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Chapter · July 2021

DOI: 10.1007/978-3-030-80142-7_2

Muhsiung Chang
National Yunlin University of Science and Technology

Ren-Chung Huang

Chih-Ming Liao

Togani Cahyadi Upomo
Universitas Negeri Semarang

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Muhsiung Chang[1(✉)], Ren-Chung Huang[1], Chih-Ming Liao[1], Togani C. Upomo[2], and Rini Kusumawardani[3]

[1] Department of Civil and Construction Engineering, National Yunlin University of Science and Technology (YunTech), Yunlin County, Douliu City, Taiwan
changmh@yuntech.edu.tw

[2] Graduate School of Engineering Science and Technology, National Yunlin University of Science and Technology (YunTech), Yunlin County, Douliu City, Taiwan

[3] Department of Civil Engineering, Universitas Negeri Semarang (UNNES), Central Java, Indonesia

Abstract. Choshui River alluvial fan-delta (CRAFD) has been and still is the single-largest subsiding area in Taiwan. Some key infrastructures, including Taiwan High Speed Rail (THSR) and Expressway 78 (Expwy78) that come across this area, are suffering serious problems by the subsidence. Due to complexity of the issue, causes of the subsidence and their influences are not easily identified and quantified. This paper tends to disclose the above puzzles through a numerical approach that would allow separate applications of various factors and examination on their individual effects. The intersection of THSR and Expwy 78 is our primary concern since the subsidence at this location has become most serious along the entire route of THSR and the induced differential settlements are threatening the safety of the transportation artery. An 8-year subsidence monitoring data at the study site is used for calibration of material data adopted in the subsequent analyses. Results indicate the computed subsidence is 147.0 cm, or a rate of 10.53 cm/year, for a period approximately starting with the Expwy78 construction (01/1998–12/2011) and covering complete ranges of construction of Expwy78 and THSR of the site. Contributions due to various factors would be the greatest by previous overpumping (55.2%), followed by soil creeping (14.1%), groundwater fluctuations (11.8%), Expwy78 loading (11.6%), and the least by THSR loading (7.3%). Assessments also indicate around 1/5 and 4/5 of the total subsidence, respectively, occurred as the compression in soils with depths <70 m and >70 m, where 70 m is the average installation depth of THSR piles. Compression at shallower depths would be the greatest by Expwy 78 loading, and thus may trigger a major part of negative skin frictions and discount bearing capacity of the piles. Compression of deeper soils would be caused primarily by the previous overpumping, and would hence lead to significant settlements and distortions of vertical alignment of THSR structures.

S. Shu et al. (Eds.): GeoChina 2021, SUCI, pp. 18–36, 2021.
https://doi.org/10.1007/978-3-030-80142-7_2

1 Subsidence Issue

Land subsidence has been and is currently as well a significant threat to the living environment and transportation facilities to the western alluvial plains of Taiwan. Figure 1 indicates the locations of previous and present subsiding areas in the island. Since 1950s, Taipei basin has experienced substantial subsidence due to the excessive extraction of groundwaters for municipal purposes (Chen et al. 2007). Started approximately from 1970s as the booming of fishery farming (Fig. 2(a)), the west-coastal plains of Taiwan have become subsided as a result of overpumping of fresh groundwater, which also caused serious seawater intrusions into the ground (Hung et al. 2010). The groundwater tables were estimated lowered by more than 20 m along the coastline and about 4 m to the eastern boundaries of the plains (Chia et al. 1996, Chen et al. 2010).

As seen in Fig. 1, the western plains are still subsiding at present, especially in the area, Choshui River alluvial fan-delta (or CRAFD), with a measured maximum subsiding rate of 6.5 cm/year in 2019 (WRA 2019). The CRAFD is the largest alluvial deposit in Taiwan, encompassing Changhua County to the north and Yunlin County to the south. The deposit was formed by the longest river (Choshui River; Fig. 1) of the island and its tributaries, as well as by the influences of the sea (Taiwan Strait) (CGS 1999). In the past 200,000 years or so, the sea levels has been raised and lowered by ± 100 m several times in the history due to glacial retreats and advances (Chappell and Shackleton 1986), and thus contributed to the marine (delta) sedimentations to the western portion of the CRAFD.

In recent decades, previously significant subsidence areas along the coastline have gradually moved inlands. Figure 3 shows the shift of the subsidence hot spots in Yunlin County, the southern part of CRAFD, during the period of 1992–2011 (WRA 2011). The shift in subsidence areas was due mainly to the economic growth in the mid-CRAFD, as well as influences arise from the construction of several key transportation arteries, such as Taiwan High Speed Rail (THSR) and Expressway 78 (Expwy 78), passing across the area (Fig. 3). Excessive pumping of groundwaters for the purposes of agricultural, industrial and municipal activities has caused significant subsidence in the mid of CRAFD and threatened the safety of these transportation facilities.

The transportation safety of THSR has become a public concern since early 2000s. The alarm finally triggered in 2009 as the differential settlements between THSR piers have become so great that approached the design limits in angular distortion of 1/1000 for simple supported viaducts and 1/1500 for continuous viaducts (Hung et al. 2010, WRA 2011). The most serious section of THSR that suffered vertical alignment distortions was located at its intersection with Expwy 78. Since the construction period of Expwy 78 was approximately parallel to that of the previously-said subsidence shifting, one would suspect that, besides excessive pumping, the Expwy 78 embankment loading could also have had influences on the differential settlements of THSR piers.

Figure 4 is a photo taken at the intersection area, indicating Expwy 78 embankment as well as THSR piers that suffered the most angular distortions. Table 1 presents the subsidence (i.e., pier settlement) history at the intersection of Expwy 78 and THSR. Although the subsidence rate appeared decreasing in 2000s, the magnitude of THSR pier settlements remained significant and was detrimental to the transportation safety of the facility. Figure 2(b) shows an agricultural pumping well and the vegetation field

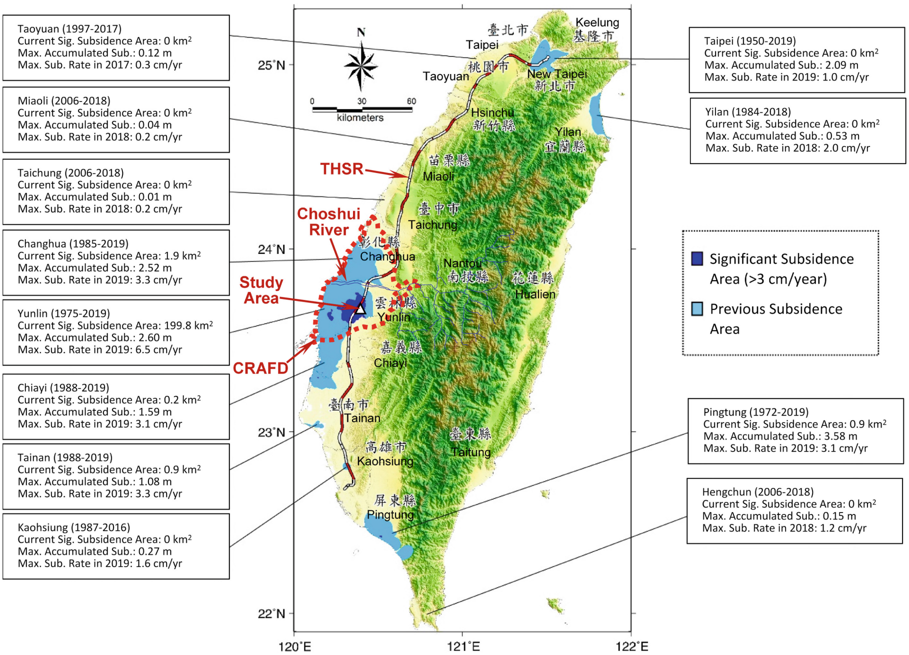


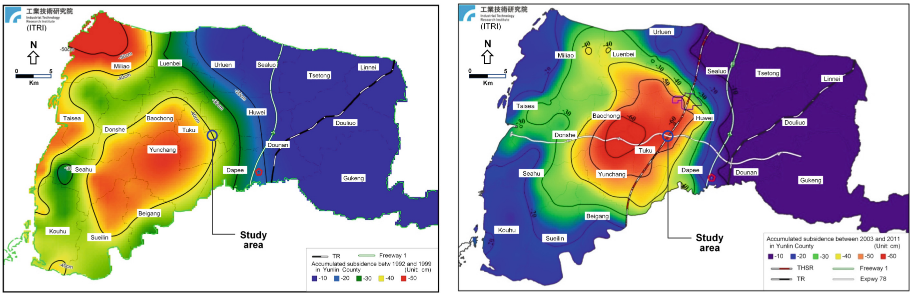
Fig. 1. Ground subsidence regions in Taiwan and study area (base map: WRA 2019; https://www.wra.gov.tw/cp.aspx?n=3679).

(a) Fishery farming (b) Agricultural planting

Fig. 2. Fishery and agricultural farming along west-coastal plains of Taiwan extracting excessive groundwaters and causing ground subsidence.

adjacent to the THSR, suggesting the groundwater extraction for agriculture purposes would be influential to the THSR safety as well.

It is obvious that the factors affecting on the subsidence of intersection area and the transportation safety of THSR would have included the excessive pumping of groundwater and the loading of Expwy 78 embankment. In fact, the loading of THSR piers as well as the groundwater fluctuations and the natural creeping of soil deposits would also be the potential causes for the subsidence. The normal consolidation of soil deposits due to natural deposition process, however, is generally believed to have completed since the CRAFD deposits where the project site is located was formed in late Quaternary



(a) 1992~1999 (b) 2003~2011

Fig. 3. Transition of subsidence areas in Yunlin County, the southern part of CRAFD, between 1992 and 2011 (base map: WRA 2011).

Table 1. Yearly subsidence at the intersection of THSR and Expwy 78 (WRA 2011)

Year	Yearly subsidence (cm/year)	Accumulated subsidence (cm)
2004	15.0	15.0
2005	10.6	25.6
2006	8.7	34.3
2007	7.5	41.8
2008	7.0	48.8
2009	6.5	55.3
2010	6.8	62.1

Note: Average subsidence rate = 8.87 cm/year

period in about 200,000 years ago (CGS 1999). In view of enormous thickness of soils in CRAFD (>750 m; CGS 1999, Hung et al. 2010), we anticipate a small amount of secondary compression (or creeping) of the soil deposits would be existing even if the normal consolidation of deposits due to natural deposition process could have completed for quite a long time.

The aim of this study is therefore set to determine the influences of various factors on the subsidence at the intersection area of THSR and Expwy 78, with particular interest in the estimation of their potential effects on the compression of soils at separate depth intervals of 0–70 m and >70 m. It is noted that the length of THSR group piles in the intersection area is around 70 m below the ground, as shown in Fig. 5. Land subsidence or soil compressions would have effects on the THSR pier structure in two folds. For the deposit with depth >70 m, the compression in soils would settle THSR pier structures and hence distort the vertical alignment of THSR route. Alternatively, for the deposit with depth <70 m, the compression in soils would cause negative skin frictions on THSR piers and thus detriment to the bearing capacity of the group piles.

Fig. 4. Intersection of THSR and Expwy 78 Embankment (viewing NE).

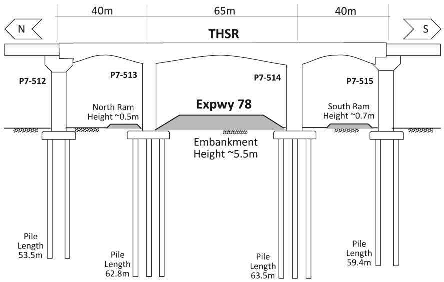


Fig. 5. Schematic illustration of THSR group piles and Expwy 78 embankment.

A numerical tool is adopted in this study for the assessment of influences of various factors on the subsidence at intersection area and the compression of soils at different depth intervals due to various factors. As shown in Fig. 6, three computation points (A, B and C) on the ground surface are assigned. Point A is located approximately 200 m away from both THSR and Expwy 78 and the subsidence at this location is considered with negligible influence by the loadings of these two transportation facilities. Point B is located along the THSR route approximately 200 m south of the intersection. The subsidence at this location is considered to be affected primarily by the THSR loading, in addition to the subsidence at Point A. Point C is located at the intersection of THSR and Expwy 78. The subsidence at this location is due mainly to the loadings of these two transportation facilities, in addition to the subsidence at Point A.

By assuming applicability of the principle of superposition, the influence of THSR pier loading can be assessed by subtracting the computed subsidence at Point A from that at Point B. Likewise, the influence of Expwy 78 embankment loading can be evaluated by subtracting the computed subsidence at Point B from that at Point C. The influences of soil creeping, excessive groundwater pumping (or termed as "previous overpumping" in the following sections) and groundwater fluctuation can be estimated in the numerical computations at Point A by switching on or off separately during the application of previous overpumping or groundwater level variations. Results of the numerical assessment will be discussed in Sects. 3 and 4.

Fig. 6. Location of study area and calculation points in numerical simulation.

2 Background Information

Prior to numerical simulations, some background information pertaining to natural or human factors that would have had impacts on the subsidence of the study area is described herein. These factors include site geology and hydrogeology setups, groundwater overpumping history, and THSR and Expwy 78 construction histories at the site.

2.1 Geology and Hydrogeology

As mentioned previously, the CRAFD was formed by alluvial depositions of Choshui River and its tributaries as well as by marine depositions due to seawater level changes in glacial periods some 200,000-year ago. Hence, the CRAFD consists of alternating layers of alluvial and marine deposits (Chiang et al. 1996, CGS 1999).

As shown in Fig. 7, a typical EW section across the fan-delta and the study area, the alluvial deposits mainly contain coarser particles like cobbles, gravels and coarse-medium sands, with their sizes distributed becoming finer from east to west. The alluvial deposits are generally abundant in groundwater and thus the water resources (aquifers) of the area. Alternatively, the marine deposits include finer particles, such as fine sands, silts and clays, which are distributed along the western coastline and near-shore regions. As the characteristics of low hydraulic conductivity, the marine deposits become barriers (aquitards) in the CRAFD. It is noted that the marine deposits to the western coastline or near-shore regions are generally unified and become a closed boundary of the CRAFD, thus render the aquifers in CRAFD as an underground reservoir (CGS 1999).

The thickness of soil deposits in CRAFD is still uncertain, however, limited documents indicated that no bedrock was encountered up to a depth of 750m below the ground surface (Hung et al. 2010). Within the upper 300m deep, four sets of aquifer-aquitard layers are identified, where the second aquifer (Aquifer 2 or F2; Fig. 7) has been the major water resource layer of the area (CGS 1999). In recent decades, however, the depth for groundwater pumping has become deeper and reached the third or fourth aquifers (F3 or F4) due to the demands of economic growth in the mid of CRAFD (Hung et al. 2010).

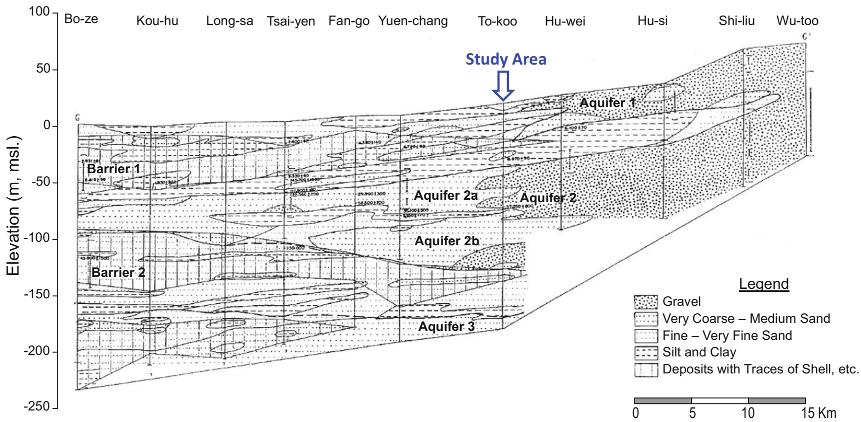


Fig. 7. Geology and hydrogeology profile of the area (based map: Chiang et al. 1996).

Figure 8 illustrates the observed piezometric levels in Aquifers F1, F2 and F3 at some monitoring stations near the study area. As seen, the piezometric levels in F2 and F3 are substantially lower than the one for F1, indicating excessive groundwater pumping has been occurring for some time in these layers and their influences are still continuing. We notice that the long-term trend of piezometric levels in F2 and F3 remains slightly declining, suggesting the influences of previous overpumping in deeper aquifers are not appreciably easing or recovering.

2.2 Previous Overpumping

Substantial lowering of piezometer levels in deeper aquifers of CRAFD as mentioned above was due mainly to excessive extraction of the groundwaters, and its influence on the subsidence of the site had been enormous. As shown in Fig. 3, the inland movement of subsidence hot spots of Yunlin County, in a period between 1992 and 2011, was in relation to the economic growth of mid-CRAFD, that involved more groundwater consumptions from deeper ground for agricultural, industrial and municipal activities.

It's difficult, however, to clearly define the period of excessive groundwater extraction of the area. In view of the observed inland shifting of subsidence hot spots that started

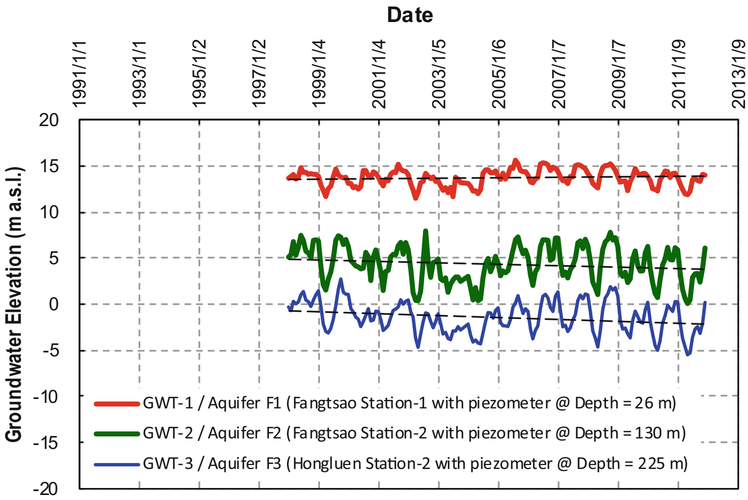


Fig. 8. Groundwater levels of confined aquifer layers in CRAFD (Chang et al. 2020).

approximately in mid 1990s (Fig. 3(a); Hung et al. 2010, WRA 2011, Li 2013), as well as a new agriculture polity promulgated in about the same period that encouraged local farmers to raise more water-consumptive vegetables instead of rice (Ho and Wang 2012), we notice that the significant drops in groundwater levels of the study area might have occurred approximately in the period of 1995–1997, and then became more or less stabilized ever since. This period, from the beginning of 1995 to the end of 1997, is therefore termed as the "previous overpumping" stage and adopted in the subsequent numerical simulations.

2.3 Expwy 78 and THSR Construction Histories

In the study area where two major transportation arteries meet, the loadings of these facilities (THSR viaduct/pier structure and Expwy 78 embankment) would play important roles on the land subsidence as well as the interactions on either of the facilities.

As mentioned previously and shown in Fig. 5, the THSR facility consists of viaducts and piers (i.e., group concrete piles; a pile arrangement of either 3 × 4 for P7–513 & P7–514 or 2 × 3 for other nearby group piles) with each pile a diameter of 2 m and an installation depth of around 70 m into the ground. Although point loads are adopted in the numerical simulations as the way of application of the loading by THSR facility, it should be noted that, since loading is applied on the pile head, the loading actually transmitted through a considerably rigid member of the pile along its shaft and at the base into the ground. Hence, THSR loading on the ground would involve influences in both shallower and deeper deposits.

For the loading by Expwy 78 embankment, a strip-type of surface loading is assumed in the numerical simulations. The loading of Expwy 78 embankment would primarily affect the compression of soils in shallower depths.

The other issue regarding the influence of subsidence behavior would be the timing of loading. Figure 9 illustrates the timeline of constructions of THSR and Expwy 78 facilities in the study area. In contrast to the short-period construction of THSR piers and viaducts, the construction of Expwy 78 embankment at the intersection had taken a much longer time, involving three major stages encompassing the THSR construction of the site. In view of the characteristics and timing of the loading, we expect the subsidence behavior as well as influences on the THSR facility of the area would be more complicated due to the involvement of lengthy construction of Expwy 78 embankment.

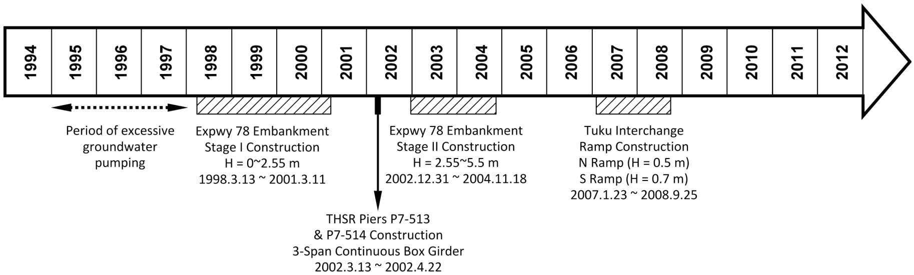
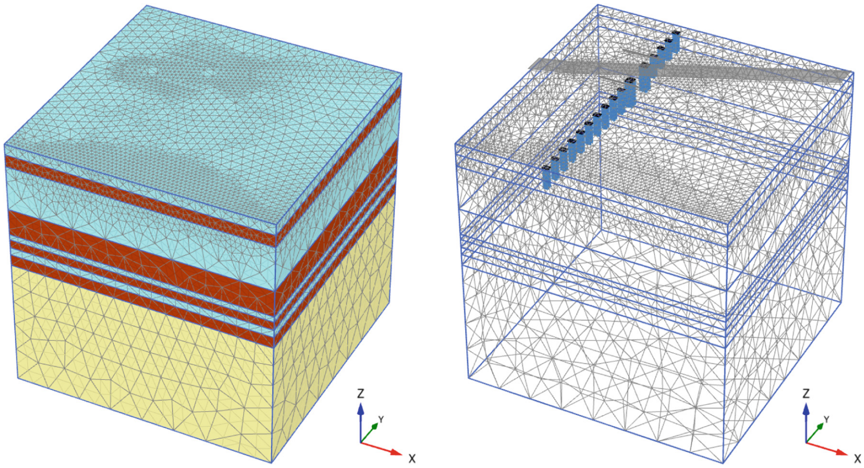


Fig. 9. Timeline for THSR and Expwy 78 constructions.

3 Numerical Simulation Scheme

A numerical software, Plaxis3D, is employed for the assessment of subsidence of the study area and influences due to various factors. As shown in Fig. 10, a 3D numerical model is set up which mimics the onsite arrangement of the two major transportation facilities (Fig. 6; THSR and Expwy 78). Material stratification of the site is assumed in terms of aquifers and aquitards revealed by the subsurface explorations with boreholes to a depth of 300 m from the ground. The loading and timing of constructions of THSR viaducts/piers and Expwy 78 embankment are based on the associated construction drawings as well as the timelines indicated in Fig. 9. As shown in the construction reports of THSR, the vertical loadings on P7–513 and P7–514 are approximately 38,500kN each, while the loadings for the remaining piers of the study area are in the range of 25,000–26,000kN (Sinotech 2003). As illustrated in Figs. 5 and 9, the width of the Expwy 78 embankment is about 55 m and the final height of embankment is 5.5 m in the intersection area. Significant drops in groundwater (or piezometer) levels and subsequent groundwater fluctuations are based on the previous overpumping period as mentioned above and the observed groundwater fluctuations (Fig. 8) at the nearby stations of the study area.

Details of the numerical simulations can be referring to Chang et al. (2020). Figure 10 indicates the numerical model adopted in the analysis, including 4 sets of aquifer (red color)/aquitard (light blue color) to a depth of 300 m, based on results of subsurface exploration of the site, and a 300 m-thick soil layer, termed as Base Soil (light yellow color), to represent remaining soil deposits in the deeper ground. The figure also shows the locations of THSR piles, represented as point loads acting on pile heads, and Expwy 78 embankment, represented as a strip loading on the ground. Generally, numerical simulations are conducted preliminarily with an assumed material data set to verify the results of 8-year onsite monitoring at Points A ~ C (10/2003–12/2011; Fig. 6). The assumed material data is calibrated and modified such that the computed subsidence of the ground at Points A ~ C and compressions of various material layers are comparable with those of the onsite monitoring. Results indicate the computed subsidence at Points A, B and C are 54.6 cm, 59.1 cm and 69.4 cm, respectively, which compare well with the monitoring data of 55.7 cm, 61.2 cm and 70.6 cm. The numerical simulations are then employed to predict the subsidence behavior of the site with a much longer computation period (01/1998–12/2011) which covers full-ranges of construction of THSR and Expwy 78 facilities at the site. With this longer period of computation, the influences of THSR and Expwy 78 loadings can therefore be completely assessed.



(a) Material layer stratification (b) FEM meshes, Expwy 78 and THSR loadings

Fig. 10. FEM model adopted in numerical simulations.

4 Numerical Assessment Results

The aims of numerical simulations in this study are to examine the contributions of various factors on the subsidence of intersection area of THSR and Expwy 78, as well as the influences of various factors on the compression of soils with depths <70 m and >70 m, that would have dissimilar effects on the safety of THSR viaduct/pier structures. Results of the numerical simulations are discussed as follows.

4.1 Contributions of Various Factors on Ground Subsidence

Results of numerical simulations on the subsidence of study area due to various factors are shown in Fig. 11 and summarized in Table 2. The computation period started from

1998/1/1 and ended on 2011/12/31, a 14-year time which covers full-ranges of THSR and Expwy 78 constructions of the site. As indicated, the computed total subsidence at the intersection area reaches 147.0 cm, or an average subsiding rate of 10.53 cm/year. This subsidence has included the influences due to groundwater-related factors, such as previous overpumping and soil creeping, as well as by the loadings of THSR and Expwy 78 facilities.

Table 2. Computed subsidence due to various factors at the intersection of THSR and Expwy 78 in a duration between 01/1998 and 12/2011

Influence factor	Subsidence of the ground		Compression in soils 0–70 m deep		Compression in soils >70 m deep	
	(cm)	(%)	(cm)	(%)	(cm)	(%)
Soil creeping	20.68	14.1	0.85	2.7	19.83	17.2
Previous overpumping	81.25	55.2	8.91	28.3	72.34	62.6
Expwy78 Embankment loading	17.09	11.6	13.51	42.9	3.58	3.1
THSR pile loading	10.67	7.3	5.55	17.6	5.12	4.4
Groundwater fluctuation	17.35	11.8	2.66	8.5	14.69	12.7
Sum:	147.04 (10.53 cm/year)	100.0	31.48 (2.25 cm/year)	100.0	115.56 (8.28 cm/year)	100.0

Figure 11 visualizes the influences of various factors on the subsidence of the site. It's obvious that the previous overpumping contributes the greatest (55.2%) to the subsidence, followed by soil creeping (14.1%), groundwater fluctuation (11.8%), Expwy 78 loading (11.6%), and the least by THSR loading (7.3%). It is noted that over 80% of the subsidence is due to groundwater-related factors (i.e., soil creeping, previous overpumping, groundwater fluctuation), and the contributions by loadings of THSR and Expwy 78 account for less than 20%.

It is also noted that the computed compression in soils with depths <70 m is 31.5 cm, or 21.4% of the total subsidence (note: average compression rate of 2.25 cm/year). The computed compression in soils with depths >70 m would be 115.6 cm, or 78.6% of the total subsidence (note: average compression rate of 8.28 cm/year). Apparently, around 1/5 of the subsidence occurs in shallower depths (<70 m) of the deposit and would tend to develop negative skin frictions and thus potentially impair the bearing capacity of THSR piles. On the other hand, around 4/5 of the subsidence would be generated at deeper depths (>70 m), which would settle the THSR piles and hence distort the vertical alignment of THSR route.

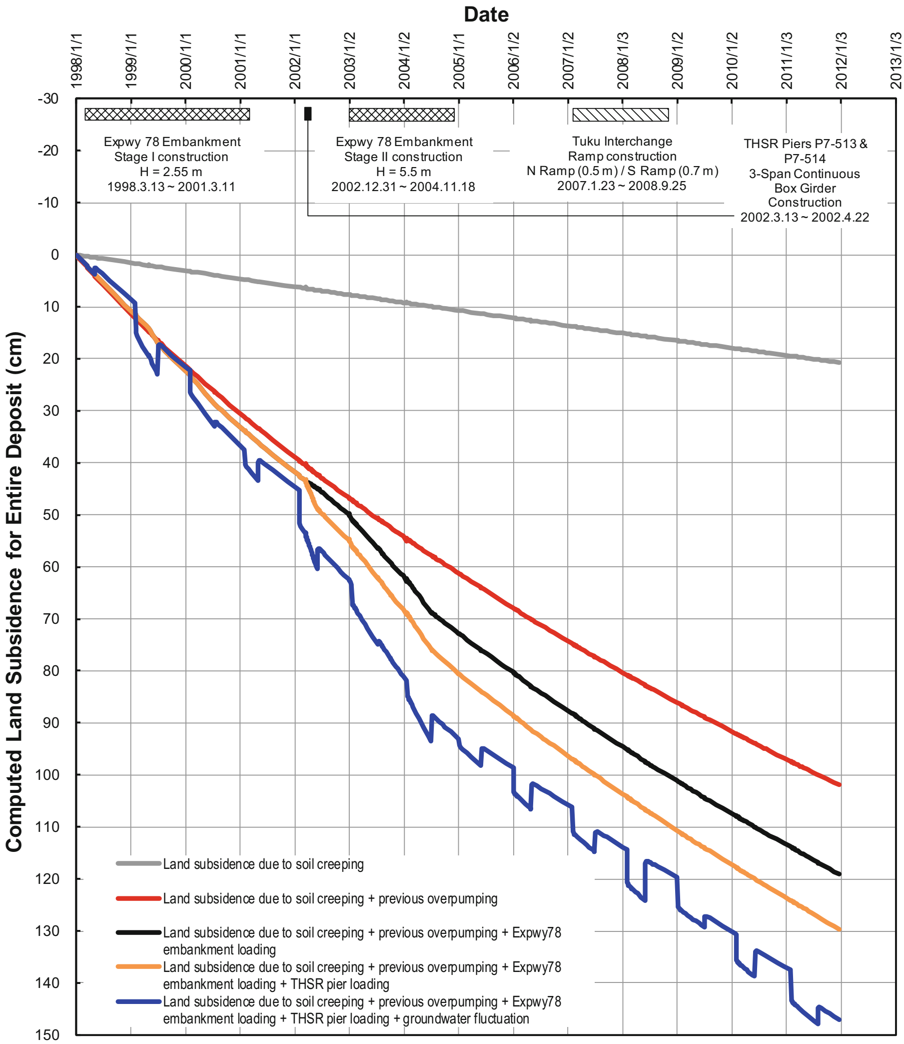


Fig. 11. Influence of various factors on subsidence at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

4.2 Influence of Soil Creeping on Compression of Soils

Figure 12 shows the influences of soil creeping on the ground subsidence as well as the compression of soils with depths < 70 m. In view of significant thickness of the deposit (600 m thick in the numerical model), a majority portion (19.83 cm) of subsidence due to soil creeping occurs at greater depths (>70 m), only a small amount (0.85 cm) would generate at shallower depths (<70 m). Hence, soil creeping would be more influential to the distortion of THSR vertical alignment than the bearing capacity of THSR piles.

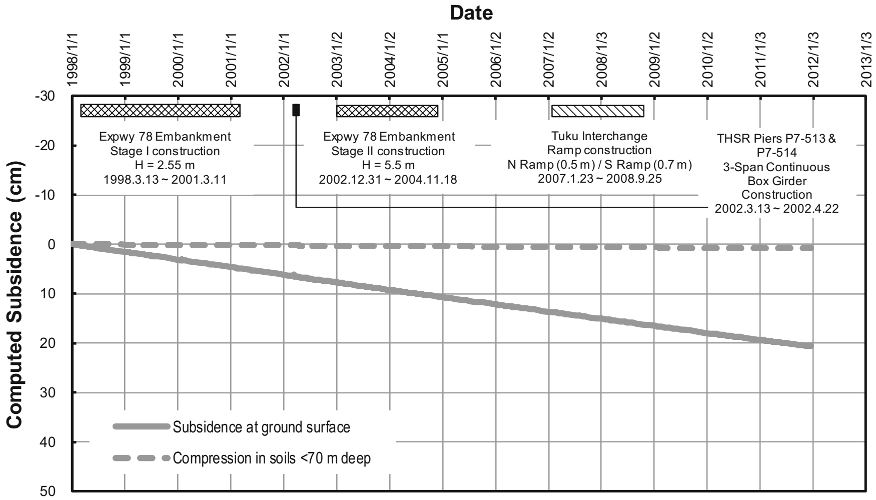


Fig. 12. Influence of soil creeping on compression of soils at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

4.3 Influence of Overpumping on Compression of Soils

Figure 13 shows the influences of previous overpumping on the ground subsidence as well as the compression of soils with depths <70 m. Since previous overpumping is the most significant factor on the ground subsidence, the computed compression in soils with depths >70 m is also substantial, and would be the greatest among other factors as indicated in Table 2. Previous overpumping also produces appreciable compression in soils with shallower depths (<70 m). Numerical simulations indicate previous overpumping would be a key factor on both the distortion of THSR vertical alignment and the bearing capacity of THSR piles.

4.4 Influence of Expwy 78 Loading on Compression of Soils

Figure 14 shows the influences of Expwy 78 loading on the ground subsidence as well as the compression of soils with depths <70 m. Although Expwy 78 loading is a minor factor on the overall subsidence, the computed compression in shallower soils (<70 m), however, has become the greatest among other factors, as indicated in Table 2. In viewing that Expwy 78 embankment, with a width (B) of approximately 50m, exerted a strip load on the ground, considerable stress increments and compressions would be generated to a depth of around two times the strip width (i.e., 2B or 100 m). Alternatively, the computed compression in soils in deeper ground (>70 m or 100 m) would therefore be insignificant as compared with the one in shallower depths.

As the construction of Expwy 78 embankment at the intersection has been divided into three separated stages, the computed subsidence due to embankment loading responds in relation to the construction stages. It is noted that the second stage of construction (2003–2004) appears to be the most influential on the subsidence of ground as compared with those in the other two construction stages. Given the fact that the

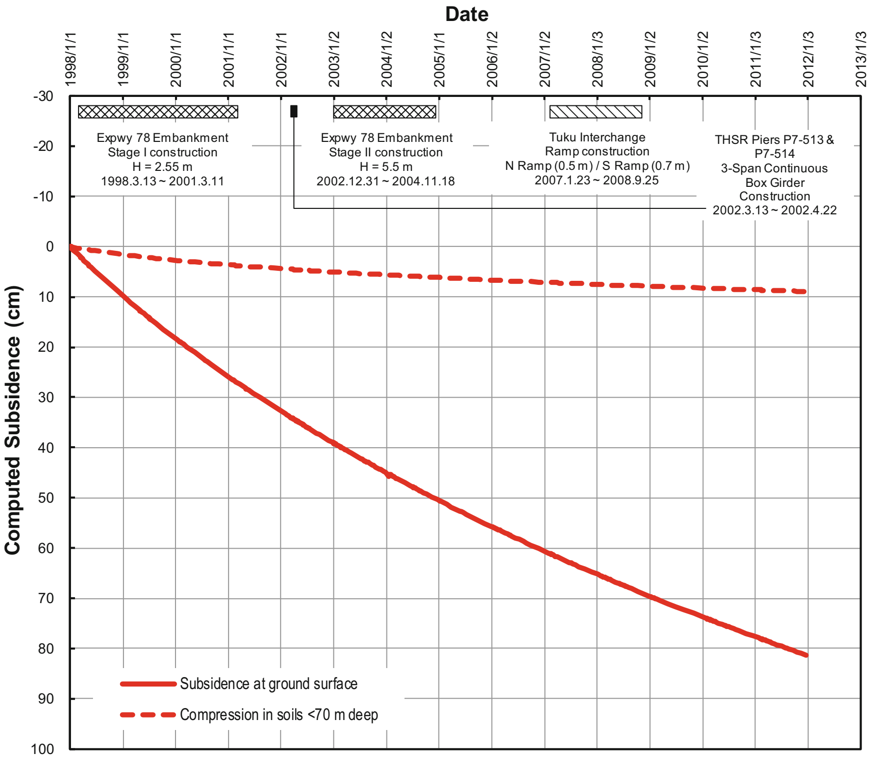


Fig. 13. Influence of previous overpumping on compression of soils at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

placements of the first two construction stages of Expwy 78 embankment were nearly the same, the greater subsidence computed in the second stage would have appeared due to several possible reasons. The THSR pier loading that was in place approximately 9 months prior to the second construction stage would have been influential to enhance the subsidence. The construction period in the second stage (~2 years) was appreciably shorter than that of the first stage (~3 years), leading to a more intensive surcharge and hence greater subsidence of the ground. Groundwater fluctuations during the period of second construction stage appeared more severe than those of the first stage, and might have contributed to a more subsidence of the second stage construction.

4.5 Influence of THSR Loading on Compression of Soils

Figure 15 shows the influences of THSR loading on the ground subsidence as well as the compression of soils with depths <70 m. As mentioned previously, THSR structure exerts point load on the pile head and transmits through the shaft and tip of pile into the ground. In accordance, both the soils along pile shaft and below pile tip would be subjected to compression. Although THSR loading produces the least contribution to the total subsidence of the site, the compressions in soils with depths <70 m and >70

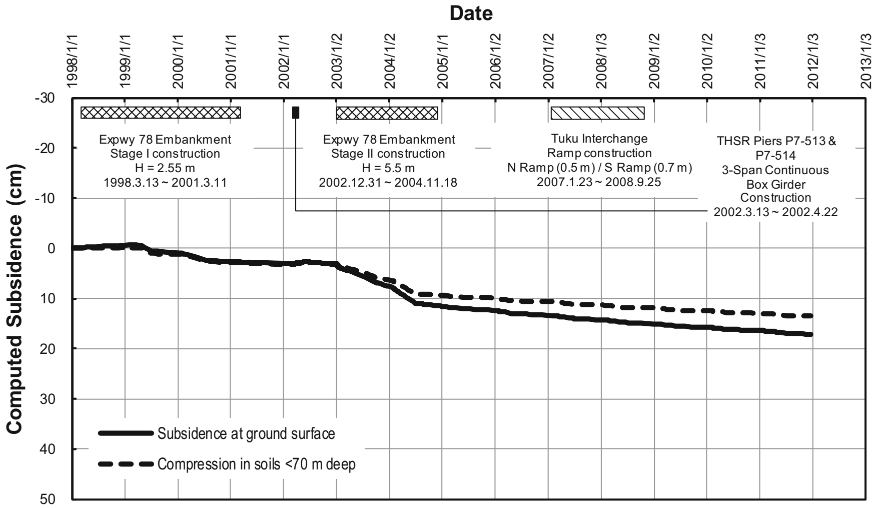


Fig. 14. Influence of Expwy 78 embankment loading on compression of soils at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

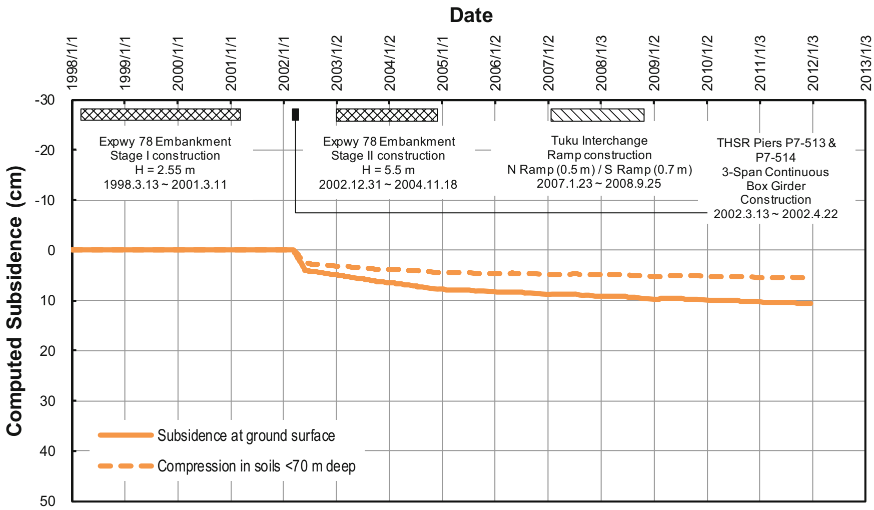


Fig. 15. Influence of THSR pier loading on compression of soils at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

m would appear to be equivalent, as shown in the figure, due to characteristics of the loading.

4.6 Influence of GWT Fluctuation on Compression of Soils

Figure 16 shows the influences of groundwater fluctuations on the ground subsidence as well as the compression of soils with depths < 70 m. During numerical simulations, the groundwater fluctuations are assigned based on the observed data as shown in Fig. 8. However, limitations of the numerical software prohibit the use of complete sets of data with detailed measurements, but only allow for simplified versions of the groundwater measurements. Hence, the observed groundwater data is simplified and assigned with the average values in wet and dry seasons of the year. As seen in the figure, the ground subsides or rebounds in accord with the lowering or rising of groundwater levels, due to the changes in wet-dry seasons and the activities for agriculture farming. Groundwater fluctuations would have more influences on the compression of soils in deeper ground. For the shallower depths (<70 m), however, the compression in soils would be minor.

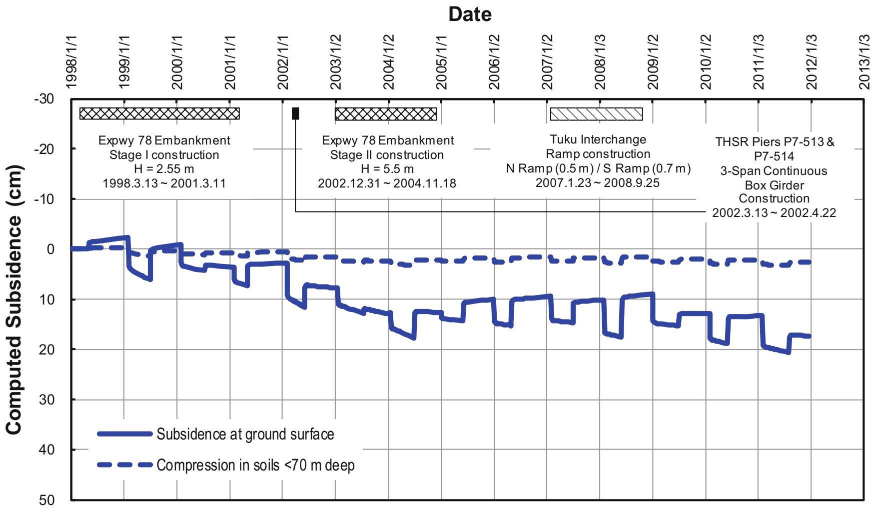


Fig. 16. Influence of groundwater level fluctuation on compression of soils at the intersection of THSR and Expwy 78 between 01/1998 and 12/2011.

5 Concluding Remarks

This paper presents results of numerical simulations on the subsidence behavior of ground at the intersection of THSR and Expwy 78, with emphases on the contributions of various factors on the subsidence as well as the influences of various factors on the compression of soils at shallower depths (i.e., < 70 m; the installation depth of THSR piles) and at deeper depths (i.e., > 70 m). The period for numerical simulations starts from 01/1998 and ends 12/2011, which covers full-ranges of constructions for THSR and Expwy 78 facilities at the intersection. In accordance, the results of simulations are able to reflect complete contributions on the subsidence by the loadings of these two transportation facilities. Some key findings of this study are summarized as follows:

- The subsidence of the study area is complicated by various influence factors, including: soil creeping, previous overpumping, groundwater fluctuation, and loadings of THSR viaducts/piers and Expwy78 embankment.
- For the 14-year period of concern (01/1998–12/2011), the numerical simulations reveal the total subsidence in the intersection area would be 147.0cm, or an average subsiding rate of 10.53 cm/year. The key contributing factor is found to be the previous overpumping (55.2%), followed by soil creeping (14.1%), groundwater fluctuation (11.8%), Expwy 78 loading (11.6%), and the least by THSR loading (7.3%), where the structural-related factors (i.e., THSR and Expwy 78 loadings) account for $< 20\%$ contribution on the total subsidence of the site.
- Numerical simulations indicate around 1/5 (or 21.4%) of total subsidence occurs as the compression in soils with depths < 70 m, and about 4/5 (or 78.6%) of total subsidence arises from the compression in soils with depths > 70 m. Accordingly, the compression rate in shallower soil deposits (<70 m) would be 2.25 cm/year, which would likely pose an unfavorable effect of negative skin friction and thus impair the bearing capacity of THSR piles installed within this depth range. Alternatively, the compression rate in deeper soil deposits (>70 m) would be 8.28 cm/year. The compression of deeper ground would settle THSR viaducts/piers and hence distort the vertical alignment of THSR route.
- For soil compressions in shallower depths (<70 m), the major influencing factor would be the Expwy 78 embankment loading, which accounts for 42.9% contribution of the compressions at this depth range. The Expwy 78 embankment exerts a static strip-load on the ground, and would be more pronounced on the stress increments and compressions as well in the shallower soil deposits.
- For soil compression in deeper ground (>70 m), the major influencing factor would be the previous overpumping, which accounts for 62.6% contribution of the compressions at this depth range. Previous overpumping that occurred approximately in the period of 1995–1997 significantly dropped the groundwater (or piezometer) levels, as evidenced by the monitoring data shown in Fig. 8, producing considerable and sustained straining on the ground mass. The influence of previous overpumping would be lasting for a long time until the piezometric levels of the onsite aquifers could be recovered and back to their original elevations.
- Numerical simulations reveal soil creeping would play an appreciable role on the subsidence of the study area (i.e., 14.1% of the total subsidence, or an average subsiding rate of 1.48 cm/year). Without groundwater infiltrations/evaporations or human activities like groundwater pumping and structural loading, the ground would still be sinking, as a result of secondary compressions (or creeping) of the enormously thick soil deposits of the CRAFD. Soil creeping occurs after the completion of primary consolidation, in a form of minor reorientations and slight adjustments of soil "grains" into a more stabilized arrangement. The primary consolidation due to natural deposition process of the soil deposits in CRAFD is believed to have completed for a long time, and the minor subsidence of ground at present, without the influences of groundwater infiltrations/evaporations and human activities, is due mainly to the creeping of the ground.
- As indicated previously, THSR facility would be suffered by the subsidence of the study area, causing negative skin frictions and reducing bearing capacity of THSR

piles due to the compression of soils in shallower depths (<70 m), as well as settling and distorting vertical alignment of THSR route as a result of the compression of soils in deeper ground (>70 m). The shallower depth compression is contributed mainly by the Expwy 78 embankment loading, while the deeper ground compression is contributed mainly by the previous overpumping. To ease the threat to THSR facility, this study suggests the identified key contributing factors, Expwy 78 embankment weight and previous overpumping, should be carefully dealt with. One potential mitigation measure would probably include a removal of earthen fill of the Expwy 78 embankment and a replacement with a light-weight structure, such as elevated road with box girders and pile foundation, EPS fill, etc. Other mitigation measure may also include a restriction of groundwater pumping and an enhancement of groundwater recharging, etc.

Acknowledgments. The authors would like to thank the funding provided by Resources Engineering Inc. Taiwan (NYUST 102–272) and Ministry of Science and Technology (previously, National Science Council), Taiwan (NSC102-2815-C-224-020-E, MOST105-2815-C-224-003-E). Some background information and monitoring data provided by Central Geological Survey, Water Resources Agency, and Directorial General of Highway, Taiwan, are highly appreciated.

References

Central Geological Survey (CGS), MOEA, Taiwan (1999). Summary report of groundwater monitoring network plan in Taiwan - phase I (1992–1998) (1999). (in Chinese)

Chang, M., Upomo, T.C., Huang, R.C., Wu, P.K., Su, P.C.: Evaluation on the behavior and contributing factors of subsidence in the intersection area of Expwy 78 and Taiwan High Speed Rail based on in-situ monitoring and numerical simulations. Bull. Eng. Geol. Env. **79**(6), 2971–2995 (2020)

Chappell, J., Shackleton, N.J.: Oxygen isotopes and sea level. Nature **324**, 137–140 (1986)

Chen, C.T., Hu, J.C., Lu, C.Y., Lee, J.C., Chan, Y.C.: Thirty-year land elevation changes from subsidence to uplift following the termination of groundwater pumping and its geological implication in the Metropolitan Taipei Basin, Northern Taiwan. Eng. Geol. **95**, 30–47 (2007)

Chen, C.H., Wang, C.H., Hsu, Y.J., Yu, S.B., Kuo, L.C.: Correlation between groundwater level and altitude variations in land subsidence area of the Choshuichi alluvial fan. Taiwan. Eng. Geol. **115**, 122–131 (2010)

Chia, Y.P., Lu, S.D., Wang, Y.S.: Hydrogeological framework of the south wing of Choshui River Fan. Proceedings of Conference on Groundwater and Hydrogeology of Choshui River Alluvial Fan, Taiwan, pp.113–125 (1996). (in Chinese with English Abstract)

Chiang, T.R., Lai, D.C., Huang, C.C., Lai, T.H., Chen, L.J. (1996). Conceptual model of hydrogeology and groundwater system of Choshui River Alluvial Fan. In: Proceedings of Conference on Groundwater and Hydrogeology of Choshui Alluvial Fan, pp.127–143 (1996). (in Chinese with English Abstract).

Ho, J.Y., Wang, G.C.: Political economics on groundwater extraction for the crisis of land subsidence in Yunlin Area. In: Proceedings of Annual Meeting on Cultural Studies, p. 23 (2012). (in Chinese)

Hung, W.C., Hwang, C., Chang, C.P., Yen, J.Y., Liu, C.H., Yang, W.: Monitoring severe aquifer-system compaction and land subsidence in Taiwan using multiple sensors: Yunlin, the southern Choshui River alluvial fan. Env. Earth Sci. **59**, 1535–1548 (2010)

Li, J.G.: Problems and mitigations of land subsidence - for areas in Yunlin and Changhua counties and along the THSR route. PPT of Keynote Speech at Geotech2013 Conference, September 11–13, Jenfushan Prince Hotel, Yunlin, Taiwan (2013). (in Chinese)

Sinotech: Calculation report of foundation, design unit: DU4.09, TK.224+259.842 ~ TK.224+404.842, Taiwan High Speed Rail. C270/DU4.09/DD, Sinotech Engineering Consultants, Ltd. (2003)

Water Resources Agency (WRA), MOEA, Taiwan (2011). Multi-sensors applied to monitor subsidence and investigate mechanism in Taipei, Changhua and Yunlin area in 2011 (in Chinese with English abstract), ISBN: 978-986-03-0205-9 (2011).

Water Resources Agency (WRA), MOEA, Taiwan (2019). Land subsidence map in Taiwan area in 2019 (2019). (in Chinese). https://www.wra.gov.tw/cp.aspx?n=3679.