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LAND SUBSIDENCE USING ABSOLUTE AND RELATIVE GRAVIMETRY: A CASE STUDY IN CENTRAL TAIWAN

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ABSTRACT

We experiment with absolute and relative gravimetry to determine land subsidence. A gravity network in the Yunlin County of central Taiwan is established to determine gravity variations that are largely due to land subsidence. Every 6 months, gravity values at two absolute gravity stations were measured by a FG5 gravimeter and those at 7 relative stations by a Graviton-EG and a Scintrex CG-5 relative gravimeter. A weighted constraint network adjustment was carried out by holding fixed gravity values at the absolute stations. Correction models for temporal gravity changes are developed and applied to raw gravity measurements. The adjusted gravity values oscillate, but in general increase with time, showing signature of land subsidence. An empirical gravity-to-height admittance factor is determined using gravity change (from FG5) and height change (from levelling) at the two absolute gravity stations. At most gravity stations, there is good agreement between subsidence rates from gravimetry and levelling. Some large discrepancies (> 1 cm/year) also exist and are caused by uncertainties in relative gravity accuracy, hydrological effects and the admittance factor. This study suggests that gravimetry has the potential to determine land subsidence to cm accuracy and is more efficient and economic than tools such as levelling and GPS.

KEYWORDS: Subsidence. Absolute gravimetry. Relative gravimetry. Central Taiwan.

INTRODUCTION

Significant land subsidence up to 10 cm/year in central Taiwan in the past decade has been detected by precision levelling and monitoring wells equipped with geotechnical sensors [**4**]. Land subsidence can be caused by man-made or natural process. In the case of central Taiwan, the major cause of land subsidence is withdrawal of ground water for agricultural use. Yunlin County (Fig. 1) in central Taiwan is a county hit hardest by land subsidence. A station of Taiwan High Speed Rail (THSR, http://www.thsrc.com.tw) will be soon built here and we expect that land subsidence will pose a serious threat to the operation of this station and THSR. A typical tool for monitoring land subsidence is levelling. Satellite-base techniques such as GPS and interferometric SAR (InSAR) are increasingly popular. Obtaining accurate land subsidence with precision levelling in a large area can be costly and time consuming. GPS is efficient to determine height, but it requires sufficiently long data records and dedicated models of environmental effects to achieve mm-level accuracy [**1**], [**8**]. InSAR will deliver two-dimensional surface deformations of limited spatial resolutions, and its accuracy is often degraded by spatial decorrelation of SAR images and atmospheric effects [**10**]. Instead of using levelling, GPS or INSAR, we will experiment with a different tool-gravimetry, to determine land subsidence in central Taiwan in this paper. At a given gravity station, gravity change is a result of the effects of free-air gravity gradient and mass change. By carefully modeling the environmental gravity variations and the admittance factor between gravity and height, gravity change can be converted to height change. This idea has been proposed by, e.g., [**13**], and

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[14], [16], [15], [7]. Relative gravity survey is more efficient than levelling survey. For example, it takes about 6 hours to complete a double-run precision levelling survey between two benchmarks distanced at 2 km on a paved road in Taiwan. By comparison, it takes about 1 hour to finish a double-run relative gravity survey for the same benchmarks.

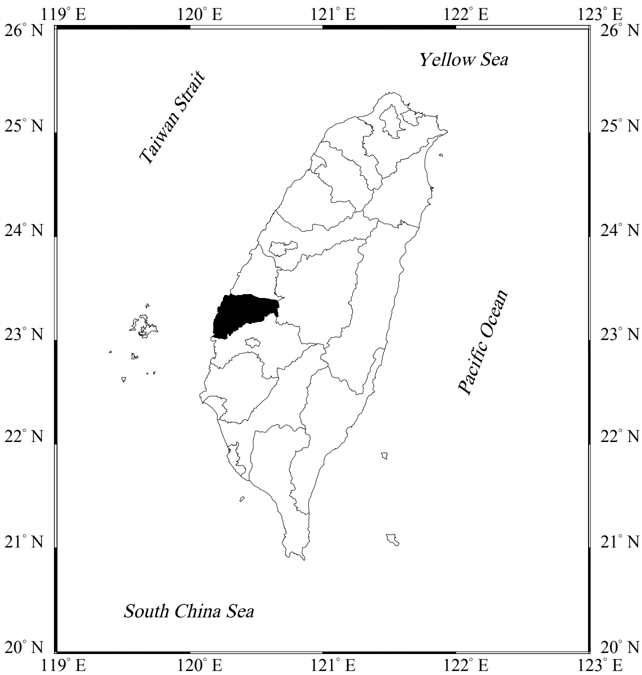

Fig. 1. The Yunlin County of central Taiwan (shaded area).

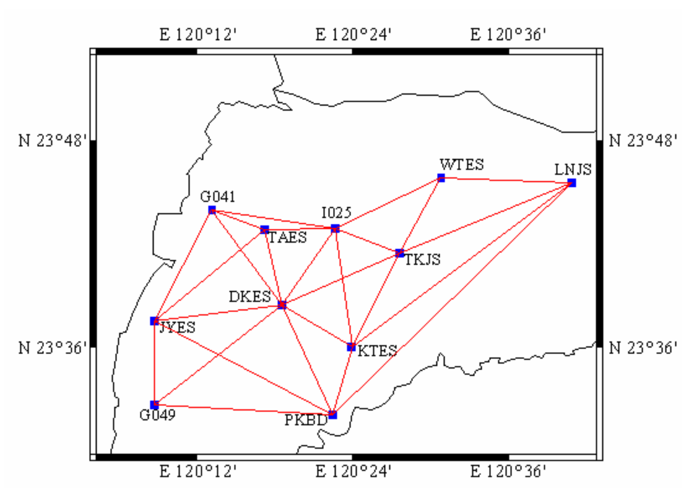

Fig. 2 Distribution of FG5 gravity stations (TAES and PKBD) and relative gravity stations for land subsidence monitoring.

Like a levelling network, a gravity network is formed by gravity stations and the gravity difference between two stations is measured by a relative gravimeter. If one wishes to determine absolute gravity changes, and therefore absolute height changes in a gravity network, at least one of the gravity stations must have an absolute gravity value, which can be determined by an absolute gravimeter. In this paper, a FG5 absolute gravimeter and two relative gravimeters - one Graviton EG (EG) and one Scintrex CG-5 (CG-5), will be used to establish a gravity network in Yunlin (Fig. 2) for subsidence monitoring. The stations in the network are chosen by considering even station distribution, logistics and availability of monitoring well of ground water. Repeated gravity surveys at these stations will yield gravity changes that can be converted to height changes.

ABSOLUTE GRAVITY SURVEY

A FG5 gravimeter (serial number: 224) was used to determine the absolute gravity values at TAES and PKBD (Fig. 2) from December 2004 to April 2007 at an interval of about 6 months. Table 1 summarizes these gravity surveys. In principle, for one campaign we collected the absolute gravity value only at either TAES or PKBD, because of a budget constraint. In some cases, both stations were occupied.

Table 1. *Summary of absolute gravity surveys at TAES and PKBD from December 2004 to April 2007*

Set interval	30 minutes
No. of drops	100 and 200
Set scatter	9.91 to 19.96 μgal
Mean accuracy	0.61 to 2.51 μgal
Mean total uncertainty	2.16 to 5.72 μgal
Length of measurement time	18 to 71 hours

The principle of gravity determination by a FG5 is documented in a manual at http://www.microgsolutions.com/. Fig. 3 shows sample FG5 observations. FG5 is one of the most accurate absolute gravimeters in the world. To determine a gravity value in a single drop, a proof mass is released from the top of the 40-cm dropping chamber. As the proof mass falls, it's traveling times and distances are determined by a rubidium clock and an interferometry-based laser, respectively. These highly accurate distances and times combine to generate a gravity value at a precision of few μgal (1 μgal = 10^{-8} ms^{-2}). The scatter of the drops in a set is a descriptor of data noise, and it increases with background noise around the gravity station. The set scatters of the FG5 in Yunlin are significantly larger than those at a quiet location in eastern Taiwan, which are typically 1 to 2μgal. This is because Yunlin is situated on an alluvial plain with thick sediments (up to 800 m in thickness) and is close to the tide and wave-energetic Taiwan Strait, compared to rocks and thin sediments in eastern Taiwan. In Yunlin, the gravity responses to the excitations of ocean waves, earthquakes and busy traffic will be large due to the resonant nature of thick sediments.

The raw FG5 gravity measurements were corrected by temporal gravity variations listed in Section 4. An accuracy in Table 1 is defined as the standard deviation of the mean gravity value obtained by averaging over all measurements. A total uncertainty is computed by the built-in FG5 software (called Micro-g Solution) and takes into account uncertainties in height reduction (the reference position is set to 1 m above the pillar) and in the models for temporal gravity variations (Section 4). The campaigns to measure absolute gravity values at TAES and PKBD started in 2004 and 2006, respectively, due to a FG5 gravimeter management problem.

Fig. 3. (left) Measuring gravity value with a FG5 at TAES, (right) Measuring relative gravity value with CG-5 (top) near a monitoring well of ground water.

RELATIVE GRAVITY SURVEY AND ADJUSTMENT OF NETWORK

The relative gravimeters

Coinciding with the FG5 measurements, we used an EG gravimeter and a CG-5 gravimeter (Fig. 3) to determine gravity differences in the gravity network given in Fig. 2. Use of the EG or CG-5 gravimeter is dictated by the availability of the gravimeter. Each line in Fig. 2 is surveyed twice (to and from), much like a double-run levelling survey between two benchmarks. The gravity stations are mostly col-located with monitoring wells of ground water. Table 2 compares selected parameters of the EG and CG-5 gravimeters. The EG gravimeter is an electronic version of the LCR-G gravimeter and is equipped with auto-levelling, auto-reading and filtering. The major gravity sensor of an EG gravimeter is the zero-length spring. The nominal repeatability of EG is one μgal. Our laboratory tests show that, to achieve one-μgal repeatability, the gravity station must be sufficiently quiet and away from oceans and busy traffic. Also, the total reading time should exceed 5 minutes and a two-minute filtering should be applied. The CG-5 gravimeter uses a fused quartz as the gravity sensor. Like EG, the operation of CG-5 is also fully automated. With filtering, the nominal repeatability of CG-5 is 3 μgal, somewhat larger than that of EG. The relative gravity measurements are also corrected for the same temporal gravity variations (Section 4) as for the FG5 measurements.

Like FG5, EG and CG-5 perform less well over an alluvial plain than over a quiet zone such as eastern Taiwan. Similar to the set scatter, the standard deviation (SD) of the readings in a set is a descriptor of noise level for EG and CG-5. SD is computed as the standard deviation of the differences between the raw 1 HZ readings and the filtered readings in a set. In this paper, the length of a set is set to 5 minutes. Filtering is automatically done in the gravimeter. As an example, Fig. 4 compares the SDs of CG-5 in Yunlin and eastern Taiwan.

In general, a gravity value with a SD larger than 0.5 mgal is not reliable and therefore not used. Also, the standard errors of the adjusted point gravity values

(Section 3.3) are proportional to the SDs of gravity readings. In some cases, a sudden increase of SD may occur due to strong winds or a large vehicle passing by the gravity station. In this case, the measurement should be repeated. A better accuracy of gravity value can be achieved by using a windshield around the gravimeter, or by night observations to avoid busy traffic.

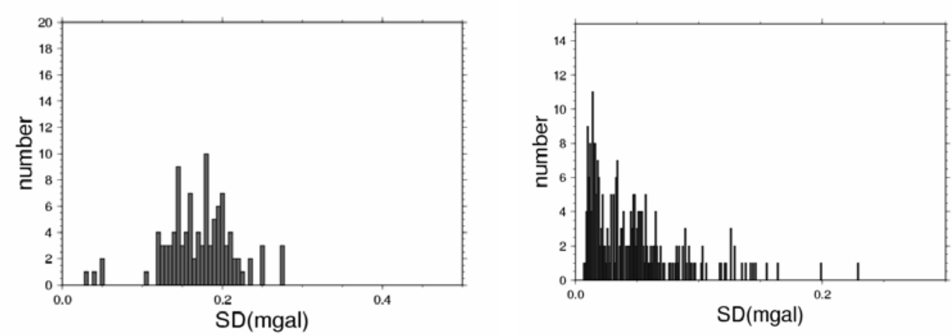

Fig. 4 a. Yunlin, July 2006 b. Southern Cross-island highway, December 2006

Gravimeter drift

The drift of gravimeter reading is one of the key factors affecting the accuracy of gravity measurement. Drift is mainly caused by transportation, and variations in temperature and pressure [**14**]. To see the drift behaviour of the EG, we carried out a laboratory test as follows. At an interval of one week, we collected 12 hours of gravity readings from the EG for 6 consecutive weeks. Fig. 5 shows the variations of zero position and the averaged daily drifts over this period.

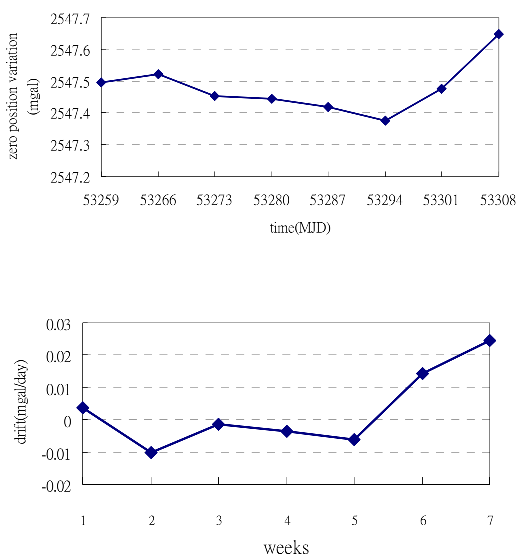

Fig. 5. (a) Variation of zero postion of the Graviton EG and (b) daily drift.

Soon after collecting readings in Week 5, this gravimeter was on a field trip for few hours and then returned to the laboratory to continue gravity readings. As shown in Fig. 5, without motion the daily drift of EG is about 0.01 mgal/day from Weeks 1 to 5, and increased to 0.03 mgal/day in Week 6 when it was moved. Therefore, transportation is mainly responsible for the large variations of zero position and drift in Week 6. The computed drifts of EG agree with the nominal drift in Table 2.

Table 2. *Comparison of the Graviton EG and Scintrex CG-5 gravimeter*

Parameter	Graviton EG	Scintrex CG-5
Sensor type	Zero length spring	Fused quartz with electrostatic nulling
Resolution	1 µgal	1µgal
Repeatability	1 µgal	3 µgal
Nominal drift	<0.03 mgal/day	<0.02 mgal/day
Data acquisition	Automatic levelling and reading	Automatic levelling and reading
Operating range	Worldwide	8000 mgal

Because the drift of a gravimeter behaves differently under different conditions [**14**], we solve for daily drift coefficients for the gravity measurements. In one day, the last gravimeter reading was always made on the station where the first reading was made, thus forming a closed loop that can be use to solve for a drift coefficient. The observation equation of gravity difference between station *i* and *j* including the drift effect is [**2**], [**14**],

$$\Delta\hat{L}_{ij} = \Delta L_{ij} + v_{ij} = (g_j - g_i) - D(t_j - t_i) \quad (1)$$

where

$\Delta L_{i,j}$: raw gravity difference

$\Delta\hat{L}_{i,j}$: drift-corrected gravity difference

V_{ij}: residual

g_i, g_j: gravity values at *i* and *j*

D: drift coefficient

t_i, t_j: times of measurements at *i* and *j*

In (1), the weights for all measured gravity differences are assumed to be equal. The unknowns in (1) are gravity values and drift coefficient. Because we are interested in obtaining the drift coefficient (*D*) and corrected gravity difference ($\Delta\hat{L}_{i,j}$) only, we adopt the datum-free least-squares solution for the unknowns. The constraint used in such a datum-free solution is [**2**]

$$\sum_{i=1}^{n} g_i = 0 \quad (2)$$

which means the average gravity value in a closed loop is zero. This constraint removes the rank defect of the adjustment system (in this case: one). According to [**2**], [**6**], the residuals and the corrected observations $\Delta\hat{L}_{i,j}$ are estimable or unique in the datum-free solution. Using the data from our relative gravity campaigns, the drifts of the EG and CG-5 are on the order of 0.02 mgal/day, which are close to the nominal values listed in Table 2. The drifts vary day to day. In general, the drift is larger than the average drift if the condition of transportation is poor, e.g., the vehicle carrying the gravimeter travels over rugged roads.

Adjustment of gravity network

The drift-corrected gravity differences (Section 3.2) are then used in the following equation for the network adjustment:

$$\Delta\hat{L}_{ij} = \Delta L_{ij} + v_{ij} = g_j - g_i \tag{3}$$

where all the quantities have been defined in (1). Therefore, gravity differences are just like differential heights from levelling, and a computer program for adjusting a levelling network can be applied to a gravity network in exactly the same way. A matrix representation of all observation equations in (3) in a gravity network can be expressed as

$$\mathbf{L^b} + \mathbf{V} = \mathbf{AX}, \qquad \mathbf{P} = \mathbf{\Sigma}_{\mathbf{L^b}}^{-1} \tag{4}$$

where vectors $\mathbf{L^b}$, $\mathbf{V}$ and X contain observations (gravity differences), residuals and gravity values, respectively, and $\mathbf{A}$ and $\mathbf{P}$ are the design matrix and the weight matrix. The elements of the row vectors of $\mathbf{A}$ are 1, -1, or 0. $\mathbf{P}$ is a diagonal matrix containing inverted error variances of gravity differences. Like a levelling network, the rank defect of a gravity network is one. This rank defect can be removed by fixing at least one gravity value in the network. A flexible way is to regard absolute gravity values at TAES or PKBD from FG5 as observations, which then form additional observation equations as

$$\mathbf{L_X} + \mathbf{V_X} = \mathbf{BX}, \qquad \mathbf{P_X} = \mathbf{\Sigma}_{\mathbf{L_X}}^{-1} \tag{5}$$

where $\mathbf{L_X}$ is a vector containing absolute gravity values, and $\mathbf{P_X}$ is a diagonal matrix containing inverted error variances in the diagonal elements (see "mean accuracy" in Table 1) and 0 elsewhere. The row vector of $\mathbf{B}$ contains 1 at the position of the absolute gravity and 0 elsewhere. The combination of observation equations in (4) and (5) yield the least-squares solution of $\mathbf{X}$ as

$$\hat{\mathbf{X}} = (\mathbf{A^T PA} + \mathbf{P_X})^{-1}(\mathbf{A^T PL^b} + \mathbf{P_X L_X}) \tag{6}$$

The error covariance matrix of the adjusted gravity values is

$$\Sigma_{\hat{\mathbf{X}}} = \hat{\sigma}_0^2(\mathbf{A^T PA} + \mathbf{P_X})^{-1} \tag{7}$$

with

$$\hat{\sigma}_0^2 = \frac{\mathbf{V^T PV}}{n - u + r} \tag{8}$$

where n and u are numbers of observations and unknowns, r is 2 if both absolute gravity values at TAES and PKBD are used, and 1 if one of them is used. The adjustment results show that, the standard errors of the adjusted gravity values (from matrix $\Sigma_{\hat{\mathbf{X}}}$) range from few μgal to tens of μgal (see also Fig. 7 below), which are much larger than the repeatabilities given in Table 2. For comparison, the standard errors of the adjusted gravity values in eastern Taiwan are only few μgal, based on relative gravity data collected in November 2006 there. This comparison shows that large SDs of gravity readings will lead to large standard errors of adjusted gravity values.

CORRECTIONS FOR TEMPORAL GRAVITY VARIATIONS

The raw, observed gravity values described in Sections 2 and 3 must be corrected for temporal gravity variations before they are used for estimating gravimeter drifts and for network adjustments. In this paper, the temporal gravity variations under consideration are the effects of solid earth tide, ocean tide, atmosphere, polar motion and groundwater level change. Because of lack of reliable data, the soil moisture effect, which amounts to few μgal and is mostly seasonal, is not applied. We have developed a self-contained computer program to evaluate the needed temporal gravity variations at any given location and time. In the program, the gravitational effects of the solid earth tide is computed by [**12**]

$$g_{st} = \frac{GM_m r}{R_m^3}\left(1-3\cos^2\psi_m\right)+\frac{3}{2}\frac{GM_m r^2}{R_m^4}\left(3\cos\psi_m - 5\cos^2\psi_m\right)+ \frac{GM_s r}{R_s^3}\left(1-3\cos^2\psi_s\right) \qquad (9)$$

where G is the Newtonian constant, r is the geocentric of the point of computation, M_m and M_s are the masses of the moon and the sun, R_m and R_s are the geocentric distances of the moon and sun, ψ_m and ψ_s are the geocentric angles between the point of computation and the moon and the sun. The quantities R_m, R_s ψ_m and ψ_s are computed using the geocentric coordinates of the moon and sun from the DE200 planetary and lunar ephemerides of JPL (http://ssd.jpl.nasa.gov). Considering only the second-degree loading effects of the attractions in (9) and using a Shida number h_2 =0.6 and loading Love number k_2 =0.3, the total gravity change induced by the solid earth tide is then

$$g'_{st} = 1.15 g_{st} \qquad (10)$$

The maximum value of this effect reaches 200 μgal in central Taiwan.

For the gravitational and loading effects of ocean tide, we use the Greens' function approach to determine the inner zone contribution from a local tide model [**5**] and the outer zone contribution from the NAO99b tide model [**11**]. Symbolically, the total gravity effect of ocean tide is evaluated as:

$$g_{ot} = \int_0^s K(\psi) H_L d\sigma + \int_s^\sigma K(\psi) H_G d\sigma \qquad (11)$$

where σ is the surface of a mean earth, s represents the inner zone centering at the point of computation, $K(\psi)$ is the kernel function, H_L and H_G are the tidal heights in the inner and outer zones, respectively. The detail of this ocean loading model is documented in [**3**], who show that this model is accurate to about 1 μgal and outperforms other models around Taiwan. Along the west coasts of Taiwan, the gravity effect of ocean tide is largest in Yunlin and can reach tens of μgal.

It turns out modeling the effect of groundwater variation is problematic, mainly due to complex local behaviours of groundwater levels. For example, at the time of a gravity measurement, pumping of groundwater at a nearby well for agricultural use might occur, and this greatly modifies the distribution of the groundwater near the gravity station. The long term gravity effect of groundwater will be more reliable than the epoch-wise effect. Therefore, instead of applying epoch corrections of groundwater variation to gravity measurements, we apply a correction of rate of gravity change due to groundwater as:

$$\dot{g}_w = 0.42 P_s \dot{H}_{GW} \qquad (12)$$

where is $\dot{g}_w$ and $\dot{H}_{GW}$ are rates of gravity change (μgal/year) and groundwater level change (m/year), and P_s is the soil porosity. Based on the study of [**9**], we adopt P_s=35 (%). For the corrections due to polar motion and atmosphere, we adopt the formulae given in [**14,** Chapter 10]. The polar motion data are obtained from the IERS website (http://www.iers.org/) and the atmospheric pressures are taken from the in-situ measurements.

LAND SUBSIDENCE FROM GRAVITY CHANGE

Gravity change and height change

Figs. 6 and 7 show the gravity values and the standard errors at the two absolute stations and 7 relative stations from repeated gravity surveys over December 2004 to April 2007. Because only one to two gravity surveys were carried out at stations LNJS and TKJS (Fig. 2), these two stations are not included in Fig.7. The gravity values at the two absolute stations increase almost linearly with time. The gravity values at the relative stations in general increase with time, but undergo large oscillations.

Table 3. *Rates of gravity change and groundwater level change*

Gravity station	Rate of gravity change (μgal/cm)	Rate of water level Change (m/year)
TAES	22.72	-0.1682
PKBD	11.99	1.0800
G041	20.68	0.1866
G049	21.63	0.1070
JYES	10.82	0.1866
KTES	35.25	-0.2227
WTES	21.00	0.3940
I025	56.75	-0.1682
DKES	47.45	-0.2227

The mean standard error of the absolute gravity values is about 2 μgal (Table 1), which is significantly smaller than those at the relative gravity stations (from few μgal to tens of μgal). The oscillations of gravity values were most likely caused by local hydrological effects. The plots of groundwater levels from monitoring wells nearby the studied sites (not shown in this paper) show dominant seasonal components, plus non-periodic and episodic signals. A regression using line fitting may act as a low pass filtering which preserves only the trend of first order. Therefore, the gravity values in Figs. 6 and 7 are fitted by a line with a constant term and a trend term. In the line fitting, gravity changes exceeding three times of standard errors are regarded as outliers and the line fitting is repeated without using the outliers. For example, at G049, the second gravity value (Fig. 7) is an outlier.

At some gravity stations, the gravity values are rather scattered, making the line fitting unreliable. Table 3 shows the rates of gravity changes (corrected for groundwater effects) and rates of groundwater level change of the nearby wells. The rates of groundwater level are not always negative, because the government of Taiwan has taken measure to reduce pumping of ground water in Yunlin.

Obtaining subsidence from gravity change is the main objective of this study. Here we assume subsidence (h) is a linear function of gravity change (g) as

$$h = fg \tag{13}$$

where f is an admittance factor. In the literature, two typical admittance factors may be used to convert gravity change to height change. One admittance factor is just the free-air gravity gradient, and the other is the sum of the free-air gravity gradient and a gradient due to the Bouguer plate. For example, the free-air gravity gradient is -3.086 μgal/cm for the GRS 1980 ellipsoid. Use of a free-air gravity gradient as the admittance factor implies that land subsidence simply consolidates the soil without changing the mass. In contrast, use of the second type of factor (free-air plus Bouguer plate) implies that the mass of the Bouguer plate between the original surface and the deformed surface is removed.

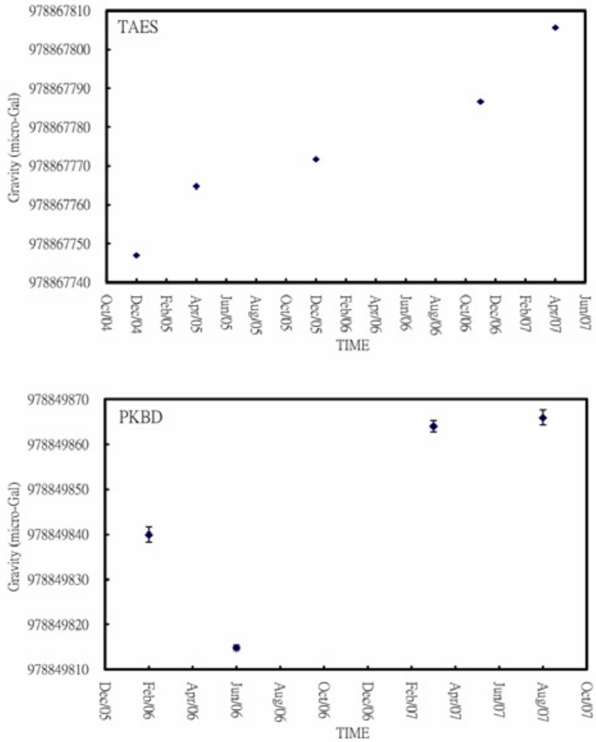

Fig. 6. Gravity values at the absolute gravity stations TAES and PKBD

In Yunlin, the mechanism of subsidence is rather complicated, and we find that neither of these two types of admittance factors fits the reality. In Yunlin, the mean measured free-air gravity gradient is -2.868 μgal/cm, instead of -3.086μgal/cm. Therefore, in this paper the admittance factor in (13) is determined empirically as follows. At the two FG5 stations (TAES and PKBD), the rates of gravity change are 22.72 and 11.99 μgal/year (Table 3), while the rates of height change are -4.5 and -2.2 cm/year. Thus, the admittance factors at TAES and PKBD are -5.04 and -5.45 μgal/cm, which are quite consistent. The adopted admittance factor is then -5.25 μgal/year, which is the mean of the empirical factors at TAES and PKBD.

Comparison of land subsidence from gravimetry and levelling

Repeated levelling surveys in Yunlin at an interval of 6 months have been sponsored by the Taiwan government since 2004, as part of a hazard mitigation project there. Fig. 8 shows contours of mean annual subsidence from levelling over May 2005 to August 2007, overlapping with the time span of gravity surveys in this paper. The contours are interpolated from the rates of subsidence at the benchmarks given in Fig. 8. Some of the levelling benchmarks in Fig. 8 are exactly the same as the gravity stations. In the levelling survey, it demands that the double-run misclosure between two neighboring benchmarks is smaller than $2.5\sqrt{k}$ mm, where k is the distance. The standard errors of the elevations are mostly at mm level. A detailed description of the levelling data processing is given in [**4**]

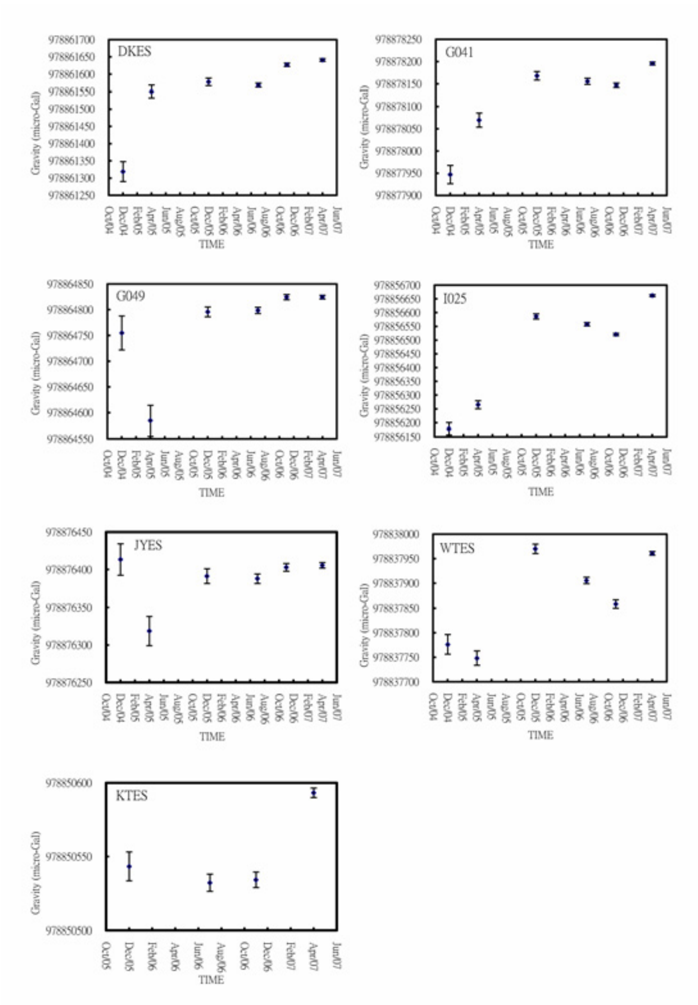

Fig 7. Gravity values at 7 relative gravity stations

Table 4 compares land subsidence from gravimetry and levelling at the gravity stations. The agreement at TAES and PKBD is the best because the adopted admittance factor is based on gravity and levelling data here. At stations G041, JYES and KTES, the rates from these two methods match to better than one cm/year. The largest discrepancy occurs at DKES, followed by I025. There is no clear dependence of discrepancy on site location, distance to shore, magnitude of subsidence and distance to the absolute gravity stations. As pointed out by Torge (1986), local disturbances on gravity measurements from groundwater variations, rainfalls, microseismics, atmospheric pressures and other non-modeled environmental effects may be responsible for some of the large discrepancies.

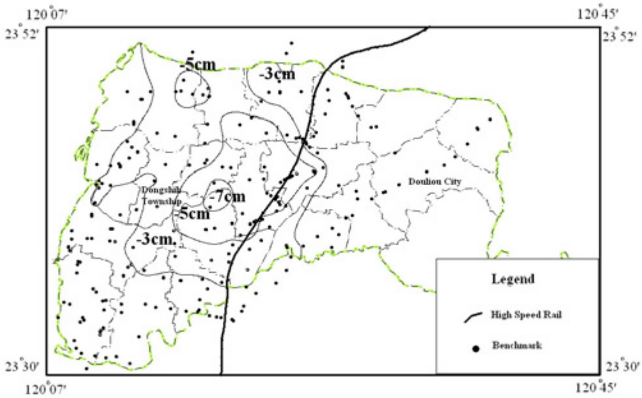

Fig. 8. Mean annual subsidence in Yunlin from precision levelling from May 2005 to August 2007.

Table 4.*Rates of subsidence (in cm/year) by gravimetry and levelling*

Station	Rate (by gravimetry)	Rate (levelling)
TAES	4.3	4.5
PKBD	2.3	2.2
G041	3.9	4.2
G049	4.1	1.5
JYES	2.1	2.0
KTES	5.3	5.4
WTES	4.0	2.3
I025	10.8	8.0
DKES	9.0	6.1

CONCLUSIONS

In this study, we attempt to determine land subsidence in central Taiwan using absolute and relative gravimetry, on the ground that gravimetry is more efficient and economic than conventional tools such as levelling and GPS. The estimated subsidence is absolute because of the use of absolute gravity measurements by a FG5. While the absolute gravimeter (a FG5) measured gravity values accurate to few μgal, the relative gravimeters (an EG and a CG-5) perform less well due to the nature of geological settings in central Taiwan. In particular, the gravity accuracies from the EG and CG-5 in Yunlin are about one order of magnitude worse than the nominal accuracy (1 to 3 μgal). An empirical admittance factor was determined using the gravimetric and levelling results at the two absolute gravity stations, and was used to convert gravity changes to height changes. At most gravity stations, there is a good agreement between subsidence rates from gravimetry and levelling, and this suggests gravimetry has the potential to determine height change to cm accuracy. However, there also exist large discrepancies (> 1 cm/year) at some gravity stations. These large discrepancies are mainly caused by large uncertainties in the relative gravity measurements and the hydrological effects. The uncertainty in the admittance factor also contributes to the discrepancies. Therefore, improvement in height determination from gravimetry can be achieved when these uncertainties are reduced. As an example, eastern Taiwan is situated over rocks and here the sediments are thin and the amplitude of ocean tides are small compared to western Taiwan. The hydrological effect in eastern Taiwan will be small because thin sediments cannot hold sufficient moisture to produce large gravity variation. According to Fig. 4, the SDs from CG-5 in eastern Taiwan are smaller than that in Yunlin (western Taiwan). As stated in Section 3.3, the standard errors of gravity are few μgal in eastern Taiwan. Such an accuracy in gravity corresponds to a cm accuracy in height. In conclusion, gravimetry is a very efficient and economic tool to detect large vertical surface motion (> 1 cm/year) given that environmental effects are properly modelled.

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