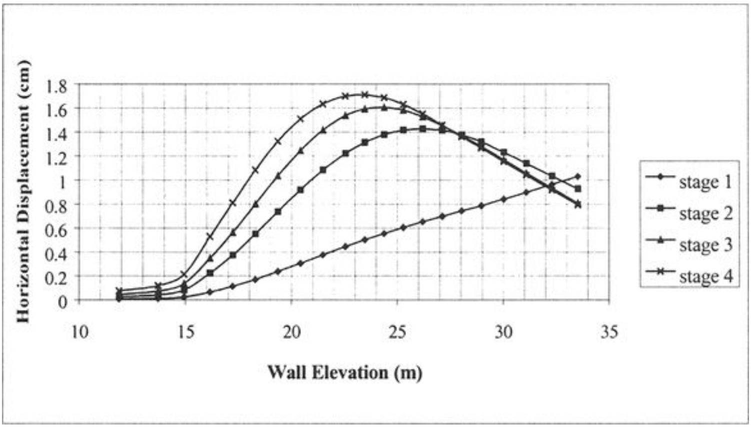

Figure 4 Slurry Wall Displacements vs. Wall Elevation for Each Excavation Stage

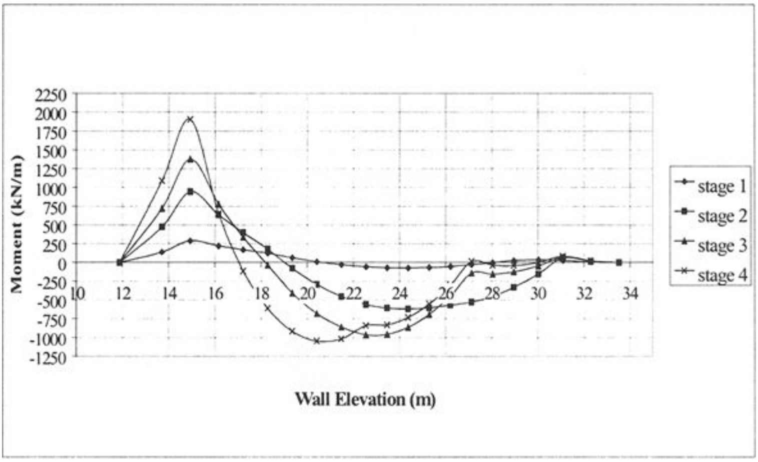

Figure 5 Slurry Wall Moments vs. Wall Elevation for Each Excavation Stage

Slurry wall designs in urban areas require special attention to details and construction procedures. When an excavation is near sensitive structures, the system must posses sufficient stiffness so that ground movements outside of the excavation are within an acceptable limit (Boscardin and Cording, 1989).

The observed horizontal displacement, in Figure 4, is about 0.1% of the excavation depth. From this displacement history, one could derive the horizontal strains and angular distortions for each buildings adjacent to the excavation. In this example, the ground movement is within the acceptable limit. In cases where the ground movement exceeds the acceptable limits, one could increase the SOE system stiffness by increasing the wall stiffness thickness or soldier pile size, by increasing the strut bracing size, by reducing the bracing layer distance, or by reducing the strut spacing distance along the tunnel axis. Boscardin and Cording's paper also provides adjusting factors for ground movements based on the types of foundations and buildings.

Figure 5 indicates the maximum bending moment in the SPTC wall occurs below the top of excavation. The exact location is at the interface of the soil and rock. This brought an interesting point for discussion. Since the maximum bending moment of the wall does not occur in the open excavation area, do we have to design the wall based on this maximum value (especially when this value is much higher than the maximum value in the open excavation region)? This requires special attention and engineering judgement, depending upon the confidence level of the geotechnical parameters provided and the constitutive law/model adopted. For example, if the rock strength is actually weaker than that assumed in the model, the resulting bending moment of the portion of the wall in rock would be lower than that predicted. This would shift the moment diagram and would result in a higher bending moment for the portion of the wall in the open excavation region.

The maximum bracing load for each strut generally occurs at the next excavation stage immediately after it is installed, as shown in Figure 3.

Modeling Issues and Discussions of 1-D and 2-D results

Numerical modeling from finite element methods (FEM) or finite difference methods with displacement boundary conditions always result in smaller bending moments and lateral wall displacements, especially with a small FEM model width. This is because of the boundary effect that increases the system stiffness. One scheme to verify whether the FEM width is suitable is to compare its in-situ horizontal stresses at stages before and after the excavations. The ground stress at a distance far away from the excavation shall remain almost constant (as the in-situ one) for different excavation stages. The influence zone from an excavation extends horizontally from the excavation support wall to a distance of approximately twice of the excavation depth. The other alternative to verify the boundary effect is by running several FEM models with different domain sizes and verifying that the convergence of the displacement results are obtained.

An SOE bracing system usually requires struts to be preloaded in place; however, it is not recommended to use this preload in the modeling, unless field data are available and the back analysis has been confirmed. This is especially crucial for an ANSYS model for the following two reasons. The first reason is to provide an additional safety factor to account for unforeseen adverse conditions in the field, such as temperature rises and drops. The second reason is to avoid the unrealistic ground movement that might be encountered from the jacking preload in the ANSYS model. Since the hydrostatic stress field is not built-in in the ANSYS model, any pushing/compressing (passive effect) to the ground will cause larger deformation (due to the lack of the presence of the pore water pressure), in the direction of the load, than what could be observed in reality. In the VECP stage of the CAT/D015A Project, it has been agreed that the jacking loads shall be removed from the ANSYS FEM model.

We compared the results between the Contractor s ANSYS (Weidlinger Associates, Inc., 1997) analysis and the SDC's FLAC analysis, and concluded the results of these two analysis approaches are similar. In most cases, the displacement results of the ANSYS analysis are generally smaller than the FLAC's. This might be because of the different assumed constitutive models, the slightly different assumed geotechnical parameters, and the assumed pre-jacking load approach in the ANSYS model, which was then abandoned and not used.

In comparison among the 1-D original SDC designs and the 2-D VECP results, both from ANSYS and FLAC, the 2-D analyses provided much more reliable displacement results and cost-effective SOE systems, resulting in reducing some strut bracing levels in displacement insensitive regions. This is because the 2-D analyses could fully mobilize the shear strength capacity of the in-situ ground, and the 1-D analyses could only estimate the soil-structure interaction behavior approximately through the classic earth pressure theory and other simplified assumptions.

Conclusion

JE/Sverdrup is the first SDC of the MHD to use FLAC, a two-dimensional explicit finite difference code with dynamic relaxation approach, for slurry wall analysis. In this paper we have outlined the FLAC methodology, discussed a simplified modeling concept, described the numerical stage excavation procedures,