In-Situ Monitoring of Ground Subsidence at the Intersection of Expwy 78 and High Speed Rail of Taiwan During 2003–2011

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Abstract. This paper discusses results of a long-term onsite monitoring on ground subsidence and soil compressibility at the intersection of Expressway (Expwy) 78 and the High-Speed Rail of Taiwan (THSR). The intersection area is located on the Chuoswei River Alluvial Fan-Delta (CRAFD), the largest and thickest alluvial deposit to the mid-west of the island. The CRAFD has been subjected to serious subsiding problems for decades because of excess extractions of groundwater for agricultural and industrial usages. The constructions of Expwy 78 and THSR in the late 1990s imposed additional loadings on the soft ground and accelerated the subsidence problem, which was becoming a threat to the safety of THSR. An 8-year onsite monitoring program at the intersection was conducted between 10/2003 and 12/2011. The subsidence and compression of soils were measured through multi-leveled magnetic rings installed in the ground along boreholes of 300-m deep, as well as a GPS station and several level-surveying benchmarks. Results indicate the ground subsidence in the intersection area was 55.7 cm for the entire deposit in the 8-year monitoring period without the loadings of Expwy 78 and THSR. The loadings of Expwy 78 embankment and THSR piers/viaducts would contribute additional subsidence of 9.4 cm and 5.5 cm, respectively, to the ground in the same period. The total subsidence in the 8-year period was 70.6 cm, with an average rate of 8.6 cm/yr. Further analysis of the compression in soils with depth <300 m indicated that the shallower deposit (depth <70 m; Aquifer F1 and Aquitard T1) was least compressible, with a strain rate of <0.01%/yr; while the deeper deposit (depth 220–300 m; Aquifers F3, F4 and Aquitards T3, T4) was most compressible, with a strain rate of 0.03–0.05%/yr. Higher compressive rates in deeper soils suggest the extraction of groundwaters has gone deeper in recent decades.

1 Introduction

Ground subsidence has been a serious issue in Taipei basin and along coastal plains of western Taiwan (Chien 1987; Wu 1987; Liao et al. 1991; Chen et al. 2007). The subsidence was due to over extraction of groundwaters for municipal usages or fishery farming. In recent decades, Chuoswei River Alluvial Fan-Delta (CRAFD), deposited by Chuoswei River to the midwest coastal plain of the island, has become a single

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largest subsiding area (Hung et al. 2010). The river divides the fan-delta into Changhua County to the north and Yunlin County to the south. Previously, the area along the coastline of CRAFD suffered most serious subsidence due to exploitations of groundwater for fishery farming. The subsiding area is now moving inlands as the need of water resources for economic growth in the middle of CRAFD and the extraction of groundwaters from deeper depths.

Figure 1 indicates the current subsiding zone in Yunlin County, the southern portion of CRAFD, based on level survey data between 2003 and 2011 (WRA 2011). The accumulated subsidence has reached about 60 cm in eight years, or an average subsiding rate of 7.5 cm/yr. The subsidence has caused a serious concern on the safety of transportation structures of the area. As shown in the figure, Expressway (Expwy) 78 and Taiwan High Speed Rail (THSR) pass through the subsiding zone. Vertical alignments of these transportation arteries were distorted and threatened the safety of the structures.

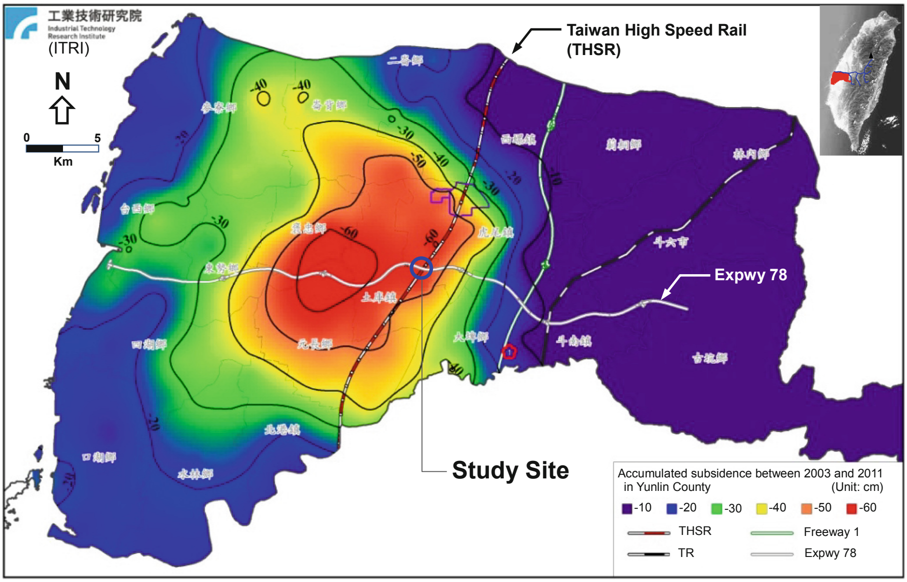


Fig. 1. Ground subsidence in Yunlin County between 2003 and 2011 (WRA 2011) and location of the study site

The aims of this study are to provide results of a long-term onsite monitoring carried between 2003 and 2011 at the intersection of Expwy 78 and THSR, as shown in Fig. 1, and to clarify the compressions of soil layers within the deposit as well as the contributions of various factors on the subsidence of the study area.

2 Background Information

The CRAFD is formed by the alluvial deposition of Chuoswei River, the longest river in Taiwan, and by the marine deposition of seawater where the sea level has been raised and lowered ±100 m several times in the recent 200 thousand years (Chappell and Shackleton 1986). In accordance, the fan-delta contains alternating layers of alluvial and marine deposits, and is considerably thick with an estimated depth of more than 350 m (Lin et al. 1992; Hung et al. 2010).

Figure 2 is a hydrogeologic model of the CRAFD. The alluvial deposits mainly consist of gravels, coarse and medium sands, and become aquifers (F-series); while the marine deposits compose of fine sand, mud and clay, and form aquitards (T-series). Based on Central Geological Survey of Taiwan (CGS 1999), four sets of aquifer/aquitard have been identified in the upper 300-m of the deposit, in which Aquifer F2 is the thickest and has been the major groundwater resources of the area.

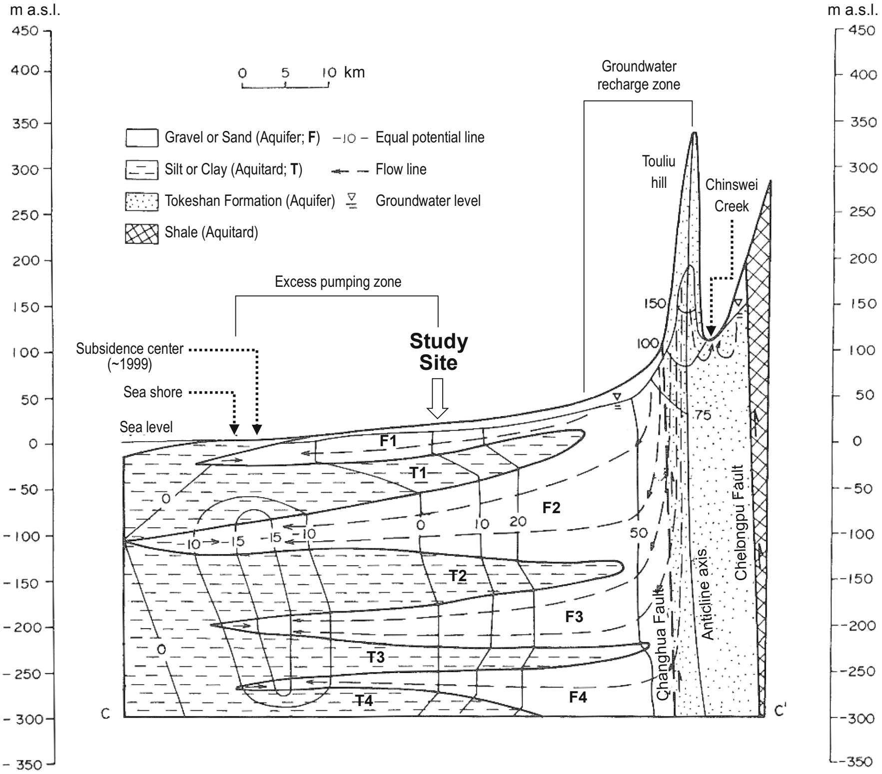


Fig. 2. Hydrogeologic model of the CRAFD (CGS, 1999)

Figure 3 indicates the layout plan of the study area. The onsite monitoring was carried out along the alignment of THSR and to the southern quadrant of the intersection of the two transportation routes. Figure 4 shows the material layer stratification of the study area based on 300-m borehole loggings at STA-1 and STA-9. The material profile indicates the deposit of the site contains interbedded layers of sandy and clayey soils, which can be further divided into four sets of aquifer and aquitard per the definitions by Central Geology Survey of Taiwan (CGS 1999).

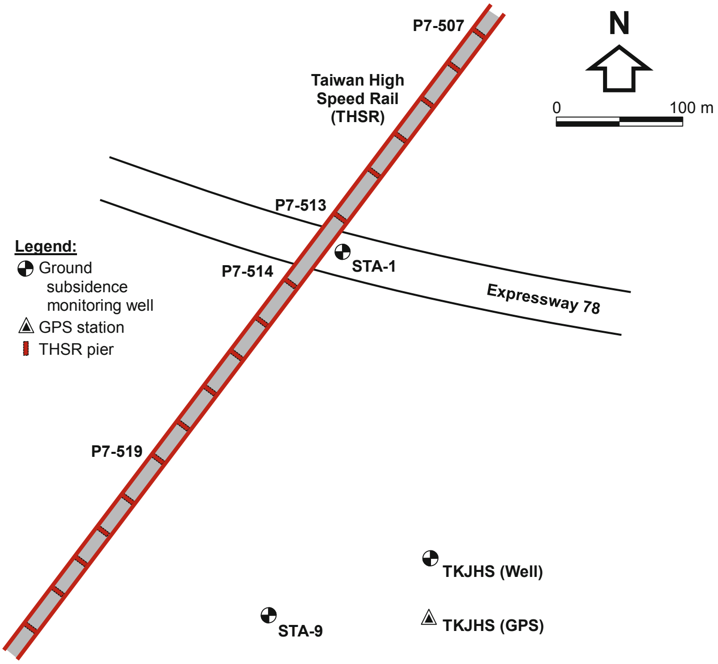


Fig. 3. Layout plan of onsite monitoring locations

Figure 5 shows the Expwy 78 and THSR of the site. Expwy 78 was built as an embankment of approximately 5.5 m high and 56 m wide, which runs in east-west direction across the CRAFD. THSR consists of a series of viaducts and piers laid in SW-NE direction and overpassed the Expwy 78 embankment in the study area. The pier foundations of THSR were formed by group piles of 2 × 2, 2 × 3 or 3 × 4 in arrangement, with each pile a diameter of 2 m and a length of 50–65 m.

The Expwy 78 embankment and THSR piers/viaducts of the site were constructed in different periods. As illustrated in Fig. 6, the construction of Expwy 78 embankment was carried out in three separated stages and at a start time much earlier than the 8-year monitoring period. The THSR piers/viaducts were fabricated in between Stages I and II of Expwy 78 construction, and were also completed 1.5 years prior to the onsite monitoring program discussed herein. The surcharging of Expwy 78 embankment and THSR pier foundations apparently contributed to the subsidence of the study area.

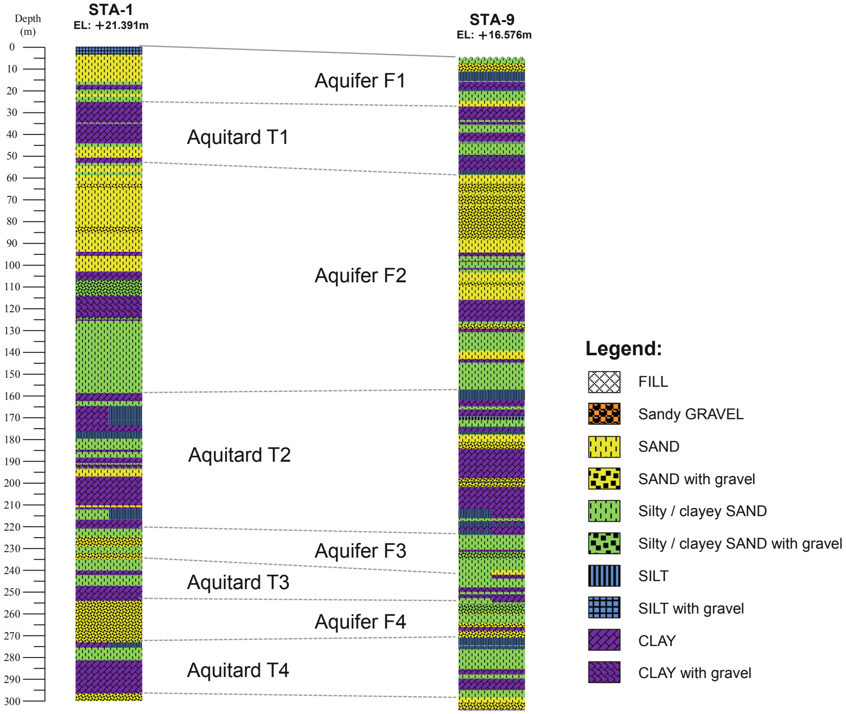


Fig. 4. Material layer stratification of the site

Fig. 5. Expwy 78 embankment and THSR piers and viaducts of the site (facing north)

Due to different construction histories, however, the contributions by Expwy 78 and THSR would not be the same in the 8-year monitoring period. To be noted, an appreciation on the complete influences of Expwy 78 and THSR on the ground subsidence could not be made based on the 8-year monitoring since both structures were constructed some times ahead of the onsite monitoring period.

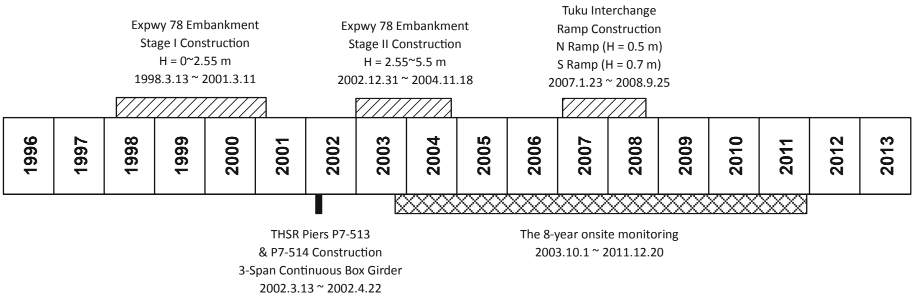


Fig. 6. Construction histories of Expwy 78 and THSR at the site

3 Ground Subsidence During 8-Year Monitoring Period

Ground subsidence behavior of the study area was observed based on various kinds of monitoring methods, including: 300-m boreholes installed with multi-leveled magnetic rings that attached to the ground (i.e., subsidence monitoring wells), a GPS station, and level survey benchmarks at the THSR piers. The monitoring of subsidence wells was conducted periodically by inserting a magnetic sensor into the well where the depths of the magnetic rings were measured and the subsidence and compressions of the ground could thus be computed. The following subsections discuss the observed subsidence as well as the contributions of various influencing factors during the 8-year monitoring period.

3.1 Summary of Different Types of Monitoring Data

Figure 7 indicates results of the subsidence monitoring well, TKJHS (well), during the 8-year monitoring period. As seen in Fig. 3, TKJHS (well) is located approximately 200 m away from Expwy 78 or THSR, as well as their intersection. The influence of the loadings from these structures on the ground subsidence at TKJHS (well) would be minimal and can therefore be neglected.

As depicted in Fig. 7, the soils within the 300-m deposit compressed progressively with time. The final subsidence of the ground at TKJHS (well) was about 40 cm in the 8-year period, or at a subsiding rate of 4.9 cm/yr, for the 300-m deposit without the influence of Expwy 78 and THSR loadings.

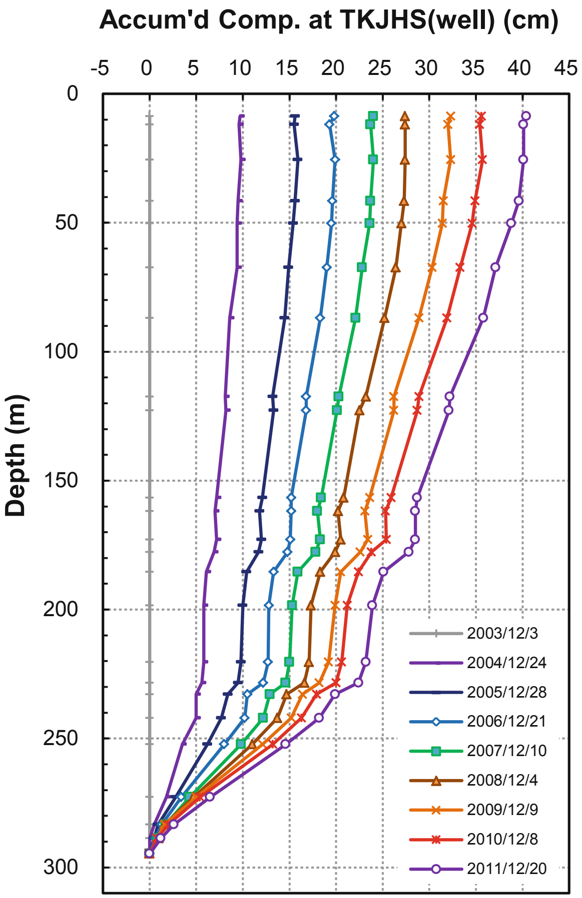


Fig. 7. Results of 8-year monitoring at TKJHS subsidence well

From the compression profile, we notice that the deeper soils with depths 220–300 m tend to compress more than does the shallower soils with depths <70 m, as depicted by the slopes of the curves. Details of the compression behaviors of the soil deposit will be discussed in the following section.

Figure 8 indicates the results of various types of monitoring at different locations. The characteristics of the monitoring data are described below:

- TKJHS (well) data – provides compressions of soils through the measurements of 300-m deep subsidence monitoring well. The monitoring location is located away from Expwy 78, THSR and their intersection (Fig. 3). The monitoring data is primarily influenced by the factors other than the loadings of Expwy 78 and THSR, i.e., nonstructural-related factors, and reflects the compressions of soils within 300 m deep.

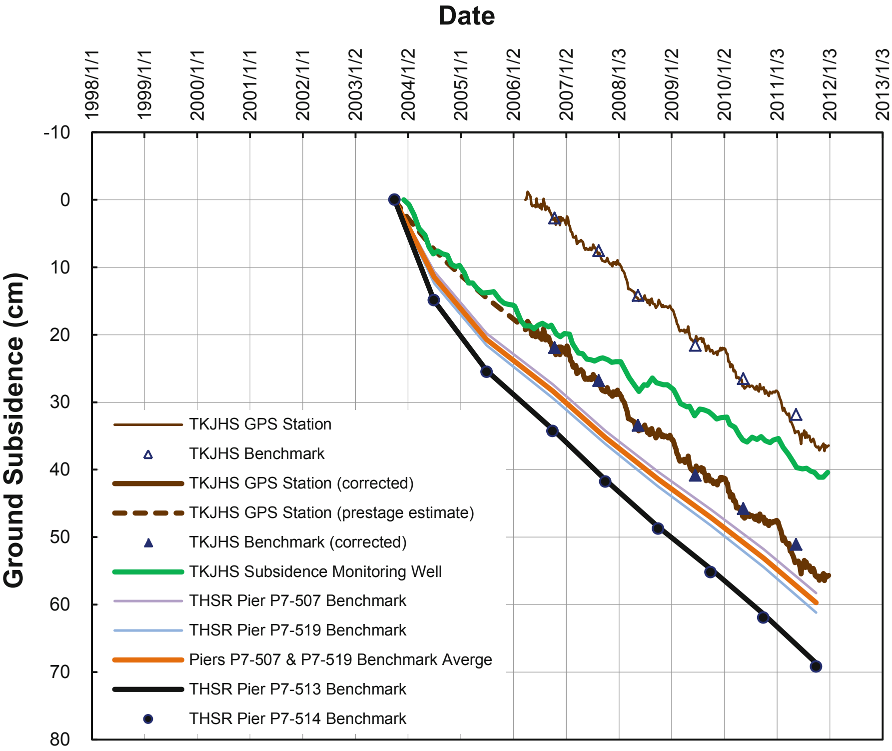


Fig. 8. Summary of different types of monitoring data during at the study site

- TKJHS (GPS) data – provides subsidence of the ground. The monitoring location is close to that of TKJHS (well) (Fig. 3). The monitoring data is also influenced by the nonstructural-related factors. However, the data reflects the compression of entire deposit, including the soils deeper than 300 m.
- TKJHS survey benchmark data – provides subsidence of the ground. The monitoring location is adjacent to TKJHS (GPS) (Fig. 3). The characteristics of the monitoring data is resembling to those of TKJHS (GPS), and reflects the compression of entire deposit, including the soils deeper than 300 m.
- THSR Piers P7-507 and P7-519 survey benchmark data – provides subsidence of the ground. The monitoring locations are along the alignment of THSR but away from Expwy 78 embankment (Fig. 3). The monitoring data is therefore influenced by THSR loading as well as nonstructural-related factors, and reflects the compression of entire deposit, including the soils deeper than 300 m.
- THSR Piers P7-513 and P7-514 survey benchmark data – provides subsidence of the ground. The monitoring locations are sitting at the intersection of Expwy 78 and THSR (Fig. 3). The monitoring data is hence influenced by the loadings of Expwy 78 and THSR, and nonstructural-related factors as well, and reflects the compression of entire deposit, including the soils deeper than 300 m.

As shown in Fig. 8, the GPS data (thin brown line) and survey benchmark data (open blue triangles) at TKJHS station agree well indicating the consistency in the measurements where the subsidence is primarily influenced by factors other than the loadings of Expwy 78 and THSR. To compare the results of subsidence monitoring well at TKJHS (well) started in late 2003 (thick green line), the TKJHS (GPS) and survey benchmark data are extrapolated based on level survey measurements of the region, as shown in Fig. 1, in approximately the same period as for the TKJHS (Well). The TKJHS (GPS) and survey benchmark data are shifted such that the ground subsidence in mid-2011 approximately equals 54 cm, as shown at the study site of the contour plot in Fig. 1.

The shifted and extrapolated TKJHS (GPS) and survey benchmark data (thick brown line and closed blue triangles) in Fig. 8 illustrate the subsidence behavior of entire deposit at the study site during the 8-year monitoring period. Compared with the data of subsidence monitoring well at TKJHS (well) (thick green line), which reflects the compression of soils within 300 m deep, we notice a substantial compression occurs in soils with depth greater than 300 m. Details of soil compressions will be discussed in the following section.

Figure 8 also shows the monitoring data at THSR pier survey benchmarks. Piers P7-507 and P7-519 are located about 200 m away from the intersection (Fig. 3), and the subsidence measured at these locations (average values in thick orange line) would b y TKJHS (GPS) (thick brown line), due to additional influence by the THSR loading. Piers P7-513 and P7-514 are situated at the intersection (Fig. 3), the subsidence measured at these locations (thick black line and closed blue dots) would also be greater than those at Piers P7-507 and P7-519 (thick orange line), due to further effect by the loading of Expwy 78.

3.2 Contributions by Various Influencing Factors

To differentiate contributions to ground subsidence by various factors, the following assumptions are made: (1) soil layers are horizontally extended; (2) groundwater level fluctuations are the same across the site; and (3) superposition principle is applicable for subsidence calculations. In accordance, the ground subsidence due to factors other than the loadings of Expwy 78 and THSR, i.e., nonstructural-related factors, can be represented by the TKJHS (GPS) data. The ground subsidence due to the loading of THSR can be estimated by subtracting the TKJHS (GPS) data from the level survey benchmark data at THSR Piers P7-507 and P7-519. Similarly, the ground subsidence due to the loading of Expwy 78 can be assessed by subtracting the level survey data at THSR Piers P7-507 and P7-519 from the level survey data at THSR Piers P7-513 and P7-514.

Figure 9 presents results of the above assessment on the contributions of various factors to the ground subsidence of the site. Table 1 indicates the contributions to the ground subsidence during the 8-year monitoring period are 13% and 8%, respectively, by the loadings of Expwy 78 and THSR. Although Expwy 78 embankment appears to be more influential than THSR piers/viaducts, their contributions to ground subsidence are significantly less than those by nonstructural-related factors.

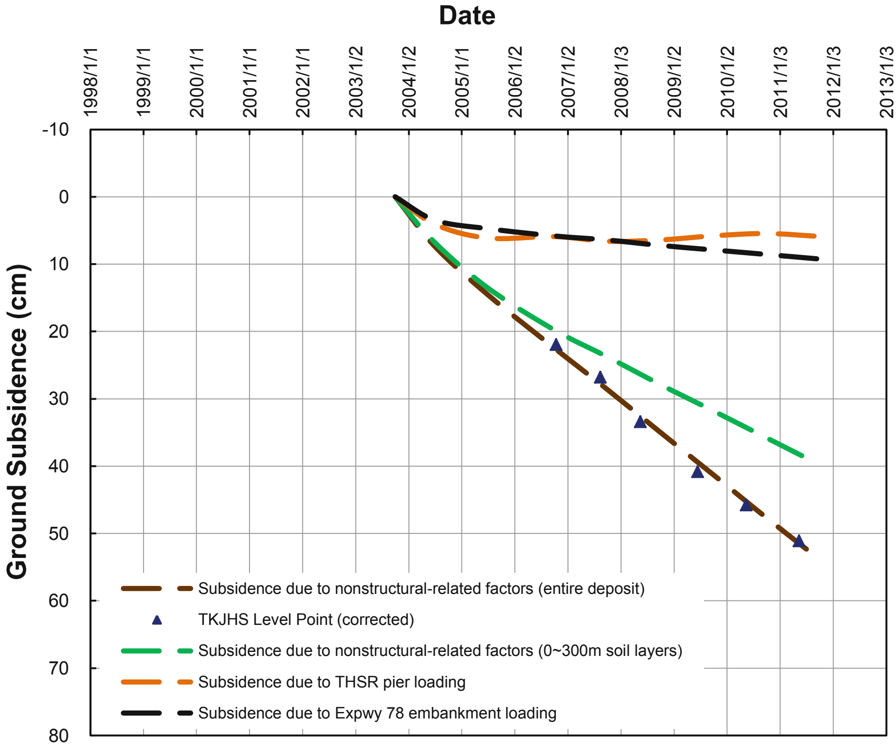


Fig. 9. Influences of various factors on the subsidence behavior of the site

Table 1. Contributions of various factors on the subsidence of the site during the 8-year monitoring period (2003.10.1– 2011.12.20)

Influence factor	Subsidence contribution		
	(cm)	(%)	(cm/yr)
Nonstructural-related factors: groundwater fluctuation, overpumping, soil creeping, etc.	55.7	79	6.78
Expwy 78 embankment loading	9.4	13	1.14
THSR pier loading	5.5	8	0.67
Total	70.6	100	8.59

The nonstructural-related factors in a broader sense would include the short-term fluctuations and long-term declines of groundwater levels due to infiltration or evaporation of rainfalls or surface waters, or due to human extraction of groundwaters, as well as the creeping of soil deposit due to its great amount of thickness. As indicated previously, the subsiding area has been moving inlands of the CRAFD in recent decades due to economic growth of the areas and extractions of groundwater from deeper depths. Apparently, the drops in groundwater levels by overpumping would have a significant contribution on the subsidence of the site. Besides, the CRAFD consists of soil deposits of more than 350 m in thickness (Lin et al. 1992; Hung et al. 2010). In spite the soils might have completed their normal consolidation process, insignificant creeping in soils can still accumulate deformations with time to an amount that cannot be neglected.

It should be noted, however, the contributions of various factors on the subsidence of the site cannot be fully addressed based solely on the results of 8-year monitoring. As pointed in Fig. 6, the constructions of Expwy 78 embankment and THSR piers and viaducts consisted of separated stages and started prior to the 8-year monitoring. The influences of Expwy 78 and THSR loadings would be decreasing with time. In the 8-year monitoring period, the contributions of Expwy 78 and THSR loadings to the subsidence were apparent in the first two years, and then became stabilized as shown in Fig. 9.

4 Soil Compression During 8-Year Monitoring Period

This section discusses compressions and compressibility of soil layers based on the monitoring data of magnetic rings installed in the subsidence well TKJHS (well).

4.1 Compressions of Soils at Different Depth Intervals

As shown previously in Fig. 7, the compression profile at TKJHS (well) can be divided into three depth intervals, of which the calculated compressions and compressive strains are indicated in Table 2. In the shallower depth of less than 70 m, the compression would be the least, accounted for 6% of the total subsidence in the 8 years, and the compressibility would be the smallest, with a strain rate of 0.047 cm/m. For the deeper depth range of 220–300 m, however, the compression would be the greatest, accounted for 42% of the total subsidence in the 8 years, and the compressibility would be the largest, with a strain rate of 0.290 cm/m.

Table 2. Compressions of soil at different depth intervals of the deposit during the 8-year monitoring period (2003.10.1–2011.12.20)

Depth interval	Compression & compressive strain		
	(cm)	(%)	(cm/m)
0–70 m	3.3	6	0.047
70–220 m	13.9	25	0.093
220–300 m	23.2	42	0.290
>300 m	15.3	27	–
Total	55.7	100	–

The depth range of 220–300 m comprises aquifers F3 & F4 and aquitards T3 & T4. Since Aquifer F2 (depth range 55–160 m, approx.) used to be the major groundwater resource of the area, the observed greater compressions and compressibility of deeper layers suggest the extraction of groundwaters should have gone deeper in recent decades.

Table 2 also indicates the compression of soils with depth deeper than 300 m, based on the difference of monitoring data between TKJHS (GPS) and TKJHS (well), as depicted in Fig. 8. Results indicate the compression of soils deeper than 300 m (i.e., the monitoring depth of subsidence well TKJHS (well)) would be substantial, accounted for 27% of the total subsidence in the 8 years.

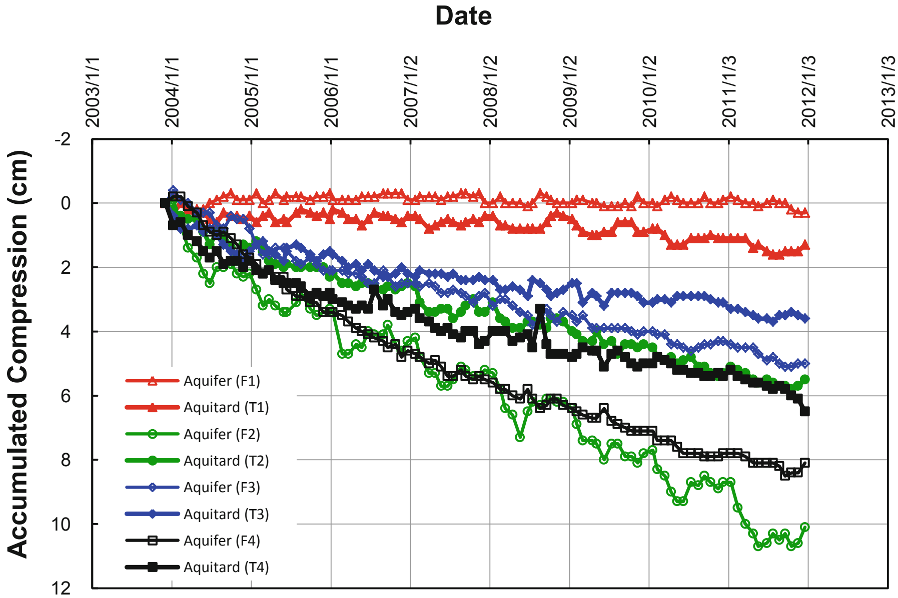
In view of the installation depth of THSR group piles of 50–65 m, the compression of shallower soils (i.e., 3.3 cm in 8 years; for depth <70 m) appears small and would not cause adverse effects (i.e., negative skin frictions) on the piles. The compression of deeper soils (i.e., 52.4 cm in 8 years; for depth >70 m), however, is substantial and would be detrimental to the vertical alignment of the THSR structure.

4.2 Compressions of Aquifer and Aquitard Layers

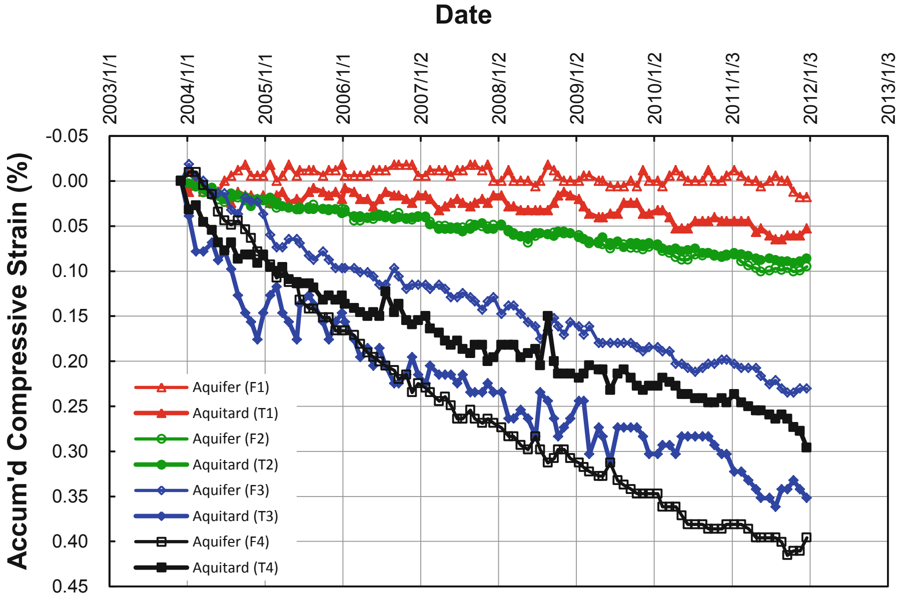
Compressions of soils are further analyzed in terms of aquifer and aquitard layers, and results shown in Fig. 10 and Table 3. As illustrated in Fig. 10(a), Aquifer F1 and Aquitard T1 presented least compressions, while Aquifers F2 & F4 experienced most compressions, over the 8-year monitoring period.

However, the amount of compression would be affected by the layer thickness. The compressive strain or compressive strain rate is adopted instead. As shown in Fig. 10(b) and Table 3, Aquifer F1 and Aquitard T1 have least compressibility, or a compressive strain rate of <0.01%/yr; while Aquifers F3 & F4 and Aquitards T3 & T4 exhibit greatest compressibility, or a compressive strain rate of 0.03–0.05%/yr.

Aquifer F1 and Aquitard T1 of the site are situated at a depth of <60 m. The minimal compressibility of the layers might suggest the associated soils are in a slightly overconsolidated (OC) condition. Aquifers F3 & F4 and Aquitards T3 & T4 are located at a depth range of 220–300 m. The greater compressibility of these layers, however, indicates the associated soils are approximately in a normally consolidated (NC) state. Greater compressibility of deeper soils might also suggest the extraction of groundwaters of the study area had gone deeper in the recent decades.



(a) Accumulated compressions in soil layers



(b) Accumulated compressive strains in soil layers

Fig. 10. Compressions and compressive strains of soil layers at the site

Table 3. Compressions of aquifers and aquitards measured at TKJHS Station during the 8-year monitoring period (2003.10.1–2011.12.20)

Soil layer	Thickness (m)	Compression (cm)	Compression rate (cm/yr)	Compressive strain rate (%/yr)
Aquifer F1	16.83	0.3	0.04	0.002
Aquitard T1	24.70	1.3	0.16	0.007
Aquifer F2	106.28	10.1	1.25	0.012
Aquitard T2	63.75	5.5	0.68	0.011
Aquifer F3	21.70	5.0	0.62	0.029
Aquitard T3	10.23	3.6	0.44	0.044
Aquifer F4	20.46	8.1	1.00	0.049
Aquitard T4	21.97	6.5	0.80	0.037
Total	285.92	40.4	4.98	0.018

5 Conclusions

This paper discusses results of a long-term monitoring carried between 2003 and 2011, an 8-year onsite monitoring at the intersection of Expwy 78 and THSR, with the aims to clarify the compression behavior of soils in the CRAFD and the contributions of various factors on the subsidence of the study area. Major findings of this study are listed as follows:

- The ground subsidence in the intersection area is 55.7 cm for the entire deposit in the 8-year monitoring period without the loadings of Expwy 78 and THSR, i.e., structural-related factors.
- The loadings of Expwy 78 and THSR would contribute additional 9.4 cm and 5.5 cm, respectively, to the ground in the same period.
- Nonstructural-related factors appear dominating the subsidence behavior of the site. Nonstructural-related factors generally include the short-term fluctuations and long-term declines in groundwater levels due to infiltration or evaporation of rainfalls or surface waters, or due to human extraction of groundwaters, as well as the creeping of soil deposit which is enormously thick (>350 m).
- To be noted, the contributions of various factors on the subsidence cannot be fully addressed based solely on the results of 8-year monitoring. In viewing that Expwy 78 embankment and THSR piers/viaducts were constructed in separated stages and started prior to the 8-year monitoring, the influences by Expwy 78 and THSR loadings would only be partially reflected in the period considered in this study.
- The monitored compressions in soils reveal the shallower deposit (depth <70 m; Aquifer F1 and Aquitard T1) is least compressible, with a strain rate of <0.01%/yr; while the deeper deposit (depth ranged 220–300 m; Aquifers F3 & F4 and Aquitards T3 & T4) is most compressible, with a strain rate of 0.03–0.05%/yr.
- The compression of shallower depths (<70 m; 3.3 cm in 8 years) appears small and would not cause adverse effects (i.e., negative skin frictions) on THSR piles.

However, the compression of deeper depths (>70 m; 52.4 cm in 8 years) is substantial and would be detrimental to the vertical alignment of THSR structures.

- Higher compressibility of deeper soils suggests the extraction of groundwaters in the study area has gone deeper in the recent decades.

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