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Estimating coefficients of volume compressibility from compression of strata and piezometric changes in a multiaquifer system in west Taiwan

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Abstract

This paper estimates the coefficients of volume compressibility from variation in compressible layer thickness and changes in piezometric heads by using detail ground surface surveys and a multilayer monitoring well at a selected site (Shigang) within the Choshui River alluvial fan in west Taiwan. The paper integrates various types of in situ monitoring tools, including leveling surveys, continuous global position system (GPS) stations, multilevel layer compression and groundwater pressure head-monitoring wells, to investigate the situation and progress of the subsidence problem in the region. The results from the cross-analyses of the measured data show that surface settlement caused by the compression of strata is between the depths of 60 and 210 m where the clayey stratum within 120–180 m was most pronounced and contributes up to 53% of the total compression. The results indicate that the clayey stratum is under normal consolidation. The results also reflect the fact that 20% of settlement contribution comes from the sandy stratum within 90–120 m; the elasto-plastic behavior of this sandy stratum is clear. The coefficients of volume compressibility of the clayey and sandy stratum analysed from the stratum's compression records; they were 6.38×10^{-8} and 5.71×10^{-9} m^2/N, respectively. Ultimately, this parameter estimation would permit to control and predict land subsidence based on change in pressure head which are related to groundwater extraction.

Keywords: Land subsidence; Groundwater; Multilevel monitoring well; Coefficient of volume compressibility; The Choshui River alluvial fan; GPS

1. Introduction

Land subsidence due to heavy withdrawal of groundwater has become a worldwide problem (Prokopovich, 1991). Many countries or areas experienced this costly geological hazard (Freeze, 2000). To effectively clarify the mechanism of land subsidence,

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one has to fully understand the characteristics and behavior of the strata compression due to the decrease of pressure head or the increase of the effective stress. The compression of strata can be explained by the change in effective stress due to pore–water pressure decrease after pumping. Hence, the essential key elements in subsidence investigation are groundwater level variation and soil-stratum compressibility. A successful investigation should aim to identify and characterize these key elements.

To find the compressibility and relevant soil properties of strata, the common approach is through field exploration and sampling undisturbed specimens for laboratory soil tests. Laboratory tests may provide evidence of the strata characteristics before the actual pressure depletion takes place. However, results of laboratory tests tend to overestimate stratum compressibility, comparing to the evidence from in situ measurements (Cassiani and Zoccatelli, 2000). Hence, land subsidence investigation relies very much on field monitoring (Brighenti et al., 2000).

Sato et al. (2003) made use of a global position system (GPS) to monitor the ground subsidence in Ojiya, Japan. By correlating the amount of ground subsidence with water pressure change, they estimated the "average apparent" compressibility of strata by assuming linear relation between the globally averaged volumetric strain in clayey layers as a whole and the effective stress change. Sneed et al. (2000) analysed the stress–strain relation from the extensometers and the piezometric head at the Las Vegas, NV, USA; they yielded the compressibility parameters called the aquifer system elastic-specific storage and inelastic-specific storage. Macini and Mesini (2000) reported the Radioactive Marker Technique (RMT) applied in the Adriatic Sea, The Netherlands, the North Sea and the Gulf of Mexico. In some field examples, the uniaxial compressibility coefficients derived from RMT matched with the ones obtained from the surface subsidence observed in the field.

Excess land subsidence induced by overpumping of groundwater is a complicated geological hazard. The feature of subsidence can be quite different because of large geo-material variation over various regions in a complicated soil formation. Any effective monitoring program aiming to understand the extent, mechanism and trend of the geo-hazard has to take space and time factors into account. This paper integrates various types of in situ monitoring tools to investigate the situation and the progress of the subsidence problem in the Choshui River alluvial fan, west Taiwan. The monitoring tools include leveling survey, continuous GPS stations, multilevel layer compression-monitoring wells and multilevel piezometric head-monitoring wells. Cross-analyses of the various measured data were carried out to estimate the coefficients of volume compressibility of different soil strata at a selected site (the Shigang village). The obtained parameters would permit to control and predict land subsidence.

2. Site description

The Choshui River alluvial fan is the most important agricultural area in western central Taiwan; Fig. 1a shows its geographic location and regional geology (CGS, 1999). The sediments originated from the rock formation in the upstream watershed; the rock types including slate, metamorphic quartzite, shale, sandstone and mudstone, the thickness of the sediments is greater than 750 m (Lin et al., 1992). Fig. 1b illustrates the soil profile along section a–a′ from groundsurface to the depth of 300 m. The soil formation is very complicated; it contains interbedded or lens-structured clay, fine sand, medium sand, coarse sand and gravel layers. Based on sedimentology with the evidence from the studies of rock properties, dating, fossil and permeability, Fig. 2a presents the conceptual hydrogeology model in this area: the interbedded soil formation between surface and the depth of 300 m can be considered to be composed of four aquifers and four aquitards. Aquifers 1–4 have the extent with a depth of 19–103, 35–217, 140–275 and 238–300 m, respectively, below the groundsurface; and the average thickness is about 42, 95, 86 and 24 m, respectively. The aquifers contain sediment size ranging from medium sand to gravel; Table 1 illustrates the permeability ranging from 10^{-3} to 10^{-4} m/s and could be classified as good aquifers (Tyan et al., 1996). The aquitards contain fine sediment size ranging from clay, silt to fine sand. Illite and chlorite are the major clay minerals found in the aquitards (Yuan et al., 1996).

The coastal regions of the Choshui River alluvial fan are in short of available surface water. For a long

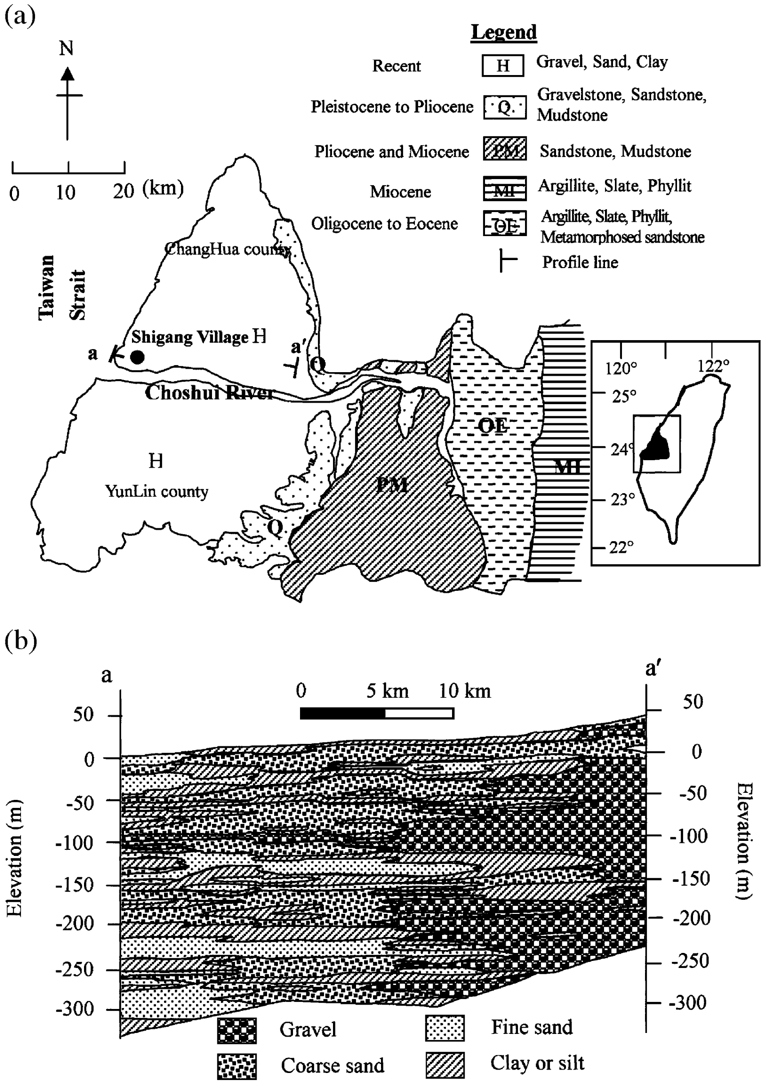

Fig. 1. (a) Geographic location and regional geology of the Choshui River alluvial fan (modified from CGS, 1999). (b) The hydrogeological profiles of a–a′ in the Choshui River alluvial fan. Profile line is indicated in panel (a).

time, groundwater has been abundantly used for serving the high water demand from agriculture and aquiculture. The estimated discharge of groundwater was around 21.0×10^8 m^3 in 1992 but the estimated total recharge was only around 9.0×10^8 m^3. In other words, the groundwater was withdrawn much faster than it could be replenished (Liu et al., 1996). Therefore, the groundwater table has dropped gradually. To monitor the piezometric head of each aquifer in the Choshui River alluvial fan, about 85 multilevel wells have been installed since 1992; the wells' location is shown in Fig. 2b (MOEA, 1999). The data revealed that Aquifers 2 and 3 have been overpumped significantly in the coastal regions and the piezometric head have been reduced to below 10 m by 1999 (refer to Fig. 2a).

Land subsidence has resulted from the groundwater withdraw. Fig. 2b shows the contours of annual subsidence of the Choshui River alluvial fan in 1994. Most areas with severe land subsidence in the

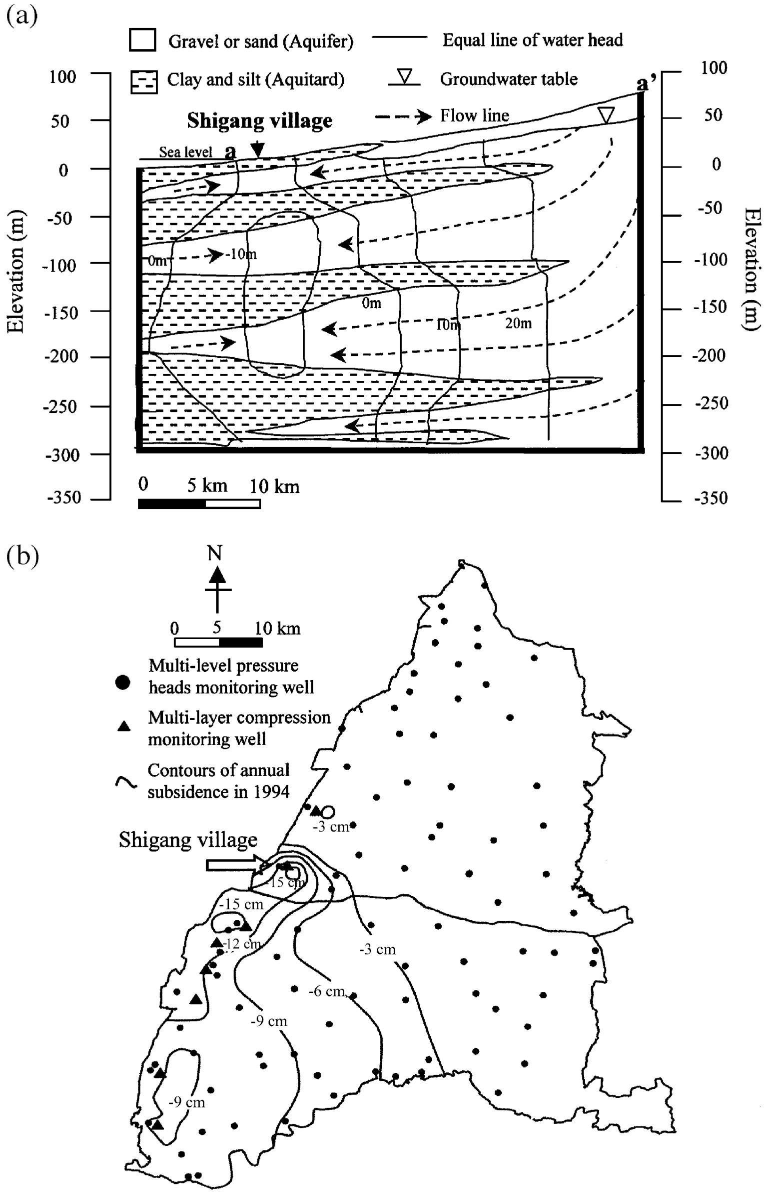

Fig. 2. (a) Conceptual hydrogeology along section a–a′. (b) The locations of multilevel pressure heads monitoring wells (●) and multilayer compression-monitoring wells (▲).

Choshui River alluvial fan were close to the seaside; hence, eight multilevel compression-monitoring wells were installed along the seaside.

The Shigang village is located in the southwestern corner of the Changhua County. The elevation of the area is about 4–5 m above sea level. It is very close to the place where the Choshui River is flowing into the Taiwan Strait, and is near the toe of the Choshui River alluvial fan. The regional strata consist mostly of soft clay and fine sand; the strength and the permeability of this soil are relatively low. It is therefore natural to expect a large potential for severe consolidation settlement if subjected to groundwater overpumping. For a decade or so, this site has become the popular

Table 1
Hydraulic parameters of aquifers in the Choshui River alluvial fan (Tyan et al., 1996)

Aquifer no.	K (m/s)	T (m^2/min)	Q/S (cmh/m)
Aquifer 1	0.0006	0.8583	35.08
Aquifer 2	0.0005	0.9020	37.2
Aquifer 3	0.00057	1.0185	42.03
Aquifer 4	0.00053	0.9939	25.57

K = hydraulic conductivity; T = hydraulic transmissivity; Q/S = discharge per unit drawdown.

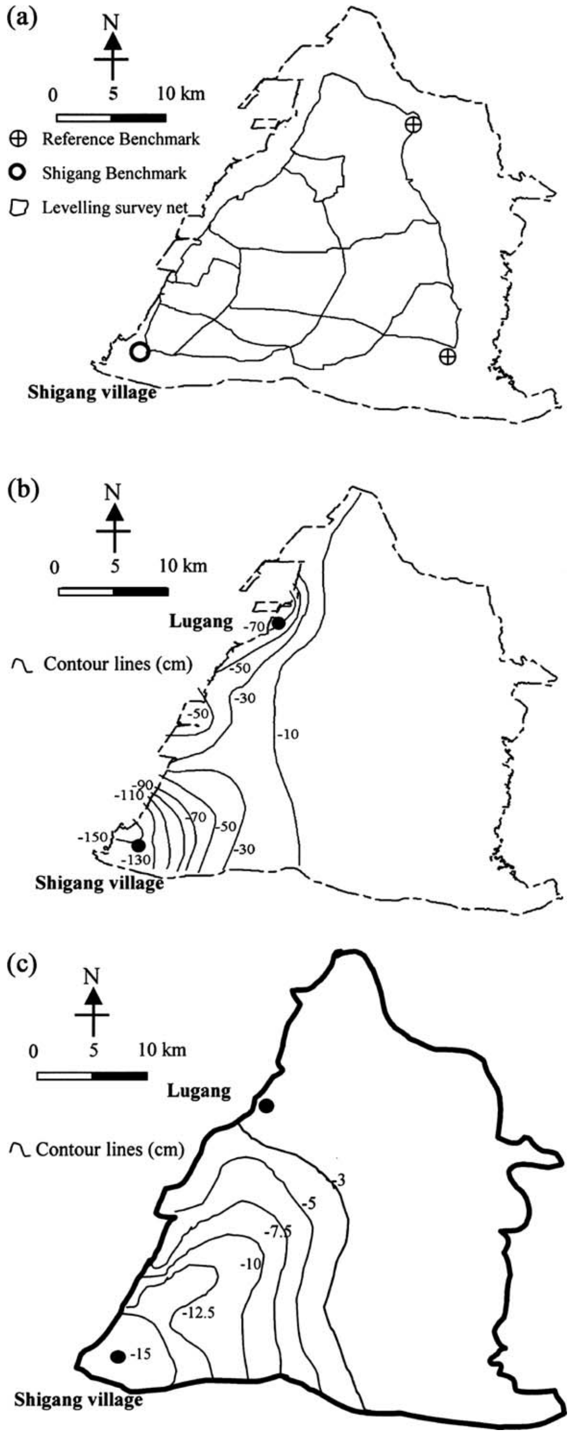

Fig. 3. (a) The framework of leveling survey in Changjua. (b) Contours of accumulative subsidence between 1976 and 1997. (c) Contours of annual subsidence between 1998 and 2001.

spot for studying land subsidence; many relevant investigations sponsored by the government have been carried out here. Therefore, this paper also selects Shigang as the example site, aiming to illustrate an example for the characterization of a subsidence problem and the estimation of the compressibility of critical strata.

3. Integrated monitoring system for subsidence

3.1. Leveling survey

Since 1976, the Shigang village has suffered from land subsidence. The investigation by leveling survey in this area has been continued for a long time. The leveling survey was carried out in reference of a stable benchmark point with no subsidence. Elevation variation at different timeframe reveals the progress of ground subsidence. The groundsurface settlement distribution and extent in a large area can be determined if the leveling survey has continuously covered a wide area.

The leveling survey monitoring system around the Shigang village is under the framework of the leveling survey network, Changhua County (Fig. 3a). The reference stable benchmark is about 30 km away from the Shigang village. The accuracy specification of the error of closure is within 3 mm $\sqrt{km}$ (km is the length of survey in kilometer). Leveling survey was carried out every one or two years.

3.2. Continuous GPS station

In practice, the leveling survey cannot be very frequent and cannot obtain continuous data. For an investigated area with severe subsidence problem, any rapid and continuous technique for determining the change in elevation is of advantage. Recently, global position system (GPS) has become prevailing; the accuracy of GPS has also been improved significantly. Successful establishment and application of GPS land subsidence monitoring network were adopted in many countries such as United States, Japan, Italy and Iran (USGS, 1999; Sato et al., 2003; Tosi et al., 2000; Mousavi et al., 2001). GPS appears to be a very good tool with the potential and the possibility for continuous monitoring of land subsidence.

A continuous GPS station was established in 2000 in the Shigang village; it receives satellite signals around the clock. The GPS instruments include satellite receiver and antenna. The Shigang village station uses a satellite receiver made by AOA, USA (Model type: Bench Mark). In stationary GPS survey, the errors in horizontal coordinates and in elevation, respectively, are 2 mm + 1 ppm (parts per million) and 7 mm+ 1 ppm, respectively. It can continuously record 12 GPS satellites in 36 parallel channels.

3.3. Multilevel layer compression-monitoring wells

A monitoring well is the most direct way to distinguish the compressions of individual layers. It is also the best approach to identify the major contribution of layer compression for land subsidence. Several types of monitoring system were developed to satisfy the monitoring requirements. The radioactive marker technique (RMT) was adopted most early for determining the strata compression due to underground gas or undersea oil field development. However, the problem of radioactivity and environmental pollution may be troublesome (Macini and Mesini, 2000). The use of borehole extensometer has the advantage of simplicity. However, each borehole can only monitor two or three layer compressions. For complicated soil strata with large variation in compressibility, borehole extensometers may not be desirable (USGS, 1999).

Monitoring wells with installed conductive rings are more appropriate for complicated soil strata (Laier and Brenner, 1984). In this method, metal rings are anchored in a borehole at different depths according to the variation of soil type; metal detectors linking to a measuring tape can find the depth of each metal ring. The change in the depth difference of two adjacent rings indicates the compression of the soil layer within the two rings. When a number of installed rings are installed, the contri-

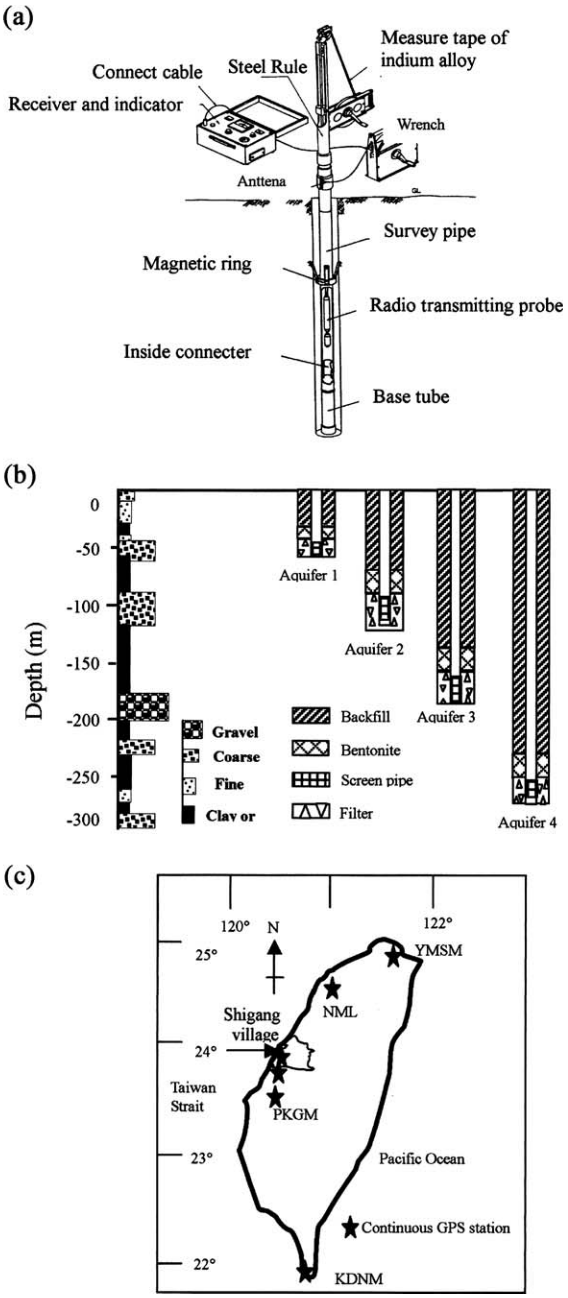

Fig. 4. (a) Multilevel layer compression-monitoring well. (b) Multi-level groundwater piezometric head-monitoring wells. (c) Locations of the Taiwan reference continuous GPS stations for calibration.

bution of each layer's compression on ground subsidence can be estimated. The monitoring system used in the Shigang village adopted a modified system similar to the concept of conductive rings. The system developed was by Doboku Sokki, Japan. It has the advantage of high precision, durability and stability and is appropriate for a deep monitoring well.

The installation of a monitoring well began with drilling a borehole; subsequently, geophysics loggings (natural gamma and resistivity) were carried out to identify soil type. Magnetic rings were installed at those positions that the soil type changes. Each magnetic ring contains three flexible legs, with their outer rim radius greater than the radius of the open borehole. Once the three legs of a ring open up, they can hook into the borehole wall and fix the ring in the borehole. Three legs of each magnetic ring were first tied to the outer rim (with three legs tied) of PVC casings according to each ring's designed position. Then, PVC casings were installed one by one into the open borehole. After all the casings were installed, heating was applied to melt the ties; once the ties broke, the rings escape from the casings and fix onto the borehole. Once all magnetic ring sensors were in position, it was ready for monitoring compression deformation in various individual layers.

Measurement of depth of each magnetic ring was carried out by lowering down a probe connected to a measuring tape made of indium alloy. The probe can continuously transmit electromagnetic wave of the frequency of 10.7 MHz. As the probe approaches magnetic ring, a faradic current would be generated and the probe with radio transmitter inside would send out electromagnetic wave of frequency between 400 and 1000 Hz. No faradic current would exist when the

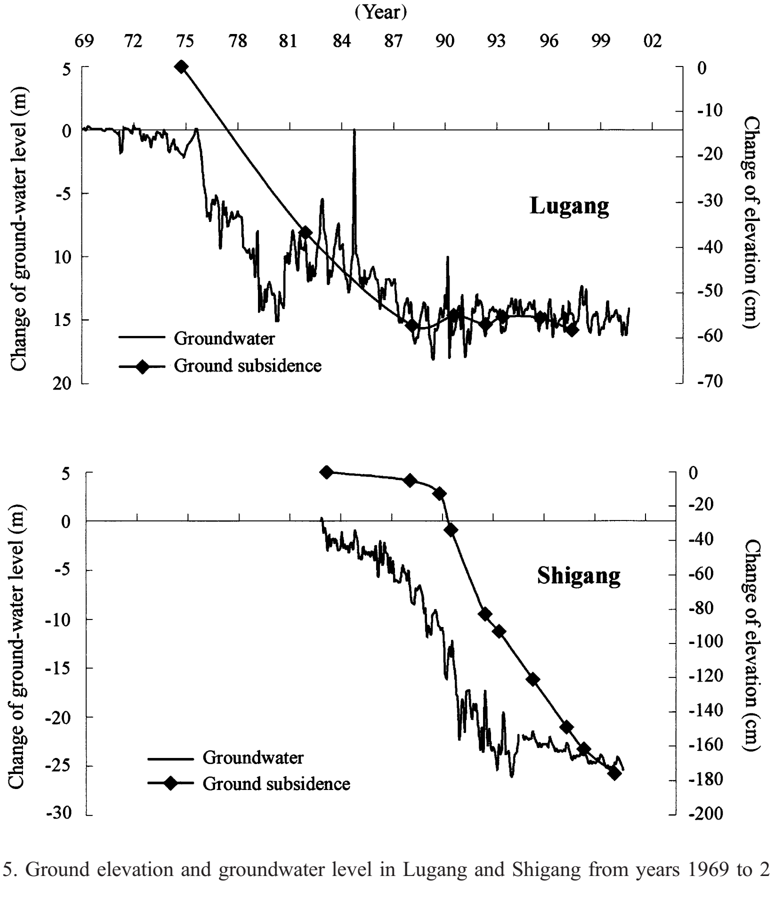

Fig. 5. Ground elevation and groundwater level in Lugang and Shigang from years 1969 to 2001.

probe was right in position of the center of the magnetic ring. Thus, a current indicator can help to locate the position of the ring precisely. With the indium alloy measuring tape, the depth of the magnetic ring can be located as precise as 1 mm. Monitoring proceeded in a regular monthly frequency. Consequently, individual layers' compression can be monitored in a long period as illustrated in Fig. 4a. The monitoring well depth was around 300 m that can cover the majority of compressed strata subjected to the influence of groundwater discharge, and installed 25 magnetic rings to fit the complicate stratum (ERL, 1999).

3.4. Multilevel piezometric head monitoring

Groundwater pumping causes the change in pressure head; the water pressure change will result in the stratum compression. Monitoring the change in pressure head will help to reveal the mechanism of land subsidence. Multilevel piezometric head-monitoring wells were also installed since 1994 at the level near those layers monitored by the multilevel compression-monitoring wells in the Choshui River alluvial fan. In Shigang, these wells were used to monitor the piezometric head of individual aquifer. The monitored aquifers were at the depths of 43–56, 90–107, 181–199 and 259–276 m, respectively (Fig. 4b).

4. Monitoring results and discussion

4.1. Results of subsidence monitoring

Fig. 3b presents the contours of accumulated surface settlement within 1976–1997, obtained from the results of leveling survey in the whole county of Changhua (TPWCD, 1997). It appears that subsidence during this period concentrated in North Lugang and South Shigang. Fig. 5 presents the yearly variation of ground elevation and groundwater head of the ordinary monitoring wells in Lugang and Shigang. In Lugang, the groundwater level rebounded; as a result, the groundsurface settlement there has ceased since 1986. On the contrary, in Shigang, the groundwater level continuously dropped about 22 m until 1993. Obvious ground subsidence began to develop since 1990 and reached 1.8 m in 2001. Fig. 3c shows the contours of annual ground subsidence rate in the Changhua County between 1998 and 2001. The area near the Shigang village was the center of subsidence concentration; however, the area near the Lugang had no more subsidence. The Shigang village is the appropriate site for studying the mechanism of land subsidence.

Before 1997, there was lack of data of individual layers' compressions; hence, it was difficult to identify the mechanism of soil compression causing the land subsidence. One 300-m deep multilevel monitoring well for stratum compression was installed at the Shigang village since August 1997. Readings of stratum compression were taken monthly. Fig. 6 shows the stratum compression analysed by the

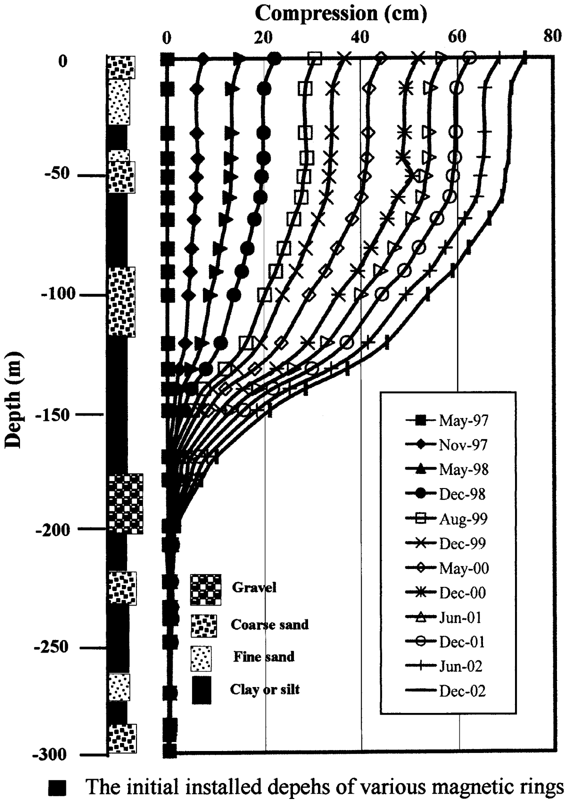

Fig. 6. Continuous stratum compression related to the borehole bottom, obtained from the depth changes of various magnetic rings between May 1997 and December 2002 in the Shigang village.

depth records of the underground magnetic rings from May 1997 to December 2002. The primary stratum compression took place in the strata within the depths of 60 and 210 m. The average total strata compression rate within the whole monitoring well was around 14 cm/year. Between June 2000 and August 2001, the total strata compression determined by the monitoring well was 15.9 cm and the surface settlement determined by level survey was 16.4 cm (ERL, 2001). It appears that 97% of ground subsidence was due to the compression in the strata between the groundsurface and the depth of 300 m. Fig. 7 shows the distribution of compression for individual stratum. Each of the three strata, namely clayey stratum (approximately 60–90 m), sandy stratum (approximately 90–120 m) and clayey stratum (approximately 120–180 m), contributed compression more than 10% of total subsidence; and the three strata make 89% of total subsidence. The stratum compression within the depths of 120 and 180 m was most pronounced; it contributed up to 53% of total subsidence and had a key role in the resultant groundsurface settlement.

GPS monitoring station in the Shigang village was established in 2000. This station can receive and transmit satellite signals continuously for monitoring the ground subsidence distribution. The GPS signals may be affected by ionosphere scintillation, multipath effect, natural- or human-caused noise and diffraction due to obstacles, among others. The quality of the received signals was examined by the package TEQC; the results showed that the value of MP1 was about 0.2–0.3 and MP2 was about 0.3–0.4. These results satisfied the IGS specification that indicated a good quality of signal (IGS, 1999).

The data calculation was carried out by the package Bernese v 4.2 together with the use of IGS accurate ephemeris time. The reference continuous station is located at NML; four other stations (YMSM, PKGM, KDNM and YLSS) were also calculated simultaneously for calibration (Fig. 4c). To estimate the GPS measurement accuracy, the standard deviation of height difference on the baseline of NML–YMSM was calculated due to their stable positions. The result of calculation was around 1.2 cm. Fig. 8a shows the calculated daily elevation data between July 2001 and December 2002. The difference of GPS elevation is around 17 cm which indicated that the ground has settled down 17 cm during this period. Fig. 8b compares the weekly settlements estimated from GPS and the monthly

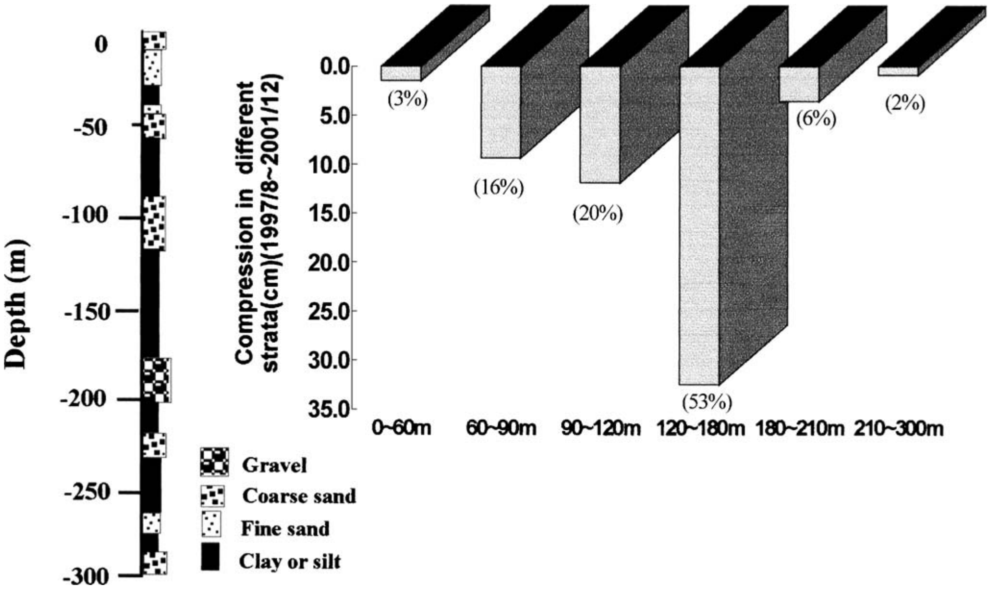

Fig. 7. Distribution of compression for individual strata in the Shigang village.

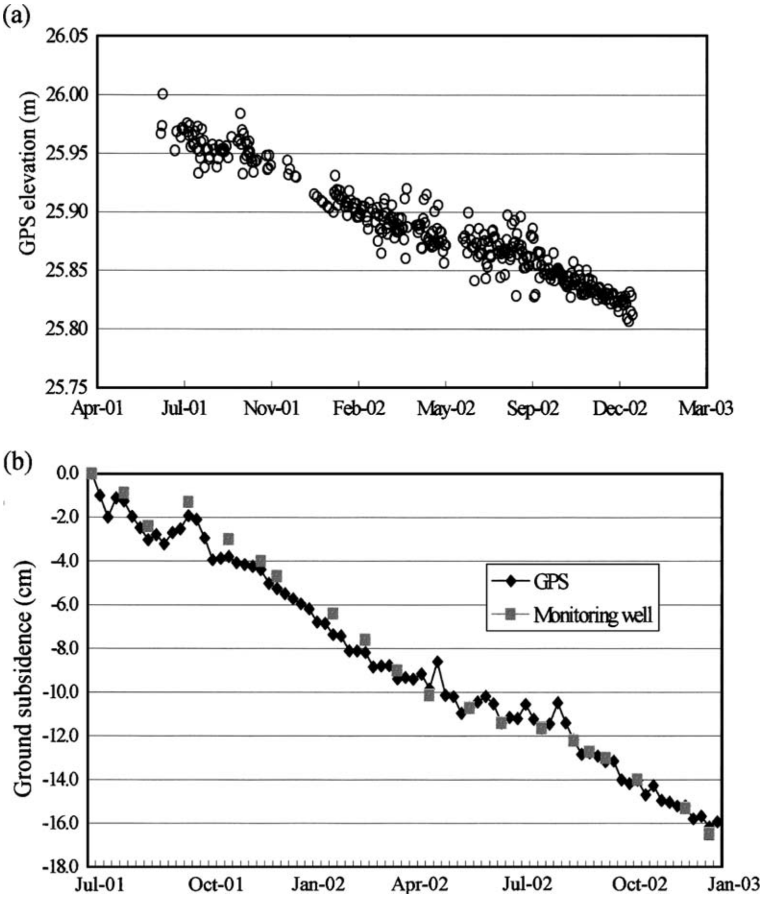

Fig. 8. (a) Calculated daily GPS elevation data between July 2001 and December 2002. (b) Comparison of the weekly surface settlements estimates from GPS (♦) and the monthly total strata compression from monitoring well (■) between July 2001 and December 2002.

total strata compaction from monitoring well; and the agreement appears very good.

The results obtained from leveling survey, multilevel monitoring well and GPS are in good agreement. All of these results show that the subsidence in the region near the Shigang village was still quite severe; the annual settlement rate was still as much as 12–14 cm/year.

4.2. Mechanism of subsidence

Fig. 9a,b shows the monthly groundwater levels in various aquifers and the monthly compression changes in three major compressible strata (60–90, 90–120 and 120–180 m) from the multilevel monitoring well. The results indicated that the stratum's compression within 60–90 m has stopped since 1999 because the water head in Aquifer 1 had rebounded and had been stable. However, the decrease in pressure head in Aquifer 2 (depths between 90 and 120 m) and Aquifer 3 (depths between 180 and 210 m) was more obvious. Their pressure heads dropped significantly within 1996–1997 and within 1998–2000, respectively. This has much to do with the fact that groundwater discharge in the region has primarily occurred in those aquifers in that period; and this also explained why the primary compression took place in the strata within 60–210 m recently. The piezometric head variation in Aquifer 4 (depths between 259 and 279 m) was insignificant because that groundwater had not yet been withdrawn from this depth. Thus, negligible strata compression near Aquifer 4 was expected.

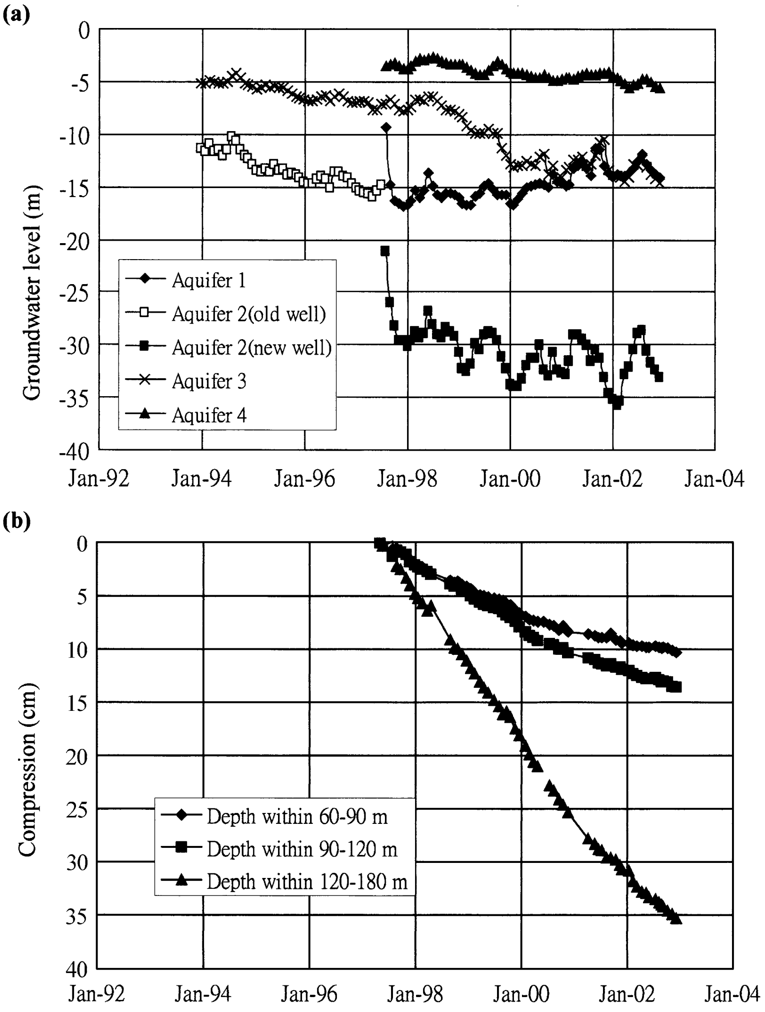

Fig. 9. (a) Monthly groundwater levels in various aquifers from January 1994 to December 2002. (b) Monthly change of strata compression in different depth ranges from August 1997 to December 2002.

Fig. 10a shows the variations of surface settlement, compression in depths within 120–180 m and groundwater piezometric level changes in Aquifers 2 and 3 between August 1997 and December 2002. It was noted that the compression in the clayey stratum between 120 and 180 m continued even when pressure head rebounded. For a short-term minor rebound of pressure head in an aquifer, the adjacent thick clayey stratum appears to be still subjected to the influence of previously existing excess pore water pressure. The clayey stratum is as thick as 60 m. Dissipation of pore water pressure in the stratum apparently takes a long time. Very likely, the stratum remained in a consolidating state during the oscillation of pressure head in aquifers; thus, stratum compression would continue, except when slowed down a little. In other words, short-term minor rebound of pressure head in aquifer would only reduce the consolidation rate of the clayey stratum slightly and temporarily. As long as the water head decreases again, the consolidation rate will accelerate again. Owing to the compression within 120–180 m was most pronounced and may become the dominant contributor to the land subsi-

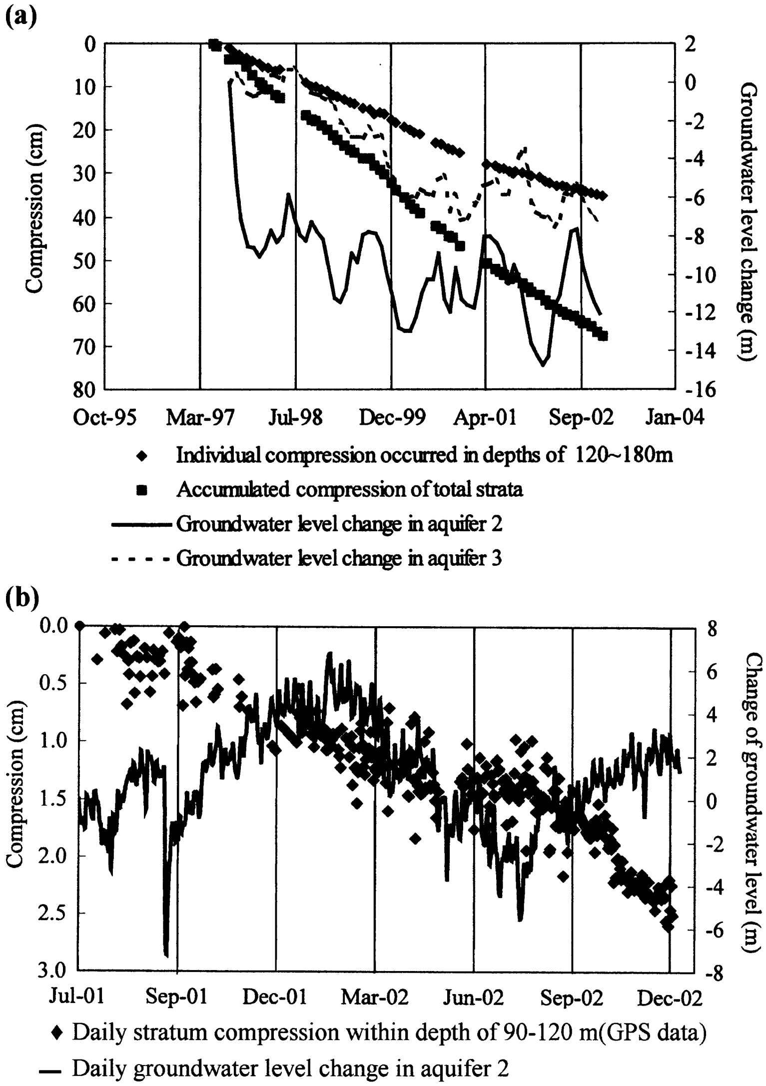

Fig. 10. (a) Monthly variations of different stratum compression and groundwater level change in Aquifers 2 and 3 from August 1997 to December 2002. (b) Daily changes of stratum compression obtained by GPS and groundwater level of Aquifer 2 between July 2001 and December 2002.

dence; the groundsurface settlement continuously developed in this region.

5. Characteristics of stratum compressibility

The common approach to find the compressibility soil properties of strata is through field exploration and sampling undisturbed specimens for laboratory consolidation tests. However, sampling for complicated and thick soil strata in a large area may not be representative, undisturbed and inexpensive. Hence, direct estimation of stratum compressibility from monitoring data is reliable and realistic.

Using the monitoring data in the Shigang village as an example, this work investigated individual stratum's compressibility and found that the major stratum compression took place in the clayey stratum within 120–180 m, contributing 53% of the total settlement. Surprisingly, another 20% of settlement contribution came from the sandy stratum within 90–120 m. The compressibility of these two types of stratum is discussed in detail below.

5.1. Compressibility of clayey stratum

The stratum within 120–180 m is mainly composed of fine soil, with fine content more than 52%; the specific gravity is 2.69, the liquid limit is 41, and the plastic limit is 15. The primary clay minerals of the soil are illite and chlorite (Yuan et al., 1996). The monthly compression variation of the stratum and groundwater level change in the adjacent aquifer (Aquifer 2) within 1997–2002 is shown in Fig. 10a. Fig. 11a plots the compression strain of stratum, ε, versus the logarithm of load (effective stress), p' (transferred from the change of groundwater level in Aquifer 2). The coefficient of volume compressibility (m_v) computed by the graphic method was around 6.38×10^{-8} m²/N. Furthermore, adopting Terzaghi's consolidation theory and assuming the soil has a void ratio equal to 0.7, saturated unit weight

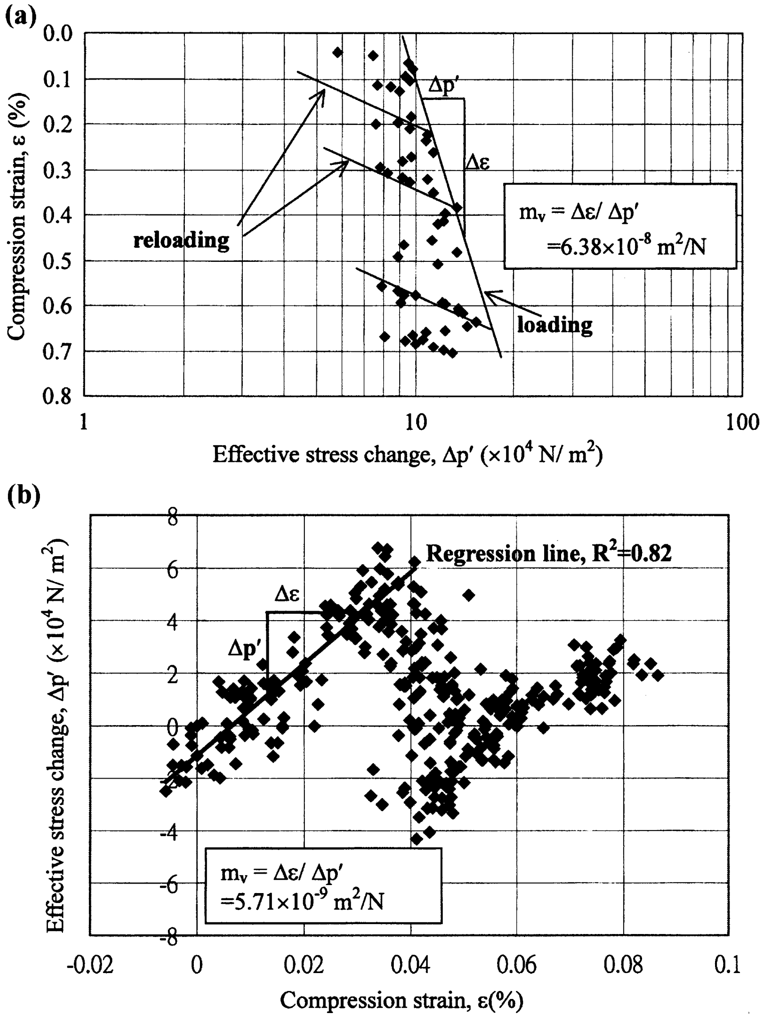

Fig. 11. (a) Relations between the monthly compression strain and effective stress change from August 1997 to December 2002. (b) Correction between daily compression strains and stress changes induced by the fluctuation of groundwater level between July 2001 and December 2002.

equal to 20 kN/m^2, the estimated compression index (C_c) and reloading index (C_r) were 0.38 and 0.07, respectively.

5.2. Compressibility of sandy stratum

The stratum within 90–120 m is sandy soil with grain size characteristics as follows: $D_{10} = 0.25$ mm, $D_{50} = 0.55$ mm, $D_{60} = 0.85$ mm, $C_u = 3.4$ and $C_c = 1.42$. The estimated coefficient of permeability of the sandy stratum is 6.3×10^{-4} m/s. Because of its high permeability, the excess pore water pressure can dissipate very quickly; the required time for compression to develop would be very short. Fig. 10b shows the daily compression and change of groundwater level in the sandy stratum between July 2001 and December 2002. The daily compression deformation of the sandy stratum then was estimated based on the percentage of compression deformation in various strata and total groundsurface settlement. Fig. 11b plots the compression strain versus the effective stress induced by the fluctuation of pressure head; elasto-plastic behavior of the sandy stratum can be clearly noted. As the groundwater level dropped, the stratum continuously deformed; the coefficient of volume compressibility estimated was around 5.71×10^{-9} m^2/N. When the groundwater level rebounded, the deformation was irrecoverable. It appears that the compressibility of the sandy stratum is not ignorable. This is not consistent with the common practice that usually ignores the compression of a sandy stratum.

The high compressibility of the sandy layer in this region may be attributed to the origin of the sand particles. Many of the particles were likely produced from weathered fragments of slate and shale. From the results of SEM analysis (Hsu, 1996), it appeared the shapes of sand particles were flaky in general. The grain assemblage of flaky particles may create a card-house structure (Terzaghi et al., 1996); it may have a high hydraulic conductivity and may have significant compression strain if effective vertical stress rises to certain level. The flaky structure also tends to produce a fabric with more preferred long-axis direction along horizontal; when subjected to vertical loading, the fabric evolution is unlikely recoverable and hence may result in permanent deformation.

6. Summary and conclusion

The land subsidence due to groundwater pumping may exhibit variation in space over a period. Any effective monitoring program for understanding the exact mechanism has to take space and time factors into account. The presented work integrated various types of field-monitoring tools to clarify the situation and progress of the subsidence problem in the Choshui River alluvial fan of Taiwan. The monitoring tools include leveling survey, continuous GPS stations, multilevel layer compression-monitoring wells and multilevel groundwater pressure head-monitoring wells. Cross-examination of measured data from various monitoring tools confirmed the results. The data efficiently enhanced the understanding of the true mechanism of land subsidence; strata with major compression deformation were identified. Results from the integrated monitoring program, including stratum compression and pressure head variations, provided a mean to estimate the compressibility characteristics of soil strata. The coefficients of volume compressibility of the critical clayey and sandy strata were estimated. The gathered information will be used for control measures and remedy plan for the subsidence region.

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