

# **Nonlinear Time-Dependent Soil Behavior due to Construction of Buried Structures**

**Hasanain F. Hasan<sup>1</sup> and Zena H. Alqaissi<sup>2</sup>**

## **Abstract**

This paper represents an effort to develop an efficient and powerful finite element technique to simulate the sequences of construction buried structures (excavation, installation of buried structure and backfilling) in linear and nonlinear time dependent soil behaviour. The problem of buried structure in nonlinear soil behaviour is analyzed in three stages. First stage of analysis starts with soil excavation then the stage of buried structure construction in the excavated zone will be analyzed and finally the backfilling will be the final stage of analysis. The interaction between buried structure and adjacent soil is implemented in the finite element method using the concept of the thin layer element.

The finite element formulation of the Biot's theory for plane strain consolidation is presented. This formulation is extended to represent the linear and nonlinear time dependent behaviour of soil during excavation, construction of buried structures and finally backfilling problems.

A general finite element computer program is developed to analyze any buried structure problem in linear and nonlinear time dependent soil behaviour. Verification of the finite element technique is achieved by studying and analyzing some buried structure problems in linear and nonlinear soil behaviour.

**Keywords:** Buried Structures, Soil Constitutive Modelling, Time-dependent analysis

## **1 Introduction**

Many investigators studied the behaviour of buried structures in soil during construction. Their studies have been limited due to the fact that the problem is very complex, involving three different types of loadings (unloading, loading and re-loading), and the soil behaves in different modes at each condition stage.

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<sup>1</sup>F. Hasan, Lecturer, B.Sc., M.Sc., Ph.D Civil Engineering, Al-Mustansiriya University, College of Eng., Department of Civil Engineering.

<sup>2</sup>Zena H. Alqaissi, Asst. Lecturer, B.Sc, M.Sc. Civil Engineering, Al-Mustansiriya University, College of Eng., Department of Civil Engineering.

Unfortunately, due to complexity of the problem, many assumptions are implemented in the analysis and design of buried structures. These assumptions are such as the buried structures exist in soil and the analysis is carried out for only the backfilling stage. Also the saturated soils either develop pore pressure during backfilling (loading) with no dissipation (undrained behavior), or that no excess pore pressure exists during loading (drained behavior).

However, buried structures problems involve three stages of construction (excavation, installation of structure, backfilling) in time dependent nonlinear soil conditions. It is apparent that it would be very desirable to know the actual behaviour of buried structure and soil during and after construction.

Experience showed that, to achieve results that are in agreement with field behaviour, two conditions must be satisfied [1]:

1. The actual sequences of construction operations must be simulated in the analyses.
2. The nonlinear and stress-dependent stress-strain behaviour of the backfill must be taken into account in the analyses.

The finite element method appears to offer a numerical technique which is suited to simulate conditions during time dependent sequences of construction. Nonlinear soil response of subsoil conditions may be considered.

In modelling the sequence of incremental excavation and backfilling, the excess pore pressure, deformations, and stresses are predicted for each stage of time selected.

In order to understand the behaviour of buried structures, it is very important to investigate the distribution of stresses and deformations around underground openings. This behaviour is in general influenced by a large number of factors such as geometry of the structure system, properties of the original ground and backfill, material of the structure, type of loading, method of construction, progress of structure face, time of structure installation and materials long-term behaviour (Figure 1).

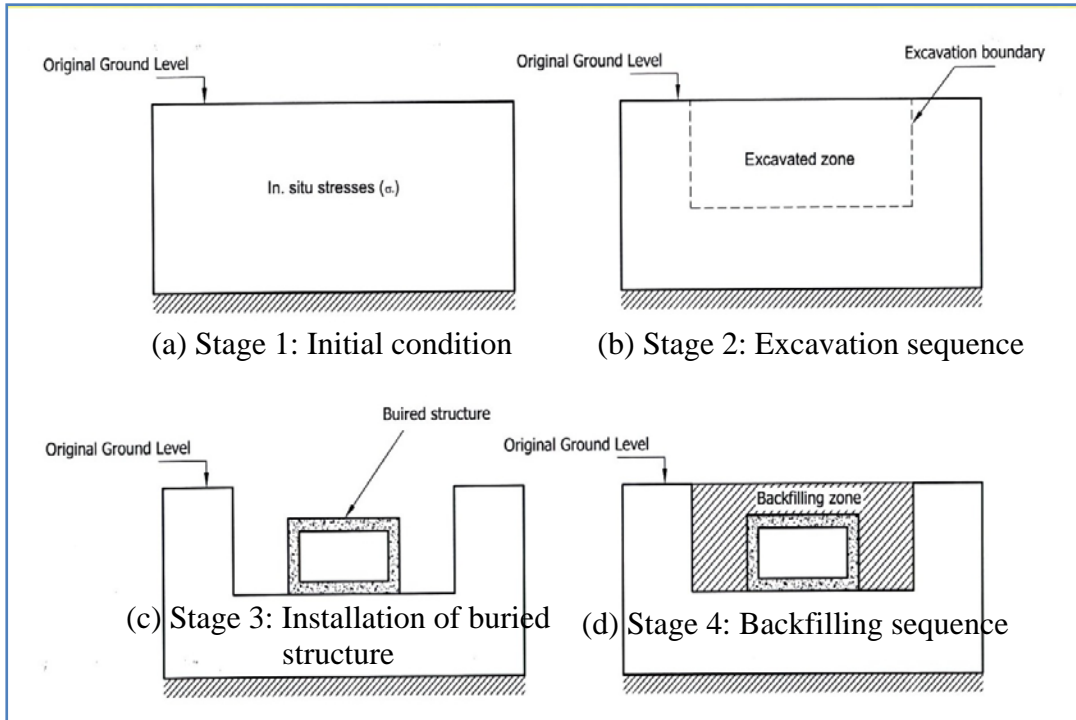


Figure 1: Construction Sequences of Buried Structure in Soil

$$\{\sigma\} = \{\sigma_o\} \quad \{d\} = \{d_o\} = 0 \quad \text{Stage 1}$$

$$\{\sigma\} = \{\sigma_o\} + \{\Delta\sigma_1\} \quad \{d\} = \{\Delta d_1\} \quad \text{Stage 2}$$

$$\{\sigma\} = \{\sigma_o\} + \{\Delta\sigma_1\} + \{\Delta\sigma_2\} \quad \{d\} = \{\Delta d_1\} + \{\Delta d_2\} \quad \text{Stage 3}$$

$$\{\sigma\} = \{\sigma_o\} + \{\Delta\sigma_1\} + \{\Delta\sigma_2\} + \{\Delta\sigma_3\} \quad \{d\} = \{\Delta d_1\} + \{\Delta d_2\} + \{\Delta d_3\} \quad \text{Stage 4}$$

The idea for simulation excavation and backfilling sequences is modelled by a technique in which nodal forces are applied to the excavation or backfilling boundary (surface) so as to reduce the nodal forces on the exposed boundary to zero. These nodal forces are determined as follows: during excavation sequences the nodal forces equivalent to the initial stresses go directly into the (global) load array and the nodal forces equivalent to the gravity body forces of the remaining elements (unexcavated elements) are added to them (Figure 2a). During backfilling sequences, the nodal forces equivalent to the initial stresses of the backfilling elements go directly into the (global) load array, and the nodal forces equivalent to the gravity body forces of the added elements (backfilling elements) are added to them Figure 2b [2].

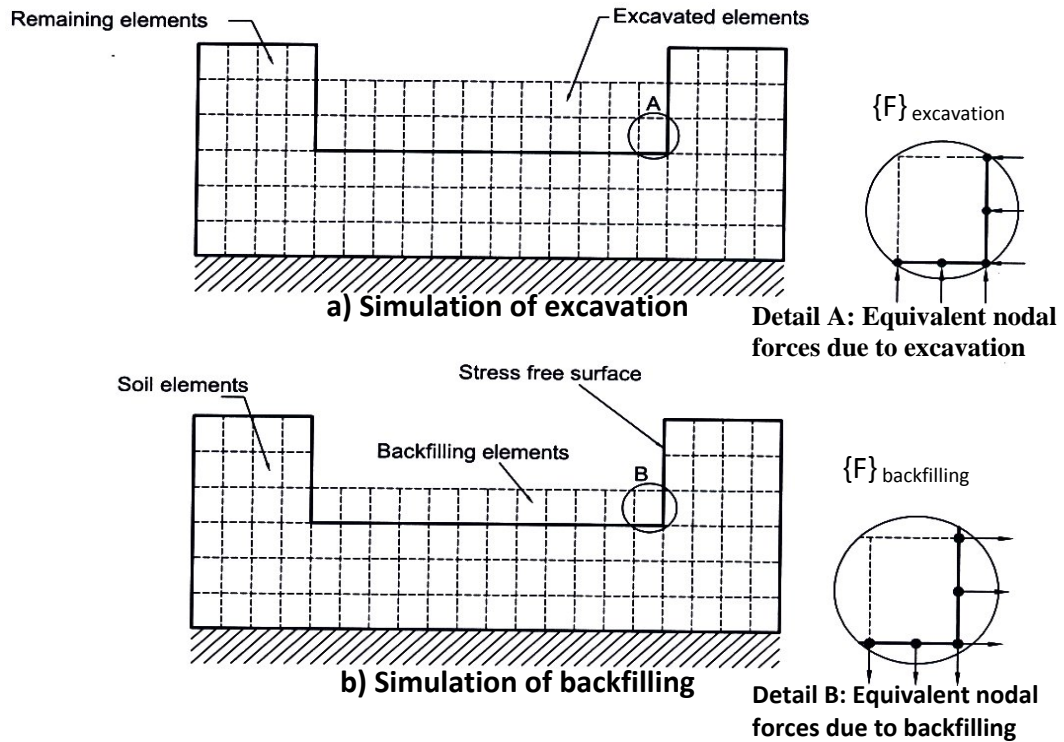


Figure 2: Simulation of Construction Sequences by General Method

In this paper the modified Cam clay model [3] has been used to present soil model also the interface element between the structure and soil which was proposed by Desai et al. 1984<sup>[4]</sup> was used to give more realistic results for a represented case. The finite element formulation of Biot's theory of consolidation [5] was used.

## 2 Modified Cam Clay Model

The stress space of this model can be represented in a three dimensional stress-specific volume space called the state boundary surface (s.b.s), as shown in Figure 3 [6]. Inside and on this surface a point representing the state of stress must lie.

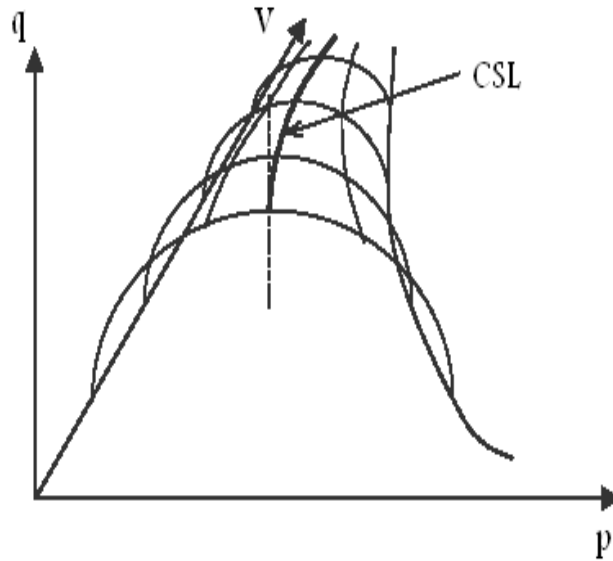


Figure 3: State boundary surface for modified Cam clay model (After Georgiadis, 2003)

In critical state theory the virgin compression, swelling and recompression lines are assumed to be straight in  $(\ln(p'), V)$  plots with slopes  $(-\lambda$  and  $-k)$  respectively, as shown in Figure 4 [7].

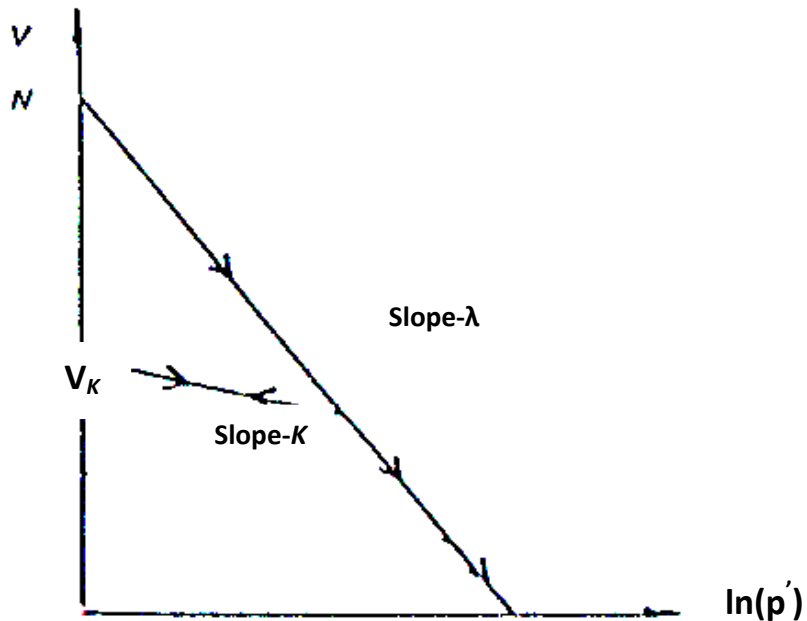


Figure 4: Identical  $(\ln(p'), V)$  Plot in Critical State Theory (after Britto and Gun, 1987)

The equation of the isotropic virgin compression line is given as:

$$V = N - \lambda \ln(p') \tag{1}$$

where  $V$  is a specific volume,  $N$  is a constant for a particular soil and it is equal to  $V$  when  $\ln(p')=0$ , i.e.  $p'=1$ , the value of  $N$  is given by the equation shown below:

$$N = \Gamma + (\lambda - k) \ln(2) \quad (2)$$

where  $\Gamma$  represents the specific volume of soil on the critical state line  $p'=1\text{kN/m}^2$ . If the sample of soil is subjected to isotropic compression stress, the point in  $\ln(p')$ - $V$  plane moves on the virgin compression line ( $\lambda$ -line), and if the load is removed, the point will be moved on the swelling ( $k$ -line). The equation of the  $k$ -line is given as:

$$V = V_k - k \ln(p') \quad (3)$$

The initial state of the soil in a  $(p',q)$  plot is  $(p'_c, 0)$  and when the sample of soil is subjected to load in triaxial test, soil is sheared and a point moves in the  $(p',V,q)$  space. The route from initial point to the point at the end applied is called effective stress path. The mean stress at the critical state is calculated from<sup>[7]</sup>:

$$p_c = p + q^2 / p \cdot M^2 \quad (4)$$

$$p_{cs} = \frac{p_c}{2} \quad (5)$$

Where  $M$  is a model parameter and  $P'_c$  is the isotropic yield stress. The volume at the initial stress and at the critical state is calculated from:

$$V_o = N - \lambda \ln(p'_c) + k \ln(p'_c / p_o) \quad (6)$$

$$V_{cs} = \Gamma - \lambda \ln(p'_{cs}) \quad (7)$$

### 3 Excavations and Backfilling in Modified Cam Clay Model

In contrast to linear analyses, the evolution of stresses in nonlinear analysis requires the numerical integration of the equilibrium equations over a finite time increment [8].

$$w_{INT}(t) = w_{EXT}(t) \quad (8)$$

where

$$w_{INT}(t) = \int_{\Omega(t)} \nabla w \cdot \sigma \cdot d\Omega \quad (9)$$

represents the internal virtual work and

$$w_{EXT}(t) = \int_{\Omega(t)} \mathbf{w} \cdot \mathbf{b} d\Omega + \int_{\Gamma_T(t)} \mathbf{w} \cdot \mathbf{T} d\Gamma \quad (10)$$

represents the external virtual work.

Where:  $\Omega$  is the problem domain,  $\mathbf{T}$  surface traction and  $\Gamma_T$  is the boundary problem.

The constitutive equation for a nonlinear analysis is of the form:

$$\sigma_{n+1}^k = \sigma_n + \delta^k(\epsilon_{n+1}, \epsilon_n) \quad (11)$$

where  $\sigma_n$  and  $\epsilon_n$  are the converged stress and strain vectors of the previous time step, respectively, and  $\delta^k$  is the incremental stress function consistent with a given stress integration algorithm. The expression of nonlinear moduli obtained by taking the variation:

$$D_{n+1}^k \equiv \frac{\partial \sigma_{n+1}^k}{\partial \epsilon_{n+1}^k} = \frac{\partial \delta^k(\epsilon_{n+1}^k, \epsilon_n)}{\partial \epsilon_{n+1}^k} \quad (12)$$

#### 4 Governing Equation for Fully Saturated Soils

The complete behaviour of the two phase skeleton-fluid state in fully saturated soils is governed by the equation [9].

$$\begin{bmatrix} K & L \\ L^T & -0.5\Delta t \cdot H \end{bmatrix} \begin{Bmatrix} du^n \\ dp^n \end{Bmatrix} = \begin{Bmatrix} dF(\Delta t) \\ \Delta t \cdot H \cdot p^n(t) \end{Bmatrix} \quad (13)$$

where  $K$  is the tangential stiffness matrix given as:

$$K = \int_{\Omega} \mathbf{B}^T \mathbf{D}_t \mathbf{B} \cdot d\Omega \quad (14)$$

$L$  is the coupling matrix given as:

$$L = \int_{\Omega} \mathbf{B}^T \mathbf{m} \cdot \mathbf{N}_p^T d\Omega \quad (15)$$

and  $H$  is the flow matrix given as:

$$H = \int_{\Omega} (\nabla \cdot \mathbf{N}_p^T)^T \frac{K_p}{\gamma_w} \nabla \mathbf{N}_p^T d\Omega \quad (16)$$

## 5 Construction Sequences of Buried Structures in Fully Saturated Cam Clay Soil

The construction of a two dimensional opening in a soil where pore pressure dissipation occurs is a complex problem with moving drainage boundaries and changing geometry.

This situation is well suited for analysis by the developed finite element program "EXCBAC". The selected construction zone cross section with boundary conditions is, as shown in Figure 5. A 6m wide by 6m deep excavation is made into a homogenous, saturated soil deposit that is of 15m depth and under-laid by an impervious hard layer. The finite element mesh representing the problem is illustrated also in Figure 5; only one half of the construction zone is considered since the problem is symmetrical about the center line.

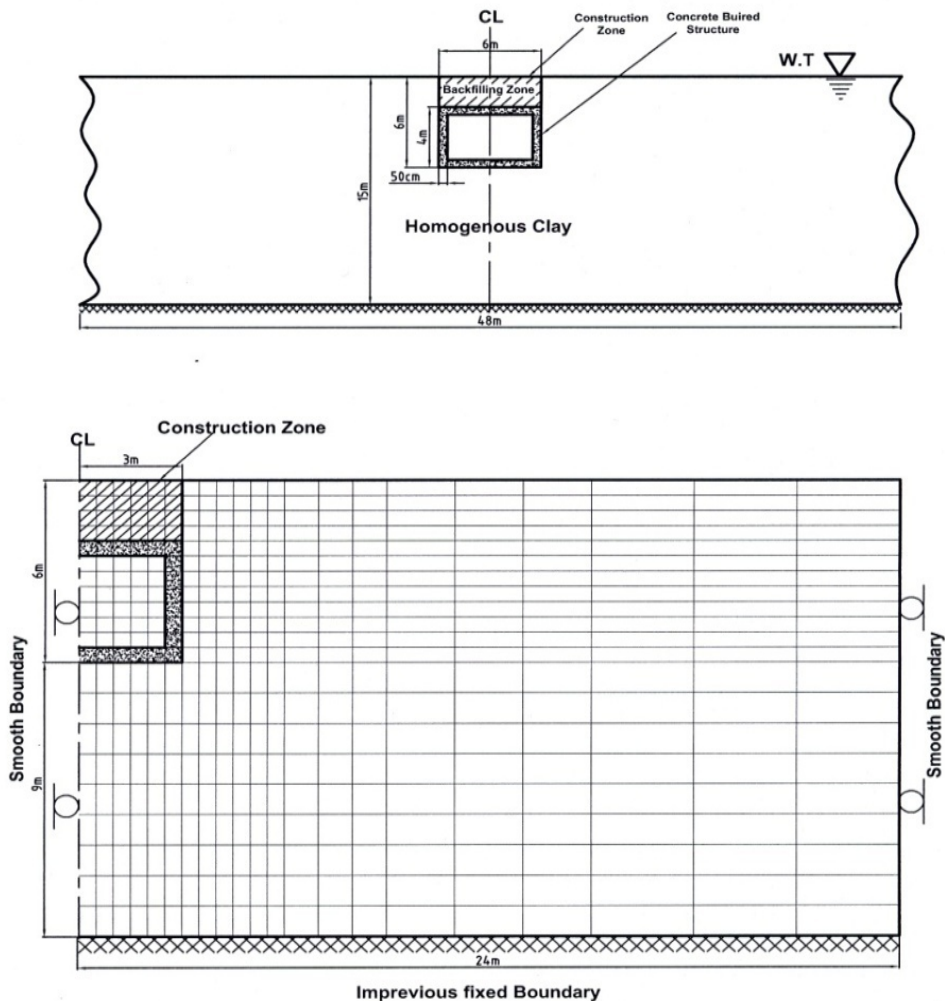


Figure 5: Finite Element Mesh and Geometry of Problem Used in Two Dimensional Construction Sequences of Buried Structures Analyses



The soil is assumed to be fully saturated and a failure criterion is specified in this analysis. The Mohr-Coulomb shear strength parameters  $c'$  and  $\phi'$  are used to define the failure. The material properties for the soil and structure are given, as below:

Table 1: Material Properties for Soil and Buried Structure

Material Type	Material properties									
	E (kN/m <sup>2</sup> )	N	$\gamma$ (kN/m <sup>3</sup> )	$k_o$	K	$\lambda$	M	$\Gamma$	$k_x$ m/day	$k_z$ m/day
Modified Cam clay	3,000	0.3	20	0.613	0.062	0.161	0.888	2.789	$1 \times 10^{-6}$	$1 \times 10^{-6}$
Structure	$2400 \times 10^4$	0.2	24	-	-	-	-	-	-	-

Five stages of analyses are performed; as shown in Figure 6:

1. The first stage is the soil excavation in the construction zone to -6.0 m, Figure 6a. A rate of excavation of 0.2 m/day is used to remove six layers which is a typical of that expected in practice. Thirty days are required to complete the excavation.
2. Casting or installation of the reinforced concrete footing of the buried structure, (0.5 m thickness) at the dredge line Figure 6b. Five days are required to complete this stage.
3. Casting or installation of the reinforced concrete wall of the buried structure (0.5 m thickness), Figure 6c. Five days are required to complete this stage.
4. Casting or installation of the reinforced concrete slab of the buried structure, (0.5 m thickness), Figure 6d. Five days are required to complete this stage.
5. The final stage is backfilling the soil layers above the buried structure to the original ground level (2 m thickness), Figure 6e. A rate of backfilling of 0.15 m/day is used to backfill two layers; fifteen days are required to complete the backfilling.

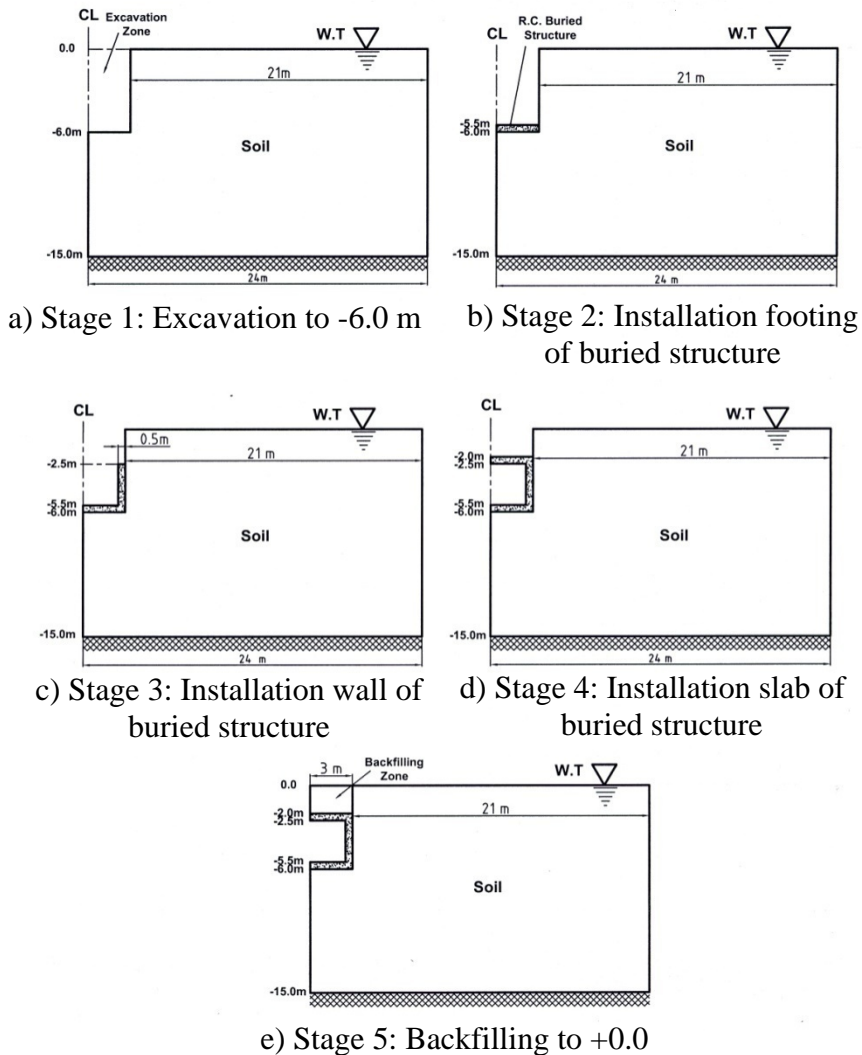


Figure 6: Construction Sequences of R. C. Buried Structures in Cam Clay Soils

Predicted deformations, deformation profiles, shear stress and excess pore water pressure contours at the end of construction are shown in Figures 7 to 22 respectively. The predicted deformation in soil shows expected patterns of behaviour, with the maximum heave that appear at the dredge line and the maximum lateral movement in soil near the bottom of excavation. These maximum values are obtained at the end of excavation. The contours of shear stresses predicted in each stage are very similar to each other, and close to those predicted by the dry soil analysis. As in all the previous cases, the largest values and concentration of shear stress occur in the soil beneath the excavation bottom where the soil movement is the largest. The contours of excess pore water pressures predicted in each case are also very similar to each other. Negative values of excess pressure are developed during excavation. Installation of structures and backfilling reduce these negative values, and this is due to the fact that pressure of buried structures and backfilling prevent lateral water dissipation.

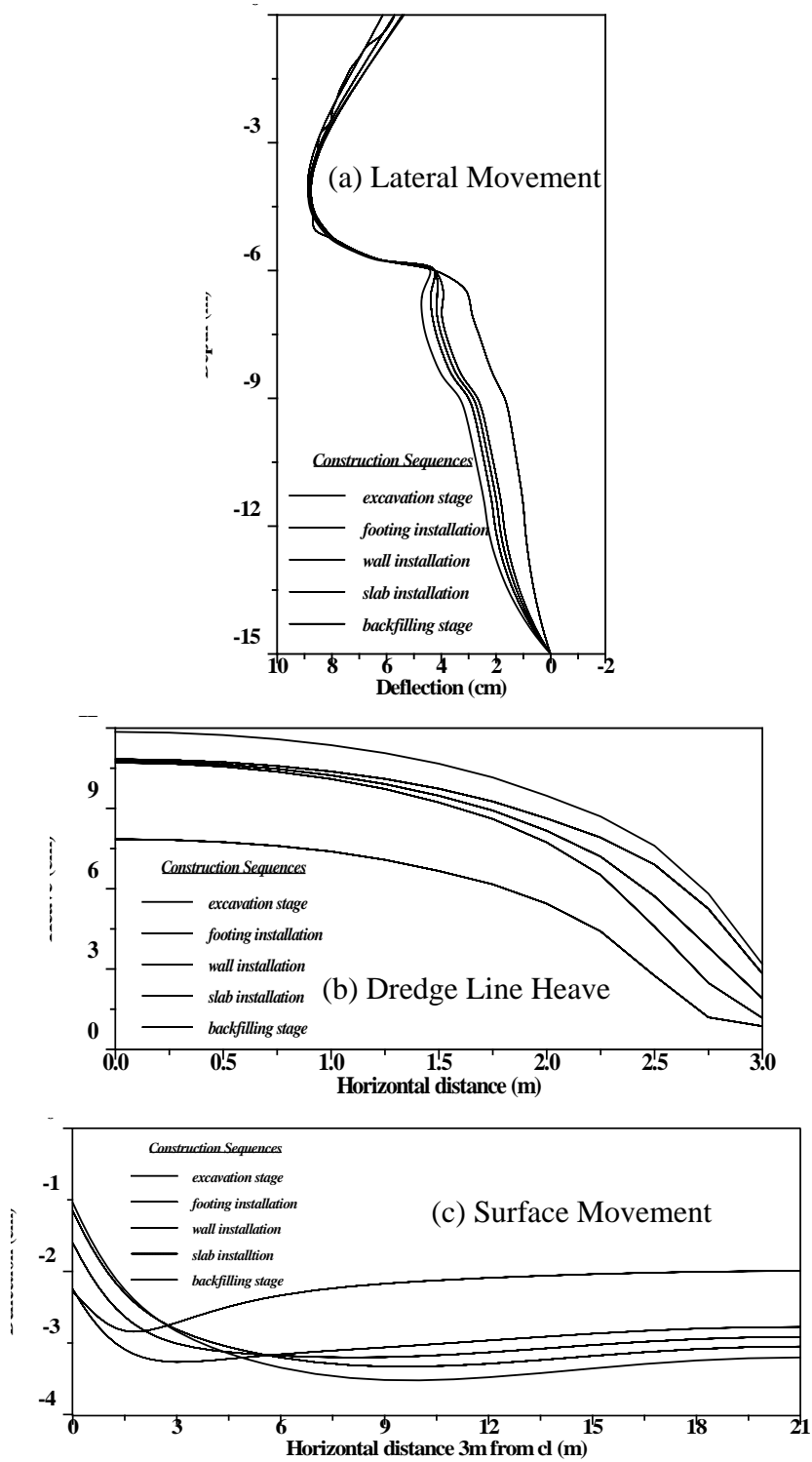


Figure 7: Predicted Deformation in Modified Cam Clay Soil during the Sequences of Construction Buried Structure

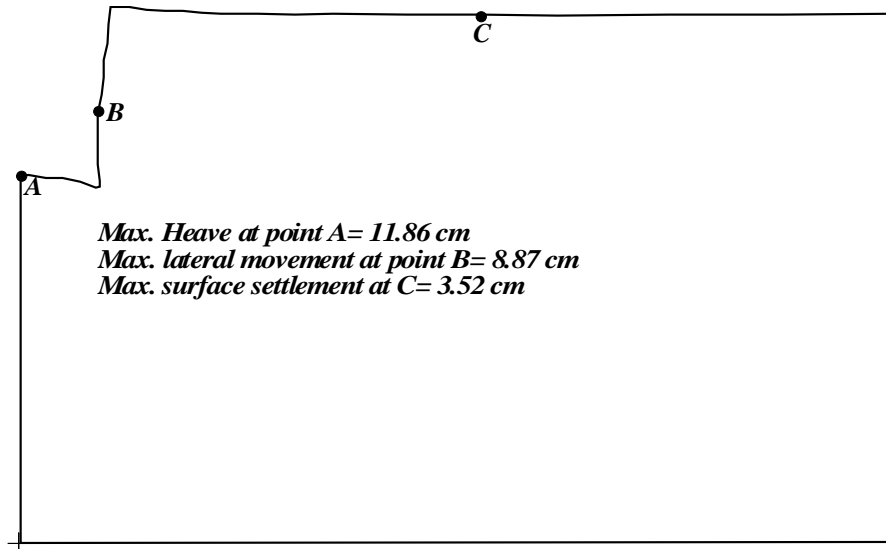


Figure 8: Predicted Deformed Shape in Modified Cam Clay Soil after Excavation to -6.0 m (deformation exaggerated by a factor of 10)

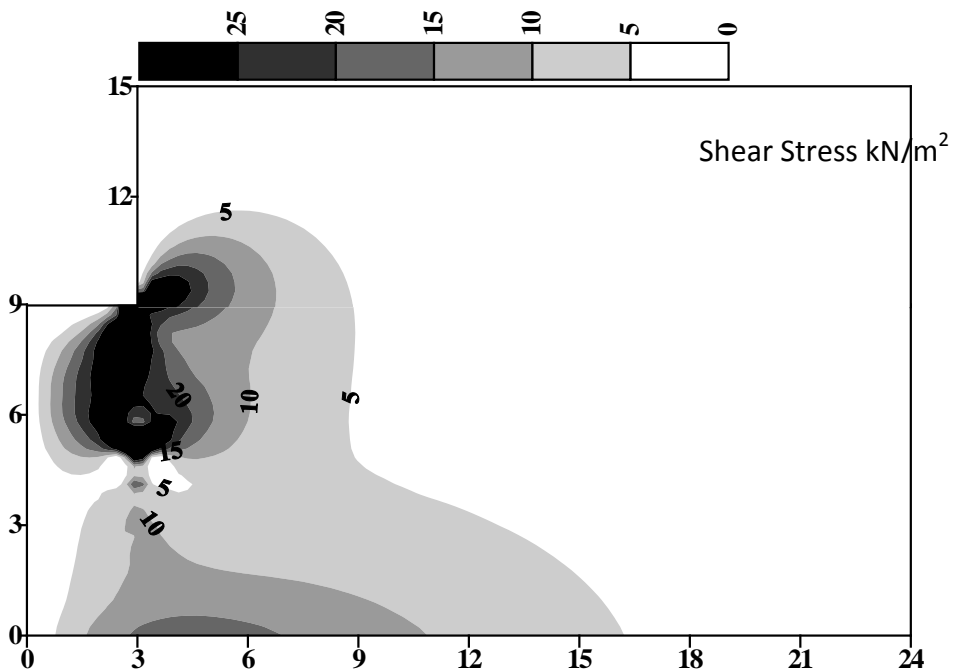


Figure 9: Predicted Contour Lines of Shear Stress Distribution in Modified Cam Clay Soil after Excavation to -6.0 m

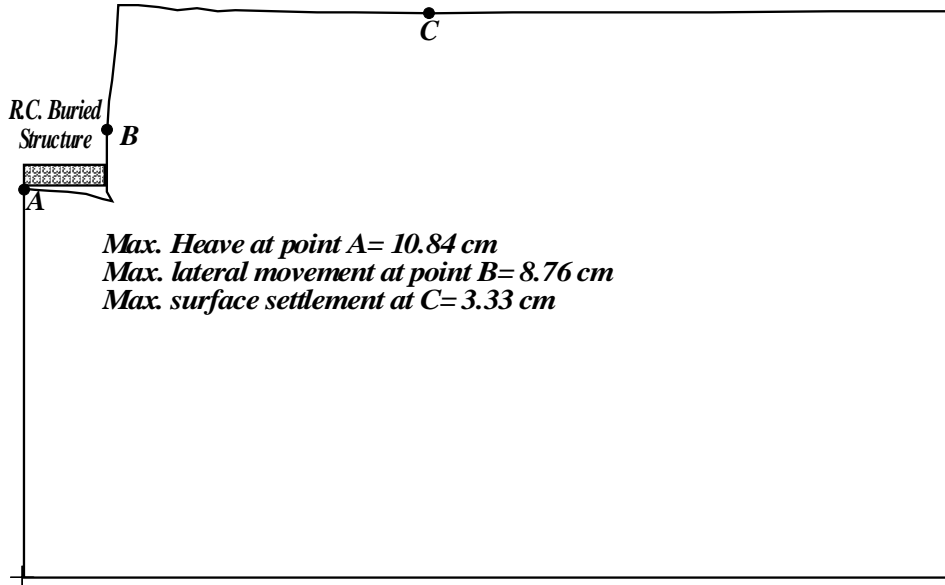


Figure 10: Predicted Deformed Shape in Modified Cam Clay Soil after Installation Footing of the Buried Structure

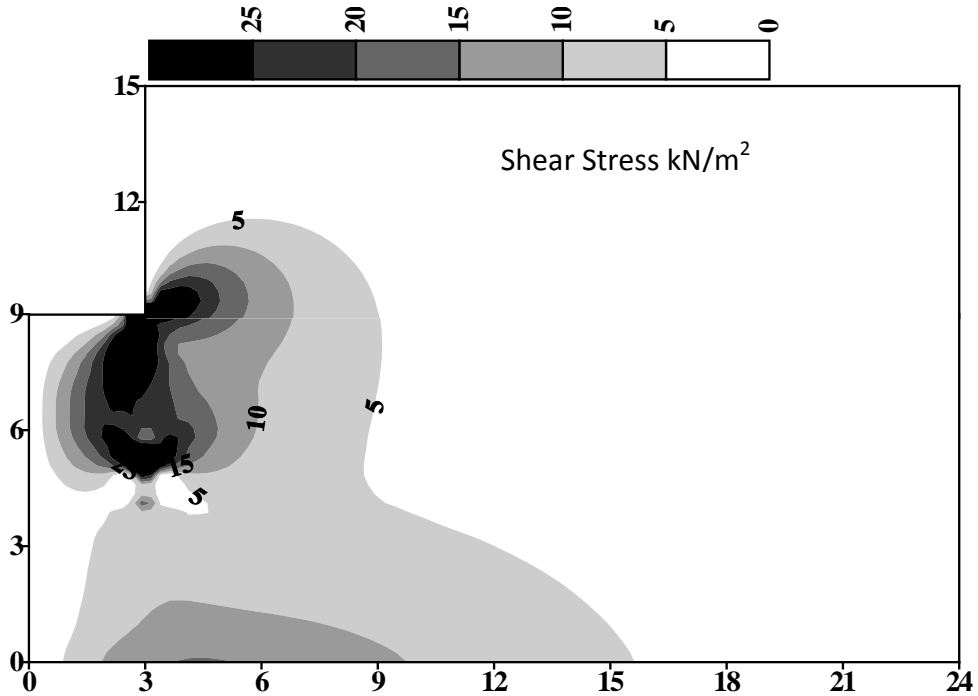


Figure 11: Predicted Contour Lines of Shear Stress Distribution in Modified Cam Clay Soil after Installation Footing of the Buried Structure

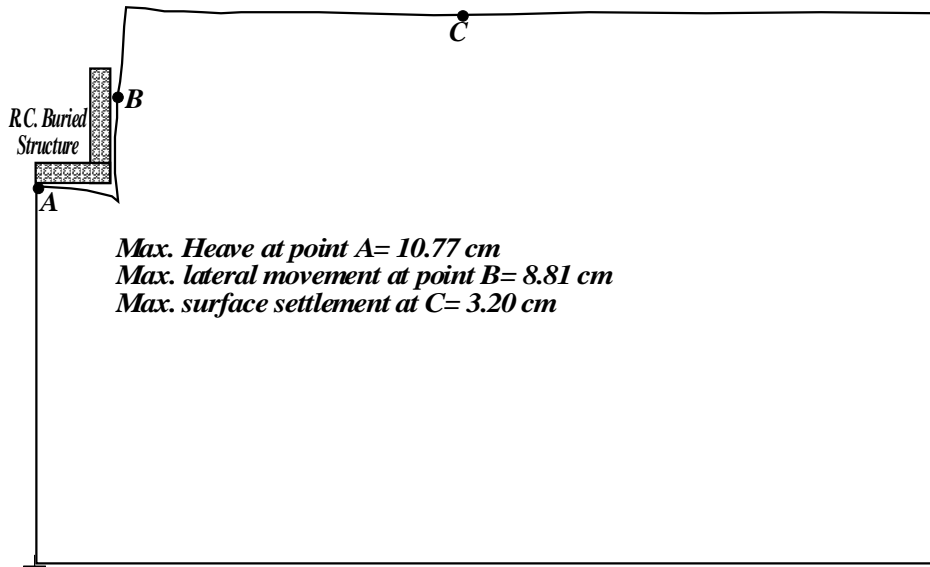


Figure 12: Predicted Deformed Shape in Modified Cam Clay Soil after Installation Wall of the Buried Structure

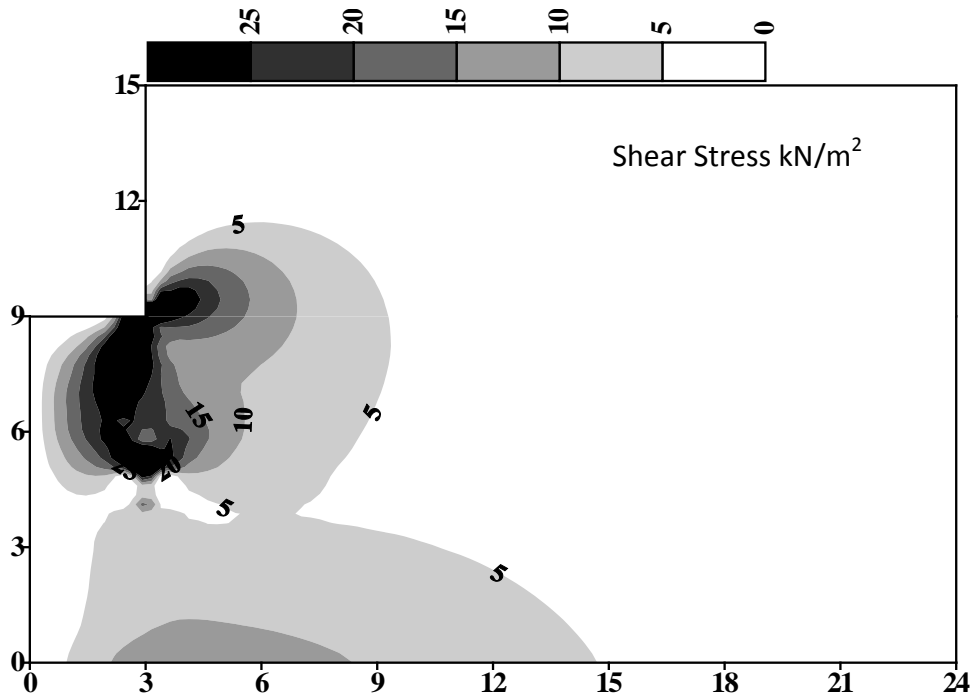


Figure 13: Predicted Contour Lines of Shear Stress Distribution in Modified Cam Clay Soil after Installation Wall of the Buried Structure

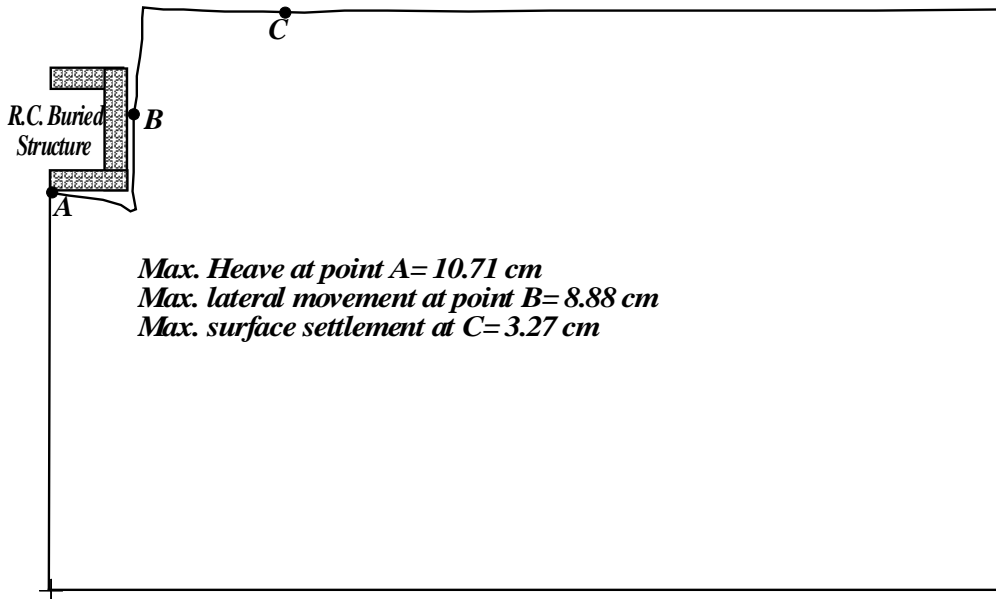


Figure 14: Predicted Deformed Shape in Modified Cam Clay Soil after Installation Slab of the Buried Structure

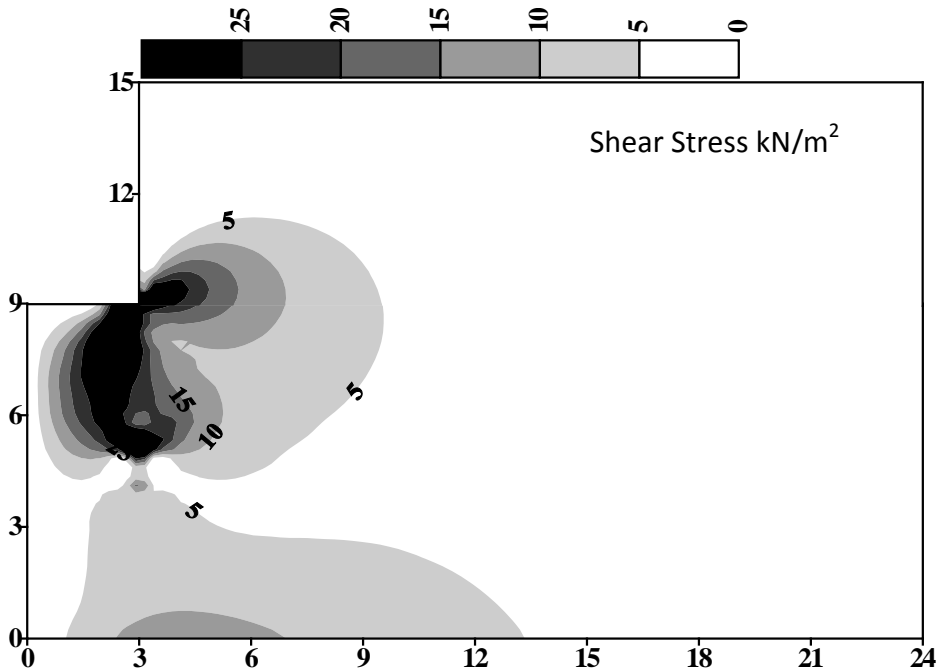


Figure 15: Predicted Contour Lines of Shear Stress Distribution in Modified Cam Clay Soil after Installation Slab of the Buried Structure

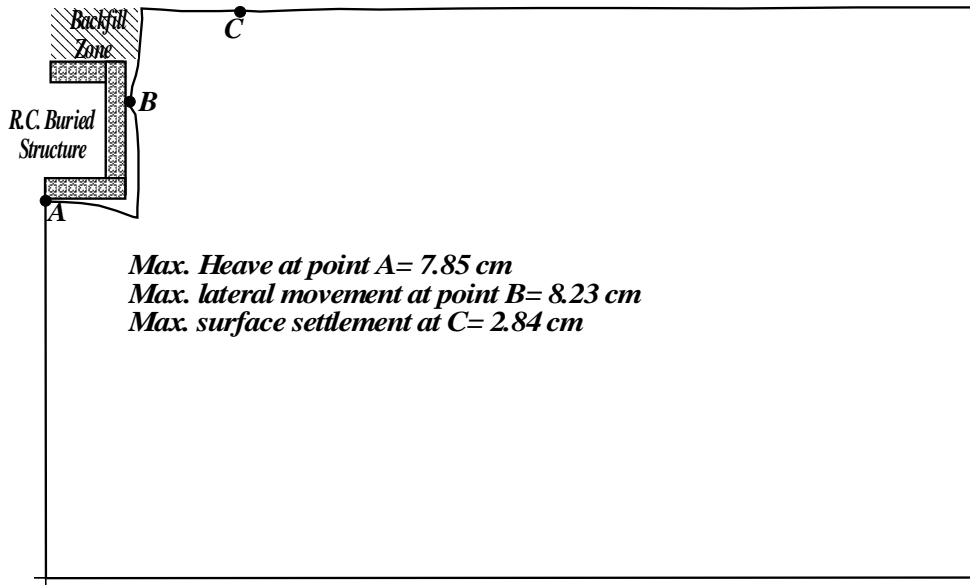


Figure 16: Predicted Deformed Shape in Modified Cam Clay Soil after Backfilling to +0.0

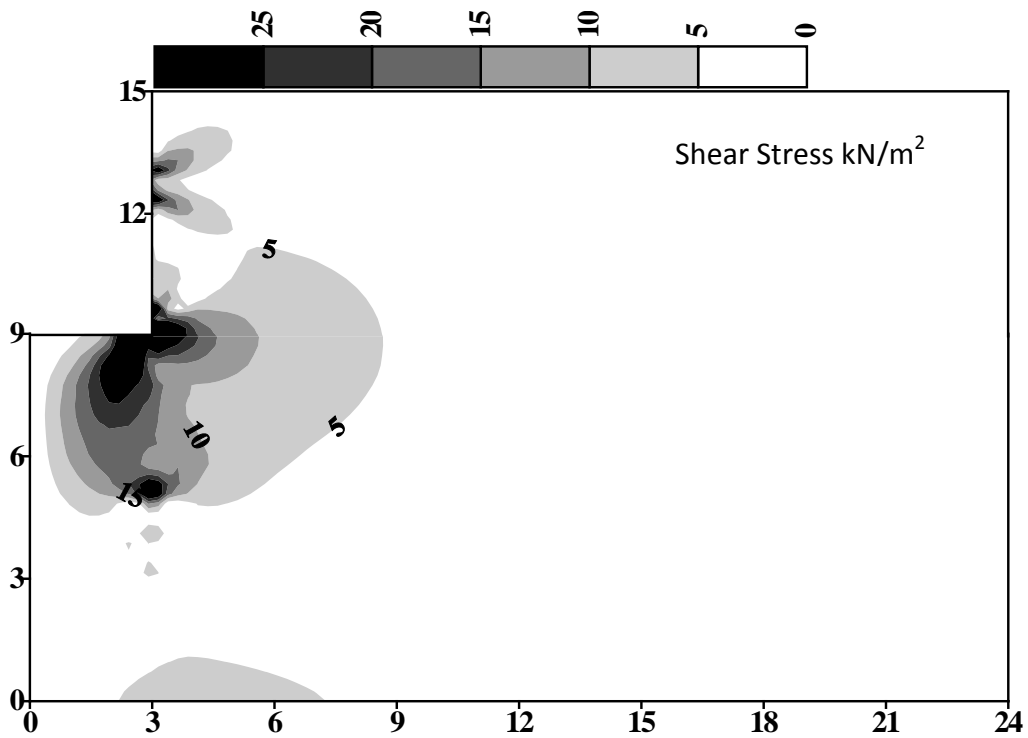


Figure 17: Predicted Contour Lines of Shear Stress Distribution in Modified Cam Clay Soil after Backfilling to +0.0



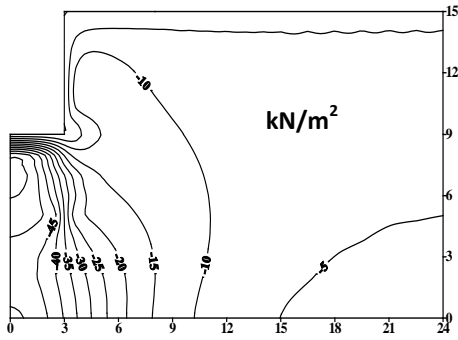


Figure 18: Contours of Excess Pore Pressure after Excavation to -6.0 m in Modified Cam Clay So

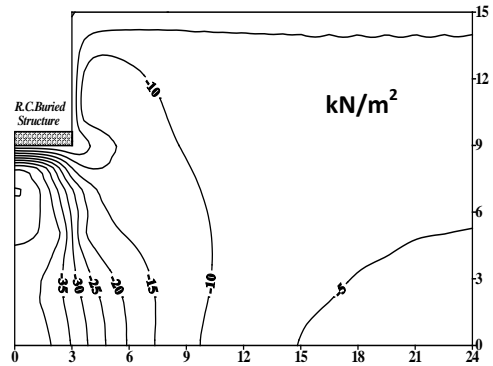


Figure 19: Contours of Excess Pore Pressure after Installation Footing of the Buried Structure in Modified Cam Clay Soil

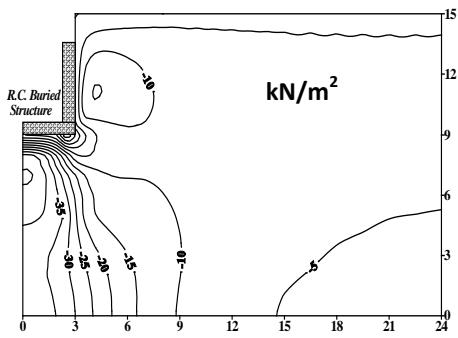


Figure 20: Contours of Excess Pore Pressure after Installation Wall of Buried Structure

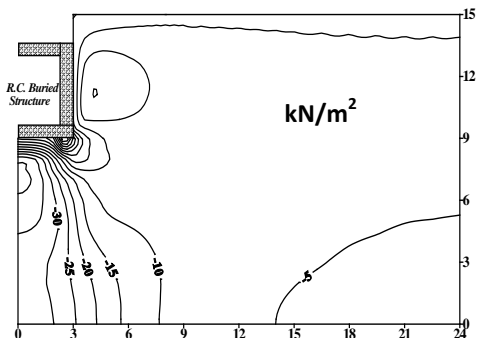


Figure 21: Contours of Excess Pore Pressure after Installation Slab of Buried Structure in Modified Cam Clay Soil

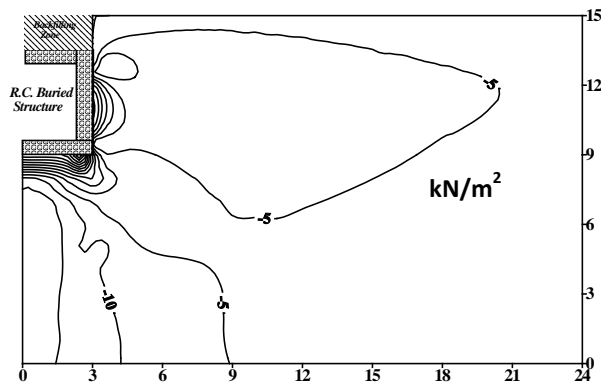


Figure 22: Contours of Excess Pore Pressure after Backfilling to +0.0 m in Modified Cam Clay Soil

## 6 Conclusions

This paper is directed towards the development of a finite element technique to simulate the sequences of construction of buried structures (realistic sequences) in linear and nonlinear time dependent soil behaviours.

1. High values of excess water pressure developed during unloading stage (excavation), and these values are decreased when soil is subjected to reloading condition (installation of buried structure and backfilling stages). This is due to the fact that the pressure of buried structures is found to slow the dissipation of excess pore water pressures.
2. The structure serves as a flow barrier that prevents lateral water movements.
3. High excess pore water pressures exist in the soil only at the end of excavation, because drainage is essentially limited to the vertical direction.

## References

- [1] Duncan, J.M., "Behavior and Design of Long-Span Metal Culverts," *J. Geotechnical Engineering Div.*, ASCE, **105**, No.GT3, March, 1979, pp 399-417.
- [2] Hassan, F.H., "Time Dependent Behavior of Earth Retaining Structures using Finite Element Method," B.Sc. thesis, Nahrain University, Iraq, 1995.
- [3] Atkinson, J.H., and Bransby, P.L., "*The Mechanics of Soils An Introduction to Critical State Soil Mechanics*," McGraw-HILL Book Company Limited, U.K.,1978.
- [4] Desai, C.S., Zaman, M.M., Lightner, J.G., and Siriwardane, T.H.J., "Thin-Layer Element for Interfaces and Joints," *International Journal for Numerical and Analytical Methods in Geomechanics*, **8**(1), 1984, pp. (19-43).
- [5] Biot, M.A., "General Theory of Three - Dimensional Consolidation," *Journal of Applied Physics*, **12**, 1941, pp. (155-164).
- [6] Britto, A.M., and Gunn, M.J., "*Critical State Soil Mechanics via Finite Elements*," Ellis Horwood Limited, U.K., 1987.
- [7] Georgiadis, K. "Development, Implementation and Application of Partially Saturated Soil Model in Finite Element Analysis," thesis submitted to the University of London in Partial fulfilment of the requirements for the degree of Doctor of Philosophy in civil engineering (2003).
- [8] Borja, P.T., Lee, S.R., and Seed, R.B., "Numerical Simulation of Excavation in Elasto-plastic Soils," *International Journal for Numerical and Analytical Methods in Geomechanics*, **13**, 1989, pp. (231-249).
- [9] Lewis, R.W., Roberts, G.K., and Zienkiewicz, O.C., "A Non-Linear Flow and Deformation Analysis of Consolidation Problems," *Proceeding Second International Conference in Numerical Methods in Geomechanics, Blacksburg, Virginia, U.S.A.*, **2**, 1976, pp. (1106-1118).