5. *Tilting Motion of the Earth Crust caused by Secondary Undulations of Tides in a Bay.*

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In the last number of this Bulletin,[1] the present author gave some account of the tilting motion of the earth crust caused by tidal loading. The present paper is a continuation of that work and describes the results of observation of the tilting motion of the earth crust caused by seiches or secondary undulations of tides in a bay with some discussions.

Our knowledges about the mechanical behaviour of the earth crust seem to be still meagre except for those deduced from the observations of earthquakes and from the experiments on the elastic properties of the constituent rocks of the crust.

Observations regarding the movements of the crust in a larger scale, or of its mechanical behaviour under the action of a force of a longer period than those playing rôle in the cases cited above, have been quite limited and wanted.

Block movements of the crust in meizo-seismal regions were brought to light by the results of the precise levellings carried out after the destructive earthquake which occurred recently in our country. Land blocks consisting the earth crust were proved to be able to change their directions of tilting quite independently to each other as if there were no elastic connections between them.[2] On careful examinations, however, of the results of these precise levellings carried out over seismic regions, the land blocks seem to be subjected to bendings as well as to tiltings.

Bending of a land block and other movements of a medium scale taking place in a block as the results of the isostatic force or other local causes, have escaped the eyes of geophysicists and the most of them are left untouched.

One class of the motion of the crust belonging to this category may

1) R. TAKAHASI, *Bull. Earthq. Res. Inst.*, 6 (1929), 85–108.

2) C. TSUBOI, *ibid.*, 6 (1929), 71–83.

be that due to the tidal loadings. In the last paper of the present writer, he studied a case of the last mentioned subject and pointed out, firstly, that the rise of the sea surface of the Aburatubo Bay, Sagami, by 34 cm. produces a tilting of $0''\cdot22$ of the crust at a point 22·6 metres distant from the nearest beach line; and, secondly, that the value of the effective rigidity of the crust increases abruptly at the distance of about 150 m. from the observing station. Moreover, it was suggested that the minute indentations superposed on the record of the tilting caused by tides may probably be due to the secondary undulations or the seiches of the sea water which are predominant in the Aburatubo Bay.

The present observation was undertaken to ascertain the last mentioned view and to know, if possible, how the elastic properties of the crust vary according to different periods of force which is being exerted on it. In the winter vacation of this year, the present author, with the kind assistance of Professor M. Ishimoto and Mr. N. Miyabe, made a series of simultaneous observations of the seiches in the Aburatubo Bay and of the tilting of the crust near the bay. The results obtained will be given in the following pages.

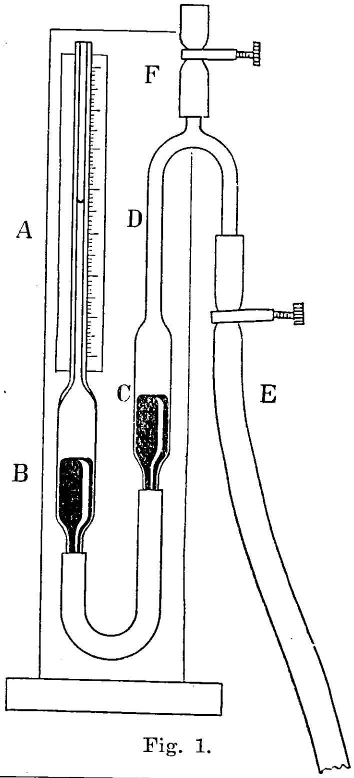


Fig. 1.

Apparatus.

The apparatus[3] used for the measurement of seiches in the present observation is shown diagramatically in Fig. 1. It consists essentially of two glass tubes *A-B* and *C-D* connected with each other by a piece of thick-walled rubber tube to form a U-tube. The tube *A-B* consists of a glass tube *B* 12 mm. in its inner diameter and 15 cm. long, and a capillary glass tube *A* with an inner diameter of 2 mm. and a length of 50 cm. connected with the upper part of *B*. The tube *A-B* is mounted on a stand with a scale behind the capillary part of the tube. The tube *C* is of equal diameter with *B* and is narrowed at the upper part *D*. The tube *C-D* is attached to the same stand with the tube *A-B* and its vertical position can be adjusted

3) Designed by Prof. M. ISHIMOTO.

up and down parallel to the tube *A-B*. One end of a long piece of thick-walled rubber tube *E* is connected with *D* and the other end is immersed in the sea water. The lower part of both *B* and *C* tubes are filled with mercury. The upper part of *B* is filled with sea water of a quantity such that the meniscus of the water reaches the middle part of the capillary tube *A* when the mercury head is at the middle point of the tube *B*. The part *D* of the tube *C-D* and the rubber tube *E* are filled with sea water, this being effected by sacking through a short branch tube *F* by mouth. A stop cock is provided to *E* to regulate and damp the quick oscillations of the sea water, thus facilitating the reading of the height of meniscus in the capillary tube *A*. The vertical position of the tube *C-D* is so adjusted that the mercury meniscuses in the tubes *B* and *C* will remain at their respective original positions in successive observations.

Denoting by *A, B, C, D* and *E* the heights shown in Fig. 2, we have

$$A\rho+B\rho'+E\rho=D\rho+C\rho',$$
$$B+C=\text{const.}=L,$$
$$C+D=\text{const.}=K,$$
$$\frac{d\,(A+B)}{dB}=\frac{S}{s}$$

where ρ is the specific gravity of sea water,
ρ' the specific gravity of mercury,
s the cross-sectional area of the capillary tube,
S the cross-sectional area of the glass tube under the capillary tube.

From these equations we have

$$\frac{d}{dE}(A+B)=-\frac{(S/s)\,\rho}{(S/s)\,\rho+2(\rho'-\rho)}.$$

As can be seen by this equation, the magnification coefficient of this apparatus approaches to unity as the ratio S/s increases.

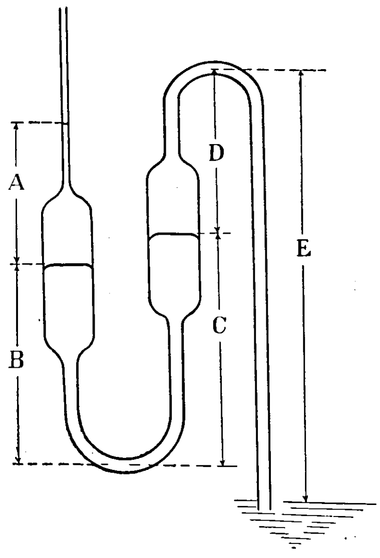


Fig. 2.

In the present observation of the seiches in the Aburatubo Bay, three of the apparatus of this type were used. In each of the apparatus, S was about 113 mm.^{2} and s 3·1 mm.^{2} Therefore, the ratio S/s was about 36. The calibration of the apparatuses made just before the observations gave the following respective constants:

Apparatus	No. 1	No. 2	No. 3
Magnification Coef.	0·557	0·663	0·586

The apparatus with which the simultaneous observations of the tilting of the earth crust were made was a pair of tiltmeters described in the last paper. As in the former observations the tiltmeters were installed in a horizontal cave on the hill side facing to the neck of the Aburatubo Bay. The position of the tilmeter is 22·6 m. distant from the nearest beach line and 8·7 metres high above the mean sea level. The sensibility of the tiltmeters was so adjusted in the present observation that they give 3 cm. deflection on the record when the crust is tilted by 1″. The recording drum was made to rotate once a day, the time marks being made automatically in every one hour by extinguishing the light source for two minutes interval.

Observation.

In each series of simultaneous observations of the seiches, the measuring apparatuses were installed at three points selected on the coast of the Aburatubo Bay or the Moroiso Bay, or sometimes of both, and observations

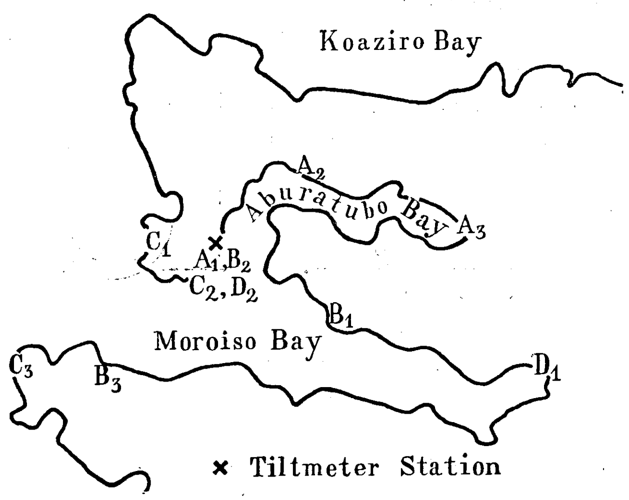
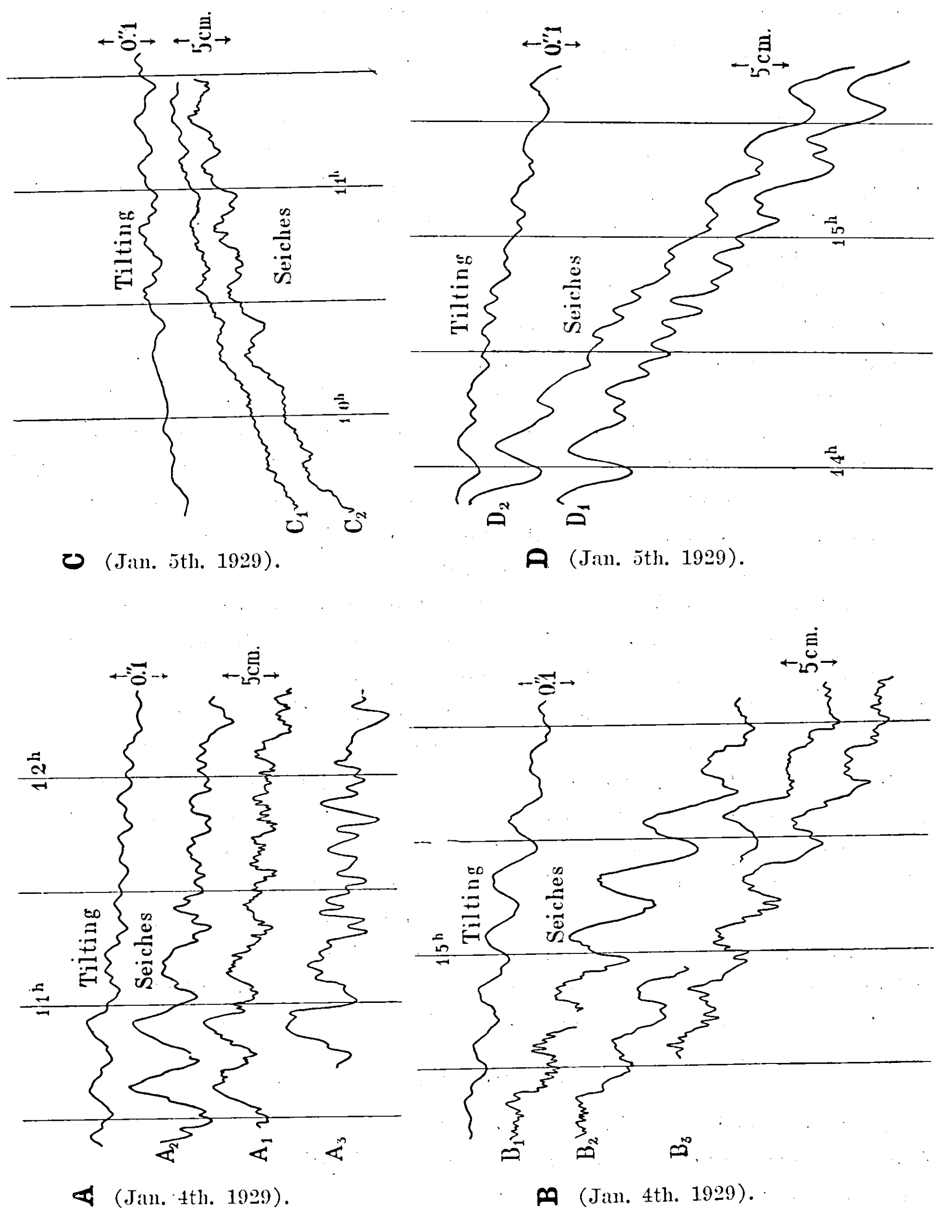


Fig. 3.

were made simultaneously at these three points in each set. In Fig. 3 the letters A, B, C, D and E indicate the positions of the sets of points where



A (Jan. 4th. 1929).
B (Jan. 4th. 1929).
C (Jan. 5th. 1929).
D (Jan. 5th. 1929).
Tilting
Seiches
0.″1
5cm.
11h
12h
15h
10h
14h
A1
A2
A3
B1
B2
B3
C1
C2
D1
D2

Fig. 4.

simultaneous observations were carried out and suffixes 1, 2 and 3 show the ordinal number of the appratus used at that point. Thus A_1 shows, for instance, that an observation was made at that point indicated by the letter using No. 1 apparatus, and that this observation was made simultaneously with those carried out at the points indicated by A_2 and A_3. The heights of the meniscus of the water in the capillary tube of the apparatus were measured at every thirty seconds, and the measurement was continued for two hours in each series of observations. The results of the observation are shown graphically in Fig. 4 together with the record obtained with the tiltmeters which is given at the top of each series.

From these results it has become clear that there is a foundamental oscillation of sea water with a period of 14–16 minutes having the node of the vertical displacements off the mouth of the Aburatubo Bay. Superposed on this oscillation there is another with which the sea water in the Aburatubo Bay oscillates in alternate phase with that in the Moroiso Bay. This mode of oscillation is of a period of about 7 minutes. Beside these two modes there seems to be still others (probably the third and higher harmonies) of periods less than 3·5 minutes.

The foundamental oscillation of the Aburatubo and Moroiso Bays was studied formerly by Professor K. Honda.[4] According to his results, the period of this oscillation is 13·8–15·0 minutes. It seems that the upheaval of the coast of the Aburatubo Bay connected with the Great Kwantô Earthquake has probably made the period of the seiches predominating in the bays a little longer. Comparison of the record obtained with the tiltmeter with the curves of the seiches observed at the coast nearest to the tiltmeter cave, shows that the indentations on the record of the tilting is quite similar to the curves of seiches proving that they are caused by the seiches in the bay. There seems to be neither lag nor advance in the phases of seiches relative to the corresponding tilting. The rise of the sea surface by 1 cm. produces the tilting of the crust of the amount of $0''\cdot0086$ which is 1·3 times as large as the corresponding tilting in the case of the tides.

Conclusion.

As was described in the last paper, the value of the effective rigidity of the earth crust undergoes a sharp increase at the distance of about 150 m. from the observing station. In other words, the load which is really effec-

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4) *Publication Earthq. Inv. Comm.*, **26** (1908).
Journ. Coll. Sci., Tokyo, **24** (1908).

tive in producing the tilting of the observing station is that located within the distance of 150 m. from the station. This characteristic relation regarding the effective rigidity of the crust, which was found to hold in the case of tides, seems to hold also in this case of seiches. The record obtained by the tiltmeter is quite similar to the curve of the seiches observed at a point 22 m. distant from the station, but is not so to those observed at points distant more than 150 m. from the station. The ratio of the amount of tilting of the crust to the height of seiches is, as is said above, 1·3 times as large as the ratio taken in the case of the lunar semidiurnal tide. This unequality of the ratios may be approximately accounted for by assuming firstly that the effective rigidity of the crust is a function both of the distance between the load and the observing station and of the period with which the load varies, and secondly that the shorter the period of the variation of the load is, the more rapidly the amplitude of the tilting motion decays with the distance from the load. The absolute depression of the crust caused by the load of the seiches may be much smaller than that caused by the load of the lunar tides, even if the amplitudes of the loads were supposed to be the same in both cases. The tilting of the crust at the observing station can on the contrary be greater for the former case. The tilting caused by a load with a shorter period is not, however, always greater than that by a load of a longer period. Whether the load of a longer period will produce a greater tilting at a given station than that of a shorter period or will not, depends on the relative position of the station to the load, the period of variation of the load and also on the functional form accordingly to which the effective rigidity of the earth crust at that station varies with the distance.

In conclusion, the author wishes to express his most cordial thanks to Professor M. Ishimoto and Dr. N. Miyabe for their kind assistance and to Professors T. Terada and C. Tsuboi for their valuable discussions.

5. 油壺灣內の海水の副振動に因る地殼の傾斜運動

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概 要

(1) 本論文は携持用檢潮器三臺と、一對の石本式傾斜計とを使用して、油壺灣內の副振動と、同灣の頸部に面する一地點に於ける地殼の傾斜變化とを同時に觀測し、以て兩者の關係を調査研究したものである。

(2) 檢潮器は第一圖に示せる如きものであつて、海面の昇降に伴ふ器內水銀面の昇降を、毛細管を利用して擴大し、海面昇降を約 0·6 倍にして讀取るものである。

(3) 檢潮器を油壺灣、諸磯灣の各所に据付けて副振動の同時觀測を行ひ、之を傾斜計の記錄と比較した。其の結果、傾斜計の記錄は傾斜計据付所脇に於ける副振動の記錄と全く相似であるが、傾斜計より 150 m 以上離れた場所に於ける副振動の記錄とは最早相似して居らぬ事が判明した。之に依つて見れば、地殼の有效剛性値は、太陰半日潮に對する場所と同じく、短週期の副振動に對しても亦觀測點より 150 m 以內の距離に於て急激なる增加を爲すものと思はれる。

(4) 油壺灣の入口に節を有する 14-16 分の週期の第一次振動に因る地殼の傾斜變化は、海面の上昇 1 cm に對して 0″·0086 の割合であつて、太陰の半日潮に對する値の約 1·3 倍となつてゐる。此の如く、海面變化に伴ふ傾斜の變化量の、海面變化に對する割合が兩者に於て其の値を異にする事實は、次の假定を作る事に依つて大體說明しうるのである。

(イ) 地殼の有效剛性値は觀測點と負荷との距離の函數なるのみならず、負荷の變化する週期の函數でもある事。

(ロ) 負荷變化の週期が少なる程、傾斜運動の振幅は觀測所海岸間の距離と共に速に減衰する事。

(5) 尙上記海水の第一次振動の外に油壺灣內の海水が、油壺灣に隣接する諸磯灣內の海水と交互に昇降する、約 7 分週期の振動も觀測された。