Effect of Construction Sequence and Soil Nonlinearity On The Behavior of Sheet Pile Walls

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Abstract

This study deals with assessing the behavior of a sheet pile wall by estimating the stresses and displacements of the sheet pile wall and surrounding soil throughout the different construction stages. The finite element method is used to carry out a comparison study to assess the effect of the soil nonlinearity on the behavior of sheet pile wall. The nonlinear hyperbolic model is used to represent both the soil and interface behavior of soil-sheet pile wall system.

The analysis of sheet pile wall was carried out using a nonlinear incremental stress dependent finite element computer program capable of simulating the different construction stages of the system. It was found that increasing excavation depth reduces both active and passive pressures below that calculated by Rankine theory and that shear stresses concentrate around sheet pile wall and increase with increasing excavation depth. It also noticed that adopting nonlinear soil properties leads to a more economical design of the sheet pile walls.

تأثير السلوك اللاخطي للتربة ومراحل الإنشاء على سلوك جدران الركائز اللوحية

الخلاصة

تعنى هذه الدراسة بتقييم سلوك الركائز اللوحية وذلك بحساب الاجهادات والازاحات للجدار والتربة المحيطة خلال مراحل التنفيذ المختلفة.استخدمت طريقة العناصر المحددة لتنفيذ دراسة مقارنة لتقييم تأثير السلوك اللاّخطي للتربة على الركائز اللوحية. تم استخدام النموذج اللاخطي ذي المقطـع الزائد (nonlinear hyperbolic) لتمثيل سلوك كل من التربة والسطح البيني او المتداخل بين التربة والجدار (interface). تحليلات التربة والجدار نفذت باستخدام برنامج حاسـبة ذي طـابع تزايـدي، لاخطي، يعتمد على الاجهـاد (nonlinear, incremental, and stress dependent) قـادر علـى تمثيل مراحل تنفيذ هذا النظام. وجد ان زيادة عمق الحفر يقلل من قيم ضغط التربة الفعـال (active) و المؤثر (passive) الى ما دون القيم المحسوبة بموجب نظرية رانكين، كما لوحظ ايضـا ان قـيم اجهادات القص تتركز حول جدار الركائز اللوحية و تزداد بزيادة عمق الحفر. كما لوحظ ان اعتمـاد السلوك اللاخطي للتربة يوفر تصميما اكثر اقتصادية لجدران الصفائح اللوحية.

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1. Introduction

Sheet pile wall is a row of interlocking, vertical pile segments driven to form an essentially straight wall whose plan dimension is sufficiently large that its behavior may be based on a typical unit (usually one foot) vertical slice [Engineer Manual No.1110-2-2504, 1994].

Sheet pile walls are widely used for both large and small waterfront structures, temporary constructions and lightweight construction where sub-soil is poor for supporting [Bowles, 1996].

2.Objective of Study

This study deals with the fundamental principles of analysis of sheet pile wall problems. This theoretical study has been made to asses the effect of the soil nonlinearity and construction sequence on the behavior of sheet pile walls and especially the role of progressive failure, and also to discuss the use of alternative methods of analysis for estimating the local failure in the soil and the overall stability of wall-soil system using stress level.

The study provides a simple and useful means of studying the development of failure zones within sheet pile wall system.

Analysis in this study may be of considerable value for understanding the behavior of sheet pile wall because the procedures employed can be used to calculate stresses and displacements around the wall.

3.Finite Element Method

The technique of finite element has been adopted to the general problem of the sheet pile, tied, or braced wall by a number of investigators; its value to the excavation problem lies in its ability to predict deformation of both the wall and the soil media during the different stages of construction.

The finite element method has been used in the analysis of a number of actual tied-back walls where comparisons of computed and observed behavior showed good agreement

The finite element method can be considered as the most efficient and rational method of sheet pile analysis and design currently available [Bowles, 1996].

Recently the finite element method is very widely used in the problem of sheet pile, tied back walls, and braced walls because it consists of analyzing the soil mass and the wall by using proper models for the elements of mesh. This method leads to the prediction of the bending moment and axial load in the wall, the anchor load distribution, and the deflection of the wall and soil surface subsidence [Al-Kaaby, 2002].

4.The Finite Element Program Used

The finite element computer program modified by AL-Shlash (1979) in Fortran language was used in the finite element analysis carried out during this research. Four different types of element can be used in the finite element mesh in solving, soil, structural, and soil structure interaction problems under plane or axisymmetrical conditions; this

program also is able to simulate the different construction activities which are associated with braced or tied back systems such as excavation, filling or placing of concrete, anchor or braced installation and prestressing. The four element are, the two dimensional quadrilateral, the triangular element, the one dimensional interface element, and the one dimensional bar element.

Three models can be used in this program to represent the behavior of the soil and the soil structure interaction, these models are, linear elastic model, (ii) bilinear elastic-completely plastic model, (iii) hyperbolic incremental stress-dependent.

The model that used in this work is the hyperbolic, incremental, stress dependent, nonlinear technique [Duncan and Chang, 1970] on primary loading with a different stress dependent modulus on unloading or reloading.

By using this program, one can obtain the results associated with the deformations of the nodal points and the stresses with their directions at the centroid of each element at the end of each solution increment.

This program can also plot the path of each nodal point movement throughout the different construction stages.

5.The Basic Problem

The basic problem must be introduced after taking some important facts into consideration. The basic problem must simulate the real problem as closely as possible, must be simple, and amendable to future alterations and complications.

When choosing the basic problem, it is essential to consider the material characteristics, and the geometry of excavation.

6.Problem geometry

The basic problem adopted in this study shown in Figure (1) involves the construction of PZ-27 sheet pile wall to support a 4m depth vertical excavation in medium clay. The finite element mesh used to analyze the basic problem shown in Figure (2) consists of 289 nodal points and 253 elements. The soil is represented by 234 two dimensional quadrilateral elements, the steel sheet pile wall is represented by 6 quadrilateral elements, and the wall soil interface is represented by 13 one dimensional interface elements.

The equivalent thickness of the sheet pile wall (t) was calculated as follow:

$$EI_{\text{sheet pile}} = EI_{\text{equivalent}}$$

For basic problem (section PZ-27):

$$115 * 10^{-6} = b\, h^3 / 12$$

$$h = t = 0.11\text{m}$$

7. Material Characteristics

The medium clay, which has a coefficient of at rest pressure, K_o = 0.961 and a unit weight of 19.866 kN/m^3 is assumed to behave non-linearity. The tangential modulus and the unloading-reloading module of elasticity are to be calculated according to the nonlinear parameters given in Table (1) while Poisson's ratio of the soil is assumed to be constant.

For steel, the modulus of elasticity and Poisson's ratio are assumed to be constant.

Suitable values for the nonlinear interface parameters, as well as for the interface coefficients, K_n and K_s at failure are selected.

8. Construction Stages

The construction stages of the basic problem are represented by two steps. These steps represent the process of excavation, during which two rows of elements are removed.

9. Results of the Analysis of the Basic Problem

9.1 Lateral sheet pile wall movement

The lateral sheet pile wall movements throughout the two excavation stages are shown in Figure (3), from which it can be seen that as excavation is carried out the sheet pile wall moves laterally towards the excavation. The final lateral sheet pile wall movement is about 35mm.

9.2 Soil surface movements

Figure (4) shows the soil subsidence of the retained soil during the two excavation stages. It can be seen that due to the excavation, the soil behind the sheet pile settles due to the lateral sheet pile movement towards the excavation. The final settlement of the soil behind the sheet pile is about 21mm. Figure (5) shows the soil heave along the excavation face during the two excavation stages, the soil rises due to the lateral sheet pile movement towards the excavation and due to the settlement of the soil behind the sheet pile.

The same behavior of the sheet pile and soil surface movement discussed above can be seen in Figure (6) which shows the displacement vectors throughout the two construction stages, from which it can be seen that the retained soil tends to move towards the excavation, and that soil heave increases during the two excavation stages and that sheet pile moves laterally towards the excavation side.

9.3 Pressure and stress distribution

Figure (7) shows the horizontal stress contours throughout the two excavated stages, from which it can be seen that the horizontal stresses decreases as excavation continued.

Figure (8) shows the active and passive stresses on the sheet pile wall, from which it can be seen that the effect of excavation leads to decrease the lateral pressure on the sheet pile wall towards the active and passive state. Also it can be seen that the active and passive stresses calculated according to Rankine Theory are greater than those calculated according to the finite element method.

Figure (9) shows the shear stress contours during the two excavation stages, from which it can be seen that the shear stress concentrates around the sheet pile wall and increases with progressing of excavation.

9.4 Stability of the soil - sheet pile wall system

Mohr Coloumb failure criterion used in this study depends upon the stress level, as defined by [Chang and Duncan, 1970]:

$$S = \frac{(s_1 - s_3)}{(s_1 - s_3)_f}$$

In which:

$(\sigma_1-\sigma_3)$ = the deviator stress,

$(\sigma_1-\sigma_3)_f$ = the deviator stress at failure.

The factor of safety for the stability of the two stages of excavation is obtained on the base of stress level for each element (F.S = 1 / S) is shown in Figure (10), from which it can be noticed that the factor of safety is sufficient to control the failure and the over all stability of the system.

10. Effect of Soil Nonlinearity

To investigate the effect of soil nonlinearity, the nonlinear soil in basic problem is considered once again as linear.

Figures (11), (12), and (13) shows the lateral sheet pile wall movement, retained soil subsidence, and soil heave, from which it can be seen that the sheet pile wall and soil movements for the case of nonlinear soil are more real.

From Figures (15) and (17) and as compared with Figures (7) and (9) it can be noticed that the lateral and shear stresses are closely similar.

From Figure (18) and as compared with Figure (10) it can be noticed that the factor of safety for the case of considering the soil linear is smaller than for nonlinear soil. Because the soil behavior is nonlinear; therefore, the analysis considering the soil as nonlinear material is seemed to be more economical.

11. Conclusions

From the results of the present study, the following conclusions can be raised:

1- Adopting nonlinear soil properties together with the finite element technique provides excellent prediction of the behavior of sheet pile walls.
2- Retained soil behind sheet pile settles while soil at excavation side rises during excavation stage.
3- Increasing excavation depth reduces both active and passive pressures below those calculated according to Rankine theory.
4- Shear stresses concentrate around sheet pile wall and

increase with increasing depth of excavation.

5- Analyzing sheet pile walls by adopting nonlinear soil behavior seems to be more economical than adopting linear elastic soil behavior.

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Table(1) material properties used in the analysis of basic problem

Parameters	Soil (medium clay)	Sheet pile wall (steel)	Exavation material
Unit weight, γ, kN/m^3	19.866		-19.866
Coefficient of at rest earth pressure, K_o	0.961		0.961
Cohesion intercept, *c*, kN/m^2	50	*	*
Angle of internal friction, φ, degree	0	*	0
Poisson's ratio, µ	0.49		0.49
Modulus of elasticity, *E*, kN/m^2	Variable	210000000	17097.463
Nonlinear modulus of elasticity parameters			
K	180	*	*
K_{ur}	220	*	*
N	1	*	*
R_f	0.83	*	*
E_f, kN/m$_2$	0.001 of pre-failure	210000000	17097.463
Interface parameters			
D	10	*	10
K_I	40000	*	40000
n^-	1	*	0.9
R^-_f	0.9	*	0.9
K_{nf}	10000	*	10000000000
K_{sf}	0.1	*	0.1

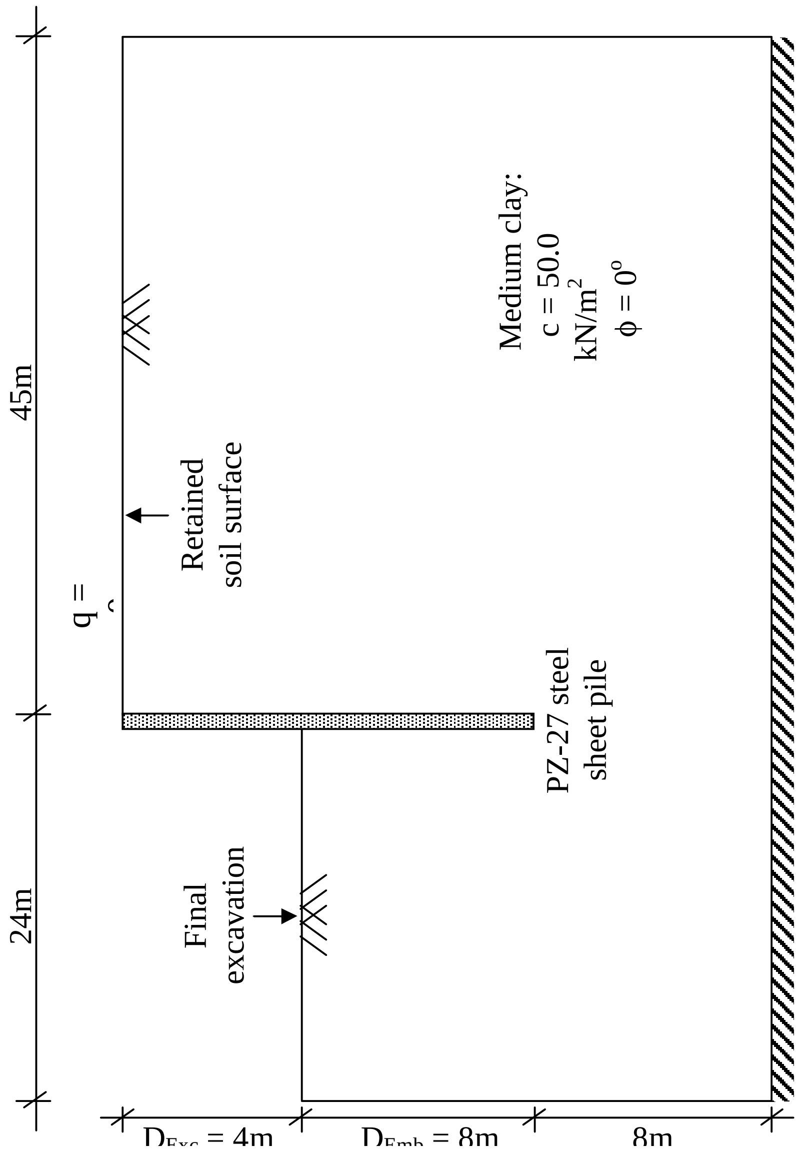


Figure (1) The Basic problem for the parametric Study

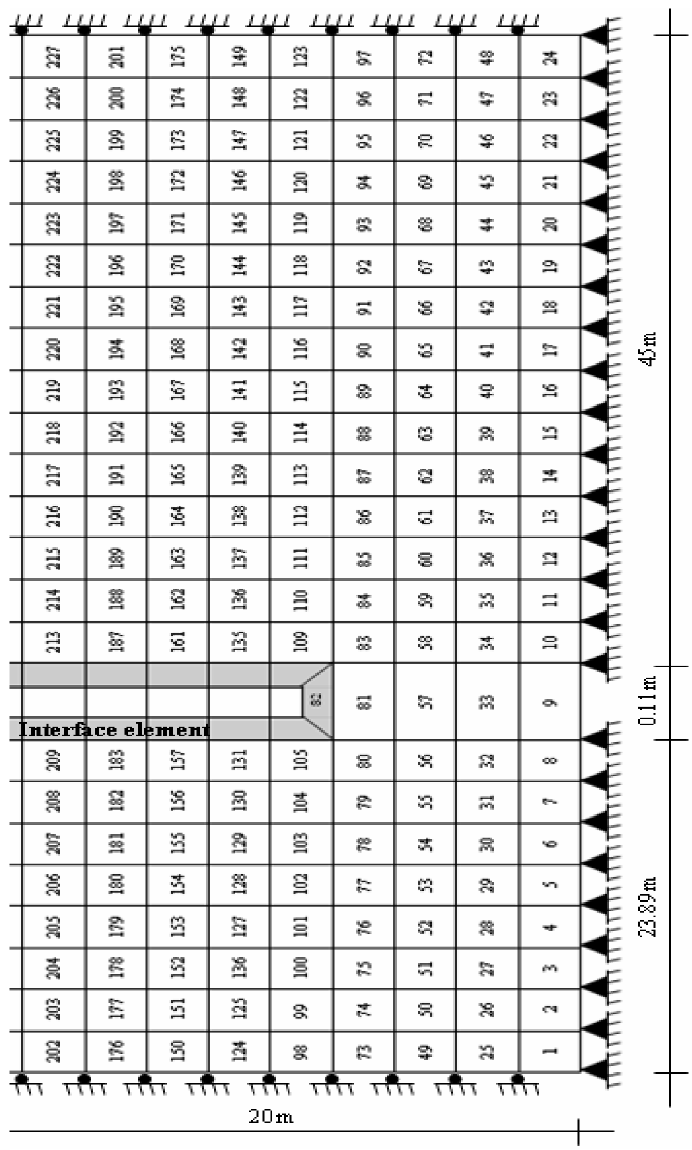
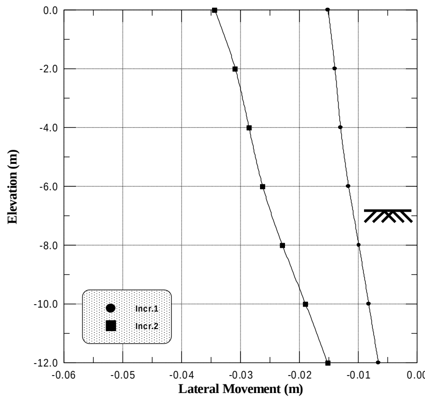


Figure (2) The finite element mesh of the basic problem



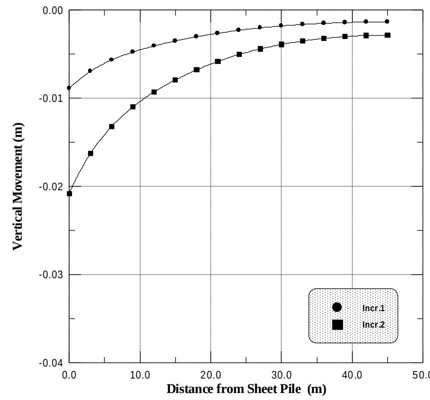


Figure (3) -Lateral sheet pile wall movement throughout Through out the two excavation stages the two excavation stages

Figure(4)-Retained soil surface

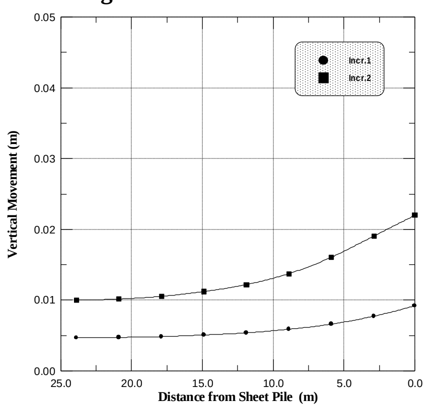
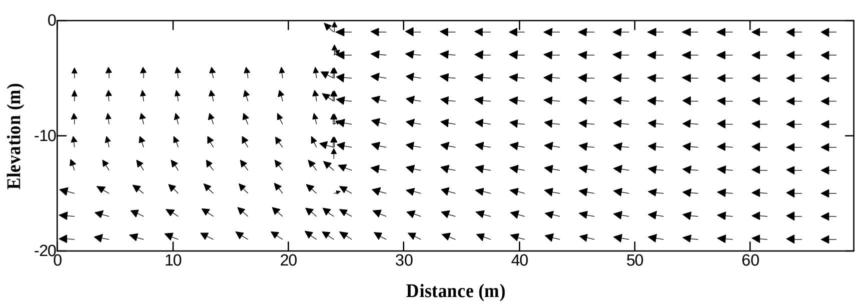
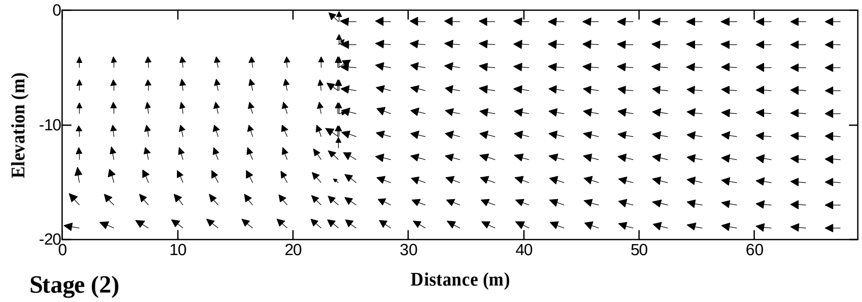


Figure (5) – soil heave along the excavation level Throughout the two excavation stages

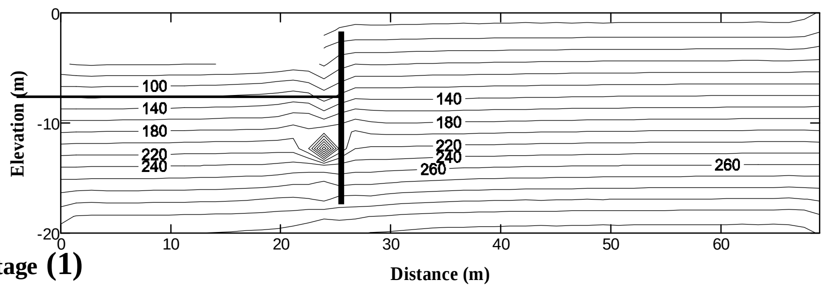


Stage (1)

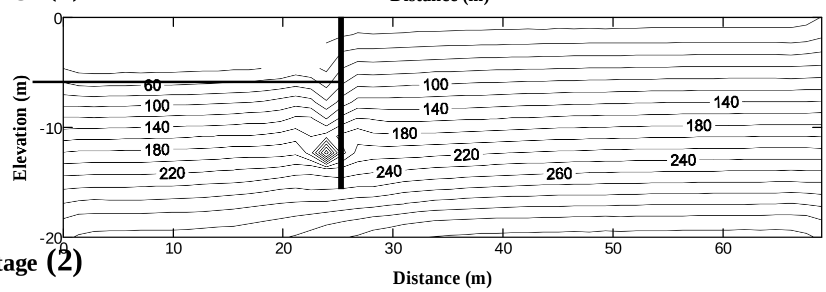


Stage (2)

Figure (6) – Displacement vectors throughout the two excavation stages (basic problem)

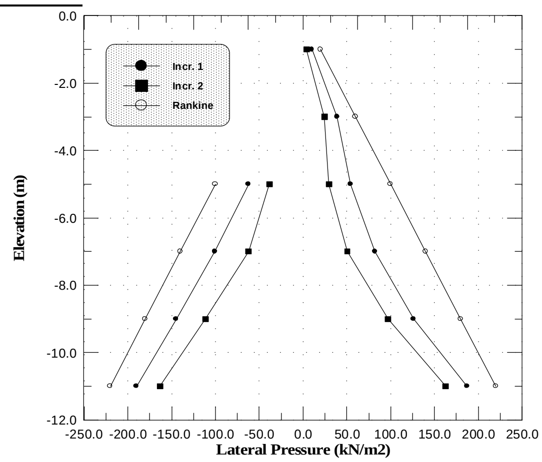


Stage (1)



Stage (2)

Figure (7) – Lateral Stresses contours (KN/m²) throughout the two excavation stages (basic problem)



Figure(8) – Lateral pressure distribution (active and passive states) on the sheet pile wall throughout the two excavation stages

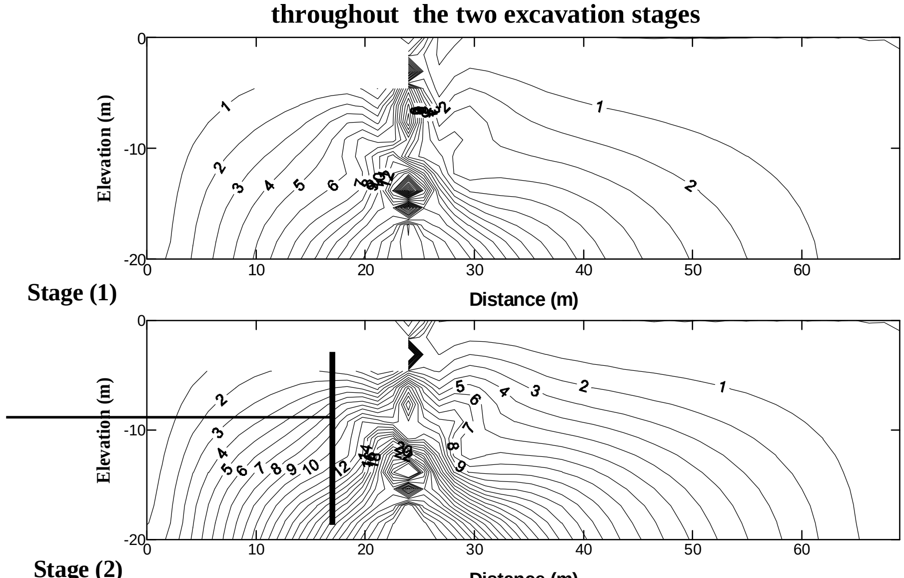
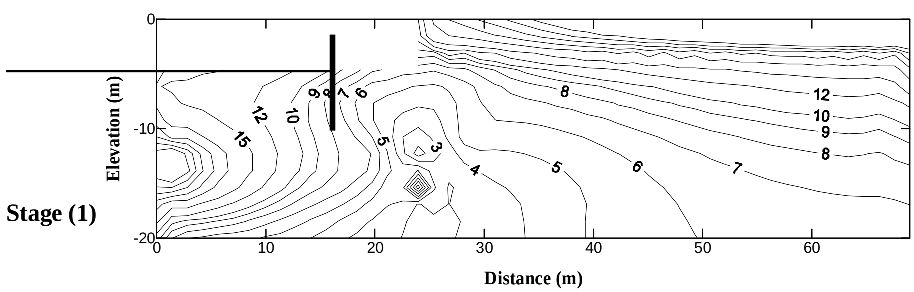


Figure (9) – Shear stresses contours (KN/m²) throughout the excavation stages(basic problem)



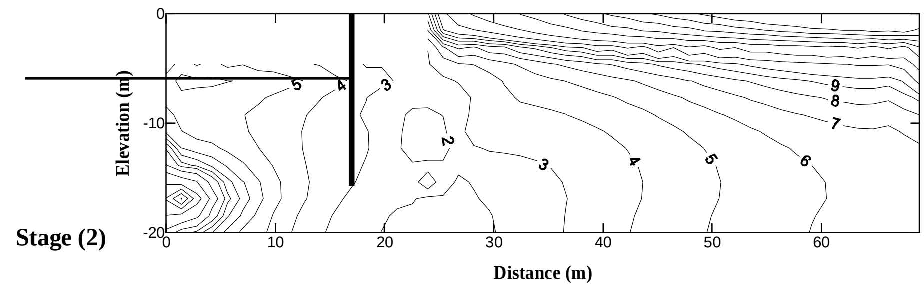
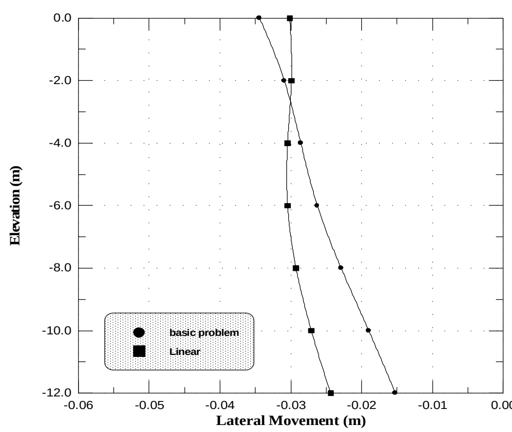
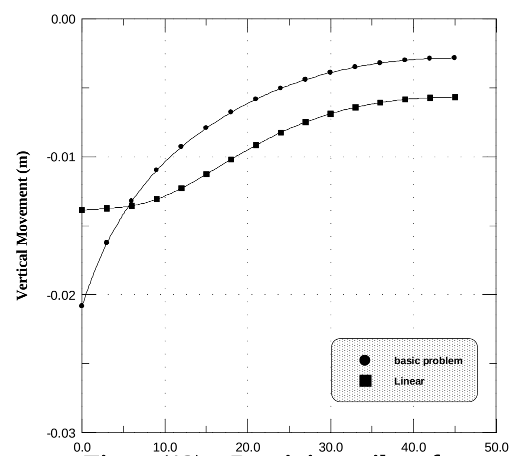


Figure (10) – Factor of safety contours throughout the two excavation stages(basic problem)



Figure(11) – Lateral sheet pile wall movement After the final stage (Linear soil)



Figure(12) – Retaining soil surface subsidence after the final Stage (Linear soil)

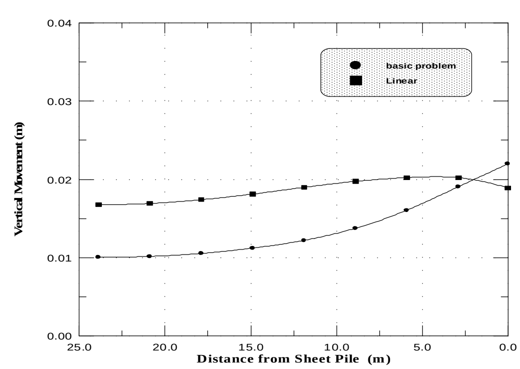
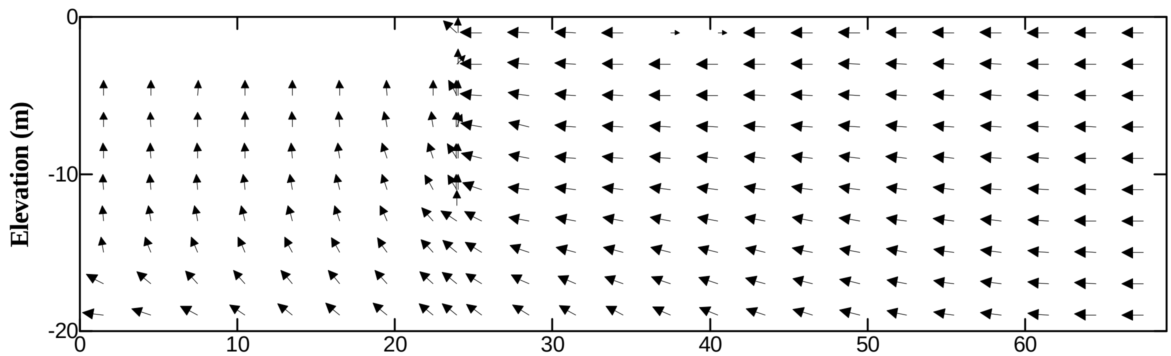
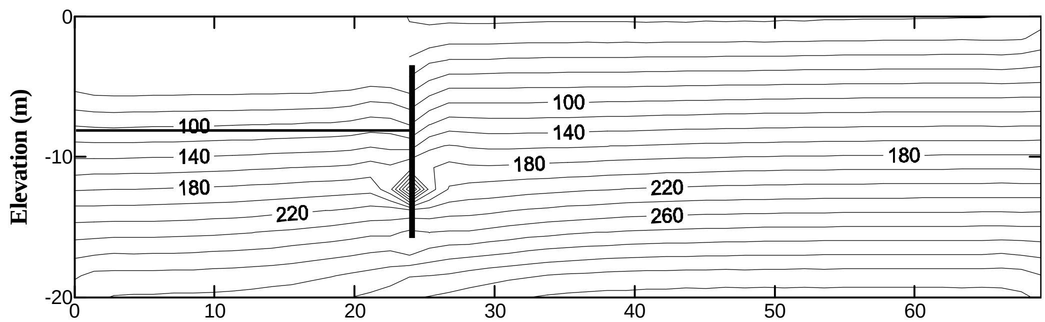


Figure (13) – Soil heave along the excavation level After the final stage (Linear soil)



Figure(14) – Displacement vectors after the final stage (Linear soil)



Figure(15) – Lateral stress contours after the final stage (Linear soil)

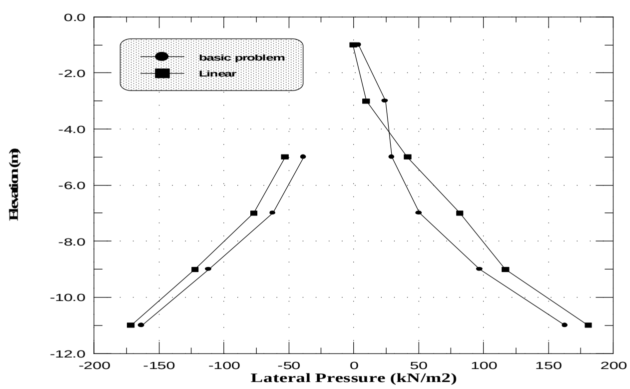


Figure (16) – Lateral pressure distribution (active and Passive states) on the sheet pile wall after The final stage(linear soil)

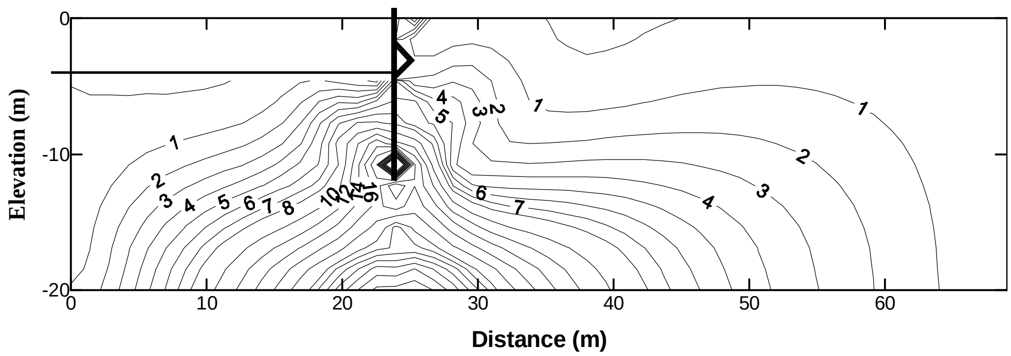


Figure (17) – Factor of safety contours after the final stage(linear soil)

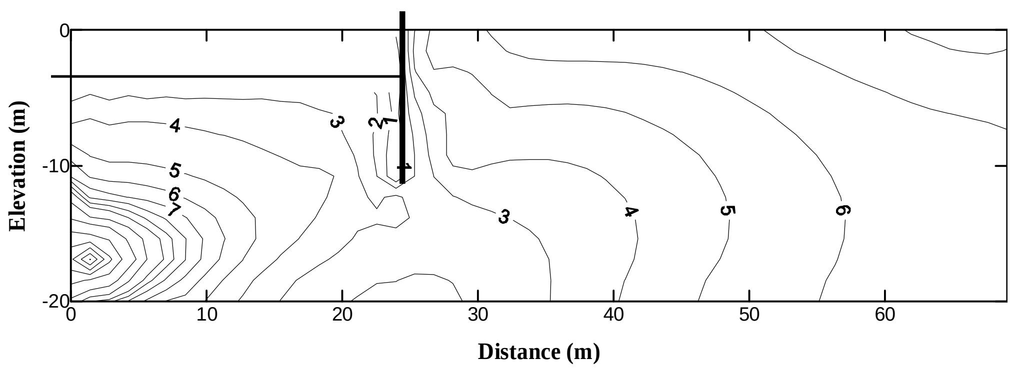


Figure (18) – Factor of safety contours after the final stage (Linear soil)