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SYNOPSIS: This paper presents the design criteria, finite element modeling and actual behavior of a braced sheetpile excavation in Detroit soft clay. Due to the close proximity of existing structures to the excavation, a detailed analysis was performed to design and construct an earth retention system to avoid damage to these structures. The excavation involved a 170 ft by 220 ft area. The maximum depth of excavation was 23.5 ft. The subsurface soil consists of soft to very soft Detroit clay from the excavation level to a depth of 80 ft and has an undrained shear strength as low as 360 psf.

INTRODUCTION

The City of Detroit Water and Sewerage Department has undertaken a major construction project currently ongoing in Southwestern Detroit. The project involves several excavations with different earth retention systems in very soft to soft clays. A major feature of the project are new Grit Chambers whose earth retention system is the subject of this report.

The Grit Chamber site, as shown in Figure 1, is a 1.0 acre area within the Detroit Wastewater Treatment Plant, was formerly used as ash lagoons to store ash from the plant incineration operations. The eastern portion of the site is the location of the sheetpile retaining structure for the construction of a portion of the Grit Chambers adjacent to the existing Sludge Thickener Tanks.

This paper discusses the performance of the sheetpile retaining structure based on geotechnical instrumentation and compares these field measurements to those predicted by the finite element method. The effects of construction sequencing are also discussed.

GENERAL GEOLOGY

The Detroit area was covered by several glacial ice sheets during the Pleistocene epoch. The advancing ice deposited a thin discontinuous stratum of very dense glacial till, locally referred to as hardpan, directly over the limestone bedrock of the Dundee formation. Subsequently, rising global temperatures melted the glaciers and the meltwater created the forerunners of the present Great Lakes. Glacial streams flowing into these lakes carried glacial debris that was deposited in the lakes. Coarser sand and Gravel particles generally were deposited near shorelines as deltas and the finer silt and clay particles were generally deposited in deeper water. The clay deposit at the treatment plant site is a result of this type of deep fresh water deposition although it exhibits considerable stratification.

The stratification or layering found within the deposit is a consequence of variable flow conditions which occur typically near the fronts of stagnating or receding ice sheets. Following its deposition, the surface of the clay was exposed to the air, apparently due to lower lake levels, which caused a partial drying and stiffening of the upper 10 to 15 feet. Sands deposited probably by the meandering Rouge River overlie the clay.

SOIL CONDITIONS

The soil conditions for the project were determined from three subsurface investigations. In addition, considerable soil data have been collected from previous investigations of the site. In-situ vane shear tests and laboratory tests were performed within the clay depth. Figure 2 shows the generalized subsurface profile and relevant test results.

The top of the clay stratum is approximately elevation 98 feet and extends down to elevation 25. The upper 10 feet of the clay layer is desiccated and consequently has a medium consistency and an undrained shear strength in the 750 to 800 psf range. At approximately elevation 86 the consistency becomes soft to very soft, the undrained shear strength decreases to approximately 350 psf, the moisture content increases and the dry unit weight decreases.

The shear strength gradually increases with depth reaching a value of about 700 psf below elevation 48. The clay is normally consolidated or slightly over consolidated below about elevation 75. The clay is generally classified as low plasticity clay in the Unified Soil Classification System, however, occasional samples are classified as highly plastic clay based on Atterberg limits tests. Stratification or layering was observed in samples taken from the upper clay stratum. The layering typically consists of thin bands of silt or sand, and clay.

The clay is underlain by a glacial till, locally referred to as a hardpan, which consists of a very dense mixture of silt clay, sand and gravel. A limestone bedrock underlies the hardpan and is characterized as a massive, competent, gray limestone.

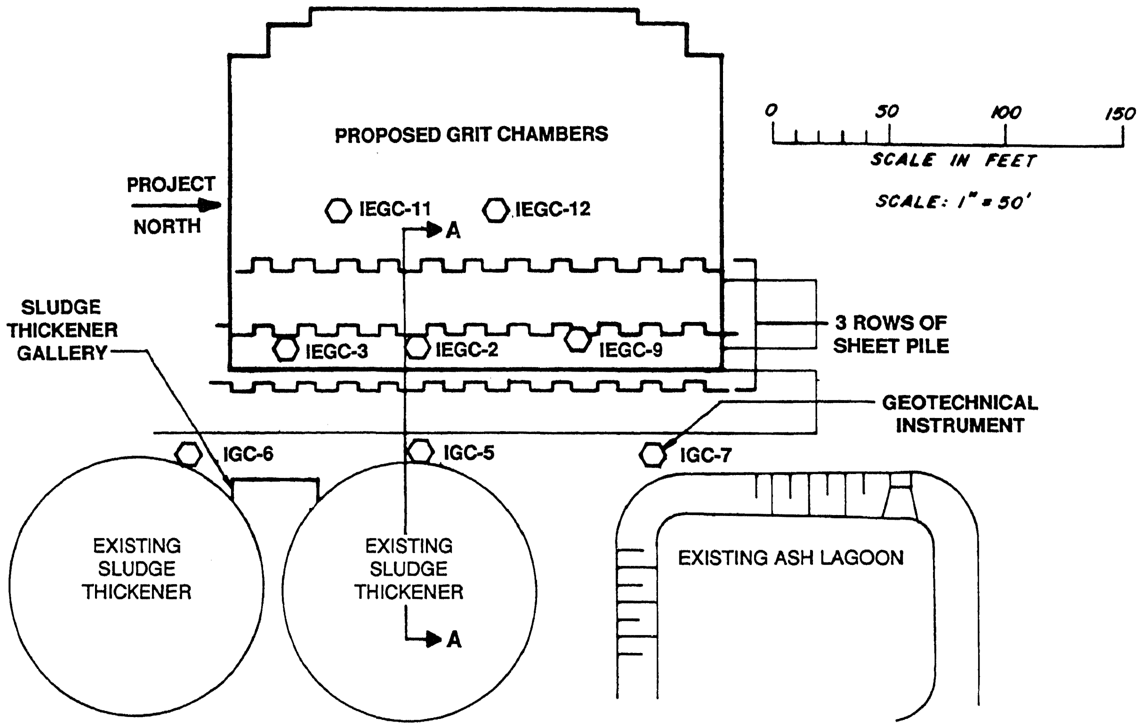

Figure 1. Project Site and Location of Geotechnical Instruments

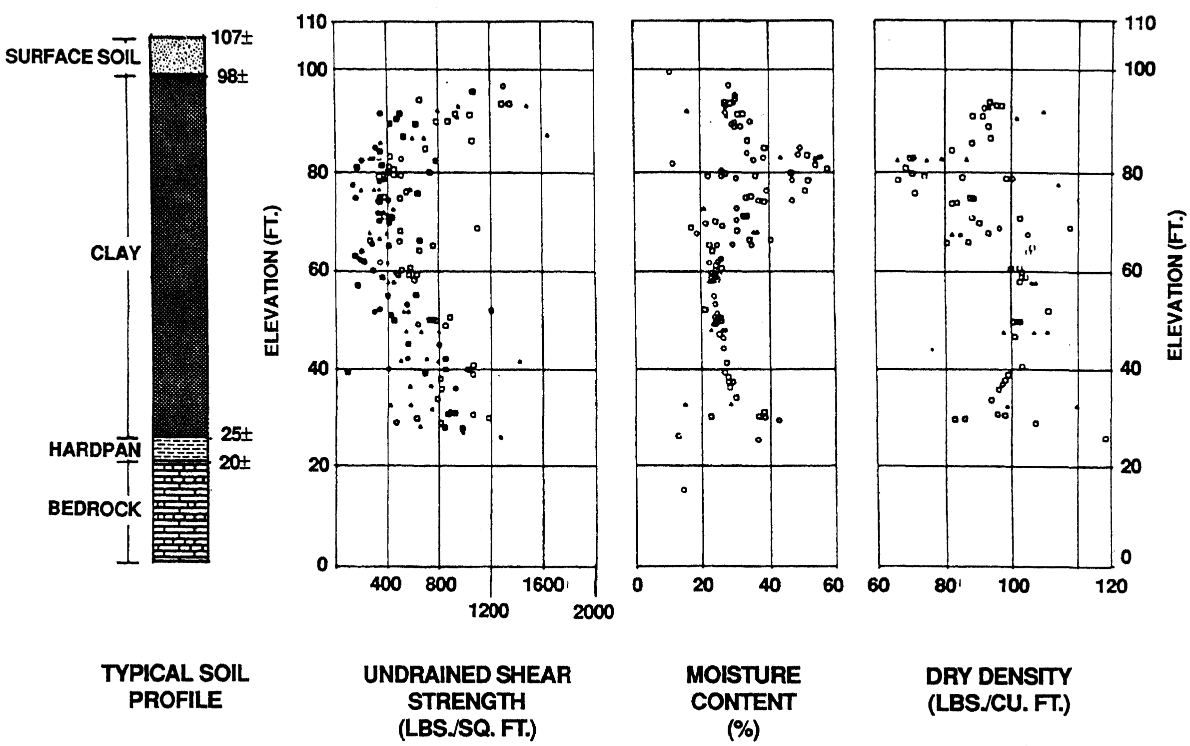

Figure 2. Generalized Subsurface Profile and Test Results

DESIGN CONSIDERATIONS

Major design considerations included: (1) minimizing the potential soil movements beneath the existing structures, (2) preventing slope instability, and (3) avoiding basal heave. To satisfy the above requirements, a braced steel sheetpile wall was utilized with a staged excavation. Each stage consisted of excavating a portion of the total area. A concrete filled steel pipe pile foundation was installed for the structure prior to commencement of excavation. The final design approach was determined after performing slope stability analyses and finite element modeling for several alternative excavation schemes.

EXCAVATION PROCEDURE

As shown in Figure 1, three rows of PZ-35 sheetpiles were installed for the excavation adjacent to the existing sludge thickener tanks and temporary ash lagoon. These tanks must remain operational after completion of the construction of the proposed Grit Chamber facility, therefore, measures were taken to minimize any soil movements to prevent existing tank subsidence and/or cracks. An excavation sequence for the east end of the proposed Grit Chamber adjacent to the Thickener Tanks was designed and implemented during construction. Support of the Grit Chamber foundation consists of concrete filled pipe piles installed prior to any excavation. These piles were driven to the hardpan, filled with concrete and internally cut to the bottom of foundation level.

The excavation sequence involved an eight-foot open excavation (pre-excavation) to elevation 92 followed by a two-stage braced excavation. Figure 3 shows the general excavation sequence and excavation stages. The sheetpiles were driven from elevation 100 prior to any excavation to elevation 65 which is about 11.0 feet below the lowest level of excavation with every forth sheetpile driven to the bottom of clay layer. The major focus of the specified excavation sequence was to minimize soil movements which could affect the existing adjacent structures. Slope stability and the stability of the bracing system and deflection of the sheeting were all considered.

INSTRUMENTATION

The field instrumentation consisted of inclinometers, extensometers, and surface markers. Figure 1 shows the Instrumentation Plan at the excavation site. Inclinometers/Extensometers Nos. 3, 2 and 9 are located adjacent to the Stage one braced excavation and were positioned to measure horizontal and vertical movements adjacent to the sheetpiles.

Inclinometers 5, 6 and 7 were located along the berm in front of the Sludge Thickener Tanks and temporary ash lagoon to measure horizontal movements associated with potential slope stability failure. Inclinometer/Extensometers 11 and 12 were located 30 feet to the west of stage one excavation to avoid conflict with the excavation and construction traffic.

FINITE ELEMENT METHOD

The finite element method was utilized during the design stage to model excavation sequence and predict movements of the earth retention system and the adjacent unexcavated soils and structures. Additional analyses were performed during the excavation phase to properly model the actual construction sequences. References cited are some of the available literature which utilized a finite element method to predict movements associated with excavation.

The analyses were performed with the program SOIL-STRUCT, developed by Clough and Tsui (1974), to study soil responses by simulating incremental construction and loading sequences under undrained, plane strain conditions. The program uses a nonlinear, stress dependent hyperbolic model for soil under primary loading. For soil under unloading and reloading, a stress dependent linear response is used. It also uses a bilinear stress-strain model for interface elements and a linear elastic model for structure elements. There also are bar elements, which take compression and tension only, to represent the installation of struts.

The basic soil parameters used in the analyses are listed in Table 1. Figure 4 shows the finite element mesh employed for modeling the construction sequences. Construction sequences include excavation, strut installation, excavation equipment loading, and pile driving equipment loading used during pile installation. Note that the effect of previously installed pipe piles was not considered in the modeling because they move with the clay and do not contribute significant resistance to soil movements.

The PZ-35 sheetpiles were treated as 2-foot thick structural elements with equivalent flexural stiffness. Also, a bar element is attached between the tip of the sheetpile and the fixed bottom boundary to model a hinge at the bottom of the sheetpile. Such a bar element provides end restraint for the sheetpile. No interface elements are used in the analysis.

The finite element method was utilized for the following purposes:

- To study the magnitudes and patterns of the soil movement under different schemes of excavation sequences during the design phase.
- To simulate the actual construction method and field loading conditions during the construction phase. The results are compared with the observed field data.
- To conduct a parametric study of different variables. The variables include soil shear strength, excavation sequence, surface loading conditions, and stiffness of braced system during the design and construction phase.

PILE MOVEMENTS

The proposed structure was designed to be supported on end bearing piles. Concrete filled pipe piles were installed and cut to the foundation level 23.5 ft below ground level prior to excavation. During excavation, it was observed that a number of piles had moved laterally up to 18 inches at the pile top. Due to such movement, the allowable compressive capacity of piles was re-evaluated by way of an analytical evaluation and a static pile load test. It was concluded that the allowable compressive capacity of piles is within the design capacity required.

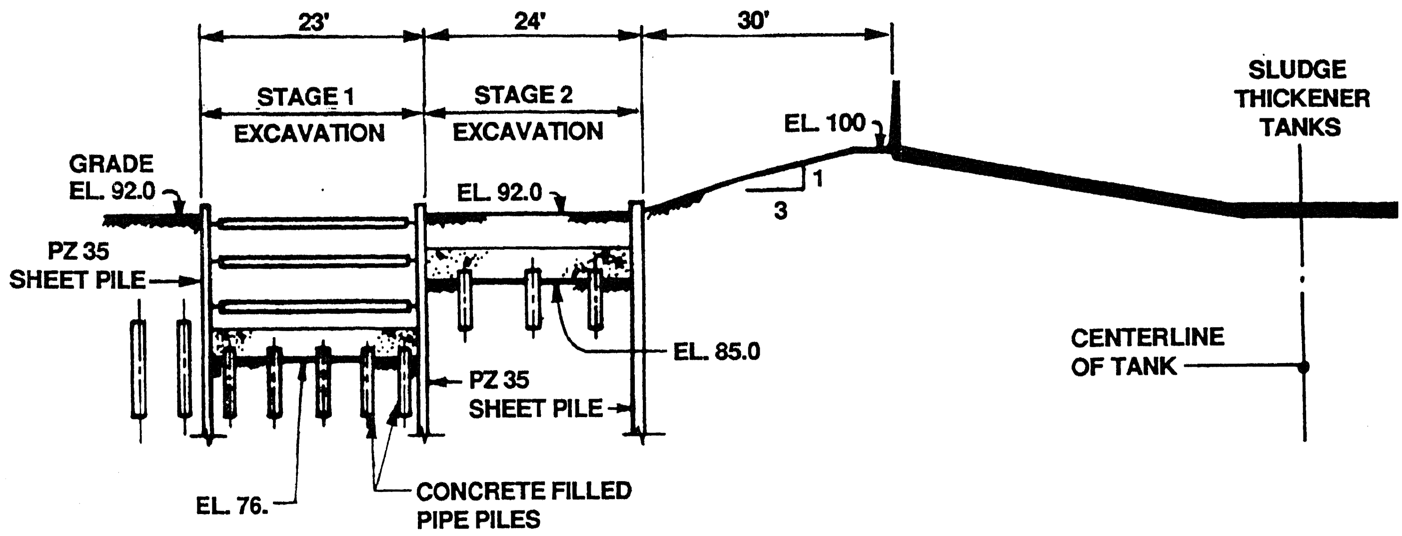

Figure 3. Excavation Sequence

Table 1. Basic Parameters Used in Finite Element Analysis

PARAMETER	VALUE
Soil Unit Weight and Undrained Shear Strength, Su	See Figure 2 (Typical Profile)
Soil Initial Tangent Modulus	600 x Su
Coefficient of Lateral Earth Pressure at Rest	0.90
Equivalent Young's Modulus for Sheetpile Walls	113,000,000 psf or 28,250,000 psf (Depends on Sheetpile penetration depth)
Young's Modulus of Concrete	432,000,000 psf

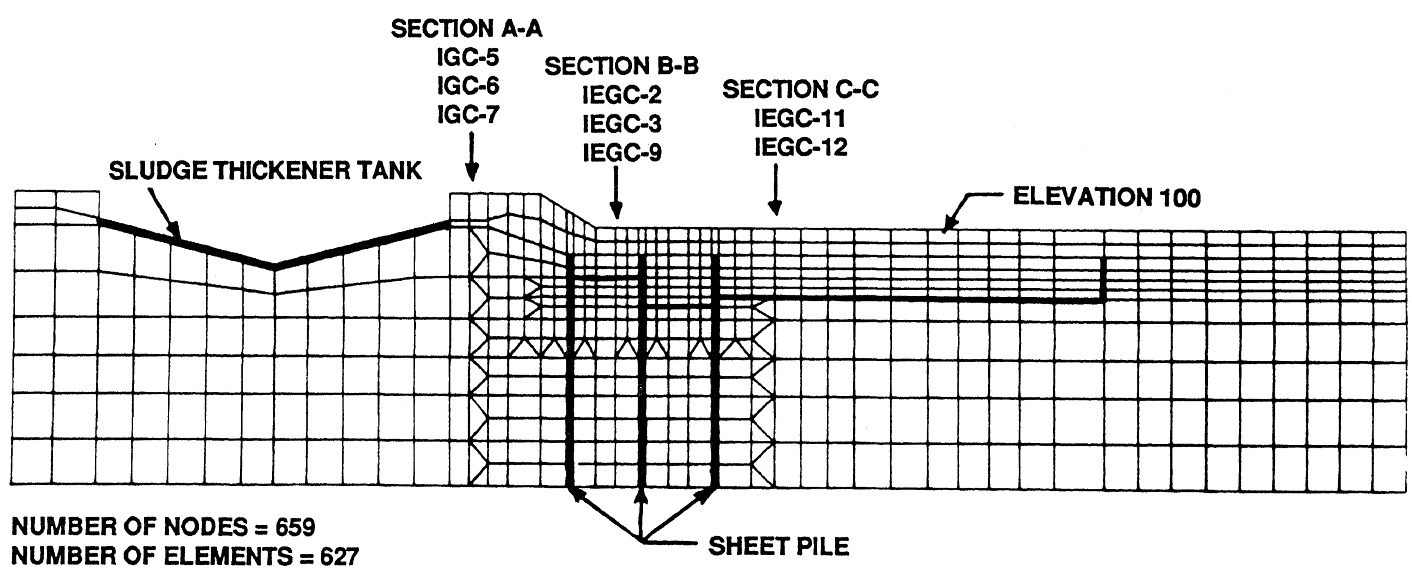

Figure 4. Finite Element Mesh

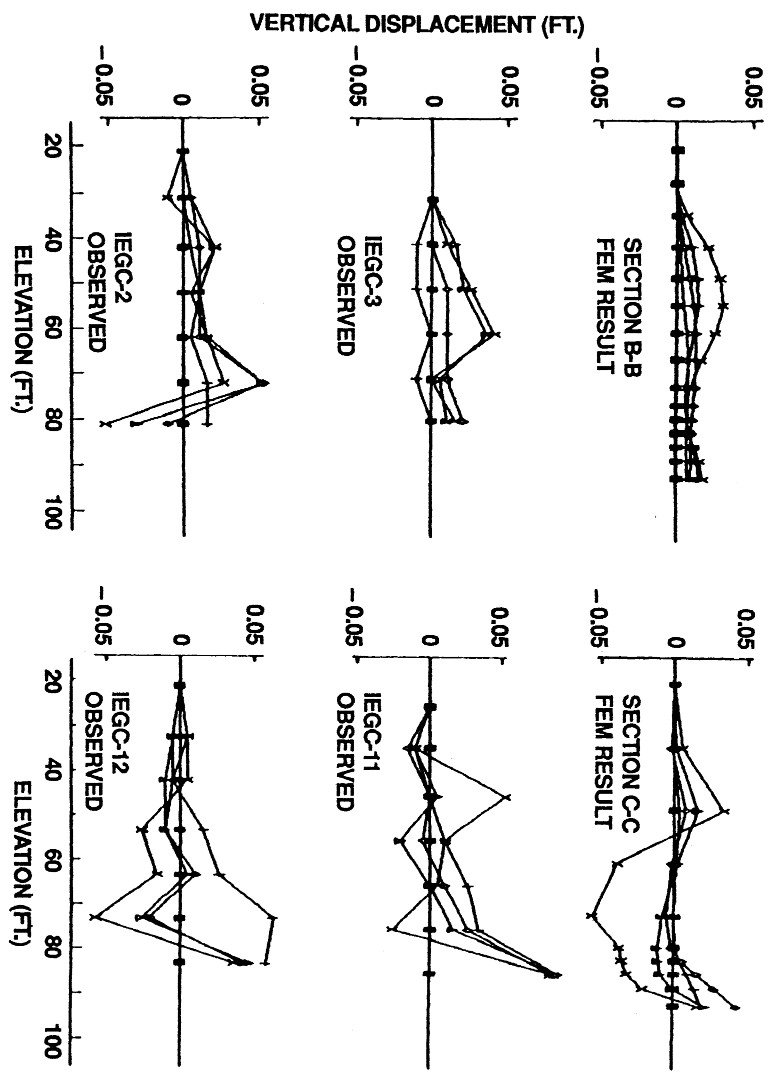

Figure 6. Predicted and Observed Vertical Movements

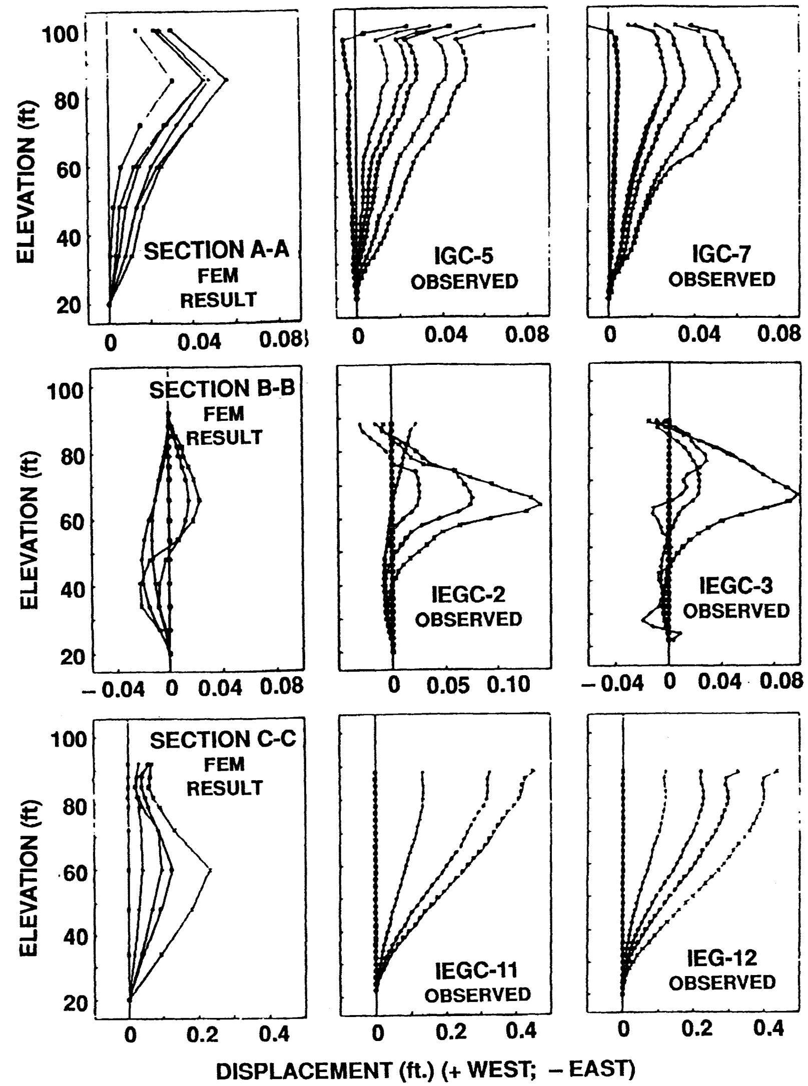

Figure 5. Predicted and Observed Horizontal Movements

DISCUSSION AND CONCLUSIONS

The predicted and observed horizontal and vertical movements are shown in Figures 5 and 6, respectively. Figure 5 shows the horizontal movements at three locations designated as Sections A-A, B-B, and C-C (refer to Figure 4 for Sections). The sections coincide with the geotechnical instrument locations. The vertical movements are shown on Figure 6 for Sections B-B and C-C. The predicted movements are those computed by the finite element method (referred to FEM in Figures). The observed movements were obtained from monitoring of the geotechnical instruments during excavation. The movements are cumulative from pre-excavation through stages 1 and 2 excavations.

A comparison between the predicted and observed movements leads to the following observations.

- In Section A-A, the predicted and observed horizontal movements are similar in both magnitude and pattern.
- In Section B-B, the observed horizontal movements are three to five times the predicted movements, however the movement patterns are similar.
- In Section C-C, the observed horizontal movements are about three times the predicted movements. The movement patterns are similar for the lower clay layer and are significantly different in the upper clay layer.
- In Sections B-B and C-C, the predicted and observed vertical movements are similar in both magnitude and pattern.

The discrepancy between the observed and predicted movements could be attributed either to one or a combination of the following.

- During the removal of top 8-foot of soil, the excavation was carried out in strips from east to west, and maintained almost vertically before reaching the bottom of pre-excavation. Based on the instrumentation data, about 6 inches of horizontal movement occurred at the top toward the east during this stage. This movement extended to the bottom of clay. The magnitude of this movement decreased linearly to the bottom of the clay layer. For this type of deep lateral movement any restraint provided by the struts, especially at the upper soil layer, would not be effective. A similar type of horizontal movement (cantilever excavation) has been discussed by Clough, et al. (1989).
- During all stages of construction, the excavation equipment was operating close to the edge of the cut and travelled back and forth frequently. Such activities could have disturbed the top layer of the soil, and induced additional horizontal movement.
- Soils parameters utilized are based on the laboratory and in-situ test results. The actual soil parameters could be different from those used in the finite element modeling.
- Exact simulation of the excavation behavior requires three-dimensional modeling. The two-dimensional modeling by SOIL-STRUCT could contribute in discrepancy in the predicted movements.
- Sequence and method of construction are the two important factors influencing the movements and must be accounted for in the analysis. For example in Section A-A, which is close to the Sludge Thickener Tanks, no excavation equipment was allowed and as previously stated the predicted and observed movements are essentially the same.

In conclusion, finite element predictions for the Grit Chambers excavation agreed reasonably well with the measured movements in Section A-A. Deviations in the sequence and method of construction accounts for most of the discrepancy between predicted and measured movements in Sections B-B and C-C. The accuracy of finite element predictions may be enhanced by a more detailed modeling of these effects.

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