PANEL DISCUSSION:GROUNDWATER CONTROL DURING THE CONSTRUCTION OF TAIPEI MRT

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Panel discussion: Groundwater control during the construction of Taipei MRT

Débat de spécialistes: Maîtrise de l'eau souterraine pendant la construction du MRT à Taipei

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ABSTRACT: The construction of the Taipei Rapid Transit Systems (TRTS) involves deep excavations in soft ground consisting of alternating layers of silty clay, fine sand, and silt. A thorough understanding of the groundwater conditions is required during the design and construction stages of the project. This paper describes the pumping history in the Taipei Basin, reviews the groundwater effect on construction, and presents various groundwater control schemes used in the TRTS construction.

1 INTRODUCTION

The priority network of the Taipei Rapid Transit Systems (TRTS) is 86.8 km long, with 79 stations. Over half of the stations and track are located below grade. The typical size of the underground stations is in the range of 200 to 300 m long and between 15 to 28 m deep. An additional 12.5 km of cut-and-cover excavation is also included in this project to accommodate crossovers and pedestrian shopping malls. Most cut-and-cover excavations are supported by internally braced diaphragm walls. Approximately 18 km of the underground track are constructed in 5.6 m diameter twin bored tunnels.

2 GEOLOGICAL CONDITIONS OF THE TAIPEI BASIN

The Taipei Basin is a tectonic basin covered with more than 200 m thick of Quaternary sedimentary deposits overlying the Tertiary bedrock. The Quaternary deposits can be divided into three major formations from the ground surface downward: Sungshan, Chingmei, and Hsinchuang Formations (Table 1). The final invert for the underground portion of TRTS generally lie within the two upper formations (Sungshan and Chingmei).

The Sungshan Formation the top surficial formation typically consists of six alternating cohesive and cohesionless soils labeled Layer VI (at the top) to Layer I (at the bottom). In summary, Layers VI, IV, and II are silty clay and clayey silt while Layers V and III are basically silty sands. Layer I, the lowermost layer, is variable and contains both clayey and sandy sublayers. Significant spatial variation exists within the Sungshan Formation due to its dependence on the depositional environment associated with the three major rivers which flow into the Taipei Basin.

Below the Sungshan Formation is the Chingmei Formation which consists of mainly gravel and sand. The composition and distribution of the Chingmei Formation is highly variable (Fu et al., 1990). This Chingmei Formation is an aquifer which has experienced dramatic cycles of deep well pumping. The piezometric level in the Chingmei Formation is critical during TRTS construction.

Table 1. Profile of the sedimentary deposits in Taipei Basin

LAYER		THICKNESS (M)		DESCRIPTION
TOP SOIL		1~6		YELLOWISH BROWN CLAY
SUNGSHAN FORMATION	SUBLAYER VI	2~8	40~70	GRAYISH BLACK SILT (CL ML)
	SUBLAYER V	2~20		GRAY SILTY FINE SAND (SM)
	SUBLAYER IV	6~29		GRAY SILTY CLAY (CL/ML)
	SUBLAYER III	0~19		YELLOWISH GRAY SILTY FINE SAND (SM)
	SUBLAYER II	0~19		GRAY SILTY CLAY (CL ML)
	SUBLAYER I	0~15		SILTY SAND (SM)
CHINGMEI FORMATION		0~140		YELLOWISH BROWN GRAVEL
HSINCHUANG FORMATION		0~125		GRAY TO YELLOWISH BROWN SANDY CLAY
TERTIARY SEDIMENTARY ROCK (IGNEOUS ROCK IN PEITOU, SHILIN AND KUNGKUAN)				

3 HISTORY OF GROUNDWATER PUMPING AND ASSOCIATED GROUND SETTLEMENT

During the development of the modern city of Taipei, changes in the groundwater regime, have been dominated by the extensive pumping from the Chingmei Formation to supply water for the city. Similar to other cities which have experienced the same phenomenon, significant of pumping-induced settlement occurred.

Figure 1 shows the typical water pressure drawdown in Chingmei gravel and the associated settlement data for the downtown area of Taipei. Pumping of the groundwater from the Chingmei gravel began prior to 1960. Despite of restrictions imposed by the government in 1968, pumping from the Chingmei Formation continued until the mid-1970's, when the greatest drawdown was reached. Thereafter, there is a trend of recovery of water pressures in the gravel layer indicating the reduction in pumping. As shown in Fig. 1, the ground surface settlement associated with pumping is closely correlated with the piezometric level within the Chingmei Formation.

Another effect of water pressure reduction in the Chingmei gravel was the reduction in water pressures in the overlying Sungshan deposits. The effect of pressure extended through reduction the bottom three layers of the Sungshan Formation Layers I to III. Layer IV, which consists of silty clay, acted as an aquitard and essentially preserved hydrostatic conditions in the overlying materials. Figure 2 focuses on these changes of groundwater pressure profile within the Sungshan Formation over the past 20 years. As shown in Fig. 2, in 1980, prior to the TRTS construction, the groundwater pressure in the Lower 4 layers of the Sungshan Formation is significantly lower than the hydrostatic pressure. Recent measurements have shown consistent increases in the piezometric pressure approaching the hydrostatic condition.

4 GROUNDWATER RECOVERY

As shown in Figures 1 and 2, the water pressures in the Chingmei gravel and the lower Sungshan deposits have been recovering since the mid-1970's. Figure 3 illustrates this groundwater recovery between 1974 to 1995 by including the typical water pressure data in the Chingmei gravel, Layer III of the Sungshan deposits, as well as measurements from Layer V. The data indicate a relatively slow rate of recovery between 1976 and 1981. From 1981 to 1988, the recovery rate increases with an average head of +2 to 3 m/year. The recovery trend of Layer III closely follows the pressure within the Chingmei gravel while the piezometric head in Layer V is independent from the underlying aquifer. Despite of the consistent groundwater recovery, recent monitoring records indicate that the current groundwater pressure is still below the hydrostatic level (Fig. 2). It should be noted that the slight drop in groundwater pressure in 1994 (see Fig. 2) is due to large scale TRTS pumping from the Chingmei gravel. The TRTS construction dewatering reached its peak stage in 1993-1995 and exceeded the rate of natural recharge.

The past pumping with large reductions in groundwater pressure in the Taipei Basin have generally benefited previous excavations in the city. These excavations, typically for building basements, were well above the piezometric level in the lower Sungshan deposits therefore groundwater control measures were not required. The performance of these braced excavations was reasonably good in terms of wall deflections and ground movements; the favorable groundwater conditions undoubtedly contributed to the good performance.

For the TRTS excavations, groundwater control measures were required as the combination of greater excavation depth and the groundwater recovery places the excavation invert well below the piezometric level. Several construction failures occurred at TRTS sections which can be attributed to the higher groundwater pressure; therefore, the control of these water pressures is critical in achieving stability of the walls and limiting wall deflections and ground movements. Nevertheless, the past regional pumping also has some beneficial effects on the TRTS excavations. The past pumping in the Taipei Basin have caused the lower Sungshan deposits to become overconsolidated, thereby, reducing the compressibility of the cohesive layers to 10%-20% of that in the normally consolidated range. Since pumping associated with TRTS construction would caused less water pressure reduction over a shorter period than in the past, this reduction in compressibility also translates into limited and acceptable level of surface settlements even with groundwater drawdown outside of the excavation.

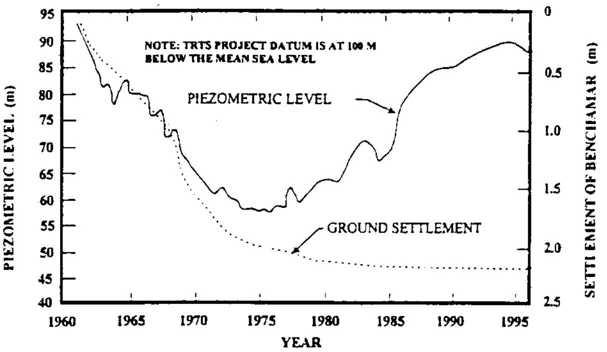

Figure 1. Groundwater drawdown and ground settlement in Taipei

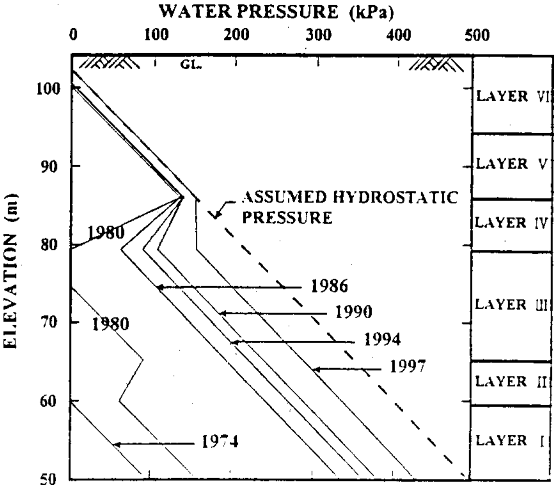

Figure 2. Groundwater pressure profile in Taipei Basin

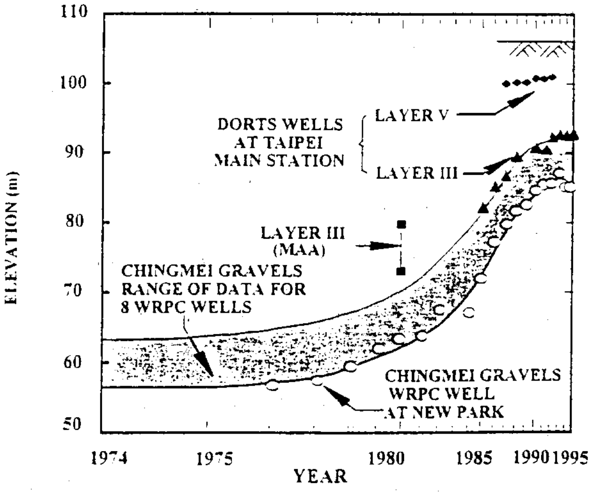

Figure 3. Piezometric level of Chingmei gravel in Taipei Basin (after Chin et al. 1992)

5 CONTROL OF GROUNDWATER PRESSURES

Depending on the subsurface conditions and configuration of the underground structures, various groundwater related issues need to be considered (Chin et al., 1992). This paper focuses on two types of groundwater and soil conditions which affect stability of the excavation: (1) When the materials below the excavation base are permeable and extend below the toe of the wall, groundwater control is required to prevent significant upward flow (i.e. "piping") from outside of the excavation, and (2) If the materials below the excavation invert are impermeable, the stability of the base is provided by the weight of the clay plug. The uplift/buoyancy and water-proofing of the permanent buried structure are some of other groundwater-related concerns which are outside the scope of this paper.

There are a number of different approaches which can be used to overcome problems associated with high groundwater pressures. Three approaches are used for the TRTS excavations: reducing groundwater pressure by pumping, reducing the permeability of the ground, and excavation underwater. These methods are described and evaluated below (Table 2):

Table 2. Advantages and disadvantages of various groundwater control approaches (after Chin et al., 1992)

APPROACH	ADVANTAGE	DISADVANTAGE
(1) REDUCING WATER PRESSURE BY PUMPING	The water pressures can be monitored. It is a flexible approach.	Lowering of groundwater can induce settlement. Pumping and disposal of large volume of water is required.
(2) REDUCING THE PERMEABILITY OF GROUND	The treated ground has an increased strength.	It is difficult to check the integrity of the treated zone. Problems can develop suddenly and are difficult to predict.
(3) EXCAVATION UNDER WATER	It is a "fail-safe" approach.	Large volume of wet soil need to be disposed. It is slow and difficult to inspect.

(1) *Reducing Water Pressures by Pumping*:

The most commonly used approach to overcome problems associated with groundwater is to reduce water pressures by pumping from permeable deposits. The water pressures are controlled by pumping from wells, educators, well points and/or conventional well points outside the excavation. Relief wells, wicks, pumped wells and/or well points can also be used inside the excavation. Only pumping wells were installed in the TRTS works.

At the Ventilation Shaft B of CP261, the excavation depth was 34 m (Fig. 4) and the groundwater level of the Chingmei gravel was required to be drawn down from elevation 89.0m to elevation 79.5m to prevent blow-in failure. Hwang et al.(1996) reported that ten 82m deep pumping wells were installed. Each well was equipped with an 80 hp submersible pump. With the total capacity of 3800 m^3/h, the total drawdown of 9.5m was reached in about 10 days. Since then this level of drawdown had maintained for a period of 100 days. As discussed before, the piezometric level of the Chingmei gravel was one time as much as 40m below its present level. The overlying Sungshan Formation had been consolidated to a much greater effective stress state and thus the ground settlement resulted from this 9.5m drawdown in the Chingmei gravel was minimal. Observations of the adjacent settlement markers indicated that the ground settlement which could be attributed to pumping did not exceed 5mm.

(2) *Reducing the Permeability of the Ground*:

An alternative to minimize groundwater drawdown is to prevent groundwater flow by reducing the permeability of the ground instead of reducing the water pressure. This is achieved by creating either complete or partial cut-off zones in the appropriate

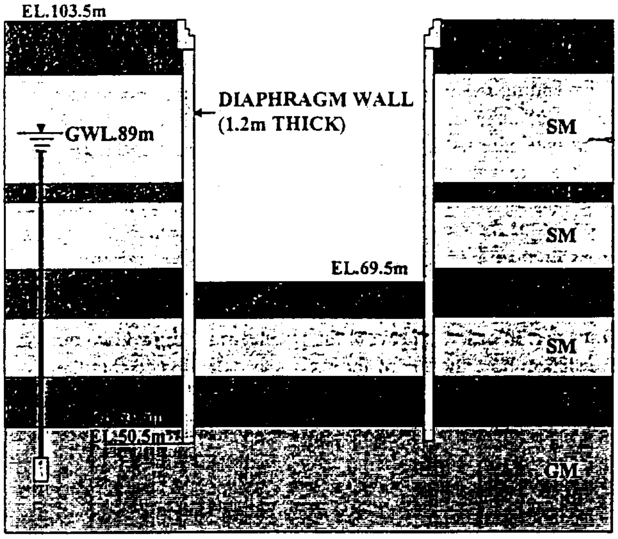

Figure 4. Soil profile at shaft B of CP261

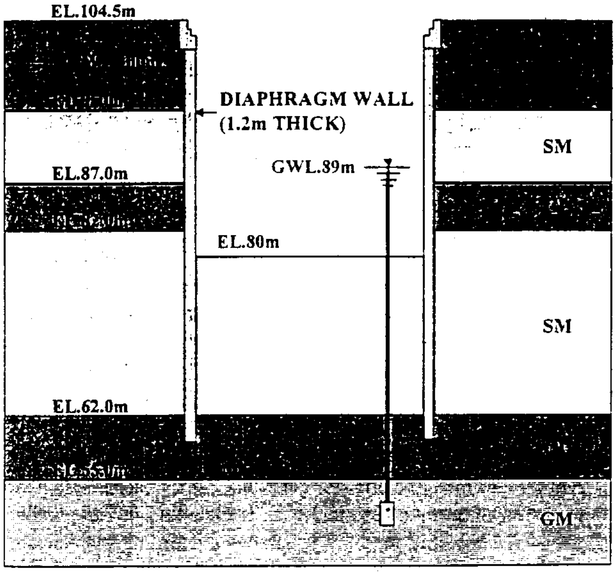

Figure 5. Groundwater cut-off with diaphragm wall

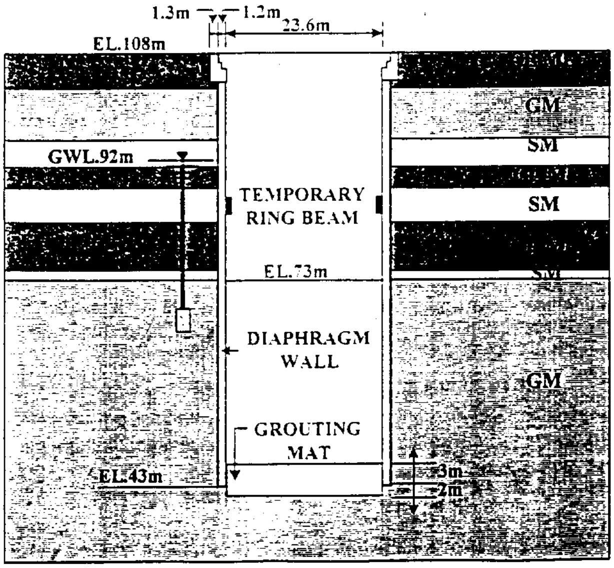

Figure 6. Grouting mat at the ventilation shaft of CH221

pervious deposits. Various methods are available to reduce permeability, such as grouting or freezing outside, inside and/or below the excavation.

Extending the diaphragm wall into the impermeable layer as the cut-off is commonly used. While the Sungahan Formation consists of alternating sandy and clayey layers, the seepage path into the excavation area can be blocked by the diaphragm walls extending to the underlying impervious layer. Figure 5 presents a section of the excavation of CN252 Station which is a typical excavation of TRTS station box. Concerning the stability of the excavation, the required length of the diaphragm wall was estimated to be about 36 m. Its toe would rest into the sand layer. However, in order to prevent the groundwater drawdown outside the station box, the toe of the wall was extended so that the diaphragm wall penetrates 2 m into the clayey Sublayer II to achieve the cut-off purpose.

Grouting has also been widely applied to cut-off the drainage of flow. Both grout plug and grout curtain have been used in the excavation of very deep shafts. Grout curtains were used at two cross-passages in CC277. The grouting were conducted by the tube-a-manchette, i.e. the sleeve grouting, technique. The cement/bentonite grout were injected in the primary stage and the sodium silicate grout were injected in the secondary stage.

Grouting and freezing were used in the construction of CH221 shaft at different stages. Grouting mat for groundwater control was used at the ventilation shaft of CH221. As shown in Fig. 6, with the provision of the grouting mat at the toe level of the diaphragm walls, the self weight of the soil plug alone between the bottom level of the mat and the excavation level provided a factor of safety of 1.25 against blow-in. The grouting mat was formed in the gravelly subsoil. The tube-a-manchette method was used to inject the silicate base grout which comprises the cement/bentinite and sodium silicate materials. The construction of the shaft was successfully completed. However, a piping failure occurred with a large amount of water flushed into the shaft when the contractor tried to break the grouted area around the interface between the completed tunnel and the shaft. Although ground freezing is generally more expensive than other types of ground treatment in Taipei, this technique was used for the restoration for this shaft. According to Fan and Chiao(1997), in order to reinstate the damaged tunnel lining caused by piping failure, ground freezing around the annulus of the bored tunnel was adopted. The freezing pipe were spaced at 0.8 m interval around the tunnel. Under the ambient temperature of 24°C, circulating the brine at a temperature of -25°C, a freezing zone of about 1.2m in radius was achieved in about 70 days. A total of 38 horizontal and 56 vertical pipes were installed along a 22 m section of the bored tunnel. After the freezing zone was formed the soil in the tunnel was then removed and the damaged linings were replaced without difficulty.

(3) *Construction Underwater:*

This is a completely different approach which does not rely on pumping nor the ground treatment. The excavation takes place completely underwater, and the base slab is constructed by the tremie method. Though this approach was successfully implemented in the construction of Singapore MRT(Hulme et al., 1989), this method was not proposed nor adopted for any sections of the TRTS excavations. However, under very adverse conditions, some constructions did take place underwater as a part of restoration work.

6 CONCLUSIONS

1. For deep excavations with high groundwater pressure, it is extremely important to have a thorough understanding of the ground and the groundwater condition.
2. Permeability of the gravel is highly variable and difficult to estimate. Therefore, final evaluation of the feasibility and cost estimate of the groundwater control scheme must include site-specific field pumping tests for each construction section.
3. Observational method should be applied to all deep excavation projects under high water pressure. Groundwater pressure must be carefully and continuously monitored during construction.
4. For excavations with high groundwater pressure, there is generally a very limited reaction time when an adverse condition develops. Therefore, it is crucial to define and prepare for contingency plans prior to construction.

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