Observations of Crustal Movements by Newly-Designed Horizontal Pendulum and Water-Tube Tiltmeters with Electromagnetic Transducers (1)

By Masaaki KATO

(Manuscript received December 27, 1977)

Abstract

In order to detect temporal variations in the amplitude and phase of earth tidal tilts, in relation to crustal deformations, horizontal pendulum and water-tube tiltmeters with electromagnetic transducers have been newly designed. The horizontal pendulum tiltmeter has a pendulum of 2.6 kg weight, with a free period of about 6 sec and the mechanical amplification factor of about 45. A differential transformer is used as a transducer. The water-tube tiltmeter consists of three detectors, which are located at the vertices of a triangle and connected by vinyl chloride tubes. Each detector has a float of glass, and its displacement in accordance with the level change of the water surface is detected by a magnetic sensor.

Two components of the horizontal pendulum tiltmeters and one set of the water-tube tiltmeter were installed in December 1975 and July 1976, respectively, in the observation vault of the Kamitakara Crustal Movement Observatory (36°17′N, 137°20′E, H=800 m) and the observations have been continued since that time. The overall sensitivities of two kinds of tiltmeters are $4'' \times 10^{-4}$ and $3'' \times 10^{-4}$/mm on the recording chart, respectively.

In this paper, the structures, principles and calibration techniques of these instruments are described, and some preliminary results from tidal analyses of the tiltmeter records are also presented.

1. Introduction

It has been reported by some geophysicists[1)~4)] that the changes in elastic constants in dilatant crustal regions cause some variations in the amplitude and phase of the earth tides. Continuous monitoring of the earth tides, therefore, is now suggested as one of the most useful methods for earthquake prediction if such dilatancy actually precedes earthquakes.

It is desirable that the instruments used for the observations of earth tidal tilts satisfy severe conditions such as high sensitivity and high stability together with an automatic recording system. Considering these requirements, the short-period horizontal pendulum type tiltmeter with a differential transformer transducer has been designed. Short-base instruments such as pendulum tiltmeters, however, are very sensitive to local ground deformations[5),6)]. To avoid these local effects, a water-tube tiltmeter of the float type with transducers of magnetic sensors has also been designed here. Similar types of water-tube tiltmeters have been used by several geophysicists[7)~11)], but the present tiltmeter seems slightly more complete for the observations of earth tides in the point of the reliability of sensitivity measurements.

The purpose of the present paper is to describe in detail the design and theory of the instruments as well as to provide preliminary observed results for earth tidal tilts.

2. Tiltmeter of Horizontal Pendulum Type

2.1 Structure

Photograph and design of the horizontal type tiltmeter are shown in Figs. 1 and 2, respectively. The gross weight of the detector is 55 kg, and the pendulum, which is made of brass, has a weight of 2.6 kg. It is supported by a stainless steel wire of 0.3 mm in diameter from the upper suspending point. The lower suspending device consists of three crossed leaf springs made of steel. The dimension of the main spring which undertakes the rotation of the pendulum is $3 \times 4 \times 0.05$ mm. Not to force an unfavorable distortion on this spring, two additional springs, the dimension of which is $3 \times 15 \times 0.1$ mm, are also combined in a horizontal position. A differential transformer is used as a transducer. The core is fixed to the pendulum, which has an oil damper with silicon oil of 50 cSt, and the coil is fixed to the calibration table supported from the base by two thick steel leaf springs.

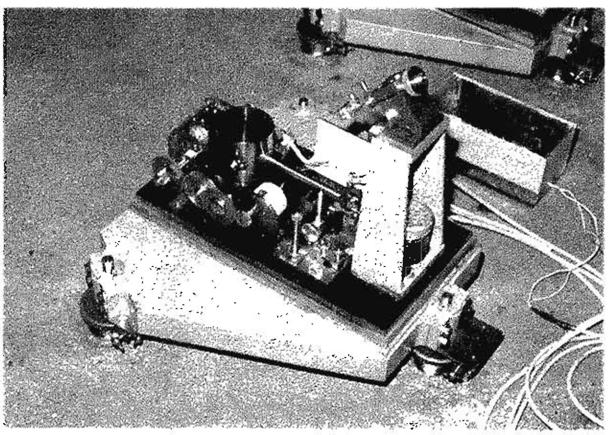

Fig. 1. Photograph of the horizontal pendulum type tiltmeter.

2.2 Observation system

The block diagram and electronic circuits of the observation system are shown in Figs. 3 and 4. To excite the primary coil of the differential transformer, a 2-kHz crystal oscillator is used. The AC output voltage generated in the secondary coil is amplified and phase-detected by an pre-amplifier, converted into

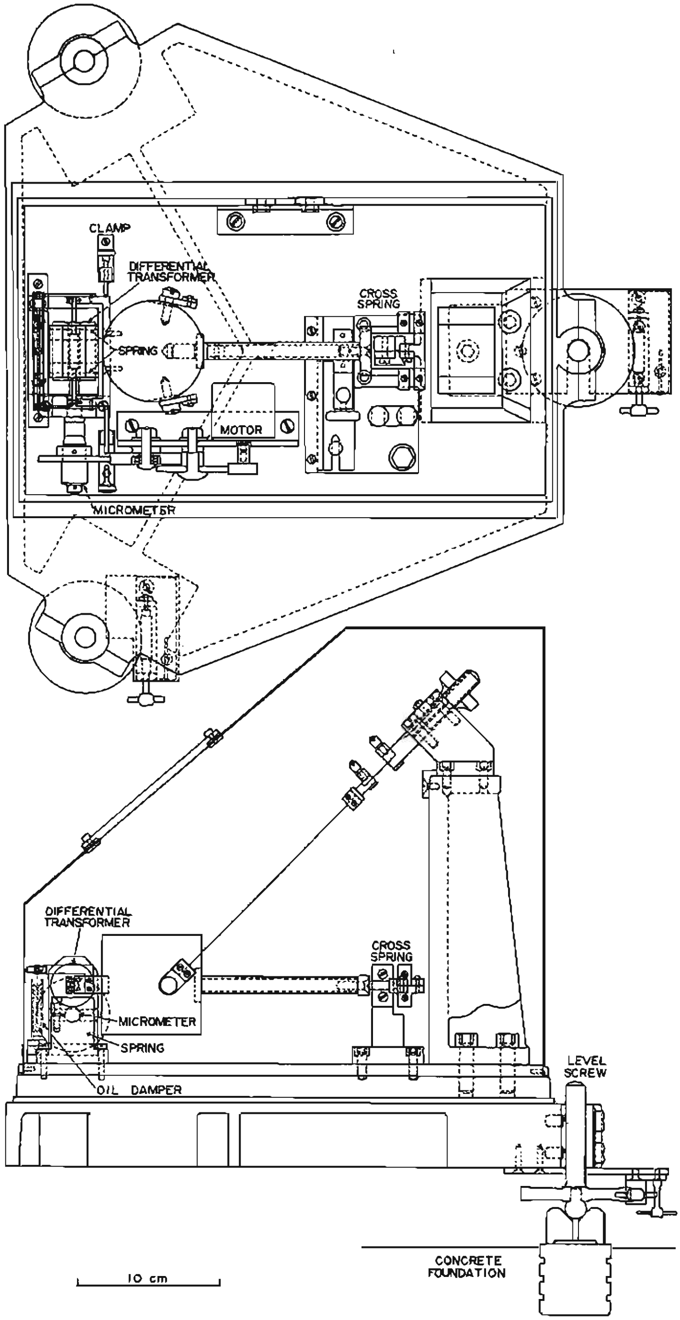

Fig. 2. Tiltmeter of horizontal pendulum type.

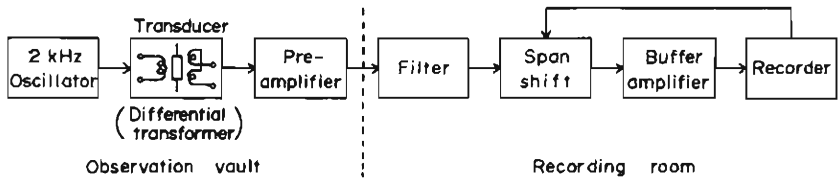

Fig. 3. Block diagram of the observation system of the horizontal pendulum type tiltmeter.

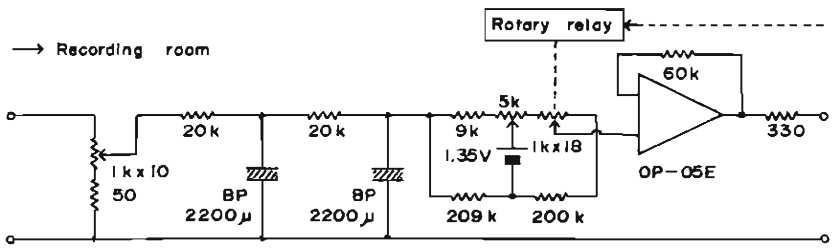

Fig. 4. Electronic circuit of the horizontal pendulum tiltmeter.

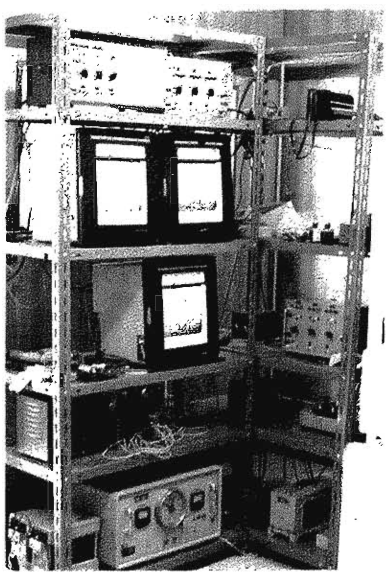

Fig. 5. Photograph of the recording room just outside the Kurabashira observation vault.

DC output, sent by cables to the recording room (see Fig. 5) just outside the observation vault and passed through a low-pass filter with a cut-off frequency of 0.0013 Hz. A multi-point recorder of the potentiometer type is employed for the present recording system. An apparatus for span-shifting is coupled with the recorder to prevent output signals from going-off scale. If one of the signals scales off the range between 0 and 10 mV, it is automatically shifted by 6 mV towards the center of the chart by the span shift device. This operation can be successively repeated 18 times at most in one direction. The width of the recording chart is 180 mm, which corresponds to 10 mV. The paper speed is adjusted to 25 mm/hour. These signals are also recorded in a digital form, in which 1 mV corresponds to 200 digits.

2.3 Theory of the horizontal pendulum tiltmeter

The equation of motion of the horizontal pendulum is given by

$$I\frac{d^2\phi}{dt^2}+2D\frac{d\phi}{dt}+(MgH\theta+k_w+k_f+k_t)\phi=MgH\psi \tag{1}$$

where

I =moment of inertia of the pendulum (7.22×10^5 g·cm²),
ϕ =rotation angle of the pendulum,
D =viscous damping coefficient relating to viscosity of silicon oil,
M =mass of the pendulum (2.60 kg),
g =acceleration of gravity,
H =distance between the rotation axis and the center of gravity of the pendulum (15.9 cm),
θ =angle between the plumb line and the rotation axis of the pendulum,
k_w =moment of force by the suspending wire (3.2×10^3 dyn·cm),
k_f =moment of force by the suspending springs (6.4×10^3 dyn·cm),
k_t =moment of force by the attraction acting between the core and coil of the differential transformer,
ψ =tilt angle of the ground in the direction perpendicular to the pendulum.

Since the periods of the earth tides and the secular ground tilt are sufficiently long compared with the period of the pendulum, we can confine ourselves to a static study. In this case, omitting dynamic terms in Eq. (1), we get a particular solution,

$$\phi=\frac{MgH\psi}{MgH\theta+k_w+k_f+k_t} \tag{2}$$

The natural period of the pendulum is given by the following equation,

$$T=2\pi\sqrt{\frac{I}{MgH\theta+k_w+k_f+k_t}} \tag{3}$$

Referring to Eq. (3), Eq. (2) can be rewritten as,

$$\phi=\left(\frac{T}{2\pi}\right)^2\left(\frac{MgH}{I}\right)\psi\equiv n\psi \tag{4}$$

We call n an amplification factor[12] where $n=(T/2\pi)^2(MgH/I)$. In practice, we measure the period of damped oscillation T'. The relation between T and T' is expressed by,

$$T=T'/\sqrt{1+0.5372\Lambda^2} \tag{5}$$

where $\Lambda=\log v$, v being the ratio of the two successive double amplitudes of the damped oscillation.

2.4 Determination of sensitivity

Denoting the distance from the rotation axis of the pendulum to the core by H' (225 mm), the rotation angle of the pendulum by ϕ, the displacement of the core by d, and the output voltage by V, respectively, we have

$$d=\phi H' \tag{6}$$

Considering Eq. (6), the output voltage from the transducer per a unit rotation angle, which we call the sensitivity of the transducer, is written by

$$S'=V/\phi=(H'V)/d \tag{7}$$

The unit displacement of the transducer's coil, say 1 μm/sec, can be given by rotating a synchronous motor. Since the attracting force acting between the core and coil is negligibly small, we can easily measure the sensitivity of the transducer in this way. For example, using the characteristic values, $v=1.24$ and $T'=5.51$ sec, the amplification factor n becomes 43.0 for one of the two tiltmeters, HP2, in the present observations.
The overall sensitivity of the tiltmeter is given by,

$$S=nS' \tag{8}$$

Substituting $n=43.0$ and $S'=2.908$ mV/(arc sec) into Eq. (8), we obtain $S=125.0$ mV/(arc sec).
Errors within several percents or so in the estimated sensitivity seems unavoidable, in view of the accuracy of the above measurements. Therefore, it is more desirable to measure directly the output voltage by tilting the base of the tiltmeter. To do this, we used the method of lifting a point of the base with level screws. As the displacement given by the level screws is required to be very small, some errors are inevitably introduced in the mechanical accuracy. To overcome such a defect, we adopted a new device described as follows. Two coils of differential transformers are set at both sides of the base (see Fig. 6). The stand equipped

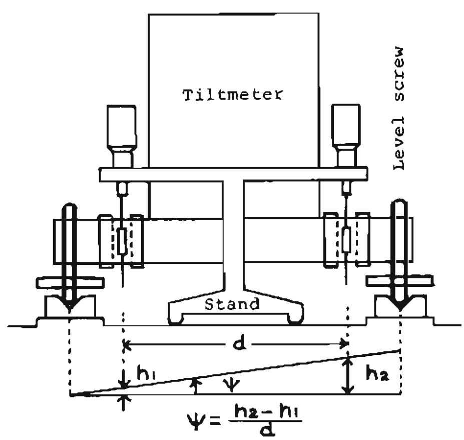

Fig. 6. Device to determine the tilt angle of the base of the horizontal pendulum tiltmeter.

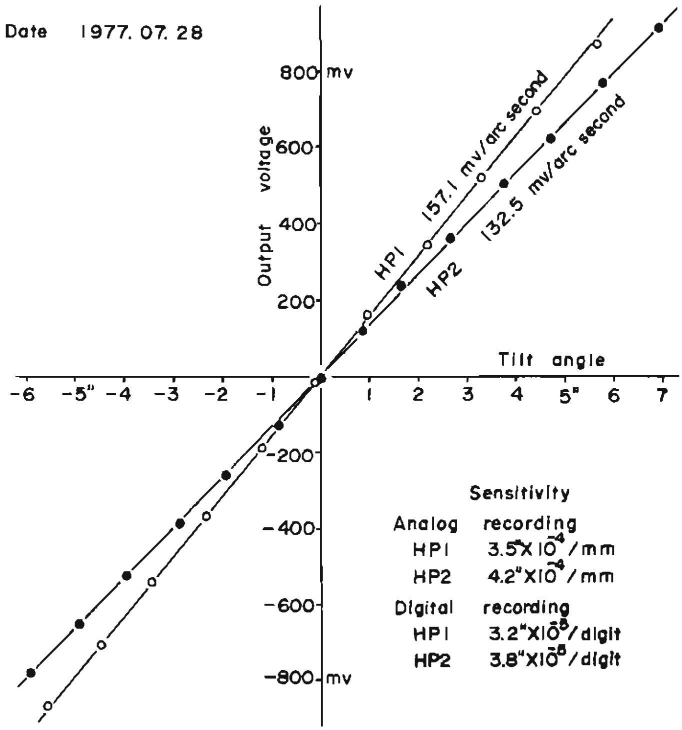

Fig. 7. Relation between the tilt angles and the output voltages.

with two cores is put on the ground. Using the two sets of differential transformers, we can measure the displacements and hence the changes in output voltages at the two points of the base with high precision. The tilt angle is thus obtained as the ratio of the difference of displacements at the two points to the distance between them. By adopting this method, the absolute sensitivity can be easily determined with sufficient accuracy. The results obtained by this method are shown in Fig. 7. The overall sensitivities thus estimated are 132.5 mV and 157.1 mV/(arc sec) for two tiltmeters, HP2 and HP1, respectively. Once the absolute sensitivity is obtained, it is then possible to check its time variations only by measuring the period of the pendulum and the sensitivity of the transducer.

3. Wate-Tube Tiltmeter of Float Type

3.1 Structure

The water-tube tiltmeter consists of three detectors connected by vinyl chloride tubes with an inside diameter of 16 mm (see Fig. 8). A glass pot, a glass float within it, a metal arm supporting the float and a transducer form the main part of the detector, photograph and design of which are shown in Figs. 9 and 10, respectively. The inside diameter of tube was chosen to satisfy the condi-

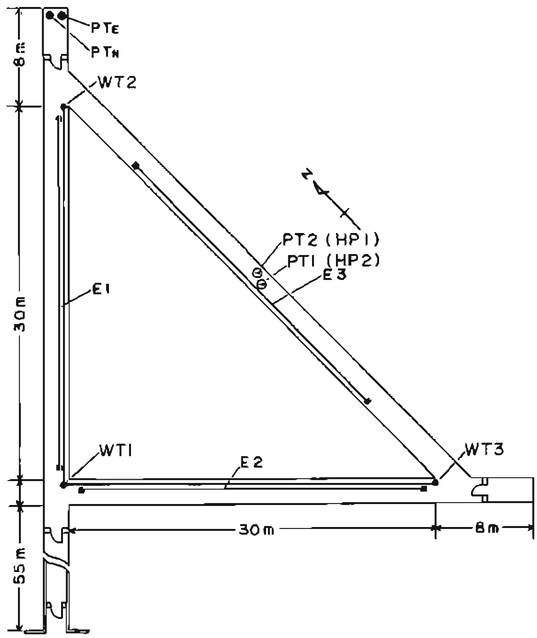

Fig. 8. Location of the instruments installed in the observation vault.

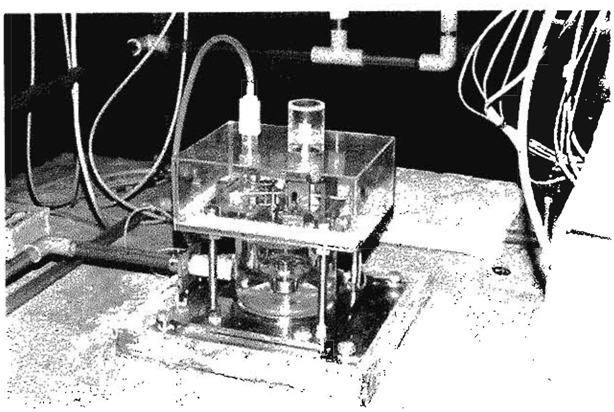

Fig. 9. Photograph of the detector of the float type water-tube tiltmeter.

tion of critical damping in the detector-tube system. The pot has an inside diameter of 13.3 cm and the float has an outside diameter of 8.9 cm. The float is equipped with a mercury reservoir at the bottom to keep its balance and fixed to the metal arm. It is suspended by two horizontal steel leaf springs with a dimension of $5\times4\times0.05$ mm and two vertical stainless steel wires with a diameter of 0.19 mm. A magnetic sensor (made by SONY MAGNESCALE INC.) is used as the transducer, which is composed of a magnet, a head and a detecting unit. The magnet is fixed to the top of the arm, and the head is fixed to the calibra-

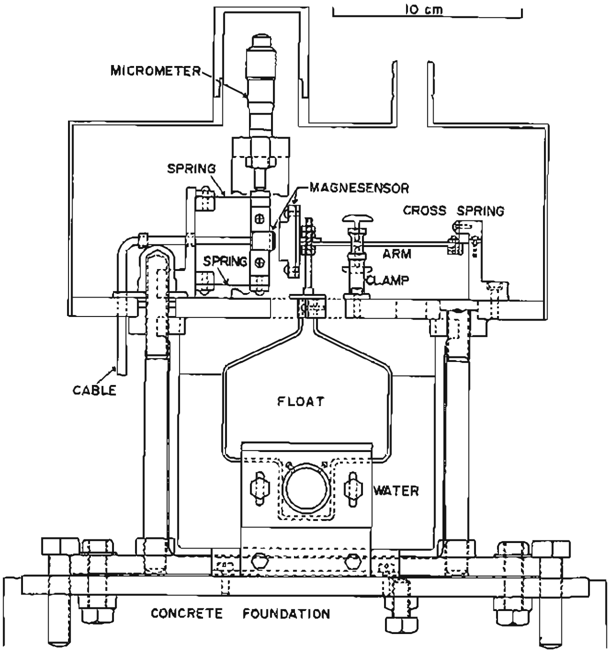

Fig. 10. Detector of the float type water-tube tiltmeter.

tion table supported by two thick steel leaf springs from the frame. The clearance between the magnet and the head is about 1.5 mm. We can measure the sensitivity of the transducer, by providing the displacement to the head by rotating a micrometer. It is possible to clamp the arm at an arbitrary height. The water surface in the three pots provides a common reference level with a high precision for detecting the change of the relative height of three detectors.

3.2 Observation system

The block diagram and electronic circuits of the observation system are shown in Figs. 11 and 12. The signals detected as DC currents are sent to the recording room and passed through low-pass filters with a cut-off frequency of 0.13 Hz. The apparatus for span-shifting and the recording system are almost the same as in the tiltmeter of the horizontal pendulum type.

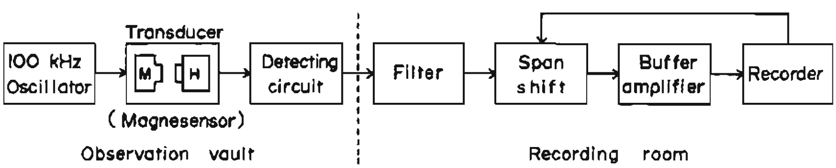

Fig. 11. Block diagram of the observation system of the float type water-tube tiltmeter.

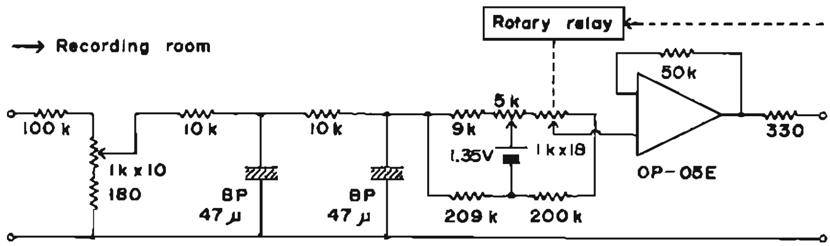

Fig. 12. Electronic circuit of the water-tube tiltmeter.

3.3 Static characteristics and sensitivity measurements

To estimate the static characteristics and the sensitivity of this type of tiltmeter, a proper volume $\varDelta V$ of water is added into one of the three pots. After a static equilibrium has been reached, the changes of water levels in the three pots attain to the same value $\varDelta H$ (see Fig. 13). The displacement of each float is reduced from the change of water level $\varDelta H$, by $k_{ti}\varDelta H$ due to the attracting force between the magnet and head, and by $k_{si}\varDelta H$ due to the elastic forces of four springs. Therefore the final displacement is given by

$$\varDelta H_{fi}=\{1-(k_{ti}+k_{si})\}\,\varDelta H \quad (i=1,2,3) \tag{9}$$

The relation between the added volume of water and the change of water level is expressed as,

$$\varDelta V=\{3(S_1+S_2)-\sum_{j=1}^{3}(k_{ti}+k_{si})S_2\}\,\varDelta H \tag{10}$$

where S_2=cross-sectional area of the float, and S_1+S_2=cross-sectional area of the pot.

First, we shall determine the values of k_{ti}'s. Suppose that the arms of all the three pots are clamped, and then the sensitivity of three transducers is mea-

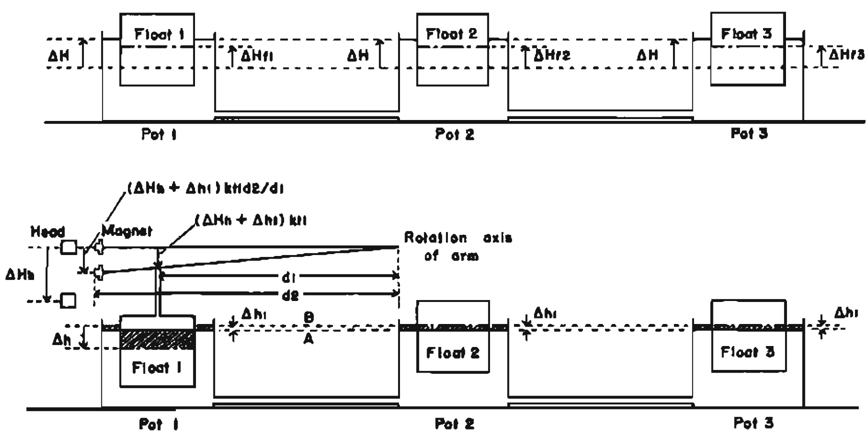

Fig. 13. Schematic diagram to find a relationship between the level change of the water surface and the displacements of the three floats.

sured by giving a displacement ΔH_h to each of the heads by using the micrometer. Next the clamps of the three arms are released and then three floats are put into a static equilibrium. In this state, we give a displacement ΔH_h to the head of the i-th pot. The float is attracted by the force between the head and magnet towards the direction of displacement of the head. Consequently, the water line, where the float contacts the water surface, changes by Δh with respect to the original level before giving a displacement, and the water level changes by Δh_1 (see Fig. 13). Then, the following approximate equations are obtained:

$$\Delta h = k_{ti}\Delta H_h \quad (i=1, 2, 3) \tag{11}$$

$$S_2(\Delta h - \Delta h_1) = \{S_1 + 2(S_1+S_2)\}\, \Delta h_1 \tag{12}$$

Combining Eqs. (11) and (12), we obtain,

$$\Delta h_1 = \{k_{ti}S_2/3(S_1+S_2)\}\, \Delta H_h \quad (i=1, 2, 3) \tag{13}$$

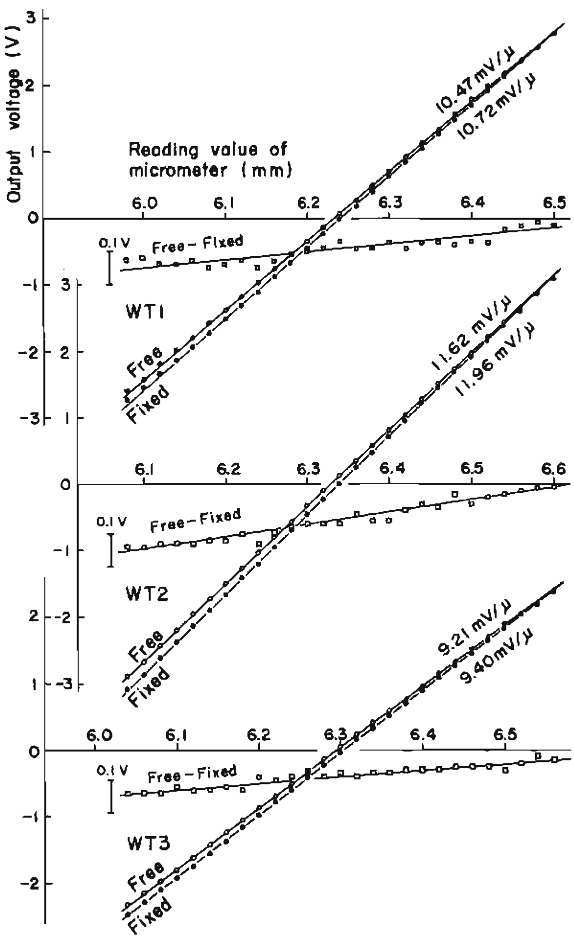

Fig. 14. Relation between the displacements of the magnetic sensors's heads and the output voltages.

When the displacement ΔH_h is given to the head, the displacement of the magnet relative to the head is given by

$$\Delta H_{mi} = (\Delta H_h + \Delta h_1)(1 - k_{ti} d_2/d_1) \quad (i=1, 2, 3) \tag{14}$$

where d_1 and d_2 are the distances between the rotation axis of the arm and the center of the float, and between the axis and the magnet, respectively. Referring to Eq. (13) and neglecting the second order term of k_{ti}, Eq. (14) can be rewritten as follows.

$$\Delta H_{mi} = [1 + \{S_2/3(S_1+S_2) - d_2/d_1\} k_{ti}] \Delta H_h \quad (i=1, 2, 3) \tag{15}$$

If we denote ΔE_{hi} as the change in the output voltage of the transducer caused by the displacement ΔH_h of the head in the state of clamping the float, and ΔE_{mi} as that in the state of releasing, we have

$$\Delta H_{mi}/\Delta H_h = \Delta E_{mi}/\Delta E_{hi} \quad (i=1, 2, 3) \tag{16}$$

Denoting this ratio by n_i, Eq. (15) is rewritten as,

$$n_i = 1 + \{S_2/3(S_1+S_2) - d_2/d_1\} k_{ti} \quad (i=1, 2, 3) \tag{17}$$

In Fig. 14, we give the relation between the output voltage and the displacement of each head in both the clamped and free states. From these experiments, we obtain

$$n_1 = 0.977,\ n_2 = 0.972 \text{ and } n_3 = 0.980.$$

Substituting these three values into Eq. (17) together with $S_1 = 76.3\ \text{cm}^2$, $S_2 =$

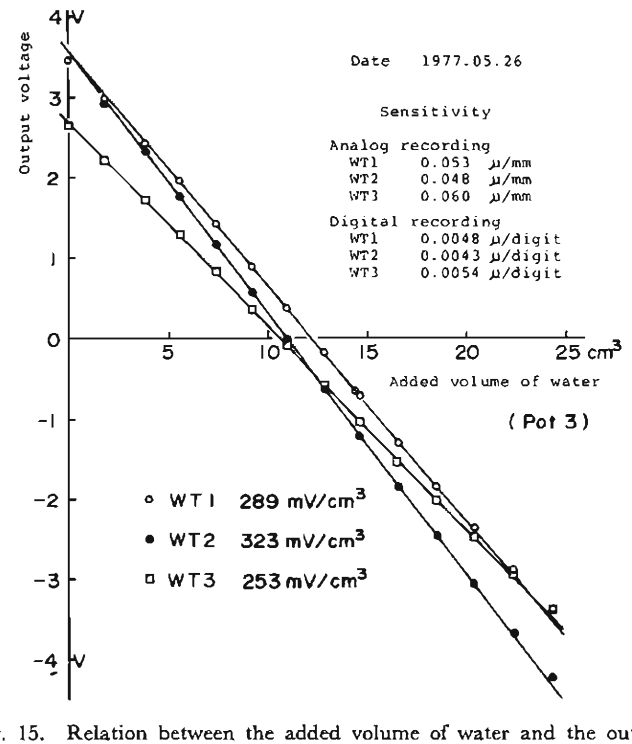

Fig. 15. Relation between the added volume of water and the output voltages of the three detectors.

62.7 cm^2 and $d_2/d_1=1.195$, we can obtain the values of k_{ti}'s.

$k_{t1}=0.022$, $k_{t2}=0.027$ and $k_{t3}=0.019$.

Second, we shall determine the values of k_{si}'s. They are obtained by adding a proper volume of water into one of the three pots. Denoting the changes in the output voltage of the transducer caused by the change of the water level ΔH by ΔE_i, and defining the sensitivity as $S_i'=\Delta E_i/\Delta H$, we can write

$$S_i' \equiv \Delta E_i/\Delta H = \{1-(k_{ti}+k_{si})\}\,(d_2/d_1)\,(\Delta E_{hi}/\Delta H_h) \quad (i=1,2,3) \tag{18}$$

Combining Eqs. (10) and (18), the following equation is obtained.

$$(\Delta E_i/\Delta V)\,\{3(S_1+S_2)-\sum_{i=1}^{3}(k_{ti}+k_{si})S_2\} = \{1-(k_{ti}+k_{si})\}\,(d_2/d_1)\,(\Delta E_{hi}/\Delta H_h) \quad (i=1,2,3) \tag{19}$$

In Fig. 15, the relation between the output voltage from each transducer and the added volume of water is shown. The experiment shown in Fig. 15 represents the case when a volume of water was poured into pot 3 with a pipet. We also attempted the same experiments by pouring water into pots 1 and 2. It was found that the values of $(\Delta E_i/\Delta V)$ almost did not depend on the choice of the pots into which water was added. So we take the average values as,

$\Delta E_1/\Delta V=289$ mV/cm^3, $\Delta E_2/\Delta V=321$ mV/cm^3 and $\Delta E_3/\Delta V=255$ mV/cm^3. From the gradients of the lines denoted by "Fixed" in Fig. 14, $(\Delta E_{hi}/\Delta H_h)$ values are obtained as,

$\Delta E_{h1}/\Delta H_h=10.72$ mV/μm, $\Delta E_{h2}/\Delta H_h=11.96$ mV/μm and $\Delta E_{h3}/\Delta H_h=9.40$ mV/μm. These values together with the other characteristic values obtained previously are substituted into Eq. (19), and all the three values of k_{si}'s are calculated as follows.

$k_{s1}=0.080$, $k_{s2}=0.081$ and $k_{s3}=0.080$.

The obtained values for k_{si}'s are almost the same, indicating that the elastic forces of springs give nearly equal effects on all the three detectors. These values are well consistent with those calculated theoretically by the condition of balance for the force moments around the rotation axis of the arm. The sensitivities S_i' are calculated from Eq. (18) as follows.

$S_1'=11.47$ mV/μm, $S_2'=12.75$ mV/μm and $S_3'=10.12$ mV/μm.

If k_{ti} and k_{si} remain constant through a passage of time, we can also determine the sensitivity from the relation $\Delta E_{hi}=\Delta E_{mi}/n_i$, by measuring $\Delta E_{mi}/\Delta H_h$.

In practice, the output voltages from the three transducers are attenuated through electronic circuits. Denoting the attenuation factor in each component by a_i, the recording sensitivity is given by

$$S_i=a_iS_i' \quad (i=1,2,3) \tag{20}$$

Using the values of $a_1=0.09156$, $a_2=0.09115$ and $a_3=0.09140$, the recording sensitivities are obtained as,

$S_1=1.050$ mV/μm, $S_2=1.162$ mV/μm and $S_3=0.925$ mV/μm.

4. Observational Results

20 signals of crustal movements including tiltmetric, extensometric, and meteorological data observed at the Kurabashira observation vault have been telemetered by a telephone line to the Kamitakara Crustal Movement Observatory,

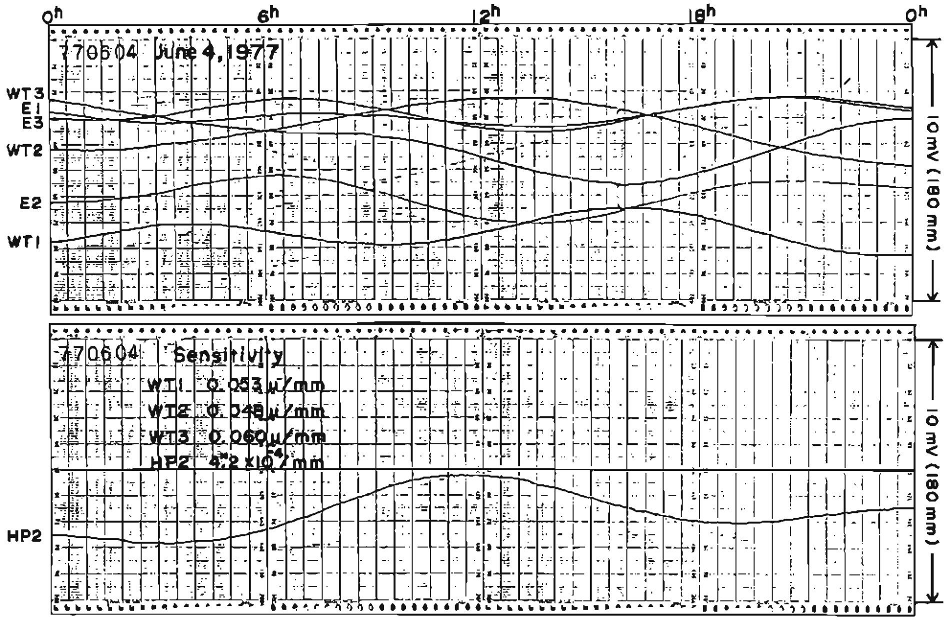

Fig. 16. Upper: Records of the water-tube tiltmeter and the silica-tube extensometers. Lower: Record of the tiltmeter of horizontal pendulum type.

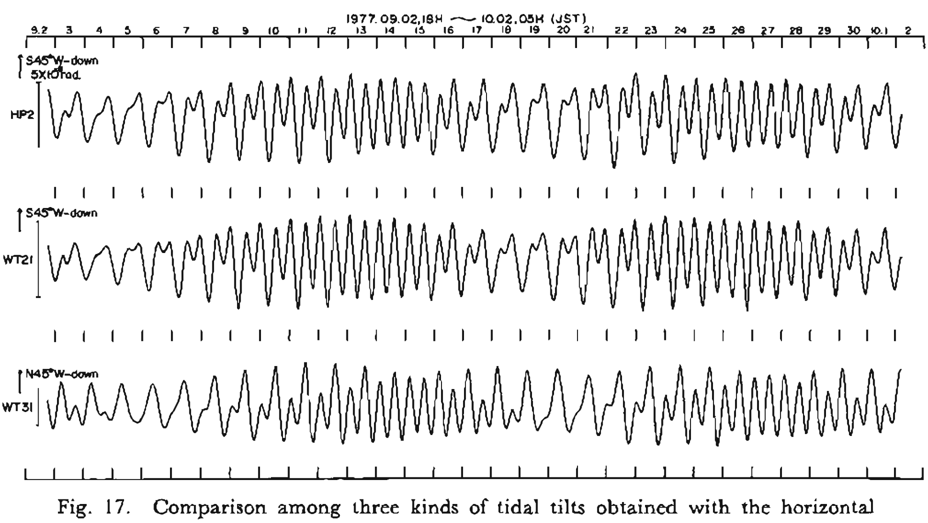

Fig. 17. Comparison among three kinds of tidal tilts obtained with the horizontal pendulum and water-tube tiltmeters.

which are about 3 km apart, since April 1977. 7 signals out of them have been sent in the same way to the Disaster Prevention Research Institute, Kyoto University which is about 200 km distant from the Observatory. In Fig. 16 shown are analog records of crustal tilts and strains on June 4, 1977 obtained at the Institute. A preliminary analysis of earth tides has been carried out using the tiltmetric data for 31 days from Sept. 2, 00^h00^m to Oct. 2, 23^h00^m, 1977 (JST). After the removal of the drifts by the Pertzev filter (see Fig. 17), the least squares method[13] has been applied to get the amplitudes and phases of the major constituents. The corresponding theoretical tilts[14] over the same period have been analyzed in the same way. These results are summarized in Table 1. Comparing the same tilt-components, HP2 (horizontal pendulum) and WT21 (water-tube), installed in the S45°W direction, we find that the amplitudes of major tidal constituents from the former are generally larger than those from the latter except in case of

Table 1. Results from the tidal analyses of observed and theoretical tilts.

S45°W (down) components

Constituent	Observed (HP2)		Observed (WT21)		Theoretical	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
M_2	1.76×10^{-8}	−175.1°	1.58×10^{-8}	161.8°	3.63×10^{-8}	132.5°
S_2	0.89	60.6	0.96	33.0	1.78	43.9
N_2	0.31	− 40.4	0.30	− 59.8	0.58	− 99.5
K_2	0.19	−172.1	0.18	125.5	0.31	138.7
K_1	5.82	− 86.3	4.27	−112.6	6.32	−130.4
O_1	1.06	137.1	0.80	127.0	0.85	89.6
Q_1	0.17	−106.7	0.12	−116.9	0.14	−150.0
P_1	4.21	−113.4	3.24	−149.3	4.82	−158.6
S_1	8.96	80.0	6.76	48.6	10.20	35.7

N45°W (down) components

Constituent	Observed (WT31)		Theoretical	
	Amplitude	Phase	Amplitude	Phase
M_2	2.56×10^{-8}	159.2°	3.63×10^{-8}	−166.2°
S_2	1.39	67.3	1.76	104.1
N_2	0.45	− 71.3	0.59	− 35.8
K_2	0.31	146.0	0.35	−162.4
K_1	7.50	128.3	4.15	152.8
O_1	1.54	− 21.0	0.86	34.1
Q_1	0.22	93.2	0.13	163.2
P_1	4.07	91.2	2.64	106.7
S_1	9.84	− 70.8	5.93	− 51.9

Notes: Period of analysis; Sept. 2, 00h00m–Oct. 2, 23h00m, 1977, (JST).
The phase is the argument at the time of the commencement of the analysis (Sept. 2, 00h00m, 1977, (JST)).

the S_2 constituent, and that the phase lags of all the constituents from the former are behind those from the latter. Though the reason for the discrepancy remains unclarified, the cavity effect on HP2 is supposed to be one of the origins of it. It is also remarkable that the differences between the observed and theoretical amplitudes and phases are considerably large in both of two perpendicular directions. Since the main cause of the differences is considered to be attributable to the oceanic effects, we have estimated the oceanic effect on the M_2 constituent applying the Green's function by Farrell and the M_2 tidal model by Hendershott[15]. As is evident from Table 2, the greater parts of the residuals (the observed minus the theoretical) may well be explained as the oceanic effects. They are only preliminary results from the analysis over a short period of one month. More detailed discussion will be made in subsequent papers.

Table 2. Comparison of the differences between the observed and theoretical M_2 tilt tides with the calculated oceanic effects for the Gutenberg-Bullen A earth model.

Symbol (Azimuth)	Observed		Theoretical solid		Observed minus theoretical solid		Calculated oceanic effect	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
WT32 (N)	0.70×10^{-8}	154.9°	2.62×10^{-8}	253.1°	2.80×10^{-8}	87.4°	2.80×10^{-8}	98.3°
WT21 (S45°W)	1.58	161.8	3.63	132.5	2.38	−66.4	2.17	−62.2
WT31 (N45°W)	2.56	159.1	3.63	193.7	2.10	57.4	2.06	77.6

Notes: Period of analysis; Sept. 2, 00h00m–Oct. 2, 23h00m, 1977, (JST).
The phase is the argument at the time of the commencement of the analysis (Sept. 2, 00h00m, 1977, (JST)).

Acknowledgements

The author would like to thank Professor T. Mikumo and Dr. T. Tanaka for their helpful advice, encouragement and considerable assistance with the computer programs during the course of this work. He wishes to express special thanks to Dr. I. Nakagawa who offered his computer program of the least squares method. He also wishes to express his sincere thanks to Mr. Y. Tsushima who constructed the mechanical parts of the observational instruments. His thanks are extended to Messrs. H. Doi, Y. Wada, H. Wada, M. Koizumi and Y. Hoso, who worked together in assembling the electronic circuits, installing the instruments and measuring their sensitivities. Computations involved were made at the Data Processing Center, Kyoto University and the Computing Center of the Institute for Chemical Research, Kyoto University, Uji.

References

1) Beaumont, C. and J. Berger: Earthquake Prediction: Modification of the Earth Tidal Tilts and Strains by Dilatancy, Geophys. J. R. Astr. Soc., Vol. 39, No. 1, 1974, pp. 111–121.
2) Tanaka, T. and M. Kato: On the Change of Crustal Elasticity and Earth Tides, J. Geod.

Soc. Japan, Vol. 20, No. 3, 1974, pp. 125–132.
3) Tanaka, T.: Effect of Dilatancy on Ocean Load Tides, Pageoph., Vol. 114, 1976, pp. 415–423.
4) Mikumo, T., M. Kato, H. Doi, Y. Wada, T. Tanaka, R. Shichi and A. Yamamoto: Temporal Variations in Earth Tidal Strain Amplitudes Associated with the 1969 Central Gifu Earthquake, J. Phys. Earth, Supplement Issue, 1977.
5) King, G. C. P. and R. G. Bilham: Tidal Tilt Measurement in Europe, Nature, Vol. 243, 1973, pp. 74–75.
6) Harrison, J. C.: Cavity and Topographic Effects in Tilt and Strain Measurement, J. Geophys. Res., Vol. 81, No. 2, 1976, pp. 319–328.
7) Kato, M. and Y. Tsushima: A Water Tube Tiltmeter of Differential Transformer Type, Disas. Prev. Res. Inst. Annuals, Kyoto Univ., No. 16B, 1973, pp. 55–63.
8) Technical Division, Earthq. Res. Inst.: A Float-Type Water-Tube Tiltmeter, Special Bull. Earthq. Res. Inst., Vol. 10, No. 9, 1973, pp. 1–8.
9) Yamauchi, T. and M. Yamada: Observation of Ground Tilts with Float-Type Water Tube Tiltmeters, J. Geod. Soc. Japan, Vol. 20, Nos. 1–2, 1974, pp. 57–64.
10) Ishii, H., T. Sato and K. Tachibana: On the Characteristics of Water-Tube Tiltmeter (1)—Static Characteristics—, J. Geod. Soc. Japan, Vol. 23, No. 2, 1977, pp. 88–98.
11) Ishii, H., T. Sato and K. Tachibana: On the Characteristics of Water-Tube Tiltmeter (2)—Dynamic Characteristics—, J. Geod. Soc. Japan, Vol. 23, No. 2, 1977, pp. 99–109.
12) Melchior, P.: Current Deformations of the Earth's Crust, Advances in Geophysics, Vol. 12, Academic Press · New York and London, 1967, pp. 1–77.
13) Nakagawa, I. and Y. Sato: Analysis for Gravimetric Tidal Data by the Least Square Method, J. Geod. Soc. Japan, Vol. 12, No. 2, 1966, pp. 71–76.
14) Mikumo, T. and M. Kato: Time Domain Analysis of Earth Tide Records, Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 26, Part 2, 1976, pp. 71–81.
15) Tanaka, T. and P. H. Sydenham: The M_2 Earth Tides at Coony Geophysical Observatory in Armidale, Eastern Australia, 8-th Intern. Symp. on Earth Tides, Sept. 1977.