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Tidal strain observations in Chu-Chie, Taiwan

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Abstract

In Chu-Chie, Taiwan, tidal strain observation with a borehole strainmeter system has been carried out since 2001. The Chu-Chie station (N23°31′39″, E120°35′59″, $h = 300$ m) is located in the central part of Taiwan and is about 40 km distant from the epicenter of the destructive Chi-Chi earthquake ($M_L = 7.3$) which occurred on September 21, 1999. The strainmeter system detects three components of horizontal strains in 82°, 202° and 322° measured from the North in clockwise directions using differential transformers. We analyzed tidal strains and determined amplitudes and phase lags of 13 major constituents by applying the tidal-analysis program **BAYTAP-G** to 1-year strain data of 2003. The "observed" tidal strain amplitudes were compared with the "theoretically expected" amplitudes that were obtained from the **GOTIC2** program. As a result, the ratio of the observed amplitudes and the theoretically expected amplitudes ranges between 0.7 and 3.3. Some parts of these discrepancies may be caused by uncertainty of determination of scale factors of instruments. Other reasons to be considered are complicated geological and topographic effects around the observation site.

Keywords: Crustal strain; Tidal strain; Borehole strainmeter; 1999 Chi-Chi earthquake; Taiwan

1. Introduction

The main island of Taiwan is located at the corner of the Manila Trench and Ryukyu Trench on a convergent plate boundary between the Eurasian plate and the Philippine Sea plate. The present convergence rate in Taiwan is estimated to be 7.4 cm/year in the northwest direction (Seno, 1994). Several large thrust faults extend in the direction of NNE–SSW. Faults on the western side of the island tend to dip toward the east (Fig. 1).

Faults along the eastern seaboard tend to dip toward the west. Many large earthquakes have occurred in and around Taiwan. In 20th century, five earthquakes greater than $M_L = 7$ occurred in Taiwan in 1906, 1935, 1941, 1951 and 1959 before the occurrence of the destructive Chi-Chi earthquake ($M_L = 7.3$, $M_w = 7.6$) that occurred on September 21, 1999,

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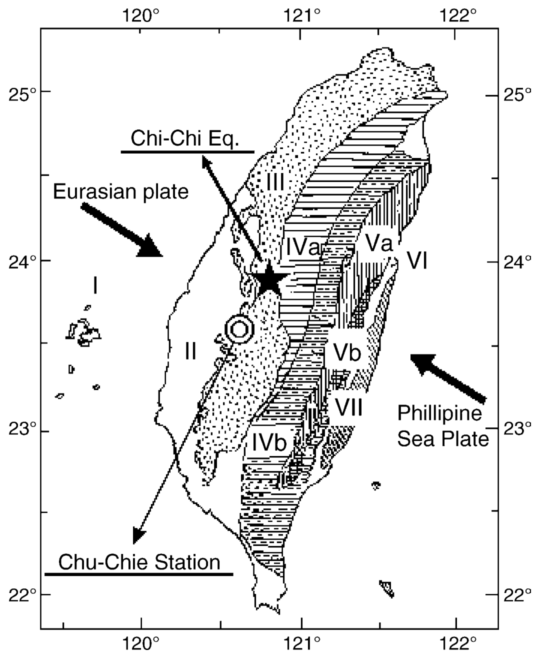

Fig. 1. Geologic provinces of Taiwan and relative positions of the epicenter of the 1999 Chi-Chi earthquake and the Chu-Chie station. (I) Penghu islands, (II) Coastal Plain, (III) Western foothills province, (IV) Western Central Range belt, (IVa) Western Hsuehshan Range belt, (IVb) Eastern Backbone Ridge belt, (V) Eastern Central Range belt, (Va) Western Tailuko belt, (Vb) Eastern Yuli belt, (VI) Taitung Longitudinal Valley and (VII) Eastern Coastal Range.

at 1:47 a.m. (local time) along the Chelungpu thrust fault. The epicenter of the earthquake was located near Chi-Chi (N23°51′, E120°48′) at the depth of 7 km.

The 1999 Chi-Chi earthquake can be regarded as a subduction zone earthquake in a tectonic sense (Seno et al., 2000). The direction of the earthquake slip vector is consistent with slip directions of the surface faults mostly in NW–SE. At the northwest corner of the earthquake fault, significant uplifts and multiple thrusts in the river bed occurred. These might all be related to the fact that the shallow portion of the earthquake fault cut the weak accretionary prism and the sediment on it.

In 2001, the Central Geological Survey of Taiwan installed a borehole strainmeter system together with velocity type seismometers (velocity meters), accelerometers and a thermometer as well as a water level meter at the Chu-Chie station (Fig. 2). The station (N23°31′39″, E120°35′59″, $h = 300$ m) is located in the central part of Taiwan and is about 40 km distant from the epicenter of the 1999 Chi-Chi earthquake. Relative positions of the station and the epicenter of the Chi-Chi earthquake are also shown in Fig. 1.

In this paper, we first report tidal strain analysis based on 1-year data of 2003 obtained from the borehole strainmeter system in Chu-Chie, Taiwan.

2. Observation system

The borehole strainmeter system which is used in the Chu-Chie station was developed by Sakata and Sato (1986) and manufactured by the AKASHI Corporation, Japan. The fundamental idea of the strainmeter is similar to that of the Sacks–Evertson strainmeter that detects volume strain changes of a cylinder in a borehole by means of a magnetic sensor (Sacks et al., 1971). Sakata and co-workers in National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan improved the Sacks–Evertson strainmeter to be able to detect three-component crustal strains independently by dividing the cylinder filled with oil into three parts. The outside of the borehole strainmeter system is covered by the SUS 316L stainless steel pipe with 1500 mm in length, 114.3 mm in outer diameter with the thickness of 3 mm, inside of which is filled with about 5 l of oil with viscosity of 10 cst. The detector unit of equipment

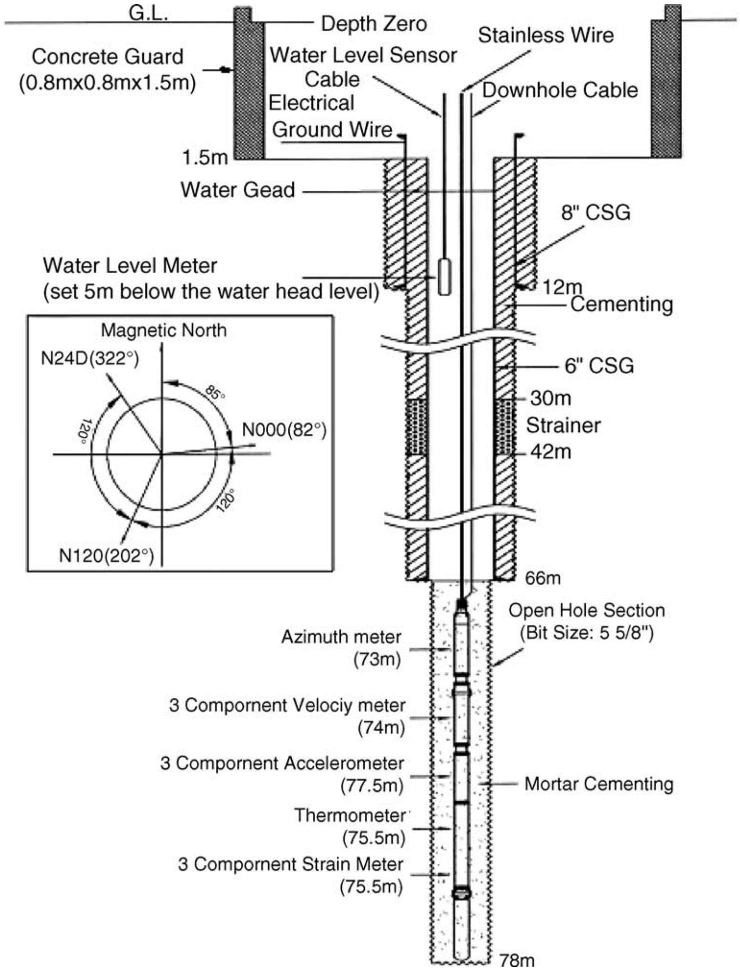

Fig. 2. Borehole measurement system of the Chu-Chie station.

consists of a dual cylinder, the inside of which is equally divided into three independent blocks of every 120° by rigid partition walls. Each block is filled with silicon oil connected to its own bellows with a pipe. The up-and-down movements of the three independent bellows are detected by the differential transformers with the excitation frequency of 4 kHz. Dynamic range of strain measurement is 10^{-11} to 10^{-3}.

As shown in Fig. 2, the system consisting of three component horizontal strainmeters (N000, N120 and N240) was installed in the borehole at the depth of 77 m from the surface at the Chu-Chie station. Azimuths of three components are 82° (N000), 202° (N120) and 322° (N240), respectively, measured from the North in clockwise directions. The azimuth of each sensor was decided by measuring a magnetic azimuth based on the direction of terrestrial magnetism with the azimuth meter of the flux gate type after equipment was set up. As shown in Fig. 2, the azimuth meter is equipped in the borehole measurement system. The geodetic azimuth was then decided using the magnetic azimuth.

Output signals from sensors in the borehole are provided to the MS1000 data acquisition system installed in the observation hut (Fig. 3). In the MS1000 system manufactured by the JGI, Inc., each strain signal is divided into long-period component (LP) and short-period component (SP). Frequency characteristics are DC to 0.33 Hz (−12 dB/OCT) in LP and 0.00056 Hz (−6 dB/OCT) to 0.1 Hz (−12 dB/OCT) in SP, respectively. In tidal analysis, we used LP comportments with the sensitivity of $2.5 \times 10^{-7}\ V^{-1}$. The clock of MS1000 is controlled by a GPS receiver. Strain and environmental monitoring data are sent to the Central Geological Survey in Taipei area through the public telephone line.

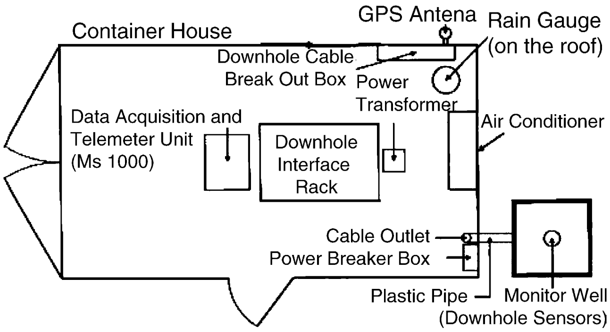

Fig. 3. Observation hut of the Chu-Chie station.

3. Tidal analysis

Fig. 4 shows an example of observed strain changes together with changes of water level, barometric pressure and borehole temperature as well as precipitation for a month (January 18–February 17, 2003). In this figure, we can recognize that tidal strain changes observed with the N240 component is most significant compared with other two components (N000 and N120). The rainfall of the order of 20 mm/day does not directly affect on groundwater level and strain changes.

Next, we analyzed tidal strains by applying the **BAYTAP-G** program (Tamura et al., 1991) to 1-year data of 2003 obtained from three components (N000, N120 and N240) of the borehole strainmeter system. Results are shown in Fig. 5, in which the mark "A" is original data, "B" is tidal changes, "C" is response to barometric and temperature changes and "D" is trend, respectively. Original raw data "A" contains many spikes and steps. We removed these spikes and steps manually before the tidal analysis using the **BAYTAP-G** program.

As shown in "B", tidal change observed with the N240 component is most remarkable compared with these observed with N000 and N120 components. The peak-to-peak amplitude of tidal change of N240 reaches 2×10^{-7}. On the other hand, those of N000 and N120 are about 8×10^{-8} and 4×10^{-8}, respectively.

We thus compared "observed (O)" tidal strain amplitudes with the "theoretically expected (E)" amplitudes that were obtained from the **GOTIC2** program for computation of the oceanic tidal loading effect (Matsumoto et al., 2001). Fig. 6 shows comparisons of O and E of 13 major constituents of tidal strains. In each component, the ratio of "O" and "E" is systematic. We previously mentioned that apparent tidal strains observed with the N240 component are most significant. This is reasonable because the loading effects of ocean tides for semi-diurnal tides in the azimuth of 322° have almost the same amplitudes and phases as those of solid Earth tides. Therefore, "expected" tidal amplitudes in this direction have almost twice the amplitudes expected from the solid Earth tides only.

Table 1 shows comparison of "O" and "E" of O1 and M2 constituents. The ratios of "O" and "E" for the N000 component are remarkably different between diurnal and semi-diurnal tides, i.e. 1.76 for O1 and 3.29 for M2, respectively.

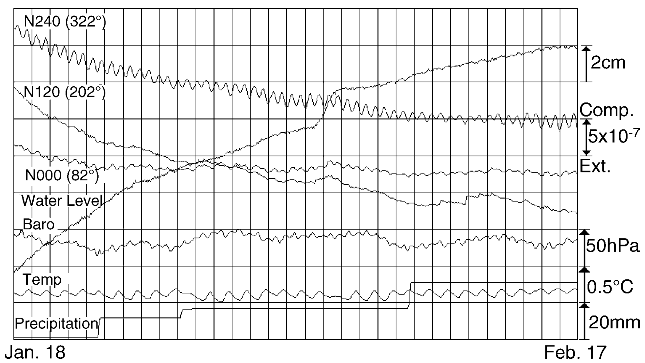

Fig. 4. Example of records of three components of strains (N000, N120 and N240), water level, barometric pressure (Baro), temperature (Temp) and precipitation for a 1 month from January 18 to February 17, 2003. "Comp." is compression and "Ext." is extension.

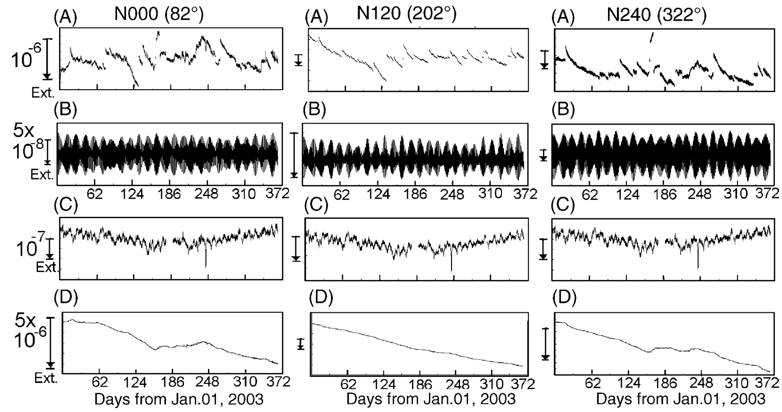

Fig. 5. Result of tidal analysis of three components of strains (N000, N120 and N240) obtained by applying the BAYTAP-G program to 1-year data of 2003. (A) Original, (B) tidal components, (C) response for barometric and temperature changes and (D) trends.

On the other hand, such a difference cannot be seen in N120 and N240 components, though the former (N120) is relatively small (0.86–0.71) and the latter (N240) is large (2.78–2.59). These discrepancies may be caused by uncertainty of determination of scale factors of instruments as well as topographic and geological effects.

Fig. 7 shows the comparison of observed and expected phases of 13 major constituents. As mentioned previously, the ratios of "observed" and "theoretically expected" tidal amplitudes are different for diurnal and semi-diurnal tides in the N000 component. With regard to phase characteristics of this component, observed phases and theoretically expected ones are almost consistent for diurnal tides but observed phases lead expected values for semi-diurnal tides.

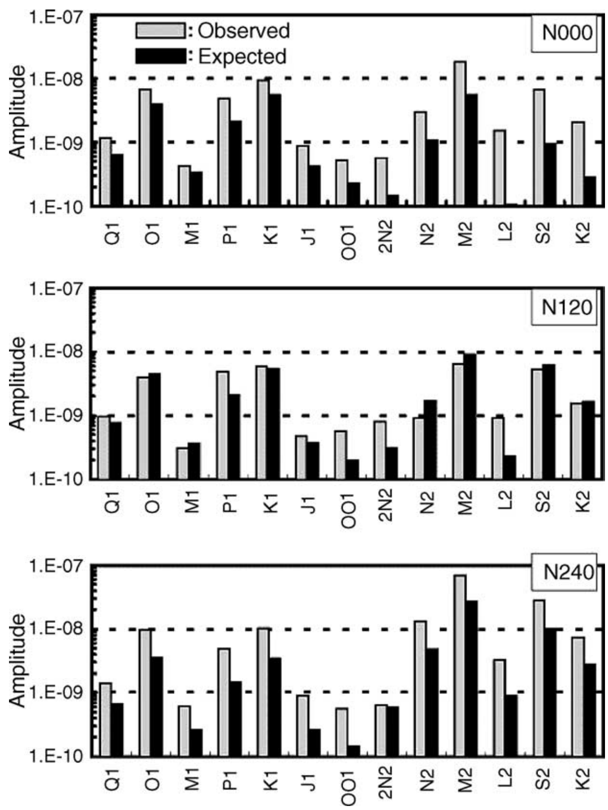

Fig. 6. Comparison of observed and theoretically expected tidal strain amplitudes of 13 constituents. Left (bright): observed and right (dark): theoretically expected.

Table 1
Comparison of "observed (O)" and "expected (E)" amplitudes of O1 and M2 constituents

Component (direction)	Constituents	Observed (O) ($\times 10^{-9}$)	Expected (E) ($\times 10^{-9}$)	O/E
N000 (82°)	O1	6.85	3.89	1.76
	M2	18.3	5.56	3.29
N120 (202°)	O1	3.93	4.56	0.86
	M2	6.41	9.04	0.71
N240 (322°)	O1	9.87	3.55	2.78
	M2	70.5	27.2	2.59

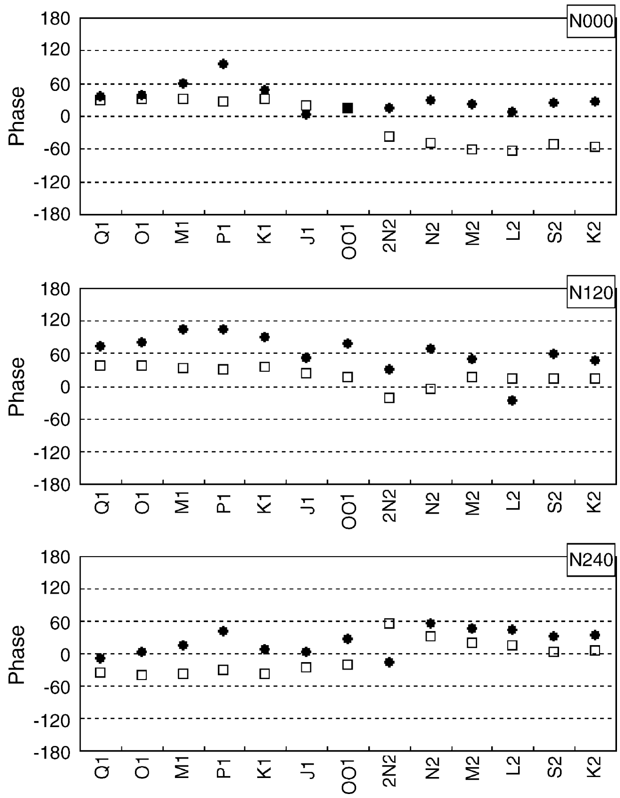

Fig. 7. Comparison of observed and theoretically expected phases of 13 constituents (dark circle: observed, square: theoretically expected).

In N120 and N240, however, observed phases lead expected ones in both diurnal and semi-diurnal tides. These phase differences also may be caused by topographic and geological effects.

4. Discussion and concluding remarks

We analyzed tidal strains observed with the borehole strainmeter system consisting of three component horizontal strainmeters in the Chu-Chie station, Taiwan. As a result, some interesting systematic features of strain tides were found out. (1) The ratio of "observed" and "theoretically expected" tidal amplitudes is systematic and acceptable. In detail, however, it not only differs between components but is also different between diurnal and semi-diurnal tides. (2) Phase lags also show different characteristics according to the component and to diurnal and semi-diurnal tides. Some parts of these discrepancies may be caused by uncertainty of determination of scale factors of instruments. Calibrations of instruments are made by heating up the cylinder filled with oil by a nichrome wire. Displacements of differential transformers caused by the volume change of the heated cylinder are compared with the current added to the nichrome wire. It can be considered that determination of scale factors by this method will have uncertainty of at least 30%. We cannot explain, however, all discrepancies between observed and expected tides by insufficiently accurate determination of scale factors of instruments.

Other reasons to be considered are complicated geological and topographic effects around the observation site. In order to explain these characteristics, it is necessary to estimate effects of local inhomogeneities around the observation site, such as topographic and geological effects by means of the finite element method. However, this approach is not so easy because the topographic and geological features around the observation site are complicated. Topography within several hundred meters is characterized by a small valley in N–S direction in the west side of the station, but in the wider area within 5 km, mountainous geographical features in the NE direction are dominant. Geological features around the observation site are mainly characterized by muddy sandstone, alternation of sandstone and shale, and tectonically separated by Shuisheliao fault in NWW–SEE and Sinkuping fault in NE–SW. In spite of these complicated circumstances, we will examine topographic and geological effects by means of finite element calculations.

Other results obtained from this study are as follows. Responses of strain changes to barometric pressure and borehole temperature changes ("C" in Fig. 5) are about 1×10^{-7} in all components (N000, N120 and N240). Long-term trends ("D" in Fig. 5) show extension in all components. These tendencies are consistent with decrease of underground water level, though the water level has tentatively increased during 1 month shown in Fig. 4. Extensions of 4×10^{-6}, 2×10^{-5} and 8×10^{-6} year^{-1} for N000, N120 and N240, respectively, were observed according to decreasing of water level of 2.5 m/year in 2003.

We are expecting that basic studies of strain data at the Chu-Chie station including tidal analysis and investigation of environmental effects, such as caused by groundwater level changes, will contribute to search for anomalous strain changes before the next destructive earthquake which may occur in the central part of Taiwan.

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