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Development of effective stress soil-structure interaction analysis program for deep excavation

Développement d'un programme d'analyse effectif de l'interaction sol-structure pour les creusements profonds

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ABSTRACT: This paper describes the development of an effective stress soil-structure interaction analysis program for deep excavation. The program adopts fully coupled model to consider the generation of excess pore pressure during excavation as well as the consolidation due to dissipation of excess pore pressure and the change of water level during construction. Functions for staged excavation and timing of support installation were also included in order to simulate the construction procedures more closely. From the comparison of field measurements and numerical results obtained in a case study, good agreement in results can be obtained.

RESUME: Ce rapport décrit le développement d'un programme d'analyse efficace de l'interaction entre la structure du sol et la pression pour des fouilles en profondeur. Ce programme adopte un modèle entièrement associé pour prendre en considération la production d'une pression interne excessive durant les fouilles, ainsi que la consolidation due à la dissipation de la pression interne excessive et le changement duniveau d'eau pendant la construction. Les fonctions pour les fouilles par palier et le choix du moment pour l'installation du support ont aussi été inclus dans le but de stimuler les procédés de construction de manière plus étroite. De par la comparaison des mesures du champs et résultats numériques obtenus dans l'étude d'un cas, un bon accord dans les résultats peut étre obtenu.

1. INTRODUCTION

Deep excavation is now a routine work for almost every construction project in Taiwan urban area. It is common to excavate the soft soil deposits up to 16~26m in the 80 MRT stations in Taipei and many high-rise buildings. Numerous abnormal behaviors which, sometimes, lead to damage to adjacent properties or even failure have occurred. However, in the current engineering practice, 1-D elasto-plastic model was the mainstream in the design of support structures. Finite element method (FEM) has not been used widely with the exception of certain special cases. For the FEM codes used, total stress approach was employed without considering the generation and dissipation of excess pore pressure during the course of excavation. Interface between support work and soils has also not been considered.

Soil movements induced by braced excavation including dissipation of excess pore pressure are more appreciated by researchers (Borja 1990, 1992, Borja and Kavazanjian 1984, Debidin and lee 1980, Finno and Harahap 1991, Kishnani and Borja 1993, Yong *et al.* 1989). Since the total stress approach is not able to handle the problems of deep excavations involving soil-pore fluid interaction. This paper describes the development of a fully coupled numerical model for the effective stress analysis of deep excavation. The model was implemented by a finite element code which is based on the CRISP (Britto and Gunn 1987) program and the application of this code to a practical excavation case was investigated.

2. NUMERICAL MODEL

The effective stress analysis of deep excavation involves the calculation of soil displacements, pore pressures, drawdown of the water table, excavation forces etc. The following main theories of analysis are involved in the solution of an excavation problem.

2.1 *Theory of consolidation*

Finite element formulation for consolidation in soils had been developed by Sandhu and Wilson (1969), Britto and Gunn (1987), and Hsi and Small(1992). In this study, Britto and Gunn's procedure which utilizes a backward difference time marching scheme was adopted. From the principles of virtual work and the three-dimensional consolidation theory proposed by Biot (1941, 1956), the governing equations for solving coupled consolidation problem can be expressed in incremental form as follows

$$\boldsymbol{K}\Delta\boldsymbol{d}^{(i)} - \gamma_w \boldsymbol{L}^T \Delta\boldsymbol{h}^{(i)} = \Delta\boldsymbol{f}^{(i)} \tag{1}$$

$$-\gamma_w \boldsymbol{L}\Delta\boldsymbol{d}^{(i)} - \gamma_w \Delta t\boldsymbol{\Phi}\Delta\boldsymbol{h}^{(i)} = \gamma_w \Delta t\boldsymbol{\Phi}\boldsymbol{h}^{*(i-1)}_{t+\Delta t} - \gamma_w \boldsymbol{L}\boldsymbol{d}_t + \gamma_w \boldsymbol{L}\boldsymbol{d}^{(i-1)}_{t+\Delta t} \tag{2}$$

where $\boldsymbol{K}$ is the elasto-plastic stiffness matrix; $\boldsymbol{L}$ is coupling matrix; $\boldsymbol{\Phi}$ is flow matrix; $\Delta\boldsymbol{d}$ and $\Delta\boldsymbol{h}$ are displacement and total water head increments at the current time step; $\Delta\boldsymbol{f}$ is nodal load increments due to external load; $\boldsymbol{h}^*$ is total water head of previous time step; γ_w is the unit weight of pore fluid; Δt is the magnitude of time step; and i is the iteration step.

2.2 *Simulation of overburden removal*

The simulation of excavation by the use of finite element techniques involves removal of elements from the mesh and to apply the out-of-balance forces at the excavation boundary. The out-of-balance forces which are based on Brown and Booker's (1985) formulation have been improved in effective stress form and has the following expression (Hsi and Small 1992)

$$\Delta\boldsymbol{f}'_k = -\int_{V_k} \boldsymbol{B}^T \boldsymbol{\sigma}'^{*}_{k-1}\, dV - \gamma_w \boldsymbol{L}^T\left(\boldsymbol{h}^*_{k-1} - \boldsymbol{h}_{EL}\right) + \int_{V_k} \boldsymbol{N}^T \gamma\, dV + \int_{\Gamma_k} \boldsymbol{N}^T \boldsymbol{t}^*\, d\Gamma \tag{3}$$

in which $\boldsymbol{B}$ is displacement-strain matrix; σ' is the effective stress of soil; N is the element shape function matrix; γ is the unit weight of the removed element; t^* is external traction; h_{EL} is total elevation head; and k is the solution stage of excavation.

2.3 *Transient free surface seepage*

Transient unconfined seepage problem is the most complicated type of seepage problems. The solution is time dependent and has a moving boundary of free surface. The free surface boundary conditions associated with equation (2) are

$$h^* = h_{EL} = f(x,t) \tag{4}$$

$$-k_n \frac{\partial h^*}{\partial n} = S_y \frac{\partial h^*}{\partial t}\cos\beta \tag{5}$$

where S_y denotes the specific yield; β is the angle between the free surface segment and the horizontal direction; and k_n is the permeability normal to the free surface.

The variation of fluid volume due to drawdown of free surface is

$$Q = \frac{-v_n ds\, dz}{dh^* \cos\beta\, ds\, dz} = -v_n \frac{1}{dh^* \cos\beta} \tag{6}$$

where v_n is fluid velocity normal to free surface; ds is the length of a segment of free surface; and dz is the thickness normal to x-y plane.

Substituting equation (5) and Darcy's law into equation (6) gives

$$Q = \left(-S_y \frac{\partial h^*}{\partial t}\cos\beta\right)\frac{1}{dh^* \cos\beta} = -S_y \frac{1}{dt} \tag{7}$$

The Residual Flow Procedure proposed by Desai(1976) is used to locate the free surface. As the water table drops, the soil above the free surface becomes unsaturated and reduced flow occurs in this region. To model this, the permeability of the soil above the free surface is reduced. The reduction of the permeability follows a permeability - pore pressure relationship (Bouwer 1964) and can be idealized as shown in Figure 1.

2.4 *Fully coupled method*

The governing equations for solving fully coupled problems for excavations involving drawdown of water table can be developed by combining the equations of consolidation, equations (1) and (2), overburden removal, equation (3), and transient free surface seepage, equation (7) for the kth stage of excavation and ith iteration step and are given by

$$\begin{bmatrix} \boldsymbol{K} & -\gamma_w \boldsymbol{L}^T \\ -\gamma_w \boldsymbol{L} & -\gamma_w\left(\Delta t\boldsymbol{\Phi} + \boldsymbol{f}^{FS}\right) \end{bmatrix} \begin{Bmatrix} \Delta \boldsymbol{d}^{(i)} \\ \Delta \boldsymbol{h}^{(i)} \end{Bmatrix} = \begin{Bmatrix} \Delta \boldsymbol{f}^{(i)} - \Delta \boldsymbol{f}_k' \\ \gamma_w \Delta t \boldsymbol{\Phi} \boldsymbol{h}_{t+\Delta t}^{*(i-1)} - \gamma_w \boldsymbol{L}\boldsymbol{d}_t + \gamma_w \boldsymbol{L}\boldsymbol{d}_{t+\Delta t}^{(i-1)} \\ +\gamma_w \boldsymbol{f}^{FS}\left(\boldsymbol{h}_{t+\Delta t}^{*(i-1)} - \boldsymbol{h}_t^*\right) + \gamma_w \Delta t \boldsymbol{Q} \end{Bmatrix} \tag{8}$$

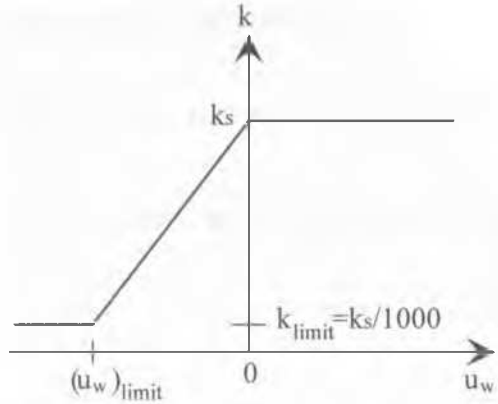

Figure 1 Permeability - pore pressure relationship

where f^{FS} is the flow term due to free surface drawdown and Q is point sink to simulate well pumping.

A finite element program DEXC2D, coded in the FORTRAN 77 language, has been developed to solve the fully coupled governing equations.

3. FEATURES OF FINITE ELEMENT PROGRAM

The finite element program DEXC2D which is developed based on the well known program CRISP (Britto and Gunn 1987) has the following features:

(1) Structure elements such as beam and bar are incorporated in the program.
(2) Hyperbolic and plasticity soil models are included in the program.
(3) DEXC2D includes finite thickness interface element to model the slippage between soils and the support structure.
(4) The program can analyze excavation problems that incorporate seepage induced soil movement and drawdown of water table.
(5) To increase the solution accuracy, the program utilizes the incremental iteration scheme to solve the fully coupled equations.

4. CASE HISTORY

Application of the fully coupled numerical program DEXC2D to the analysis of an excavation case history is presented. Complete field measurements for this case history are available including basal heaves, wall deflections, strut loads, surrounding ground settlements, and drawdown of the water table (Hsi 1992). Comparisons between the numerical results and the field data are described.

4.1 *Site description and geotechnical characteristics*

Hong-Hsi Garden Field Building is located at Section 5, Hsin - Yih Road, Taipei, Taiwan. The site location is shown in Figure 2. The excavation site had an area of 3812m^2. As the soils at the construction site are mainly soft silty clays, two boreholes were drilled to a depth of 50m and below which a firm layer of weathered rock was found. Above the firm base, the soil deposit can be simplified into four layers.

It was found that the groundwater table was initially at about 1m below the ground surface. The groundwater pressure was distributed hydrostatically over a depth of 14m. Below this

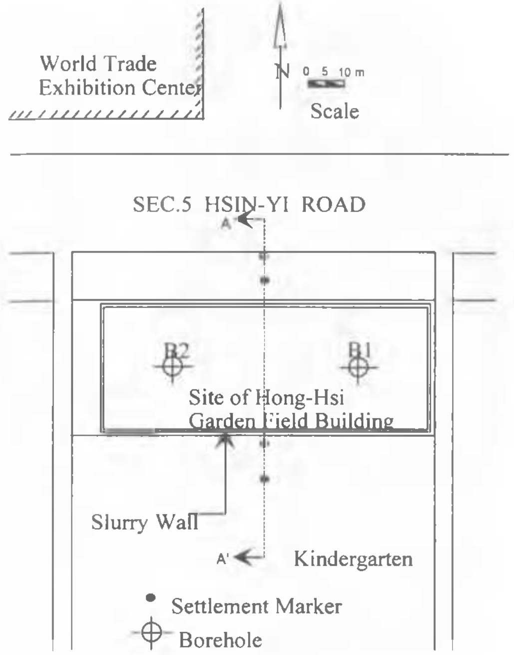

Figure 2 Location of Hong-Hsi Garden Field Building

depth, the groundwater pressure was slightly lower than the hydrostatic water pressure.

As the excavation was carried out in silty clays, the Modified Cam Clay model was used to simulate the nonlinear behavior of the soil. The soil parameters used for analysis are summarized in Table 1.

Table 1. Soil parameters used for analysis

Layer number	1	2	3	4
Classification	CL	CL	CL	CL
Elevation (*m*)	10~-1	-1~-12	-12~-22	-22~-40
Total unit weight (*kN/m³*)	18.4	18.0	17.9	20.7
K_0	0.43	0.52	0.45	0.47
Permeability (*m/day*)	1.0E-1	5.0E-2	5.0E-2	1.0E00
e_{cs}	1.008	1.129	1.127	0.574
M	1.16	1.04	1.20	1.17
λ	0.15	0.16	0.18	0.09
κ	0.015	0.017	0.013	0.008

4.2 *Support system and monitoring system*

The length and width of the excavation site are 96m and 34m respectively. The diaphragm wall penetrated to a depth of 26m and had a thickness of 60cm and are propped by four rows of steel struts (H300 × 300 × 10 × 15mm for the upper two rows and H400 × 400 × 13 × 21mm for the lower rows). The strut parameters in the analysis are given in Table 2.

An extensive monitoring system for the excavation was installed as is shown in Figure 3. Five inclinometers (SI1- SI5) were installed adjacent to the diaphragm wall so that deflections of the wall could be recorded. Eighteen settlement markers (M1-M18) were set on the ground surface to the south of the excavation and 2 markers (M19 and M20) to the north. The strut loads were measured through three load gauges (L1-L3) installed on the props. Four heave bars (H1-H4) were installed for the measurement of basal heaves of the soil. Two observation wells (OW1 and OW2) were installed adjacent to the north and the west side of the wall to provide information about changes in groundwater table.

Table 2. Parameters of struts for analysis

Strut	Elastic Module E_{eq} (kN/m²)	Poisson's Ratio ν	Section area A (m²)	Preload (tons)
1	3.72E7	0.2	0.012	60
2	3.72E7	0.2	0.012	60
3	3.72E7	0.2	0.022	80
4	3.72E7	0.2	0.022	80

At the same time as the construction of the wall, 23 bored piles were installed beneath the base level (El. -3m) of the excavation for supporting the future loading of the structure. The existence of the supporting poles and bored piles need to be considered in the analysis as they will affect the movement of soil below the base of the excavation.

4.3 *Numerical simulation of construction sequence*

The excavation was carried out to a depth of 13m in five stages which started on July 13 and finished on September 7, 1988. The actual and simulated excavation sequences are shown in Figure 4. A plane strain analysis was used and a north-south section (A-A' in Figure 1) was adopted for the analysis. The problem can be treated as being symmetric and only half of the construction domain needs to be considered. Figure 5 shows the finite element mesh for the analysis.

4.4 *Comparison of numerical results with field data*

The numerical results of the analysis of the excavation are compared with the field measurements in five stages, dated July 25, August 3, August 13, August 27, and September 7 (Figure 4). The measured data and calculated results for the wall deflections are shown in Figure 6 in which SI2 and SI5 indicate the inclinometers on either side of the analyzed section A-A' (Figure 2). However some discrepancies occur between measured and calculated values at early stages. Such discrepancies could arise because in the simulation the installation of struts and the excavation sequence may not exactly correspond to actual conditions.

In Figure 7, it shows the measured and calculated ground settlements . Although there is some scatter of the measured data, the calculated settlements with distance from the wall show reasonably good fit to the measured data.

Equivalent stiffness springs are always used for numerical simulation to the brace members of retaining systems and the forces of the brace members must be calculated indirectly. Bar elements was used for struts in the analysis of the excavation The measured strut loads were compared with the values calculated from the analysis in Figure 8. In the figure, maximum and minimum values for strut loads at the same level are presented. It may be seen that reasonably good agreement in results was obtained at all stages.

Heaves of the base of the excavation were dependent on the location where heave indicators installed. The calculated heaves increased as the excavation proceeded and values fall within the measured band as shown in Figure 9. However the numerical solutions were smaller than the measured data in early stages of the excavation.

Although the excavation was carried out in silty clay soils, the groundwater table was observed to have fallen about 1m to 2m during the period of the excavation. The observed groundwater surface (well OW1 in Figure 3) and the predicted free surface level against elapsed time during the excavation are shown in Figure 10, in which reasonable agreement can be seen. The

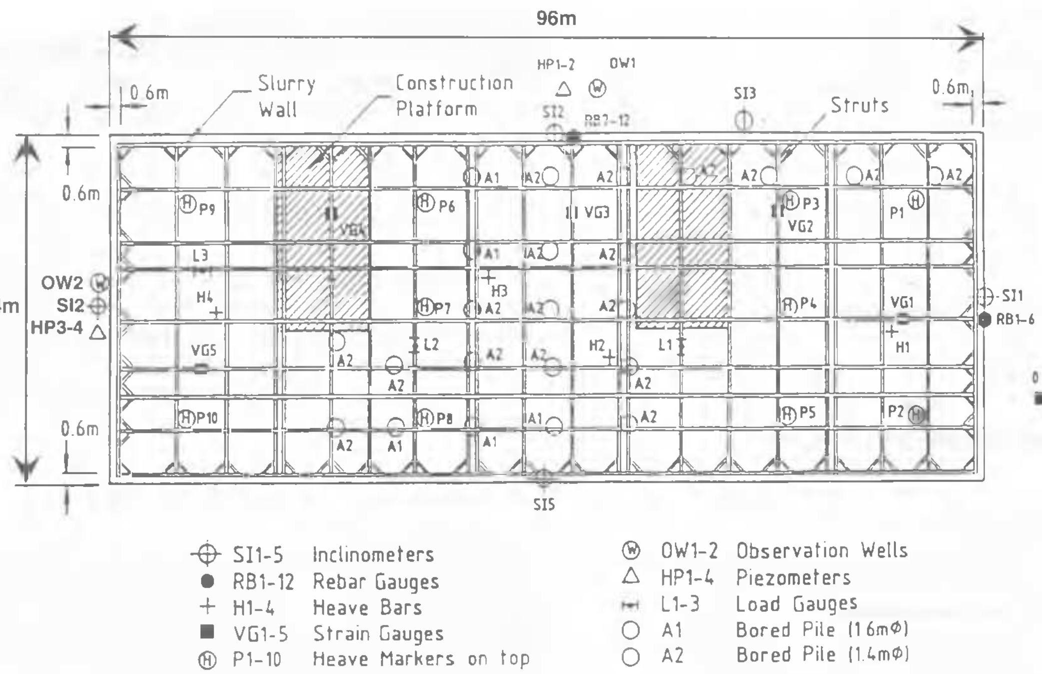

Figure 3 Plane of supporting and monitoring system of excavation

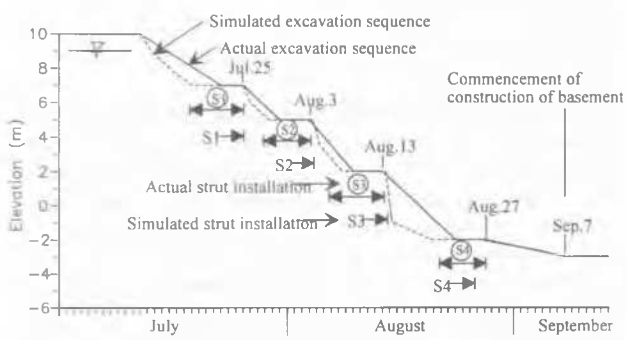

Figure 4 Excavation sequence

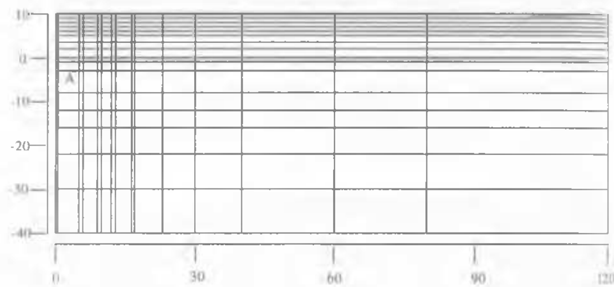

Figure 5 Finite element mesh used for analysis

measured drop in the ground water level is more rapid over the first 30 days than that predicted. It could because that the large pumping of groundwater was performed over the first 30 days during the excavation and the ground water level is steadily fallen through the analysis. The calculated pore pressure distribution after final stage of excavation is shown in Figure 11.

5. CONCLUSIONS

This paper describes the effective stress soil-water-structure interaction finite element code which utilizes the fully coupled consolidation theory including transient unconfined seepage formulation. A case history of deep excavation was used to illustrate the application of the code. The main conclusions can be summarized as follows.

(1) Effective stress analysis of excavation including the drawdown of the water table and dissipation of excess pore pressure is important in predicting the settlements behind the wall and the response of soil deposit. Fully coupled method can model the variation of the strength and the deformation of soils influenced by the change of excess pore pressure.

(2) Simulation of excavation could lead to errors if the excavation forces were not calculated correctly. It was found that using an effective stress form of Brown and Booker's method could correctly evaluate the excavation forces due to overburden removal.

(3) It was found that the drawdown of the water surface during the excavation process would increase the settlement of the ground surface behind the wall significantly. The Residual Flow Procedure was adopted to determine the location of the free surface. The results show that the Procedure could give a realistic estimation of ground settlement.

(4) The results of case study carried out in this paper demonstrate the capabilities of the DEXC2D program. By using the appropriate soil parameters and reasonable modelling of construction sequence, the wall deflection, ground surface settlement, strut load, basal heave, and drawdown of the water table could be predicted by the program reasonably well.

ACKNOWLEDGMENTS

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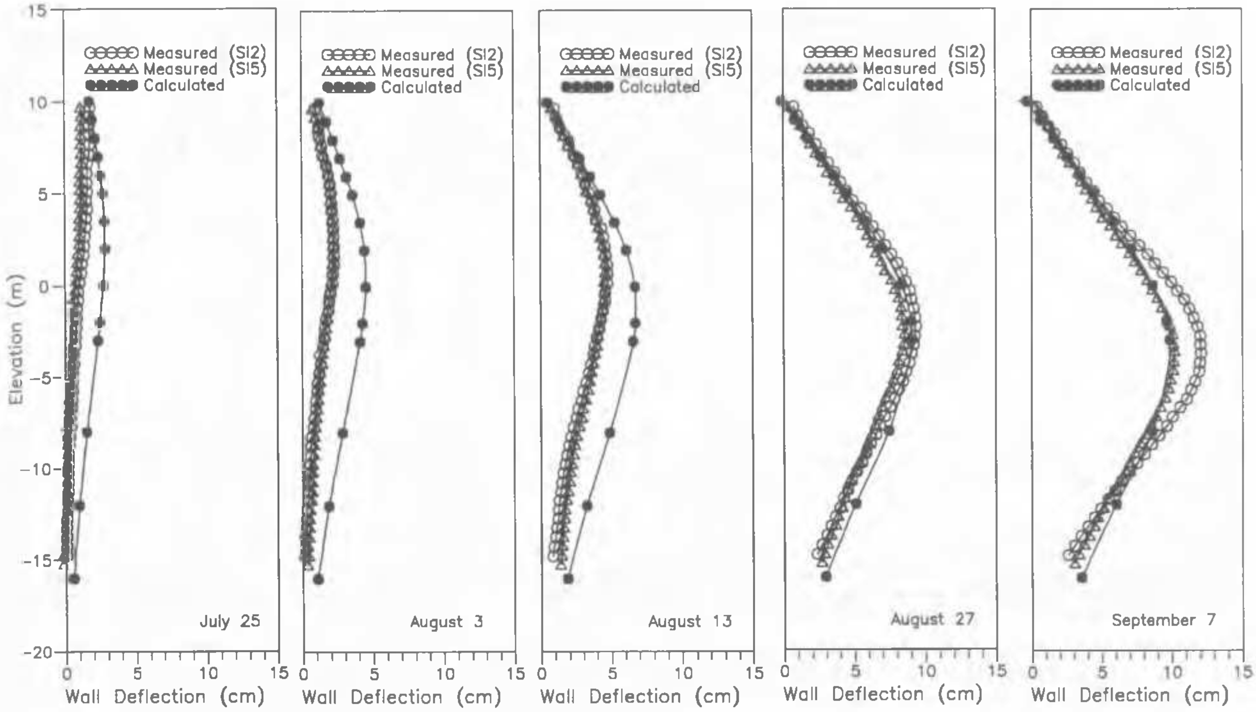

Figure 6 Measured and calculated wall deflections

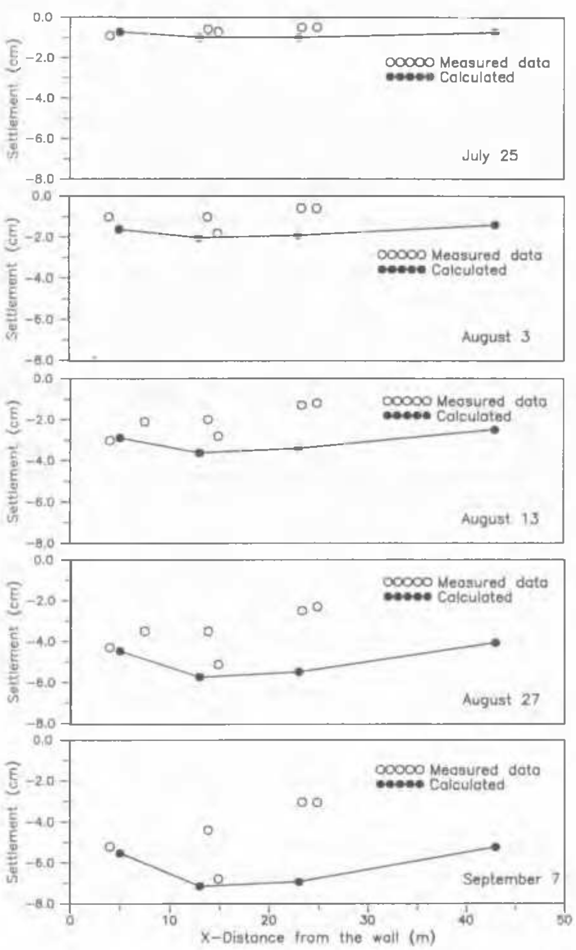

Figure 7 Measured and calculated ground settlements

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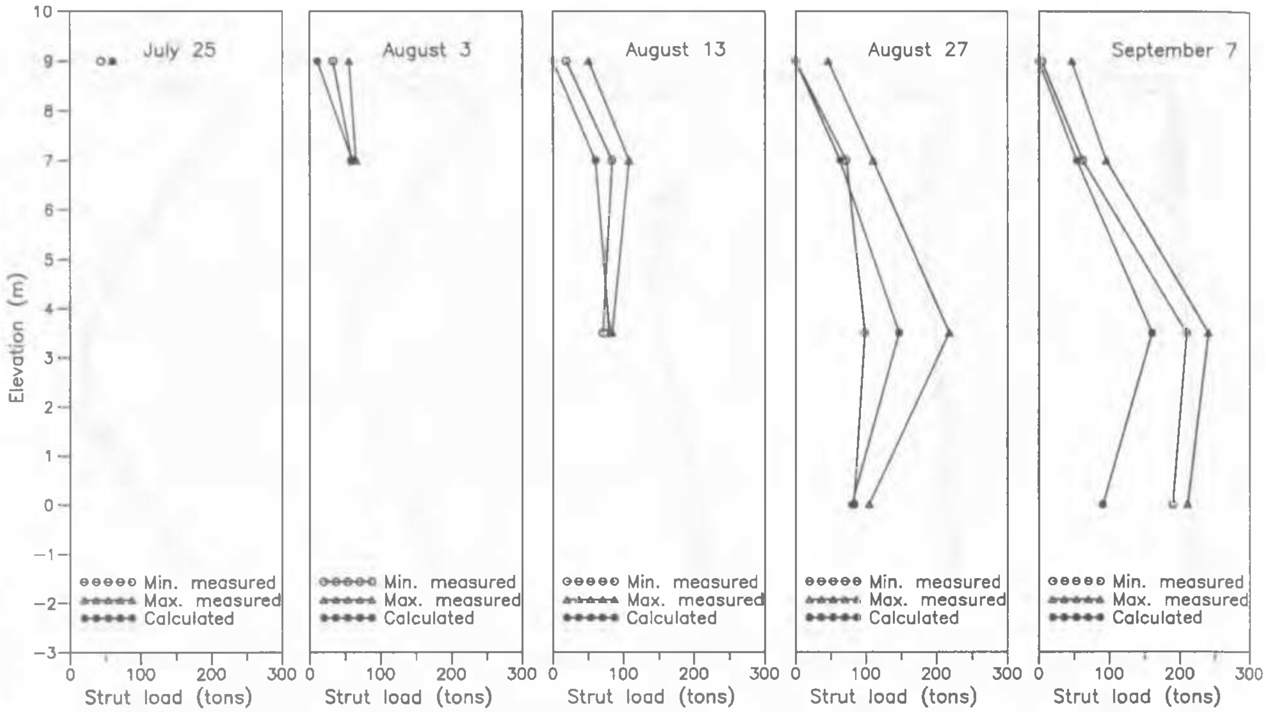

Figure 8 Measured and calculated strut loads

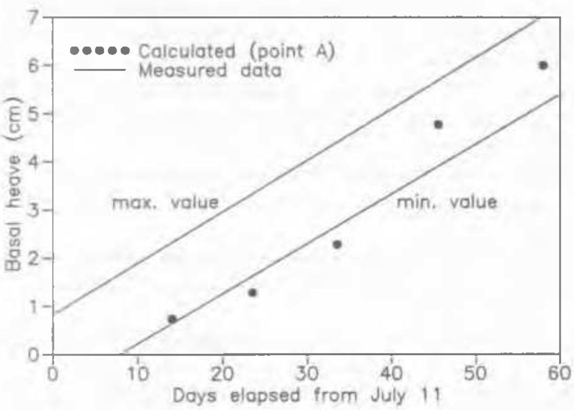

Figure 9 Measured and calculated basal heaves

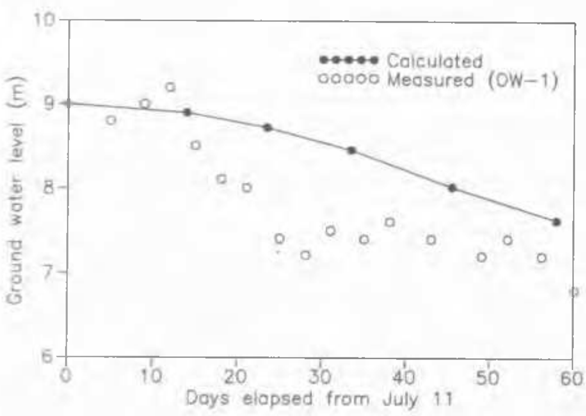

Figure 10 Measured and calculated ground water levels

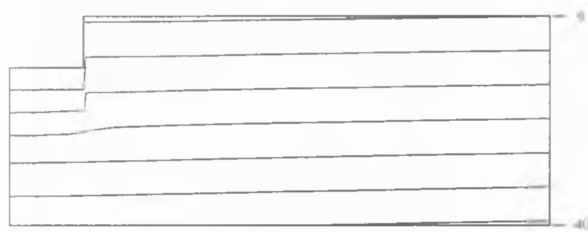

Figure 11 Calculated pore pressure distribution at the end of excavation

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