GEOTECHNICAL CONSIDERATIONS FOR UNDERGROUND MASS RAPID TRANSIT SYSTEMS

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SYNOPSIS: As results of rapid economic developments in the last two decades, improvement of infrastructure systems becomes one of the major development tasks for many metropolitan areas. Construction of new mass rapid transit systems or extension of existing systems is the most effective way to alleviate the ever growing urban traffic problem. Geotechnical engineering plays a critical role in the implementation of such systems, particularly for the underground systems. On the other hand, construction of such systems results in significant improvement in the local geotechnical practices. This paper uses the Taipei Rapid Transit Systems which is at present under construction to illustrate some of the more significant geotechnical concerns associated with underground rapid transit systems in soft ground. Discussions are made on the effects of groundwater lowering and recovery, regional subsidence, soil liquefaction, and presence of gas. For cut and cover construction, considerations on strength characterization, swelling in the base of excavation, pore water changes during construction, and wall friction are elaborated.

INTRODUCTION

Due to rapid economic development in Asia, construction of new rapid transit systems and extension of existing systems have become extremely important tasks for infrastructure development for many major metropolitan areas in the region. Geotechnical engineering plays a critical role in the implementation of rapid transit projects. On the other hand, construction of such systems results in significant improvements in the geotechnical practice. One of the major rapid transit projects currently under construction in Asia is the priority network of the Taipei Rapid Transit Systems (TRTS). This paper will use TRTS as an example to illustrate the more significant geotechnical concerns associated with rapid transit systems in soft ground.

The first part of the paper describes the ground conditions within the Taipei Basin. The main focus is on the nature of geotechnical information required for a major project such as the TRTS. The second part of this paper describes how design of diaphragm wall supported excavations has been refined in Taipei. The effect of differences between assumed and actual ground conditions is discussed in relation to the performance of open excavations and the construction of bored tunnels. Finally, the implementation of geotechnical instrumentation and monitoring system for the TRTS project is described.

TAIPEI RAPID TRANSIT SYSTEMS

The priority network of TRTS (Fig. 1) includes 6 lines with a total of 84.7 km of track and 77 stations. About half of the stations and track will be constructed below grade. Each of the 37 underground stations will typically be 200 to

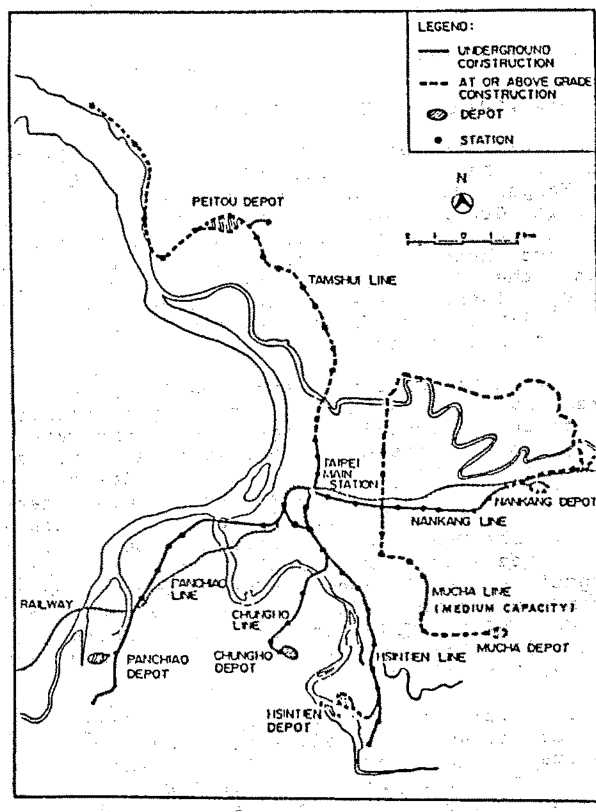

Fig.1 Priority Network of Taipei Rapid Transit Systems

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300 m long and between 15 to 28 m deep. In addition, cut and cover work is planned for crossovers, pedestrian shopping malls and the like. Most of the cut and cover excavations will be supported by internally braced diaphragm walls, with a total length of about 45 km of diaphragm walls. The remaining underground track will be constructed in 5.6 m diameter twin bored tunnels. The rest of the track and stations are elevated or at grade. Majority of the network is located in soft ground except one section of the Mucha Line which is a rock tunnel. The main depot is located at Peitou. Small yards and light maintenance facilities are located at the end of each line (Fig. 1).

The Department of Rapid Transit Systems (DORTS) was set up by the Taipei Municipal Government in 1987 to control the design and construction of the TRTS project. The network is divided into many design lots with each design lot subdivided into several construction contracts; detail design of each of the construction contract was carried out by detail design consultants. DORTS appointed Moh and Associates (MAA) as an independent Geotechnical Engineering Specialty Consultant (GESC) to review the geotechnical design work and to provide advice on geotechnical engineering aspects of the work during construction.

Detail design for the project started in 1987 and construction of the project commenced with the Peitou Depot advance earthworks contract in July 1988. The entire priority network is planned for revenue operation by 1998.

SUBSOIL CONDITIONS OF THE TAIPEI BASIN

Regional Geology of the Taipei Basin

Taipei City is located in a triangular shaped basin in the northern part of Taiwan (Fig. 2). The Taipei Basin is enclosed by the Tatun Volcanic Group, Linkou Tableland and hilly terrain consisting of Tertiary sedimentary rock. There are three major rivers flowing through the basin; the Keelung, Hsintien and the Tahan Rivers. These three rivers merge into the Tamshui River which flows into the Taiwan Strait at the town of Tamshui.

The Taipei Basin is a tectonic basin which was formed by the settlement of nappes between thrusts in the foothill range of northern Taiwan during the Pliocene and Pleistocene periods. The primary strata in the Taipei Basin are sedimentary deposits of the recent Quaternary period and bedrock formation of the Tertiary period. The Quaternary deposits can be divided into three major formations: the Hsinchuang, Chingmei and Sungshan Formations. Basic information on these deposits is given in Table I. Most of the TRTS underground construction works will take place in the Sungshan and Chingmei Formations.

The Chingmei Formation, which is frequently referred to as "Chingmei gravel layer" mainly consists of boulders, gravel and sand. The maximum particle size can be as large as 60 cm or even larger. In the past, the Chingmei Formation has served as the aquifer for deep well pumping to provide Taipei's water supply. This layer also serves as the bearing stratum for deep foundation supporting many TRTS structures. However, it should be noted that a recent study (Fu et al, 1990) indicates that the nature and distribution of the Chingmei Formation are very variable across the basin.

The Sungshan Formation which overlies the Chingmei gravel deposits typically consists of six alternating layers of cohesive and

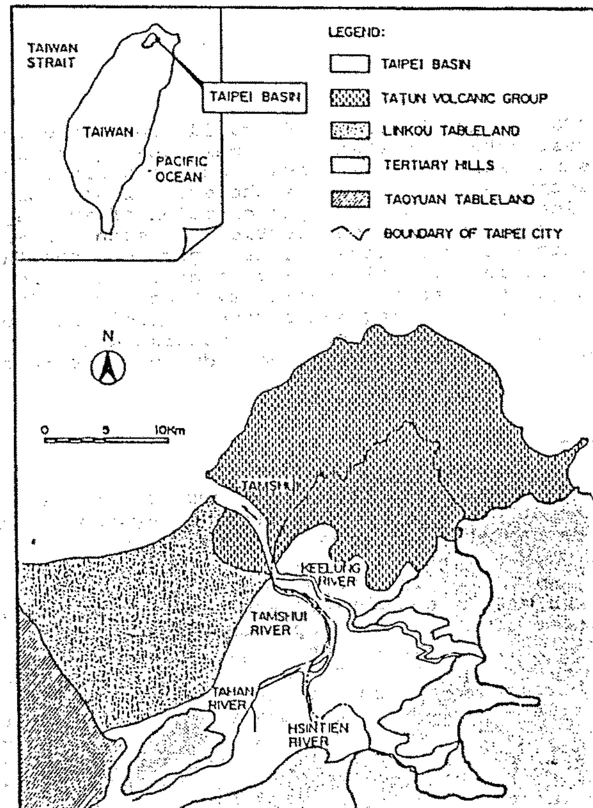

Fig.2 Geological Conditions of the Taipei Basin

Table I Profile of the Sedimentary Deposits in Taipei Basin

FORMATION		THICKNESS(m)		SOIL DESCRIPTION
TOP SOIL (CL,CL/ML)		1-6		YELLOWISH BROWN CLAY
SUNGSHAN FORMATION	LAYER VI (CL/ML)	2-8	40-70	GRAYISH BLACK CLAYEY SILT
	LAYER V (SM)	2-20		GRAY SILTY FINE SAND
	LAYER IV (CL/ML)	6-29		GRAY SILTY CLAY
	LAYER III (SM)	0-19		GRAY SILTY FINE SAND
	LAYER II (CL/ML)	0-19		GRAY SILTY CLAY
	LAYER I (SM)	0-15		GRAY SILTY FINE SAND
CHINGMEI FORMATION		0-200		YELLOWISH BROWN GRAVEL
HSINCHUANG FORMATION		0-120		GRAY TO YELLOWISH BROWN SANDY CLAY WITH OCCASIONALLY INTERBEDDED THICK GRAVEL LAYER
TERTIARY SEDIMENTARY ROCK (VOLCANIC ROCK IN PEITOU, SHIHLIN, AND THE VICINITY OF KUNGKUAN).				

cohesionless soils. Due to the relatively high percentage of silt-size particles both in cohesive and cohesionless soil layers, the Sungshan Formation is often referred to as the "Taipei Silt" (Moh and Ou, 1979). In general, Layers VI, IV and II comprise silty clay and clayey silt soils Layers V and III are basically silty sands. The lowermost Layer I is variable and contains both clayey and sandy sublayers.

Based on collation and synthesis of extensive borehole and laboratory data, MAA (1987) proposed subdivision of the Sungshan Formation into areal zones according to the depositional environment associated with the three major rivers which flow into the basin. This subdivision indicates significant areal variation within the Sungshan Formation (Fig.3). This geotechnical mapping work has been proven to be extremely useful for the planning and preliminary design for the TRTS project. From an overall point of view, the three major stratigraphic conditions encountered in underground work for the TRTS project are:

- relatively uniform T2 area consisting six alternating layers of cohesive and cohesionless soils as discussed above.
- K1 and K2 areas which are underlain by deep deposits of soft clay, and
- areas underlain by gravel.

Though this simplified model is helpful in the planning and preliminary design stages, the

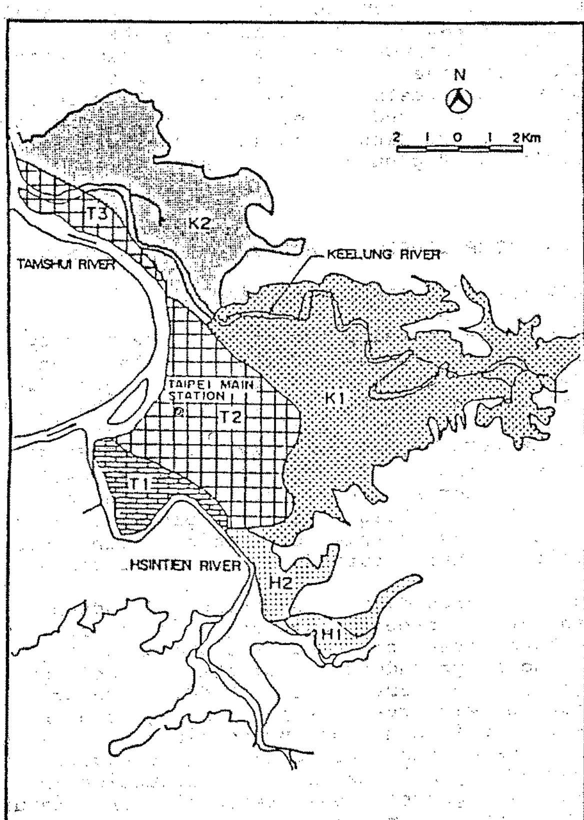

Fig.3 Location of Subzones in the Sungshan Formation

ground conditions are in fact very variable in terms of both the stratigraphy and soil properties. Therefore detailed site investigations were carried out for final design purposes. Even with this additional information, it is not possible to "design out" all the problems involved in the construction of underground structures. Varying ground conditions will have a significant influence on the TRTS construction.

Soil and Rock Properties

Quite extensive geotechnical site investigations have been conducted in Taipei in the past two decades mainly for foundation design for commercial and residential buildings. Local geotechnical practice usually involves borings, samplings and laboratory test; little in-situ testing has been carried out in the past. A number of papers have been published to describe the engineering properties of the Taipei soils (e.g. Hung, 1966; Moh and Ou, 1979; Wu, 1979). Based on the abundant data accumulated in the past, the general soil properties of Taipei and the variation of soil stratification within the Basin are well understood. However, for a major project such as the TRTS which involves much difficult constructions in soft ground, further understanding of the behavior of the soils within the Taipei Basin is required. During the design of the TRTS project, further work of this nature has been carried out to ensure economic and safe construction of the project. Instead of describing the general properties of Taipei soils, this section will emphasize on information required for construction of the rapid transit system in Taipei.

Cohesive soils in Taipei are silty and can be classified as CL, with only a small portion classified as ML and CL-ML. In the past, local geotechnical practice relied mainly on total stress parameters C and ϕ from CIU tests to characterize the strength of these materials for engineering analyses. There was little consideration of the importance of the stress history of the deposits. The results of additional studies carried out for the TRTS project has provided a better understanding of the behavior of cohesive soils in Taipei and some fundamental research results on clay strength have been published in the last two years (e.g. Chin et al, 1989; Liu et al, 1991). These studies verified that the strength behavior of the cohesive soils of Taipei could be well represented in terms of the stress history of the material. They also indicated a significant variation in the normalized strength behavior with varying plasticity of the soil. Dilatant behavior of some of the more silty materials was also noted. Effects of anisotropy and principal stress rotation have been observed. The SHANSEP approach (acronym for Stress History and Normalized Soil Engineering Properties, Ladd and Foott, 1974) was found to be particularly useful for characterizing the strength of cohesive deposits. Further studies on strength behavior are ongoing which include Ko consolidated drained and undrained triaxial compression, triaxial extension and direct simple shear tests with varying OCR. Refinements in the interpretation of one-dimensional consolidation test results have been made based on the strain energy approach proposed by Becker et al (1987). This approach appears to provide a reliable estimate of the maximum past pressure of the Taipei Silts despite the rounded nature of the e-log $\bar{\sigma}_v$ curves for these soils. Further tests to determine in situ effective horizontal stresses especially the determination of Ko with varying OCR, will be conducted at MIT in a joint research program with MAA. Strength characterization for diaphragm wall design will be further discussed in later section to illustrate the importance of clay behavior in terms of open excavation design and construction.

Most of the sandy soils in Taipei are classified as SM with a high percentage of silt size particles. Soil parameters generally required for TRTS design have been estimated on the basis of laboratory tests, local experience and empirical correlations based on SPT N-values. Further refinements in determining the properties of the sand layers can be expected in the future. Of particular interest is the application of the "state parameter" approach (Been and Jefferies, 1985) to characterize sand behavior. In the SHANSEP approach for cohesive soils, the virgin compression line is used as a reference for quantifying the state of the material in terms of OCR. Material properties such as strength, are then correlated with OCR. The state parameter approach for sands is similar in concept and uses the steady state line as a reference to quantify the current state of a sand. This approach provides a rational basis for estimating sand properties and also provides a suitable framework for the interpretation of in-situ test results such as cone penetration tests (Been et al, 1986).

Very little is known about the engineering characteristics of the Chingmei gravels. Usually, the strength of the Chingmei gravels is estimated based on SPT N-values and correlations developed for other deposits. Not many deep test pits have been put down into the Chingmei gravel and basic information such as particle size distribution is limited. Drillability for piling equipment and diaphragm walling machines is therefore a major concern for designers and contractors. Another major concern related to the Chingmei gravel is its permeability. Only a few borehole permeability tests and pumping tests have been carried out to date and the results of these tests indicate that the permeability of the gravel can vary by 1-2 orders of magnitude. A review of the data related to the permeability of the Chingmei gravel indicates that the average value of the permeability in Taipei Basin is approximately 0.05 cm/sec from a regional point of view. This study also noted that because of the limited data available and the expected variability across the basin, this value should only be used for preliminary design. Pumping tests should be conducted before construction for any contract involving significant pumping from the Chingmei gravels.

Most of the bedrock encountered along TRTS route is Tertiary sedimentary rock except that andesite is found to be the bearing stratum for piles in the Tamshui line. Some tuff will be encountered in the southeast corner of the Basin on contracts which involve tunnelling on the Mucha and Hsintien Lines. The major concerns related to rock properties are the shearing resistance in estimating socket strength and bearing capacity for pile and barrette foundations, deformation moduli in calculating the settlement of deep foundations, permeability in evaluating the effectiveness of diaphragm walls as cut-offs, and the ability of diaphragm walling equipment to penetrate into rock. The top few meters of bedrock is weathered and fractured; rock cores soften quickly when wetted. RQD was very low and is almost zero in many areas. Therefore, it is difficult to conduct laboratory tests to determine the rock properties. Most TRTS design has been based on unconfined compression tests; not many other types of tests have been carried out. Current design practice is still highly dependent upon correlations with SPT N-value and RQD. It is expected that understanding of sedimentary rock properties in Taipei can be greatly improved when more large scale instrumented test results become available as a result of the TRTS project.

Field tests have been carried out for TRTS final design work and have been very helpful in estimating soil properties and delineating soil stratigraphy. In-situ tests included cone penetration tests, pressuremeter tests, vane shear tests, borehole permeability tests, etc. However, the benefits of these tests have not been fully realized because of the lack of established local correlations. For a major project such as the TRTS project, correlations for interpretation of in-situ test results should be established at an early stage of the project by the use of either calibration chamber tests in the laboratory and large scale instrumented tests in the field. In-situ tests will also be used for quality control purpose during construction, such as in the performance evaluation of ground improvement.

GROUNDWATER CONDITION AND GROUND SUBSIDENCE

History of Groundwater Pumping

Before the development of the modern city of Taipei, the groundwater table in the area was close to the ground surface and the groundwater pressure was hydrostatic. Since the 1950s, there have been significant changes in the groundwater regime, mainly as a result of extensive pumping from the Chingmei Formation to supply water for the city. As is the case in many other cities where pumping from deep aquifers was carried out, significant ground subsidence has occurred in the Taipei Basin.

Typical groundwater pressure drawdown and associated ground subsidence data for the downtown area of Taipei are shown in Fig. 4. Pumping of groundwater from the Chingmei gravel began in the years prior to 1960. Although the practice was restricted by the government in 1968, significant pumping continued until the mid-1970s when the greatest drawdown has occurred. The water pressure reduction in the Chingmei gravel was regional in nature, Thereafter, there has been a reduction in pumping and there is a trend of recovery of groundwater pressures in the gravel. This deep

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well pumping also resulted in a regional ground subsidence across the Basin. Maximum subsidence of more than 2 m had occurred in central Taipei corresponding to a drawdown of approximately 42 m. Although the main source of water extraction was in the central area of the city, the drawdown extended to the extreme limits of the Basin. The associated regional settlement was consistent and also extended to the limits of the basin.

Water pressure reduction in the Chingmei gravel caused reduction in water pressures in the overlying Sungshan deposits, extended through Layers I to III. However, Layer IV acted as an aquitard and essentially preserved hydrostatic conditions in the overlying materials.

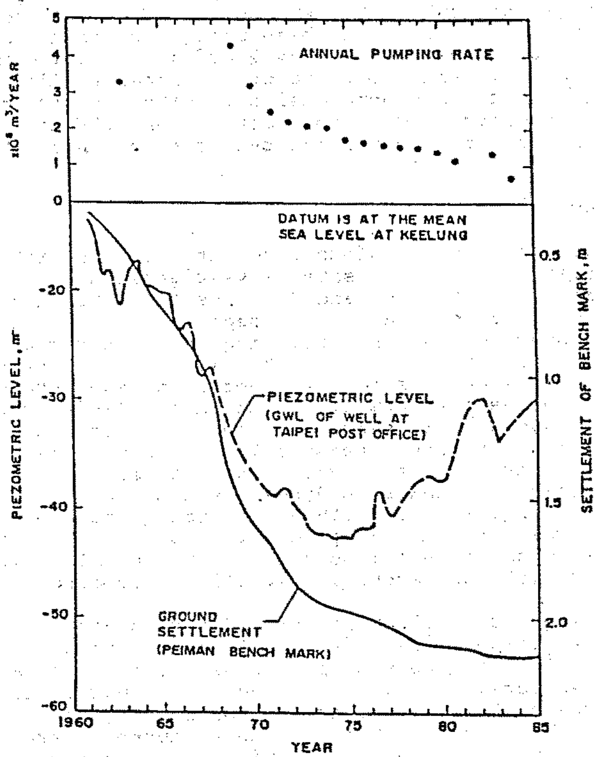

Fig.4 Groundwater Drawdown and Associated Ground Settlement in Taipei

Groundwater Recovery

As noted above, the water pressures in the Chingmei gravel have been recovering since the mid-1970s. Typical data illustrating the trend of recovery in the gravel, based on information from the city center area, is shown in terms of piezometric level in the gravels in Fig. 5 (Chin et al, 1991). Also shown in Fig. 5 are data from piezometers installed in the Layer III Sungshan deposits. Initially, the rate of water pressure recovery was slow. However, from 1981 until 1988, recovery was more rapid with an average head increase of 2 to 3 m/year. The recovery trend in the Layer III sands is generally similar to the piezometric level in the Layer III stratum being about 3 m higher than the average piezometric level in the underlying gravel. Recent monitoring records indicate that the current groundwater pressure distribution throughout the Sungshan deposits is still lower than hydrostatic.

Effect of Groundwater Recovery on TRTS

Groundwater recovery will significantly influence future construction works in the Taipei Basin. Some adverse effects should be considered; for example, groundwater recovery may lead to increase in the liquefaction potential in sandy soils, increasing difficulty in carrying out tunnelling work, reduction in the capacity of tension piles, etc. For TRTS works, the most crucial effect of groundwater recovery is on the cut and cover construction (Chin et al, 1991).

Deep well pumping which was carried out in the Taipei Basin in the past and its associated effects have been beneficial for previous excavation works in the city. The inverts for typical basement excavations in the city center area were generally well above the groundwater elevation in the lower Sungshan deposits. Thus, groundwater control measures were not usually required for excavations. Performances of these braced excavations were reasonably good in terms of wall deflection and ground movement. A major factor which lead to this good performance was undoubtedly the favorable groundwater conditions. For the TRTS work, because of greater excavation depths and recovery of water pressures, the groundwater elevations in the lower Sungshan Formation will be well above the excavation inverts. Therefore, control of groundwater will be critical in achieving stability of the walls and limiting wall deflections.

The past regional pumping has also had other beneficial effects for TRTS work, mainly because the lower Sungshan deposits have been overconsolidated. Compressibility of cohesive soils in the overconsolidated range is usually 10-20 percent of that in the normally consolidated range (Ladd, 1973). Since pumping associated with TRTS construction will ca

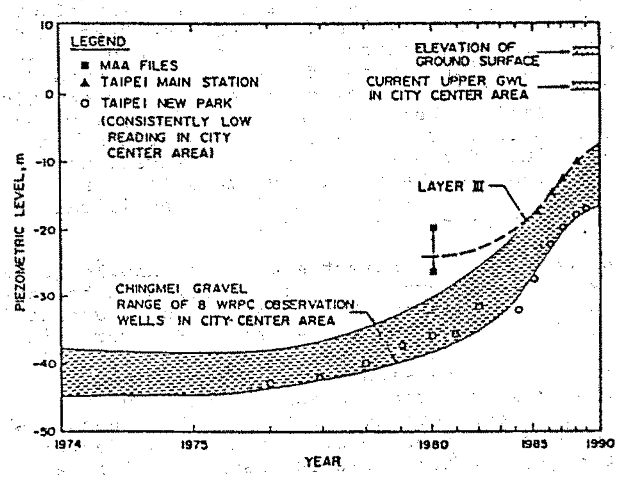

Fig.5 Groundwater Recovery in Taipei Basin

less water pressure reduction over a shorter period than has occurred in the past, the overall effect of groundwater drawdown in the soils outside the excavation areas should not result in very large surface settlement. However, around the edge of the Basin, large surface settlements may occur due to TRTS construction because the soil deposits at the edges of the Basin may not be as over-consolidated as in the central area.

For cut-and-cover construction of TRTS, the groundwater pressure is critical to the basal stability during construction. In addition, the groundwater pressure during excavation controls the strength of the soil and thus significantly affects the performance of the diaphragm wall and associated ground settlement. Consequently, groundwater pressure must be strictly controlled and continuously monitored during construction.

GEOLOGICAL HAZARDS

Major geological hazards relevant to TRTS project are natural and man-made obstructions, soil liquefaction and gas emission.

Natural and Man-made Obstructions

Due to the complex depositional environment during formation of the Taipei Basin deposits, many unexpected obstacles are likely to be encountered during tunnelling and excavation work. A buried tree trunk a few meters in length has been observed in an excavation site adjacent to the TRTS route. Also, many constructed facilities have already been built along the route of TRTS. These natural and man-made obstructions could cause problems during shield tunnelling and diaphragm walling.

Soil Liquefaction

Soil liquefaction affects the design of the TRTS work in that it can lead to increase of lateral loads on side walls of underground structures, loss of lateral support of piles, increase of uplift force acting on the bottom of structures, etc. Therefore, assessments of liquefaction potential have been made for all contracts. Most of the liquefaction assessments have followed the traditional simplified approach proposed by Seed et al (1984) which is based on an empirical correlation between the imposed cyclic shear stress ratio during a seismic event and the SPT N value of the soil deposit. However, the sand deposits in Taipei are quite silty, and only limited data are included in the empirical data base for silty sand deposits.

Based on the present state of knowledge and available information, it is difficult to make a conclusive statement on the risk of liquefaction of the Taipei sandy deposits. However, it is considered that only a small portion of the Layer V silty sand is likely to liquefy under the maximum credible earthquake with a ground surface acceleration of 0.18g. In the analysis, the groundwater level is a critical factor. If the groundwater table is assumed to lie near the ground level, a significantly large volume of soils could possibly liquefy.

There are other uncertainties regarding assessment of liquefaction potential. For example, the use of a single value of ground acceleration is regarded as appropriate for the purpose of designing general structures of common use. However, for an important project like TRTS, site specific characteristics of seismic motions should be thoroughly investigated and duly considered because TRTS will stride broad areas with very different geological subsurface conditions. Furthermore, site specific information on cyclic strength of soils can be obtained only by means of carefully performed cyclic triaxial tests on good quality undisturbed samples of sandy soils. Further studies involving cyclic shear strength tests on Taipei silty sands are required. The use of SPT N values for characterizing sand strength also has' its limitations due to the poor repeatability of the SPT. Recently, use of cone penetration test has been recognized as a more reliable means for evaluating liquefaction potential mainly because of the repeatability of this test. A comprehensive in-situ test program is required to develop correlations between CPT cone resistance and the cyclic strength of the Taipei silty sands.

Gas

Gas has been encountered at six different locations during site investigations in the Taipei Basin (Woo and Moh, 1990). There have also been several verbal reports of gas being encountered during drilling and construction work in Taipei. Although only at one location the gas was positively identified as methane, given the environment of the Taipei Basin, which includes coal seams within the sedimentary rocks, it seems reasonable to conclude that majority of the gas encountered contains methane. Methane is dangerous because it forms an explosive mix with air at concentrations of between 6 and 16 percent. Whilst poisonous gases become progressively safer when mixed with air, methane becomes, initially, more dangerous.

There is no clear pattern of gas occurrence in the Taipei Basin and all areas should be considered areas of potential methane hazard. Therefore, all tunnel constructions, irrespective of the ground conditions, should be checked for methane. Where tunnels are in ground with a known risk of encountering, methane, the level of checking needs to be greatly enhanced.

Even if large reservoirs of methane are not encountered during construction, there is a risk that methane could be present in the groundwater. Groundwater entering tunnels or other underground structures could result in a slow build-up of methane in unventilated areas. This risk will be primarily to the operating railway rather than to the work during construction. In order to identify the potential for this problem, it is necessary to take water and air samples for laboratory measurements for very low concentrations of methane. Although this is primarily a risk to the operating railway, this testing program should start during construction to identify particular risk areas and to take precautionary measures at appropriate time.

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CUT-AND-COVER CONSTRUCTIONS

General

The general standard of local geotechnical engineering practice with respect to design of open excavations has been significantly improved as the result of design and construction of the TRTS project. This is not surprising since the construction of the subway is a very major challenge involving extensive excavations in soft ground in a built up urban environment. Also this project has provided the opportunity to collect relevant information based on past experiences in a systematic manner. The introduction of new construction techniques will also result in improvement in ground construction technology.

The following sections will use the design of open excavations to illustrate the nature of changes which can occur as a result of design and construction of a rapid transit project.

Design Considerations

A very large proportion of the TRTS project involves underground construction by cut and cover techniques. These structures include stations and associated entrances, together with crossover, running tunnels and various types of shafts. Therefore, design of open excavations is a very important part of the project. The methods which will be used to support most of the deep open excavations for the TRTS project will follow traditional Taipei practice, i.e., using internally braced diaphragm wall systems.

From a geotechnical viewpoint, the design of diaphragm wall supported excavations requires accurate representation of the stratigraphy, correct interpretation of soil properties, in particular soil strength, and some basis on which to judge if the predicted performance is reasonable. The current practices related to these three aspects are briefly reviewed below.

(1) Stratigraphy - Even before the TRTS design work began, there was a good understanding of the nature and distribution of the soils in the Taipei Basin, which formed a very good basis for planning the work and for preliminary design. Additional site specific investigations were carried out for detailed design of the individual lines and structures. However, this additional work did not significantly change the existing geological model of the Taipei Basin.

(2) Past experiences - Many basement excavations have been constructed in Taipei in the past 20 years and good monitoring records are available which provide valuable information as to how TRTS excavations will perform. The TRTS project provided the opportunity to summarize the extensive information collected on individual projects in the past. This information was extremely valuable in assessing the reliability of analytical predictions which were commonly used in local practice. It will be greatly augmented by the massive TRTS monitoring results and will become an important source of information for the international geotechnical community.

(3) Soil Properties - Determination and selection of strength parameters of soils are probably the most important step in designing diaphragm walls. It is the area where most of the changes in local practice took place. In the past 20 years, many wall designs were carried out on a largely empirical basis which used a c-ϕ approach to define soil strength. Depending on the computer program used, different assumptions were made regarding friction between the wall and the surrounding soil, distribution of water pressures and development of stiffness of the soils. These local empirical methods seemed to provide reasonable predictions for typical basement excavations although some predictions were consistently inaccurate, for example, bending moments. In the initial stages of design of open excavations for the TRTS project, concern arose that despite its past successful use, the traditional empirical approach might not be appropriate because the TRTS structures would be:

- significantly deeper,
- open for longer periods and therefore more swelling and weakening of the soil in the base of the excavation would occur,
- located, in some cases, in areas of mainly clayey soils (i.e. the K1 area) where there was very limited past experience using the empirical approach and where some failures of excavations have occurred, and
- subject to quite different groundwater conditions than has been in the past cases.

As a result of these concerns, a more fundamental approach was developed for wall design which involved the consideration of swelling during excavation, effect of wall adhesion/friction and strength characterization.

Swelling in the base of excavations

One of the first decisions that the designer must make is how to represent the strength of the soil. The basic question is the degree of swelling which will occur in the passive zone over the time that the excavation stays open. Swelling (i.e. the component of volume increase in addition to elastic rebound) occurs as a result of unloading due to the excavation which causes a decrease in porewater pressure below the ambient pressure. With time, flow of water takes place and the soil takes in water. Eventually, the water pressures equalize and swelling is complete.

The rate at which swelling occurs depends on the following factors:

- coefficient of consolidation of the material in the passive zone (c_v). Laboratory data indicate that this value can vary significantly for the Taipei silts. Yet, with good quality samples and a clear understanding of the stress history of the deposits, it should be possible to make reasonable estimates of the in-situ c_v.
- length of the "drainage path" (i.e. how far the water has to travel through the

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soil). Even with very detailed investigation, not all of the layers/lenses of coarser soils could be included in the analyses. This has a major effect because in the calculation of degree of swelling, the "length" term is squared.
- time that the excavation remains open.

For TRTS excavations in the T2 area, analyses indicated that complete swelling would occur and strength should be defined in terms of effective stress. These predictions were confirmed by field monitoring data. In effective stress analyses, the groundwater pressure has a very important influence on the computed strength and thus has a significant impact on the estimated wall deflection and settlement of adjacent structures. A comparison was made (Moh et al, 1989) to illustrate the significant effect of water pressures on wall deflection. Figure 6 shows a typical station configuration of TRTS with two water pressure profiles:

- U1 is the profile resulting from pumping from the passive zone within the excavation;
- U2 is the profile without groundwater control and, as shown, reflects higher water pressures.

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 that for the lower water pressure profile (U1). For many excavations, it was found that water pressures have to be controlled (i.e. lowered to below the level that would occur naturally during construction) in order to achieve acceptable performance and to ensure overall stability. It is vital that during construction, the contractor achieves the groundwater pressures assumed in the design. If they are higher, wall deflections and settlements will be higher and in the extreme, it is quite possible that overall failure of the excavation would occur.

For the K1 area, the degree of swelling of the cohesive deposits below the excavation level controls the passive resistance of the soil and thus influences the performance of the diaphragm wall. During excavation in cohesive soils, a negative excess pore pressure increment will be induced in the passive zone. Swelling and strength reduction will then take place with time. Provided that the degree of swelling can be reasonably estimated, the shear strength reduction in the passive zone can be fairly reliably estimated using the SHANSEP approach. Results of analyses (Chin et al, 1991) indicated that, compared with the fully undrained condition on the passive side of excavation, there is an approximate 20 percent increase of the maximum wall deflection if the degree of swelling reaches 50 percent (Fig. 7).

It should be noted that analysis of problems involving the coupled processes of swelling and transient flow is very difficult. Due to the uncertainty in estimating the degree of swelling and its significant influence on wall deflection and overall stability, pore water pressures in the passive zone must be continuously monitored during excavation.

<u>Wall adhesion and wall friction</u>

Wall adhesion/friction will reduce the earth pressures acting on the active side and increase the earth pressure on the passive side. This reduces the lateral movements, and thus has a significant impact on diaphragm wall design and building protection assessment.

Using the case presented in Fig. 7, a comparison was made between wall deflection assuming that no wall adhesion develops and assuming that wall adhesion equal to 2/3 of soil strength develops. The results indicate that lateral movement of the wall assuming no friction is about twice that of the case when wall adhesion is included.

The degree to which wall adhesion/friction develops during construction is difficult to predict. Furthermore, very little information on this important topic for cohesive soils is available on a worldwide basis. Therefore, test sections of instrumented diaphragm wall panels are recommended to be included in some of the TRTS construction contracts.

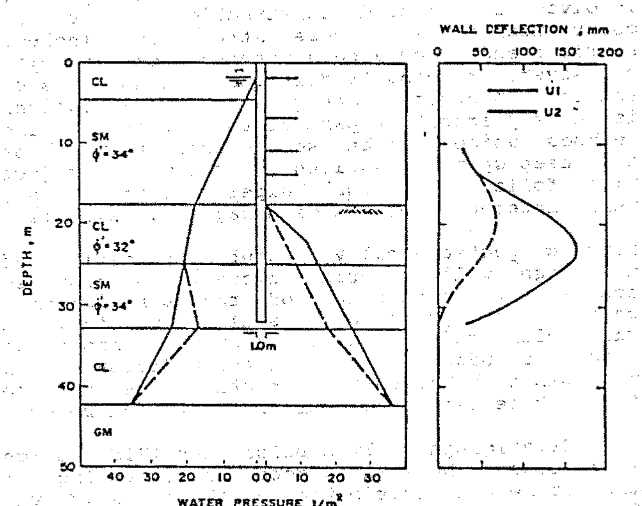

Fig.6 Effect of Water Pressure on Diaphragm Wall Deflection (After Moh et al, 1989)

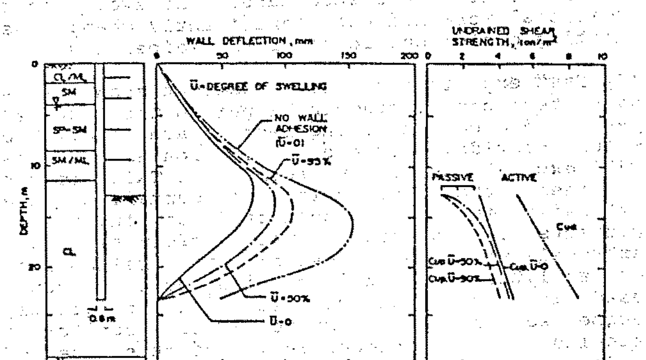

Fig.7 Effect of Swelling on Diaphragm Wall Deflection (After Chin et al, 1991)

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Undrained shear strength characterization

The major factors affecting the undrained shear strength of clay deposits are anisotropy, strain rate, stress history and sample disturbance. UU and CIU test cannot take all these factors into account and problems associated with these tests have been discussed in the soil mechanics literature for many years. In 1989, MAA conducted an extensive study together with Professor C.C Ladd of MIT on the stress-strain-strength characterization of cohesive Taipei deposits for diaphragm wall design. This study again demonstrated that the use of UU and CIU tests is not satisfactory for the Taipei silts and the SHANSEP approach was recommended (Ladd, 1989).

SHANSEP is applicable to recent unstructured cohesive deposits where the mechanism that caused overconsolidation is mechanical. Cohesive Taipei soils were deposited in such an environment. Results of some preliminary studies (Chin et al., 1989; Liu et al., 1991) further indicate that the cohesive Taipei soils do exhibit normalized behavior and the SHANSEP approach can be applied. The implementation of SHANSEP will be more fully developed during a future study associated with the TRTS project.

Though full application of SHANSEP has not yet been implemented on the project, the importance of strength anisotropy has been recognized particularly in areas of thick soft clays. Below the bottom of excavation, the wall moves inward and the soil is sheared in a plane strain passive mode. The undrained shear strength in this mode of shearing is very close to that obtained in a Ko-consolidated undrained triaxial extension test. Outside the excavation, the wall moves toward the excavation and the soil element experiences a plane strain active mode of shearing. The undrained shear strength in this mode of shearing is very close to that obtained in a Ko consolidated undrained triaxial compression test. Preliminary results indicate that the strength ratio, (i.e. undrained shear strength at normally consolidated state divided by the vertical effective consolidation stress), is about 0.33 ± 0.03 and 0.19 ± 0.03 for compression and extension modes of shearing, respectively.

SOFT GROUND TUNNELLING

There are a great number of ways in which ground conditions will affect tunnelling work for the TRTS project. Some of these are discussed below.

Settlements due to Shield Tunnelling

One of the major factors associated with bored tunnelling for the TRTS project is the magnitude of ground movements and associated settlements which can affect existing structures. Accurate prediction of settlements due to tunnelling is extremely difficult and the actual settlement which occurs is largely dependent on the tunnelling method used and the quality of workmanship employed. A further factor is variation in local ground conditions.

Consider the situation where a closed face machine is used which is expected to be a common situation on the TRTS project, most of the settlement during tunnelling through the Sungshan deposits will be the result of the ground closing in around the completed liner when the shield is shoved forward, (i.e. the ground collapses into the space between the shield and the lining). If the soil can support itself until the annulus is grouted then the settlement will be much reduced. However, if the soil has little or no stand-up time, settlement will occur regardless of how quickly grouting behind the rings is carried out. This will likely be the case in the soft K1 area.

In the T2 area where significant lengths of tunnel are to be driven through the Layer IV silts, it is not well known how the ground will behave. This material is silty and tends to dilate when it shears. In the short term, dilation results in increased strength due to negative pore water pressures. However, these negative pore water pressures dissipate rapidly with time and the soil becomes weaker. Strength data for the Layer IV silts show that the degree to which the material dilates during shear is very variable depending on its gradation (Fig. 8). Therefore, even relatively small local variations in material type will probably have a major effect on settlement over tunnels.

Muck Handling

Another aspect of tunnelling where the nature of

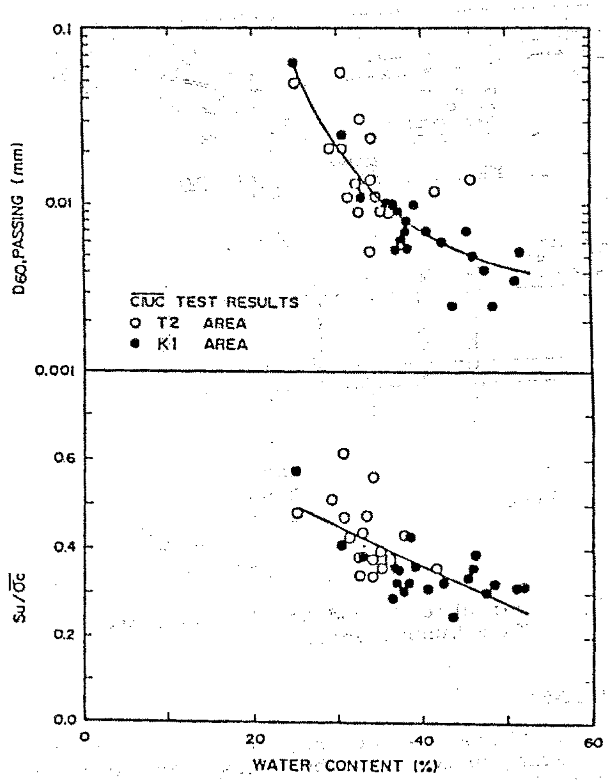

Fig.8 Dilation Effect on Undrained Shear Strength of Cohesive Soils in Taipei

the material plays an important role is in the handling of the spoil. The two main types of full face machines which are likely to be used on the TRTS project, are the earth pressure balanced machine (EPBM) and the slurry machine. The spoil from an EPBM is removed from the face using a screw type feed and carted out of the tunnel in muck cars. In the slurry machine, the spoil is transported out in slurry form and separated on the surface. There is a potential problem with slurry transport in that if the spoil is plastic, it will tend to form into lumps which would block the slurry pipes. From reports of local tunnelers, this has happened in Taipei soils. However, it is not clear at this time exactly at what degree of plasticity this problem would occur. Again, local variation in terms of plasticity can be expected to be a factor in the slurry transport of spoil.

Mixed Face Conditions

The effect of local variations in ground conditions on tunnelling will be most obvious where the tunnel passes through mixed ground conditions. This is a major consideration for one particular TRTS contract where the 1.3 km tunnel will pass through very varied conditions such that at any time there may be 2 or 3 material types in the tunnel face (Fig. 9). The actual nature and distribution of these materials will have a critical effect on tunnelling progress.

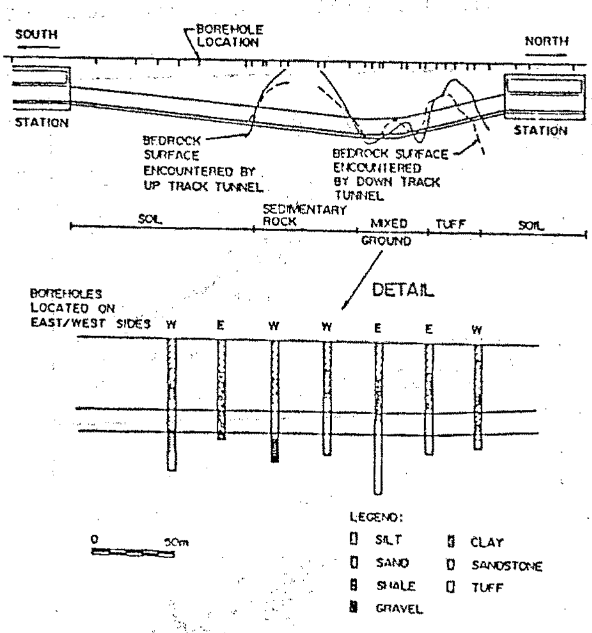

Fig.9 Variable Ground Conditions along a TRTS Tunnel Section

Obstacles

Finally, there is the problem of the tunnel encountering unexpected obstacles. For example, tunnels through gravel will likely encounter boulders; normally a tunnelling machine will be able to cope with boulders up to about 400-500 mm. However, little is known about the size of boulders in the Chingmei deposits and larger boulders may be encountered. If they are, the operation must be halted and the boulder removed manually. Boulders are not the only obstacles that tunnels will encounter; as discussed previously, buried tree trunks have been found in the Sungshan formation. Also, there will be man-made obstructions along the route; the exact location, depth and nature of these obstacles can never be really known precisely and could pose serious problems during construction.

Discussion

The message that the authors attempted to convey in this presentation is that design for underground construction is based on simplified assumptions regarding the nature of the ground and behavior of the soils. In reality, it is inevitable that conditions in the field would be quite different than expected. In some cases, the effect of the differences between assumed and actual conditions will be significant. The owner, designer, consultant and contractor must be prepared for these situations. Harding (1981) stated this message as follows:

"In most civil engineering works worthy of the name the unexpected happens; to be prepared for such eventualities and to forestall their effects is the test of good constructional practice."

GEOTECHNICAL INSTRUMENTATION AND MONITORING SYSTEMS FOR TRTS

As the TRTS project involves major construction work that is located in a densely populated urban area and may affect the local environment, it is very important to maintain good engineering practice through both design and construction stages. Following the concept of the "observational approach" as suggested by Peck (1969), the implementation of an appropriate geotechnical instrumentation and monitoring system for the TRTS is considered critical. Significant effort has been invested by GESC to develop project guidelines and systems which include the following: to establish the procedures for various organizations to follow during design and construction; to set up guidelines for selection of instruments for compatibility with the system requirement; to prepare specifications and other contract documents related to monitoring; and to plan the project system to gather/transmit/report/store/analyze the data.

Detailed Design of Instrumentation System

The detailed design consultants for the TRTS were responsible to carry out the design of geotechnical instrumentation and monitoring systems for each construction contract. This includes selection of the instruments, preparation of the special provisions, locations of instruments, monitoring frequency, and setting the alert level and action limits based on predictions of behavior. It should be noted that instrumentation design shown on the contract drawings is regarded only as a minimum requirement for construction and the contractor may need to add more instruments and/or increase

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the frequency of measurements when necessary.

A large variety of monitoring devices have been specified for the TRTS project. These include almost every instrument available on the international market to measure groundwater pressures, displacements, settlements, stresses and load (Table II). The general specifications require that all instruments must be able to provide adequate capacity to cover the ranges in magnitude of the parameters to be monitored, supply reliable data for the duration of the construction, and be easily recalibrated, maintained and repaired.

Table II Types of Instruments Used in TRTS Construction

GROUNDWATER LEVEL/PRESSURE	OBSERVATION WELL	
	PIEZOMETER	OPEN STANDPIPE
		PNEUMATIC
		ELECTRICAL
DISPLACEMENT	INCLINOMETER	IN SOIL/ROCK
		IN DIAPHRAGM WALL
	TILTMETER	
	CONVERGENCE METER	
	CRACK METER/GAUGE	
SETTLEMENT	BENCH MARK	
	SETTLEMENT POINT/MARKER	SURFACE TYPE
		STRUCTURE TYPE
		UTILITY TYPE
	SETTLEMENT INDICATOR	DEEP SUBSURFACE
		SHALLOW SUBSURFACE
	EXTENSOMETER	SINGLE
		MULTIPLE
	HEAVE STAKE	
LOAD/STRESS	EARTH PRESSURE CELL	
	REBAR STRESS TRANSDUCER	
	STRAIN GAUGE	VIBRATING WIRE
		RESISTANCE
	LOAD CELL	

Location of monitoring instruments and installation details are shown in detail on the contract drawings. Layout of instruments is planned to provide reliable and meaningful data so that they can be used to assure the safety of construction and to prevent damage of adjacent structures. Of particular concerns are several critical sections of shield tunnelling under or immediately adjacent to existing structures and deep cut and cover station construction in soft ground adjacent to existing buildings. These sections are always extensively instrumented as indicated in Figs. 10 and 11, respectively. Monitoring frequency is specified either in the drawings or in the specifications. It should be noted that for such a project each construction contract will take 3 to 4 years to complete, it is necessary to specify different monitoring frequencies for each instrument at various stages of construction. During construction the GESC will assist the DORTS engineers to supervise contractors installation of the instruments, to carry out check monitoring, to interpret and to analyze the data.

The specified alert levels and action limits of monitoring data of each instrument are established for the purpose of signaling proper actions which should be taken by site engineers. In general, once the alert level is reached, site engineers should check the readings, take more frequent readings, review the analyses, and be ready to take appropriate action. Once the action limit is approached, certain construction activities may have to be changed and building protection measures may need to be implemented. It is important to bear in mind that the purpose of the alert levels and action limits is to provide site engineers with an "early warning" system in their review of monitoring data. Whether action and/or protection measures should be taken is still highly dependent on the conditions at site.

TRTS Project Data Processing System

Contractors are required to monitor all of the instruments according to the designated frequencies and submit the results on a daily basis. Independent check readings and review of contractors' results will also be carried out. The GESC will be responsible to store all submitted data, make independent analyses of the monitoring data and provide advice to DORTS. It is estimated that approximately more than 30,000,000 items of monitoring data will be collected during TRTS priority network construction. Establishing and operating a

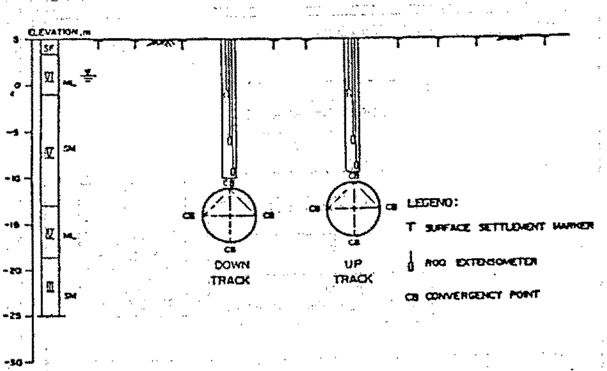

Fig.10 A Typical Monitoring Instrumentation Layout for a Tunnel Section

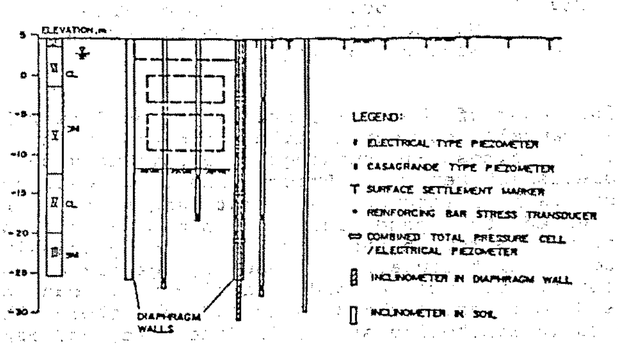

Fig.11 A Typical Monitoring Instrumentation Layout for a Cut-and-Cover Section

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computer based data processing system to handle all these data is clearly an important task.

GESC has set up a data processing system for TRTS geotechnical instrumentation and monitoring program (Fig. 12). The data processing system will mainly consist of an Integrated Data Storage Center (IDSC) located at GESC's office and many monitoring stations located at sites (i.e. approximately one monitoring station for each 2-3 construction contracts).

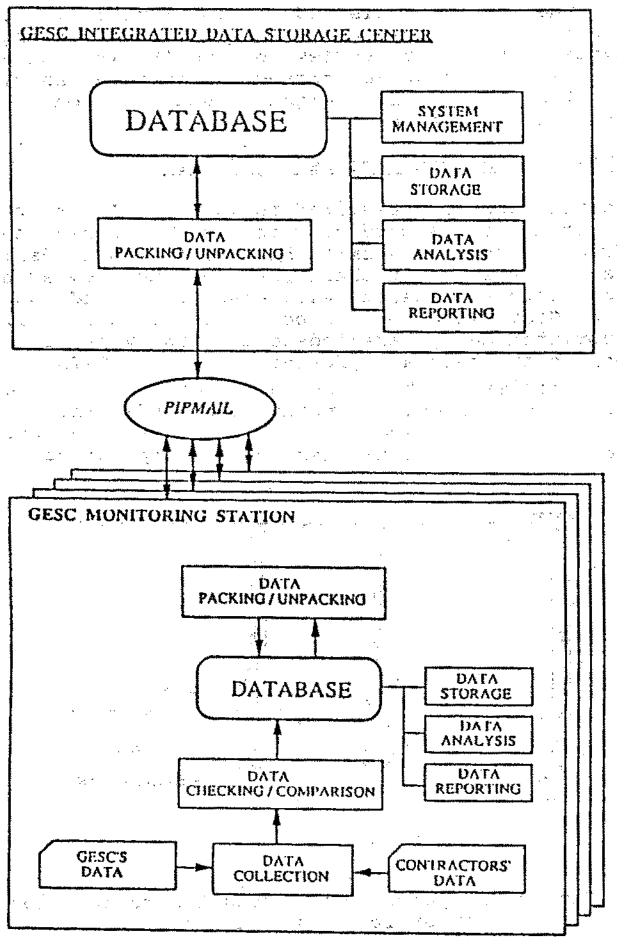

Fig.12 Data Processing System of TRTS Geotechnical Instrumentation and Monitoring Program

Since most of the TRTS instrumentation data will be manually collected, site engineers have to key-in almost all readings into computers on a spreadsheet report. A "macro" has been designed for each instrument so that engineers are required to spend only a minimum amount of effort to key in the readings. The processing code will calculate the results, generate the report, produce a condensed file that can be used to transmit the data to IDSC and store the data in monitoring station's data base, and make a comparison sheet showing abnormal readings and readings reaching alert levels and action limits. The data base system which has been developed includes storage, retrieval, display and maintenance as its major functions. Engineers can readily recover data for any instrument during any period from this data base to carry out analysis or to plot it according to the specified format. The data transmission between IDSC and monitoring stations are through the PIPMAIL (Public Information Processing) system which is an electronic mail system provided by the Directorate General of Telecommunications of the R.O.C. All monitoring stations are required to pack all of the data, which will include many data from many instruments on different construction contracts, into one file, and send this packed file into the "mailbox". Engineers at IDSC will get this file from the "mailbox", then unpack the file and put the data into the data base of the IDSC. Without PIPMAIL and the "pack/un-pack" program, it would be extremely difficult to systematically and economically gather all data from so many job site offices.

IDSC will handle all TRTS data collected from different monitoring stations. The database system at IDSC is exactly the same as that used in each monitoring station except that the IDSC database deals with much more data than any individual monitoring station. IDSC is also responsible for the back up of all the data of TRTS. In addition, more advanced, sophisticated and system-wide analyses will be conducted at IDSC whereas some basic and simple analyses only related to a limited area will be conducted at monitoring station level. IDSC is also the control center to dispatch monitoring data to relevant organizations of the TRTS project.

SUMMARY AND CONCLUSIONS

In the past, like in many other parts of the world, design of cut-and-cover construction for underground structures in Taipei area has been largely based on a semi-empirical approach. Due to significantly deeper depth of excavation, longer period for construction, limited past experience in some areas and recovery of the drawdown of watertable, design of cut-and-cover construction for the underground rapid transit systems in Taipei has to consider the problems of changes in pore water pressures, swelling in the base of excavations, and wall adhesion/friction. The SHANSEP approach has been found to be useful in characterizing the strength of Taipei deposits. The importance of observational method in underground construction is emphasized.

One of the important message which the authors attempt to convey is that design for underground construction must be based on certain simplified assumptions regarding the nature of the ground and behavior of the soils. 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. The entire team consisting of the owner, designer, consultant and contractor must be prepared for these conditions and must work together to resolve any possible problem.

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Any opinion, error or omission in this paper is solely the responsibility of the authors, and any explicit or implicit opinion stated by the authors should not be inferred as official policy or procedure of the DORTS or MAA.

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