RECENT DEVELOPMENTS IN DEEP EXCAVATION IN SOFT GROUND

by

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SUMMARY

This paper describes some of the most recent advancements in the field of deep excavation. Major developments in design and construction of infrastructures involving deep excavations are described with reference to the current practice in Taipei. The influence of groundwater pressure on excavation performance, development of earth pressures, behavior of retaining wall, induced ground surface settlement and building protection concern during excavation are discussed. Instrumentation monitoring is emphasized as an essential factor in ensuring safety during construction and in enhancing the existing database which forms a valuable basis in further developing the techniques.

KEY WORDS: Deep Excavation, Instrumentation, Monitoring, Earth Pressure, Building Protection

1. INTRODUCTION

During the last few years, geotechnical engineering practice in Taiwan has been marked by dramatic advancements in the field of deep excavation. With the advent of large infrastructure projects such as the Taipei Rapid Transit Systems (TRTS) involving large amount of deep excavation works, design and construction techniques have been much refined. Extensive soil investigation, advanced research on soil behavior and well-conducted back-analyses were key factors in achieving the current state-of-the-art. This paper summarizes the most recent findings in geotechnical engineering as related to deep excavation. Discussions will focus on the current practice in Taipei with reference to major technical developments brought about by the construction of the TRTS.

2. BACKGROUND

Deep excavations, especially in soft soil deposits are supported by certain forms of retaining systems such as diaphragm walls, sheet piles and soldier piles with lagging. These retaining structures are prevented from experiencing significant deflections or collapse by internal bracings in the form of struts or by using the tie-back system of support.

The choice of an appropriate retaining system depends on certain factors such as subsoil characteristics, groundwater conditions and building protection considerations. If an excavation site is underlain by relatively permeable layers of soil with high groundwater table, a watertight retaining structure should be used. If the area adjacent to an excavation is occupied by sensitive structures or several multi-storey buildings, the retaining structure should have enough rigidity to prevent excessive wall deformation that could cause considerable ground movements and consequent damage to structures.

Considering the type of soil, groundwater conditions and existence of many buildings in Taipei, diaphragm walls have been widely adopted as the retaining structure for most buildings as well as for the TRTS cut-and-cover structures due to its high rigidity and watertightness. Sheetpiles are used for relatively shallow excavations such as for ancillary structures of the TRTS which include ventilation shafts and station entrances. Soldier piles with lagging are mostly adopted in areas underlain by relatively thick gravel deposits. Behavior and performance of internally-braced retaining systems depend on factors such as method of construction, preloading of struts, groundwater control, and so on.

There are three alternative methods of construction which are commonly used. These are the bottom-up, the top-down and the semi-top-down methods of construction. The bottom-up method is considered the "conventional" method of construction. The method has been used in many construction projects such as the Taipei World Trade Convention Center as described by Moh and Chin (1991A). Construction of the 13-storey CPH Building in Taipei (Moh and Hwang, 1993) typifies a case where the top-down method is used. The semi-top-down method was adopted in some TRTS stations.

3. MONITORING SYSTEM

Due to limitations in the current state of knowledge in soil mechanics and the complex nature of soil behavior, design of excavation, including the support system, still heavily relies on semi-empirical approaches. Use of instrumentations to monitor the performance of excavations should be considered as an essential element of the total technique. The functions of instrumentation are summarized by Moh and Chin (1991A) as shown in Table 1.

For very large excavation projects such as the TRTS, design can at most be based only on certain simplified assumptions regarding the nature of the ground behavior of the soils (Moh and Chin, 1991B). It is not possible to design for every conceivable condition. It is inevitable that conditions in the field could be quite different from that expected. In order to maintain good engineering practice through both design and construction stages, the implementation of an appropriate geotechnical instrumentation and monitoring system for the TRTS is considered critical.

A large variety of monitoring devices have been specified for the TRTS project. These include almost every instrument available in the international market to measure groundwater pressures, displacements, settlements, stresses and loads (Table 2). The general specifications require that all instruments must be able to provide adequate capacity to cover the ranges in magnitudes of the parameters to be monitored, supply reliable data for the duration of excavation and construction, and be readily recalibrated, maintained and repaired. A typical instrumented excavation section of the TRTS is shown in Fig. 1. Due to the large volume of monitoring works involved for the TRTS, an efficient system to collect, transmit, store, and analyze the monitoring data is very important. A data processing system consisting of an Integrated Data Storage Center which links with the many monitoring stations at different sites of the TRTS Network has been set. This instrumentation monitoring processing system is illustrated in Fig. 2.

4. GROUNDWATER CONCERN

During excavation, various groundwater-related problems need to be considered depending upon the nature of soil deposits and geometry or configuration of the underground structure (Chin et al., 1991). Where the materials below the excavation base are permeable and extend to below the toe of the diaphragm wall, groundwater control is required to prevent significant upward flow from outside of the excavation which could cause "piping" (Fig. 3A). If the materials below the excavation level are impermeable, there must be enough weight of soil to form a clay plug to prevent "blow-in" failure of the excavation base (Fig. 3B). Flotation of buried permanent structures must also be considered in design. The influence of groundwater pressure in determining the required diaphragm wall depth for deep excavation is illustrated in Fig. 4 (Wong et al., 1993).

Groundwater pressure is critical with respect to the diaphragm wall performance and thus with the ground settlement adjacent to excavations. Since majority of deep excavations are supported by internally-braced diaphragm walls, the stability and deflection of these walls depend on the bracing system and on the strength of the soil, especially in the passive zone. The passive strength of the soil is dictated by pore water pressure. The effect of water pressure on strength is more significant when the soils in the passive zone consists of silty and/or sandy materials. The design of a wall assumes a water pressure distribution within the passive zone which in many cases requires lowering of water pressures below the naturally occuring water levels. If the assumed water pressures are not achieved, then the soil in the passive zone is weaker, and as a result, the deflections of the wall will be greater than that anticipated by the design. In this case, ground movements and settlements around the excavation can adversely affect a greater number of adjacent buildings than expected. The significance of the effect of variation in water pressure conditions in the passive zone on wall deformation is illustrated in Fig. 5 (Moh et al., 1989). As indicated by the results of analyses, the maximum deflection associated with the higher water pressure profile (U2) is approximately 1.5 times greater than the case for the lower water pressure profile (U1).

In cohesive soils, the degree of swelling of the deposits below excavation level controls the passive resistance of the soil and thus influences the performance of the diaphragm wall. During excavation, a negative excess pore pressure increment will be induced in the passive zone. Swelling and strength reduction will then take place with time, depending on the soil properties, stratigraphy and length of time that the excavation is open. Provided the degree of swelling can be estimated, the shear strength reduction in the passive zone can be reasonably estimated using the SHANSEP approach (Ladd and Foott, 1974). It should be noted that the coupled swelling and transient flow due to pumping is very difficult to analyze reliably. Due to the uncertainty in estimating the degree of swelling and its significant influence on wall deflection, pore water pressures in the passive zone must be continuously monitored during excavation.

There are a number of different approaches which can be used to overcome problems associated with high ground water pressures. Reducing groundwater pressure by pumping from wells, reducing the permeability of the ground by grouting or creating complete or partial cut-off zones, and carrying out the excavation underwater by casting the base slab using tremie method, are three of the major methods in dealing with high groundwater pressures during excavation.

5. EARTH PRESSURES

Understanding the porewater and earth pressure development during excavation can be considered as the most vital aspect of excavation, yet there remains a major uncertainty in the current state of knowledge in excavation. As mentioned earlier, it is essential that both water pressures and earth pressures be monitored during excavation. Significant information can be derived from earth pressure/piezometer cells installed in both the active and passive faces of diaphragm walls. With available good monitoring data, total and effective stress paths for soil elements adjacent to walls can be developed based on these data which can provide useful insights on actual soil behavior and shearing mechanisms during excavation.

Idealized stress paths for typical soil elements in the active and passive zones have been presented by Lambe (1970) which are illustrated in Fig. 6. It should be appreciated that the stress paths shown in the figure are simplified and that actual stress path behaviors can vary. Based on analyses for Taipei soils (Chin et al., 1991), the stress paths for excavation in clay indicate a decrease in both horizontal and vertical stresses in the passive side during excavation. Furthermore, swelling appears to occur as the excavation proceeds since the effective stress path does not exhibit a significant negative water pressure. In the analysis for sandy soil, it is found that the effective stress path proceeds downwards to the left as excavation progresses. The water pressure on completion of excavation is consistent with a hydrostatic water pressure distribution with respect to the excavation base. In this case, complete swelling occured during construction and water pressures in the passive zone can be readily described in terms of steady state seepage.

It has been considered that during the development of earth pressures during an excavation, wall friction develops to a certain degree which cannot be easily quantified. In design, the commonly adopted assumption is that the vertical pressures on the two sides of the retaining walls for braced excavations are equal to the overburden pressures. Theoretically, however, the total vertical stresses can vary because of the existence of wall friction. A recent case study (Moh and Hwang, 1993) indicates that in soft to medium stiff sites, it seems reasonable to assume that the angle of wall friction is equal to the angle of internal friction of the soils when used in computing the limiting earth pressures. However, it should be noted that earth pressure is also a function of wall deflection and the limiting active and passive pressures will develop only when wall deflection is sufficiently large.

6. WALL DESIGN CONSIDERATIONS

One of the most significant factors to be considered in the design of diaphragm walls is the definition of soil strength, particularly in the passive zone. Since soil strength is controlled by effective stress, accurate assessment of porewater pressures throughout the construction period is required. This is an extremely difficult problem since the porewater pressure regime that develops in the vicinity of an excavation during construction will be the result of a number of independent processes. A full analysis would have to include the combined effects of swelling, unloading, shear-induced porewater pressure, transient flow leading to steady state flow, and measures to control ground water pressures. Such analysis are not warranted given the uncertainties involved in terms of selection of soil parameters and stratigraphic model, numeric modelling, etc. A simplified approach which basically involves only an assessment of swelling can be adopted as deemed appropriate for the type of soil in the Taipei Basin.

In Taipei soils, where excavations will be in deep deposits of soft clays, analyses based on previous works indicate that little or no swelling occur at the time the excavations remain open. Design has been based on undrained strength which implicitly includes shear-induced porewater pressures. In these cases, the effects of groundwater control measures are not directly relevant for wall design; however, such measures are still required in some cases for the control of blow-in.

In the more permeable layers where thick sands are present, it is expected that complete swelling can occur during construction. As a result, effective stress strength parameters are used in wall design. Pore water pressures are predicted assuming that steady state conditions will develop with boundary conditions that reflect the imposed effect of groundwater control measures on the in-situ water pressure regime. The effect of shear-induced porewater pressures is ignored.

The approach described above is highly simplified. Given the silty nature of the Taipei soils together with likely differences between assumed and actual stratigraphy, predicted porewater pressures will not likely be realized in many cases. Thus, monitoring of porewater pressures throughout the construction period will be essential.

7. SETTLEMENT IN ADJACENT AREAS

Excavations in urban areas necessitate a good prediction of adjacent ground settlements. Field monitoring data from previous wall-supported excavations in local soils form a valuable basis for evaluating wall performance and predicting the behavior of future excavations. A very useful method to study such problem is through development or use of a sophisticated finite element program to simulate and predict the behavior of excavation. In a recent study, Whittle et al. (1993) describes the application of a finite element analysis for modelling the top-down construction of a seven-storey, underground parking garage at Post Office Square in Boston. The analysis incorporates coupled flow and deformation within the soil, for real time simulation of construction activities, a numerically accurate algorithm for excavation in non-linear soil, and advanced constitutive modelling of clay behavior. The results demonstrate that reliable and consistent predictions of soil deformations and transient groundwater flow can be achieved in a single analysis without recourse to parametric iteration.

In Taipei, where the area is underlain by relatively sandy materials, maximum wall deflections are as high as about 0.5 percent of the maximum excavation depth (Chin et al., 1991). In areas underlain by deep deposits of soft clay, maximum wall deflections are greater at 0.50 to 0.75 percent of the maximum excavation depth. The maximum ground surface settlement is related to the maximum wall deflection. In the more sandy area, maximum ground surface settlement is about 50 percent of the naximum wall deflection. In the clayey area, this ratio is jenerally higher at about 75 percent.

Predicting whether buildings adjacent to excavations are bound to suffer damage requires a more careful assessment than merely knowing how much maximum settlement will occur due to excavation. This is a soil-structure interaction problem. It should be realized that in usual cases, it is the differential settlement and distortion which are more likely to cause damage to building structures than simply the magnitude of the maximum or total settlement. Thus, knowledge of settlement behavior likely to be induced by excavation in a particular type of soil deposit is essential. Reliable information on such behavior can only be obtained from a reasonably large amount of reliable data taken from previous monitored excavation projects. In Taipei, available data from previous experience still remain only indicative; the existing database certainly require consistent updating. Carefully selected data from previous monitored deep excavations in the more sandy area in Taipei (Wong and Patron, 1993) shows a settlement behavior as given in Fig. 7. This figure provides useful information in deciding a reasonable "influence zone" for use in design, within which, significant ground settlements can occur and where instrumentation and monitoring should be considered critical during an excavation. As observed in the figure, significant change in the slope of settlement troughs occur within about 1.5 to 2.0 times the maximum excavation depths.

8. BUILDING PROTECTION

In deep excavations, ground movements are inevitable due to relaxation of stresses as the retaining wall moves and/or lowering of groundwater as a result of seepage flow below the toe of retaining wall and/or leakage through wall membranes leading to consolidation of mainly clayey deposits. In urban areas, ground movements often become one of the major concerns during excavations because of the presence of numerous structures in close proximity to the site. Building protection, in a broad sense, includes all the measures taken in both design and construction stages. Major steps in the process of building protection include risk assessment, precautionary measures, instrumentation and monitoring, and remedial measures.

The main basis in working out building protection programs for an excavation project is the definition of the "influence zone" as previously described. Design practice in Taipei uses an influence zone as illustrated in Fig. 8. Based on previous local case records of building and structure damages caused by adjacent excavations or by adopting information from reliable published literature such as that provided by Burland and Wroth (1974), settlement criteria for building protection can be set. In the TRTS design for example, limits on total settlement generally vary from 25 mm for normal structures on footings to 50 mm for frame buildings on mat or piles. Differential settlements are generally limited to 1/500 for the former and 1/300 for the later. Considerations are also given to age, quality of construction and/or conditions of structures.

Several measures of building protection are illustrated in Fig. 9 (Wong et al., 1993). Recent experience in Taipei indicates that the most effective measures of reducing damage potential to structures adjacent to excavations is by reducing ground movements at the source (Moh et al., 1994). Significant reduction in wall deflection can be achieved by preloading the struts. Further reduction can be achieved by improving the soils inside the excavation such as forming buried struts or grout slabs by jet grouting.

9. CONCLUSIONS

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. Use of instrumentations to monitor the performance of excavations should be considered as an essential element of the total technique. Even with the current state of knowledge and most modern soil investigation techniques, uncertainties in geotechnical engineering will exist. Previous experience is necessary for good design yet this may not be sufficient as a tool to guarantee excellent performance. Different soil conditions exist at different locations. Moreover, construction practice varies from one locality to another. Therefore a deeper and insightful understanding of the performance of deep excavations is imperative. Use of a sophisticated constitutive model in an advanced finite element program to treat deep excavation as a typical boundary value problem, such as demonstrated in the study on the Boston's Post Office Square provides a very encouraging role model in fulfilling this objective.

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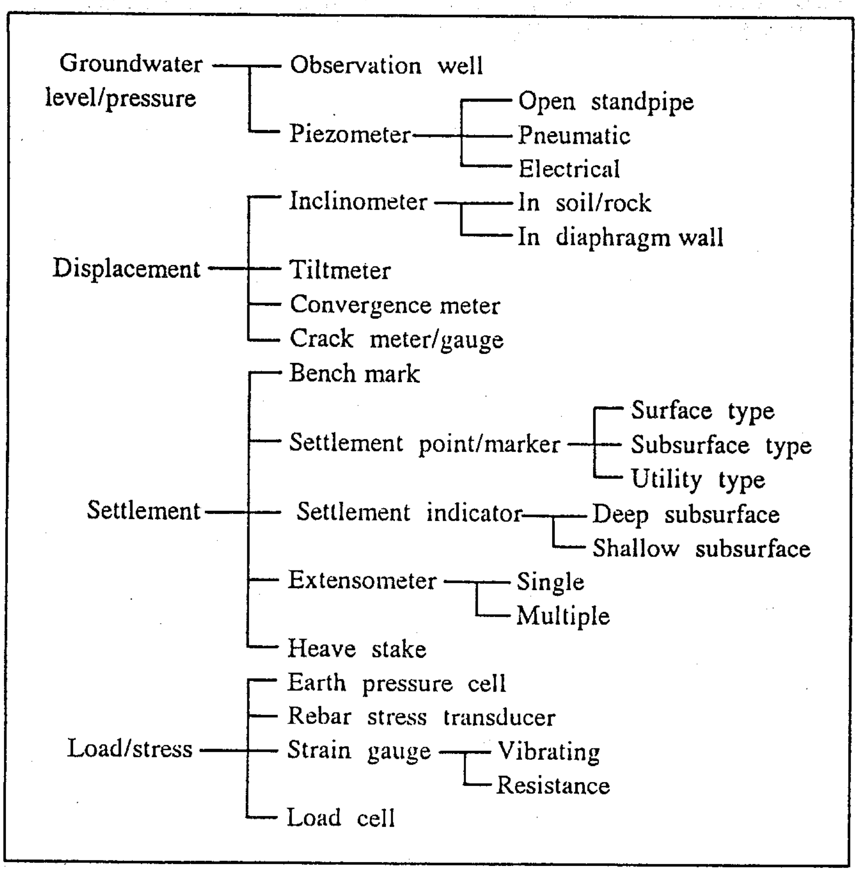
Table 1 Functions of Instrumentation (after Moh and Chin, 1991A)

Stage	Function
Design	Establish initial conditions Proof testing Design for impending failure / danger
Construction	Safety control Construction control Data for contruction 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

Table 2 Instruments Used in TRTS Construction (after Moh and Chin, 1991B)



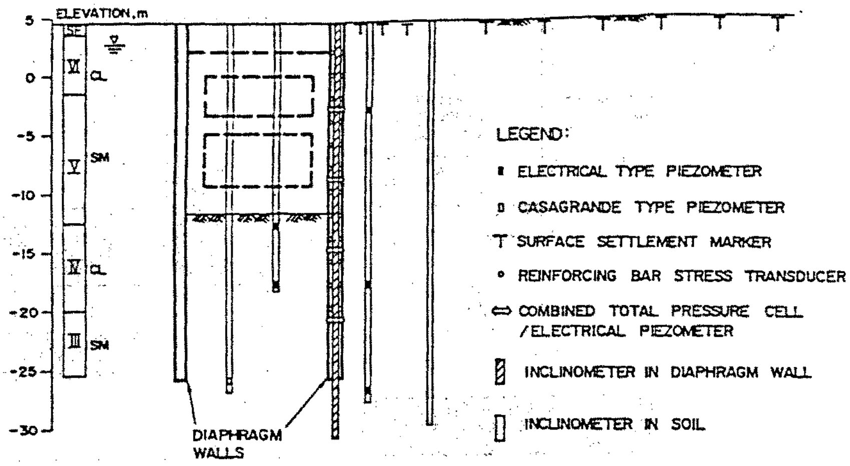


Fig. 1 Typical Instrumented Section (after Moh and Chin, 1991B)

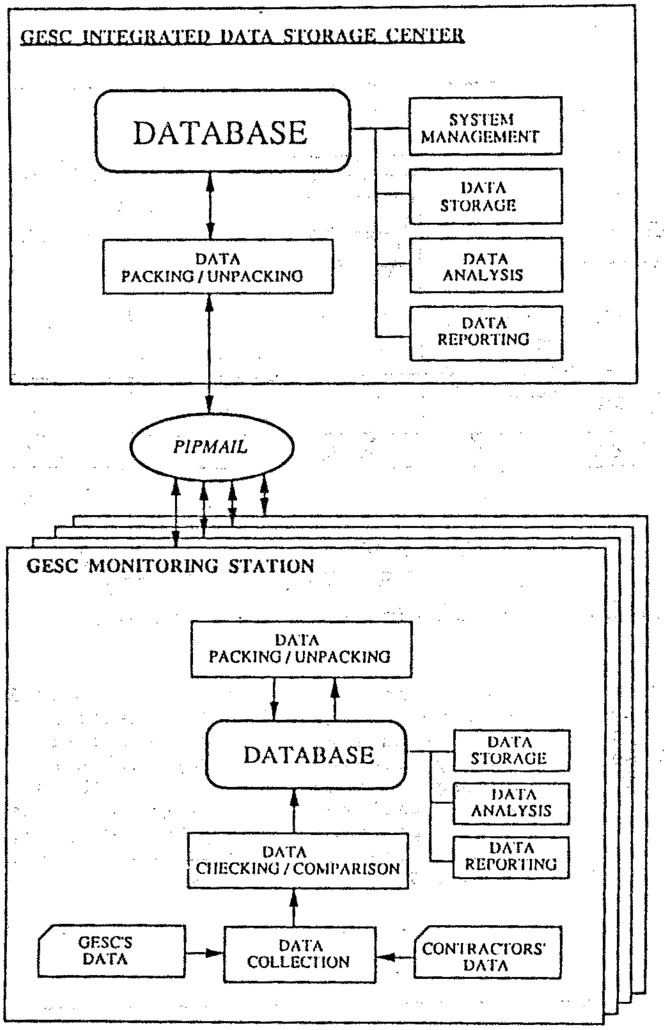
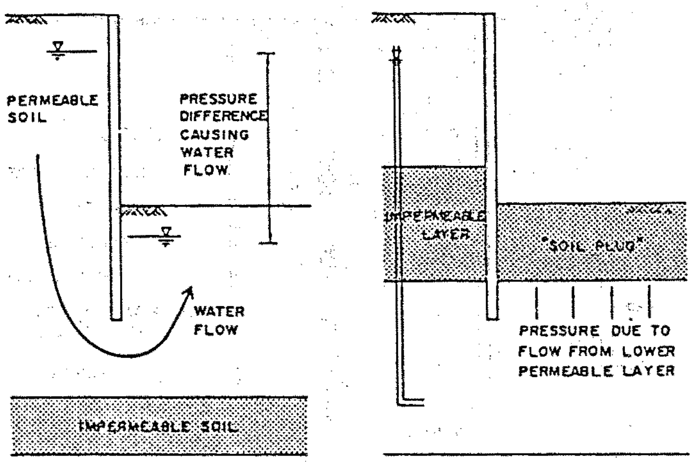
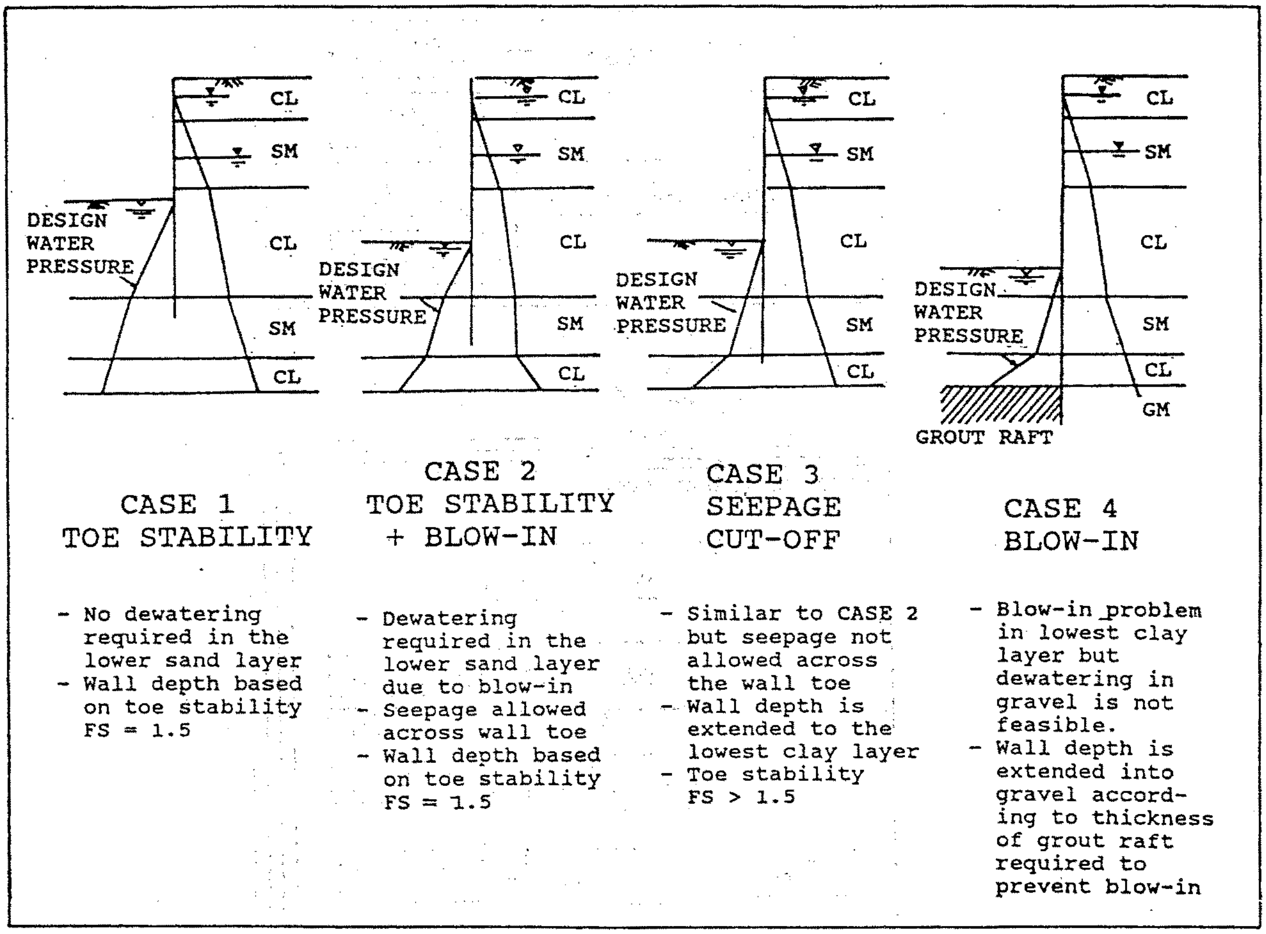


Fig. 2 Data Processing System of TRTS Geotechnical Instrumentation and Monitoring Program (after Moh and Chin, 1991B)



A. "PIPING" B. "BLOW-IN"

Fig. 3 Conditions of Piping and Blow-in (after Chin et al., 1991)



CASE 1
TOE STABILITY

- No dewatering required in the lower sand layer
- Wall depth based on toe stability FS = 1.5

CASE 2
TOE STABILITY + BLOW-IN

- Dewatering required in the lower sand layer due to blow-in
- Seepage allowed across wall toe
- Wall depth based on toe stability FS = 1.5

CASE 3
SEEPAGE CUT-OFF

- Similar to CASE 2 but seepage not allowed across the wall toe
- Wall depth is extended to the lowest clay layer
- Toe stability FS > 1.5

CASE 4
BLOW-IN

- Blow-in problem in lowest clay layer but dewatering in gravel is not feasible.
- Wall depth is extended into gravel according to thickness of grout raft required to prevent blow-in

Fig. 4 Effect of Water Pressure on Wall Penetration Depth (after Wong et al., 1993)

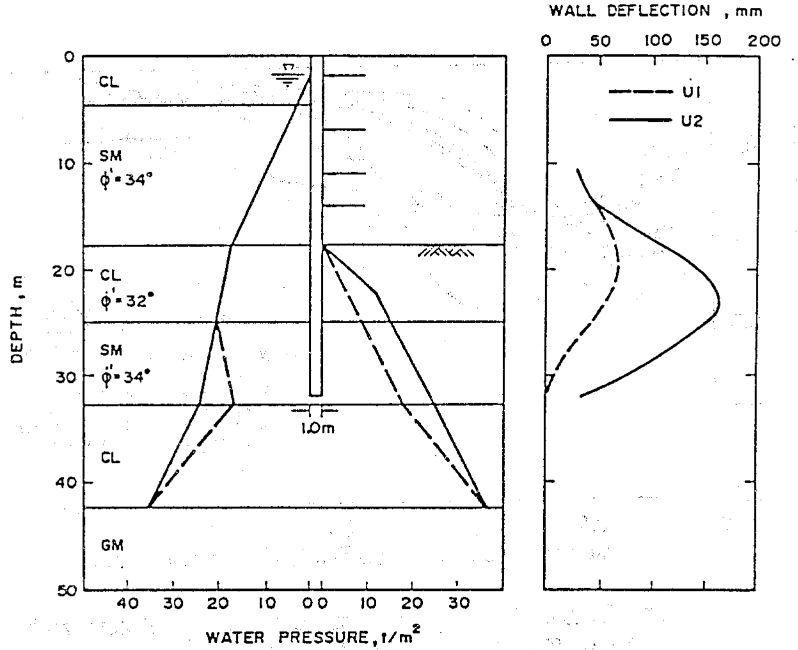
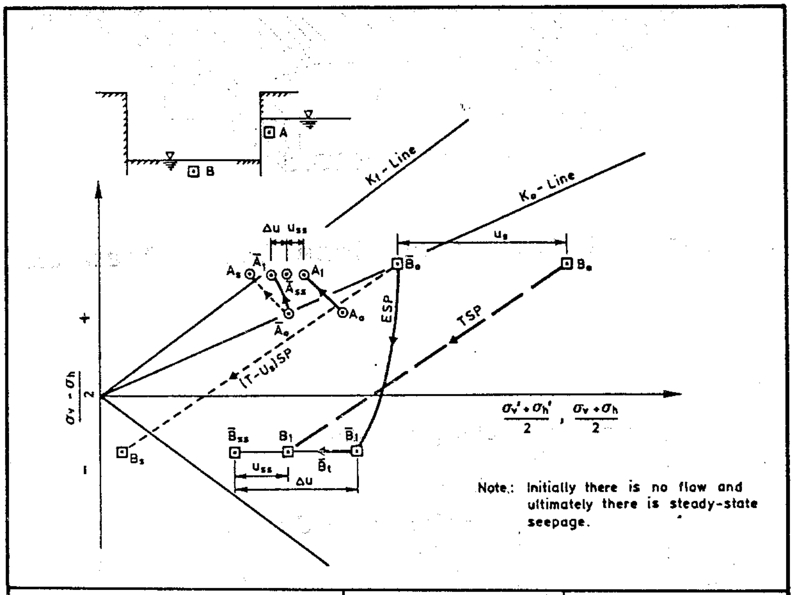


Fig. 5 Effect of Water Pressure on Wall Deflection (after Moh et al., 1989)



Stresses and Strains for Soil Elements near an Excavation	Soil Element A	Soil Element B
Initial (Static) Pore Pressure, u_s	$A_0\bar{A}_0$	$B_0\bar{B}_0$
Pore Pressure at Steady-state Flow, u_{ss}	$A_1\bar{A}_{ss}$	$B_1\bar{B}_{ss}$
Pore Pressure upon Unloading	Decreases	Decreases
Pore Pressure during Consolidation	Decreases	Increases
Strain upon Unloading	Vertical compression	Vertical extension
Strain during Consolidation	Vertical compression	Vertical extension
Undrained Shear Strength during Consolidation	Increases	Decreases

Fig. 6 Stress Paths for Soil Elements in an Excavation (after Lambe, 1970)

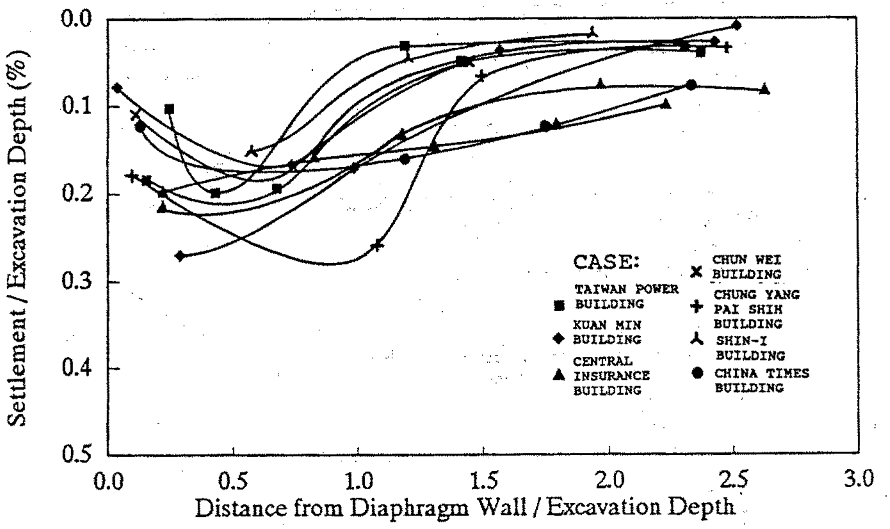


Fig. 7 Settlement Adjacent to Deep Excavations in the T2 Zone of the Taipei Basin (after Wong and Patron, 1993)

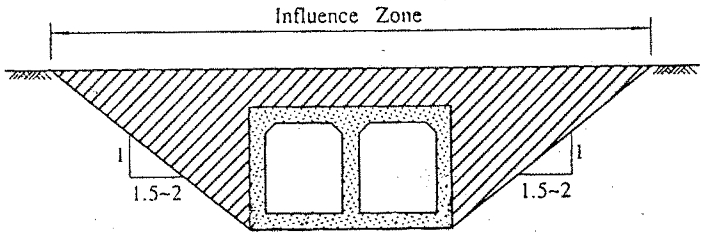


Fig. 8 Typical Influence Zone for a Deep Excavation

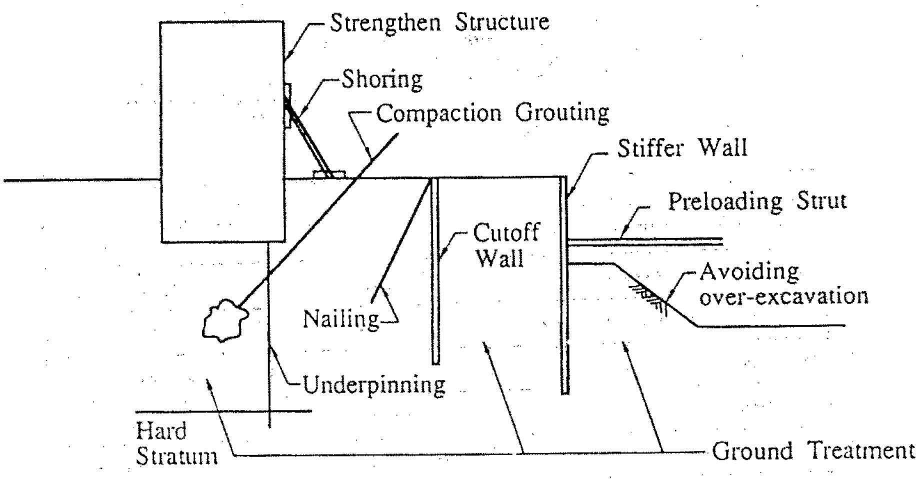


Fig. 9 Concept of Building Protection (after Wong et al., 1993)