GPS Monitoring Ground Subsidence Associated with Seasonal Underground Water Level Decline: Case Analysis for a Section of Taiwan High Speed Rail

Chia-Chyang Chang and Tien-Nan Wang

ABSTRACT: Ground subsidence induced by heavy withdrawal of underground water has resulted in environmental hazard and potential risk in Taiwan, particularly in the Chuo-Shui River alluvial fan where the Yun-Lin section of the Taiwan High Speed Rail is being constructed. In this paper, seasonal effects of ground subsidence occurring in the study area are investigated. The rate of ground subsidence was estimated using a regression analysis of a series of weekly GPS height solutions. The average rate of ground subsidence in the study area over the period of 1995- 2001 was 3 cm/year, with a high correlation coefficient of 0.9. Based on data collected at the piezometer, the variation of ground subsidence rate appears to be associated with an unstable underground water level, which drop gradually during winter and either remains constant or rises during summer time. As a result, ground subsidence rates vary considerably from 1.5 cm/year for the summer data to 9.0 cm/year for the winter data. The seasonal effect of the GPS height variation is borne out by correlation coefficients ranging from 0.3 to 0.7.

Introduction

Ground subsidence is a recurring problem in the alluvial fan of the Chuo-Shui River, the main river of the south central part of Taiwan. It is believed that ground subsidence is caused by a deformation of clay or sand layers by compression, accompanied by heavy withdrawal of underground water near the coastal regions of Yun-Lin County (Liu et al. 2004). A long history of underground water over-pumping, especially in areas with soft ground features, has contributed to a rate of subsidence of up to one decimeter per year (Chang 2000; Liu et al. 2001). Due to the growth of population and the increasing need of fresh water from aqua farms, the problem of ground subsidence has escalated in the recent years, reaching further inland. This trend could damage the engineering structure and upcoming service of the Taiwan High Speed Rail (THSR) in Yun-Lin.

The Taiwan High Speed Rail (THSR), which is being constructed under Build-Operate-Transfer model, will initially be operated by the private sector. Upon the expiry of the concession period, the rail will be transferred to the government. The THSR is one of the most challenging infrastructure projects in the world, made possible by the largest private sector investment to a public construction project so far. The high speed rail system is expected to start revenue service by the end of 2006. The completed rail is designed to be 345 km long, operate at the speed of 300 km/hr during normal operations, and carry over 300,000 passengers a day. In order to keep the highest possible safety standards, the THSR system will be operated on an exclusive railway and each train will be equipped with detectors to alert train operators to any possible dangers, such as earthquakes, high winds, rockfalls, and torrential rains, all of which frequently occur in Taiwan (THSR 2004). Ground subsidence due to natural hazards may, over a period of time, result in engineering damages that may compromise the security of THSR. To avoid such a situation, it is important to monitor ground subsidence using modern geodetic techniques and develop a better understanding of the problem.

The Global Positioning System (GPS) and other advanced geodetic surveying techniques are capable of delivering the type of high-accuracy geodetic monitoring (Herring 1999) required in Taiwan for its THSR project. The highest accuracy of GPS can be based on the Observations made by continuously operating GPS arrays to monitor crustal deformation due

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to earthquakes were found to yield the most accurate GPS heights (Bock et al. 1997). With shorter observation sessions and fewer observation days, GPS monitoring campaigns using either static or kinematic GPS are now able to determine the 3-D coordinates of sites at the cm-level of accuracy. This level of accuracy is sufficient for small-scale applications, such as landslide or ground subsidence monitoring (Bitelli et al. 2000; Malet et al. 2002; Sato et al. 2003).

It is generally believed that excessive pumping of shallow underground water makes underground water level decline (Larson et al. 2001). However, ground subsidence can also result due to variations in underground water level (Chen et al. 2003; Munekane et al. 2004). Hence, the need to investigate water-related subsidence in order to prevent future problems, such as changes in the elevation and gradient of water facilities, sea level rise along coastal areas, increased flooding frequency, and damage to civil engineering structures (Sun et al. 1999). Data collected by episodic GPS campaigns at geodetic control stations or long-term GPS observations recorded at the tracking site near the Yun-Lin section of THSR, were analyzed to determine any seasonal variations in height. The historical records of average rainfall, underground water levels, and GPS height changes were mutually examined to identify possible correlations between the data measured during summer and winter.

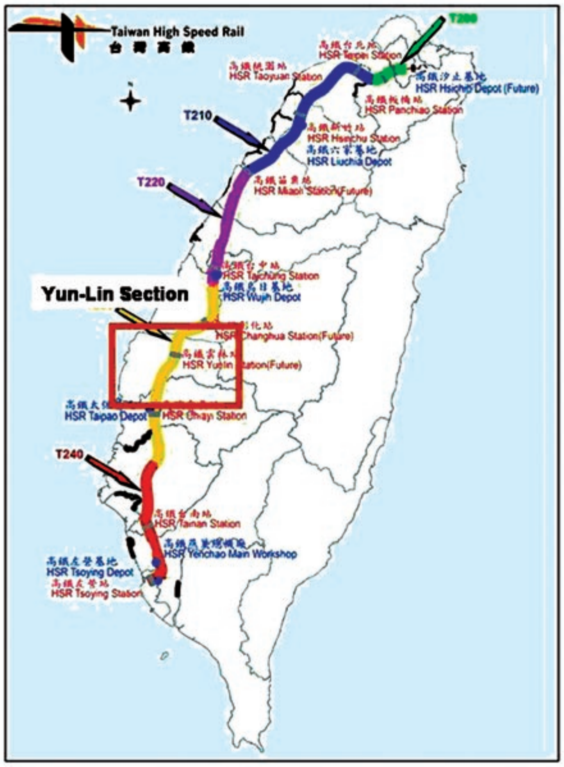

Figure 1. A section of Taiwan High Speed Rail in the study area.

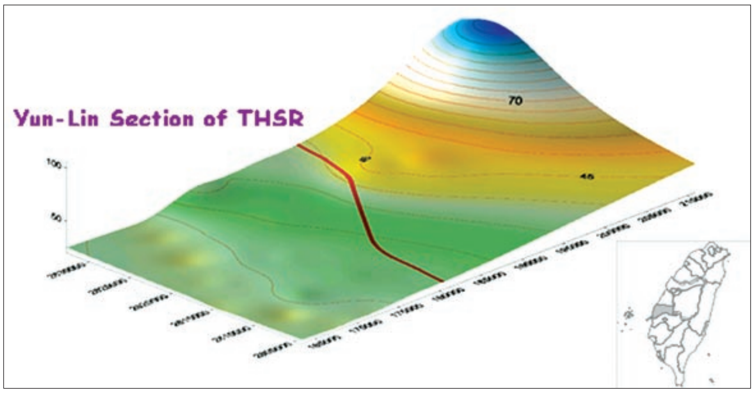

Figure 2. Topographic relief of Yun-Lin County (in meters).

The Study Area

The THSR line will run from Taipei to Kaohsiung, passing 14 major counties and crossing a mix of manufacturing areas, agricultural land, freeways, rivers, residential areas, and open countryside, all of which present their own unique civil engineering problems and solutions. The civil work infrastructure of THSR includes 39 km of mined tunnels, 8 km of cut and cover tunnels, 251 km of viaducts and bridges, 21 km of station and passing bays, and 31 km of cut and fill embankments. The civil works are being constructed under 12 separate contracts. In this paper, the spotlight is on the Yun-Lin section of THSR because of its significant ground subsidence (see Figure 1).

The Yun-Lin County lies in the west central part of Taiwan, in the alluvial fan of the Chuo-Shui River. With an area of 1,290 square kilometers and a general elevation below 100 m, the county is an important agricultural area (see Figure 2). The soil formation in the central and toe regions of the fan, i.e., near the coastal area, is mostly composed of soft clay and fine sand. As the strength and the permeability of this kind of soil are relatively low, over-pumping of the underground water from this soil layer easily results in a significant decline in water level and leads to the consolidation of soil layers. It

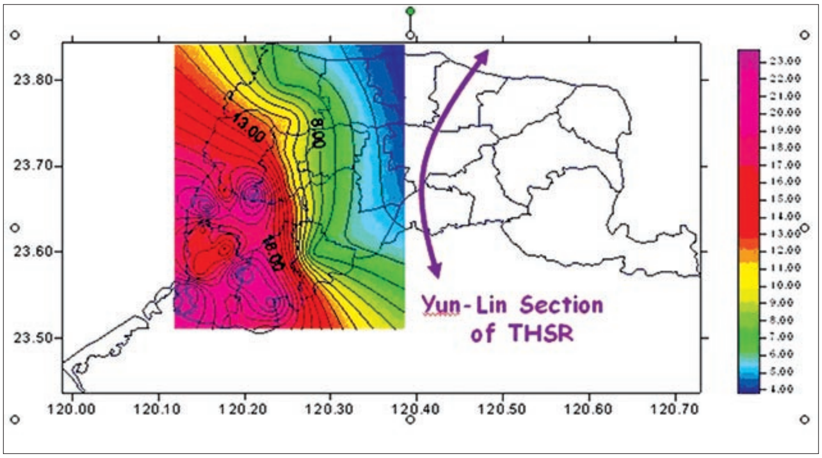

Figure 3. Annual subsidence rate estimated in 1998 using GPS (in cm/year).

is therefore not surprising that this area has a severe ground subsidence problem.

In order to monitor the subsidence rate, The government of Taiwan has carried out leveling measurement in Yun-Lin County for almost three decades in order to obtain a better idea of the subsidence rate in the county's coastal areas. It has been estimated from historic leveling data that ground subsidence increased from 87 to 196 cm between 1975 and 1996, as a result of a significant underground water withdrawal triggered by booming aquafarms (Hydraulic Bureau 1996). GPS measurements at the monitoring sites are believed to offer a higher level of accuracy than leveling, enabling therefore more effective determination of ground subsidence. A set of epoch data comprising with network solutions based on two GPS campaigns was obtained in 1998 for the purpose of conducting longer-term studies of ground subsidence in Yun-Lin (Chang 2000). The data indicate an average, annual subsidence rate of 15.6 cm/year (see Figure 3).

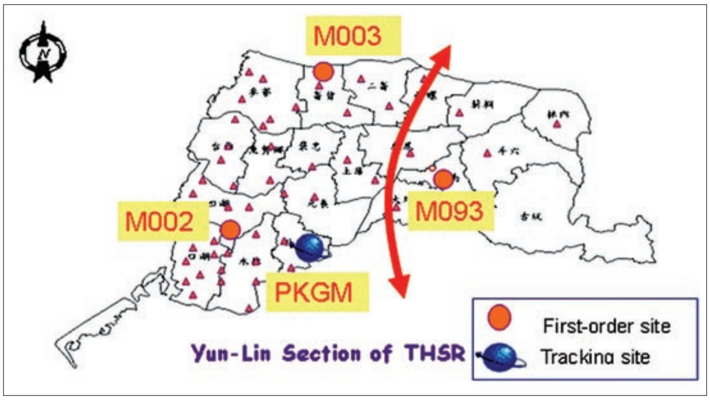

Figure 4. Distribution of GPS fundamental stations in the study area.

Aspects of Ground Subsidence

Evidence of Vertical Land Movement

High-accuracy coordinate solutions based on GPS tracking data recorded at Peikang (PKGM) from 1995 to 2001 were used to determine the temporal features of ground subsidence in Yun-Lin County. Three episodic GPS data sets obtained in 1997, 2000, and 2002 at three first-order control stations in the study area were also collected to investigate the spatial features of ground subsidence (Figure 4). The GPS sites at which the data were collected are part of the fundamental geodetic network in Taiwan and are thus believed to yield high-accuracy network solutions (Chang and Tseng 1999).

GPS tracking data are routinely used to determine long-term trends for vertical land movement. We used a series of GPS weekly solutions from PKGM to present the temporal features of ground subsidence in Yun-Lin County. Figure 5 shows the variation in heights at PKGM. In order to determine the tracking site's subsidence rate, a linear regression was carried out for all 360 weekly solutions. The regression resulted in an average ground subsidence rate at PKGM of about 3 cm/year over the period 1995 to 2001. The high correlation coefficient (>0.9) between the heights and time period indicates a constant subsistence rate (Figure 5).

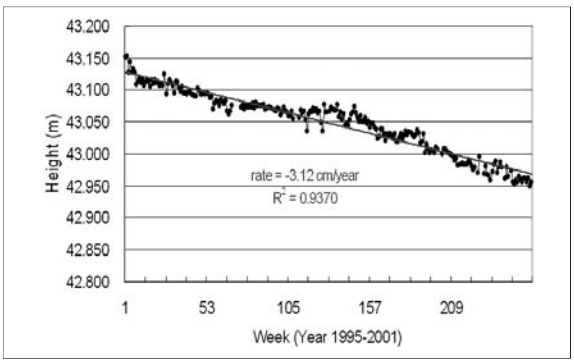

Figure 5. Height variations of GPS weekly solutions at the tracking station of PKGM.

Year	Station		
	M002	M003	M093
1997	27.433 m	37.012 m	49.308 m
2000	27.178 m	36.544 m	49.316 m
2002	26.885 m	36.208 m	49.045 m
Subsidence Rate	11.0 cm/year	16.1 cm/year	5.2 cm/year
Correlation Coefficient	0.999	0.996	0.853

Table 1. Height solutions based on three episodic GPS campaigns.

Other spatial features of vertical land movement can be investigated using the GPS coordinate data sets measured at the three control stations during 1997-2002. The GPS height solutions obtained as a result of three GPS campaigns carried out in 1997, 2000, and 2002, are listed in Table 1. Based on these solutions, the annual subsidence rates at the test sites were estimated to between 5 and 16 cm/year. A relatively low level of subsidence rate was found at station M093; since this station is located near the railway, the finding is promising in terms of the future maintenance of THSR. Severe ground subsidence rates were found at M003, a station close to the Chuo-Shui River, and at M002, which is in the coastal region freshwater aquafarms have been on the rise. While subsidence rates derived from data collected at three GPS sites only cannot be considered to be representative of the entire study area, they do, however, provide certain evidence of ground subsidence in Yun-Lin County.

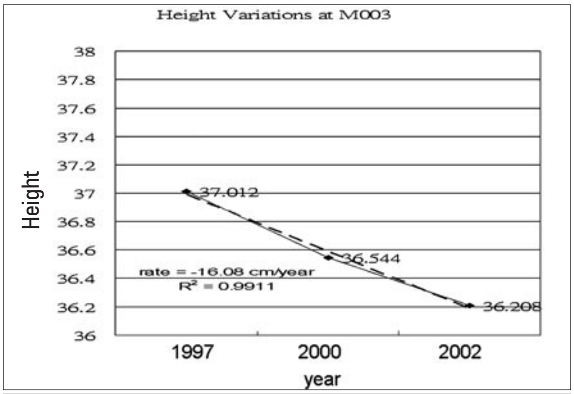

Figure 6. Height variations of three episodic GPS campaigns at M003.

Data from GPS measurements repeated several times in January and November 2002 were analyzed to develop a 3-D model of land movement in the study area. Figure 7 shows that vertical movement occurred mainly in the western part of the study area. The observed variation in the height of the ground may be attributed to the over-pumping of underground water by aquafarms. Figure 8 shows contour lines and directions of underground water variations in April 2002 based on data collected by piezometers installed at monitoring wells. As can be

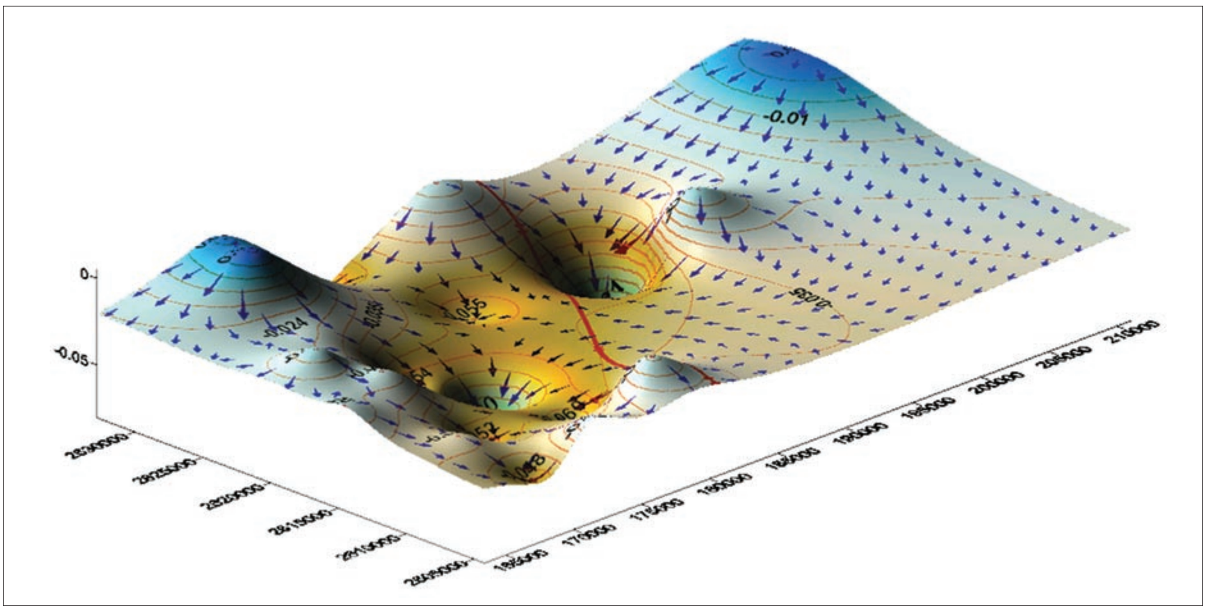

Figure 7. Land movement analyzed for the construction of THSR in 2002.

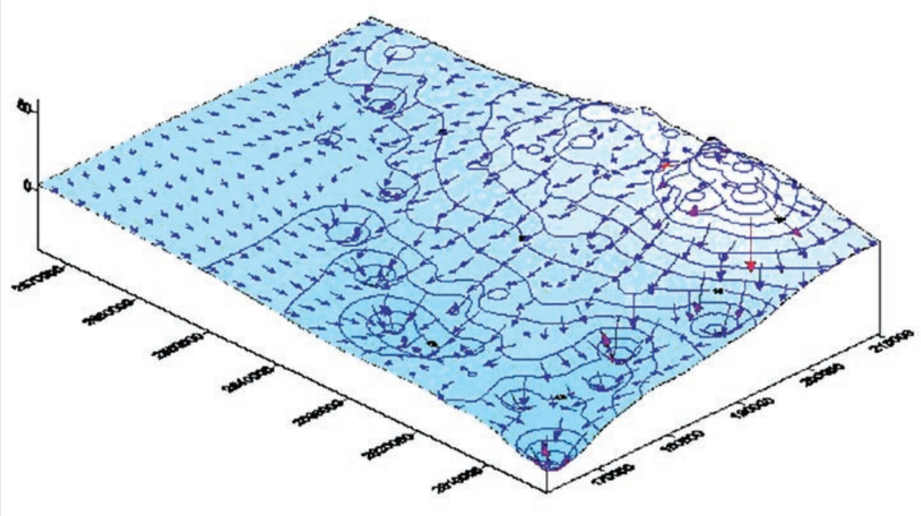

Figure 8. Direction of underground water flow in April 2002.

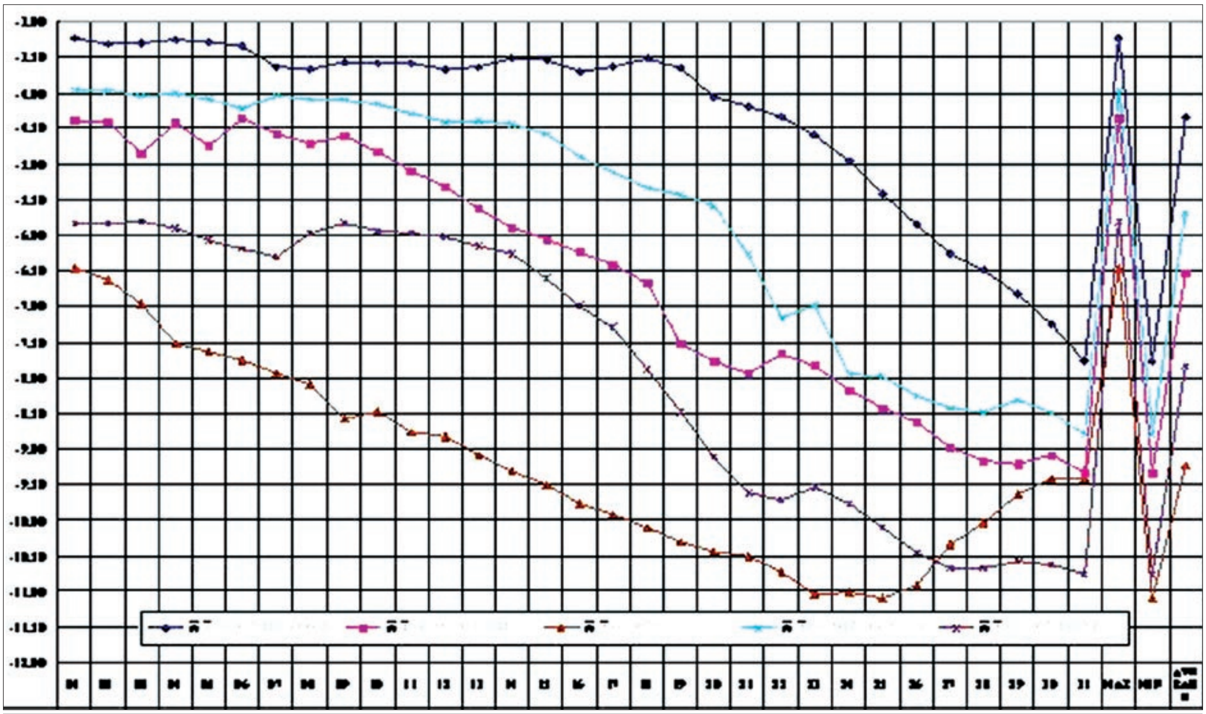

Figure 9. Water levels typically decline in January (data for1999-2003).

seen, areas with more significant ground subsidence are likely those with variable underground water level.

Seasonal Variations of Water Level

Apart from being caused by excessive underground water draw-down, variations in the level of underground water may also be due to seasonal effects, such as different rainfall during summer and winter. Data on the level of shallow underground water were collected during 1999 to 2003 at a piezometer located near the Yun-Lin section of THSR. The trends depicted in Figures 9 and 10 were calculated using a one-month water level data collected in January and July each year. Figure 9 shows that underground water levels tended to fall in January at the representative site; this phenomenon is typical for water levels observed in winter. In Figure 10, however, underground water levels are either constant or somewhat higher than in other seasons, which is consistent with more frequent or heavier rainfall in the area during summer.

Table 2 lists historic rainfall data provided by the Central Weather Bureau for the period 1971 to 2000, as well as average rainfall in Yun-Lin County during four seasons (CWB 2004). As can be seen, rainfall in the study area is highly correlated with seasonal effect, with a seven-fold

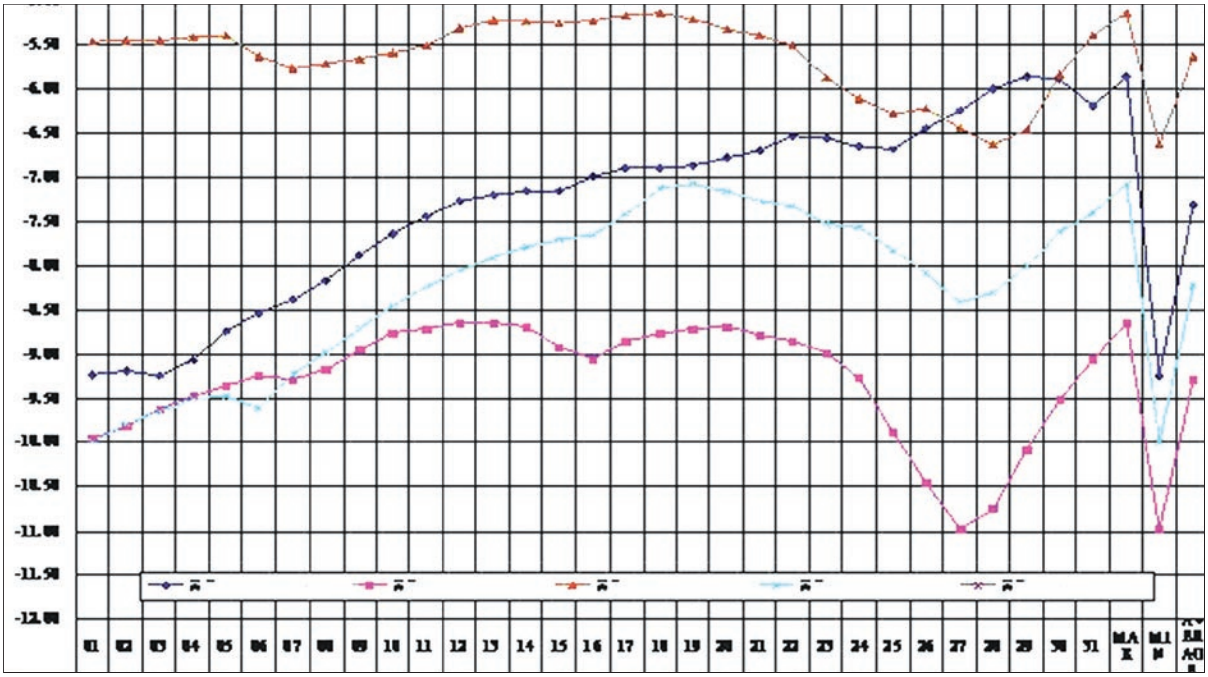

Figure 10. Water levels relatively steady in July (data for 1999-2003).

difference found between summer and winter. It is because underground water levels in the study area declined during winter that the seasonal effect on ground subsidence caused by variations in the level of underground water were deemed worthy of further investigation.

Season	Month Defined	Rainfall (mm)
Spring	March-May	136
Summer	June-August	331
Autumn	September-November	53
Winter	December-February	43

Table 2. Average rainfall in the study area over four seasons.

Regression Analysis for Seasonal Ground Subsidence

Estimation of Ground Subsidence Rate

If we postulate that the lowering of the water level is one of the main factors leading to ground subsidence, and if we further postulate that season-dependent variations in underground water level leads to land movement in the study area, then it can safely be assumed that a linear trend of land movement exists at the long-term GPS monitoring sites. It is assumed that we will find different subsidence rates (or correlation coefficients) for GPS heights observed during winter and summer.

If vertical land movement is correlated with time period on a seasonal basis, the following linear regression can be written:

$$h_i = h_0 + \beta t_i + \varepsilon_i \quad i = 1, 2, \ldots, 13 \text{ (in one season)} \quad (1)$$

where:

t_i = the *i*th epoch in time span, i.e. the week number in one season;

h_i = the *i*th epoch of height at GPS monitoring site;

h_0,β = parameters of intercept and slope (or vertical ground movement rate); and

ε_i = errors from linear model fitting.

Year	Annual Rate (cm/year)	
	Summer	Winter
1995	-6.6	-13.8
1996	-1.4	-8.8
1997	+1.3	-4.4
1998	+1.4	-9.5
1999	-3.6	-12.2
2000	+2.4	-4.4
2001	-4.1	-9.8
Average	-1.5	-9.0
All-span (1995-2001)	-3.1	

Table 3. Vertical movement rates in two seasons.

For the least-squares estimation of β, the season-based value can be extended to an annual rate, with a negative sign representing ground subsidence. Annual rates have been

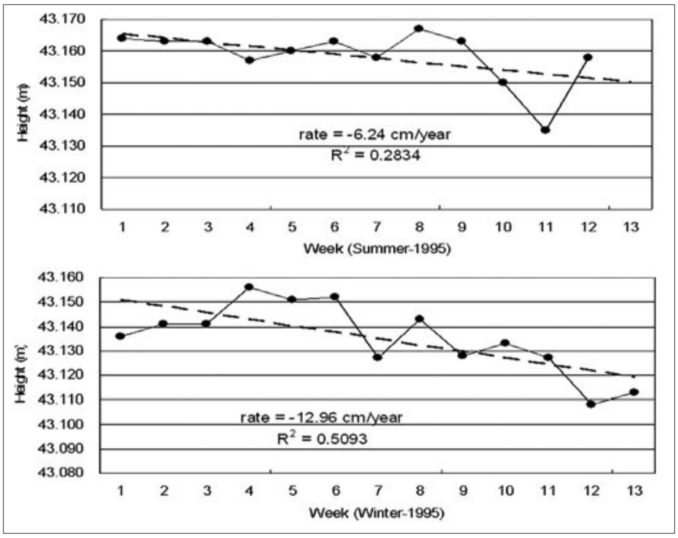

Figure 11. Regression analysis for seasonal GPS height variations in 1995.

estimated for two sets of GPS weekly height measurements at PKGM—for data recorded during summer (GPS week 022-034) and winter (GPS week 048-008) for the period of 1995 to 2001 (see Figures11-17). The annual subsidence rates obtained from GPS height data measured during winter and summer are given in Table 3.

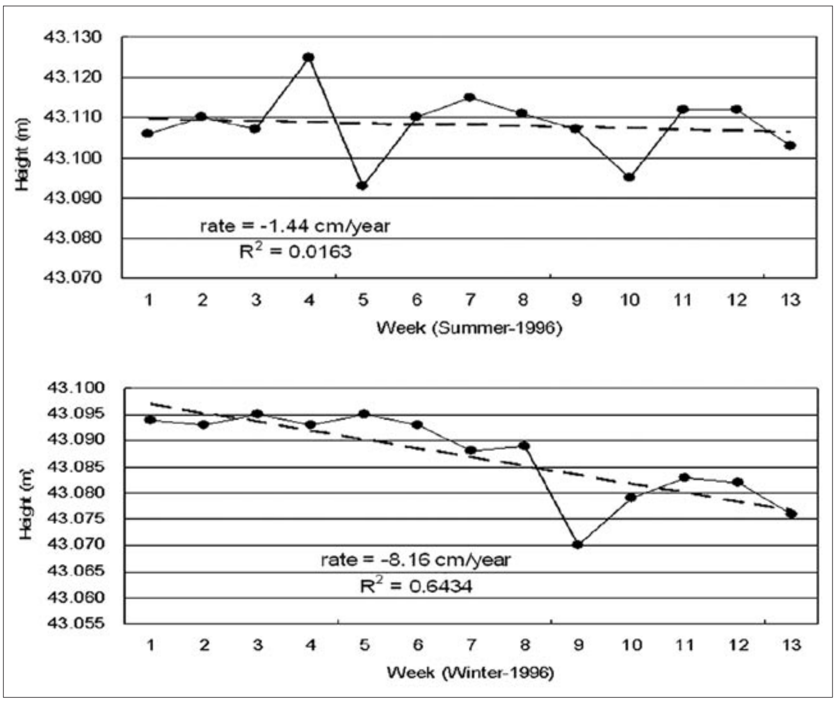

Figure 12. Regression analysis for seasonal GPS height variations in 1996.

The average subsidence rates were 1.5 cm/year and 9.0 cm/year for the summer and winter data sets, respectively. Clearly, ground subsidence was exacerbated during the rainfall-poor winter for each year of GPS data collected. By contrast, the rate of ground subsidence remained relatively steady, and a rebound rate of 1-2 cm/year was seen in some years' summer data. Note that the average subsidence rate in summer is slightly lower than the all-span average, whereas that of in winter is much higher.

Coefficient of Determination and Correlation

Regression analysis can be carried out to provide a summary statistic, with the coefficient of determination (R^2) which indicates how well the regression fits the data being given by (Hogg and Ledolter 1987):

$$R^2 = \frac{SSR}{SSTO} = 1 - \frac{SSE}{SSTO} \tag{2}$$

Using Equation (1), the total sum of squares (SSTO) is written as:

$$SSTO = \sum_{i=1}^{13} \left(h_i - \bar{h}\right)^2 \tag{2-1}$$

where $\bar{h}$ is the mean GPS height.

The regression sum of squares (SSR) is expressed as:

$$SSR = \sum_{i=1}^{13} \left(\hat{h}_i - \bar{h}\right)^2 \tag{2-2}$$

where $\hat{h}_i$ is the least-squares fitted height of the regression model. For the error sum of squares (SSE), this value can de defined as:

$$SSE = \sum_{i=1}^{13} \varepsilon_i^2 \tag{2-3}$$

where $\varepsilon_i = h_i - \hat{h}_i$ is an expression of the fitted residuals of the regression model.

The coefficient R^2 gives $0 \le R^2 \le 1$; this value can be explained with $R^2 = 1$ for all observations of h_i lying on the fitted regression line. Note, therefore, that $R^2=0.937$ (see Figure 5 and Table 4) is the best-fitted linear regression function for an effective estimation of the rate of vertical land movement.

The coefficients of determination derived from the regression functions for GPS heights indicate a definite change between the two seasons. It can be seen in Table 4 that the heights varied in winter have an average coefficient of 0.541, whereas a lower value of 0.133 is found for the regression function based on summer data. A better value of the coefficient of determination was calculated for almost every year of the winter data sets. These results suggest that the GPS height variation in winter is more significant than that in summer, due to a higher vertical land movement rate and a better regression (see Tables 3 and 4). The reasonable explanation of this trend is that less amount of rainfall led to a decline in underground water level in the study area, particularly during winter.

A similar analysis can be carried out to assess the degree of seasonal effect on GPS height variations. Assuming the coefficient of determination is equal to the square of the correlation coefficient (r), then the significance test can be written as:

$$r = |R^2| \geq CV \qquad (3)$$

If $r \geq CV(\alpha = 1\%)$, then the two function variables are said to have a high correlation; if $CV(\alpha = 5\%) \leq r < CV(\alpha = 1\%)$, then a medium correlation exists; a low correlation then satisfies $r < CV(\alpha = 5\%)$. The critical value (CV) is 0.553 and 0.684 for the significance levels $\alpha=5\%$ and $\alpha=1\%$, respectively, if the regression analysis is performed for one season (n=13) of GPS data (He and Liu 2001).

Year	Coefficient of Determination	
	Summer	Winter
1995	0.283	0.509
1996	0.016	0.643
1997	0.139	0.134
1998	0.010	0.593
1999	0.208	0.901
2000	0.018	0.205
2001	0.259	0.799
Average	0.133	0.541
All-span (1995-2001)	0.937	

Table 4. Coefficients of determination for regression functions in two seasons.

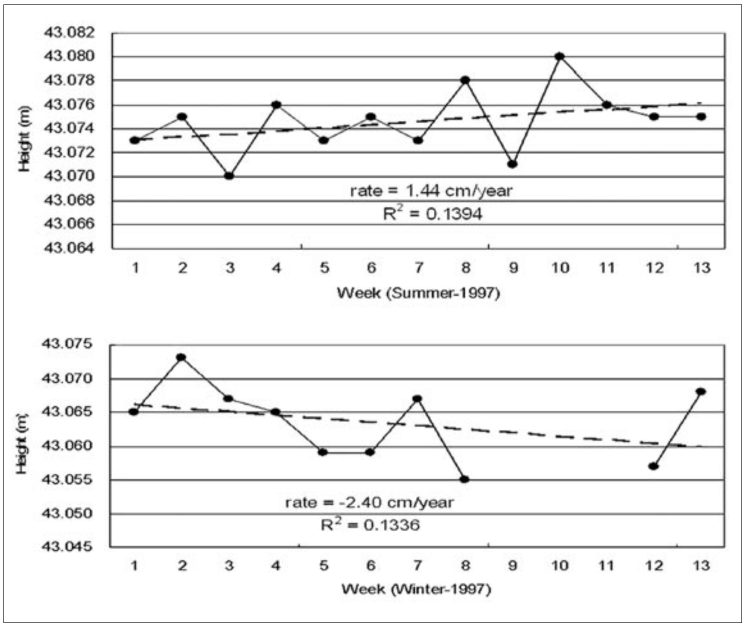

Figure 13. Regression analysis for seasonal GPS height variations in 1997.

The correlation coefficients obtained from two seasonal data sets are listed in Table 5. It is clear to see that high correlation coefficient, expressed with the value larger than 0.684, can be identified for most of the winter data sets. It is also believed that a strong seasonal effect is likely acted on GPS height variation for the test site since most years of GPS data collected during the winter have shown a high correlation, whereas that of in summer is not the case at all.

As can be seen in Tables 4 and 5, the highest coefficients of correlation were found for the set of long-term GPS data (360 weekly solutions for almost 7 years of observations). This confirms that long-term observation of height is essential for the monitoring of vertical land movement.

Conclusions and Recommendations

A summary of this research and some suggestions for future work are as follows:

- The long history of ground subsidence occurring in the study area is believed to be related to the compressional deformation of clay or

Year	Correlation Coefficient	
	Summer	Winter
1995	0.532	0.714
1996	0.128	0.802
1997	0.373	0.366
1998	0.099	0.770
1999	0.456	0.949
2000	0.133	0.453
2001	0.509	0.894
Average	0.319	0.707
All-span (1995-2001)	0.968	

Table 5. Correlation coefficients for the regression function in two seasons.

sand layers, and accompanied with heavy withdrawal of underground water for the need of aqua farms.

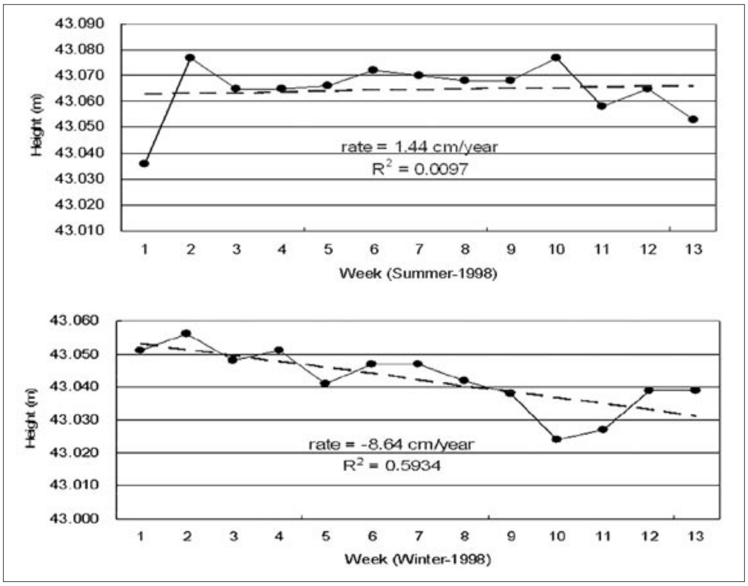

Figure 14. Regression analysis for seasonal GPS height variations in 1998.

- Because of potential damages to the Taiwan High Speed Rail, it was deemed important to investigate ground subsidence along THSR and monitor underground water-related seasonal variations in height.
- Based on a series of weekly GPS height measurements, the average rate of temporal ground subsidence in the study area during 1995-2001 was calculated to be 3 cm/year; the correlation coefficient was high at 0.9.
- Data collected from monitoring piezometers revealed that the ground subsidence rate in the study area is most likely due to underground water level variations in winter and summer.
- The average ground subsidence rate was 1.5 cm/year for GPS heights measured during summer, while during winter it was -9.0 cm/year.
- Ground subsidence increased significantly during winter for each year between 1995 and 2001, due to seasonally low rainfall. The summers during the same period showed a steady subsidence or even a rebound of 1-2 cm/year.
- The correlation coefficient of GPS height variation estimated for winter was generally higher (0.7) than that for summer (0.3). The strong seasonal effect on GPS height variation at the test site was confirmed by the regression analysis.
- Some evidences has been presented for a seasonal change of ground subsidence rate associated with the anomalous extraction of underground water. It is thus recommended that the management of underground water resources in the Yun-Lin coastal area be comprehensively addressed, including putting in place adequate ground subsidence prevention measures to ensure safe operation of the Taiwan High Speed Rail.

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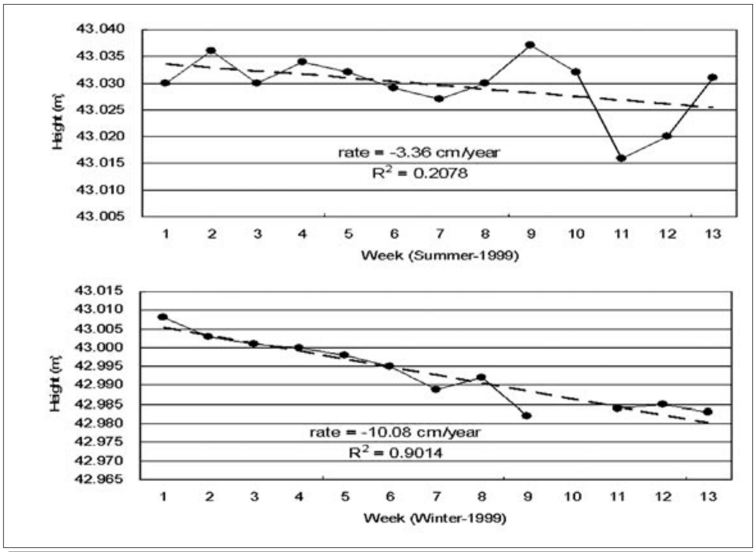

Figure 15. Regression analysis for seasonal GPS height variations in 1999.

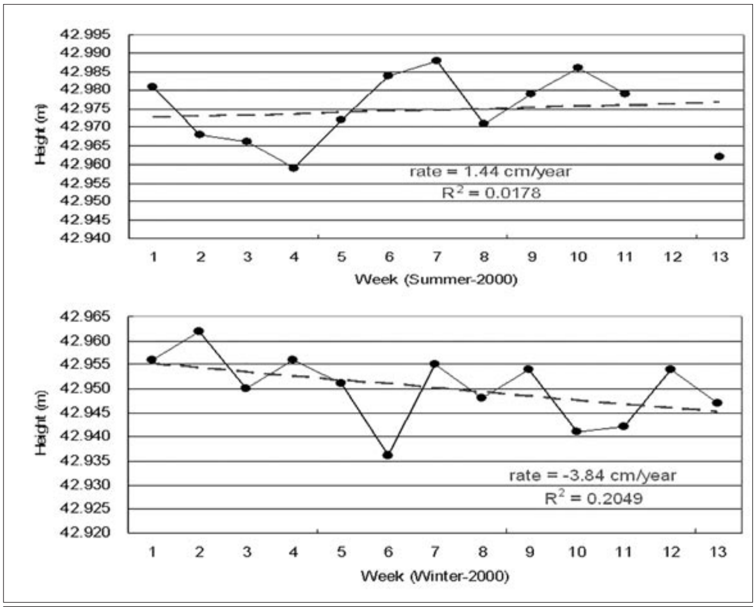

Figure 16. Regression analysis for seasonal GPS height variations in 2000.

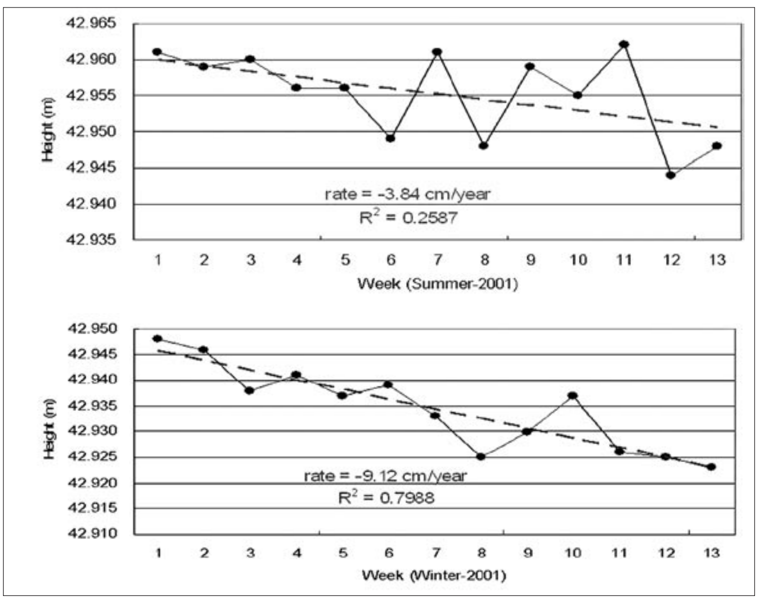

Figure 17. Regression analysis for seasonal GPS height variations in 2001.