行政院國家科學委員會專題研究計畫 成果報告

以絕對重力研究台灣造山運動:觀測與模式比較
研究成果報告(精簡版)

計畫類別：個別型
計畫編號：NSC 99-2923-M-009-002-
執行期間：99年08月01日至100年07月31日
執行單位：國立交通大學土木工程學系（所）

計畫主持人：黃金維
共同主持人：趙丰
計畫參與人員：學士級-專任助理人員：高綉雯
博士班研究生-兼任助理人員：高瑞其
博士班研究生-兼任助理人員：謝文祺
博士班研究生-兼任助理人員：M. Mouyen
博士後研究：蕭宇伸

報告附件：出席國際會議研究心得報告及發表論文

公開資訊：本計畫可公開查詢

中華民國 100年10月31日

中文摘要：自2006年開始，由台灣及法國團隊共同合作的計畫－利用重力、GPS及水準測量對台灣造山運動之研究(AGTO)，這團隊研究的課題還包含台灣的重力基準、地體動力變化及環境變遷等，以新竹的超導重力、絕對重力及GPS同時分析的經驗，用5年的實測超導重力數據來建立固體潮及海潮負載模式，再將非地殼變動所引起的大氣、水文及極移效應加以改正，求得之剩餘重力來和GPS及水準測量結果比較。根據GPS觀測結果可知台灣南部的水平位移最大偏移量可達到每年7-8公分的變化，AGTO五年來的成果中，重力變化每年為-1.39±4.21 μgal，GPS每年變化為0.50±0.94公分，所歸納出重力跟高度變化為每公分2.78 μgal。本計畫在執行期間，遭遇2008年8月的莫拉克颱風侵襲，使得AGTO點位中的AG3及AG6分別有53 μgal及27 μgal的重力變化，化算成AG3及AG6附近河床淤積的高度約為2.45公尺及1.25公尺。

英文摘要：A joint Taiwan-France project, called Absolute Gravity for Taiwanese Orogen (AGTO), was initiated in 2006 to study the orogeny of Taiwan using gravimetry, GPS and leveling measurements. This project is focused on the analysis of gravity datum, geodynamics and environmental change in Taiwan. Most experiments of Superconducting gravimetry (SG), Absolute gravimetry (AG) and global positioning system (GPS) are conducted over Taiwan and at Hsinchu (HS). Solid and ocean tide gravity effects are estimated from five years of SG data and are compared with models. We model the gravity variations of non-tectonic origins due to atmosphere, hydrology, and polar motion. Based on the GPS measuring results, the horizontal rates of plate motion in southeastern Taiwan are about 7-8 cm year-1. AGTO measurements show that the average gravity and GPS vertical rate are -1.39±4.21 µgal year-1 and 0.50±0.94 cm year-1, respectively, leading to an average gravity-height ratio (2.78 µgal cm-1). Large (in absolute magnitude) gravity-atmosphere admittances are found during major typhoons. Typhoon Morakot (August 2008) caused large landslides at AG3 and AG6 (two stations of AGTO) that created gravity changes of 53 µgal and 27 µgal, and sediment thickness changes of 2.45m and 1.25m.

行政院國家科學委員會補助專題研究計畫 **■成果報告**
□期中進度報告

以絕對重力研究台灣造山運動:觀測與模式比較

計畫類別：■個別型計畫　　□整合型計畫
計畫編號：NSC 99－2923－M－009－002－
執行期間：99 年 8 月 1 日至 100 年 7 月 31 日

執行機構及系所：國立交通大學土木工程學系

計畫主持人：黃金維
共同主持人：趙丰
計畫參與人員：高瑞其、高綉雯、蕭宇伸、謝文祺、Maxime Mouyen

成果報告類型(依經費核定清單規定繳交)：■精簡報告　□完整報告

本計畫除繳交成果報告外，另須繳交以下出國心得報告：
□赴國外出差或研習心得報告
□赴大陸地區出差或研習心得報告
■出席國際學術會議心得報告
□國際合作研究計畫國外研究報告

處理方式：除列管計畫及下列情形者外，得立即公開查詢
　　　　　□涉及專利或其他智慧財產權，□一年□二年後可公開查詢

中華民國 100 年 7 月 31 日

中文摘要

自 2006 年開始，由台灣及法國團隊共同合作的計畫－利用重力、GPS 及水準測量對台灣造山運動之研究(AGTO)，這團隊研究的課題還包含台灣的重力基準、地體動力變化及環境變遷等，以新竹的超導重力、絕對重力及 GPS 同時分析的經驗，用 5 年的實測超導重力數據來建立固體潮及海潮負載模式，再將非地殼變動所引起的大氣、水文及極移效應加以改正，求得之剩餘重力來和 GPS 及水準測量結果比較。根據 GPS 觀測結果可知台灣南部的水平位移最大偏移量可達到每年 7-8 公分的變化，AGTO 五年來的成果中，重力變化每年為-1.39±4.21 µgal，GPS 每年變化為 0.50±0.94 公分，所歸納出重力跟高度變化為每公分 2.78µgal。本計畫在執行期間，遭遇 2008 年 8 月的莫拉克颱風侵襲，使得 AGTO 點位中的 AG3 及 AG6 分別有 53 µgal 及 27 µgal 的重力變化，化算成 AG3 及 AG6 附近河床淤積的高度約為 2.45 公尺及 1.25 公尺。

關鍵詞：絕對重力、超導重力、全球定位系統、水準測量、造山運動

Abstract

A joint Taiwan-France project, called Absolute Gravity for Taiwanese Orogen (AGTO), was initiated in 2006 to study the orogeny of Taiwan using gravimetry, GPS and leveling measurements. This project is focused on the analysis of gravity datum, geodynamics and environmental change in Taiwan. Most experiments of Superconducting gravimetry (SG), Absolute gravimetry (AG) and global positioning system (GPS) are conducted over Taiwan and at Hsinchu (HS). Solid and ocean tide gravity effects are estimated from five years of SG data and are compared with models. We model the gravity variations of non-tectonic origins due to atmosphere, hydrology, and polar motion. Based on the GPS measuring results, the horizontal rates of plate motion in southeastern Taiwan are about 7-8 cm year^{-1}. AGTO measurements show that the average gravity and GPS vertical rate are -1.39±4.21 μgal year^{-1} and 0.50±0.94 cm year^{-1}, respectively, leading to an average gravity-height ratio (2.78 μgal cm^{-1}). Large (in absolute magnitude) gravity-atmosphere admittances are found during major typhoons. Typhoon Morakot (August 2008) caused large landslides at AG3 and AG6 (two stations of AGTO) that created gravity changes of 53 μgal and 27 μgal, and sediment thickness changes of 2.45m and 1.25m.

Keywords：absolute gravity, superconducting gravity, GPS, leveling measurement, orogeny

Table of Contents

List of Tables

List of Figures

1. Introduction

Taiwan is located at the converging zone of the Eurasia Plate and the Philippine Sea Plate. The tectonic motions create vertical displacements and mass changes that may be detected by repeated gravimetric and GPS measurements. The joint Taiwan-France team was using gravimetry, GPS and leveling to study the orogeny of Taiwan from 2006.

National gravity datum service (NGDS) also establishes and maintains a network of absolute gravity sites on Taiwan and offshore islands. NGDS is also responsible for delivering SG data at HS to GGP. Taiwan joins GGP since 2006 and the SG data from Taiwan (HS) have been used by most of the SG scientists. In fact, GGP recommends that both AG and SG are submitted to the GGP data center for a variety of purposes, including CF determination, SG drift estimation and regional plate tectonics study.

Fig. 1-1 shows the geological structure (Ho, 1986; Hickman et al., 2002; Mouyen et al., 2009) and distribution of the AG sites, including those for the ATGO project. The gravity values at the AGTO sites (AG1 to AG9) are collected every November from 2006 to 2010 by a joint Taiwan-France team. Other gravity sites in Fig. 1-1 are occupied by AG irregularly. Measurements on some of the sites in Fig. 1-1 have been suspended. Repeated measurements of gravity values at most of these sites over different times yield gravity changes that were used for geodynamic studies.

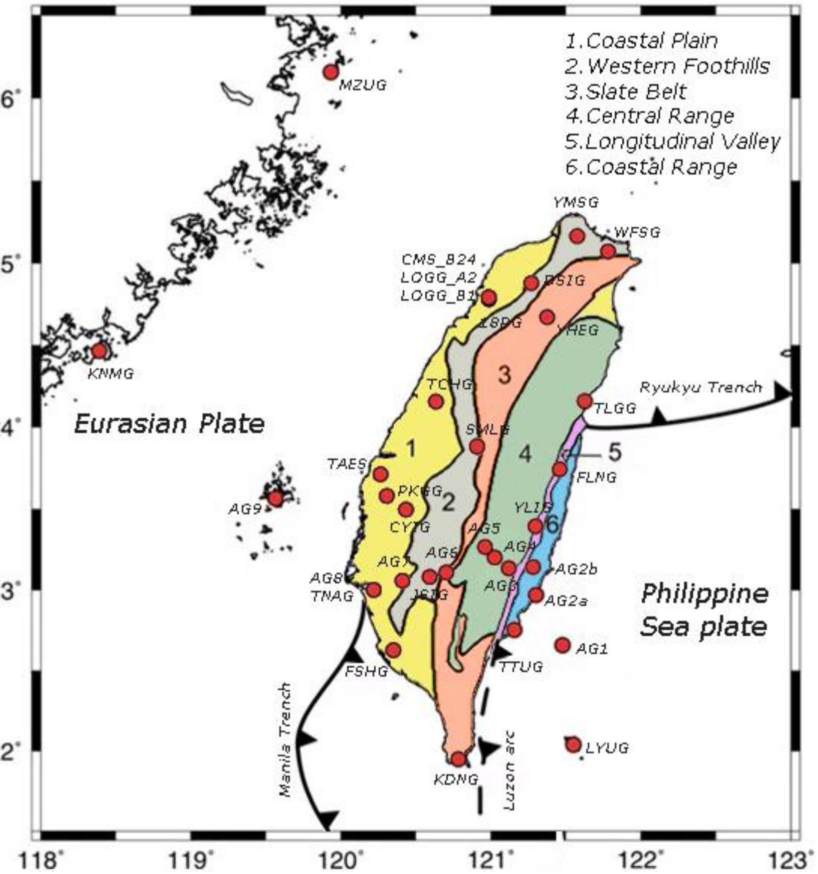

Fig. 1-1 General geology and absolute gravity sites in Taiwan established by MOI

2. Estimation of absolute gravimetry

2.1 Gravity gradient for gravity reduction

Gravity gradient is needed to reduce the height effect on gravity observations. For example, a raw FG5 observation may refer to a reference point along the dropping chamber and it may be reduced to a gravity value at the pillar marker or at a desired height for later applications. The relationship between vertical position z and gravity g is:

$$\frac{d^2 z}{dt^2} = g + g_\gamma z \tag{2-1}$$

where t is traveling time of the test mass, g and g_γ are gravity and gravity gradient. The traveling distance is a function of time, velocity and gravity:

$$z(t)=\frac{1}{2}g(t^2+\frac{g_\gamma t^4}{12})+v(t+\frac{g_\gamma t^3}{6})+x(1+\frac{g_\gamma t^2}{2}) \tag{2-2}$$

where x and v are the initial position and velocity. In this project, a GRAVITON-EG gravimeter is used to measure gravity gradients.

A GRAVITON-EG is a fully automated and portable gravimeter for determination of relative gravity. For gravity gradient determination, a GRAVITON-EG is set up at different heights (Fig. 2-1), where the gravity values are measured. The ratio between the differences in gravity and height is the gravity gradient. The measured gravity gradients at pillar A1, A2, A3 and B1 of laboratory of geodesy and geodynamics (LOGG) are listed in Table 2-1 and are used for gradient reductions for AG measurements at LOGG. Six campaigns of gravity gradient measurements are illustrated in Fig. 2-2. We find that gravity gradient measurements at A3 are more stable than those at A1, A2 and B1 (pillars at the LOGG, Hsinchu). Because a gradient is computed as the ratio:

$$g_r=\frac{g_2-g_1}{h_2-h_1} \tag{2-3}$$

where g_2, g_1 are the measured gravity values at different height h_2, h_1. We can determine the standard error of gravity gradient as :

$$\sigma_{g_r}=\frac{\sqrt{\sigma_{g1}{}^2+\sigma_{g2}{}^2}}{h_2-h_1} \tag{2-4}$$

where σ_{g_r} is the standard error of each site. The mean gravity gradients at A1, A2, A3 and B1 range from -2.69 to -2.57 μgal cm^{-1}. Such variations are due to different accuracies of the GRAVITON-EG that are largely results of environmental noises. For example, a large rainfall, a strong wind and a busy traffic will lead to large gravity perturbations that result in a degraded gravity measuring accuracy. The mean values in Table 2-1 are used for gravity reduction. Table 2-2 shows the gradients of different AG sites in Taiwan.

Table 2-1: Gravity gradients and standard errors at different times

pillar / time	A1 (μgal cm^{-1})	A2 (μgal cm^{-1})	A3 (μgal cm^{-1})	B1 (μgal cm^{-1})
1	-2.60± 0.19	-2.60 ± 0.19	-2.38 ± 0.17	-2.52 ± 0.18
2	-2.50 ± 0.18	-2.54 ± 0.18	-2.36 ± 0.17	-2.69 ± 0.19
3	-2.59 ± 0.19	-2.63 ± 0.19	-2.39 ± 0.17	-2.60 ± 0.19
4	-2.52 ± 0.18	-2.70 ± 0.19	-2.72 ± 0.20	-2.68 ± 0.19
5	-2.51 ± 0.18	-2.62 ± 0.19	-2.80 ± 0.20	-2.73 ± 0.20
6	-2.69 ± 0.19	-2.63 ± 0.19	-2.82 ± 0.20	-2.89 ± 0.21
mean	-2.57 ± 0.08	-2.62 ± 0.08	-2.58 ± 0.07	-2.69 ± 0.08

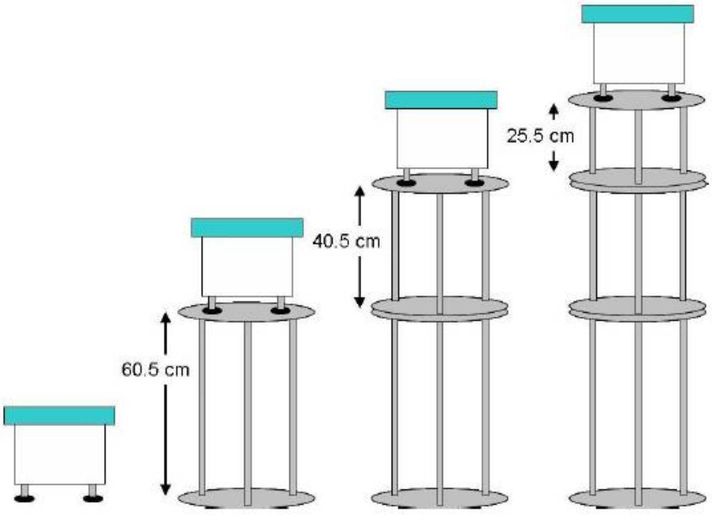

Fig. 2-1 Measuring gravity values at different heights for gradient determination

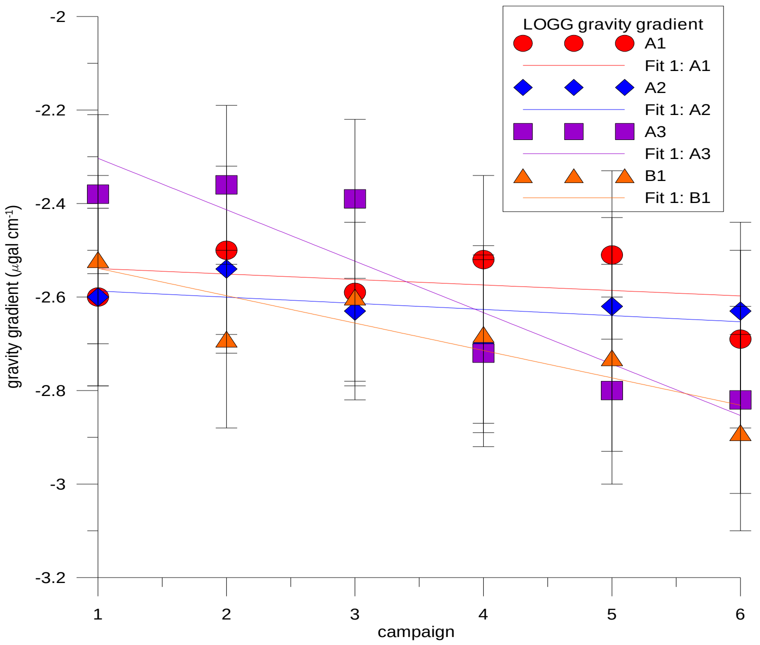

Fig. 2-2 Gravity gradients with standard errors (vertical bars), and the trends of gradient

Table 2-2: Gravity gradients and standard errors of AG sites at different times

AG sites	2005	2008
	gradient (μgal cm^{-1})	gradient (μgal cm^{-1})
18PG	------	−3.26±0.11
CYIG	−3.13±0.07	−3.15±0.06
DSIG	−2.73±0.13	−3.31±0.07
FLNG	------	−2.90±0.03
HCHG	−2.52±0.01	−2.60±0.06
JSIG	−2.51±0.07	−2.90±0.06
KDNG	−2.26±0.06	−3.39±0.02
LYUG	------	−4.30±0.28
PKGG	------	−2.72±0.03
SMLG	−3.35±0.04	−3.52±0.01
TAES	------	−3.09±0.04
TCHG	−2.70±0.06	−2.72±0.15
TLGG	−1.77±0.03	−2.31±0.02
WFSG	−3.72±0.09	−4.00±0.05
YHEG	−2.69±0.08	−2.44±0.01
YLIG	−1.76±0.02	−2.32±0.06
YMSG	−2.82±0.05	−3.61±0.06

2.2 Quality assessment of AG measurement

The estimated precision of an AG gravity value is based on the repeated measurements from the total drops, plus the standard errors (uncertainties). First, the standard error of a single gravity measurement is estimated from repeated measurement at the same location as :

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(g_i - \overline{g})^2}{n-1}} \qquad (2\text{-}5)$$

where σ is the standard error, n is the number of measurements, g_i is the measurement, and $\bar{g}$ is the average of the measurements. The standard error of the mean value is

$$\sigma_{\bar{g}} = \frac{\sigma}{\sqrt{n}} \tag{2-6}$$

In addition to measurement errors, the uncertainties in models include the environmental gravity effects. A corrected mean gravity is:

$$\bar{g}' = \bar{g} - \sum_{i=1}^{k} C_i \tag{2-7}$$

where C_i are the environmental gravity effects. If the gravity effects are uncorrelated, the total standard error (or total uncertainty) is

$$\sigma_{\bar{g}'} = \sqrt{\sigma_{\bar{g}}^2 + \sum_{i=1}^{k} \sigma_{C_i}^2} \tag{2-8}$$

where $\sigma_{C_i}^2$ are the error variance of the model corrections. The g software can estimate the total uncertainties based on repeat measurements and the built-in correction models.

FG5 #231 has been set up at LOGG to measure gravity values on B1 and T48 is set up on B2. More than 70 AG observation records have been collected on B1 from 2006 to 2011. There is a sample of AG measurements on B1 in 2010 (Table 2-3). The mean gravity gradient of B1 is -2.69 μgal cm^{-1} (see Table 2-1) and it is used for the reduction of raw FG5 records to ground values. The mean gravity from 2006 to 2011 is 978,901,463 μgal. Fig. 2-3 shows the gravity values with standard errors. The total standard errors (uncertainties) range from 0.14 to 0.53 μgal, and such variations in the total standard errors are mostly due to background noises/vibrations that affect the laser frequency.

Table 2-3: Absolute gravity measurements and result on B1 from FG5 #231 in 2010

Time	Drop number	Gravity (μgal)	Standard error of mean (μgal)	Total uncertainty (μgal)
January 27, 2010	2977	978,901,199	0.25	2.06
January 31, 2010	21976	978,901,199	0.16	2.03
March 6, 2010	2591	978,901,192	0.53	2.08
March 15, 2010	3786	978,901,194	0.48	2.08
July 23, 2010	28310	978,901,187	0.14	2.03
September 16, 2010	2989	978,901,202	0.18	2.02

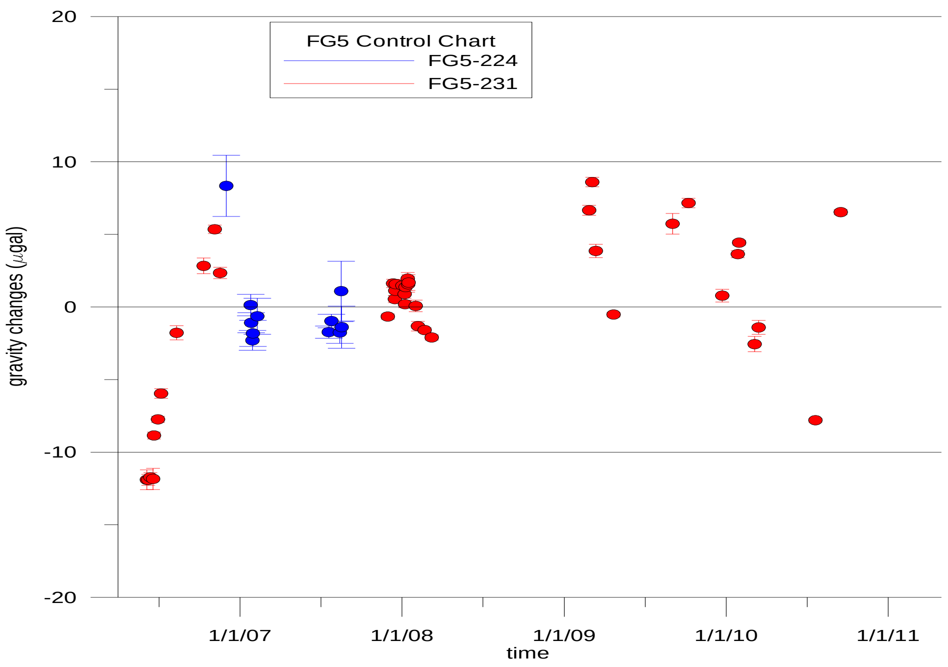

Fig.2-3 Gravity values (relative to the mean of all measurements) and standard errors (vertical bars) at pillar B1 observed by the FG5 #224 and #231 gravimeters

3. Environmental effects

3.1 Ocean loading effect

The raw absolute gravity values must be corrected for environment-induced gravity changes as follows. First, ocean tide will exert extra attraction and deform the earth, resulting in ocean tide loading gravity effect, which can be clearly identified in SG records, where the ocean tidal amplitude of M_2 is about 1.7 m in HS. The ocean tide loading gravity effect can be expressed as the convolution between ocean tide and the Green's function:

$$\Delta g = \frac{G\rho_w}{R^2} \iint \frac{h(\phi,\lambda)(p-u)}{(1+p^2-2pu)^{3/2}}\, ds - \rho_w \iint h(\phi,\lambda) K(\psi) ds \qquad (3\text{-}1)$$

where G is the Newtonian gravitational constant, ρ_w is the density of sea water, R is the mean earth radius, h is tidal height (depending on latitude ϕ and longitude λ), ψ is spherical distance, $u = \cos\psi,\ p = (R+H)/R,\ ds = R^2 \cos\phi d\phi d\lambda$, and K is Greens' function based on the loading love numbers of Farrell (1972). The first and second terms of the right-hand side of Eq. (3-1) represent the effects of attraction and loading, respectively. The detail of our ocean tide loading model and software development used in the study is given by Hwang et al. (2009). Note that the Newtonian (attraction) effect depends on station height H through variable p.

In the Taiwan Strait, the amplitude of the M_2 ocean tide increases toward the central part of the Strait and it reaches a maximum (about 2.2 m) at a latitude about 24°N, and then decreases almost linearly northwards to the East China Sea and southwards to the South China Sea. Also, there is a standing M_2 ocean tide near the central Taiwan Strait (Jan et al., 2004). As an example, the M_2 amplitudes at Keelung (25.2°N, near the East China Sea), Hsinchu (24.8°N, near HS) and Pintung (22.0°N, near the South China Sea) are 0.6, 1.6 and 0.2 m, respectively.

SG observations can also be used to estimate ocean tide loading gravity effects, as carried out by Boy et al. (2004). This is achieved by removing an adopted solid earth tide model from the SG data, and all the other known, well modeled signals, so that the residual SG gravity values are assumed to contain the ocean tide loading gravity effects only. However, such an estimated ocean tide loading gravity effects will be highly dependent on the adopted solid earth tide model. As an experiment, we removed the DDW solid earth tide of Dehant et al. (1999) from the raw SG gravity records. The remaining gravity values were then used to estimate ocean tide loading gravity effects at HS by ETERNA software. The estimated ocean tide loading gravity effects will be then called the "observed" ocean tide loading gravity effects. Fig. 3-1 shows the amplitudes of the "observed" ocean tide loading gravity effects at HS and the amplitudes of the ocean tide at the SHJU tide gauge station. In the amplitude spectra of Fig. 3-1, six leading components are identified: O_1, P_1, K_1, N_2, M_2 and S_2. It is interesting to note that the relative magnitudes of these components are different between the ocean tide loading gravity effects and the ocean tide. For ocean tide loading gravity effects, the order is M_2, O_1, K_1, S_2, N_2, and P_1, while for the ocean tide, the order is M_2, S_2, N_2, K_1, O_1, and P_1. For both the ocean tide and its gravity effects, the M_2 component is dominant. For ocean tide, M_2 contributes 47% to the total signal, while for ocean tide loading gravity effect the M_2 contribution is only 23%. In addition to M_3, several other non-linear tides are also present in Fig. 3-1. The SG observation in HS is used to study non-linear tides in the Taiwan Strait, as done by Boy et al. (2004) for European shallow waters.

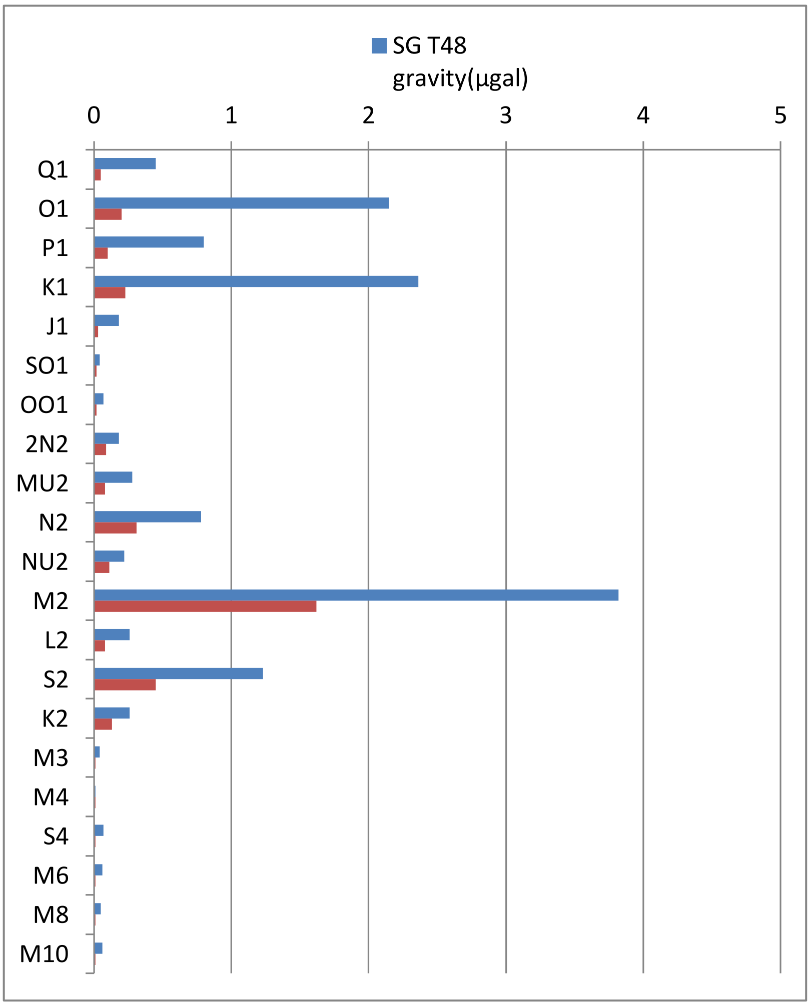

Fig. 3-1 Amplitudes of ocean tide from tide gauge records at the Hsinchu Harbor (8.6 km to HS), and amplitudes of ocean tide loading from the SG gravity measurements at HS

3.2 Hydrological effect

The hydrological gravity effect is largely due to variations in groundwater and soil moisture. Based on the model of a Bouguer plate and a homogeneous horizontal layer, the gravity effect of groundwater is computed by

$$\delta g_w = 2\pi G \rho_w P \delta H = 0.42 P \delta H \tag{3-2}$$

where P is the porosity of soil in percentage, ρ_w is the density and δH is groundwater level variation in m and the average of groundwater level is 24.54 m. For the soil moisture effect, we adopt $P = 5\%$ as the optimal porosity for the Toukeshan formation so that

$$\delta g_s = 2\pi G \rho_w H \delta P = -0.65 H \delta P \tag{3-3}$$

where H is the depth of unsaturated soil layer and δP is the recorded soil moisture change in percentage . Here we adopt $H = 2m$ and the average of soil moisture is 14.2 %. The minus sign in Eq. (3-3) is due to the fact that T48 is housed in a tunnel beneath the unsaturated soil.

3.3 Atmospheric pressure effect

Time-dependent gravity variations sensed by a SG are caused by a number of phenomena. In this section, we model the gravity variations that are of non-tectonic origins (Torge, 1989), namely, the gravity effects due to atmosphere, hydrology, and polar motion. First, atmospheric pressure variations affect the gravimeter output in two ways: directly by the gravitational effect and indirectly by the deformation effect (Warburton and Goodkind, 1977). A simple Bouguer plate model of atmospheric pressure gravity effect is:

$$\delta g_p = A \delta p \tag{3-4}$$

where A is gravity-atmosphere admittance and δp is the pressure change. According to data processing of SG, the gravity-atmosphere admittance of T48 is -0.35±0.003 μgal hPa^{-1} (average over the ETERNA and BAYTAP-G result), which is different from the standard value of -0.3 μgal hPa^{-1} (Torge, 1989).

3.4 Polar motion effect

Polar motion is the motion of the instantaneous rotating axis of the earth with respect to a mean axis. The motion of the axis results in change of gravity as

$$\begin{aligned}\delta g_p &= \delta_p \omega^2 R \sin 2\phi (x_p \cos\lambda - y_p \sin\lambda) \\ &= 1.164\times 10^8 \omega^2 R \sin 2\phi (x_p \cos\lambda - y_p \sin\lambda)\end{aligned} \tag{3-5}$$

where ϕ, λ are latitude and longitude, ω is the angular velocity and x_p, y_p are polar motion components in radian, which are available from the international earth rotation service (IERS, http://www.iers.org/). The polar motion effect on SG represents a long periodic effect. Based on Torge (1989), and the dominating frequency is associated with the period (403 days) of Chandler wobble. Ocean tides will also lead to polar motion at shorter periods (diurnal and semi-diurnal periods), but their gravity effects are too small to be considered in this project.

4. Modeling temporal gravity changes

4.1 Gravity changes from project AGTO

The AGTO used gravimeters (FG5 #228) from France and from Taiwan (FG5 #224). In this project, ten gravity-GPS sites (Table 4-1) along an east-west transect across southern Taiwan have been selected for gravity and GPS (Fig. 4-1) measurements, which are used to analyze vertical movements and mass transfers due to orogeny. Because the gravity effects of soil moisture and groundwater are mostly seasonal, we collect absolute gravity values in the same month of the years (November) to reduce the hydrological effect. The gravity changes collected over 2006 to 2010 at most sites was explained by the vertical movements from GPS, but large environment-induced gravity effects lead to significant conflicts between the gravimetric and GPS results. For example, typhoon Morakot (August 2008) caused large landslides that led to gravity change of 53 μgal at AG3 and 27 μgal at AG6 (Fig. 4-2). Here orogeny-induced gravity changes are significantly interrupted by such extreme events as typhoon Morakot.

With the river sediment data from Water Resource Agency (WRA) of Taiwan and satellite images of FORMOSAT-2 from National Space Organization (NSPO) before and after Morakot (Fig. 4-3), such gravity changes were used to estimate the sediment thickness based on a simple Bouguer plate model:

$$H \times p\% = \frac{24}{\delta\rho}\delta g \tag{4-1}$$

where $\delta\rho$ is the density of sediments in kg/m^3 in the riverbed, $p\%$ is the percentage area of the sediments and δg is the gravity change e in μgal at AG site. The sediment densities range from 1300 to 1800 kg/m^3. Fig. 4-4 shows the sediments near AG6. Within a radius of one km, there is 40 percent area lying in the riverbed. Based on the gravity changes at AG3 and AG6, the sediment thicknesses of H which was near AG6 range from 1.76 to 2.45 m, and the sediment thicknesses near AG3 range from 0.90 to 1.25 m.

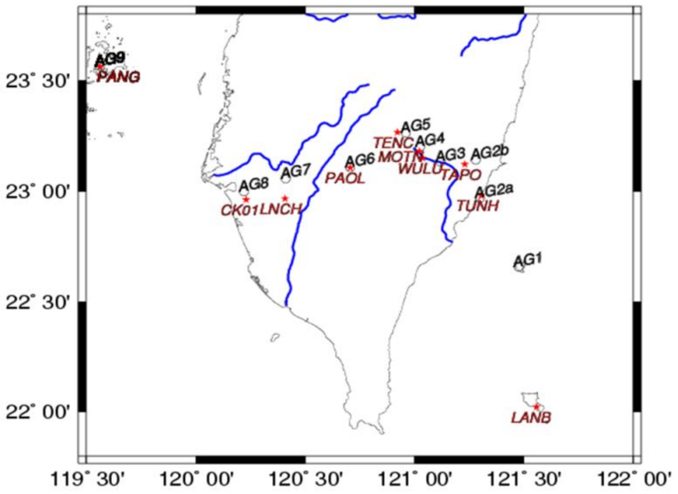

Fig. 4-1 AG sites in the project AGTO (circle) and GPS sites (star)

Table 4-1: The Location of AG and GPS sites

AG	Location (Lat, Lon)	GPS	Location (Lat, Lon)
AG1	(22.658°, 121.476°)	LANB	(121.439°,22.023°)
AG2a	(22.970°, 121.300°)	TUNH	(121.186°,22.982°)
AG2b	(23.142°, 121.280°)	TAPO	(121.111°, 23.124°)
AG3	(23.133°, 121.119°)	WULU	(120.917°,23.151°)
AG4	(23.201°, 121.026°)	MOTN	(120.933°, 23.182°)
AG5	(23.264°, 120.961°)	TENC	(120.802°,23.269°)
AG6	(23.109°, 120.706°)	PAOL	(120.587°,23.108°)
AG7	(23.057°, 120.412°)	LNCH	(120.289°,22.969°)
AG8	(22.999°, 120.220°)	CK01	(120.111°,22.963°)
AG9	(23.565°, 119.563°)	PANG	(119.543°,23.565°)

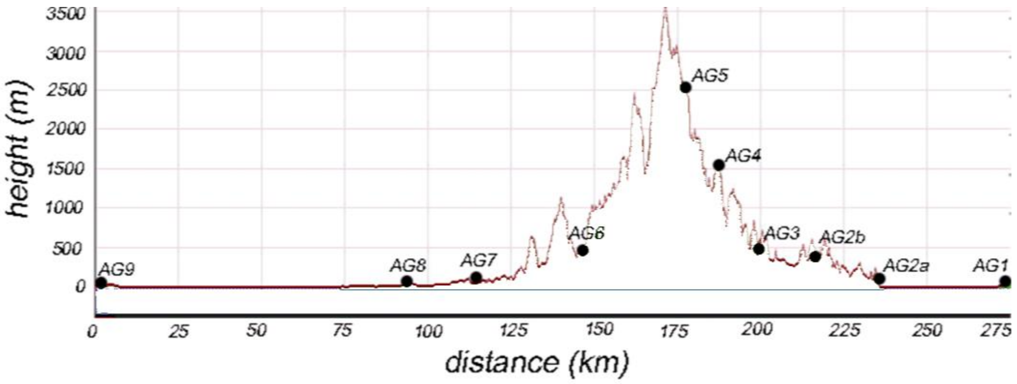

Fig. 4-2 The elevation of AG sites in the project AGTO, AG3 and AG6 are located at the mid-slope of a mountain

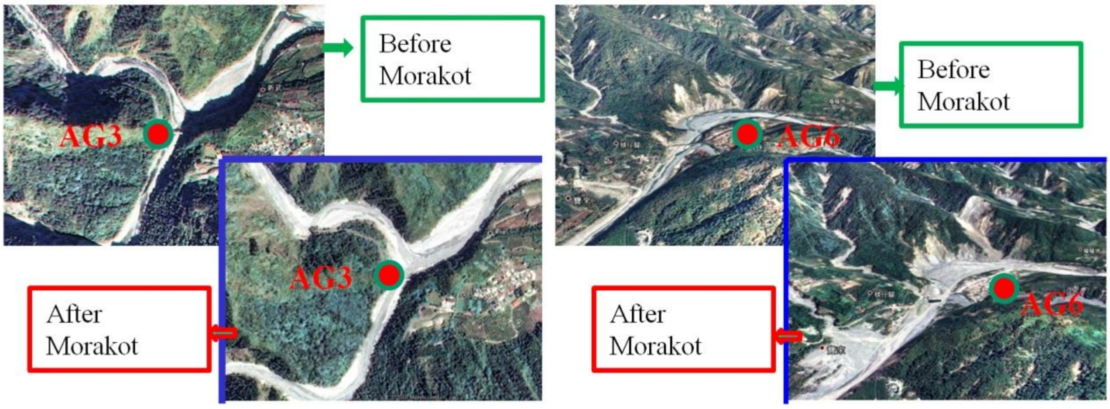

Fig. 4-3 Formosat-2 images of AG3 and AG6 before and after Morakot

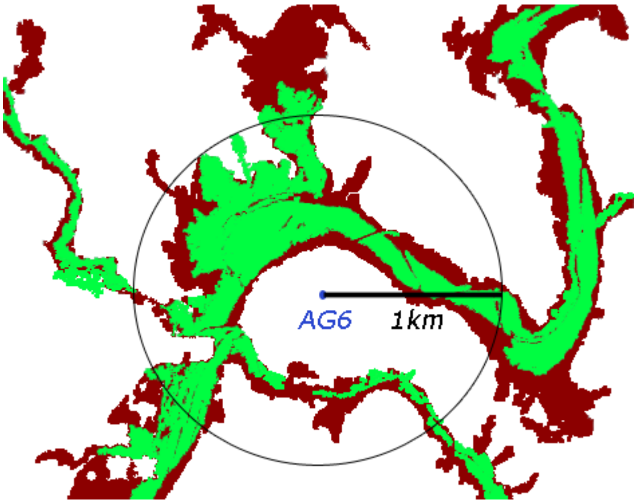

Fig. 4-4 Accumulation of soil and rock in the riverbed near AG6 due to Morakot (brown), and the original riverbed (green)

Typhoon Morakot caused erosions mainly at foothills and high mountains, rather than flat areas. The erosions lead to gravity changes at some of the AGTO sites. This difference in erosion was seen from the gravity changes at ATGO sites. For example, compared to other AGTO sites, the gravity changes at AG3 and AG6 are significantly larger. AG3 and AG6 are situated at foothills. Based on Fig. 4-2, the height difference between AG6 and AG7 is less than 300 m, while the height difference between AG6 and AG5 is over 2000 m. Likewise, the height difference between AG3 and AG2b is less than 200 m, while the height difference between AG3 and AG4 is over 1000 m. The height difference and location (foothill vs. high mounts/flat area) explain partially why the gravity changes at AG3 and AG6 are significantly larger than others.

The atmospheric gravity effect for AG data at the AGTO sites is based on the average admittance of -0.35 μgal hPa^{-1}. Also, there are no groundwater and soil moisture observations near all AGTO sites to model the hydrological effect. However, because all the observations were made in November, we expect that the hydrological effect is reduced when differencing gravity observations between two successive years at the same site. Table 4-2 summarizes the gravity values relative to the values in 2006; see also Fig. 4-5. Some of the gravity values are suspicious and outliers, e.g., the gravity value at AG8 in 2007. The large gravity values at AG3 and AG6 in 2009 are caused by typhoon Morakot. Fig. 4-6 shows the rates of gravity changes at the AGTO sites. The rates are computed without using the anomalous gravity values caused by typhoons. The gravity rates are compared with vertical displacement rates from GPS (Table 4-3). The gravity rate varies from one station to another. The average gravity and vertical rates are -1.39 ± 4.21 μgal $year^{-1}$ and 0.50 ± 0.94 cm $year^{-1}$, respectively, leading to an average gravity-height ratio (2.78 μgal cm^{-1}). This ratio is different from the ratio of 2.0 μgal cm^{-1} based on a vertical displacement a Bouguer plate with a rock density of 2.67 g cm^{-3}. The difference between the observed and theoretical rations (2.78 and 2.0 μgal cm^{-1}) is a subject of future project.

Table 4-2: Gravity changes relative to observations in 2006

Sites	2006 (μgal)	2007 (μgal)	2008 (μgal)	2009 (μgal)	2010 (μgal)
AG1	0	6.15	1.28	-2.6	-0.23
AG2a	0	3.11	-0.64	-1.68	4.01
AG2b	0	5.47	-1.17	-7.74	-5.37
AG3	0	-8.1	-14.44	38.35	61.21
AG4	0	-0.77	5.82	-6.86	1.25
AG5	0	-0.84	1.94	--	--
AG6	0	1.46	2.93	30.01	27.65
AG7	0	3.44	-1.79	-6.86	-6.9
AG8	0	-45.87	-7.84	-13.92	-9.28
AG9	--	0	-1.61	-4.45	-0.36

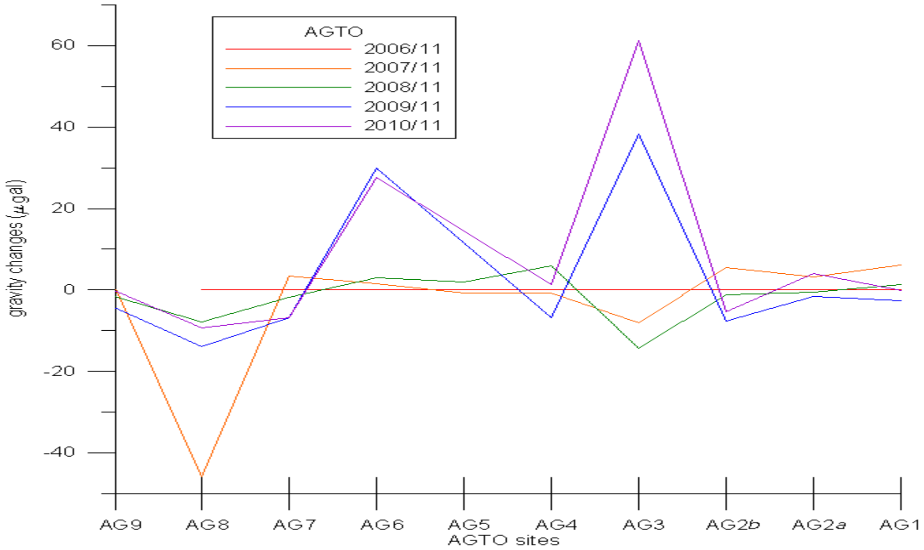

Fig. 4-5 Gravity changes relative to observations in 2006 at AGTO sites (each curve represents a year)

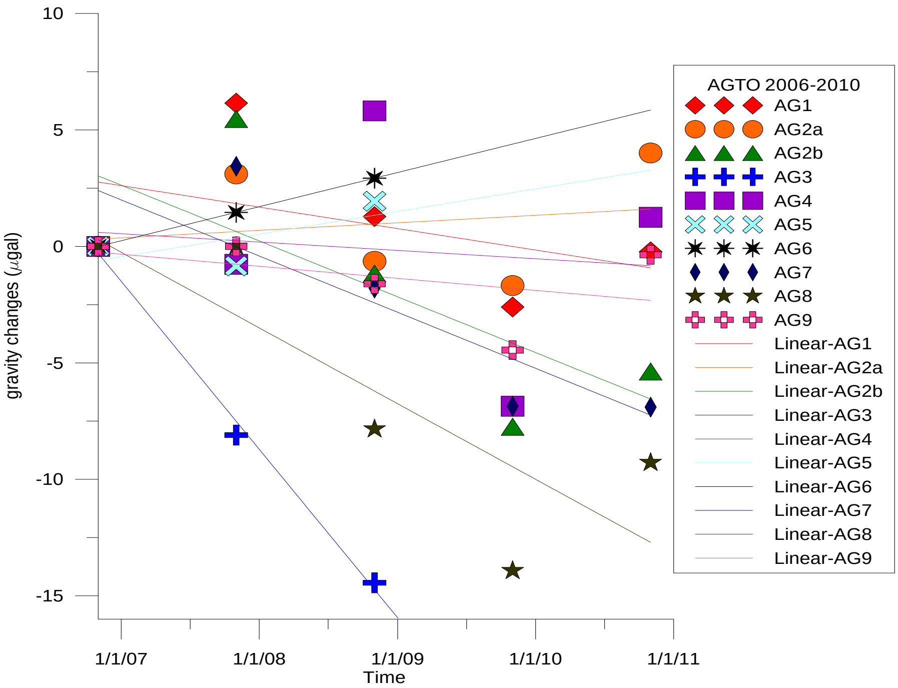

Fig. 4-6 Gravity changes relative to the observations in 2006 at the AGTO sites (each curve represents a site)

Table 4-3: Gravity changes relative to observations in 2006

Sites (AG/GPS)	Gravity rate (μgal year^{-1})	GPS rate (cm year^{-1})
AG1/LANB	-0.92±3.24	-0.07±1.10
AG2a/TUNH	0.32±2.47	0.09±0.84
AG2b/TAPO	-2.39±5.11	1.11±0.87
AG3/WULU	-7.21±7.24	0.82±1.04
AG4/MOTN	-0.36±4.56	0.25±1.07
AG5/TENC	0.97±1.43	0.05±0.99
AG6/PAOL	1.46±1.47	1.02±0.89
AG7/LNCH	-2.41±4.49	1.59±0.99
AG8/CK01	-2.82±5.79	0.30±0.88
AG9/PANG	-0.52±2.02	-0.14±0.57
AVERAGE	-1.39±4.21	0.50±0.94

4.2 Gravity changes from MOI AG campaigns

In addition to the AGTO sites, we also collected AG data at 15 MOI-defined gravity sites over the entire Taiwan and some offshore islands (Fig. 1-1). Some of sites were just visited once. At the MOI sites, we also observed gravity gradients for AG data reductions, and shows the rates of gravity change from 2004 to 2010 in Table 4-4. The average rate of gravity change is -0.58 μgal year^{-1}. Most of the gravity gradients are different from the normal gradient of -0.3086 mgal m^{-1}, suggesting that the rock densities at these sites are different from 2.67 g cm^{-3} and large gravity anomalies may have further caused the substantial deviations of the observed gradients from the normal gradient. Table 4-5 lists the gravity values in 2005 and 2008. Fig. 4-7 shows the gravity values from 2005 to 2010. Table 4-6

Table 4-4: Gravity gradients and the rates of gravity change at MOI sites

Site	Gradient (μgal cm^{-1})	Duration	Times	Gravity rate (μgal year^{-1})
18PG	-3.26 ± 0.11	--	--	--
CYIG	-3.15 ± 0.06	--	--	--
DSIG	-3.31 ± 0.07	2005-2009	2	-2.14
FLNG	-2.90 ± 0.03	2006-2009	8	0.72
HCHG	-2.60 ± 0.06	2004-2009	4	-1.37
JSIG	-2.90 ± 0.06	2005-2009	2	-2.63
KDNG	-3.39 ± 0.02	2004-2009	8	-6.98
LYUG	-4.30 ± 0.28	2004-2009	2	-0.73
PKGG	-2.72 ± 0.03	2006-2009	7	6.49
SMLG	-3.52 ± 0.01	2005-2009	2	-5.91
TAES	-3.09 ± 0.04	2004-2009	6	16.23
TCHG	-2.72 ± 0.15	2005-2009	2	-8.99
TLGG	-2.31 ± 0.02	2005-2008	2	-0.58
WFSG	-4.00 ± 0.05	2005-2008	2	0.71
YHEG	-2.44 ± 0.01	2005-2009	2	-6.06
YLIG	-2.32 ± 0.06	2005-2008	2	0.93
YMSG	-3.61 ± 0.06	2004-2010	10	1.68

Table 4-5: Absolute gravity values and uncertainties in 2005 and 2008 at MOI sites

Site	2005		2008	
	Gravity[1] (μgal)	uncertainty (μgal)	gravity (μgal)	uncertainty (μgal)
18PG	--	--	820.2	2.1
CYIG	906.5	2.2	--	--
CYIG	--	--	694.3	2.2
DSIG	684.4	2.2	675.6	2.1
FLNG	--	--	165.4	2.1
HCHG	698.6	2.2	008.7	2.0
JSIG	627.5	2.1	618.7	2.0
KDNG	504.9	2.2	512.5	2.0
LYUG	--	--	130.4	2.1
PKGG	--	--	864.0	2.1
SMLG	464.6	2.1	442.4	2.0
TAES	--	--	793.2	2.2
TCHG	510.2	2.1	477.4	2.1
TLGG	583.2	2.1	581.5	2.1
WFSG	887.6	2.1	894.0	2.1
YHEG	735.3	2.1	710.5	2.0
YLIG	891.7	2.1	894.4	2.1
YMSG	909.0	2.1	888.7	2.0

[1] relative to the mean value

Some of the gravity changes given in Fig. 4-7 is explained below. TAES is located in Yunlin County and is over an area of large subsidence. Here the gravity rate is 16.2 μgal year^{-1}, corresponding to a subsidence rate of 8.1 cm year^{-1}, provided that the rock density is about 2.67 g cm^{-3} and there is no significant plate motion here. Like TAES, PKGG is also situated over an area of subsidence, and the gravity change here is largely caused by subsidence, but with a smaller subsidence of 3.2 cm year^{-1} compared to that of TAES. YMSG is visited most frequently among all stations. Here the gravity rate is 1.68 μgal year^{-1} and it has been hypothesized that this gravity increase is potentially caused by the rise of magma in the Tatun volcano groups. More evidence is needed to support this hypothesis.

Virtually all gravity sites along the Central Range show negative rates ranging from -5.91 μgal year^{-1} (SMLG) to -6.06 μgal year^{-1} (YHEG). Station TCHG is situated in the city center of Taichung and also experiences a large, negative rate of -8.99 μgal year^{-1}. Despite fact that the gravity point density is low, in Fig. 4-8 we show a two-dimensional (also lateral) distribution of gravity rates over the entire Taiwan. In order to correlate the gravity changes with vertical displacements, in Fig. 4-9 we show the rates of horizontal displacement and vertical displacement derived from more than 300 continuous GPS stations. In Fig. 4-10 we show the rates of vertical displacements derived from more than 2000 leveling measurements. Because mass transfer originating from the orogeny of Taiwan is at the sub-μgal level (Mouyen et al., 2009), the gravity rates in Fig. 4-8 are largely explained by the vertical displacements given in Fig. 4-9 and Fig. 4-10, based on a simple Bouguer model that translates a one-cm plate uplift to a 2 μgal gravity decrease. However, deviations from such a simple Bouguer model can occur under the following conditions:

(1) Man-made movement of gravity site
(2) Large subsidence such as TAES
(3) Large hydrological effect not removed from the gravity observation
(4) Data errors
(5) Anomalous subsurface mass movement such as magma at YMSG

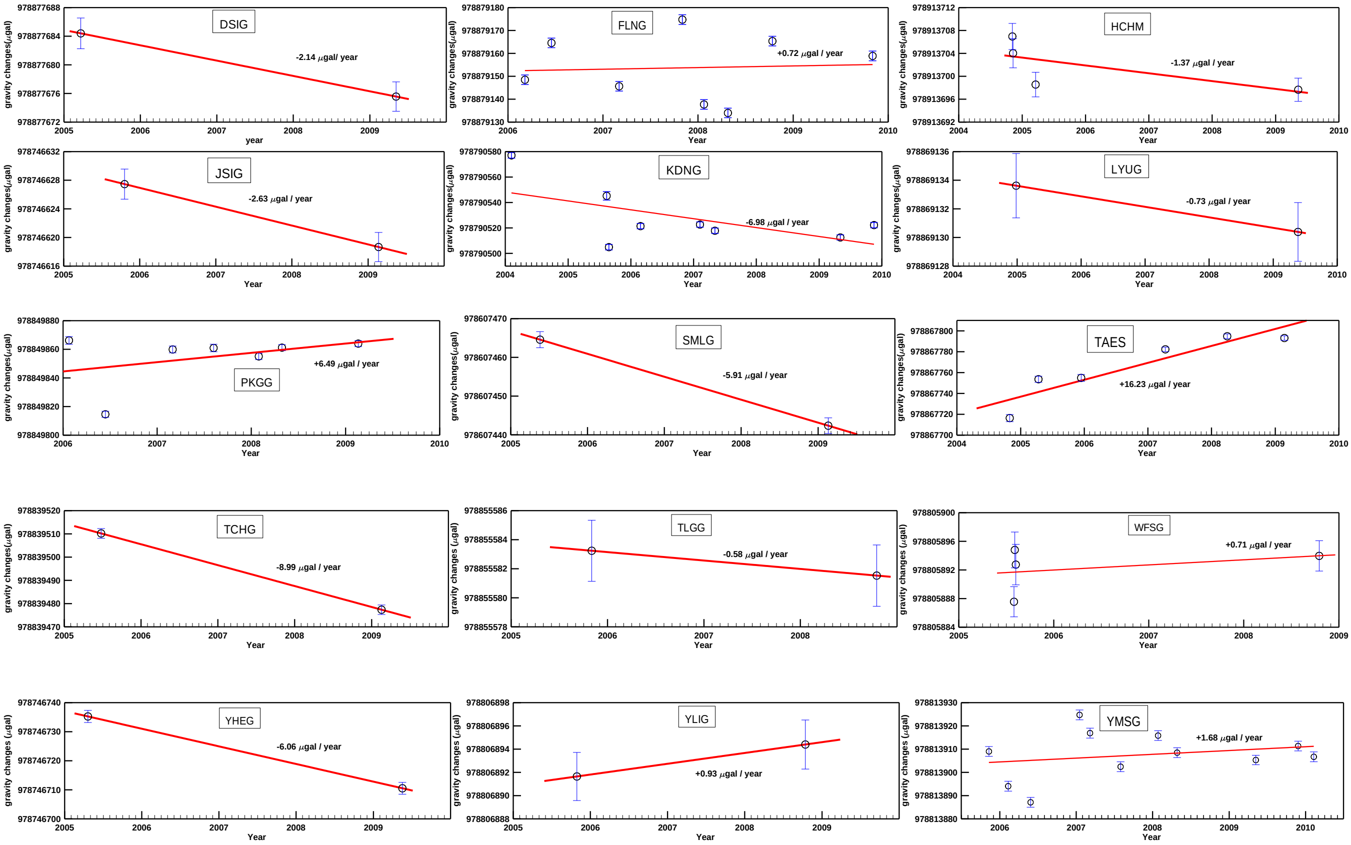

Fig. 4-7 Absolute gravity values and rate at DSIG, FLNG, HCHG, JSIG, KDNG, LYUG, PKGG, SMLG, TAES, TCHG, TLGG, WFSG, YHEG, YLIG and YMSG

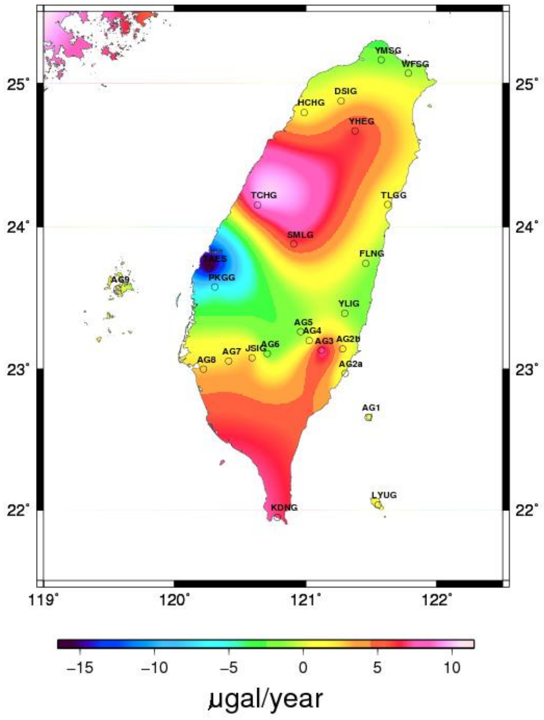

Fig. 4-8 Two-dimensional (lateral) distribution of gravity rates interpolated from the rates at AG sites

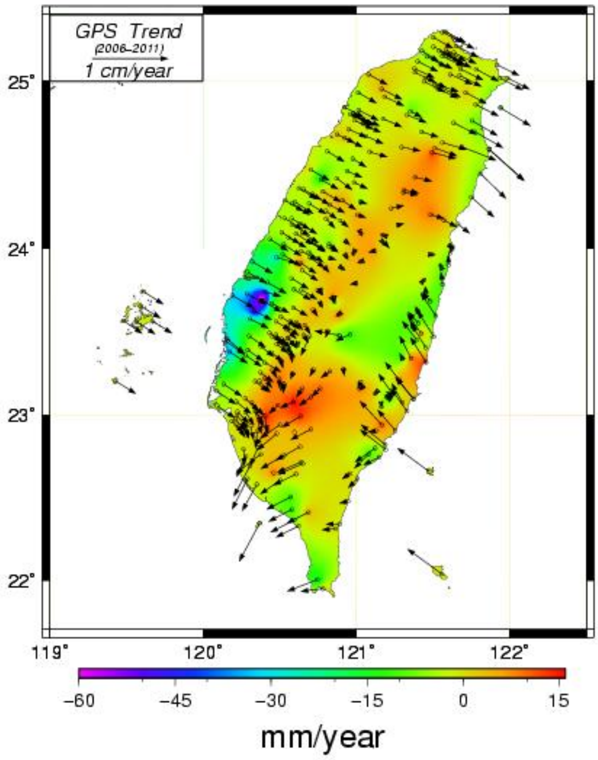

Fig.4-9 Horizontal displacement rates (arrows) and vertical displacement rates (color) from GPS. An arrow corresponds to a continuous GPS station.

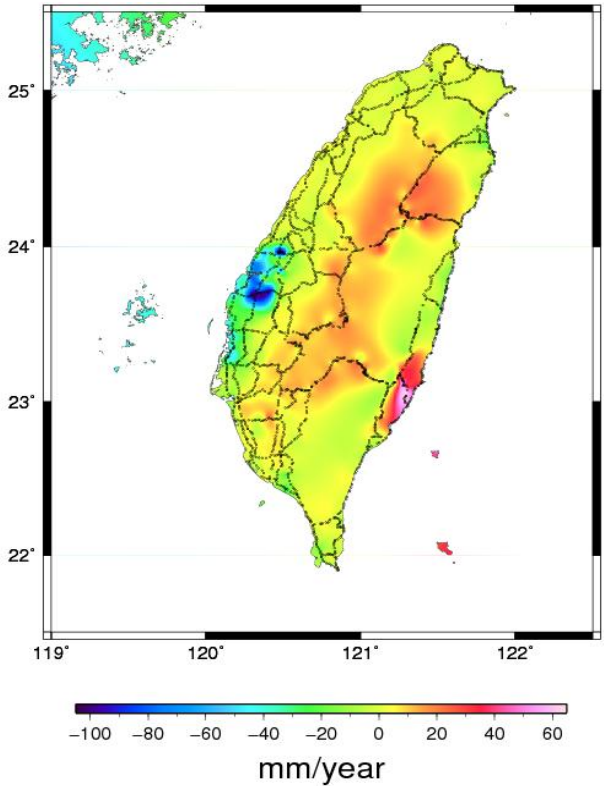

Fig. 4-10 Vertical displacement rates (color) from 2068 measurements of leveling.

5. Conclusion

This project summarizes the result of the absolute gravity measurement campaign in the AGTO project, and from the observations of two SG (serial no. 48 and 49) in Hsinchu. The major findings and potential applications of this project are listed below:

1. The mean gravity and vertical rates at AGTO sites are -1.39±4.21 μgal year^{-1} and 0.50±0.94 cm year^{-1}. The sediment thicknesses changes near AG6 and AG3 due to landslides caused by Typhoon Morakot are 2.45 m and 1.25 m.
2. The average rate of gravity change from 2005 to 2008 is -0.58 μgal year^{-1} in Taiwan. Using repeated absolute gravimetric and levelling measurements to determine gravity changes at islandwide (Taiwan) stations, and the preliminary causes of such changes are identified with the help of GPS and levelling data.
3. The SG gravimeter, T49, is currently at Hsinchu, but it can be deployed in a new location (other than Hsinchu) that has a different geodynamic feature. With two SGs at two locations, many research opportunities can be explored. For example, a proposed new site for T49 is Mt. Yangming (see Fig. 4-7, YMSG), where possible volcano eruptions can occur and hydrological changes will induce large mass and gravity changes. Records from two SG can be used to study gravity changes in sea level ocean circulation associated with the Kuroshio Current.
4. Use of gravimetry to study groundwater in central Taiwan. Since 90 % of all unfrozen fresh water is hidden underground, it is difficult to determine its volume. The volume can be estimated with a network of AG sites around central Taiwan.

The list of publications related to this project is as below:

Referee journal papers

1. Hwang, C., R. Kao, C. C. Cheng, J. F. Huang, C. W. Lee, and T. Sato, 2009. Results from parallel observations of superconducting and absolute gravimeters and GPS at the Hsinchu station of Global Geodynamics Project, Taiwan. J. Geophys. Res., 114, B07406, doi: 10.1029/2008JB006195. (IF=3.147)
2. Mouyen M., Masson F., Hwang C., Cheng CC., Cattin R., Lee CW. , Le Moigne N., Hinderer J., Malavieille J., Bayer R., Luck B., 2009. Expected temporal Absolute Gravity change across the Taiwanese Orogen, a modeling approach, J. of Geodynamics, 48, 284-291. (IF=1.692)
3. Yeh, TK, C Hwang, JF Huang, BF Chao, and MH Chang, Vertical displacement due to ocean tidal loading around Taiwan based on GPS observations, Atmospheric and Oceanic Sciences, in press, 2011. (IF=0.643)
4. Hwang, C, and JF Huang, SGOTL: model and computer program for high-resolution, height-dependent gravity effect of ocean tide loading, Terrestrial, Atmospheric and Oceanic Sciences, Vol. 22, No. 4, pp. 373-382, 2011.
5. Hwang, C and JF Huang, Numerical model of displacements due to ocean tide loading: case study at GPS stations in Taiwan and western Pacific, submitted to Journal of Chinese Institute of Engineers, 2011.
6. M. Mouyen, F. Masson, C. Hwang, C.-C. Cheng, N. Le Moigne, J. Lee, R. Kao, W.-C. Hsieh, B. Luck, J.-D. Bernard. Time-lapse absolute and relative gravimetry in Taiwan : identification of hydrology, tectonics and erosion effects, in preparation for Geophysical Journal International.
7. Mouyen M., Masson F., Mouthereau F., Simoes M., Hwang C. and Cheng CC. Gravity change in Taiwan estimated from different orogeny models, in

preparation for Tectonophysics.

Conference papers

1. Hsieh, W. C., C. W. Lee, R. Kao, M. H. Peng, C. Hwang, M. Yang, F. Masson, and N. Le Moigne. Absolute gravity measurements in Taiwan, Asia Oceania Geosciences Society, Korea, June 16-20, 2008.
2. Masson F., Mouyen M., Hwang C., Cheng C., Lee C., Le Moigne N., Hinderer J., Cattin R., Luck B., Bayer R., Malavieille J. Study of the Taiwanese orogen from absolute gravity data , AGU Meeting, San Francisco, 2008
3. Hwang, C, R Kao, CC Cheng, JF Huang, CW Lee , and T Sato, Results from two years of superconducting observations at the Hsinchu (HS) station, Taiwan, European Geophysical Union, General Assembly, Vienna, Austria, April 19-24, 2009.
4. Kao, R., C. Hwang, C. W. Lee, M. H. Peng, W. C. Hsieh, 2009. Atmospheric pressure effect of SG measurements, The 28th Conference on Surveying and Geomatics: 2009, Taoyuan, Taiwan.
5. Masson F., Mouyen M., Hwang C., Cheng C.C., Le Moigne N., Lee C.W., Kao R., Hsieh N. (2009) - Utilisation des variations temporelles de pesanteur pour l'étude de l'orogène taiwanaise : le projet AGTO, Colloque G2, Strasbourg, 2009.
6. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N., Four Years of Absolute Gravity in the Taiwan Orogen (AGTO), AGU Meeting, San Francisco, 2009.
7. Cheng, C., R. Kao, N. Hsieh, and C. Hwang, Monitoring the gravity changes of seismic deformation by the absolute gravimetric network, 2nd Asia Workshop on Superconducting Gravimetry, Taipei, 2010.

8. Hsieh,W., B. Chao, C. Lee, C. Hwang, and M. Yang, Monitoring gravity change over Mt. Yangming for detection of volcanic activity, Western Pacific Geophysics Meeting 2010, Taipei, 2010.
9. Kao. R., C. Hwang, C. W. Lee, Atmosphere Loading effects of SG48 in Hsinchu (HS), 2nd Asia Workshop on Superconducting Gravimetry, Taipei, 2010.
10. Huang, J. and C. Hwang, Modeling and observing shallow water tides at the Hsinchu (HS) station of GGP, Taiwan, Western Pacific Geophysics Meeting 2010, Taipei, 2010.
11. Cheng, C., T. Lien, and C. Hwang, Coseismic deformation monitoring by absolute gravimetry –case study of Jiashan earthquake Mw=6.4, Geodynamics and Environment in East Asia International Conference & 6th Taiwan-France Earth Science Symposium (GEEA 2010), Aix-en-Provence, France, 2010.
12. Hwang, C., C. Cheng, J. Huang and R. Kao, Superconducting and absolute gravity observations for geodynamic applications, APSG 2010, Shanghai, China, 2010.
13. Kao, R., C. Hwang, C. W. Lee, M. H. Peng, W. C. Hsieh. Taiwanese Orogeny From Absolute Gravimetry: Comparison of Observation and Model, The 29th Conference on Surveying and Geomatics : SG2010, Taipei, Taiwan, September 2-3, 2010.
14. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N. Four Years of Absolute Gravity in the Taiwan Orogen (AGTO), EGU Meeting, Vienna, Austria, 2010.
15. Mouyen M., Masson F., Mouthereau F., Hwang C., Cheng C. Modelling temporal gravity changes through the south of the Taiwan Orogen, EGU

Meeting, Vienna, Austria, 2010.

16. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N. Time-lapse absolute gravity measurements in the Taiwan Orogen, American Geophysical Union (AGU) - Western Pacific Geophysics Meeting, Hsinchu, Taiwan, 2010.
17. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N. Absolute gravity monitoring of the Taiwan Orogen, GEEA meeting, Aix en Provence, France, 2010.
18. Mouyen M., Masson F., Mouthereau F., Simoes M., Hwang C., Cheng C. Gravity change in Taiwan from kinematic orogeny models, Geodynamics and Environment in East Asia (GEEA) meeting, Aix en Provence, France, 2010.
19. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N. Absolute gravity measurements in the Taiwan orogen (invited), International Geoscience Programme (IGCP 565) Workshop 3 : Separating Hydrological and Tectonic Signals in Geodetic Observations Reno, NV, USA, 2010.
20. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N. Observation of debris flow and landslides mass transfers using time lapse gravimetry. Gravitational hazards meeting (JAG 2011), Strasbourg, France, 2011.
21. Mouyen M., Masson F., Hwang C., Cheng C., Le Moigne N., Lee C., Kao R., Hsieh N, Luck, B. Contribution of gravimetry to the Taiwanese orogeny study, AGU Meeting, San Francisco, CA, USA, 2011.
22. Kao, R., C. Hwang, C. W. Lee, F. Masson, R. Bayer, J. F. Huang, W. C. Hsieh, N. Le Moigne, M. Mouyen, C. C. Cheng, M. H. Peng. Taiwanese

Orogeny From Absolute Gravimetry and GPS: Comparison and model. IUGG 2011 General Assembly, Melbourne, Australia, June 28- July 7, 2011.

References

Boy, J. P., M. Llubes, R. Ray, J. Hinderer, N. Florsch, S. Rosat, F. Lyard, and T. Letellier, 2004. Non-linear oceanic tides observed by superconducting gravimeters in Europe, J. Geodyn., 38, 391-405.

Dehant, V., P. Defraigne, and J. M. Wahr, 1999. Tides for a convective Earth. J. Geophys. Res., 104, 1035-1058.

Farrell, W. E., 1972. Deformation of the earth by surface loads, Rev. Geophys. Space Phys., 10, 761-797.

Hickman, J.B., Wiltschko, D.V., Hung, J.-H., Fang, P., Bock, Y., 2002. Structure and evolution of the active fold-and-thrust belt of southwestern Taiwan from Global

Ho, C.S., 1986. A synthesis of the geologic evolution of Taiwan. Tectonophysics 125,1–16.

Hwang, C., R. Kao, C. C. Cheng, J. F. Huang, C. W. Lee, and T. Sato, 2009. Results from parallel observations of superconducting and absolute gravimeters and GPS at the Hsinchu station of Global Geodynamics Project, Taiwan. J. Geophys. Res., 114, B07406, doi: 10.1029/2008JB006195.

Jan, S., C. S. Chern, J. Wang, and S. Y. Chao, 2004. The anomalous amplification of M2 tide in the Taiwan Strait, Geophys. Res. Lett., 31, L07308, doi:10.1029/2003/GL019373.

Mouyen M., Masson F., Hwang C., Cheng CC., Cattin R., Lee CW. , Le Moigne N., Hinderer J., Malavieille J., Bayer R., Luck B., 2009. Expected temporal Absolute Gravity change across the Taiwanese Orogen, a modeling approach, J. of Geodynamics, 48, 284-291.

Positioning System analysis. In: Byrne, T.B., Liu, C.-S. (Eds.), Geology and eophysics of An Arc-Continent Collision, Taiwan. Geological Society of America Special Paper, Boulder, CO # 358, pp. 75–92.

Torge, W., 1989. Gravimetry. De Gruyter, Berlin.

Warburton, R. J., and Goodkind, J. M., 1977. The influence of barometric pressure variations on gravity. Geophys. J. R. astr. Soc., 48, 281-292.

國科會補助專題研究計畫項下出席國際學術會議心得報告

日期： 100 年 7 月 10 日

計畫編號	NSC 99 － 2923 － M － 009 － 002 －		
計畫名稱	以絕對重力研究台灣造山運動:觀測與模式比較		
出國人員姓名	高瑞其	服務機構及職稱	國立交通大學 / 博士生
會議時間	100 年 7 月 1 日至 100 年 7 月 7 日	會議地點	澳洲 墨爾本
會議名稱	（中文） （英文） International Union of Geodesy and Geophysics		
發表論文題目	（中文） （英文）Taiwanese Orogeny From Absolute Gravimetry and GPS: Comparison of observation and model		

一、參加會議經過

二、與會心得

三、考察參觀活動(無是項活動者略)

四、建議

五、攜回資料名稱及內容

六、其他

一、參加會議經過

由於 IUGG 是由國際冰凍圈科學學會(International Association of Cryospheric Sciences, IACS)、國際大地測量學會(International Association of Geodesy, IAG)、國際地磁及高空物理學會(International Association of Geomagnetism and Aeronomy, IAGA)、國際水文地質學會(International Association of Hydrological Sciences, IAHS)、國際氣象及大氣物理學會(International Association of Meteorology and Atmospheric Sciences, IAMAS)、國際海洋物理科學會(International Association for the Physical Sciences of the Ocean, IAPSO)、國際地震及地球內部物理學會(International Association of Seismology and Physics of the Earth's Interior, IASPEI)及國際火山及地球內部化學會 International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)等八個國際組織所共同舉辦，參加了這四年一次的 IUGG，除了聽了很多場次的相關重力研究，增長了見識外，最重要的是認識很多位重量級的重力專家，像是 BIPM 的 Dr. Zhiheng Jiang，全球超導重力組織的執行長 Prof. David Corssley 及全球重力資料中心負責人 Prof. Jean-Pierre Barriot 等，其中 Prof. Jean-Pierre Barriot 會在 8 月到台灣參加 AOGS，他還會抽空到新竹的國家重力基準站來互相交流，及討論未來幾年大溪地空載重力之合作方案。

二、與會心得

IAG 的副主席 Mike Bevis，則到會場跟所有與會國致詞，他首先感謝 GGP 所有會員國針對國際災難發生時，所提供的第一手觀測數據，這對 IAG 的科學家提供一個可靠又有用的資料來源，後來又提到 IAG 已經由過去理論模式所建構的地球，進步到即時性變化的地球模式，所依據的都是各種觀測的儀器，對於整個地球框架座標的解算，在加入全球超導的成果，將可提昇長期的趨勢變化，而超導的可貴之處在於目前已經有長期及穩定的數據，重力成果的重要性已開始浮現。

另一個比較重要的題目是討論未來大地測量的基準，也就是將量測座標的儀器像是雷射測距儀(Satellite Laser Ranging, SLR)，超長基線干涉測量技術(Very Long Baseline Interferometry, VLBI)，全球導航衛星系統(Global Navigation Satellite System, GNSS)，無線電定位系統(Doppler Orbitography and Radiopositioning Integrated by Satellite, DORIS)及基礎測量設備所組成之系統，由 Golbal Geodetic Observing System (GGOS)所主導來整合全球定位資訊之組織，目前國內太空中心已經預計在福衛七號上加裝 SLR 的反射鏡，交通大學黃金維教授邀請哈佛-史密森天體物理中心(Harvard-Smithsonian Center for Astrophysics) 的副主席 Michael Pearlman，在 AOGS 開會期間(8/8-8/12,2011)至合歡山挑選 SLR 合適的地點，本人也將一同前往及討論未來是否有合作之機會。

超導重力儀則主要是屬於國際大地測量學會底下的全球地體動力學計畫(Global Geodynamics Project, GGP)所規定的儀器，也只有擁有超導重力儀才能參加此一組織，GGP 在此次會議特別召集了所有會員國在七月二日下午 1:30-15:00 共同討論本組織目前環境及未來的走向

三、考察參觀活動(無是項活動者略)

略

四、建議

此次會議所達成的共識為：

1. 資料中心由 Information System and Data Center (ISDC)及 International Center of Earth Tides (ICET)共同保存。

2. 各會員國提供絕對重力資料至 ISDC 保存，印度則因為國內因素將等解禁後才上傳。

3. GGP 從 2007 年完成 IAG 第二階段的重力場任務後，目前所執行 IAG 第三階段-地球自轉及地體動力計畫，並持續提供成果及數據。

4. 超導重力未來扮演全球重力基準之角色，最重要是數據即時性及正確性，有效提昇與會國的處理能力是目前最重要的課題。

五、攜回資料名稱及內容

論文摘要集光碟片 GGP、GGOS，IAG, NOAA 等研究成果書面及光碟片數份、其他論文宣讀及海報投影片十餘份等。

六、其他

略

IUGG 接受函

From: IUGG Presenters [mailto:IUGG2011presenters@arinex.com.au]

Sent: Monday, March 28, 2011 11:40 PM

To: 'Cheinway Hwang'

Subject: IUGG 2011 - Oral Acceptance Letter

Ref: 4475

Mr Ricky Kao
National Chiao Tung University
2f., No.539-3, Sec. 2, Jingguo Rd., North Dist.
Hsinchu TAIWAN 300
TAIWAN

Dear Mr Ricky Kao,

IUGG 2011 General Assembly

Earth on the Edge: Science for a Sustainable Planet

28 June - 7 July 2011

Melbourne, Australia

ACCEPTANCE FOR PRESENTATION

On behalf of the Scientific Program Committee we have great pleasure in confirming your abstract(s) (details below) has been accepted for an Oral Presentation at the IUGG 2011 General Assembly, in Melbourne from 28 June - 7 July 2011.

The details of your presentation are as follows:

Abstract Title:	The orogeny of Taiwan from Absolute Gravimetry and GPS: observation and model
Abstract Number:	5595.00
Symposia Sub-theme::	JG04
Presentation Type:	Poster Presentation
Session Details:	Will be confirmed to you in due course

Please advise your fellow co-authors the above abstract has been accepted.

Registration Information

All presenters are expected to register by 11 April 2011, the Early Bird Registration deadline, to guarantee their inclusion in the program and to take advantage of the early-bird registration rate. Payment of the registration fee should also be made at this time. Payment of the registration fee after this date will attract the higher standard registration fee.

If you have not already registered, please ensure your registration is linked with your abstract account, using your existing personal record - click here

Note this registration form is only for use by the submitting/presenting author and offers registration rates minus the A$30 author deposit. Please ensure you register by 11 April 2011.

Grant Applications

Notification relating to Grant Applications (Registrations, Travel Expenses, Food and Lodging) will be communicated separately by the Local Organising Committee. Those awaiting acceptance for registration, will receive further details on how to complete their waived registration.

Presenting and Co-Author Information

If you are not the presenting author for the above abstract, please notify us by email quoting your abstract number and the reference codes as per above.

The Speaker Zone has been re-opened to allow you to check and edit the author listing for the above abstract submission. It is the responsibility of the submitting/presenting author for the accuracy of the information provided on co-authors and affiliations. The Scientific Program Committee, Local Organising Committee and the Assembly Managers do not take responsibility for this when published.

Please click here and enter your access key (EWZX7HN8K) in the field provided.

Please note you are unable to edit any other areas of your abstract as it has already been accepted. If you need to amend any other areas please email us.

Important Information

The Committee is in the process of finalising the program sessions and a preliminary program (outlining the dates for symposia sessions only) will be available 8 April 2011.

The details of your presentation including the date you will be presenting, length of presentation, time of your presentation, along with briefing notes and details on how to submit your PowerPoint presentations will be provided on 26 April 2011.

Should the release of the program affect your registration or participation, please contact the General Assembly Managers (iugg2011presenters@arinex.com.au).

Attention International Presenters

Please use this letter to apply for grants or when applying for an Australian Visa for travel. It is highly recommended that you apply for your Australian Travel VISA as soon as possible.

An online ‘Letter of Invitation’ can be completed with your details here. Please visit the IUGG 2011 website for further visa information.

Please be aware it may take up to 6-8 weeks for visas to be processed.

If you have any questions regarding your acceptance please do not hesitate to contact the IUGG 2011 General Assembly Program Managers.

The support you have shown for IUGG 2011 is greatly appreciated and we look forward to your involvement in the Scientific Program.

Kind regards

IUGG 2011 General Assembly Managers

Phone: +61 3 9417 0888

Email iugg2011presenters@arinex.com.au

Website www.iugg2011.com

所發表之論文

IUGG
MELBOURNE Australia 2011
Earth on the Edge: Science for a Sustainable Planet
28 June – 7 July 2011

Taiwanese Orogeny From Absolute Gravimetry and GPS: Comparison of observation and model

R. Kao[1,2], C. Hwang[1], C.-W. Lee[2], F. Masson[4], R. Bayer[5], J.-F. Huang[3], W.-C. Hsieh[2], N. Le Moigne[5], M. Mouyen[4], C.-C. Cheng[1], M.-H. Peng[2]
[1]*Department of Civil Engineering, National Chiao Tung University, Hsinchu, Taiwan;*
[2] *Dimensional Measurement Laboratory, Measurement Standards and Technology Division, CMS, ITRI, Hsinchu, Taiwan;*
[3] *Ministry of the Interior, Taipei, Taiwan;*
[4] *Institut de Physique du Globe de Strasbourg, Strasbourg, France;*
[5] *Géosciences Montpellier, Université Montpellier 2, Montpellier, France*

1. Introduction

Taiwan is located at the converging zone of the Eurasia and the Philippine Sea Plate and moves northwestwards at a rate of 7 cm/year (Figure 1 left). Such a plate motion creates vertical displacements and mass changes that can be detected by repeat gravimeter and GPS measurements. Ten sites which along a East-West transect crossing the south part of Taiwan have been defined for absolute gravity (AG) measurements (Figure 1 right). In collaboration with a French team led by Frederic Masson, this project aims to study Taiwanese Orogeny using gravimetry and GPS, taking advantage of the gravimetry facility provided by the Ministry of the Interior in southern Taiwan and Hsinchu. We develop models accounting for such gravity variations as solid earth tide, ocean loading, hydrological and atmospheric effects from Superconducting gravimeter. These models can help us to detect the effect of environment change. Due to large rainfall and oceanic and seismic effects, temporal gravity variations in Taiwan are significant, and aliased into the gravity signal of orogeny and must be removed.

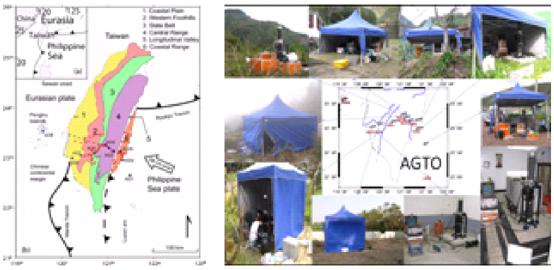

Figure 1: (Left-a) Global location and plate tectonic settings, (Left-b) general geology of Taiwan after Ho (1986) and Hickman et al. (2002). The nine sites for absolute gravity measurements of the AGTO project, from AG1 to AG9, are represented (blue dots) with also the 45 sites defined for relative gravity measurements network (red dots). Our 2D modeling study is performed along the dashed line. (Right) Ten pictures show the location and situation for AG sites (circle) , another are GPS sites (star)

2. Observation by absolute gravimetry of AGTO

The absolute gravimetry (AG) is repeated every year (2006-2010), using Taiwanese (#224) and French (#228) FG5 gravimeters. Because the ten AG sites and GPS sites are built along the southern cross-island highway (Table 1), the Table 2 describe the gravity changes and the trend of each site. Figure 2 shows the height of ten AG sites . Large gravity jumps at AG3 (53μGal) and AG6 (27μGal) between 2008 and 2009 occurred, and were caused by Typhoon Morakot (day of landfall is August 8). These jumps make the gravity trends become positive. AG5 (Yakou) is disappear after Typhoon Morakot, and we cannot rebuilt it at the same location. We prefer to rebuilt a concrete pillar at Tienchih where is near the Yakou. AG3 is located in the mountain, and the gravity change should show a trend similar to AG4 and AG5, but the result turns out to be different (Fig. 7-6). AG8 is in Tainan city, the background noise is large, it is worth continuing to explore the reasons for observation.

Table 1: Location of AG1 to AG9 in geographic coordinates

AG	Location (Lat, Lon)	GPS	Location (Lat, Lon)
AG1	[illegible]	LAND	[illegible]
AG2a	[illegible]	TUNH	[illegible]
AG2b	[illegible]	TAPO	[illegible]
AG3	[illegible]	WULI	[illegible]
AG4	[illegible]	MSTN	[illegible]
AG5	[illegible]	TENC	[illegible]
AG6	[illegible]	FACL	[illegible]
AG7	[illegible]	LNCH	[illegible]
AG8	[illegible]	CK01	[illegible]
AG9	[illegible]	FANG	[illegible]

Table 2: AG gravity values from AGTO are relative to 2006

Site	2006 (μGal)	2007 (μGal)	2008 (μGal)	2009 (μGal)	2010 (μGal)
AG1	0	6.12	1.58	-2.6	-0.23
AG2a	0	3.11	-0.64	-1.68	4.01
AG2b	0	2.47	-1.17	-7.74	-2.37
AG3	0	-2.1	-14.44	38.32	61.21
AG4	0	-0.77	2.52	-0.86	1.52
AG5	0	-0.34	1.84	--(broken)	--
AG6	0	1.40	2.53	30.01	27.60
AG7	0	3.44	-1.79	-0.30	-2.9
AG8	0	-12.87	-7.84	-12.02	-5.58
AG9	--(rebuild)	0	-1.61	-4.42	-0.38

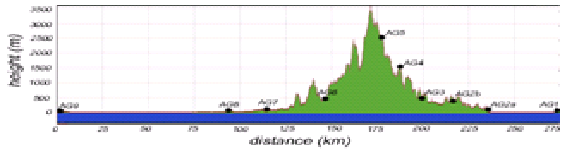

Figure 2: AG1 and AG9 are out of the Taiwan island. AG2a to AG8 are built along the southern cross-island highway. We will rebuilt a concrete pillar at Tienchih to replace AG5 which is disappear after Typhoon Morakot.

3. Vertical displacements by continuous GPS measurements

The tectonic motions create vertical displacements and mass changes that may be detected by GPS measurements and repeated gravimetry. Taiwan has 313 GPS tracking stations (Figure 3) maintain by the Ministry of the Interior, Academia Sinica, Central Weather Bureau and Central Geological Survey. This project considers the feasibility of establishing a system for continuously GPS receivers compare with 27 AG records (Figure 4, include AGTO) in Taiwan.

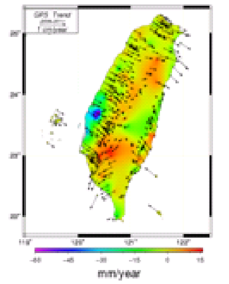

Figure 3: Horizontal velocities (vectors, scale is in the upper left corner) and vertical velocities (color scale) based on continuous GPS records over 4/2006-3/2011

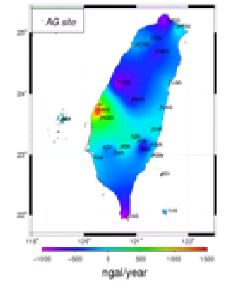

Figure 4: The trend of 27 AG changes in Taiwan. It shows the gravity change in southern is bigger than northern in Taiwan.

4. Effect of Typhoon Morakot

A typhoon is an extremely low pressure system with abundant precipitating waters on the surface and in the air. Typhoon Morakot hit the southeast of Taiwan, and bring amounts of rainfall during 5-8 August, 2009 (Figure 5). Typhoon Morakot brought mudflow and it caused 53 μGal changed in AG3 and 27 μGal changed in AG6. Typhoon Morakot caused large landslides that led to AG5 was gone after 2009. If we want to see the information from table 2, we need to separate the table into two specified time (2006 to 2008 and 2009 to 2010). Collecting the Formosat-2 images (Figure 6) before and after Typhoon Morakot was detected analysis to identify gravity change.

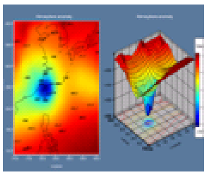

Figure 5: Typhoon Morakot with low pressure and abundant waters attack Taiwan during 5-8 August, 2009 .

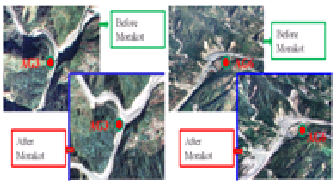

Figure 6: With river sediment data and satellite image from Formosat-2 before and after Morakot, such gravity changes were modeled.

5. Conclusion

GPS and gravimetric measurements collected in AGTO are useful tools to comparison vertical movements and mass transfers (Table 3). The final result of gravity change(-1.39μGal/year) which is consistent with the trend of GPS(0.63 cm/year). The absolute gravity measurements and GPS measurements have a strong interest to precisely separate mass transfer effects and elevation changes to support this project. After Typhoon Morakot, the soil erosion by the river is a serious problem, it raise the gravity (Figure 7). As the excavator continuous mining, so that the gravity does not increase in AG6. This project is a strong proof for us to continuous measure in the future.

Table 3: Comparison with the trend of AG and GPS, the trend of AG3 and AG6 are removed 2009 and 2010

Site (AG/GPS)	Gravity trend (μGal/year⁻¹)	GPS trend (cm/year⁻¹)
AG1/LAND	-0.92	0.06
AG2a/TUNH	0.32	0.27
AG2b/TAPO	-2.39	1.32
AG3/WULI	-7.21	0.84
AG4/MSTN	-0.36	0.28
AG5/TENC	0.57	0.16
AG6/FACL	1.46	1.16
AG7/LNCH	-2.41	1.06
AG8/CK01	-2.32	0.44
AG9/FANG	-0.33	-0.01
AVERAGE	-1.39	0.63

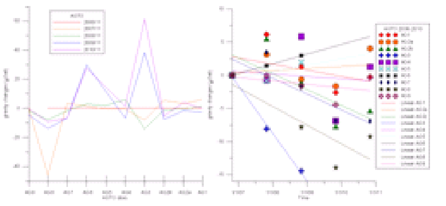

Figure 7: It shows gravity changes for each AG sites (left). Comparison of table 3, it shows the trend of each AG sites in different year (right), the trend of AG3 and AG6 are removed 2009 and 2010.

國科會補助計畫衍生研發成果推廣資料表

日期:2011/10/19

國科會補助計畫	計畫名稱: 以絕對重力研究台灣造山運動:觀測與模式比較
	計畫主持人: 黃金維
	計畫編號: 99-2923-M-009-002- 學門領域: 測地學和重磁學

無研發成果推廣資料

99年度專題研究計畫研究成果彙整表

面故事...等）

屆測量及空間資

以絕對重力研究台灣造山

方主寫 3 篇(1 篇已接收,2 篇審核中)

篇研討會論文

法屬大溪地大學(Universite de la Polynesie Francaise)將提供先進超導重力數據軟體

名稱或內容性質簡述

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

□實驗失敗

□因故實驗中斷

□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

本計畫為台法合作計畫,在重力測量方面能夠藉由實際觀測的合作模式,了解國際最先進的儀器操作及分析處理方式,參與的人員對於全世界中屬於造山運動劇烈的台灣,本計畫的成果除了可提供分析板塊擠壓造成台灣獨特地理景觀的成因外,對於人才的培養及技術的提昇有著極重要的幫助。本計畫從 2006 年開始至目前已經發表及正在審核中的國際期刊已達 7 篇,參加國際學術研討會之文章也有 22 篇,未來在經費許可的情形下,將持續觀測及研究,另外本計畫所涉及的領域包含地球科學、地質、大氣、水文、海洋及測量,台灣目前包含台灣、中央、交通、成功、台北及中正等大學,已經有興趣的教授及學生,共同組成研究團隊分享彼此的研究成果,未來還進一步對於大屯火山及雲林地層下陷等問題貢獻心力。