SOFT GROUND ENGINEERING PRACTICE IN TAIWAN

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ABSTRACT

Taiwan, being one of the Four Little Dragons for economic development in Asia, has undergone remarkable advancement in the field of infrastructure engineering and construction during the past few decades. During years of economic development, many major construction projects have involved significant amount of soft ground engineering works. Some of the areas have attained worldwide attention. This paper does not go into much technical details, but presents an overview of the soft ground engineering practice in Taiwan. Some major aspects of geotechnical characterization are discussed. The establishment and application of the geotechnical mapping of Taipei City is introduced. Soft ground engineering practices in foundation, deep excavation, tunnelling and ground treatment are described. This paper also presents recent development in the geotechnical instrumentation for various soft ground engineering projects in Taiwan.

INTRODUCTION

In hand with economic development is the onset of many major infrastructure construction projects. The rapid industrialization which Taiwan has experienced in recent years has brought in challenges to local engineering practice, especially in the field of geotechnical engineering. Advancement in the field of soft ground engineering design and construction has been realized; it is furthered with the demand for more sophisticated technical know-how in projects of mega-size proportions currently undertaken by the government.

It should be noted that most of the major cities and industrial areas in Taiwan are mainly underlain by recent sedimentary deposits. Therefore, the importance of soft ground engineering practice cannot be over-emphasized.

This paper first briefly describes the geology of the island of Taiwan. Major studies on the soil behavior and groundwater problems are summarized. Of particular interest is the development and the application of the geotechnical mapping system of Taipei City. The emphasis of this paper is focused on the various problems in soft ground engineering frequently encountered in Taiwan, such as foundation, deep excavation, tunnelling and ground improvement. From the geotechnical engineering point of view, some of the soft ground projects are very difficult compared with similar projects in other areas. Through decades of efforts, certain development in this field in Taiwan have gained worldwide attention and recognition.

GENERAL GEOLOGY

The island of Taiwan lies about 150 km off the east coast of Mainland China. It is separated from the mainland by the Taiwan Strait. The island is spindle-shaped, with the longitudinal axis extending roughly north-south for a length of 385 km. The maximum width is about 143 km and the total area of the island is approximately 35,960 sq. km.

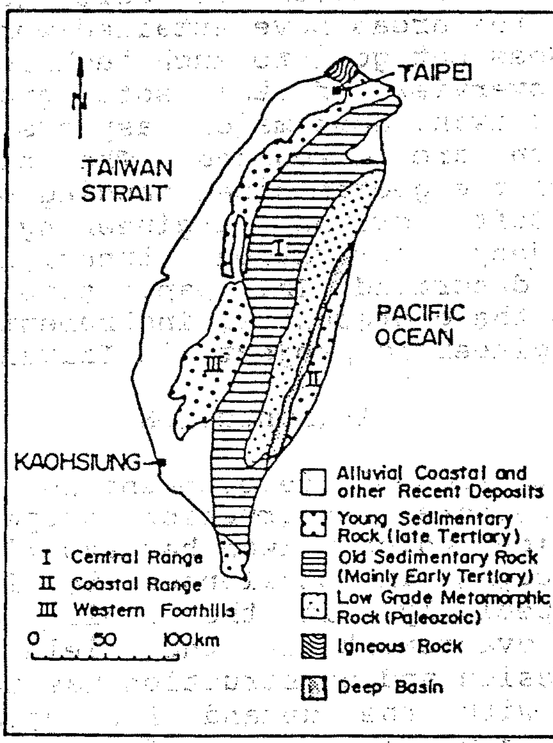

Fig.1 Geologic Map of Taiwan

The island is composed of geosynclinal deposition of Tertiary sediments to a thickness of more than 10,000 meters on a metamorphic basement. All the major rock formations on the island occur in long narrow belts roughly parallel to the longitudinal axis of the island. Taiwan can be broadly divided into three major geological provinces as shown in Fig. 1. These are the Central Range, including all the Tertiary submetamorphic and Pre-Tertiary metamorphic complex, the Coastal Range of Neogene sediments, and the Western Foothill province composed of Neogene clastic sediments (Ho, 1975).

The total area with elevation less than 100 m above the mean sea level covers about 31 percent of the entire area of the island. Most of these lands are in the alluvial plains or basins, which are underlain by soft clay and loose to medium dense sand of recent deposits. More than 20 million people thrive in these areas at a population density of more than 1,700 people per sq. km. In these plains and basins, geotechnical engineers are faced with many challenging soft ground engineering problems in various projects such as high-rise buildings, highways, power plants, rapid transit systems, etc.

Taipei, which is the major city in Taiwan, is located in the triangular shaped Taipei Basin in the northern part of the island. Many major projects had been built and several mega-size construction works are currently being undertaken. A number of major construction projects in Taipei will be used to exemplify the soft ground engineering practice in Taiwan.

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 the Pliocene and Pleistocene periods. The primary strata above the Tertiary bedrock in Taipei Basin are sedimentary deposits of the recent Quaternary period. Immediately below a thin layer of surface soil is the Sungshan Formation which extends to an average depth of approximately 50 m below ground surface. Sungshan Formation typically consists of six alternating cohesive and cohesionless soil layers. Due to the relatively high percentage of silt-size particles both in cohesive and cohesionless soils, the Sungshan Formation is often referred to as the "Taipei Silt Stratum" (Moh and Ou, 1979a). Below the Sungshan Formation is the Chingmei Formation. It is a gravel layer which has often been regarded as the bearing stratum for deep foundations. It has also served as the aquifer for deep well pumping to provide Taipei's water supply. Table 1 summarizes the profile of the sedimentary deposits in Taipei Basin. Typical soil properties of the Sungshan Formation is presented in Table 2.

GEOTECHNICAL CHARACTERIZATION

Site Investigation

In recent years, the importance of geotechnical investigation in construction projects has been recognized and appreciated. Very thorough investigations were

Table 1 Profile of Sedimentary Deposits in the Taipei Basin

FORMATION		THICKNESS (m)		SOIL DESCRIPTION
TOP SOIL (CL,CL/ML)		1-6		YELLOWISH BROWN CLAY
SUNGSHAN FORMATION	LAYER VI (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
HSINGCHUANG 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).				

Table 2 Summary of Engineering Properties of Typical Sungshan Formation Deposits in the Taipei Basin

SUBLAYER	w (%)	γ t/m^3	w_L (%)	Ip (%)	PARTICLE SIZE DISTRIBUTION GRAVEL	SAND	SILT	CLAY	Su kg/cm^2	$\overline{C}$ kg/cm^2	$\overline{\phi}$ deg.
VI	31.2	1.45	35.8	12.9	0	10	58	32	0.44	-	-
V	26.3	1.54	-	NP	1	75	19	5	-	0	32.5
IV	32.1	1.43	34.3	12.0	0	8	61	31	0.53	-	-
III	23.9	1.61	-	NP	0	60	34	6	-	0	33.3
II	27.2	1.55	30.3	9.2	0	9	67	24	0.53	-	-
I	20.3	1.70	-	NP	1	63	29	7	-	0	34.2

NOTE: 1. THE VALUES REPRESENT THE SOIL DEPOSITS IN THE T2 ZONE.
2. THE BOUNDARY BETWEEN CLAY SIZE AND SILT SIZE PARTICLES IS 0.005 mm DIAMETER.
3. THE VALUES OF UNDRAINED SHEAR STRENGTH, Su WERE DERIVED FROM UNCONSOLIDATED UNDRAINED TRIAXIAL TEST.
4. FOR SUBLAYERS I, III AND V, THE VALUES OF $\overline{\phi}$ WERE DERIVED FROM DIRECT SHEAR TEST.

conducted prior to or during the detailed design phase for many major projects, most notably in highways and rapid transit projects. Local drillers can carry out quality soil drilling, rock coring and thin-wall tube sampling works under engineer's supervision. Many research institutes and consulting firms are equipped with fairly good laboratory testing facilities. Geophysical methods of exploration are also frequently utilized in major engineering projects.

Significant changes in the local site investigation practice have been made in the past few years. Many in-situ tests, such as cone penetration test and flat dilatometer test, have been introduced to Taiwan and have become very popular. It has been widely accepted by local engineers that in-situ testing can be properly incorporated in the site investigation program in order to replace some time-consuming conventional drilling/sampling/testing works. More sophisticated laboratory tests have been required for very specific purposes in some major projects, for example, dynamic triaxial test for liquefaction assessment and Ko-consolidated stress path tests to study the behavior of cohesive deposits.. Due to these requirements, many laboratories have made significant improvement in the automation of laboratory equipment.

There are many geological hazards which could cause catastrophic damages to both ongoing projects and already constructed facilities. Major geological hazards in Taiwan have been summarized by Pan (1990). In addition to landslides, stream erosion and active faulting, there are other potential geological problems in soft ground which may cause serious damages to construction projects, e.g. gas emission, soil liquefaction, and other natural and man-made obstructions. The problems associated with these hazards have significant impact in the design and construction of the Taipei Rapid Transit Systems (TRTS). Recently, evaluation of these natural hazards and their mitigation have been regarded as one of the most important tasks in site characterization (Moh and Chin, 1991b).

Soil Behavior

Due to different sedimentary environments existing in various areas, characteristics of soft ground vary significantly in different basins and alluvial plains in Taiwan. In view of economic development and population concentration, studies of geotechnical characteristics have been concentrated mostly in metropolitan areas. The most extensively studied soil deposits is the Taipei Silt. In other metropolitan areas such as in Kaohsiung and Tainan, the study of local soil deposits still lack systematic summary and critical review.

During the past 20 years, a number of papers have been published describing the engineering properties of the Taipei soils (e.g. Hung, 1966; Moh and Ou, 1979a) . A detailed summary of the geotechnical charateristics of Taipei soils is presented in Woo and Moh (1990). It can be concluded that the general soil properties of Taipei and the variation of soil stratification within the Basin are well understood. However, for many major projects which involve very difficult underground constructions, a thorough understanding of the behavior of Taipei Silt is required. The nature of the Taipei Basin deposits is unique in that it has very high percentage of silt size particles in both cohesive and cohesionless soils. Previous researches on pure clay and clean sand cannot be applied. Since the start of the TRTS Project, many fundamental researches have been conducted with emphasis focused on the strength behavior of cohesive materials in Taipei (e.g. Chin et al., 1989; Liu et al.,1991). These researches are aimed at presenting a spectrum of behaviors, within the Taipei Basin, showing different stress-strain-strength behaviors at varying plasticity. The results will be very useful for future projects in Taipei. For example, taking strength anisotropy (Fig. 2) into account could avoid over-conservative design in certain conditions, i.e. the length of the diaphragm wall can be reduced. It is believed that these research results will also benefit the international geotechnical community. Such studies can provide a better understanding of silt behavior and partial drainage problems.

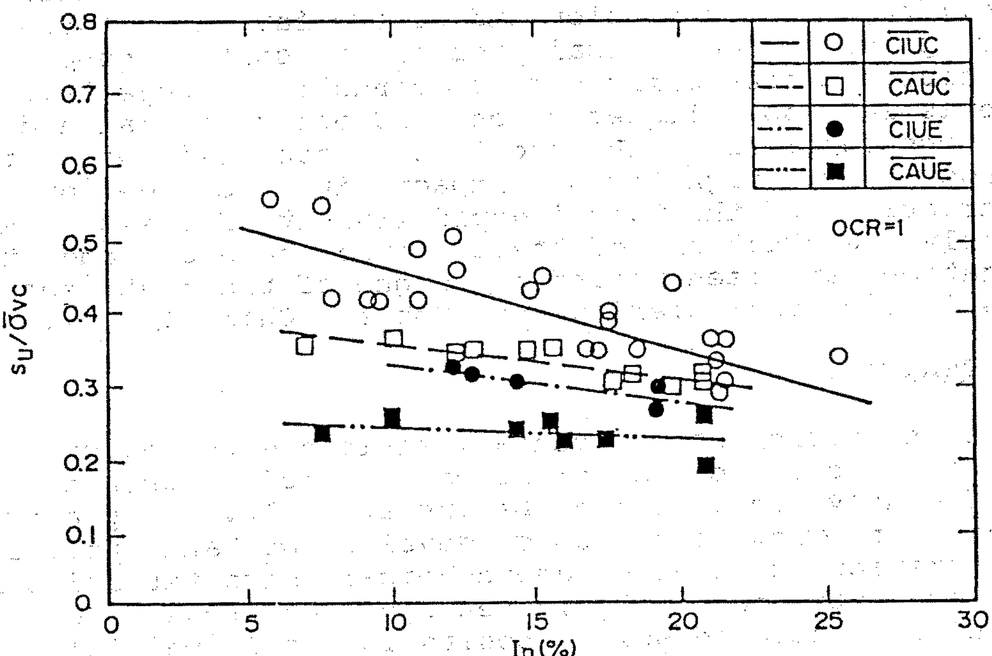

Fig.2 Normalized Undrained Strength with Varying Plasticity of Taipei Cohesive Deposits

Groundwater Conditions and Ground Subsidence

Ground subsidence due to extraction of groundwater by deep well pumping has long been recognized in many major cities around the world. In Taiwan, Taipei City and southwestern coast have suffered severe effects of ground subsidence.

Taipei Basin has experienced a very unique groundwater drawdown and recovery history. Significant amount of water has been pumped from Chingmei gravel since 1950s. In downtown Taipei, the maximum drawdown of piezometric head in Chingmei gravel reached about 45 m in 1975. Between 1950 and 1985, the ground subsidence in this area was 2.17 m. Since the restriction of deep well pumping by the government in 1968, the piezometric level of groundwater has been gradually rising and the rate of subsidence has been reduced to almost zero (Fig. 3). Although ground subsidence is no more a major problem in Taipei, the recovery of groundwater is still being monitored continuously. Careful evaluation is constantly being carried out as required for many ongoing construction projects. In deep excavations for the TRTS Project for example, the impact of the rising level of groundwater is very significant. For each specific contract, the detail design assumes a specific construction date from which the design groundwater pressure is based. Any significant variation between design groundwater pressure and the actual conditions during construction could either lead to uneconomical and over-conservative design, or catastrophic failure during construction if necessary modifications and adjustments in design are not made. Monitoring groundwater prior to construction is therefore imperative. Effective groundwater control has been regarded as the key to the success of underground construction projects in Taipei (Chin et al., 1991a)

Geotechnical Engineering Mapping

For better utilization of land, more economical and safer designs, and control or prevention of damage from natural hazards, the value of properly developed geotechnical engineering mapping cannot be over-emphasized. In Taiwan, initial efforts in systematically developing geotechnical engineering maps have been made for the Taipei City since 1984. Information on more than 700 boreholes with their associated in-situ and laboratory test results had been compiled and analyzed (Moh and Associates, 1987). On the basis of their geological origin and sedimentary environment, the subsoils in the Taipei Basin were subdivided into three major regions according to three major rivers flowing into the Taipei Basin, namely, the Tamshui River, the Hsintien River, and the Keelung River (Fig. 4). From detailed analysis of the composition and thickness of the various strata and engineering characteristics of the soils, the three major regions were further subdivided into seven zones. A series of geotechnical engineering maps were produced including a geological map, fence diagrams of soil profiles, maps showing isopachs of various sublayers, isohyp maps of the various sublayers and a geotechnical zoning map. In addition, correlations of engineering properties for the soil deposits in Taipei have also been established under this study (Moh et al., 1989). Results of this geotechnical engineering mapping work have proven to be extremely useful for many major projects in Taipei, especially for projects which extend widely over large areas such as the TRTS Project (Chin et al., 1991b).

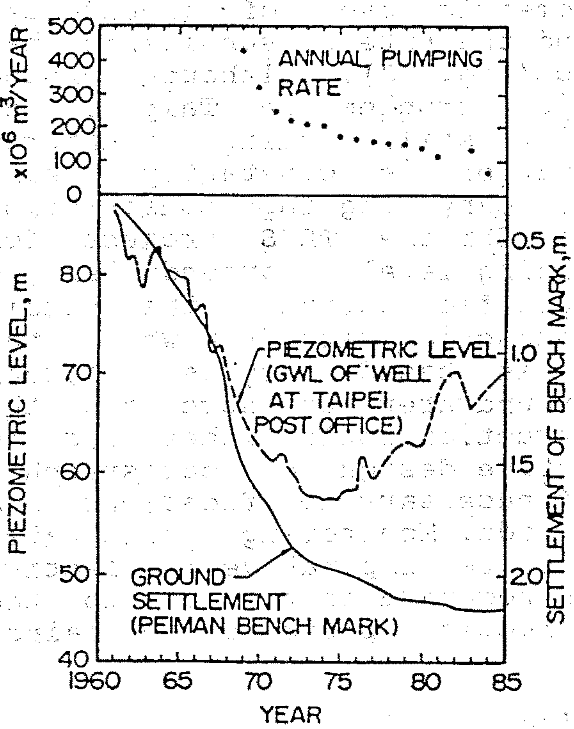

Fig.3 Groundwater Drawdown and Associated Ground Settlement in Taipei

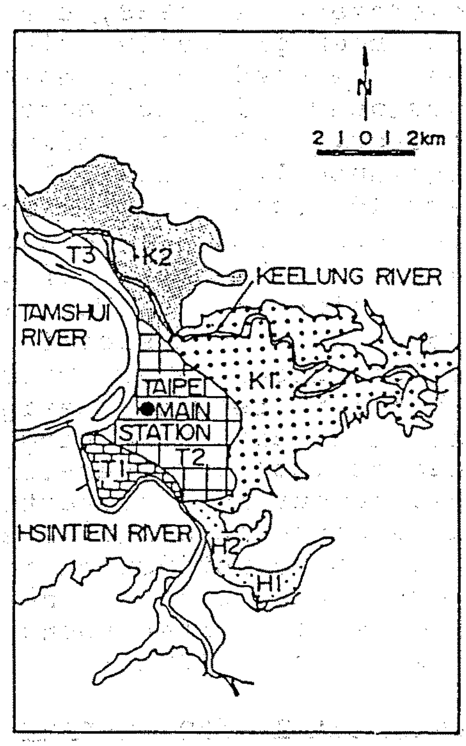

Fig.4 Sub-divisions in the Taipei Basin

GEOTECHNICAL PRACTICES

Foundations

Before 1960, there were very few tall buildings in Taiwan. Most of the structures were built with less than 4 stories. Except in areas of extremely soft soils, the most commonly used type of building foundation is spread footing. With the rapid economic development since 1960, many tall buildings and heavy industrial structures have been built. Due to poor subsoil conditions in most of the cities and industrial areas however, shallow foundations could not adequately support the heavy load imposed by these structures. Compensated foundation and deep foundation systems have thus become the most commonly used foundation types for major projects in Taiwan.

Compensated foundation or floating foundation utilizes the principle of stress reduction due to excavation to compensate full or part of the structure load. For subsoil conditions such as that in Taipei, compensated foundation for a typical 12-storey building needs to be placed at a depth of 10 to 12 m below ground surface. It has been estimated that more than half of the tall buildings in Taiwan had adopted this concept of compensating foundation (Moh and Ou,1979b). In design of compensated foundations, settlement control is always the primary concern but there are also problems related to deep excavation in the urban areas which must be taken into account.

With the dramatic increase of land value in the 1980s, more and more room spaces have been required by the developers for building projects. Since early 1980s many buildings higher than 12 storeys have been built. Where building loads are too heavy to be fully supported by compensating foundation, pile foundations are often required. In cases where building height is restricted by government regulation or where the structure is intended for a very specific use (e.g. underground parking garage), very deep basement is needed. Under such circumstances, tension piles are often used.

Due to noise and vibration concerns, the most widely used type of pile foundation in the urban areas is cast-in-situ bored concrete pile with diameter varying from 60 cm up to 240 cm. In some cases, the allowable load capacity of the pile is controlled by material strength. For a 240 cm bored concrete pile, the design load capacity can reach about 1,900 tons. The most commonly used boring equipment is of the reversed circulation type using slurry to stabilize wall of the drilled hole. A major concern in using bored concrete piles is necking which can occur along the pile shaft due to collapse of soil during pile installation. Design of recent projects in Taiwan such as the TRTS includes specification for integrity testing of the piles. In this respect, the Sonic Logging method has often been recommended. Aside from necking, concern about the cleanness of the bottom of the hole is another important consideration. If slime deposited at the bottom of the hole could not be completely removed, settlement could be very large and full end bearing would not be mobilized. During the piling of bridge piers for the Second National Freeway project in Hsinchu area, high pressure jet grouting at the bottom of the pile was carried out. It proved to be a very effective method in increasing the end bearing and reducing settlement of the bored pile. Other than the circular shaped bored piles, cast-in-situ barrette foundation has also been used in Taiwan. In a building project in suburban Taipei where the subsoil is occupied by very soft clay deposits, barrete foundation with maximum dimensions of 120 cm x 740 cm x 23.5 m was used.

Other types of piles which are frequently used in Taiwan to support structures other than buildings, such as bridges and machine foundations, include precast prestressed concrete piles, vibro piles, Raymond piles, and steel pipe piles. The Raymond pile, which is a step-tapered pile made of corrugated light-steel shells was extensively used in the first phase construction of the China Steel Coorporation in Kaohsiung. A total of 22,560 pieces (over 650,000 linear meters in total length) of Raymond piles were driven. Based on performance assessment during construction, the damage rate of Raymond pile was estimated to be 8.2 percent whilst that of the prestressed concrete piles exceeded 12 percent (Moh and Ou, 1979b). Steel pipe piles, though relatively expensive in Taiwan, have gradually gained popularity in recent years due to high material strength and high speed of installation. Steel pipe piles were used extensively for the power generating facilities and the 250 m high chimneys at the Hsin-Ta Steam Power Plant in southern Taiwan. Studies were carried out on the plugging effect of the open-ended pipe (Soo et al., 1980). The formation of soil plug inside an open-ended steel pipe pile during driving is summarized in Fig. 5. The distribution of loading capacity between shaft friction and end bearing was later studied by Yen et al. (1989).

Deep Excavation

Deep excavations have been frequently required in many building projects as well as industrial facilities. Various retaining and supporting systems have been used. The most commonly used retaining systems in Taiwan are soldier piles and lagging, steel sheet piles, cast-in-situ prepakt piles, and diaphragm walls. Major supporting systems are ground anchors and steel struts. Currently, most of the major deep cut-and-cover constructions in urban areas use internally-braced diaphragm wall system for excavation support.

In the past two decades, deep excavation has probably been the most extensively studied area of soft ground engineering practice in Taiwan. Many case histories on deep excavations have been reported in literature (e.g. Moh and Song, 1980; Woo et al., 1987, Moh and Chin, 1991a). It can be said that in 1980s, 2- to 3-storey basement excavation in soft ground is quite common and is not regarded as a particularly tough task. Indeed, deep excavation has gradually become a routine practice for building projects in Taiwan.

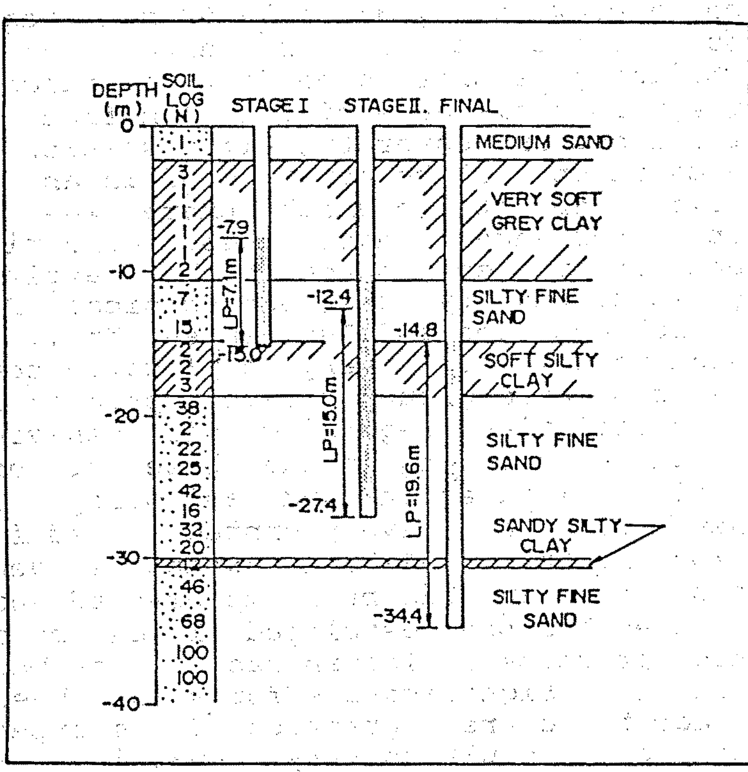

Fig.5 Development of Soil Plug During Pile Driving

There are three recently completed projects mentioned in Moh (1988) which are worthy of brief summaries here. The first is the LNG Receiving Terminal of China Petroleum Cooperation which is located in the southern part of Taiwan. The most significant task was the construction of a diaphragm wall system for the 64.5 m inside diameter and 44.8 m high underground tanks in a reclaimed land. The diaphragm wall was cast in 50 segments, each 1.2 m thick and 54.5 m deep (BES, 1987). The second project is the construction of the Taipei Main Station of the Taiwan Railway System. The Taipei Main Station excavation covers an area of 350 m by 150 m. Most sections of the excavation is 16.0 m deep. The deepest part has a depth of about 30.0 m. Steel sheet piles and diaphragm walls, which were supported either by internal bracing or prestressed earth anchors and berms were used as retaining structures. The third project is the construction of the basement for the new National Taiwan University Hospital Complex. Ground anchors varying in length from 2.3 m to 63.4 m were used (Chao and Chen, 1986). These are probably the longest ground anchors ever used in Asia. The design capacity of the anchors varied from 26 to 65 metric tons.

Though deep excavation is not uncommon in Taiwan, design and construction of the TRTS has faced many new and more difficult problems, for example: a 35 m deep excavation has been designed for a vent shaft structure with diaphragm walls penetrating 22 m into gravel formation; a large area of excavation, approximately 315 m by 60 m is required for an underground depot at 22.6 m depth; a chain of commercial buildings supported on footing foundations are located just within a distance of only 2 m from a 28 m deep excavation for a cut-and-cover tunnel; a station requiring 33 m deep excavation will be constructed in an area with very soft clay deposits in which there was only very limited past experience. Under these conditions, many design concepts and project approaches have evolved, which were mainly initiated by the Geotechnical Engineering Specialty Consultant, Moh and Associates, Inc., and the Detailed Design Consultants. Very complicated construction schemes with associated ground treament program have been proposed. Uncertainties regarding soil behavior during excavation such as swelling in the base of excavation, development of wall adhesion, and anisotropy effect on undrained shear strength, have prompted a need for further research (Moh and Chin, 1991b). Extensive geotechnical instrumentation program has been implemented and a data processing system has been developed. It can be said that deep excavation practice in Taiwan has now reached a stage of retrospection. Significant efforts have been put in order to upgrade the current practice. It is expected that such efforts would result to very rewarding experiences that could provide a deeper insight on the various mechanisms involved during deep excavations.

Soft Ground Tunnelling

Due to the rapid development in the urban areas in recent years, many underground public works have been proposed. Among the projects of relatively large scale include the underground sewage system and the rapid transit system. In view of the disruptive effect that could be caused by cut-and-cover construction, more recent projects have opted for the use of underground tunnelling. In a few special construction projects, other methods have been employed such as the pipe roof method used in an underpass project in Kaohsiung.

Tunnelling practice in Taiwan has been focused on the use of the Shield Method and the New Austrian Tunnelling Method (NATM). Shield tunnelling was first used in Taipei for the construction of a 4.5 m diameter sewage main line in 1976. Until 1988, approximately 13 kilometers of tunnels have been completed using shield machine (Ou and Tsai, 1988). Most of the works were related to sewage systems. The shield machines used varied in diameter from 3.27 to 4.83 m. Open shield, blind shield, slurry shield and earth pressure balance shield machines have all been used. Shield tunnelling usually includes auxilliary methods such as compressed air, dewatering and grouting.

One of the most important concerns when tunnelling in the urban areas is settlement control. The ground settlement that could be caused by shield tunnelling depends on actual ground condition, construction technique and the level of wokmanship. Up to the present, not enough reliable data have been accumulated and analyzed which can provide a conclusive range of ground loss and extent of influence zone caused by shield tunnelling in Taiwan. Initial findings show a wide range of variation in the volume loss, i.e. generally greater than 5 percent and as high as about 10 percent (Shirlaw, 1990). Statistics of available surface settlement measurements appear to be very high compared with properly executed shield machine tunnelling in similar grounds. The excessive settlement is believed to be mainly caused by workmanship problem.

For the TRTS Project, more than 18 km of twin bored tunnels, each with an outer diameter of 6.2 m will be constructed using shield machines. Many of them will be constructed under very difficult conditions such as under old buildings with shallow foundations, with stacked configuration having very minimal clearance (e.g. less than 1.5 m, Fig. 6), cutting through existing pile foundations,

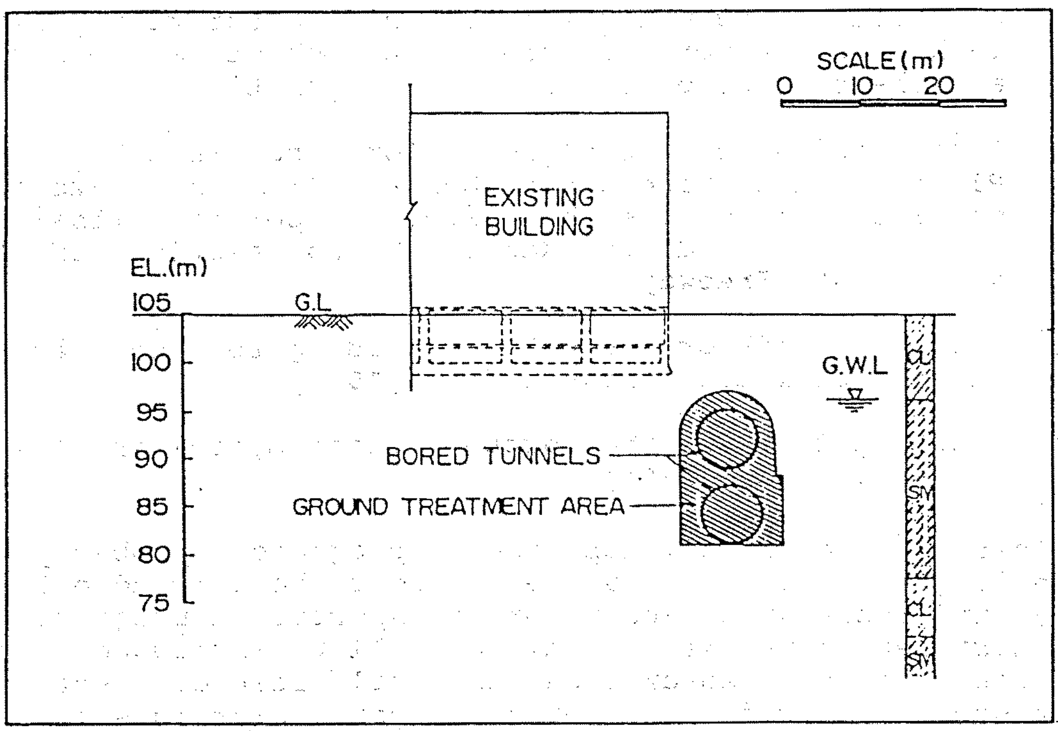

Fig.6 Stacked Tunnels Underneath Existing Building

etc. In addition to shield tunnelling, NATM is expected to be used in many short driven tunnel sections and in other areas having very variable ground conditions. In the Panchiao area, a 415 m tunnel connecting two stations is being designed entirely using the NATM method. Soft ground tunnelling is very likely to be the most challenging subject for the geotechnical engineers of Taiwan in this decade.

Soil Improvement

Soil improvement techniques have been widely used to improve or to change properties of soil deposits for the purpose of strength increase, settlement control, seepage control, reduction of liquefaction potential, and so on. In Taiwan, many soil improvement programs have been conducted in major development projects such as oil storage tank farms, power plants, freeway, railroad, sewage systems, etc. (Moh, 1985). A number of successful large scale soil improvement projects have been carried out recently such as the following:

(a) Preloading for the Yung-Kong Oil Terminal raw water storage tank (Chou et al., 1980)

(b) Compaction sand piles for reducing liquefaction potential at the Ta-Lin Thermal Power Plant and Hsin-Ta Steam Power Plant (Moh et al., 1981)

(c) Compaction sand piles with preloading for refrigerated tanks in the northwestern coast (Moh et al., 1982), and the stacker of China Steel Corporation

(d) Sand drains with preloading for the Hsin-Ta Power Plant fuel storage tanks (Moh, 1982), raw materials storage yard of the China Steel Corporation (Tsai et al., 1981), and the Keelung-Neihu section of the North-South Freeway

(e) Prefabricated drains with preloading for the Keelung River Reclamation Project (Moh, 1985)

(f) Grouting for the underground sewage system in Taipei (Lin and Hwang, 1984)

There are more soil improvement programs, probably of much larger scale, which are expected to be carried out in many land reclamation and major transportation projects in the next few years. New techniques will be introduced such as the use of geotextiles as soil reinforcement in expressway and bridge abutments. Of particular interest is the extensive use of grouting for the TRTS Project.

With the critical consideration for minimizing ground settlements adjacent to excavations, it behooves the engineers to find the most appropriate and effective means of reducing wall deflections during construction. For many stations located in the very soft clay deposits, different schemes have been critically reviewed such as using top-down construction scheme instead of bottom-up method, using crosswalls to act as buried struts between walls, using T-panels to increase the stiffness of the retaining system, and adding more struts with larger prestress load. However, analyses have indicated that the maximum lateral deflection of the wall would always occur below the base of the excavation. In such case, it appears that the most effective way of reducing wall deflection is to increase the strength of the soil below the base of the excavation. Hence certain major underground stations on very thick deposits of soft clay have resorted to the use of jet grout raft beneath the base of excavation. In the eastern part of Taipei, a 280 by 26 m station with an excavation depth of 16 m will use a 4 m thick jet grout raft (Fig. 7). Initial analysis without soil improvement indicated a wall deflection of about 150 mm. As such magnitude could lead to excessive ground settlement, the final design has specified the use of the jet grout slab which is expected to reduce the wall deflection by as much as 50 to 70 percent.

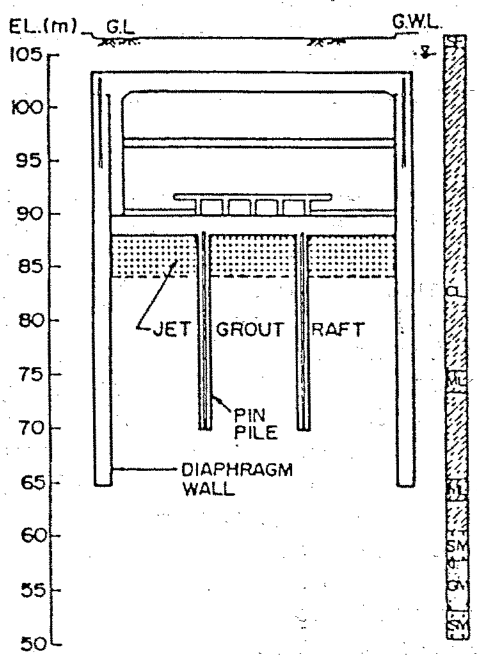

Fig.7 Jet Grout Raft to Increase Soil Strength Below Excavation Base

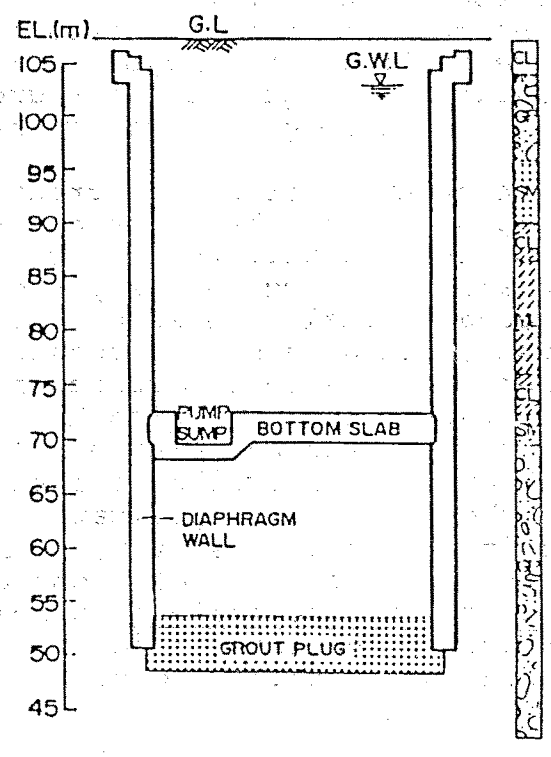

Fig.8 Grout Plug to Control Excessive Seepage

Jet grout plugs are also used to control excessive seepage during excavation. In some areas covered by the TRTS, the relatively shallow depth of the highly permeable Chingmei Gravel Formation has necessitated the use of grout plugs placed at the toe level of the diaphragm walls. For a circular vent shaft in the Hsintien Line designed with 26 m diameter and a maximum excavation depth of 35 m (i.e. reaching the top of the gravel layer), a grout slab of at least 5 m thick has been specified (Fig. 8).

Extensive grouting will be carried out during the construction of bored tunnels for the TRTS. As the shield method of tunnelling will be widely used, backfill grouting will be performed from within the shields or through grout holes in the lining plates to fill in the tail voids. Apart from backfill grouting, cement grouting and chemical grouting are required in sections such as sumps and crosspassages which do not employ the use of shield machine but are normally formed by manual excavation. In some areas with very difficult subsoil conditions, and where ground movement consideration is extremely critical, ground treatment by jet grouting will be carried out in a much larger scale. In Chungho Line for example, a 258 m long twin tunnel running in a stacked position between two stations is to be driven entirely into soft clay with sand and silt lenses. The line passes underneath buildings with overburden of about 11 m. The alignment is so difficult to construct in untreated ground that any other measure would likely lead to a major risk to public safety. Thus, the design has required a jet grout annulus to be formed for the entire length of the tunnel.

Another major use of grouting is for building protection purpose. For the type of soils in Taipei, compaction grouting and jet grouting can be used. Compaction grouting entails forcing a very viscuous cement grout into the ground, usually in sand to form a bulb thus replacing the lost ground caused by adjacent construction activities. A case history on the successful use of compaction grouting in the Baltimore Region Rapid Transit System Project has been reported by Baker et al. (1983). However there are not much other available literature describing case studies on the successful application of compaction grouting. Many design consultants for the TRTS Project have considered adopting the use of compaction grouting for building protection. The scale of compaction grouting which has been proposed in this project could be larger than the total amount of compaction grouting ever carried out in the whole world.

Instrumentation

Every geotechnical design involves some uncertainties and assumptions. Following the "observational approach", geotechnical engineers can use field instrumentation as a working tool to monitor the ground response during construction. Proper implementation of a monitoring program can make the design and construction safe and economical. The importance of field instrumentation was appreciated in Taiwan only until the late 1970s with the pioneering works carried out by Moh and Associates, Inc. One of the very first successful applications of field instrumentation was in the deep excavation for the China Airlines Building (Moh and Song, 1980). Instruments installed at the site include heave stakes, settlement points, piezometers, strut strain gauges and inclinometers. Settlement contours drawn from settlement points observations for the mat foundation of the main structure during construction (Fig. 9) has prevented the structure from experiencing an unacceptable magnitude of differential settlement which would have otherwise occurred without instrumentation monitoring.

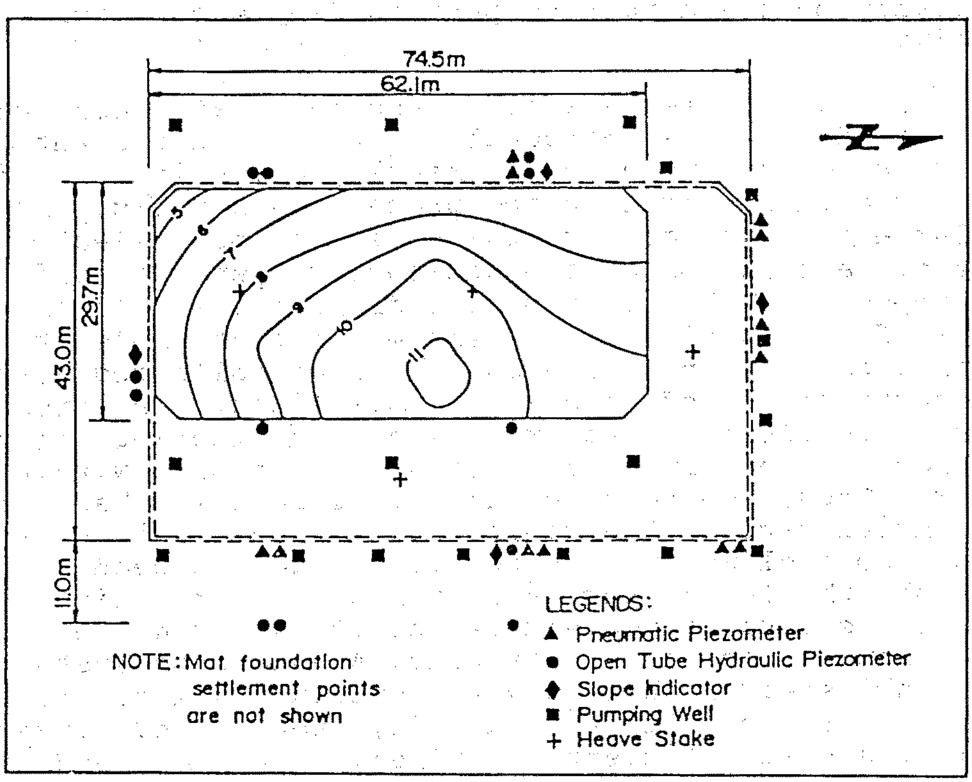

Fig.9 Settlement Contours of a Mat Foundation

Field instrumentation has also played a critical role in some of the major projects with longer period of excavation, e.g., Taipei Main Station. For the entire duration, the excavation and construction were controlled by monitoring an extensive system of instrumentation including earth pressure cells, piezometers, inclinometers, reinforcing bar stress transducers, and tiltmeters for surrounding structures (Moh and Associates, 1986-1988). A recent case of a monitored instrumentation for an open excavation, i.e. Taipei World Trade Center (Moh and Chin, 1991a) has been the subject of an ongoing research about soil-structure interaction during excavations. With the extensive data gathered from earth pressure cells, piezometers, inclinometers, heave stakes, settlement points, etc., the case study could reveal valuable informations on the actual mechanisms experienced by the soil during unloading. A preliminary analysis has been carried out by Chin et al. (1991b) using Stress Path Method.

Other than deep excavations, field instrumentation has also been implemented in other projects such as the Keelung River Reclamation project (Moh, 1985), pile load tests for the Hsin-Ta Steam Power Plant (Yen et al.,1989), shield tunnelling for the Taipei Sewage System (Li, 1987), and others. Today, the use of monitoring system has practically become a routine part in deep excavation works in Taiwan.

In the past few years, attention has been mostly concentrated on the introduction of new instruments for various kinds of projects. Currently, attention is being given to data acquisition and processing systems. Due to the large quantity of data which need to be collected and analyzed, automation of the monitoring system in order to save manpower has become almost indispensable. In the TRTS Project for example, it is estimated that more than 5 million items of monitoring data will be collected just for the construction of one of the six lines. In order to further facilitate data processing, monitoring stations have been distributed at various locations within the network. Thus, remote communication capability has become an essential part of the monitoring system. From an overall project control point of view, it was deemed necessary to establish the Integrated Data Storage Center which shall serve as the data management center for all the monitoring data from 21 monitoring stations. A data base system has been established which is a very powerful working tool for the engineers to collect, transmit, store, and interpret data in the most efficient and timely means (Moh and Chin, 1991b).

Previous case histories have repeatedly indicated that the geotechnical instrumentation can only be best used after the timely and proper interpretation of the data. It has to be emphasized that no matter how advanced and sophisticated are the "hardware" and "software" used, these tools can never fully replace the engineer's judgment.

SUMMARY AND CONCLUSION

During the period of the Ten Major Construction Projects from 1967 to 1972, most geotechnical engineering works specifically in the design aspect, were undertaken with the help of foreign experts. Since then, the capability to carry out geotechnical engineering works by local engineers has gradually developed (Moh, 1988). It is believed that with the current construction of several major projects, soft ground engineering practice in Taiwan will be significantly upgraded to world class level in 1990s.

This paper has presented a review of some major aspects of soft ground engineering practice in Taiwan. Studies made on the engineering properties of soil deposits in Taipei have significantly improved the understanding of silt behavior. It has been illustrated how groundwater drawdown and recovery could have critical influence on current and future construction works, and that it requires continuous monitoring. Geotechnical mapping system in Taipei has proved to be extremely useful. It is strongly suggested that geotechnical mapping should be established for other rapidly developing metropolitan areas.

Use of the various types of foundation system have been mentioned. The quality control of bored piles is still under intensive investigation. Development in deep excavation practice is probably the most interesting aspect of soft ground engineering in Taiwan. New construction techniques have been developed for special and difficult conditions. It is expected that the monitoring of deep excavation projects, especially for the TRTS will constitute a most valuable database for deep excavation works in the world. Soft ground tunnelling is just beginning in Taiwan. The total volume of work currently undertaken has demanded great efforts during design and it still requires a more indepth study.

Various ground improvement techniques have been successfully used in Taiwan, such as the use of prefabricated vertical drains and compaction sand piles. However, grouting experience in Taiwan still needs further enhancement in order to meet the requirements of future major construction projects. New grouting techniques will be introduced in Taiwan especially in the TRTS Project and it is expected that the method of grouting suitable for local soil conditions can be further developed.

The importance of instrumentation has been illustrated. Development of an efficient data processing system can greatly enhance the engineer's ability to collect, transmit, store, analyze and interpret monitoring data. This could be the most essential step in ensuring safety during construction.

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