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Back Analyses of Historical Ground Subsidence Induced by the Lowering of Groundwater Table

R.N. Hwang[1] and Z.C. Moh[1]
[1]*Moh and Associates, Inc. Taipei, Taiwan*
E-mail: richard.hwang@maaconsultants.com

ABSTRACT: Numerical analyses were conducted to correlate the ground settlements observed in the central area of the Taipei Basin with the variations of the piezometric levels in the Jingmei formation. The relationship of the historic changes of the piezometric levels and the ground settlements induced by the consolidation of the Songshan formation was established by matching the results of the analyses with the observed settlements. The influence of replenishing water from rivers and infiltration of surface water into the Songshan formation was accounted for by assuming a linear distribution of water pressures with zero pressure at a level of replenishment and a pressure corresponding to the piezometric level in the Jingmei formation at the bottom of the Songshan formation.

The records of the ground settlement and piezometric levels in the Jingmei formation obtained in the Beimen area were used in the analyses and the results of analyses indicated that the ground could have settled by 0.38 m before the initial reading of settlement was taken in 1950, giving a total settlement of 2.55 m, instead of 2.17 m reported in literature (Wu 1987). It has also been found that consolidation of the sandy layers contributed to more than half of the settlement.

KEYWORDS: Taipei Basin, Jingmei formation, Songshan formation, Groundwater pumping, Dewatering, Ground settlement, Consolidation.

1. INTRODUCTION

Figure 1 shows the geological map of the Taipei Basin and Figure 2 shows a west-east cross-section of the basin. As can be noted, there exists a thick layer of soft deposits, i.e., the so-called, Songshan formation at the surface, underlain by the so-called, Jingmei formation (Jigmei Gravel as often referred to). The Songshan formation consists of young sediments brought to the basin by the Tamsui River and her three tributaries, i.e. Dahan Creek, Xindian Creek, and Jilong River. The Jingmei formation consists of a wide range of granular particles, varying from very large boulders, cobbles, gravels to coarse sand, and is extremely permeable and water-rich. It was once the sole source of the water supply of the Taipei City. As the population in the city grew, the groundwater was over-drawn from the Jingmei formation, leading to significant ground settlement as a result of the consolidation of the soft sediments in the Songshan formation.

The purpose of this study is to evaluate the validity of using the available hydrogeological data and the fundamental consolidation theories to back calculate the ground settlements in the central area in the Taipei Basin, and to calibrate the pertinent geotechnical parameters in the consolidation analyses with the actual settlement records. This is done with the intent that the derived soil and groundwater parameters can be used in similar analyses to predict ground settlements due to the lowering of the piezometric levels in the Jingmei formation and the degrees of consolidation of soils in other geological zones in the basin in the future. The central area of the city, where Taipei Main Station is located, was chosen for this preliminary study because it is the zone most developed with more data available from site investigations conducted for the constructions of buildings and infrastructures.

The analyses were conducted by using an in-house finite difference computer software, CONSET, which evolved from its predecessor CONCOL originally released by the University of California, Berkeley (Duncan et al. 1988) back in the 1970s for one-dimensional consolidation analyses. This software has been substantially enhanced to cope with the continuous drawdown of the groundwater with a large quantity of discretized pumping records. Options have also been added to deal with various modes of porewater pressure generation and dissipation, including the one with replenishment of groundwater at a certain level as to be discussed in Section 5.3.

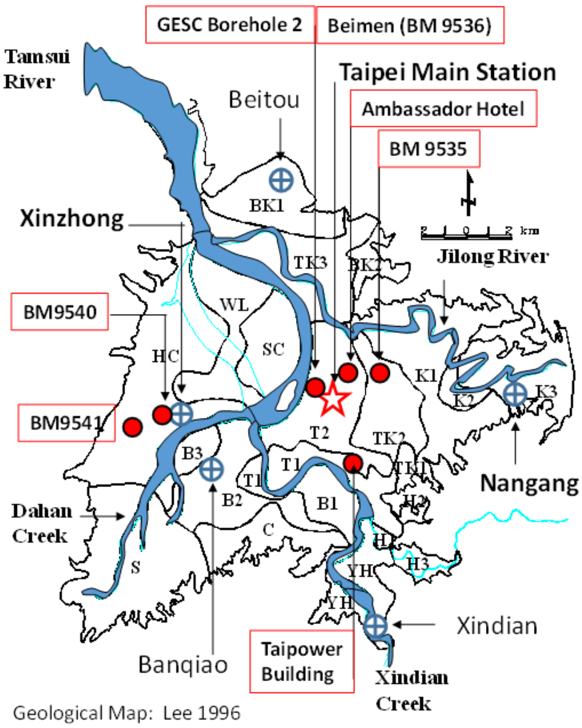

Figure 1 Geological map of the Taipei Basin and locations of interest

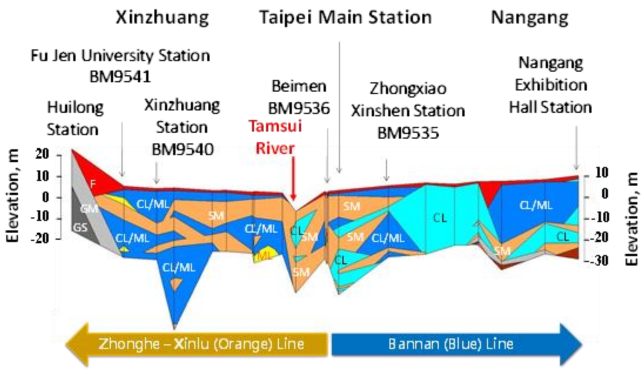

Figure 2 West-East cross-section of the Taipei Basin

2. RECORDS OF DRAWDOWN OF PIEZOMETRIC LEVELS IN JINGMEI FORMATION

Pumping for drawing groundwater has been carried out for domestic water supply since 1895. In a field study conducted in 1894-1896, W. K. Bardon and others found that flowing artesian wells were present in localized areas at various places in the basin. The piezometric levels in the Jingmei formation varied, reportedly, from EL. +8 m to EL+10.5 m in 1895; and dropped to EL-1 m to EL-0.75 m in 1957, averaging to an annual drawdown of 0.15m over this 60-year period. Subsequently, the piezometric levels further dropped by, as much as, 24m in the period between 1957 and 1964, averaging to a drawdown of 2.3 m to 3.4 m annually. The lowest level of EL-49.65 m was recorded at a well located near BM9541 in the vicinity of Fu Jen University, refer to Figure 1 for location, in 1974 while the lowest level at BM 9536, Beimen, was EL-42.7 m recorded in 1973 (Wu 1987).

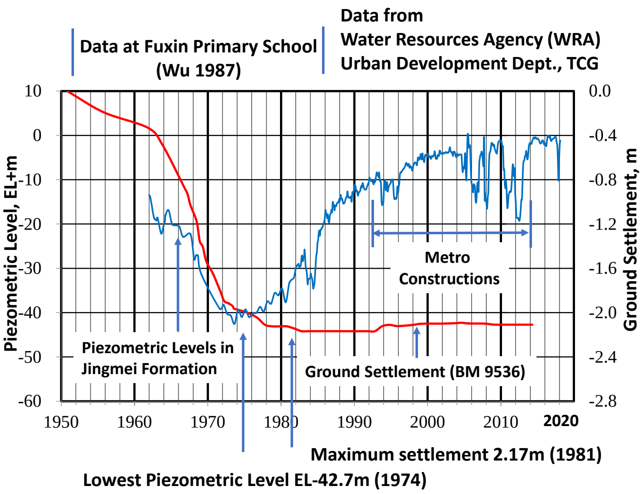

Figure 3 Changes in piezometric levels in the Jingmei formation and ground settlements in the vicinity of Taipei Main Station

Figure 3 shows the changes in piezometric levels in the Jingmei formation obtained at Fu Xin Primary School, which is located about 150m to the West-South-West of BM 9536 in Beimen Circle, and the associated ground settlements in the period between 1950 and 1985 (Wu 1968; 1987). Also shown in the figure are the subsequent piezometric levels obtained from Water Resources Agency (WRA) of Ministry of Economic Affairs and the settlement records from Urban Development Department (UDD) of Taipei City Government (TCG).

As the ground settlements in the basin became alarming, the drawing of groundwater was banned in the mid-1970s. The piezometric levels in the Jingmei formation rapidly rose to EL-10m in 1993. The recovery was interrupted subsequently due to the lowering of the water heads for maintaining the safety of deep excavations in many megaprojects, namely, Railway Underground Project, High Speed Rail and, particularly, Taipei Metro. As nearly all the underground constructions for infrastructures in the central area of the city had been completed, the recovery of the piezometric level resumed its pace in the mid-2010s.

3. RECORDS OF GROUND SETTLEMENTS

The settlement records obtained at BM9536 in Beimen Circle, refer to Figures 1 and 2 for location, were selected for the analyses. Wu (1987) pointed out that the ground surface was at, roughly, EL+7.05m at this location in 1950. Figure 3 depicts the subsequent settlement records at BM9536 and; as can be noted, the ground had settled by as much as 2.17 m by 1983. It is most interesting to note that the settlements continued till 1981 after the piezometric level in the Jingmei formation recovered from its lowest level in 1974 when the piezometric level reached its lowest level at this location. This indicates that substantial undissipated excess porewater pressures remained in the Songshan formation clayey soils after the groundwater in Jingmei formation was allowed to recover from its lowest drawdown level.

The rebound of the ground as the piezometric levels recovered was rather small, about 59 mm in total as of 2014.

4. SOIL PROPERTIES IN THE CENTRAL AREA OF CITY

A comprehensive study was conducted in 1986 for geological mapping of the basin for Taipei City Government and the index properties of the soils obtained from the study are depicted in Table 1 (MAA 1987; Huang, et al. 1987). The typical 6-layer sequence of alternating silty clay (CL/ML) and silty sand (SM) layers of the Songshan formation is clearly identifiable. Regarding the mechanical properties and strength parameters of the soft deposits in the Songshan formation, a considerable amount of data have been collected in the past 30 years or so from the numerous deep excavations made in the Basin for major private and public development works.

A research project was conducted in 1991 and 1992 as a Designated Task (Designated Task, hereinafter) by Geotechnical Engineering Specialty Consultants (GESC), engaged by the Department of Rapid Transit of Taipei City Government, for determining the characteristics of soils for the design and construction of Taipei Metro. Undisturbed soil samples of high quality were obtained from 3 boreholes under stringent supervision and laboratory tests were carefully conducted. The test results for soil samples obtained from Borehole 2, which is located nearby BM9536 in Beimen (Figure 1), are given in Figure 4. Unfortunately, the object of this study was primarily to provide design parameters for deep excavations and tunneling and, as such, very little information was provided on the consolidation of soils.

The consolidation properties of soils available in literatures (MAA 1987; Wu 1987; Chin and Liu 1997) are cited in Table 2. As can be noted, there are wide variations in the three sets of data, as typically expected in geotechnical studies, indicating the drastic uncertainties associated with soil properties and the heterogeneity of soil mass from place to place.

5. NUMERICAL ANALYSES

Figure 5 shows the soil model adopted with a total thickness of 46m and Figure 6 shows the groundwater regime and the parameters adopted in the consolidation computation. The Jingmei formation is considered as the base of the numerical model. The overlying Songshan formation is divided into 23 sublayers with thicknesses varying from 1.5 m to 3 m each. Drainage is allowed at the bottom of the model, i.e., at the interface between the Songshan formation and the Jingmei formation.

The analyses started from 1895. As reported by Wu (1987), the piezometric level in the Jingmei formation was 2.1 m to 4.5 m above the ground level in 1895, corresponding to EL+8 m to EL+10.5. It is thus postulated that the initial ground surface would be at EL+7.5 m or so.

5.1 Time history of piezometric levels in the Jingmei formation

The records of piezometric levels in the Jingmei formation after 1962 are available as depicted in Figure 3. Prior to this date, the piezometric levels have to be assumed to enable analyses to be carried out. Since the piezometric levels in the Jingmei formation varied from EL+8 m to EL+10.5 m in 1895 as reported in Wu (1987); an initial piezometric level of EL+10 m was thus assumed in the analyses. The changes in the piezometric level between 1895 and 1962 shown in Figure 7 were obtained based on the results of back analyses by fitting the predicted settlement curves with the actual settlement records, and this will be further discussed in Section 6. Computations were carried out for a total of 680 discrete time steps.

Table 1 Descriptive statistics of physical properties of T2 soils (after MAA 1987; Huang et al. 1987)

Layer	Statistical Items	Thickness (m)	γ_d (kN/m^3)	w_n (%)	G_s	w_l (%)	I_P (%)	Grain Size Distribution (%)			
								Gravel	Sand	Silt	Clay
VI	mean	4.5	14.5	31.2	2.72	35.8	12.9	-	10	58	32
	COV	0.46	0.06	0.14	0.01	0.17	0.37	-	0.74	0.18	0.36
	n	251	545	559	417	433	415	389	388	388	388
V	mean	10.1	15.4	26.3	2.68	-	NP	1	75	19	4
	COV	0.28	0.07	0.18	0.01	-	-	5.79	0.19	0.62	0.78
	n	259	1288	1316	996	-	-	950	950	950	950
IV	mean	9	14.3	32.1	2.72	34.3	12	-	8	61	31
	COV	0.63	0.06	0.13	0.01	0.15	0.37	-	1.06	0.15	0.38
	n	258	1441	1463	1071	1085	1064	1068	1068	1068	1068
III	mean	10.6	16.1	23.9	2.69	-	NP	-	60	34	7
	COV	0.55	0.06	0.18	0.01	-	-	-	0.29	0.82	0.69
	n	225	1116	1135	766	-	-	760	760	761	761
II	mean	8.4	15.5	27.2	2.72	30.3	9.2	0	9	67	25
	COV	0.57	0.06	0.15	0.004	0.16	0.36	-	0.81	0.12	0.36
	n	181	951	957	657	683	608	651	651	651	651
I	mean	4.5	17.0	20.3	2.69	-	NP	1	62	29	7
	COV	0.73	0.07	0.21	0.01	-	-	5.10	0.28	0.51	0.70
	n	112	273	281	183	-	-	184	184	184	184

Notes: COV = coefficient of variation; n = number of data

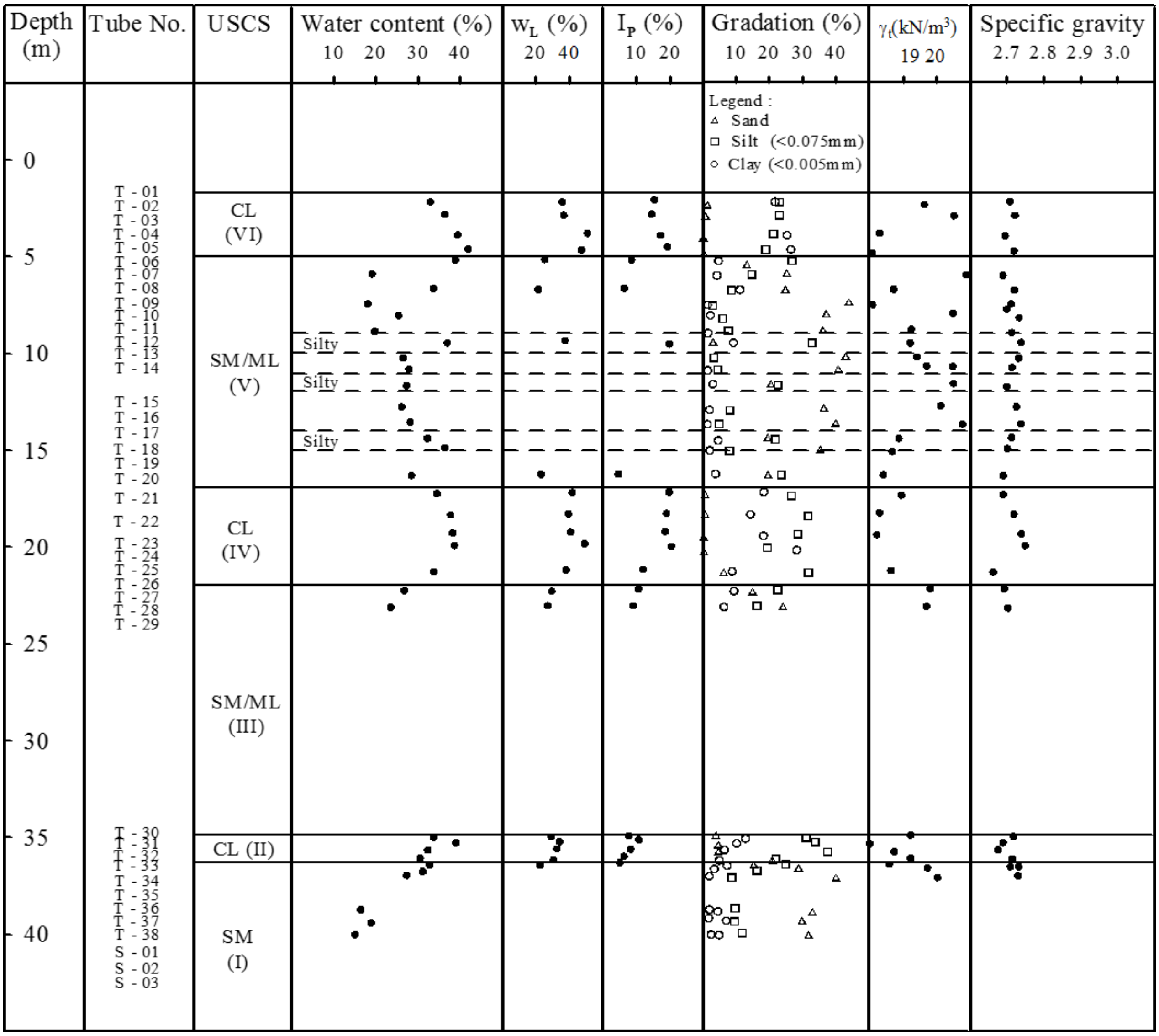

Figure 4 Index properties of T2 soils (after Chin et al. 1994; Chin, et al. 2007, MAA 2007)

Table 2 Parameters for consolidation of clayey soils in T2 Zones

	MAA (1987)				Wu (1987)				Chin and Liu (1997)		
Layer	SPT N	Void Ratio e_0	Cc	Kv cm/sec	Unit Weight t/m^3	Water Content %	Void Ratio e_0	Cc	Water Content %	Void Ratio e_0	CR
VI	5	0.87	0.29	4.4 x 10-7	1.52 ~ 1.90	20 ~ 60	0.5 ~ 0.7	0.09 ~ 0.36			
V					1.91 ~ 2.25	15 ~ 30	0.56				
IV	8	0.94	0.39	1.4 x 10-7	1.80 ~ 2.00	20 ~ 40	1.0	0.09 ~`0.3	38 40 42	1.07 1.10 1.17	0.175 0.180 0.183
III					1.91 ~ 2.25	15 ~ 30	0.5 ~ 0.56				
II	19	0.84	0.33		1.80 ~ 2.00	20 ~40	0.1 ~ 0.67	0.09 ~ 0.27			
I					1.91 ~ 2.25	15 ~30	0.5 ~ 0.7				

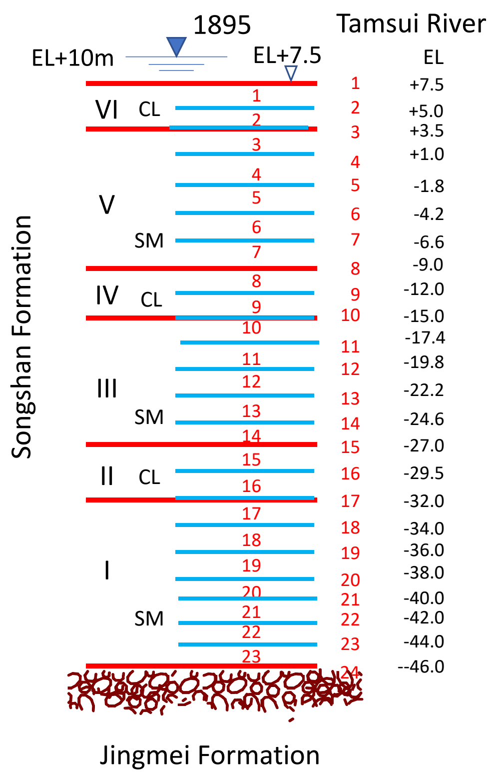

Figure 5 Soil profile adopted in the numerical analyses

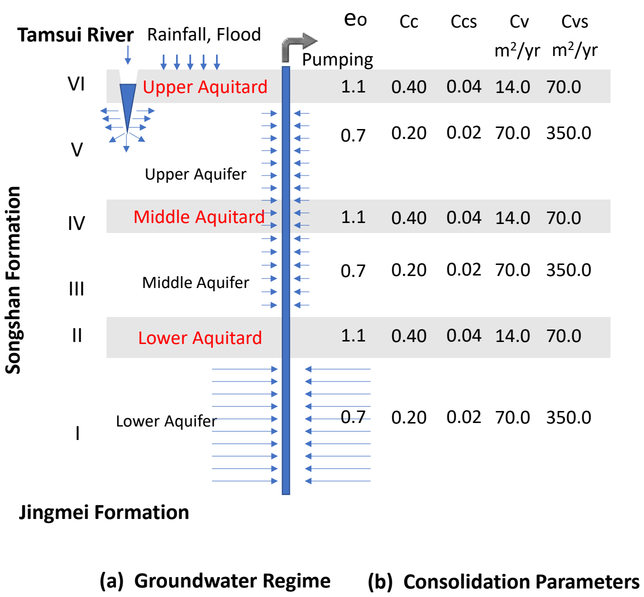

Figure 6 Groundwater regime and consolidation parameters

According to Wu (1987), the pumping wells were in general shallow prior to 1950 and deep well pumping started in 1950 by Taiwan Sugar Corporation, presumably, for irrigation. In 1958, more deep wells were drilled by the City Government for domestic usages. In 1961, Taipei Water Treatment Plant was inaugurated as a subsidiary company of Taipei City Government to supply water to families in the city. As the population grew, the number of registered deep wells increased to 1150 in the central city area, and 2250 in total including the nearby suburbs, by 1964. The sharp drops in the piezometric level in the Jingmei Formation shown in Figure 7 corresponded to these scenarios very well. It is envisaged that there would be many more wells, registered or unregistered, in the 1970s before pumping was banned.

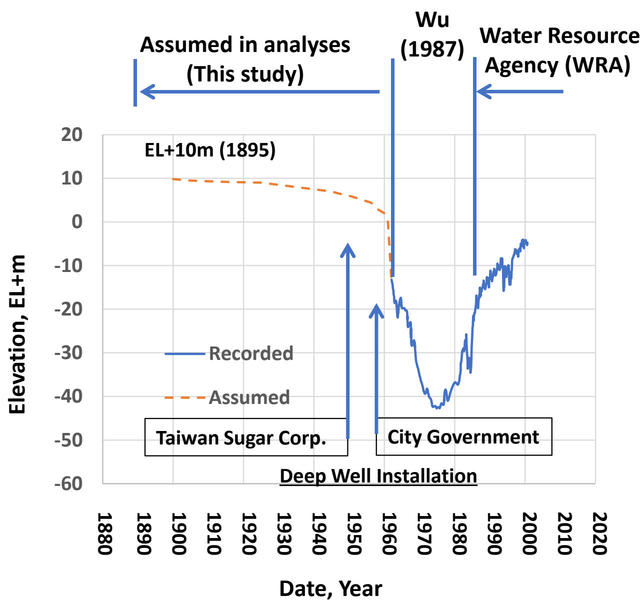

Figure 7 Piezometric levels in the Jingmei formation adopted in the numerical analyses

5.2 Soil Parameters adopted in the analyses

Since the data available are insufficient for distinguishing the properties of soils in different layers, the same parameters are adopted for all the 3 clayey layers and the same parameters are adopted for all the 3 sandy layers for simplicity. As can be noted from Table 2, the void ratios of the clayey layers, i.e., Layer II, IV and VI, were generally high. They were believed to be even higher since the reported values in Table 2 were obtained after the ground had settled for a certain amount due to the prior groundwater lowering. In the analyses of the ground subsidence at the site of Ambassador Hotel, it was reported that the void ratio for Sublayer VI dropped from 1.29 to 1.0 and from 0.94 to 0.86 in Sublayer IV in the 10-year period between 1957 and 1967 (Wu 1987). For simplicity, a void ratio of

1.1 is assigned to all the clayey layers and, a void ratio of 0.7 is assigned to all the sandy layers.

The soils were assumed to be normally consolidated at the initial stage because they were deposited decades or even centuries ago. For studying the consolidation of soils, the two most important parameters are the compression index, Cc and the coefficient of consolidation, C_v for primary consolidation the corresponding Ccs and Cvs for swelling and recompression. The former governs the magnitudes of settlements and the later governs the speed of consolidation, i.e., the time rate of settlements. Unfortunately, reliable data are unavailable for estimating the values of these two parameters. The results obtained from laboratory tests can only be used in the initial trial in back analyses due to the inevitable soil sample disturbance effects, which tend to underestimate the compression index and coefficient of consolidation. The more reliable values must be obtained by matching the results of settlement analyses with the actual field settlement readings. Numerous trials have been made accordingly and the back-calculated Cc, Ccs, Cv and Cvs are given in Figure 6(b). It shall be pointed out that these back-calculated values are valid for the cases analyzed only because of the heterogeneity of soil masses and the uncertainties associated with the performance of soils subjected to loadings from place to place and from case to case.

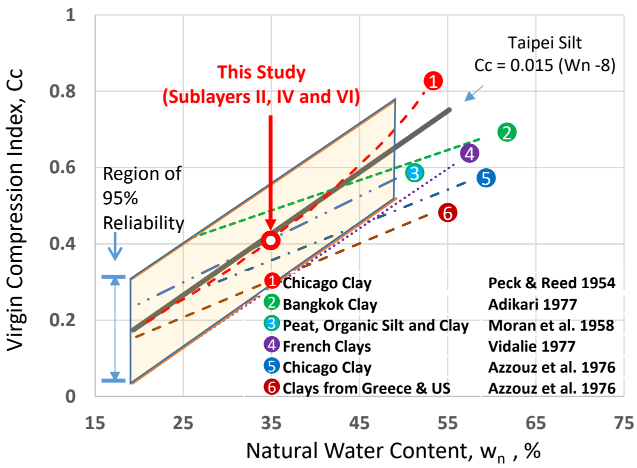

Figure 8 Compression indices of Taipei silt (redrawn from Moh et al.1989)

For the clayey layers, the Cc value of 0.4 adopted in the analyses is near the upper bound of the values given in Table 2 but falls in the range for a water content of 35% (refer to Table 1) as depicted in Figure 8 (Woo and Moh 1990). Woo and Moh (1990) also proposed the following equation for estimating the Cc values for Taipei silts based on void ratios:

$$Cc = 0.54\,(e_o - 0.23) \tag{1}$$

which yields a Cc value of 0.47 for an initial void ratio, e_o, of 1.1. Therefore, the value of 0.4 adopted is deemed reasonable. The coefficient of consolidation for swelling, i.e., Ccs, is assumed to be one-tenth of the Cc value by engineering judgment. It, however, should be noted that the Cc values vary in a rather large range as depicted in Figure 8 and a deviation of 30% from the value proposed is quite possible. The coefficient of consolidation, i.e., Cv, of 14 m^2/year (0.0044 cm^2/sec) is also consistent with the value proposed in Woo and Moh (1990) as depicted in Figure 9. It can be noted that the upper bounds and the lower bounds of the Cv values for any given liquid limit differ by a factor of 10. Much larger variations were experienced in field tests and in back analyses of the settlements observed in many projects involving surcharging. The coefficients of consolidation for swelling, i.e., Cvs, were assumed to be 5 times the Cv value.

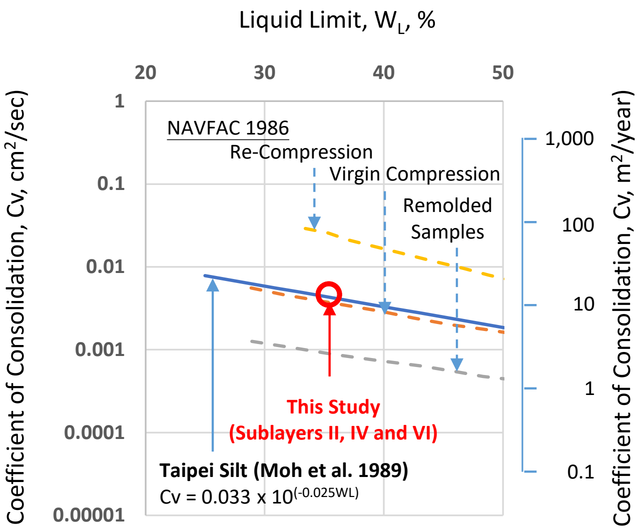

Figure 9 Coefficients of consolidation of Taipei Silt (redrawn from Woo and Moh 1990)

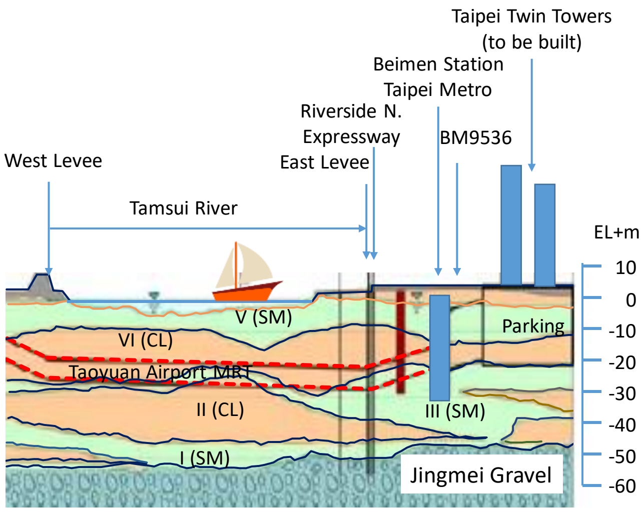

Figure 10 Geological profile under the Tamsui River and the vicinity

For the sandy layers, there is practically no data available for determining the parameters to be used in the consolidation analyses because it is usually believed that compression of sands occurs rather quickly so the time effects on the compression of sands are insignificant. In some cases, for example, in the analyses conducted for Ambassador Hotel, the compression of the sandy layers was totally ignored and settlements were attributed to the consolidation of clayey layers only (Wu 1968; Hwang and Wu 1969). It is interesting to note from the back analyses presented herein that a Cc value of 0.2 had to be adopted for the sandy layers in order to fit the settlement records. These sandy layers in the central area of the city have relatively high fine contents as can be noted from Figure 4. it is then not a total surprise to obtain a value of the same order as that for the clayey layers.

5.3 Generation and dissipation of excess porewater pressures

Bench Mark BM9536 is approximately 500m away from the bank of the Tamsui River which, refer to Figure 1, is the mainstream in the basin. Figure 10 shows a profile of subsoils under the Tamsui River and, as can be noted, the river bed lies at EL-10 m or below and is directly underlain by the sandy Sublayer V. It is therefore expected that Sublayer V, which is a sandy layer with high permeability, is constantly replenished by the water from the river.

It is unsure how far and how deep the influence of the rivers on the piezometric levels in the Songshan formation can reach. In a study conducted in the period of 1979 to 1981 about 60 pneumatic type piezometers were installed in the central city area and monitoring of piezometric levels at various depths continued for two to three years. The fact that Sublayer V was replenished by the water from the Tamsui River is evidenced by the data obtained as the groundwater tables in the upper layers were found to be at EL+0m, refer to Figure 11, in all the wells in the central city area and the pressure distributions were more or less linear versus the depth in this layer (Ou, et al. 1983).

Wong and Hwang (2010) reported that the water levels at the locations of the estuary of the Tamsui River, Taipei Bridge and Hsinhai Bridge varied from EL-2 m to EL+2 m. In consideration of the fact that BM9536 is 500m off the east bank of the Tamsui River, a level of replenishment of EL+0 m was adopted in the analyses. The distribution of excess porewater pressures induced would thus be in a triangular shape as depicted in Figure 12.

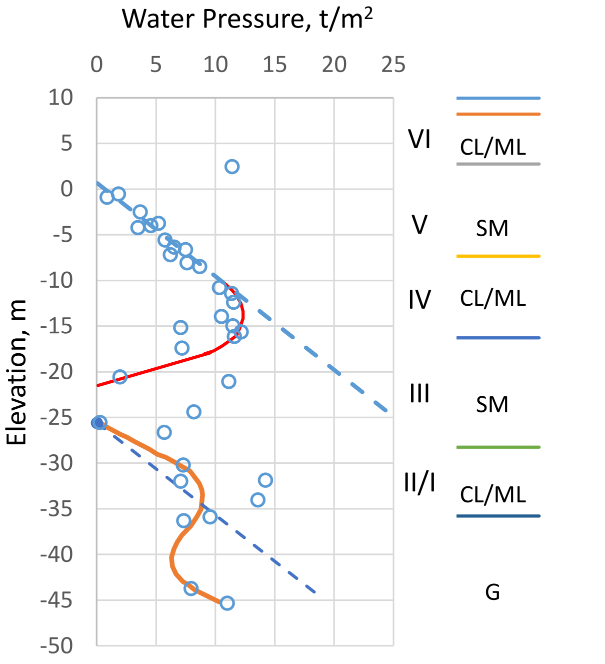

Figure 11 Distribution of water pressures in the Beimen area in the period of 1979-1981 (after Ou et al. 1983)

6. RESULTS OF ANALYSES

As depicted in Figure 13, the calculated ground settlements from the analyses, fit the records exceptionally well in view of the many assumptions and simplification made. The agreement between the results of the analyses and the observed ground settlements justifies the soil and groundwater parameters adopted in the analyses with the understanding that they still may vary in wide ranges as depicted in, for example, Figures 8 and 9. Based on the results of the analyses, the ground started to settle in 1925 as the piezometric level fell below the ground level of EL+7.5m and. had settled 0.38m by 1950, giving a total settlement of 2.55m instead of the 2.17m reported in Wu (1987).

6.1 Water pressures in the Songshan formation

The computed total water pressures in the Songshan formation in the stage of lowering of piezometric level are shown in Figure 14 and those in the stage of recovering of piezometric level are shown in Figure 15. To illustrate the phenomenon observed from Figure 3 that the ground continued to settle for quite a few years after the piezometric pressures in the Jingmei formation started to rise in 1974, Figure 16 shows the remaining excess porewater pressures in 1974 and the subsequent years. As can be noted, there were still excess porewater pressures of significant magnitudes un-dissipated in 1974. The dissipation of these residual excess porewater pressures was responsible for the subsequent settlements. The settlement continued till 1981 as these residual excess porewater pressures were nearly fully dissipated.

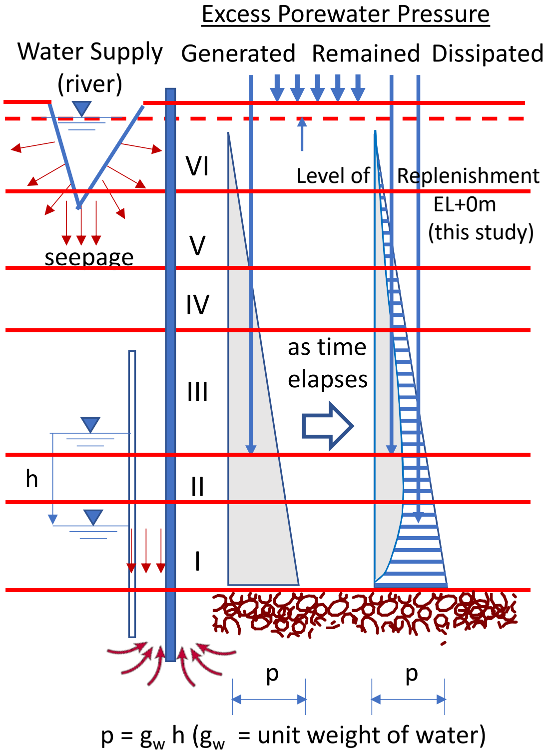

Figure 12 Generation and dissipation of excess porewater pressures due to the lowering of groundwater table with replenishment of water at shallow depths

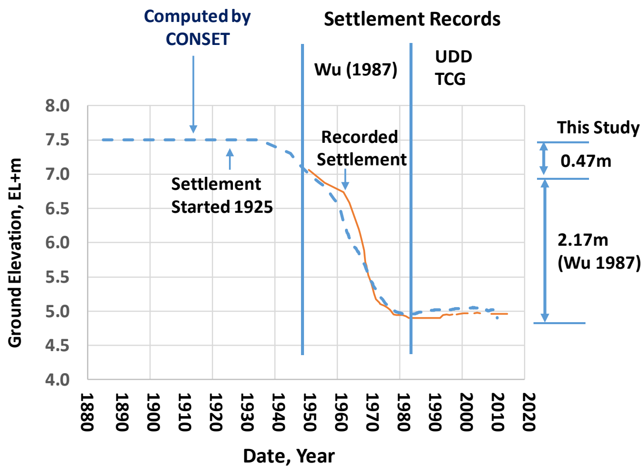

Figure 13 Comparison of the computed ground settlements with settlement records

The piezometric levels in the Jingmei formation rose rapidly in the 1970s and 1980s, the excess porewater pressures became negative, i.e., suction, in the early 1980s, causing the soils to rebound, leading to ground heave, as a result. However, the ground heaves were very small with a maximum magnitude of only 59 mm. The reconsolidations of the soils were also very small as can be evidenced by the fact the settlements were un-noticeable in the late 2000s as the piezometric levels in the Jingmei formation dropped from EL-4 m to EL-18 m as a result of lowering of groundwater table for ensuring the safety of deep excavations and tunneling for the developments of underground spaces.

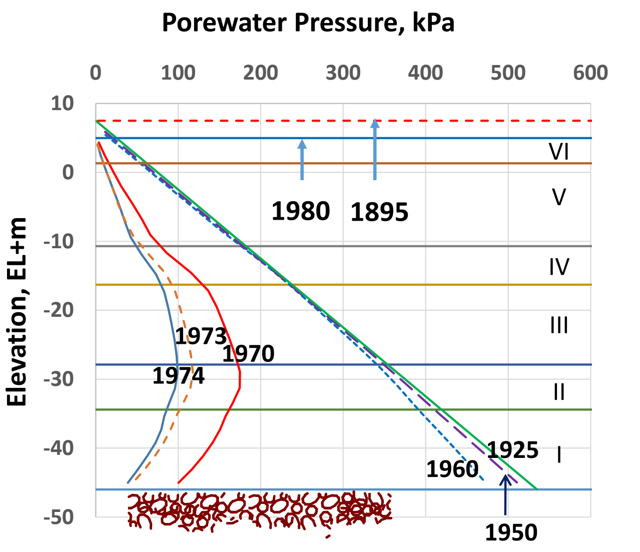

Figure 14 Distribution of water pressures in the Songshan formation as the piezometric level in the Jingmei formation dropped

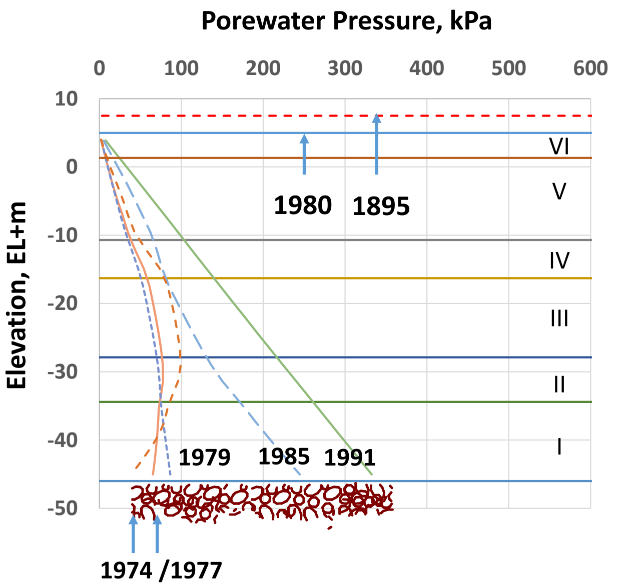

Figure 15 Distribution of water pressures in the Songshan formation as the piezometric level in the Jingmei recovered

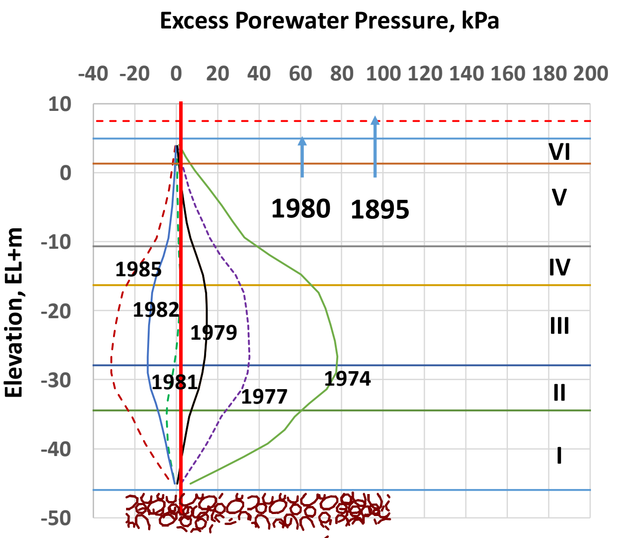

Figure 16 Excess porewater pressures in the Songshan formation

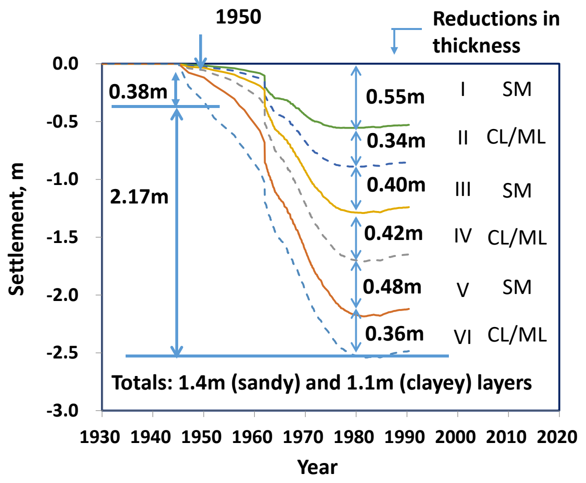

Figure 17 Contributions of sandy and clayey layers to ground settlements in analyses

6.2 Contributions of sandy layers to ground settlements

Figure 17 shows the reductions in the thicknesses of all the six layers. The reductions in the thicknesses of the sandy layers total to 1.4 m, which corresponds to 56% of the total settlement of 2.55 m. It can be noted from Figures 4 and 5 that the total thickness of the sandy layers is nearly twice that of the clayey layers, it is thus reasonable to expect that a significant amount of the settlements can be attributed to the compression of these sandy layers.

Very limited information is available in the literature for estimating the consolidation parameters of sandy materials. A Cc value of 0.2 was adopted in the analyses in order for the computed settlements to match the settlement records. This Cc value falls in the range for quartz sands with 10% to 20% fines content as proposed by Mesri and Vardhanabhuti (2009) and can be used as a starting value for similar studies in the future.

In addition to the Cc values, it is also important to realize the time rates of the compression of the sandy layers. Because of their high permeabilities, sands are usually considered as perfect drained materials and the compression of sands would thus be immediate upon loading. Therefore, very few studies discussed the time rates of the compression of sands, and as such, very little information is available for estimating the Cv values of sandy soils. In this study, the Cv values of the sandy layers were assumed to be five times the values of the clayey layers. The agreement between the computed settlements and the settlement records proves that these values are reasonable for the sandy layers in the central area of the city.

7. FACTORS AFFECTING THE RESULTS OF ANALYSES

Since the lowering of the piezometric levels in the Jingmei formation was uniform over the central area of the city (or basin), the use of one-dimensional analyses appears to be a reasonable engineering approach for practical purposes. However, the analyses presented herein can only be considered as the first-order approximations to the case of interest because there were many deviations from the conditions assumed in the analyses. The following are the factors that would have significant influences on the results obtained.

7.1 Cross-flows between soil layers

Figure 6(a) shows that the groundwater regime can be divided into three aquifers, i.e., the upper, middle and the lower aquifers, by the two clayey layers, i.e., Sublayers II and IV, as aquitards. Sublayer I is combined with the Jingmei formation as one aquifer because of its high permeability. However, as depicted in Figure 2, these two clayey layers are not continuous, therefore cross-flows are inevitable. The flows across these two aquitards tend to speed up the consolidation in the Songshan formation as a whole and increase the Cv values of all types of soil deposits.

7.2 Influence of radial drainage of pumping wells

It was, and still is, a common practice to use perforated steel tubes in the pumping wells for withdrawing water. Therefore, as illustrated in Figure 6, these wells worked as drains in the phase of lowering of groundwater levels and as recharging wells as the groundwater level recovered.

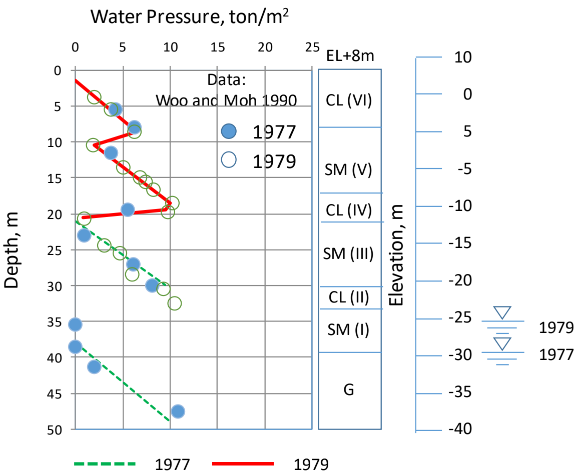

Figure 18 Pressure distributions at Taipower Building (after Woo and Moh, 1990)

The observed profiles of water pressures were sometimes different from those shown in Figures 14 and 15. For example, Figure 18 (and Figure 11 as well) shows the groundwater pressures recorded in the 1970s in the vicinity of Taipower Building which is located near the southern rim of the T2 Zone as depicted in Figure 1 (Woo and Moh, 1990). Because of the differences in permeability, the dissipation of excess pore water would be much faster in the sandy layers than in the clayey layers. The zigzags in the pressure profiles are very likely caused by radial flows induced by pumping in a nearby well as illustrated in Figure 6(a). As mentioned in Section 5.1, there were 2250 deep wells in the basin in 1964 (Wu 1987) and there would certainly be many more in the 1970s. Therefore the probability of having a pumping well in the vicinity of any monitoring point was very high.

Because of the relatively low permeability of the soils in the Songshan formation, in comparison with the Jingmei formation, the influence of radial flows in the Songshan formation is expected to be localized. The magnitudes of the ground settlements in the basin as a whole are unlikely to be much affected unless a significant amount of fine particles was pumped out but the speed of consolidation would certainly have been increased.

7.3 Replenishment of groundwater

In addition to the surface seepage flows from the rivers and the irrigation canals, the groundwater in the basin is constantly replenished by the water from the highlands on the south and the east. Figure 18 shows that the piezometric level in the Jingmei formation was at a depth of 37m from the ground surface, or EL. -29m, in 1977. In comparison, it was recorded at EL-40m at BM9536 shown in Figure 3. For a distance of 4 km between these two locations, the hydraulic gradient was about 3m/km. This hydraulic gradient diminished as the differences of the piezometric levels at these two locations decreased as the groundwater recovered.

The frequent storms and floods in tropical cyclones also replenish the groundwater from time to time. Besides, by the water leaking from water supply conduits also contributed a significant amount of the replenishment. For example, 19.7% of a total of 822 million tons, or 162 million tons, of total water supply seeped into the ground in Taipei Metropolis in 2002 (NAO 2004). Since data are very limited, it is not possible to quantify the influences of all these factors on the consolidation settlements of the ground.

To investigate the sensitivity of the replenishment on the results of the analyses, Figure 19 compares the results of analyses with different levels of replenishment. It can be noted that replenishment would retard ground settlements and reduce the magnitudes of the settlements. The differences between the results for the cases with the levels of replenishment at EL+4 m and EL+0 m are however insignificant.

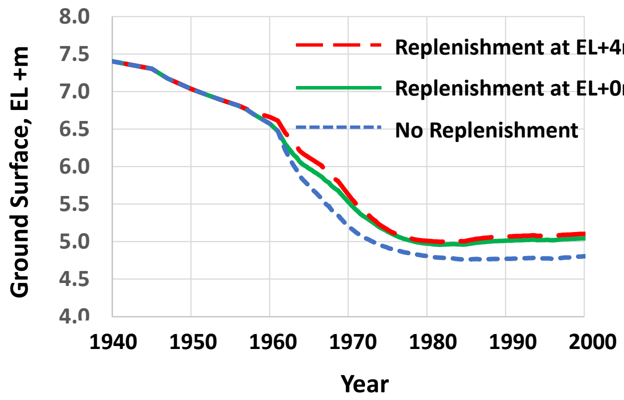

Figure 19 Effects of replenishment on ground settlements

8. CONCLUSIONS

Because of the uncertainties associated with the various factors affecting the consolidation of the soft deposits in the Songshan formation and the limited soil and groundwater data available for the analyses, this study is conceptual in nature and the results obtained are subject to further verification. The following findings will nevertheless be useful for future studies:

(a) The ground in the central city area could have settled by 0.38 m prior to 1950 and this amount should be added to the 2.17 m reported in the literatures, giving a total of 2.55 m.

(b) For the clayey layers, a Cc value of 0.4 and a Cv value of 14 m^2/year (0.0044 cm^2/sec) appear to be appropriate. For the sandy layers, the Cc value of 0.2 and the Cv value of 70 m^2/year (0.022 cm^2/sec) were obtained.

(c) More than half of the settlement experienced in the central area of the city could be attributed to the consolidation of the sandy materials in the Songshan formation.

(d) The zigzags in the profiles of water pressures in the Songshan formation published in literatures could be due to the lateral flows toward pumping wells as the water was drawn from nearby wells.

(e) The replenishment of water from various sources retarded the ground settlements and reduced the magnitudes of settlements. A level of replenishment of EL+0m, was assumed for the case of interest.

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