Earth Tide Observation by Borehole Strainmeters and Extensometers in Tohoku District, Japan

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Earth Tide Observation by Borehole Strainmeters and Extensometers in Tohoku District, Japan

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Abstract: A study is made of the temporal variations of M_2 constituent in the strain earth tides. The strain data observed by extensometers and borehole strainmeters in Tohoku district, Japan, are analyzed by using the tidal analysis program BAYTAP-G. No significant amplitude changes that may be related to the crustal response to a change in tectonic stresses are found out for the observation period under consideration. The observed temporal variation of volumetric strain is different from that of dilatational strain because of the different effects of weather phenomena such as atmospheric changes and rainfall. The M_2 amplitudes obtained from the observed data by extensometers and borehole strainmeters are significantly smaller than those computed by the theory of earth tides. In the case of the data obtained by extensometers, however, the consistency between the observed and the theoretical amplitudes, which include both the solid and the ocean load tides computed by the program GOTIC, is improved by taking the cavity and topographic effects into account. In comparison with the amplitude result, the observed phases are satisfactorily consistent with the theoretical ones, though the formers are slightly in advance of the latters.

1. Introduction

The dilatancy model was proposed by Nur (1972) and Scholz *et al.* (1973) in order to explain a decrease in V_p/V_s ratio before occurrence of an earthquake, where V_p and V_s are P and S wave velocities, respectively. The elastic constants in a dilatant zone are different from those in the surrounding normal zone. Beaumont and Berger (1974) indicated by using a finite element method that the amplitude of the strain earth tides increases by 40% in the dilatant zone with a decrease of 15% in P wave velocity. Tanaka and Kato (1974) examined the effect of dilatancy on the earth tides in which the ocean load tides were also taken into account. In their model the changes in elastic constants are assumed to be caused in a dilatant region beneath the sea near the observation points under consideration. They estimated a decrease of 15% in amplitude of O_1 constituent at Kishu, Japan, and 8% in amplitude of M_2 constituent at Makimine, Kyushu, Japan, where Lame's constant λ in the upper crust shallower than 19 km was assumed to decrease by 30%. The effect of the dilatancy on the crustal response to the ocean load was estimated by Tanaka (1976) with a two-dimensional finite element

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method. He pointed out that the effect of dilatancy near the coastline is larger than that beneath the ocean.

The temporal variations in amplitude of the earth tides have been reported by many authors. Latynina and Rizaeva (1976) found a decrease of 6% in amplitude of M_2 constituent in the direction across a fault. Mikumo *et al.* (1977) reported that the tidal admittances averaged over all the tidal frequecies at Kamitakara and Inuyama stations were changed before the 1969 Gifu earthquake; the admittances at Kamitakara and Inuyama being increased by 15% and 10%, respectively. Shimada (1987) reported that the amplitudes and phases of M_2 and O_1 constituents were changed at Habu, Izu Oshima, Japan, prior to the 1986 Miharayama eruption. Yamauchi (1989) found abnormal changes in M_2 amplitude at Mikawa, Central Japan, which corresponded to the occurrence of three earthquakes with magnitude from 4.0 to 5.7 within 20 km from Mikawa station.

In this paper, we study the temporal variations of M_2 constituent with a period of 12.4 hours in the earth tides observed at stations operated by Tohoku University. The earth tide data obtained by extensometers are compared with those by borehole strainmeters. The difference between the theoretical and the observed earth tides is also discussed.

2. Data

Figure 1 shows the locations of stations at which both fused quartz-tube extensometers and a borehole strainmeter are installed. They are six stations named Gojome (GJM), Tazawako (TAZ), Sawauchi (SWU), Oga (OGA), Nibetsu (NIB) and Honjo (HOJ). Three components of extensometer are settled in different directions at each station. Table 1 shows the lengths and directions of extensometers, where a magnesensor is used as a displacement detector. The lengths of extensometers at HOJ are about 3 m. The

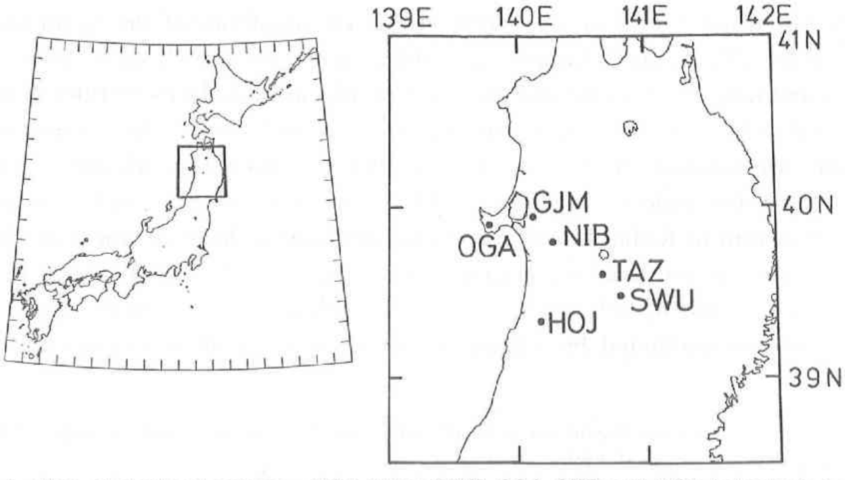

Fig. 1 Map of station locations. GJM, TAZ, SWU, OGA, NIB and HOJ indicate Gojome, Tazawako, Sawauchi, Oga, Nibetsu and Honjo, respectively.

Table 1. Directions and Lengths of Extensometers.

Station	Extensometer 1		Extensometer 2		Extensometer 3	
	Direction (N °E)	Length (m)	Direction (N °E)	Length (m)	Direction (N °E)	Length (m)
Gojome (GJM)	30.7	14.7	120.8	13.4	165.7	17.7
Tazawako (TAZ)	165.7	14.7	75.8	13.4	30.4	17.7
Sawauchi (SWU)	132.4	14.7	42.4	13.4	177.5	17.7
Oga (OGA)	140.4	26.7	50.8	23.7	5.6	29.1
Nibetsu (NIB)	23.3	25.1	111.3	24.1	67.8	27.4
Honjo (HOJ)	80.0	3.1	149.6	3.1	15.0	4.1

resolution of these short-length extensometers is not high enough to detect the amplitude of earth tides with a sufficient accuracy. We thus exclude the data of short-extensometers at HOJ from the analysis. The borehole strainmeters at GJM, TAZ and SWU are installed at depths of about 100 m and those at OGA, NIB and HOJ at depths of about 200 m (Nakao *et al.*, 1989). The instruments are of the same type as those operated by the Japan Meteorological Agency (Suyehiro, 1979).

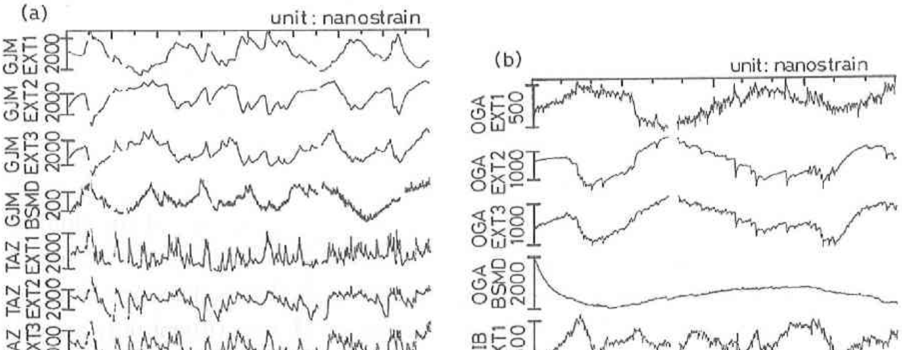

Fig. 2 Linear (EXT1, EXT2 and EXT3) and volumetric (BSMD) strain data. The linear and quadratic trends have been removed from the strain data. (a) The strain data observed at Gojome (GJM), Tazawako (TAZ) and Sawauchi (SWU) for the period from January 1984 to December 1987. (b) The strain data observed at Oga (OGA), Nibetsu (NIB) and Honjo (HOJ) for the period from January 1986 to December 1987.

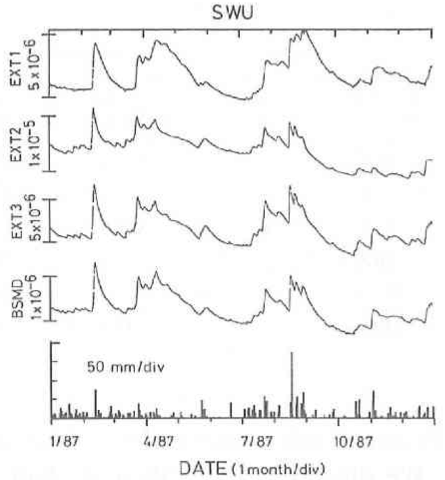

Fig. 3 Linear (EXT1, EXT2 and EXT3), volumetric (BSMD) strain data and daily rainfall observed at Sawauchi (SWU) for the period from January to December in 1987.

Figure 2 shows the volumetric strain (BSMD) and the linear strain (EXT1, EXT2 and EXT3) data observed by borehole strainmeters and extensometers, where Fig. 2(a) shows the data at GJM, TAZ and SWU from January 1984 to December 1987, and Fig. 2(b) those at OGA, NIB and HOJ from January 1986 to December 1987. The linear and quadratic trends have already been removed from the raw data of extensometers and borehole strainmeters. As the strain data observed at SWU were seriously affected by the rainfall and the spring thaw, the signal to noise ratio of the earth tides is very poor, as shown in Fig. 3. We thus exclude the strain data at SWU from the analysis.

3. Analysis and Results

The temporal variation of M_2 constituent is studied by the use of the tidal analysis program BAYTAP-G (Ishiguro *et al.*, 1981). The hourly data are analyzed successively for a time window of 30 days, whose time origin is shifted by 5 days one after another. In the present study, the amplitude and the phase lag of M_2 constituent only are discussed because of its largest theoretical amplitude among all the earth tidal constituents.

In the program BAYTAP-G, the discrete time series of observed strains (y_i) are decomposed into the form,

$$y_i = d_i + r_i + e_i, \qquad (i = 1, 2, \cdots, n) \tag{1}$$

where d_i, r_i and e_i represent the drift component, the response to the luni-solar forces including the effects of other phenomena such as atmospheric pressure changes, and the irregular components, respectively. It is assumed that d_i approximately satisfies the relations,

$$K_{2i} = d_i - 2d_{i-1} + d_{i-2} = 0 \qquad (i = 1, 2, \cdots, n) \tag{2}$$

or

$$K_{3i} = d_i - 3d_{i-1} + 3d_{i-2} - d_{i-3} = 0. \qquad (i = 1, 2, \cdots, n) \tag{3}$$

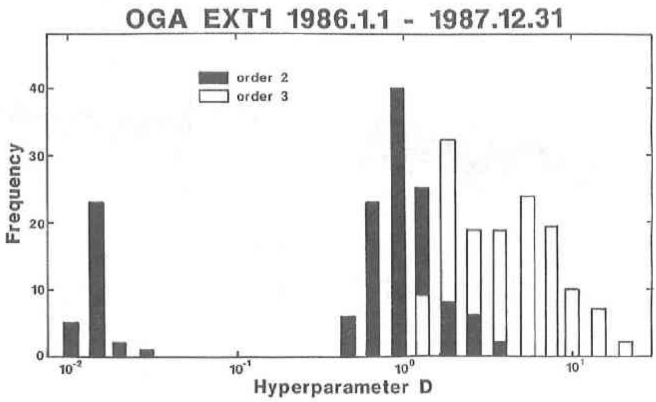

Fig. 4 The frequency distribution of the D values obtained from the observed data by an extensometer at OGA from January 1986 to December 1987. Solid rectangles are for the second-order trend model, and open rectangles for the third-order trend model.

Parameters r_i and d_i can be estimated by minimizing

$$J(a, d)=\sum_i \{|y_i-r_i-d_i|^2+D^2|K_{ji}|^2\}, \qquad (j=2 \text{ or } 3) \tag{4}$$

providing that d_0, d_{-1} and D, which are called hyperparameters, are properly chosen (Ishiguro, 1981). It is natural to expect that the hyperparameter D should be larger than

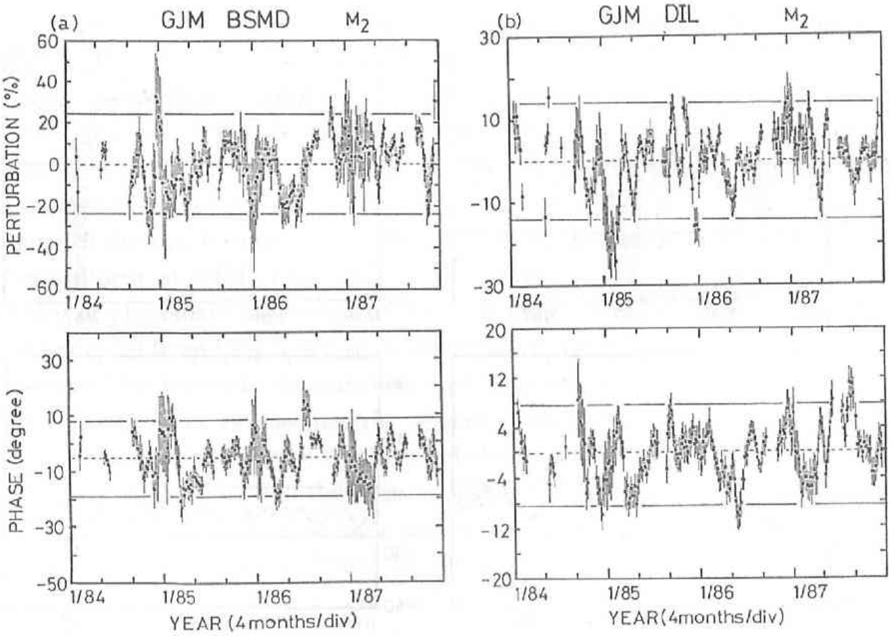

Fig. 5 (a) The amplitude perturbation and the phase variation observed by borehole strainmeter at GJM. (b) Those observed by extensometers at GJM. The results are plotted only when the number of missing observations is less than 20% of the total number.

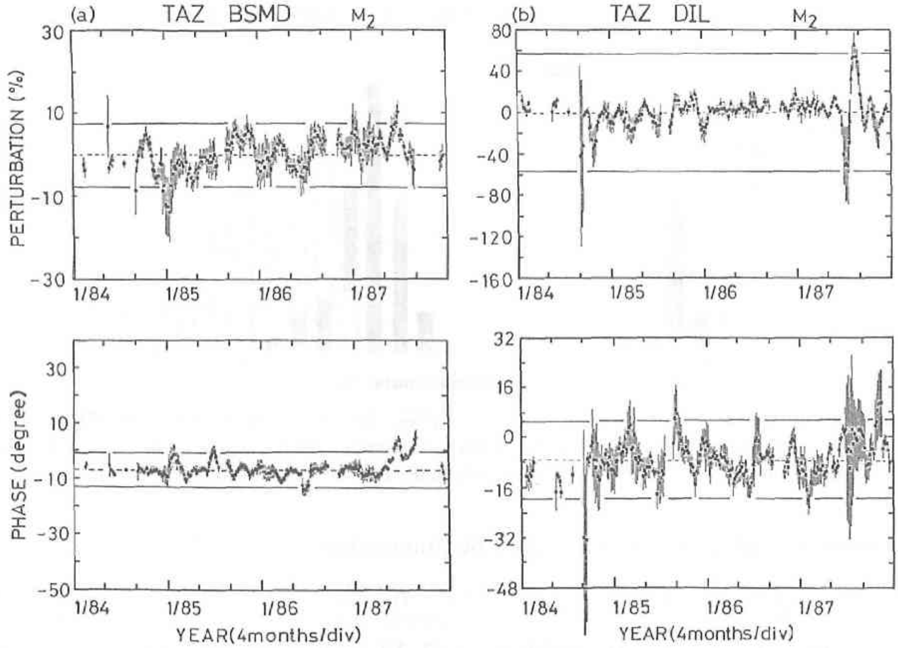

Fig. 6 (a) The amplitude perturbation and the phase variation observed by borehole strainmeter at TAZ. (b) Those observed by extensometers at TAZ.

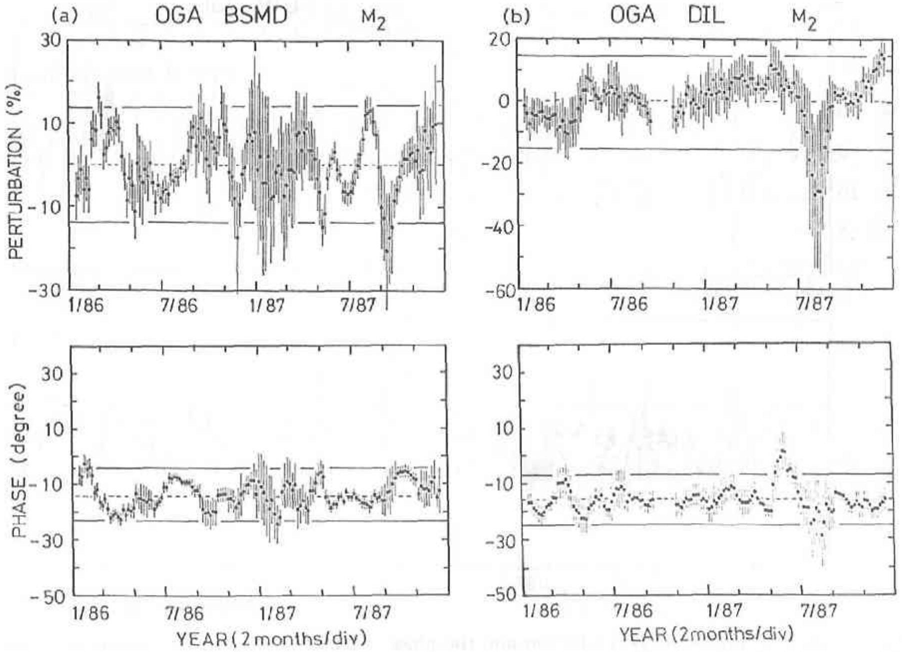

Fig. 7 (a) The amplitude perturbation and the phase variation observed by borehole strainmeter at OGA. (b) Those observed by extensometers at OGA.

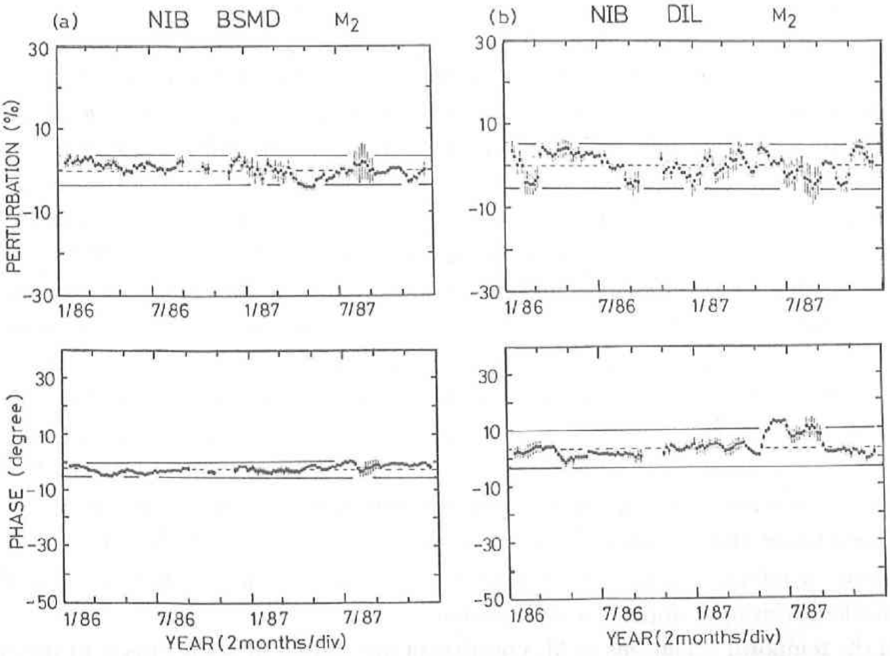

Fig. 8 (a) The amplitude perturbation and the phase variation observed by borehole strainmeter at NIB. (b) Those observed by extensometers at NIB.

unity (Akaike, 1989), bacause all the tidal components should theoretically be separated from the trend component. In practice, if we adopt (2) as a trend model, the values of D in many cases are determined to be smaller than unity, as shown in Fig. 4 in the case of the data of an extensometer (EXT1) at OGA. On the other hand, if we use (3), the values of D become lager than unity in most cases (*cf.* Fig. 4). The third order trend model expressed by (3) is thus adopted in this paper.

Figures 5 through 9 show the results of temporal variations in amplitude and phase of M_2 constituent at GJM, TAZ, OGA, NIB and HOJ, where the estimated values of amplitudes or phases are expressed by dots and their standard deviations are by error bars. Figures (a) from Figs. 5 to 8 show the temporal variations of the volumetric strain tides observed by borehole strainmeters, and Figs. (b) show those of the dilatational strain tides observed by extensometers. Figure 9 exhibits the temporal variations of the volumetric strain tides observed by the borehole strainmeter at HOJ. The top in each figure is the perturbation from the average amplitude, and the bottom the phase angle, where a negative value indicates a lag from the local potential tide. Dashed lines in each figure denote the average amplitude or the average phase, and solid lines its 95% confidence interval. BSMD and DIL indicate the data observed by borehole strainmeters, and those by extensometers, respectively. The temporal variations of DIL and BSMD at NIB (*cf*. Fig. 8) are the smallest among all the components analyzed. The deviation of DIL amplitude at OGA from its mean value is remarkable in August 1987, amounting to −30% as shown in Fig. 7(a). However, their standard deviations indicated by the error bars are also very large.

It is not easy to judge whether or not given observed data deviate significantly from its corresponding mean value. Let us consider in the present paper that the deviation is statistically significant only when not only the estimated data point but also its error bar is out of the 95% confidence interval. Significant deviations from the respective mean values are found in the figures for the following components and periods; a) DIL amplitude at GJM from January to February in 1985, b) DIL phase at GJM from July to August in 1987, c) BSMD phase at TAZ from May to August in 1987, d) DIL phase at OGA in May, 1987, e) DIL phase at NIB from May to June in 1987. The significant deviation of (a) was found only for DIL at GJM, no significant deviations being found at other stations. It is safe to consider that this was caused probably by the local effect of the melted snow. In contract to (a), (b) through (e) described above are all indicating some phase advances for periods between May and August in 1987. Since similar phase advances in the linear strain components observed by extensometers in the same period have been found also for some other stations in Tohoku district (Nakao *et al.*, 1990), this should not be interpreted as local phenomena. It is interesting to note that no significant amplitude deviation is found for any station.

If the temporal variations of M_2 constituent are caused by some effects of the crustal response to the tectonic stresses, there should exist some coherency between two time series of amplitudes or phases obtained for two nearby stations. The results given in Figs. 5 to 9, however, apparently show poor coherency. To see this quantitatively, we calculate the cross-correlation of two time series of amplitudes or phases. The results are summarized in Table 2. The correlation coefficients ρ between volumetric and dilatational strains at GJM are calculated as 0.63 for the amplitude and 0.53 for the phase. This case of GJM is exceptional. We find generally poor correlations even between volumetric and dilatational strains at the same station. The volumetric strains were obtained from borehole strainmeters, while the dilatational strains were derived from extensometers installed in observation vaults at shallower depths relative to the boreholes. The poor correlation between them is probably due to the different effects of weather phenomena. Figures 10(a), (b) and (d), respectively, show the perturbations of BSMD and DIL amplitudes, and the daily rainfall at OGA. The DIL amplitude is seen from the figure to decrease by 30% in the rainy period from July to August 1987. On the other hand, the BSMD amplitude is little affected by the rainfall. Further, we found from Figs. 10(a) and (c) no clear correlation between the BSMD amplitude variation and the atmospheric pressure change obtained at the Akita Meteorological Observatory, where the distance between OGA station and the Akita observatory is about 30 km. From this, the main reason of the poor correlation is considered to be the very local effects of the rainfall and the spring thaw.

4. Discussion

Table 3 shows the average amplitudes and the average phases of M_2 constituent

Table 2. Correlation Coefficients.

	GJM-B		GJM-D		TAZ-B		TAZ-D		OGA-B		OGA-D		NIB-B		NIB-D	
	A	P	A	P	A	P	A	P	A	P	A	P	A	P	A	P
GJM-B			●	○	○	○	×	×	○	○	×	×	×	○	▲	×
GJM-D	●	○			○	○	×	×	○	○	×	×	×	○	△	○
TAZ-B	○	○	○	○			×	○	×	×	×	×	×	●	△	●
TAZ-D	×	×	×	×	×	○			×	○	△	×	×	○	×	×
OGA-B	○	○	○	○	×	×	×	○			△	×	○	○	×	×
OGA-D	×	×	×	×	×	×	△	×	△	×			△	×	○	○
NIB-B	×	○	×	○	×	●	×	○	○	○	△	×			△	×
NIB-D	▲	×	△	○	△	●	×	×	×	×	○	○	△	×		

●: $0.6 \leqq \rho \leqq 1.0$ B : Volumetric strain.
○: $0.3 \leqq \rho < 0.6$ D : Dilatational strain.
×: $-0.3 < \rho < 0.3$ A : Amplitude of M_2 constituent.
△: $-0.6 < \rho \leqq -0.3$ P : Phase of M_2 constituent.
▲: $-1.0 \leqq \rho \leqq -0.6$ ρ : Correlation coefficient.

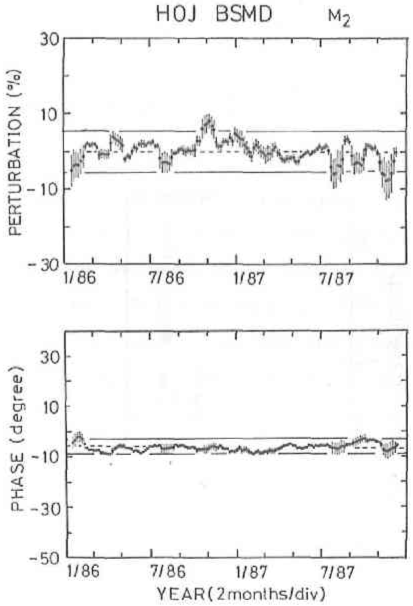

Fig. 9 The amplitude perturbation and the phase variation observed by borehole strainmeter at HOJ.

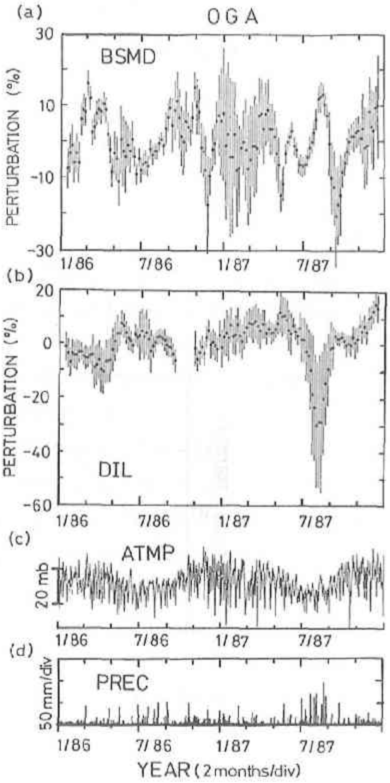

Fig. 10 (a) The temporal variation of BSMD amplitude at OGA, (b) the temporal variation of DIL amplitude at OGA, (c) the atmospheric pressure change observed at the Akita Meteorological Observatory, and (d) the daily precipitation at OGA from January 1986 to December 1987.

observed at stations. These observed values are compared in Fig. 11 with the theoretical values, which include the solid tides and the ocean load tides calculated by the program GOTIC (Sato and Hanada, 1984). The observed amplitudes are seen to be much smaller than the theoretical ones. Harrison (1976) estimated the effects of the cavity and the topography for the vault observation by both an analytical method and a two-dimensional finite element method. According to his results, strains in the vicinity of a tunnel are increased by about 5 to 10% due to the cavity effect, and the strains observed in a vault on mountainside are decreased by about 50% due to the topographic effect. When the cavity and topographic effects are taken into account, the consistency of the observed amplitudes with the observed ones are considerably improved. The

Table 3. Average Amplitudes and Phases[1] of Observed M_2 Constituent Together with Their Standard Deviations.

Station	Dilatational Strain		Volumetric Strain	
	Amplitude (S.D.) (nano)	Phase (S.D.) (deg)	Amplitude (S.D.) (nano)	Phase (S.D.) (deg)
GJM	4.99 (0.36)	−0.18 (4.08)	1.41 (0.17)	−5.47 (7.00)
TAZ	10.87 (1.58)	−7.17 (6.30)	3.91 (0.15)	−6.54 (3.04)
OGA	4.51 (0.35)	−15.83 (4.62)	1.90 (0.13)	−13.70 (4.64)
NIB	12.71 (0.35)	3.37 (3.29)	6.80 (0.11)	−2.47 (1.21)
HOJ	— (—)	— (—)	4.96 (0.14)	−6.29 (1.38)

[1] The observed phase with negative sign implies that the observation lags behind the local potential tide expected for the theory.

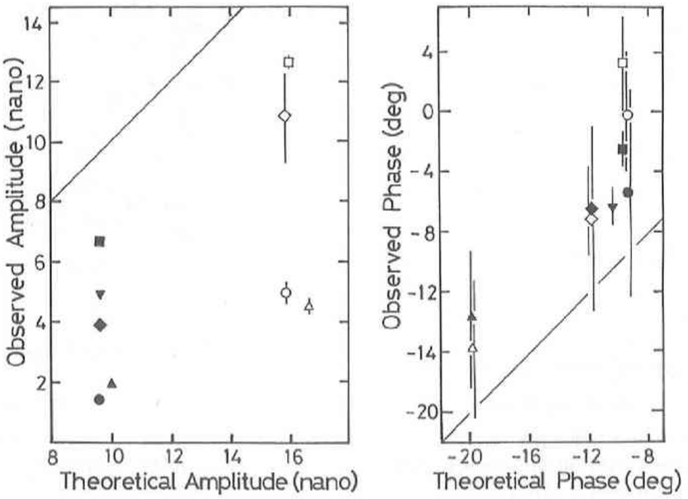

Fig. 11 Comparison between the observation and the theory. The left figure is for the amplitude data, and the right for the phase data. Solid symbols indicate the data of volumetric strains and open symbols the data of dilatational strains. Circles, diamonds, triangles, squares and reversed triangles denote GJM, TAZ, OGA, NIB and HOJ, respectively.

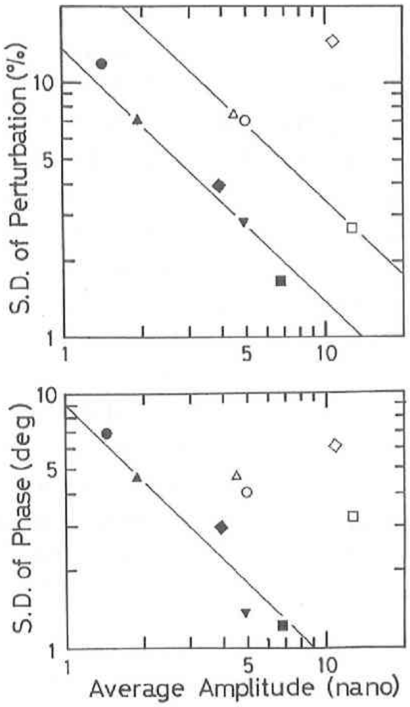

Fig. 12 The relative error of the observed amplitude (top) and the standard deviation of the observed phase (bottom) versus the average amplitude. The relative error is defined by the amplitude standard deviation divided by the average amplitude. Solid symbols indicate the data of volumetric strains and open ones the data of dilatational strains. Circles, diamonds, triangles, squares and reversed triangles denote GJM, TAZ, OGA, NIB and HOJ, respectively. The straight lines are drawn for the sake of reference.

scatter of the observed data, however, remains unexplained. The observed amplitudes given in Table 3 and Fig. 11 have not been corrected for the so-called magnification factor of borehole instruments, which is the ratio of local strain near a borehole to the far-field strain. Nakao *et al.* (1989) have estimated the factor for TAZ at a value between 2.5 and 3.5 using Sakata's formulation (1983, 1989). If we correct the observed data for the magnification factor, the consistency between observation and theory becomes much worse than it is. To improve the consistency the coupling factor of a borehole strainmeter with the surrounding medium may have a good effect. Quantitatively speaking, however, the effect does not seem sufficient enough.

A better consistency between observation and theory is seen in Fig. 11 for the phase angle, if we take the standard deviations of the observed phases into consideration. It is interesting that all the observed phases are in advance of the respective theoretical phases. Since they have negative signs except for the dilatational strain at NIB, it is possible to consider that the actual effect of the ocean load tides is less than that expected theoretically.

We plot in Fig. 12 the relative errors of the observed amplitudes (top figure) and the standard deviations of the observed phases (bottom one) versus the observed average amplitude, where the relative error is defined as the standard deviation divided by the average value of observed amplitudes. In the case of volumetric strain data, we can clearly recognize almost the same linear relation between the error and the average amplitude both for the amplitude and for the phase, indicating that the relative error is inversely proportional to the average amplitude. In the case of dilatational strain data, the data are scattered. If the datum of TAZ is excluded, similar linear relation is seen for the amplitude (top figure). The phase standard deviation at NIB as well as at TAZ is too large to apply a similar linear relation to the phase data. It is noted, however, that the significant phase advance at NIB in 1987, which was discussed previously, contributes to this large standard deviation. It is concluded from this that the noise level in absolute amplitude is nearly the same for all the stations used for the present analysis. The signal to noise ratio is thus determined only by the observed signal amplitude. Further, the noise level for extensometer observations is found to be about three times as high as that for borehole observations.

As described in section 1, anomaluos changes in M_2 amplitude due to dilatancy are expected to be from 6% to 15% (Latynina and Rizaeva, 1976 ; Mikumo *et al.*, 1977). This amount of anomalous change is critical to be detected by our observations with extensometers and borehole strainmeters. In fact, no significant changes in observed amplitudes have been found in the present study. On the other hand, some significant changes in observed phases were found, as stated before. At present, the phase data are promising rather than the amplitude data to detect an anomalous change due to dilatancy.

5. Conclusions

The temporal variations of M_2 constituent in strain earth tides were studied for the period from January 1984 to December 1987 at GJM and TAZ and for the period from January 1986 to December 1987 at OGA and NIB. The main results are summarized as follows :

(1) We found no anomalous change in amplitude with statistical significance in the observation period stated above.

(2) The temporal variation of M_2 constituent observed by borehole strainmeters has a poor correlation with that observed by the extensometers at the same station. This comes mainly from the different effects of the rainfall and the thaw.

(3) The consistency between the theory and the observation for the phase is fairly good, while that for the amplitude is poor. The consistency for the amplitude observed by extensometers is considerably improved by taking the cavity and topographic effects into account. The amplitudes observed by borehole strainmeters are much smaller than those expected for the theory. The weak coupling between a borehole instrument and the surrounding rock may account partly for this discrepancy.

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References

Beaumont, C. and J. Berger, 1974 : Earthquake prediction : Modification of the earth tide tilts and strains by dilatancy, *Geophys. J. R. astr. Soc.*, **39**, 111-121.

Harrison, J.C., 1976 : Cavity and topographic effects in tilt and strain measurement, *J. Geophys. Res.*, **81**, 319-328.

Ishiguro, M., 1981 : A bayesian approach to the analysis of the data of crustal movements, *J. Geod. Soc. Japan*, **27**, 256-262.

Ishiguro, M., H. Akaike, M. Ooe and S. Nakai, 1981 : A bayesian approach to the analysis of earth tides, *Proc. 9th Int. Symp. Earth tides*, New York, 283-292.

Latynina, L.A. and S.D. Rizaeva, 1976 : On tidal-strain variations before earthquakes, *Tectonophysics*, **31**, 121-127.

Mikumo, T., M. Kato, H. Doi, Y. Wada, T. Tanaka, R. Shichi and A. Yamamoto, 1977 : Possibility of temporal variations in earth tidal strain amplitudes associated with major earthquakes, *J. Phys. Earth*, **25**, Suppl., S123-S136.

Nur, A., 1972 : Dilatancy, pore fluids, and premonitory variations of t_s/t_p travel times, *Bull. Seism. Soc. Am.*, **62**, 1217-1222.

Nakao, S., A.T. Linde, S. Miura, M. Mishina and A. Takagi, 1989 : Nonlinear barometric response of borehole strainmeters and its interpretation, *J. Phys. Earth*, **37**, 357-383.

Nakao, S., M. Mishina, S. Miura, T. Sato, K. Tachibana, K. Hashimoto and E. Murakami, 1990 : Characteristics of temporal changes in amplitude and phase of tidal strain, *The 73rd Meeting Program and Abstracts of Geodetic Society of Japan*, 65-66 (in Japanese).

Sakata, S., 1983 : Amplification factors of dilatation detected by borehole strainmeters, *Zisin, Ser. 2*, **36**, 262-265 (in Japanese).

Sakata, S., 1988 : Amplification factors of dilatation detected by borehole strainmeters, Errata, *Zisin, Ser. 2*, **41**, 641 (in Japanese).

Sato, T. and H. Hanada, 1984 : A program for the computation of oceanic tidal loading effects 'GOTIC', *Pub. Intern. Lat. Obs. Mizusawa*, **18**, 29-47.

Scholz, C.H., L.R. Sykes and Y.P. Aggarwal, 1973 : Earthquake prediction : A physical basis, *Science*, **181**, 803-810.

Shimada, S, 1987 : Study on the time variation of the factor of the earth tide tilt observed at Izu Oshima (Habu), *The 67th Meeting Program and Abstracts of Geodetic Society of Japan*, 76-77 (in Japanese).

Suyehiro, S., 1979 : Continuous observation of crustal movement and borehole strainmeter (I), *Weather Ser. Bull.* (*Sokko Jiho*), **46**, 9-25 (in Japanese).

Tanaka, T., 1976 : Effect of dilatancy on ocean load tides, *Pageoh*, **114**, 415-423.

Tanaka, T. and M. Kato, 1974 : On the change of crustal elasticity and earth tides, *J. Geod. Soc. Japan*, **20**, 125-132.

Yamauchi, T., 1989 : Earthquake occurence and temporal variations in earth tidal strain amplitude, *J. Geod. Soc. Japan*, **35**, 149-157.