DEEP EXCAVATION IN SOFT GROUND

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Abstract

Many major cities in the newly industrialized countries, such as Singapore, Taipei and Bangkok, are located in areas with recent sedimentary deposits. Due to the rapid economic growth and urban development in recent years, underground construction becomes one of the major, and more difficult, construction activities.

This lead paper on "Advances in Underground Construction" will concentrate on the problem of deep excavation in soft ground. A review will be made on the factors affecting the engineering of deep excavations. Recent practices in the design and construction of deep excavations will be discussed, with particular emphasis on the roles of instrumentations in safety control. The discussions will be illustrated with a recent case record.

INTRODUCTION

In recent years, due to the rapid expansion of economic development in many Southeast Asian countries, maximum utilization of its expensive urban land area is one of the most important consideration for both the public sector and the private investors. Increase of usable underground spaces becomes one of its obvious solutions which has greatly contributed to the advancement of underground construction technology in the region.

Due to inherent characteristics of soft ground, e.g. low strength, high compressibility, high groundwater table etc., deep excavation in soft ground requires special attention in both design and construction. Many major cities in the Southeast Asian region, such as Singapore, Bangkok, Jakarta, Kuala Lumpur and Taipei, have extensive deposits of soft soils. Deep excavations in these soft grounds are becoming more demanding and the associated problems are also increasing, both in magnitude and difficulty. This paper presents discussions on some of the major elements in engineering on excavation, illustrated with a case study.

ENGINEERING AN EXCAVATION

Excavation in soils, particularly in soft soil deposits, is not merely a design problem or construction technique which aims at efficient and economical construction of structures. It is a total technique which must take into account the inter-relationship between soil-structure interaction and construction technique as well as the effect of construction on adjacent environment.

In layman's term, excavation is a simple process involving the removal of a mass of soil and water. With this removal, there are changes in the stress conditions in the ground including the groundwater regime. One of the most important effects of this process is soil movements below the excavation as well as surrounding the excavation. Prevention or minimizing damages to surrounding is of utmost concern to the design engineer and the constructor for any excavation work.

To engineer an excavation, the basic steps which should be carried out by the design engineer are listed as below:

(1) Soil characterization

(2) Select dimensions of excavation
(3) Survey adjacent structures
(4) Establish permissible movements
(5) Select earth retaining system
(6) Select bracing (supporting) & construction scheme
(7) Predict movements
(8) Compare predicted with permissible movements
(9) Alter bracing and construction scheme, if needed
(10) Monitor instrumentation, alter as needed
(11) Compare monitored results with predicted and permissible values
(12) Alter bracing and construction scheme, if needed.

Site characterization is the first major step to be taken by a geotechnical engineer. Most common practices tend to greatly simplify the soil profile and to select the design parameters e.g. strength, and compressibility as the basis of simple laboratory tests. On the other hand, in analyzing and designing the retaining system, sophisticated mathematical models are quite often assumed. It must be pointed out that compatibility between soil characterization and method of analysis must be observed. Many of the analytical methods, particularly those for estimating soil movements, are based on semi-empirical approach. The applicability of "local" experience or data needs to be examined carefully.

There are many factors which affect the soil movement. Among them, the more important ones are soil properties, groundwater conditions and control, dimensions of excavation, supporting system, excavation and bracing sequence, nearby structures and facilities, transient loads and time. Since soil deformation is time dependent, the importance of timely installation of support and bracing system and preloading cannot be over-emphasized. Many investigators have presented case studies to illustrate and discuss these factors (for example, Ref. 1, 2).

Since deep excavation is a total technique, proper coordination and integration of design and construction are of utmost importance. Figure 1 shows the inter-relationship among the various phases of work in carrying out an excavation.

Due to limitations in the state of current knowledge in soil mechanics and the complex nature of soil behavior, design of excavation, including the supporting system, still heavily relies on semi-empirical approaches. Furthermore, most excavation work and supporting system are temporary in nature. Low factors of safety are often adopted. Use of instrumentations to monitor the performance of excavation work should be considered as an essential element of the total technique. The functions of instrumentation can be briefly described as shown in Table 1.

CASE STUDY

Project Description

The Taipei World Trade Center (TWTC) Convention Center is a 10 storey building with 2 storey basement constructed in the eastern part of the Taipei Basin. The TWTC complex includes an exhibition hall, an office building, a hotel and an underground car park (Fig. 2). During the excavation phase for the convention center, construction of the hotel, the office building and car park were taking place.

The convention center excavation covered a total plan area of about 11,500 sq.m. It was carried out to an average depth of 12.1 m. The entire excavation work was conducted from August 1987 to January 1988. In order to understand the soil-structure interaction during the course of excavation, an extensive monitoring program was carried out. The instrumentation included settlement points, inclinometers, tiltmeters, observation wells, rebar stress transducers, strut strain gages, earth pressure cells/piezometers and heave stakes.

The following section, discusses the monitoring results. Analyses of diaphragm wall deflection, effect of strut preloading, settlement outside of the excavation, and heaving at the base of excavation are presented. Emphasis is given on the earth pressure measurements on both sides of the excavation which provided some insights on the fundamentals of deep soft ground excavation.

Construction Method

The excavation was conducted using the conventional bottom-up cut and cover construction procedure as shown in Fig. 3. A 90 cm thick diaphragm wall penetrated to a depth of 28 m was used as retaining structure. Initial excavation was carried out to a depth of 3.5 m after which the first strut was placed. When the excavation reached 6m depth, a berm of 3 m crest and sloping at 30 degrees was left until part of the basement was constructed. A total of 3 levels of struts were used to support the 12.1 m deep excavation.

Instruments were placed at various key locations of the excavation (Ref. 3). In addition to 60 settlement points and 3 tiltmeters installed to measure the ground movement, inclinometers, piezometers and rebar stress transducers were set up to control the safety of the excavation. On selected diaphragm wall panels, earth pressure cells with piezometers were installed to obtain the horizontal effective stress on soil elements in both active and passive sides. A typical instrumented section is shown in Fig. 4.

Ground Conditions

According to the geotechnical mapping of Taipei (Ref. 4), the soil deposits at the site can be categorized as typical of the soil profile in the K1 zone. The K1 zone is the area occupying the eastern section of the Taipei Basin, based on the subdivision of the Sungshan deposits into areal zones. A typical subsoil profile along with basic physical properties of the site are shown in Fig. 5. Below a 1.5 m fill is a layer of soft silty clay with thickness of about 28.5 m. Between 30 to 45 m depth is a stiff silty clay layer interbedded with thin sand lenses. Underlying the cohesive soil deposits are very dense silty sand and very stiff silty clay layers. Most of the Taipei soil deposits are underlain by the "Chingmei gravel layer". This layer is however absent in this site. Bedrock was encountered at a depth of about 45 m.

The groundwater table was very close to the ground surface. The groundwater pressure distribution as shown in Fig. 6 approximately follows hydrostatic condition down to a depth of about 15 m. Below that, the groundwater distribution was below hydrostatic owing to previous regional deep well pumping in the Taipei Basin (Ref. 5)

Monitoring Results

Wall deflection and strut loading

The lateral deflection of the diaphragm wall at each stage of excavation was calculated on the basis of inclinometer measurements. A typical result is shown in Fig. 7 for the retaining wall at the west side of the excavation. Well-defined variations in the deflection of the diaphragm wall could be observed for the different stages of excavation. An interesting point to note is the relatively large deflection at the top of the wall during the first stage of excavation. Since the first strut was not placed until the excavation depth reached 3.5 m, the wall behaved as a cantilevered section with the top part experiencing a total deflection of about 6 cm. A large amount of preloading, about 24 ton/m was then used to stress the first level strut. The effect of this preloading can be seen in Fig. 8. It is observed that the preload applied on the struts has reduced the wall deflection at the top by more than 2 cm. At the final excavation stage, the maximum wall deflection measured was about 7.5 cm.

Settlement and heave

The settlement points positioned outside the west diaphragm wall along Keelung Road yielded measurements of the settlement profile at every stage of excavation as shown in Fig. 9. Using this information, an immediate assessment of the differential settlement occurring in a major road adjacent to the excavation could be made. Analysis indicates that the maximum settlement is about 85% of the maximum lateral wall deflection. This is quite different from what one normally assumes for clay deposits, that the maximum settlement is approximately the same as the maximum wall deflection (Ref. 6). It suggests that the soil deposits in the K1 zone are quite silty in nature. Thus, using deflection curves to estimate settlement profile such as one proposed by MILLIGAN (Ref. 6) needs more care.

Heave measurement at the base of excavation provides an indication of the bottom stability of the excavation. Maintaining a good record of heaving is usually difficult since heave stakes are normally susceptible to damage by heavy equipment used in excavation. In this project, the results of heave measurements at 3 locations within the excavation are plotted in Fig. 10. The plot shows a gradually increasing amount of heave from nil at the start of excavation to a maximum heave of about 7 cm after the final excavation stage. In general, when the excavation work is well-instrumented and monitored, the factor of safety adopted in a design could be marginal.

Earth pressure and groundwater pressure

The total horizontal earth pressure was measured prior to excavation (Fig. 11). The figure indicates that the measured total horizontal stresses before excavation are very close to the theoretical values estimated by using an effective angle of shearing resistance equal to 30 degrees (Ref. 7).

During each stage of excavation, measurements of the total horizontal earth pressure were taken. The results are shown in Fig. 12. The total horizontal earth pressure distribution computed using total stress analysis and neglecting the effect of wall adhesion are also shown for comparison with the measured values. In the passive side, the theoretical distribution greatly overestimates the total horizontal earth pressure at all stages of excavation. In the active side, however , the computed total horizontal earth pressure distribution appears very close to the average measured values. Earth pressure measurements further revealed that there was a decrease in the total horizontal earth pressure in the active side during excavation.

In order to analyze the effect of wall adhesion, the total horizontal earth pressure measurements at the final excavation stage are plotted in Fig. 13. In the figure, two curves representing the computed total horizontal earth pressure distribution are also shown. The dashed lines correspond to the case assuming that a wall adhesion equal to half the undrained shear strength was mobilized. The solid line on the other hand, refers to the case neglecting any effect of wall adhesion. The figure suggests that the wall adhesion in the active side of the excavation was mobilized during excavation while in the passive side, full mobilization of the wall adhesion was not attained. It should be noted that the distribution of earth pressure during excavation is critical to the design and construction of retaining and strutting systems. The monitoring results strongly suggest that the wall adhesion has to be taken into account in estimating earth pressures during excavation.

In Fig. 14, the groundwater pressure distributions measured at different stages of excavation are presented. The general trend in both sides of the excavation are similar in that the groundwater pressure tend to decrease with excavation. The variation in the active side was however more moderate, and the groundwater pressure distribution during all stages of excavation has remained below hydrostatic. A more indepth analysis of the results in the passive side revealed that the decrease in pore water pressure during excavation was lesser than the change in the total vertical stress. This suggests that significant amount of shear-induced pore pressure has developed during excavation. The real mechanism which can explain this phenomenon is complicated, and the prediction of the shear-induced pore pressure is quite difficult to carry out at this point. This subject deserves further research.

The measured groundwater pressures could be used along with the measured total horizontal earth pressures to derive the corresponding horizontal effective stresses developed during excavation. The vertical effective stresses could also be derived from the unit weight of the soil in each layer. Thus, the effective stress paths followed by soil elements at different points on both sides of the excavation could be determined as illustrated in Fig. 15.

Understanding the stress paths followed by soil elements during excavation is a very critical issue in which the data obtained in this project could be of utmost importance. There are not many projects which have such good earth pressure and pore pressure records as this one. Further studies on the fundmentals of deep excavation are being carried out by the authors' organization in cooperation with the Massachusetts Institute of Technology.

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TABLE 1

Function of Instrumentations

Stage	Function
Design	Establish initial conditions Proof testing Design for impending failure / danger
Construction	Safety control Construction control Data for construction dispute Assisting engineering judgement
After construction	Safety during life of structure Evaluation of reliability of theory and design method Evaluation of building regulations and specifications

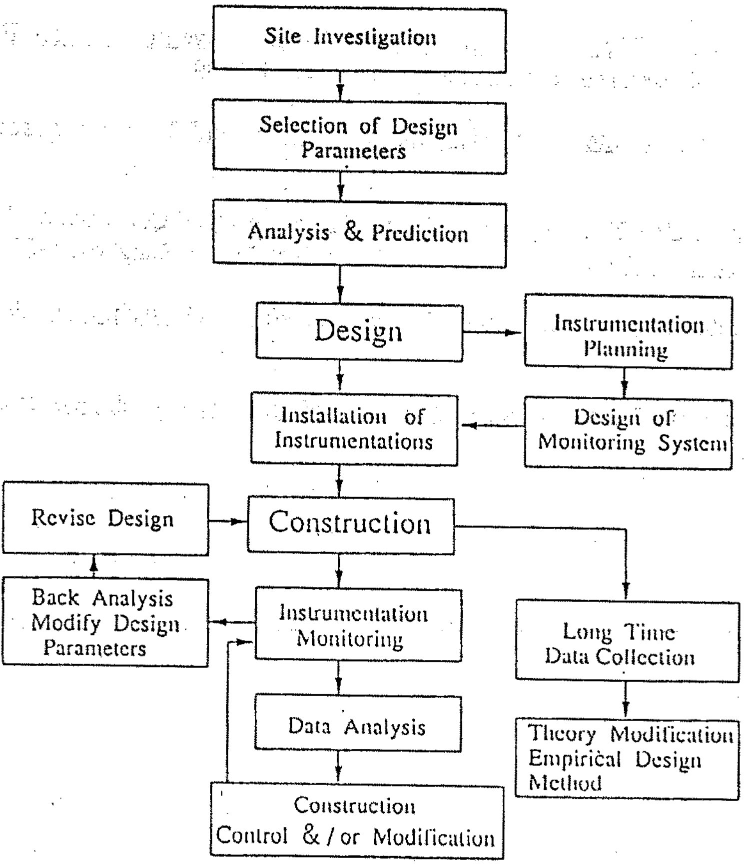


Fig. 1 Flow Diagram of Design and Construction of An Excavation

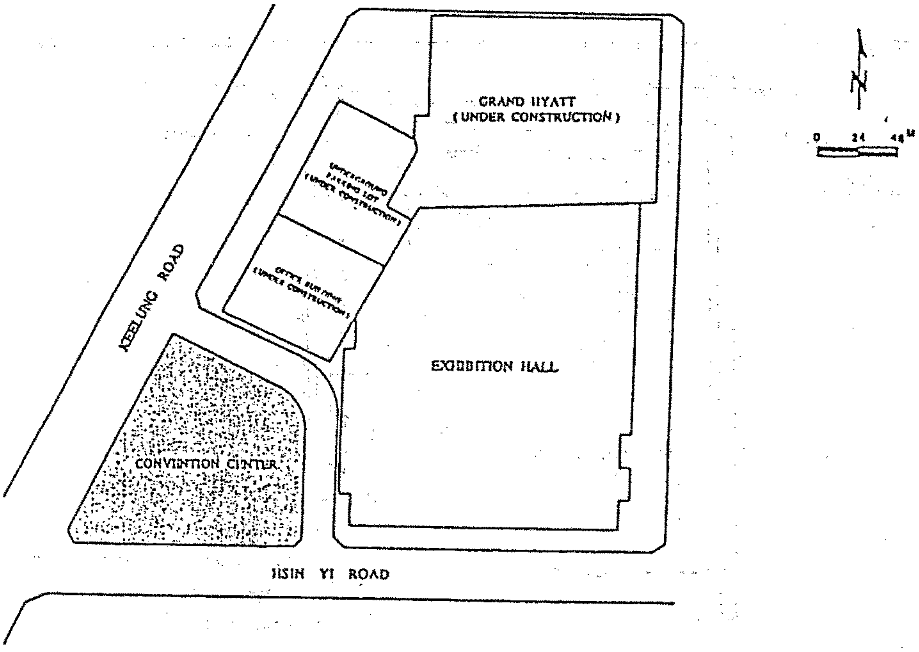


Fig. 2 Location Plan of Case Study

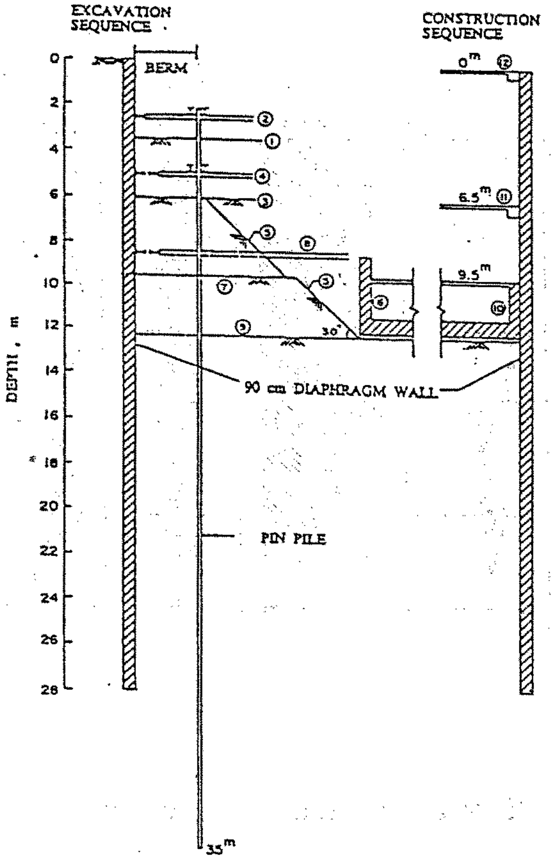


Fig. 3 Profile of Excavation and Bracing

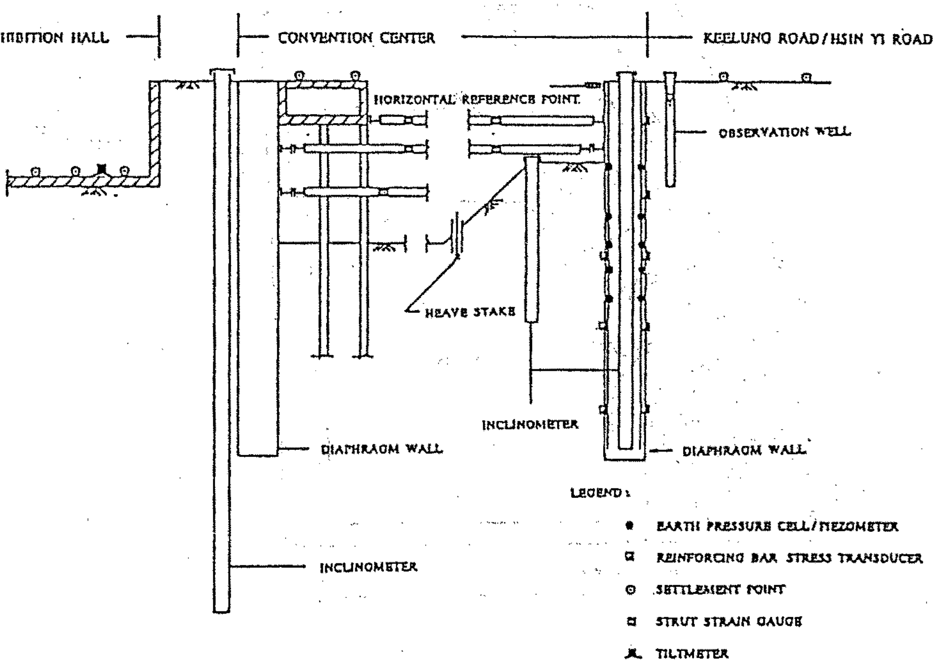


Fig. 4 Section Showing Instrumentations

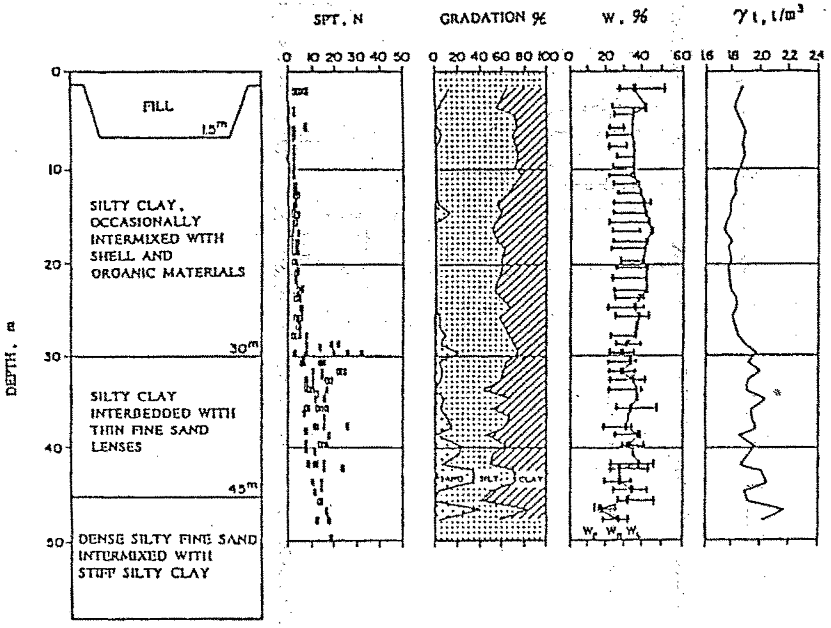


Fig. 5 Typical Soil Profile and Properties

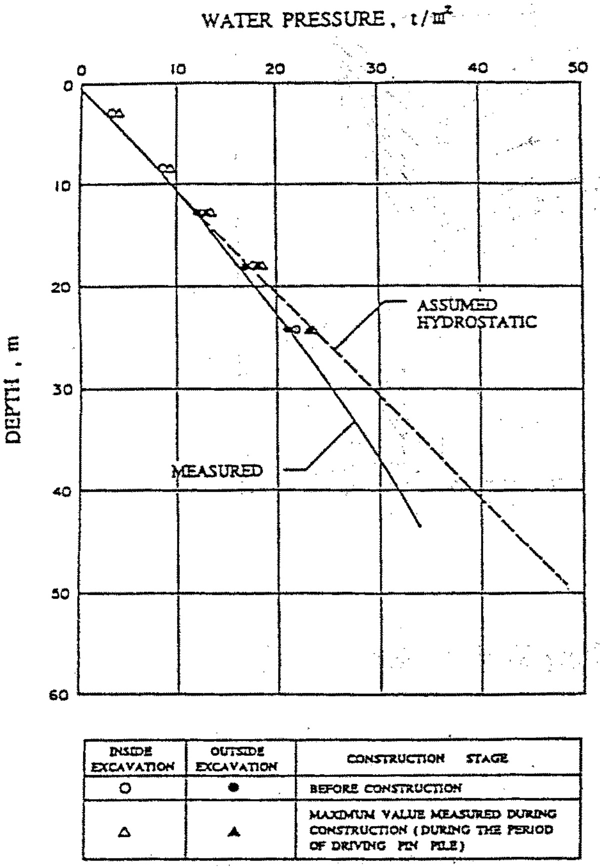


Fig. 6 Groundwater Pressure Distribution before Excavation

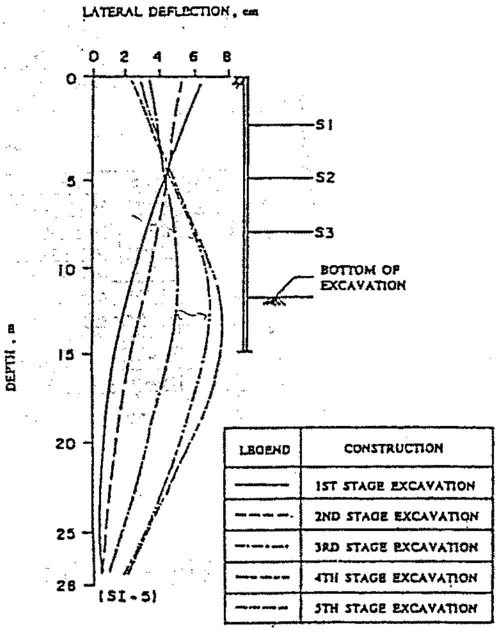


Fig. 7 Variation of Lateral Deflection of Diaphragm Wall

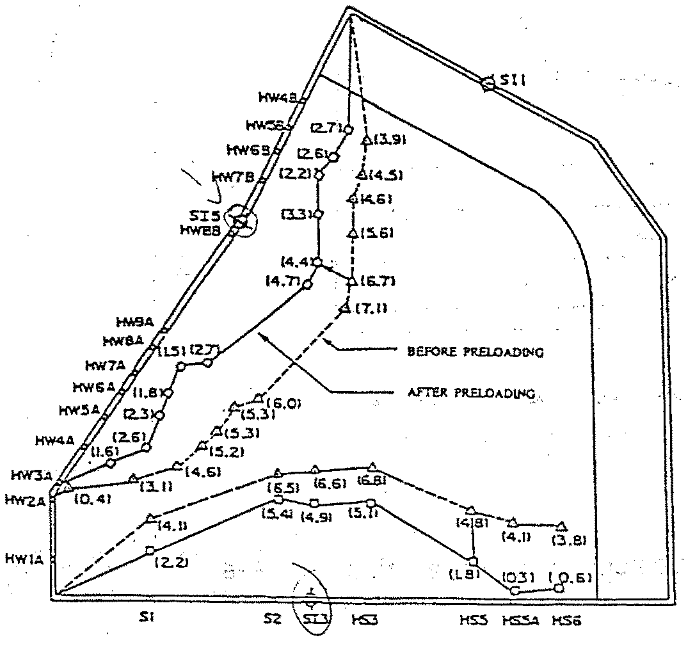


Fig. 8 Lateral Movement of Top of Diaphragm Wall Before and After Preloading of First Layer Strut

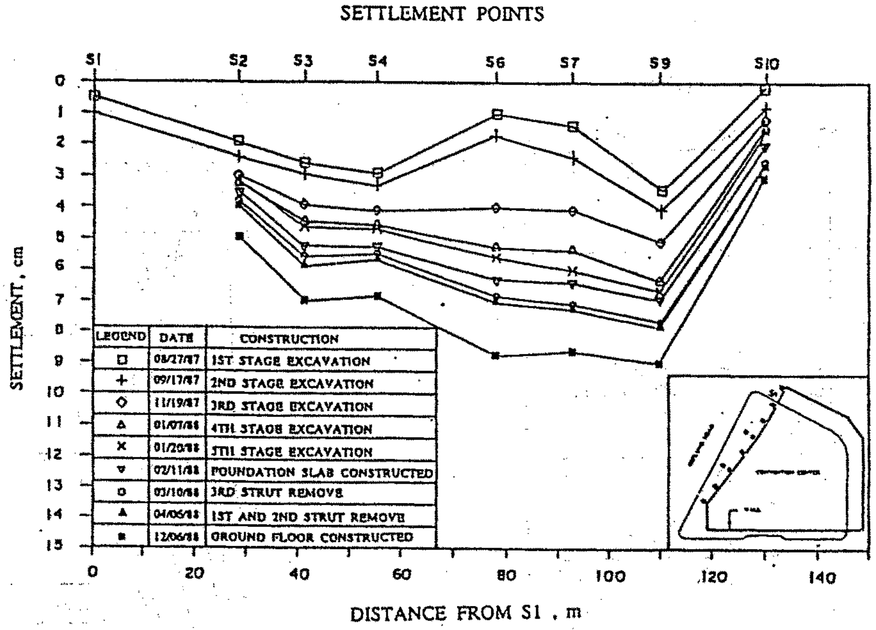


Fig. 9 Settlement Profile Along Keelung Road

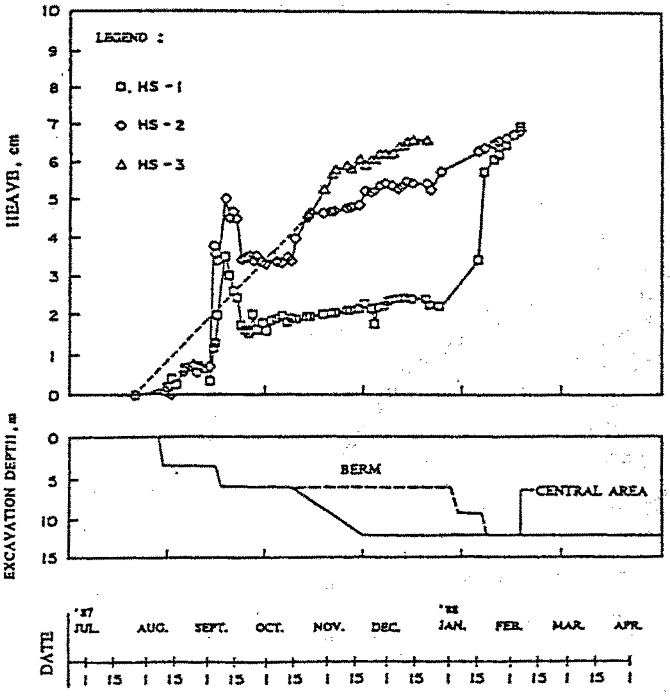


Fig. 10 Heave Measurement during Excavation

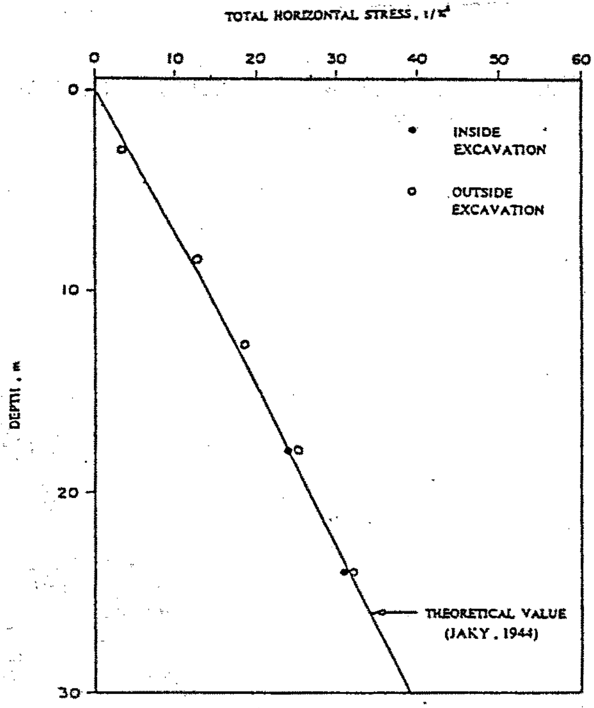


Fig. 11 Total Horizontal Stress Distribution before Excavation

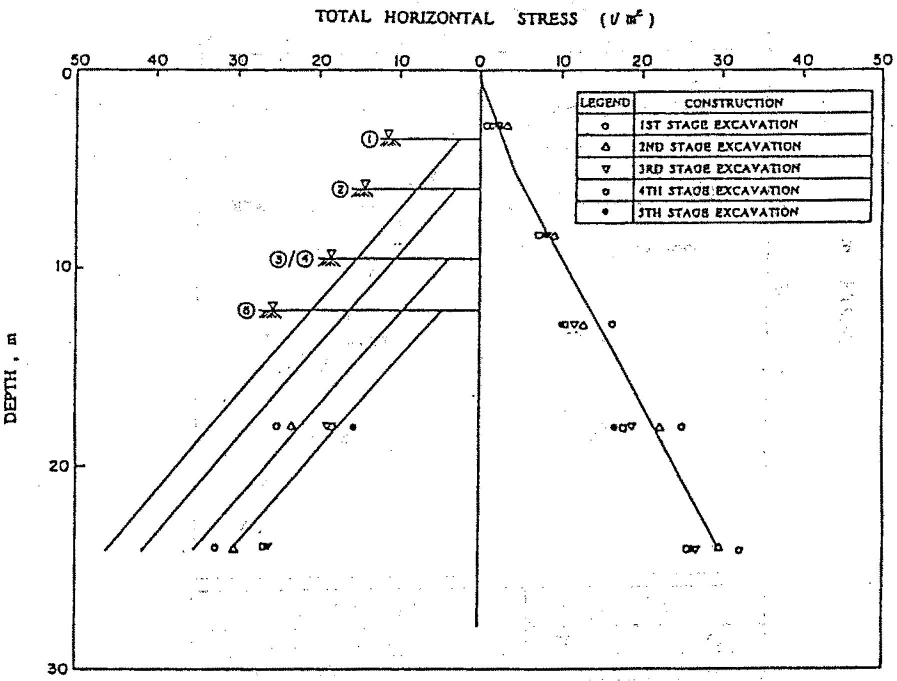


Fig. 12 Horizontal Stresses at Various Stages of Excavation

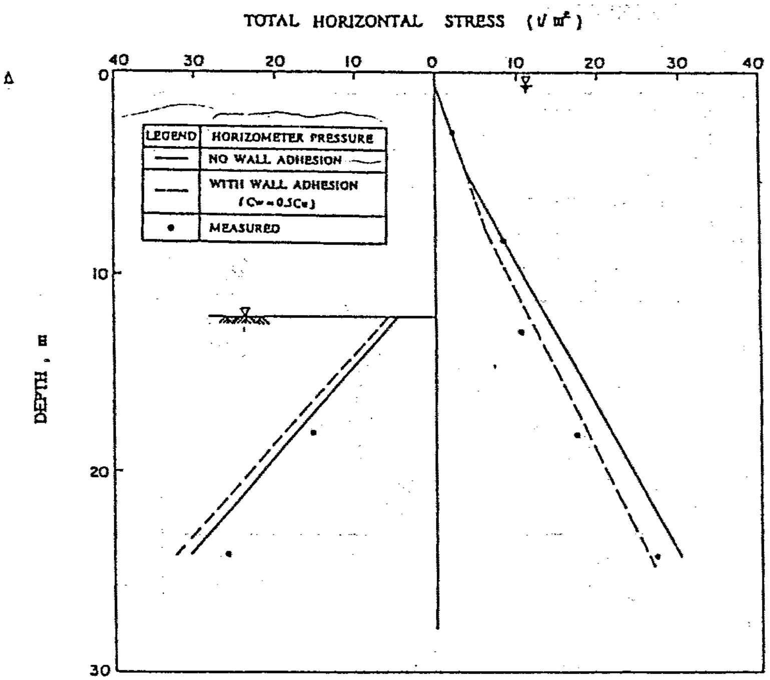
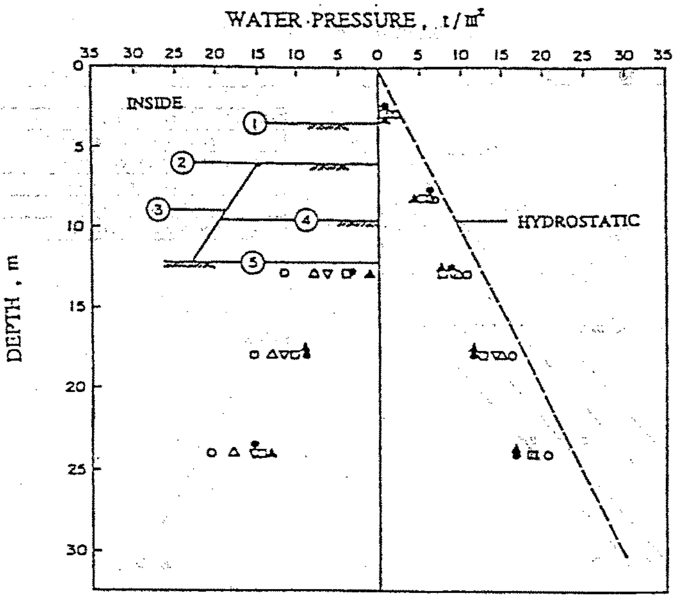


Fig. 13 Horizontal Stresses with and without Wall Adhesion at Final Stage of Excavation



LEGEND	DATE	CONSTRUCTION
○	08/07/87	1ST STAGE EXCAVATION
△	09/04/87	2ND STAGE EXCAVATION
▽	11/23/87	3RD STAGE EXCAVATION
□	01/08/88	4TH STAGE EXCAVATION
▲	01/18/88	5TH STAGE EXCAVATION
●	07/01/88	CONSTRUCTION OF THE GROUND FLOOR

Fig. 14 Groundwater Pressure Distribution at Various Stages of Excavation

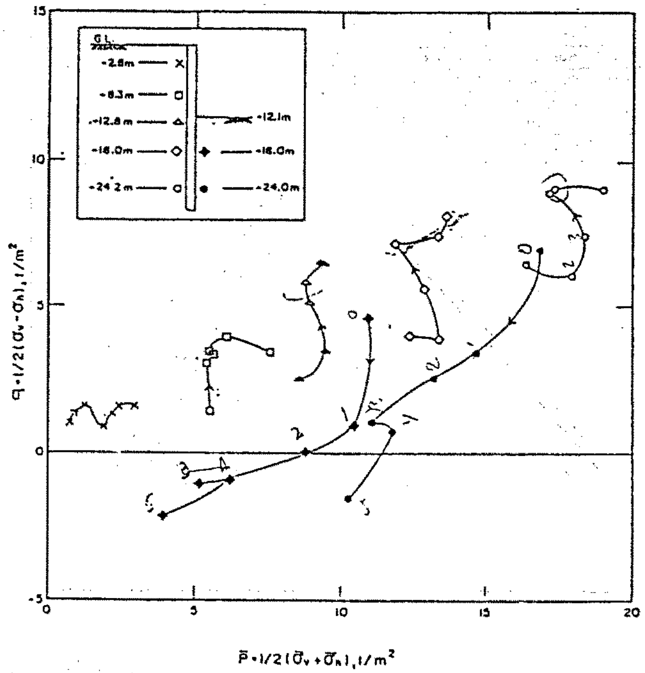


Fig. 15 Effective Stresses of Soil Elements during Excavation