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Hydraulic Characteristics of Jingmei Formation and Dewatering for Deep Excavations in Taipei Basin

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ABSTRACT: The presence of the Jingmei Formation is a unique geological feature of the Taipei Basin. This highly permeable and water-rich stratum was responsible for many failures in underground constructions. The piezometric heads in the Jingmei Formation had to be lowered by pumping for deep excavations to be carried out safely. Discussed herein are the hydraulic characteristics of the Jingmei Formation and the experience gained in large scale dewatering schemes. Attempts have been made to establish the relationship between the progression of tides in the river and the fluctuation of the piezometric levels in the Jingmei Formation.

It has been found that, the transmissivity and storage coefficient deduced from the observed groundwater drawdown are affected by not only the pumping rate, but also the duration of pumping. Therefore, the rates required tend to be overestimated based on the results pumping tests.

KEYWORDS: Jingmei Formation, Taipei Basin, Underground Construction, Deep Excavation, Dewatering

1. INTRODUCTION

The Taipei Basin, refer to Figures 1 and 2, was formed as a result of subsidence due to tectonic movements in the Middle Pleistocene Epoch. The basin was filled with debris brought by the Danshui River (or, Tamsui River as previously translated) with her three major tributes, namely, the Dahan Creek (or, Tahan Creek), Xindian Creek (or, Hsientien Creek) and Jilung River (or, Keelung River), as depicted in Figure 3, from the surrounding highlands (Teng, et al., 1999; 2004).

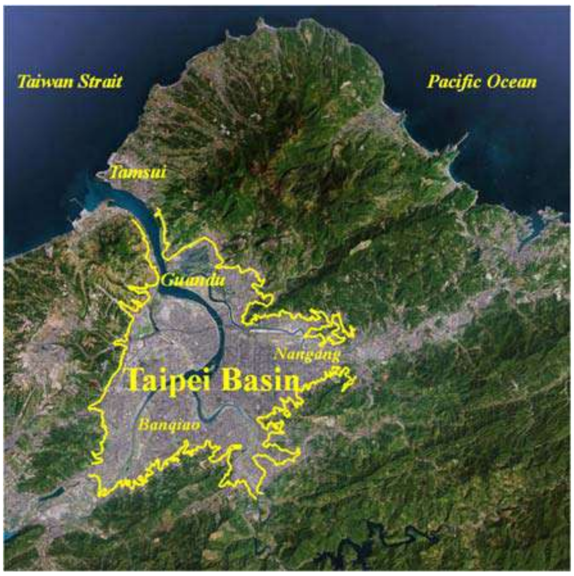

Figure 1 Satellite Image of the Taipei Basin

The Central Geological Survey (CGS) of the Ministry of Economic Affairs has conducted extensive studies to reveal the geology in the basin. As can be noted from the schematic profile shown in Figure 2, which was prepared based on the information collected from deep holes (refer to Figure 3 for locations), the sediments in the basin include, from top to bottom, the Songshan (or, Sungshan) Formation, Jingmei (or, Chingmei) Formation, Wugu Formation and the Banquiao (or, Panchiao) Formation (Teng, et al., 1999; 2004). The deepest depth to the base formation, i.e., the deformed Tertiary Strata, was 679m, revealed at Borehole WK-1E (Deep Hole 3 in Figure 3).

From an engineering point of view, the formation of the most interest is the Jingmei Formation which is sometimes referred to as Jingmei Gravel. First of all, it is a bearing stratum for deep foundations. Secondly, it was responsible for several disastrous events in the early stage of metro construction (Moh, et al., 1997; Hwang, et al., 1998). Because it is extremely permeable and water-rich, once water from the gravel finds its way to suddenly discharge into a pit, it is nearly impossible to stop the flow. Most of the disasters occurred during launching of shield machines at launching shafts or during arrival of shield machines at reception shafts (Lin, et al., 1997). In another scenario, water suddenly discharged into a station excavation as a hole was made through the overlying Songshan Formation to replace a malfunctioning piezometer installed in the Jingmei Formation. It became necessary to flood the whole pit by breaking a water main to discharge water into the pit to balance the groundwater pressure and stop the flow. It was estimated that 70,000 cubic meters of water was discharged into the pit in 18 hours (Moh, et al., 1997). The presence of this water-bearing aquifer makes the geology of the Taipei Basin unique and challenging to geotechnical engineers.

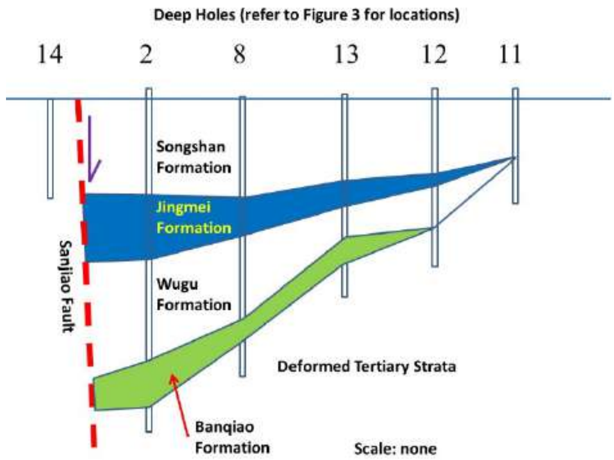

Figure 2 Schematic geological profile of the Taipei Basin

Discussed herein are the hydraulic characteristics of the Jingmei Formation and the largest dewatering scheme carried out in the Taipei Basin.

2. HYDRAULIC CHARATERISTICS OF JINGMEI FORMATION

The Jingmei Formation, which is composed mainly of cobbles and boulders embedded in matrix of sandy gravels, is an alluvial fan formed by the deposits transported by the Xindian Creek, refer to Figure 3, from the south. Teng et al. (2004) reported that this formation has the maximum thickness of 60 m near Xinzhuang and diminishes around the perimeter of the Taipei Basin. The top of this alluvial fan dips toward northwest and has the lowest elevation of 120 m below sea level at Wugu. Figure 4 shows the contours of the thickness of the Jingmei Formation based on the data collected by CGS.

Figure 3 Locations of deep holes by Central Geological Survey (CGS)

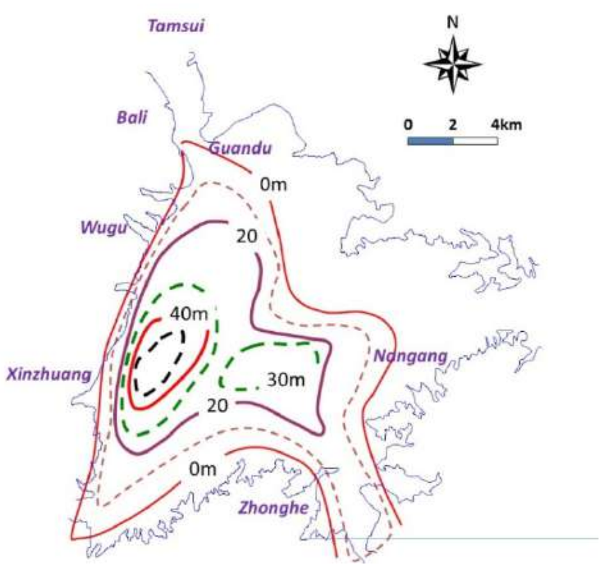

Figure 4 Contours of thickness of the Jingmei Formation (CGS)

The Jingmei Formation is a water-rich aquifer and was once the sole source of water supply of the city. The piezometric level of groundwater in the Jingmei formation was a few meters above the ground level at the turn of the 20th century (Wu, 1968) and dropped drastically as a result of excessive pumping. It was closely monitored by Water Resources Planning Commission (WRPC) before it merged into Water Resource Bureau (WRB) in 1996. Water Resource Bureau later merged into Water Resources Agency (WRA) in 2002 and the monitoring has been continuing ever since. Figure 5 shows the variation of piezometric level of groundwater in the Jingmei Formation and ground settlement observed at North Gate, which is about 0.5km to the west of Taipei Main Station, refer to Figure 6 for location, As can be noted, the piezometric level dropped to, as low as, EL- 40m, which corresponds to a depth of 44m (ground level = EL+4m) in the 1970's. Because the Jingmei Formation is extremely permeable, the groundwater drawdown was widely spreading. As can be noted from the contours showing in Figure 6, the drawdown in the Jingmei Formation in year 1975 was the largest in Xinzhuang and significant drawdown extended all the way to the rim of the basin (WRPC 1976).

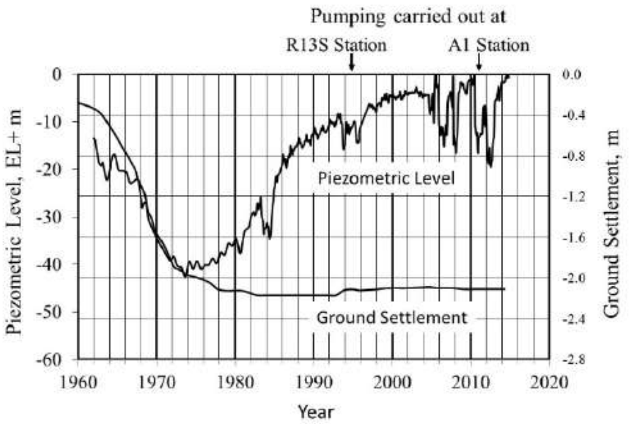

Figure 5 Piezometric level in the Jingmei Formation and ground settlement in central area of Taipei City

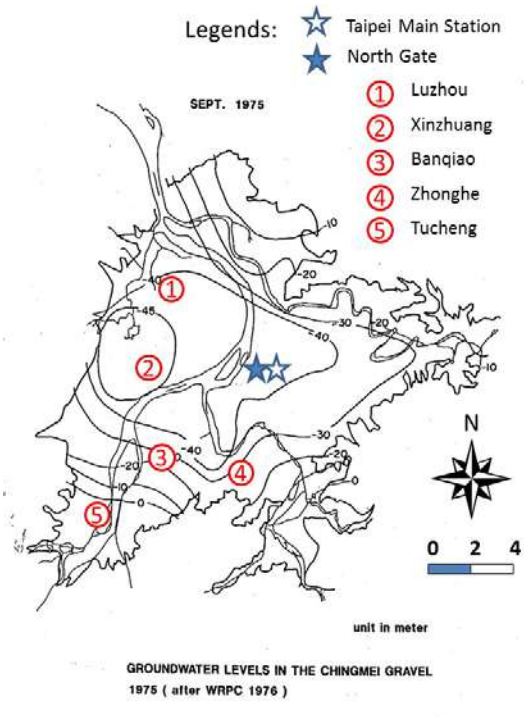

Figure 6 Contour of groundwater drawdown in the Jingmei Formation in 1975 (after WRPC 1976)

Figure 7 shows an east-west geological profile of the Taipei Basin and as can be noted that the overlying Songshan Formation consists of an alternation of layers of silty clay and silty sand. As the piezometric levels in the Jingmei Formation dropped, the soft deposits in the Songshan Formation were consolidated as the porewater pressures were reduced as a result, leading to ground settlements at surface. Alerted by the significant ground subsidence, the government started to regulate pumping of groundwater in 1971 and the piezometric levels became steady in the subsequent years. As depicted in Figure 8, the piezometric levels started to rise in the early 1980's as surface runoff gradually replaced groundwater as the source of water supply. The recovery of piezometric levels was wide spread as can be noted by comparing Figure 6 with Figure 9. The recovery, however, has been slowed down since the early 90's due to the lowering of groundwater pressures for maintaining the stability of deep excavations in several large infrastructure projects, particularly, the metro systems.

The disastrous failures experienced in Stage 1 construction of Taipei Metro back in the 1990's can be attributed to the facts that, firstly, the excavations were unprecedented at that time, as previous excavations were mostly for basements of less than 15m in depth while the depths of metro excavations generally range from 20m to 30m, and secondly, the piezometric level in the Jingmei Formation had risen by 30m from its lowest level during the 1970's. With the experience gained in the Stage 1 construction, designers and contractors were much more cautious in dealing with groundwater problems and no serious failure occurred in Stage 2 construction of Taipei Metro in the 2000's.

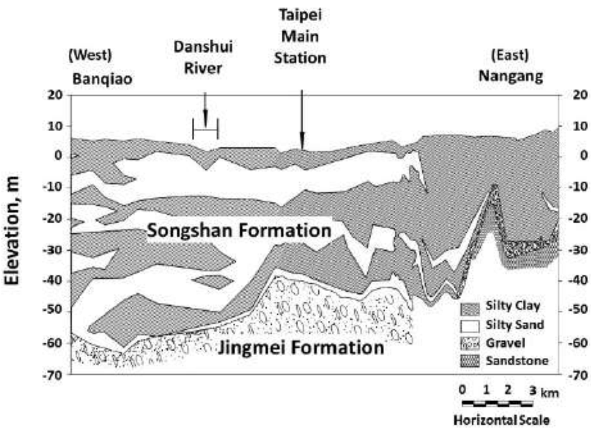

Figure 7 East-West geological profile of Taipei Basin

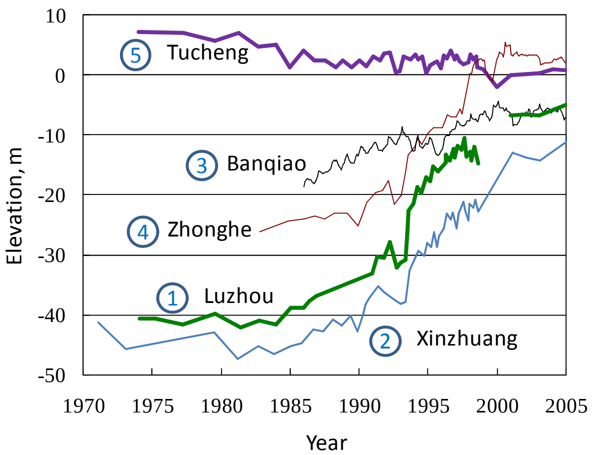

Figure 8 Changes of piezometric levels in the Jingmei Formation in suburbs

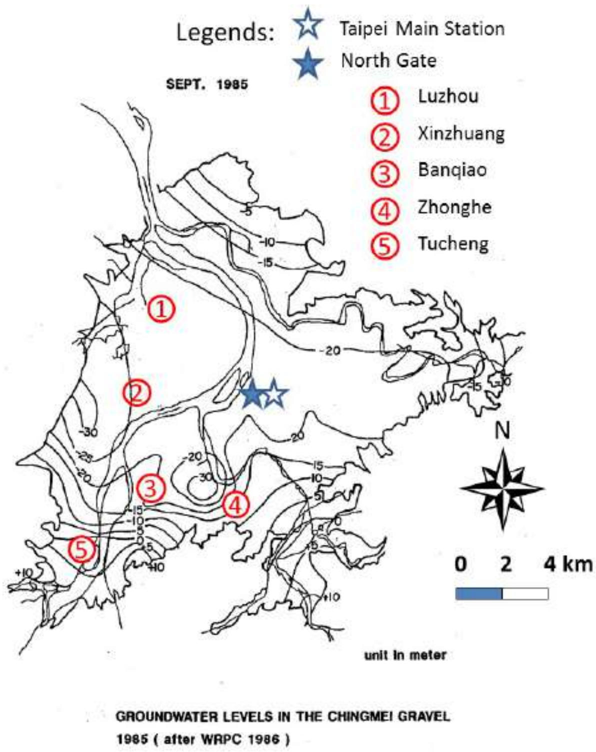

Figure 9 Contour of groundwater drawdown in the Jingmei Formation in 1985 (after WRPC 1986)

3. INFLUENCE OF TIDES

The influences of tides on the groundwater in the Jingmei Formation were first noticed by the Geotechnical Engineering Specialist Consultant (GESC) engaged by the Department of Rapid Transit Systems when the results of the pumping tests carried out by the Contractor for the Construction Contract CH221 at the site of the ventilation shaft were reviewed. As shown in Figure 10, the data became erratic hours after the commencement of pumping, making the derivation of hydraulic properties of the Jingmei Formation difficult. Furthermore, the drawdowns were too small for practical purposes. A 25 Hp (horse-power) pump was used and the pumping rate was only 2.43 m^3/min (146 m^3/hr). The influence of pumping was overshadowed by the fluctuation of the piezometric pressures of the groundwater due to tidal effects. As such, the results cannot be reliably interpreted.

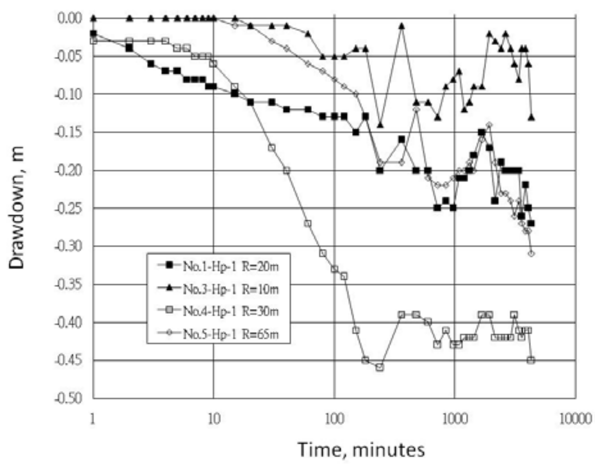

Figure 10 Results of pumping test at ventilation shaft of the Zhonghe Line

An extensive study was conducted by the GESC to investigate the influence of tides on the piezometric pressures of groundwater at the site of Ventilation Shaft B, refer to Figure 11 for location, in Construction Contract CP261 of the Panchiao Line, now renamed as the Bannan Line (Liu, et al., 1994; Liu and Yang, 1995). As shown in Figure 12, the average amplitude of fluctuation of the water level in the river was about 2.5m, peak-to-peak, while that of the piezometric level in the Jingmei Formation immediately next to the river bank was about 0.5m, or 20% of that of the water level in the river.

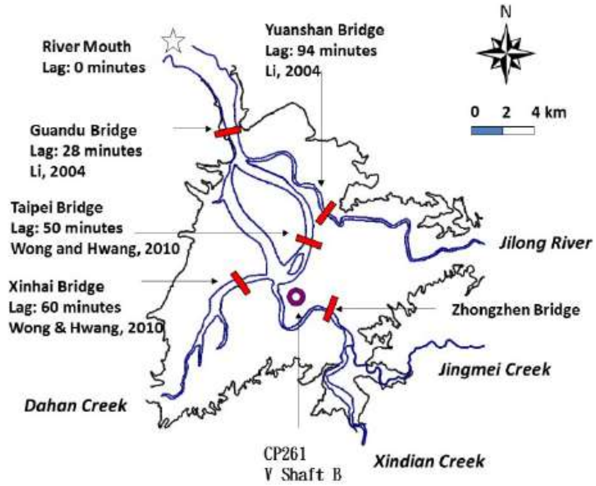

Figure 11 Locations of Ventilation Shaft B and time lags of tides along the rivers

What is interesting is the fact that the peaks and the troughs of piezometric levels in the Jingmei Formation were ahead of those of the water levels in the river. Preliminary study indicated a time lag of 1.5 to 2 hours for the latter (Liu, et al. 1994; Shao, et al. 1995); however re-analysis indicates that the time lag was only 51 minutes. When a tidal wave moves into an estuary, it is attenuate by bottom and internal friction. Its reflection continues to dampen as it moves seaward. The combination of an incoming damped wave and the damped reflection from the previous wave produced a tidal wave with complicated characteristics. The propagation of the wave will also depend on the geometry of the river. Li (2004) compared the records of 2 January, 2001 by Water Resource Bureau and found that the tides lagged by 28 and 94 minutes at the locations of Guandu Bridge and Yuanshan Bridge, respectively in comparison with those observed at the estuary of the Danshui River. Wong and Hwang (2010) conducted a similar study on the records of 3 Jan 2010 and the found that, refer to Figure 13, the lags were 50 and 60 minutes at the locations of Taipei Bridge and Xinhai Bridge, respectively. The time lags at various locations are shown in Figure 11 and the speeds of traveling of tides are summarized in Table 1.

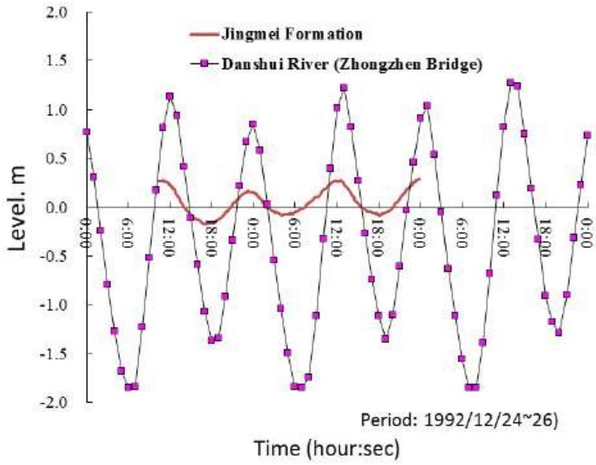

Figure 12 Piezometric levels in the Jingmei Formation as affected by tides (Shau, et al., 1995)

Shih (1998) conducted frequency analyses on the data obtained in the period of 1 November, 1995 to 31 October, 1996 and found that the time lags are different for different components of the tides. For Xinhai Bridge, the time lags were 57.21 minutes for K1 tide (with a period of 23.87 hours), 51.97 minutes for M2 tide (with a period of 12.48 hours). The time lag of 51.97 minutes observed at Xinhai Bridge for the predominant M2 tide is comparable with the 60 minutes obtained in Wong and Hwang (2010) based on the data obtained in 3 days during spring tide. As shown in Figure 14, the average propagation speed of the river tides is 23 km/hr. At a distance of 27 km from the Danshui estuary, the extrapolated time lag for the river tide at Zhongzhen Bridge is about 70 minutes. However, as can be noted from the figure, the time lag for the river tide at Yuanshan Bridge is much longer than the average, presumably due to the narrowness of the Jilong River. It is then anticipated that the time lag would be longer than what is predicted because of the narrowness of the Xindian Creek.

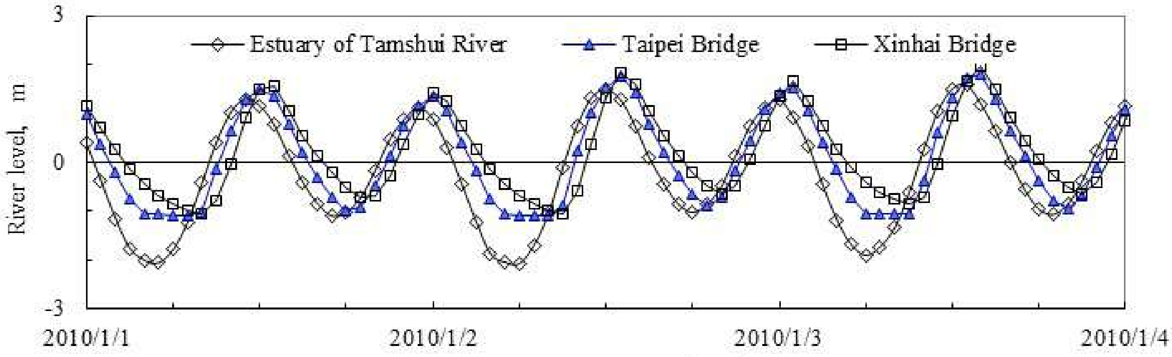

Figure 13 Changes in water levels in the Danshui River (Wong and Hwang, 2010)

Table 1 Tidal response along the Danshui River system

Reference	Period of observation	Tidal station	Distance to river entrance km	Tidal range at spring tide m	Time of tidal wave arrival min	Travelling speed km/hr
Wong and Hwang (2010)	3 Jan 2010	Danshui City	0	3.41	0	-
		Taipei Bridge	16.3	2.80	50	20
		Xinhai Bridge	22.7	2.84	60	38
Li (2004)	2 Jan 2001	Danshui City	0	3.60	0	-
		Guandu bridge	7.1	3.15	28	15
		Yuanshan bridge	17.6	3.10	94	9.5
Shi (1998)	1 Nov 1995	Tu-di-gong-bi	6.0		23.8	15
	~ 31 Oct 1996	Xinhai Bridge	22.7		51.97	25

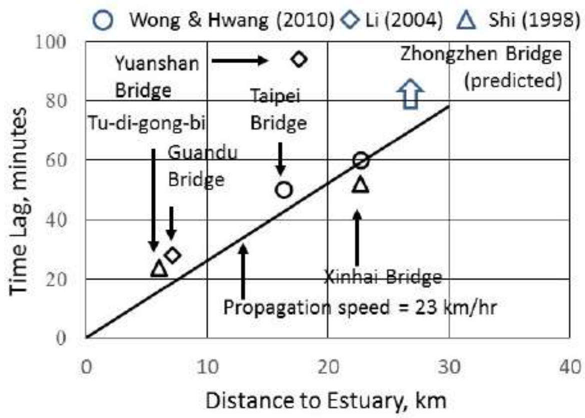

Figure 14 Time lag of tidal wave propagation in the Danshui River

The piezometric levels of ground water in the Jingmei Formation are definitely affected by the tides. The rising or falling of water level in the river directly above the point of interest, Point A in Figure 15 for example, will induce increments or decrements of pore water pressures in the subsoils, and hence, increments or decrements in piezometric heads in the Jingmei Formation. Furthermore, the piezometric heads in the Jingmei Formation are affected by the infiltration of surface water through permeable layers. As illustrated in Figure 15, the changes in water levels at outcrops of gravel layers, Locations B and C, for example, will also induce increments or decrements in the piezometric heads at Location A. The response time will depend on the transmissivity of the medium. Changes in water pressures due to flooding or ebbing river levels are almost instantly in saturated soil strata. As a result, the piezometric head increments or decrements in the confined aquifers can be transmitted very fast, much faster than the travelling of tides in the river. This partially explain the fact that the peaks and troughs of the piezometric heads in the Jingmei Formation shown in Figure 12 were ahead of the tides in the river.

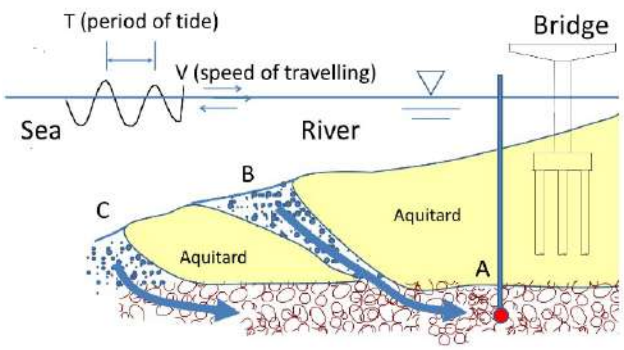

Figure 15 Schematic view of influence of tides on piezometric heads in the Jingmei Formation

Wong and Hwang (2010) demonstrated that the time lag in Jingmei Formation is proportional to the distance to the river bank. The further inland from the river bank, the longer time lag in the aquifer occurs. The mechanism of tidal influence on the piezometric heads in the Jingmei Formation, in fact, is far more complicated that what is shown in Figure 15. As can be noted from Figure 7, the overlying Songshan Formation contains an alternation of sandy and clayey sublayers. Surface water can infiltrate into the Jingmei Formation from various paths. The superposition of pressures transmitted from various paths can produce any pattern of fluctuation of piezometric heads. Therefore, the time differences between the pressure waves measured in the Jingmei Formation and the tides in the river are random in nature. Detailed discussions are available in Shih (1998) which analysed the time lags between the tides observed at the mouth of the Danshui River and the piezometric levels of groundwater in the Jingmei Formation at various locations. This, however, is beyond the scope of this paper.

4. INTERPRETATION OF RESULTS OF PUMPING TESTS

Although infiltration of surface water is likely to occur, the quantity of the seeping water is small in comparison with the large pumping rates adopted in deep excavations. For practical purposes, the Jingmei Formation can be considered as a confined aquifer. The drawdown of water level, δ, is related to the flow rate of pumping, Q, transmissivity, T, storage coefficient, S, elapsed time, t, and distance to the pumping well, r, as follows

$$\delta = \frac{Q}{4\pi T} W(u) \tag{1}$$

$$W(u) = \int_u^\infty \frac{e^{-u}}{u} du = -0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} + \cdots \tag{2}$$

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

For u ≤ 0.05, the above equations can be reduced to

$$\delta = \frac{0.183Q}{T} \log \frac{2.25Tt}{r^2 S} \tag{4}$$

The two parameters, T and S, can be obtained by curve-fitting based on the groundwater drawdown observed during pumping.

For the cut-and-cover construction for the R13S Station of Taipei Metro (Taipei Main Station for the Red Line, refer to Figures 6, 9 and 16 for location), pumping was necessary to lower the piezometric level in the Jingmei Formation from EL. -10m to EL. -15.6m (i.e., a drop of 5.6m), in order to carry out excavation to EL. –24.6m (i.e., a depth of 29m below ground level) for maintaining the stability at the base of excavation against piping or uplift. A maximum pumping rate of 2,450 m^3/hr was reached.

For R13S Station, pumping lasted for 7 months (1 May to 25 November, 1995) and based on the data obtained, the transmissivity, T, was found to vary from 0.12 m^2/sec to 0.18 m^2/sec and the storage coefficient, S, to vary from 0.001 to 0.004 (Shau, et al., 1995; Moh, et al., 1996; Hwang, et al., 1996). This set of hydraulic properties of the Jingmei Formation is consistent with those obtained earlier at two other sites (Hwang, et al., 1996). This experience is very valuable as the analytical approach adopted has been followed ever since in nearly all the projects involving dewatering of the Jingmei Formation and the parameters obtained serve as important references for estimating pumping rates and preparing pumping programs.

5. LARGEST DEWATERING SCHEME

Taipei Main Station (A1 Station) of Taoyuan International Airport Access (TIAA) MRT System is a 4-level underground complex. Airport boarding services are available at B1 level which is also a transfer level connecting TIAA to High Speed Rail, Taiwan Railways and Taipei Metro as depicted in Figure 16. The tunnel boxes for Taiwan Railways and High Speed Rail run side by side and are structurally connected. The area surrounding the station is designated as Taipei Main Station Special District by the City of Taipei with the aim of serving as a gateway to the city. Two skyscrapers, i.e., C1 (56 stories for a height of 241.5m) and D1 (76 stories for a height of 320.7m), will be constructed on top of A1

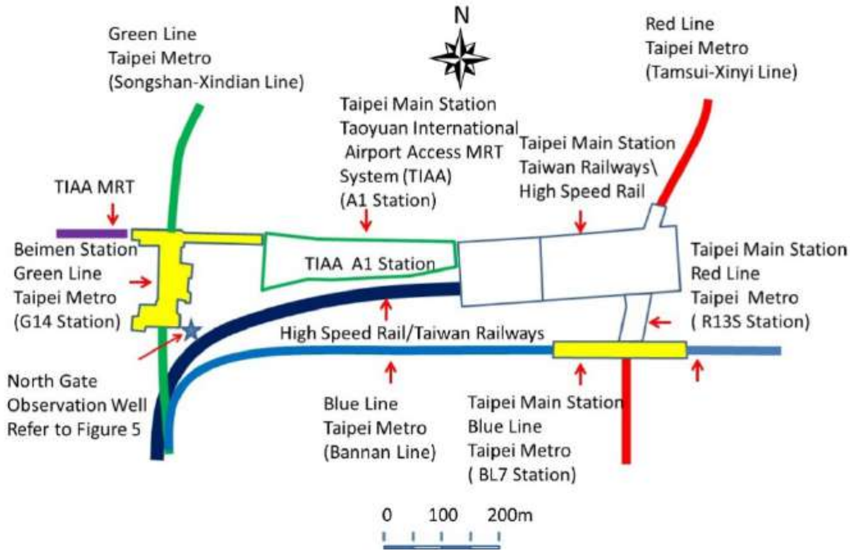

Figure 16 Location of A1 Station in relation to Taiwan Railways, High Speed Rail and Taipei Metro (Moh and Hwang, 2015)

Station as depicted in Figure 17. The first two stories of these two skyscrapers are part of the station and will be available when the station is open for service (at the end of 2015). The commercial developments above these two stories were originally tendered as a Build-Operate-Transfer package. However, the tender was not successful and the city government decided to take over the responsibility for construction. To prepare for these future developments, as depicted in Figure 17, barrettes were installed by using the diaphragm walling technique to take the heavy loads.

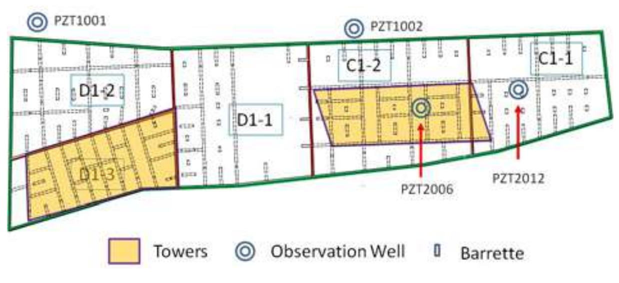

Figure 17 Diaphragm walls, barrettes and observation wells for the underground construction of A1 Station (Moh and Hwang, 2015)

As shown in Figure 5, the piezometric level in the Jingmei Formation had risen to El. -3m in 2010 when the excavation for A1 Station of TIAA was commenced. For C1 Zone, the excavation was carried out to EL. -23.2m (or a depth of 27.2m below ground level) and pumping was necessary to lower the piezometric level in the Jingmei Gravels to El. -16m (or a drop of 13m) to maintain the stability of the base of the excavation against piping and uplift. Initially 14 wells (PW1, 3, 4, 7, 10, 12, 13, 15, 17, 20, 23, 24, 29 and 30, refer to Figure 18 for locations) were installed and a test was carried out for 3 days to confirm the adequacy of the pumping program. As depicted in Figure 19, the pumping rate reached 5,000 m3/hr when the pumps in all the 14 wells were functioning and the piezometric level in the Jingmei Formation dropped to El. -9.4m. The piezometric levels rose by 2m within a few minutes after the test ended and returned to their original levels 5 days later. A transmissivity, T, of 0.18 m^2/sec and a storage coefficient, S, of 0.001 were deduced from the data obtained as depicted in Figure 20 (Yang, et al., 2012).

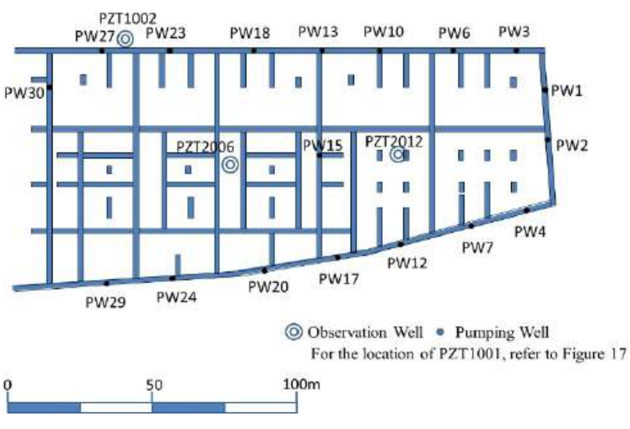

Figure 18 Locations of pumping wells and observation wells in C1 Zone (Moh and Hwang, 2015)

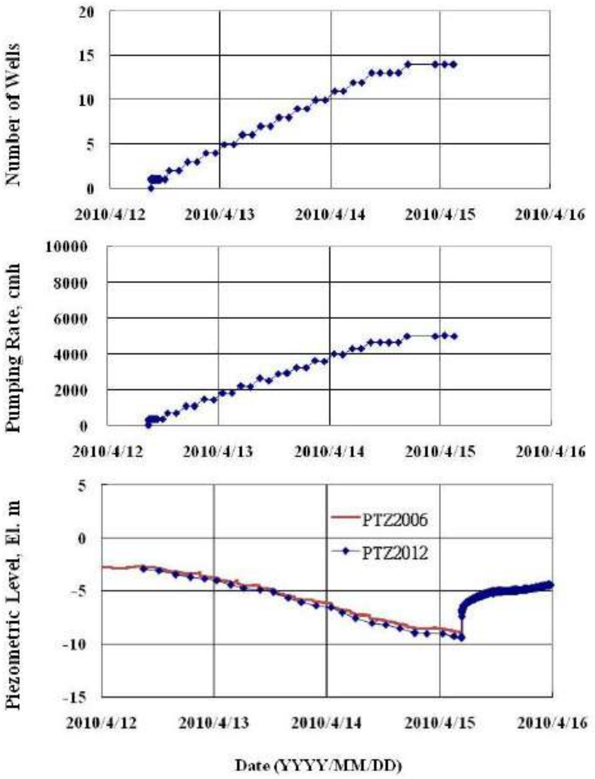

Figure 19 Results of 14-well pumping test (Yang, et al., 2012)

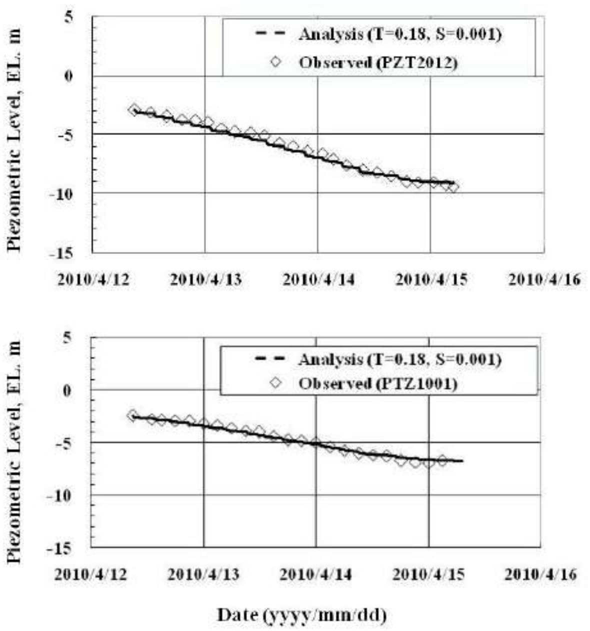

Figure 20 Back analysis of 14-well pumping test (Yang, et al., 2012)

Based on this set of parameters, it was estimated that 18 wells, with a maximum capacity of 6,480 m^3/hr, would be required for lowering the piezometric level to the desired elevation of EL. -16m. A test was again conducted after 4 additional wells were installed. The results, as depicted in Figure 21, indicated that the transmissivity, T equalled 0.12 m^2/sec and storage coefficient, S, varied from 0.001 to 0.004; and it was estimated that 15 wells, with a capacity of 5,400 m^3/hr, would be sufficient for the purpose. In fact, as depicted in Figure 22, the drawdown was even greater than what was predicted by using this set of parameters and only 11 wells were used at one time, with a maximum pumping rate of 5,000 m3/hr, as depicted in Figure 23, in the subsequent excavation. Back analysis of the final results indicates that T varied from 0.09 m^2/sec to 0.1m^2/sec and S equalled 0.001 (Yang, et al., 2012).

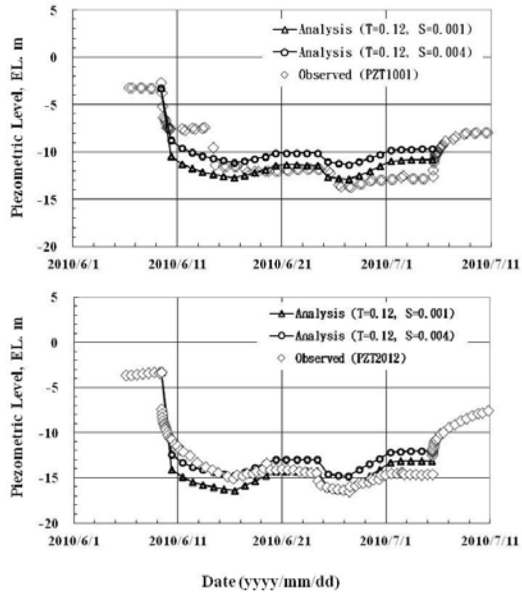

Figure 21 Back analysis of 18-well pumping test (Yang, et al., 2012)

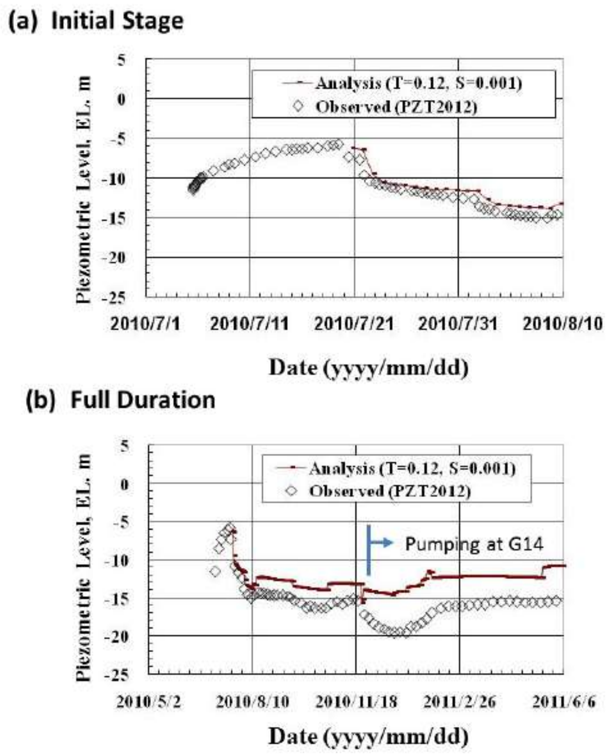

Figure 22 Comparison of observed groundwater drawdown with prediction (Yang, et al., 2012)

Table 2 is a summary of the results of pumping tests and the full scale pumping. A pumping rate of 6,480 m^3/hr would be required based on the results of the 14-well test while the actual pumping rate was only 5,000 m^3/hr. It appears that pumping tests with short durations tend to give conservative estimates of the pumping rates required. However, the 30% difference is well within the tolerance from a practical point of view and, in view of the many uncertainties to be faced, and is absolutely necessary to ensure the success of the construction.

Table 2 Results of pumping tests and the full-scale pumping

Events	Pumping Tests		Full-Scale Pumping	
	Duration (days)	Rate (m^3/hr)	Predicted (m^3/hr)	Actual (m^3/hr)
14-well Test	3	5,000	6,480	
18-well Test	26	6,500	5,400	
Full-Scale Pumping				5,000

Although the Jingmei Formation is wide spread in the basin, the influence of pumping is also far reaching. It is hypothesized that, as time goes by, the cone of drawdown (cone of depression) would approach the boundary of this gravelly water-bearing formation and the re-charging of water became insufficient for balancing the outflow. This hypothesis is supported by the fact that the drawdown was very close, as depicted in Figures 21 and 22, to the prediction in the first couple of days and gradually exceeded the prediction in the later stage of pumping.

As can be noted from Figures 23 and 24, pumping started on 22 November, 2010, at the site of the nearby Beimen Station (G14 Station), refer to Figure 16 for location, and it became possible to reduce the number of pumping wells and the pumping rate at this C1 site. It will be interesting to study the interaction between two sites and to see how the *T* and *S* values were affected. This however is beyond the scope of this paper.

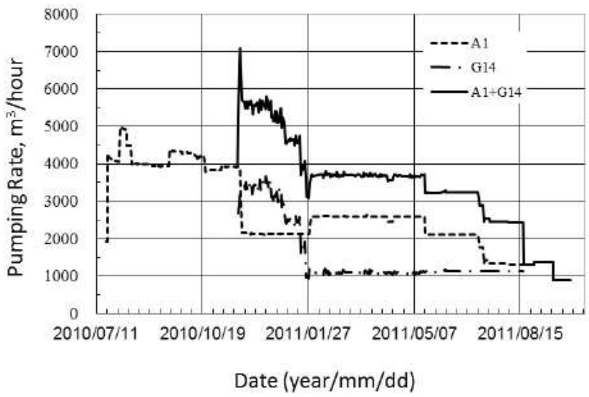

Figure 23 Pumping rates at C1 and G14 sites

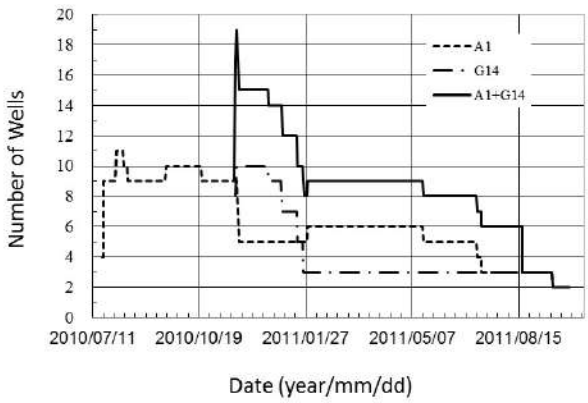

Figure 24 Number of pumping wells operating at C1 and G14 sites

For D1 Zone, although excavation was carried out to the same depth as C1 Zone, it was necessary to lower the piezometric level to EL. -22m (or a drop of 19m) because the overlying aquitard was thinner.

A total of 22 wells were installed. As excavation was carried out at its bottom depth, 18 wells were used and the maximum pumping rate reached 7,000 m^3/hr as depicted in Figures 25 and 26 respectively. This pumping rate was unprecedented and is still being held as the record high in the Taipei Basin. It could well be the record on the entire island.

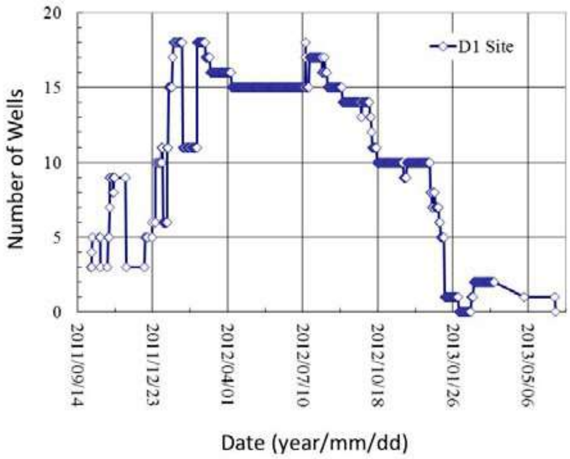

Figure 25 Number of pumping wells operated at D1 site

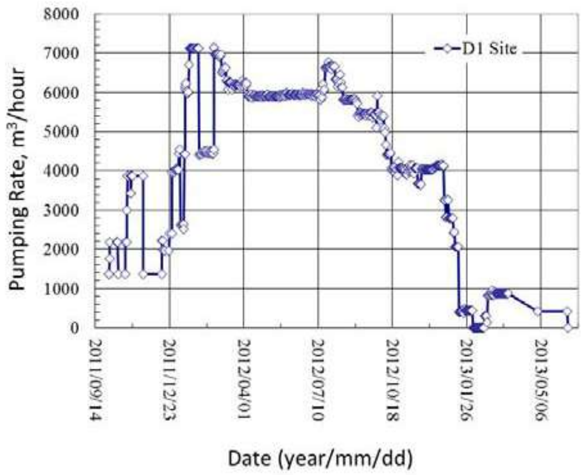

Figure 26 Pumping rates at D1site

6. CONCLUSIONS

The pumping tests carried out in the Taipei Main Station Special District (including R13S, A1 and G14 S) were well programmed and the pumping rates were accurately recorded and drawdowns of ground water in subsoils and in the Jingmei Formation were closely monitored. The large quantity and the high quality of the data available make it possible to establish methodology to estimate ground water drawdown and to confirm the validity of the empirical approaches adopted.

Based on the experience gained from the large scale dewatering schemes discussed above, it has been found that the transmissivity and storage coefficient deduced from the observed groundwater drawdown are affected by not only the pumping rate, but also the duration of pumping.

The nature of the Jingmei Formation and how the piezometric levels in the Jingmei Formation are affected by tides demand further study.

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