BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 55 (1980), pp. 331-345

16. *Observations of Seiche-Related Tilt in the Aburatsubo Observatory.*

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(Received May 19, 1980)

Abstract

It is known that the seiche in Aburatsubo Bay has the periods 13 to 16 min. In order to confirm the seiche theoretically, the author applies a Y-shaped topographical model to Aburatsubo and Moroiso Bays. As a result, it is shown that the free oscillation of sea-surface has the periods of 13.5, 7.6 and 5.1 min, which correspond to the fundamental, the second and the third harmonic waves, respectively. However, the second and higher waves cannot be detected by observation, probably because the node of the second harmonic is located near the tiltmeter station. The sea-surface behavior of Koajiro Bay seems ineffective on the seiche in Aburatsubo Bay.

The effect of the seiche on ground tilt has been observed by four sets of TEM tiltmeters and a pressure-type tide-gauge during the period February to May, 1979. The ratio of tilt and seiche amplitude is empirically determined as a function of the distance from the coast line on the basis of the results of observations. The ratio is greater than what we expected from the theory by the factor of 1.2∼1.3, but the direction of maximum tilt is in agreement at each observation site.

1. Introduction

The seiche is the free-oscillation of water at lake, bay or land shelf generated by meteorological or other causes. It has a constant period of oscillation determined by geometric dimensions such as length, width and depth of the water body.

The seiche in Aburatsubo Bay was first reported by OHMORI (1900) who was interested in the relation between the seiche and the tsunami. He investigated the seiche excited by the great tsunami accompanied with the off Sanriku earthquake on June 15, 1896 using the record of tide-gauge. The result showed that the seiche had a maximum amplitude of 10 cm and the periods 14.8 to 15.2 min. He also found that the seiche excited by the Saigoku typhoon on August 28∼30, 1899 had a maximum amplitude of 11 cm and the periods 14.2 to 15.3 min, and the wave of 3-min period was also included. HONDA et al. (1908) reported the observed period was 13.8 to 15.6 min and the theoretically calculated period was 13.4 min for Moroiso Bay, a south branch of Aburatsubo Bay.

Fifteen years later, in and around the Aburatsubo peninsula, the crust was upheaved by the Kanto earthquake on September 1, 1923. It was reported that the crustal upheaval reached 1.3 to 1.5 m. The post-earthquake observation indicated that the fundamental period of seiche in Aburatsubo Bay was 14 to 16 min and as the higher harmonics 7 and 3.5 min (TAKAHASHI, 1929). During and after the 1950s, these three bays have been reclaimed year after year and the shape of the bays have changed considerably. For the reclaimed Aburatsubo and Moroiso bays, it was found the periods to be unchanged.

There have been very few articles, however, which have discussed seiche in relation to the crustal tilt. The response of the crust to a seiche is important for investigating the elastic property of the crust in the intermediate frequency range between seismic and tidal waves. The observation of crustal tilt generated by the seiche in Aburatsubo Bay was only reported by TAKAHASI (1929). At that time, tiltmeters were not sensitive enough to detect such a small tilt as generated by the seiche. Nowadays, the accuracy of the measurements has greatly increased by the progress of instrumental techniques, and precise analyses become possible by the aid of electronic computers. The purpose of this study is to reconfirm the relation between the seiche and the crustal tilt on the basis of the actual data observed by four sets of TEM tiltmeters (TSUBOKAWA, 1970; TSUBOKAWA et al., 1970; TSUBOKAWA et al., 1974) installed in the Aburatsubo Observatory.

2. Location of the Observations

The Aburatsubo Crustal Movement Observatory is located at the southwestern tip of Miura Peninsula, about 60 km southwest of Tokyo, as shown in Fig. 1. In the underground vault the water-tube tiltmeters and quartz-tube strain meters are installed, and the data is continuously telemetered to the Earthquake Research Institute. The tide-gauge station of the Geographical Survey Institute (called GSI hereafter) is located very close to the vault (See Fig. 2).

The plan map of the vault is Fig. 3, which shows schematically the arrangement of the observational instruments. The entrance of the vault is shown at the right bottom corner of this figure, at which we can see

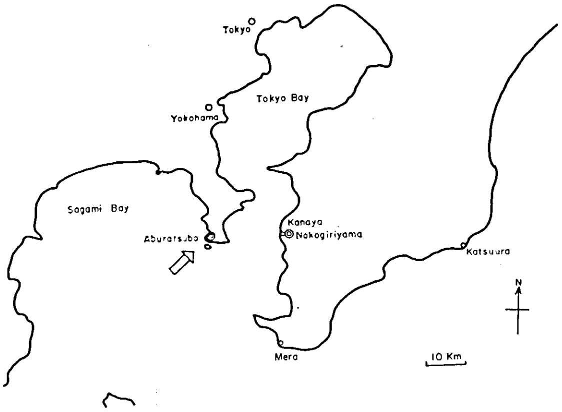

Fig. 1. Location map of the Aburatsubo Observatory.

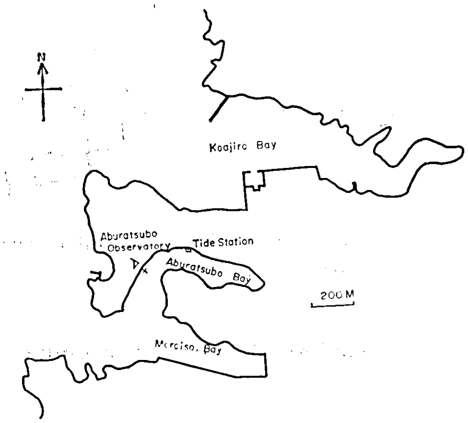

Fig. 2. Location map of the Aburatsubo tide and tiltmeter stations.

a number of shutters overcoming the influence of temperature changes. In the triangle-shaped vault, two sets of water-tube tiltmeters (denoted by WTT in Fig. 3) and three sets of quartz-tube strain meters (denoted by EXT) are arranged. ①~④ are the sites of TEM tiltmeters installed temporalily for the present study.

The tiltmeters ① and ② are both laid on the concrete blocks at the vault ends. On the other hand, the tiltmeters ③ and ④ are set directly on the floor where the base rock is coated thinly with mortar. Although such an installation may cause instrumental unstability, the tiltmeters have worked stably in actuality and the drift rate was not so large that the seiche-generated tilt could be easily extracted from the observed record.

The tide-gauge data is also used for the present study. In the early stage of the study, we used the tidal record of the Aburatsubo Tide Station by courtesy of the GSI, but later a PD-500GD pressure gauge (manufactured by Kyowa-Dengyo Co. Ltd.) was installed at sea-bottom nearby the vault. The site of the pressure gauge is shown as the symbol X in Fig. 3. The horizontal distance between the tiltmeter site ① and the pressure gauge is about 40 m.

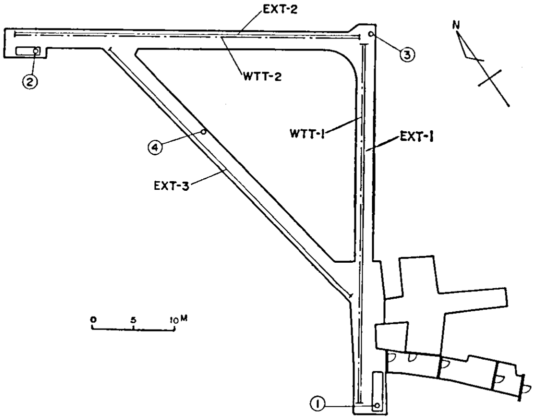

Fig. 3. Plan of the vault of the Aburatsubo Crustal Movement Observatory.

3. Specification of the Instruments

TEM Tilmeter

The TEM tiltmeter used here is a kind of horizontal pendulum-type tiltmeter devised by TSUBOKAWA (1970) and TSUBOKAWA et al. (1970). The cross suspension pendulum detects a change in tilt through a differential transformer. In the observation vault, the tiltmeter is usually put on the calibration plate, the inclination of which is made by turning a fine adjustment screw through the two-step reduction levers.

The sensitivity of the tiltmeter exceeds 0.2×10^{-3}sec of arc/mm on the recording paper. The sensitivity can be changed by using the fine adjustment screw to displace the weight of the pendulum vertically. The instrumental drift rate is smaller than 1×10^{-6} (0.2 sec of arc) per year. The sensitivity characteristics of TEM tiltmeter is shown in Table I.

The TEM tiltmeter has been actually used for many field measurements, such as Nokogiriyama (TSUBOKAWA et al., 1970) and Akagane in Japan, Walferdange (TSUBOKAWA et al., 1974) in Luxembourg, etc. These

Table I. Sensitivity characteristics of TEM tiltmeters used.

Obs. site	Comp.	Inst. Number		Mean sensitivity (10^{-3}sec. of arc/mm)
		Senser	Table	
①	E—W	S—7	S—10	4.88
①	S—N	S—5	S—5	1.35
②	E—W	T—1	T—4	0.582
②	S—N	T—3	T—3	0.778
③	E—W	T—4	T—1	1.03
③	S—N	T—2	T—2	0.549
④	E—W	S—4	S—1	1.32
④	S—N	S—6	S—4	0.816

measurements have proved the stability of the instrument for a long-term observation of tilt change.

Pressure Gauge

Simultaneously with the GSI float-type tide gauge, the pressure gauge is used for detecting sea-level changes related to seiche. The measuring range of the gauge covers 0∼0.5 $\mathrm{Kg/cm^2}$ with the sensitivity of 1 mV/1 V at full load. The non-linearity of the output is restricted within one percent of full scale. The calibration of the gauge was carried out by dipping the gauge into sea-water in a cylindrical container in the present study.

4. Observations of Seiche-Induced Tilt

The seiche in Aburatsubo Bay is known as a free-oscillation of sea-water level with the period of about 13 to 15 min. As previously mentioned, the tidal record from the GSI float-type tide-gauge is available for investigating the frequency characteristics of the seiche. Moreover, for the purpose of clarifying the behavior of the seiche, the pressure-type gauge measurement has been made in the sea-bottom nearby the vault entrance. The pressure gauge observation has been simultaneously made to the GSI gauge observation, and the comparison test has proved a good agreement between these two types of instruments in the case of diurnal and semidiurnal tides.

The observation of the seiche-induced tilt is carried out at the sites of ① to ④ (see Fig. 3) in the Aburatsubo Observatory vault by four sets of the TEM tiltmeters. In the hope of clarifying the relation between the amplitude of seiche and the distance from the sea-coast, such sets of TEM tiltmeters are arranged within the vault.

Fig. 4 shows examples of the GSI float-type data (A) and the cor-

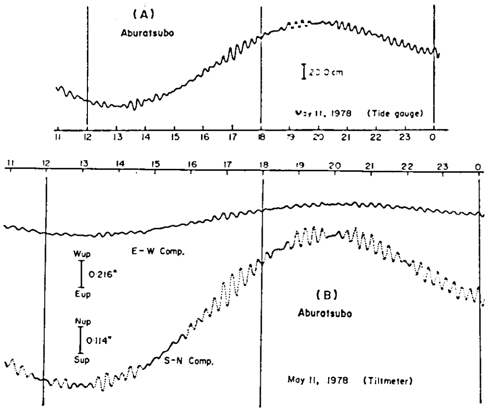

Fig. 4. Records of the GSI float-type tide gauge data (A) and the corresponding tilt (B)

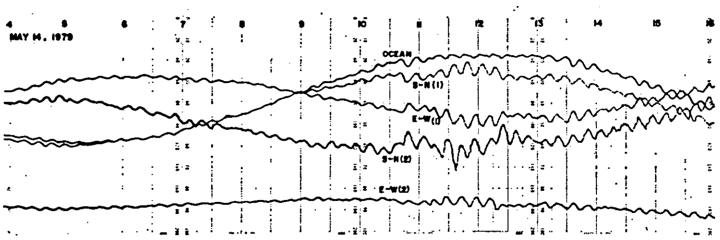

Fig. 5. Records of pressure gauge and tiltmeters.

responding tilting change components (B). Fig. 5 shows examples of the pressure gauge data (denoted by OCEAN in Fig. 5) and the corresponding components of tiltmeters ① and ②. Good correlation can be obviously seen between the tide gauge and tiltmeter records. The obtained results are summarized in Table II.

The data processing method of the tidal record is accomplished in the following way. The amplitude of the record is first read by an X-Y digitizer with a time interval of 0.3 min. Afterwards, the Fourier analysis is applied to the data obtained successively during a time span of 3.6 hours, because the seiche in Aburatsubo Bay has the duration of about 3 to 4 hours. A similar method is applied to the tiltmeter records.

The frequency characteristics of the tide gauge data and the tilting data is given in Fig. 6. It is obvious that the frequency-amplitude curves of the seiche (A) and tilt (B) have peaks at about 13 to 15 min. We can also see the fact that the peaks are split into two parts, i. e. 13.5 and 15.5 min, which correspond to the seiche of high tide and low tide respectively. The mean amplitude of the fundamental seiche waves

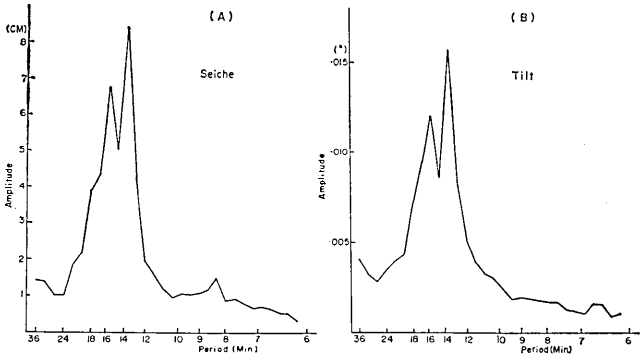

Fig. 6. Frequency characteristics of the seiche and tiltmeter data.

amounts to 85 mm.

However, the 2nd and 3rd harmonic oscillations are not clear in Fig. 4 and 5. As will be mentioned in the forthcoming section, the theoretical estimation clarifies that the 2nd and 3rd harmonic waves have the periods of 7.6 and 5.1 min, respectively. The frequency characteristics of the seiche-induced tilt change is quite similar to that of the seiche. The 2nd and 3rd harmonic tilt changes are also ambiguous in Fig. 4 and 5. The cause of absence of these waves is attributed to the nodal point which is located in the neighborhood of the vault entrance, where the pressure gauge is installed.

5. Distance-Tilt Relation

The observed data given in Table II indicates that the amplitude of seiche-induced tilt has a tendency to decrease with the distance from the coastline of Aburatsubo Bay. Such a tendency can be expected because the sea-water loading due to seiche causes a small amount of ground bending restricted locally to a seaside area.

The distance from the coastline increases in order of ①, ③, ④ and ② tiltmeter sites. The distance-tilt relation thus obtained is shown in Fig. 7. It is seen that an exponentially decreasing curve with the distance can be fitted to the observed tilt data, so that the following formula can be assumed

$$T=C\exp(-\lambda D), \tag{1}$$

where T is the ratio of the seiche-induced tilt to the seiche amplitude, D the distance from the coastline, and C and λ the constants. The least square method is applied to the obtained ratio in the semi-logarithmic coordinates, and determines these constants to be 11.7 (in the unit of

Table II. Observation data of tilt and seiche.

Obs. site	①		②		③		④		Seiche (mm)
Distance (M)	27.5		73.0		32.8		49.3		
Component / Date	E—W	S—N	E—W	S—N	E—W	S—N	E—W	S—N	
Mar. 21	7.33	5.57	1.63	5.22	3.54	6.12	3.71	3.23	150
〃 〃	7.91	6.48	1.55	5.13	3.75	5.67	3.55	3.01	139
〃 23	5.64	7.87	1.88	4.91	3.89	6.45	3.79	3.22	150
〃 31	5.63	6.29	1.57	3.70	3.56	5.02	2.93	2.69	240
Apr. 4	5.91	7.84	2.28	5.56	3.99	6.99	4.46	3.52	176
〃 〃	7.22	7.85	2.33	4.77	4.31	7.43	4.34	3.40	144
〃 6	5.98	6.07	1.46	4.68	3.33	5.63	3.39	3.29	149
〃 12	7.40	6.69	2.04	4.23	3.75	5.09	3.28	2.60	154
Apr. 16	6.63	6.34	1.34	4.58	2.36	5.96	2.09	3.80	148
〃 20	5.89	7.41	1.57	4.22	4.05	5.40	3.12	3.40	185
〃 21	7.55	8.35	2.47	4.21	3.82	5.42	2.69	3.47	188
〃 〃	7.97	8.49	2.40	4.06	4.39	6.41	3.22	4.18	192
Mean	6.76 ±0.90	7.10 ±0.98	7.10 ±0.41	4.61 ±0.54	3.73 ±0.53	5.97 ±0.75	3.38 ±0.66	3.32 ±0.43	
Amplitude	9.80±0.94		4.98±0.52		7.04±0.70		4.74±0.56		
Azimuth (°)	−43.6±5.5		−22.2±5.0		−32.0±4.9		−45.5±6.7		

(Unit; 10^{-5}sec. of arc/mm)

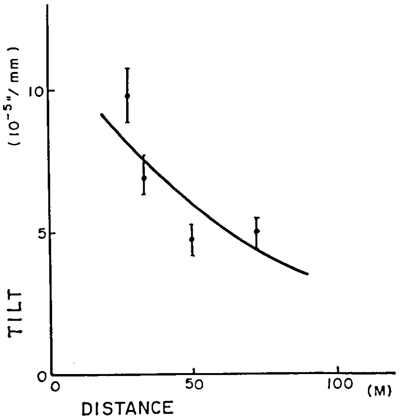

Fig. 7. Relation between the ratio of tilt and seiche amplitude against the distance from the coast line.

10^{-5}sec of arc/mm) and 0.0135 (in the unit of m^{-1}).

The expression with tilting vectors is very useful for the investigation of the behavior of the seiche-induced bending. The arrows in Fig.

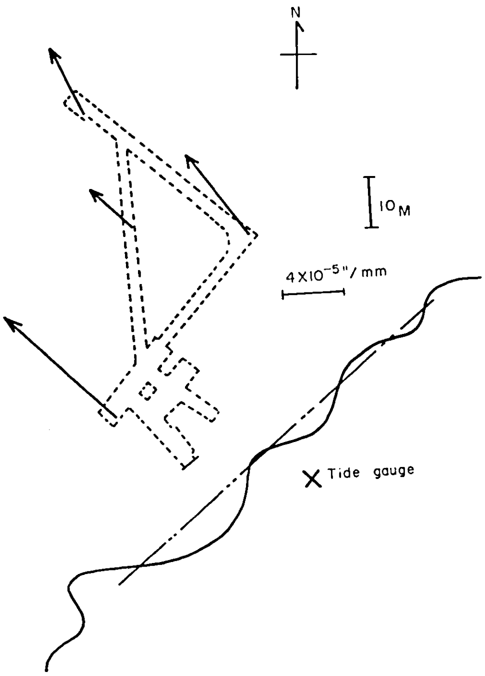

Fig. 8. Vector expression of the seiche-induced tilts.

8 illustrate the average amplitude and the direction of maximum tilt. It is obviously seen that the vectors orient landward almost perpendicular to the coastline. This fact is quite consistent with what can be expected.

6. Model Calculations

The theoretical approach to the water-level oscillation due to seiche has been first made by NEUMANN (1944a, 1944b) on the analogy of the input-output theory of an electronic circuit. The analytical method used in this paper is similar to those treated by SNODGRASS et al. (1962), MUNK et al. (1964) and AIDA (1967) for long-period waves on the continental shelf.

First, we solve the equation of incompressible fluid motion on the assumption that the effect of viscosity on the motion is negligibly small and the wave height is small in comparison with the wave-length. For numerical computations, the configuration of the bay is approximately divided into small segments. As illustrated in Fig. 9, the computation covers not only Aburatsubo and Moroiso Bays but also a relatively extensive area outside of the bays. The configuration data of the bays and the neighboring sea-bottom is obtained from both the bathymetric chart

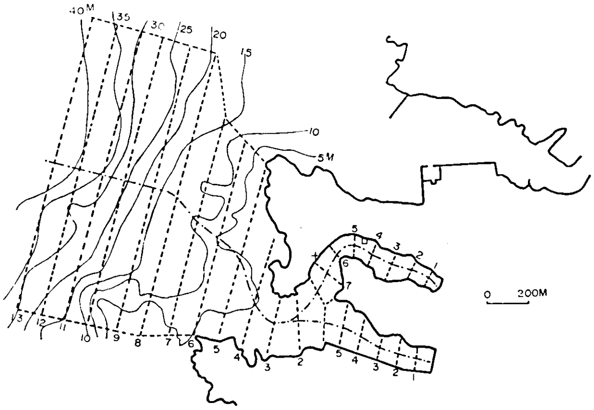

Fig. 9. Configuration for numerical computations of seiche in Aburatsubo and Moroiso Bays

(scale: 1/25,000) of the Hydrographic Office, the Maritime Safety Agency, and the 1/3,000-scaled chart fathomed by KOBAYASHI (unpublished). Although these two charts are somewhat different each other in the mean sea level, we choose the sea level so as to coincide the calculated fundamental period of seiche with the observed one, i. e. 13.5 min.

The theoretical frequency characteristics of seiche in Aburatsubo and Moroiso Bays is obtained on the basis of the above numerical procedures. Fig. 10 shows the frequency characteristics thus obtained. It is seen in this figure that the fundamental, 2nd and 3rd oscillations have the periods of 13.5, 7.6 and 5.1 min, respectively. The period of seiche is inversely proportional to the square-root of the water depth, so that, as previously

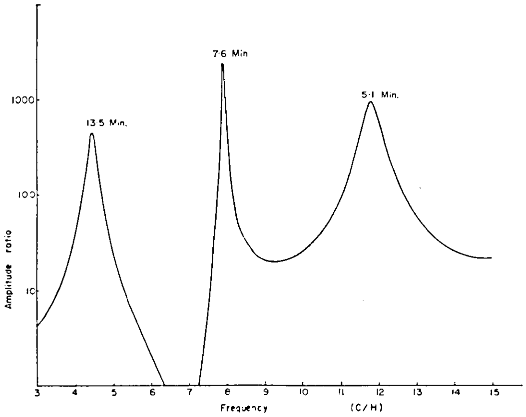

Fig. 10. Theoretical frequency characteristics of seiche in Aburatsubo and Moroiso Bays.

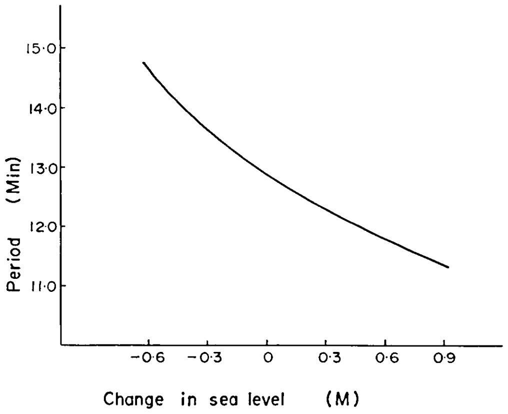

Fig. 11. Relation between the period of the fundamental seiche oscillation and the change in sea level.

mentioned, we can choose an appropriate mean sea level so as to coincide the calculated period with the observed one. Fig. 11 shows the relation between the fundamental oscillation period of seiche and the change in sea level. It is noteworthy in Fig. 10 that there is an interruption of the spectrum curve between the fundamental and 2nd oscillations, and that the 2nd has a sharp peak. These facts may be explained as the resonance of sea-water between Aburatsubo and Moroiso Bays. HONDA et al. (1908) have once estimated the period of seiche in Moroiso Bay as 13.4 min, almost equal to what the author calculates in this paper.

Fig. 12 shows the calculated amplitudes of the fundamental, 2nd and 3rd waves both in Aburatsubo and Moroiso Bays. In Fig. 12, the horizontal positions are indicated by section numbers as illustrated in Fig. 9.

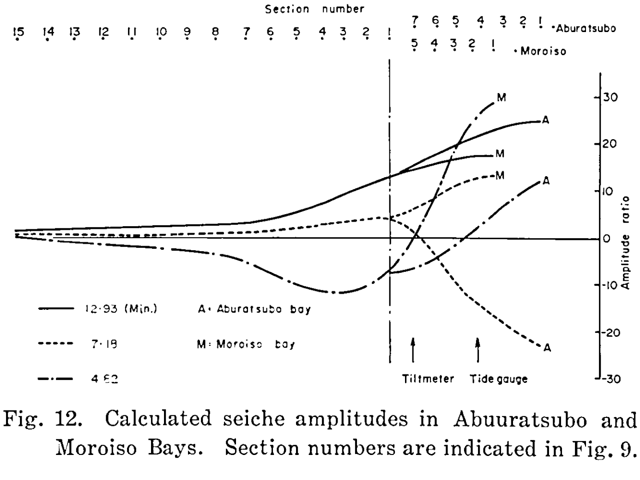

Fig. 12. Calculated seiche amplitudes in Abuuratsubo and Moroiso Bays. Section numbers are indicated in Fig. 9.

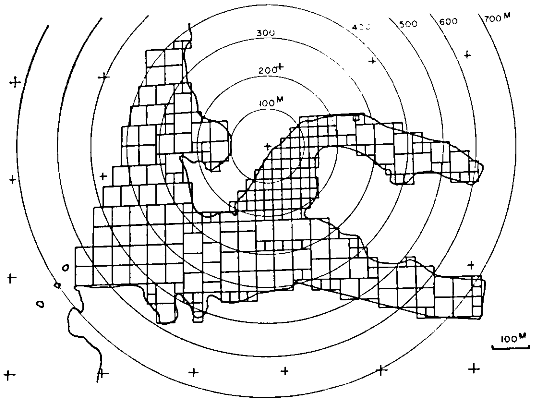

Fig. 13. Segments for numerically calcualtion of seiche-induced tilt.

Fig. 12 also indicates that the nodal point of the 2nd wave is located at a sea-coast near the observation vault. This can be evidence for the fact that, as seen in Fig. 6, the observed frequency spectrums of the seiche and the seiche-induced tilt in Aburatsubo and Moroiso Bays exclude the 2nd and 3rd oscillation modes.

It is necessary to estimate the effect of seiche in Koajiro Bay on the tilt change. In this sense, a similar computation is made for Koajiro Bay, and the periods of the fundamental, 2nd and 3rd oscillations are determined as 11.7, 6.5 and 5.2 min. The fact that the oscillation mode of Koajiro Bay is different from that of Aburatsubo and Moroiso Bays may imply the independent behavior of sea-water to each other.

Second, the tilt change response to the calculated model of seiche is estimated by summing up loadings of the sea-water volume segments. In this paper, Farrell's table (FARRELL, 1972) using the Gutenberg-Richter model earth is adopted as the method for calculating the seiche-induced tilt. For estimating the load, the bays and the adjacent sea area are divided into many segments as illustrated in Fig. 13. The calculated seiche-induced tilt is the total effect of the load of each segment

Table III. The observed and the calculated tilt.

Obs. site	Distance	Observation		Calculation	
	(M)	($10^{-5}{''}$/mm)	(°)	($10^{-5}{''}$/mm)	(°)
1	27.5	9.80	−43.6	6.40	−41.1
3	32.8	7.04	−32.0	6.00	−33.6
4	49.3	4.74	−45.5	5.50	−33.2
2	73.0	4.98	−22.2	3.26	−28.4

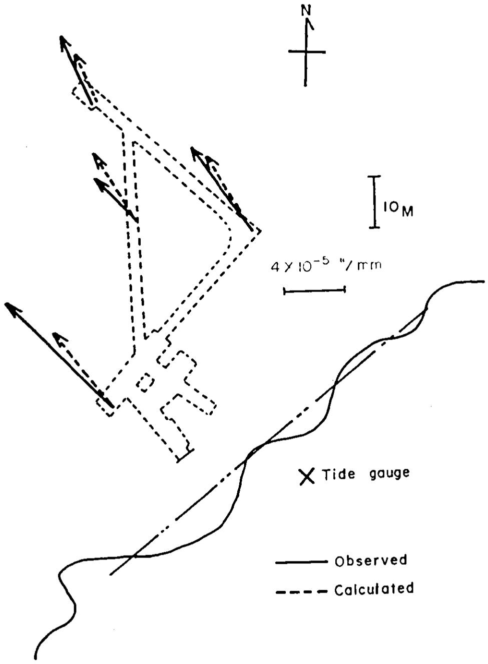

Fig. 14. Comparison between the observed and the theoretical seicheinduced tilts.

on the tilt field plus the tilt change due to the attraction of sea water. As a result, the effect of sea water within a radius of 200 m around a tilt station amounts to about 80% of the total effect.

The calculated results together with the observed results are given in Table III. Fig. 14 shows the vector representation of the observed tilt (solid line) and the calculated tilt (dashed line). As compared with both the results, we can see that the azimuths agree well each other but the calculated amplitudes are less by about 20% than the observed ones. Such differences may largely depend on settings of segments.

The Gutenberg-Richter model earth used in Farrell's table is perhaps inappropriate for the local elastic feature of the Aburatsubo area. The fine structure of the crust here, however, is not known, therefore the local elasticity cannot be taken into consideration for the present study. The Boussinesq problem in the Cartesian coordinates is better applicable to the treatment of the local elasticity than the Farrell problem.

The shape of the vault structure is effective on tilt observations, but the correction for this effect is not made in the present study. Judging from the fact that the frequency spectrum of seiche-induced tilt resembles that of seiche in Aburatsubo and Moroiso Bays, it is not necessary to take into account the effect of seiche in Koajiro Bay on the tilt observations.

7. Conclusion

The seiche in Aburatsubo Bay has been observed as a free-oscillation of sea level with the period of fundamental wave about 13.5 to 15.5 min. The second harmonic wave, however, has not been observed probably because the observation site had been located near the node of oscillation. The theoretically estimated seiche in Aburatsubo Bay has the periods of 13.5, 7.6 and 5.1 min, which correspond to the fundamental, the second and the third harmonic waves, respectively.

The observation of the seiche-induced tilt has also been carried out at the multiple sites in the Aburatsubo Observatory vault by four sets of TEM tiltmeters. The results of observation are tabulated in Table II. It is concluded that the amplitude of seiche-induced tilt has a tendency to decrease with distance from the coast line of Aburatsubo Bay.

The model calculation proves that the difference between the directions of maximum tilt observed and theoretically obtained is comparatively small, but the observed amplitudes of tilt-seiche ratio are slightly larger than the calculated ones.

In this paper, we used the Farrell table for estimating the loading effect of seiche on the tilt field. This table was based on the Gutenberg-Richter model earth structure which may not have been suitable for the local surface structure. The seiche-related tilt is thought to be a usefull tool for the study of the local fine structure of the crustal surface if compared with the model structure.

Acknowledgements

The author is greatly indebted to the Tide Branch members of the Geographical Survey Institute for offering the use of the tidal data, to Prof. K. Kasahara and Mr. T. Takahashi, the Earthquake Research Institute, for their cooperation with the observation, and Dr. I. Aida, the Earthquake Research Institute, for his advice of the seiche analyses.

The author also wishes to thank Prof. Y. Hagiwara, Dr. I. Murata and Dr. K. Nagasawa, the Earthquake Research Institute, for their encouragements and valuable suggestions throughout the course of this study.

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油壺観測所におけるセイシュに関連した傾斜の観測

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油壺湾におけるセイシュの固有振動周期は，かなり以前より13～16分であることが知られていた。このセイシュの様相を理論的に求めるためにY字形の一次元モデルを，油壺と諸磯の両湾に適用して計算を行なった。その結果，海水表面の自由振動は，基本波・第2高調波・第3高調波の順に13.5, 7.6, 5.1分であった。油壺検潮所（国土地理院）の GSI 形検潮儀の記録より求めたものは13.5と15.5分の2つのピークをもった基本波成分のみで，高次の成分は明瞭ではなかった。

セイシュに関連した傾斜観測は，油壺観測所の観測坑内の4点において，TEM 傾斜計を用いて行なった。先のGSI形検潮儀と同時に観測した傾斜観測データの周波数特性は，セイシュの分析結果に極めてよく一致している。次に，観測坑入口近くの海中に圧力型センサを投入してセイシュを観測し，このセイシュに関連した傾斜を同時に観測した。そして，セイシュとセイシュに関連した傾斜が，海岸線からの距離によって減衰することをたしかめた。またこの距離に関係したセイシュによる傾斜を理論的に計算して求める試みも行なった。それによると振幅の比は 20～30% の差があったが，その最大傾斜の方向はかなりよい一致が得られた。