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75. Study on the Relation between Local Earthquakes and Minute Ground Deformation

Part 1. On Some Statistical Results from Local Earthquakes Occurred in the Wakayama District

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1. Itroduction

It is well known that characteristic crustal deformations such as upheaval, subsidence and horizontal displacement are often found after the occurrence of a destructive earthquake near the epicentral region. For investigation of these deformations, level surveying and triangulation were commenced in Japan shortly after the Nōbi Earthquake in 1891 and much work has been done to study the relation between the earthquake-occurrence and ground deformation since then[1~5], while the highly sensitive tiltmeter of a horizontal pendulum type and a linear strainmeter were devised and have been employed in study of earth tides and the crustal deformation as station instruments[5~11]. In 1943, K. Sassa and E. Nishimura detected a peculiar tilting motion of the ground which appeared ten hours before the occurrence of the Tottori Earthquake at Ikuno[12]. Thereafter, several similar phenomena were observed, supposedly connected with destructive earthquakes[13~15], and it has become trustworthy that the geodetic measurement of the crustal deformation by triangulation and leveling is one of the promising ways to elucidate the mechanism of earthquake-occurrence and further to predict it, supplementing time variation of the deformation with continuous observations by tiltmeters and extensometers at a point in some region as a fixed station.

More than twenty observation stations are being operated for the continuous observation of the crustal deformation by the Disaster Prevention Research Institute at present. Recently, several examples of the anomalous crustal deformations which preceded destructive earthquakes, including the Ōdaigahara Earthquake, have been observed and discussed in connection with the mechanism of the generation of the earthquakes[16~20]. On the other hand, secular tilting motions of the ground at some observation stations were analyzed in reference to a series of earthquakes which occurred in a certain restricted area, and it has been demonstrated that the modes of the crustal deformations corresponded to those of the energy release and the generation mechanism of the series of earthquakes in Hyūganada and the Southern Kinki District[21,22]. But, because of the rare occurrence of great earthquakes in a few selected areas where the crustal movement has been continuously kept under observation, it requires a long time to collect sufficient data on anomalous crustal deformation connected with earthquakes. Now, if it is true that small local earthquakes are also correspondingly accompanied by small deformations of the ground close by the epicenters, an observation of these phenomena in any active area of small local earthquakes will give us a sufficient amount of data for a short period, and consequently some useful clues for elucidation of the accumulation process of energy of earthquakes and the mode of its release, further prediction of an earthquake occurrence.

For the purpose above stated, observations of the ground movement and local earthquakes by highly sensitive tiltmeters, extensometers and short period seismographs have been kept up at Oura and Akibasan in Wakayama City since March, 1960.

As is generally known, observation of the crustal deformation with these instruments must be made in a deep adit to avoid effects from meteorological disturbances. But both observation rooms in the present case are shallowly situated and near the sea coast, so that the ground deformations observed are extremely affected not only by meteorological change, but also by oceanic tides. Consequently, elimination of these disturbing factors is necessary in order to obtain the crustal deformation connected with local earthquakes which may be, in some cases, similar to destructive earthquakes. Treatments about removal of the annual variation of the deformation due to precipitation have been shown in the case of the secular variation of the ground deformation by I. Ozawa[23], M. Takada[24] and others[25,26]. A. Imamura and others[27] investigated the crustal deformation with regard to the activity of the local earthquakes at Wakayama District from the result of level surveying. We have begun with the elimination of the disturbances within a period of one or two days, seeking the instantaneous crustal deformation at the time of occurrence of an earthquake, as well as just before and after[28]. In this article we show some statistical treatments about the data from the seismological observation and a tentative method for elimination of the obstructive deformations of the ground.

2. Observation stations and instruments

Observation of the ground deformation and local earthquakes was commenced on March 27, 1960, at Oura in Wakayama City. In this distict local earthquakes have been felt very frequently, and precise seismological observations have been made by S. Miyamura[29] and T. Mikumo[30]. It is shown by S. Miyamura that the foci of the local earthquakes are distributed mainly from 3 to several km under the surface near Wakayama City, where the foci are the shallowest in this district[31]. Oura station is on the northern slope of Mt. Takatsushi (135°09′30″E., 34°11′16″N.) ; the height and depth of the observation room are about 50 m above sea level and 5 m beneath the ground surface, the bed rock of the observation room being weathered crystalline schist, while the instruments with which the Oura station is equipped are shown in Table 1.

Akibasan observation station was set up at a small hill called Akibasan on July 14, 1960, being about 1 km distant from Oura, in order to fill up and verify the results observed at Oura ; the depth of the observation room is about 10 m and the bed rock is crystalline schist too (135°10′23″E., 34°11′48″N.).

TABLE 1.
List of instruments at Oura.

Instument	Type	Azimuth	Sensitivity	Mark	Recorder speed
Tiltmeter	Horizontal pendulum	*E-W*	0.007″ /mm	*Ao*	180 mm/hour ; Mar, 26 —Aug. 29, 1960
		N-S	0.005″ /mm	*Bo*	
Extensometer	Benioff	*E-W*	2.8×10^{-9}/mm	*Eeo*	30 mm/hour ; Aug, 12, 1960 —Sept. 15, 1961
		N-S	5.0×10^{-9}/mm	*Eno*	
Barometer	Aneroid		0.18 mb/mm	*Po*	7 mm/hour ; Sept. 15, 1961 —Present
T ermometer	Bimetal		0.01°C /mm		
Seismometer	Variable reluctance	*E-W*	T_p=0.50 sec.		30 mm/min ; Mar. 26 —June 22, 1960
		N-S	T_g=0.33 sec.		75 mm/min. ; July 25 —Nov. 25, 1960
		U-D	V=3000 with shunt		12 mm/min. ; Nov. 25, 1960 —present

TABLE 2.
List of instruments at Akibasan.

Instrument	Type	Azimuth	Sensitivity	Mark	Recorder speed
Tiltmeter	Horizontal pendulum	*E-W*	0.004″ /mm	*Aa*	180 mm/hour ; July 15 —Aug. 12, 1960
		W-E	0.007″ /mm	*Aa′*	30 mm/hour ; Aug. 12, 1960 —Sept. 15, 1961
	//	*N-S*	0.004″ /mm	*Ba*	
		S-N	0.007″ /mm	*Ba′*	
Extensometer	Benioff	*E-W*	3.1×10^{-9}/mm	*Eea*	
		N-S	2.3×10^{-9}/mm	*Eea*	
Barometer	Aneroid		0.11mb /mm	*Pa*	7 mm/hour ; Sept. 15, 1961 —Present
Thermometer	Bimetal		0.01°C /mm		

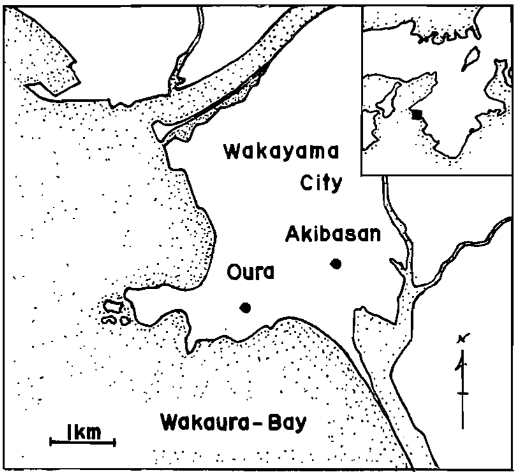

Fig. 1. Location of observation stations and their surroundings.

As will be discussed later, Akibasan station is considered to be more suitable for observation of the ground deformation than Oura, probably because of its deeper situation compared with that of Oura, and the difference of position of the room, namely at the foot of a hill in the case of Akibasan and on a mountain slope in the case of Oura. Table 2 shows the instruments at Akibasan station. At Akibasan station, two sets of the tiltmeters of the horizontal pendulum type have been operating in order to examine the instrumental error. The geographical situation of the stations is shown in Figure 1.

3. Some results on observation of local earthquakes

Seismometric observation was carried out to investigate the activity of local earthquakes at Oura by one vertical electro-magnetic seismograph of R_1 Type[32], while two seismographs of horizontal component and one of vertical were operated in a period from July 25 to November 27, 1960. As is seen in Figure 2, the frequency distribution of P-S duration time of the local earthquakes recorded at Oura station gives the maximum values in the interval between 0.9 and 1.0 sec.

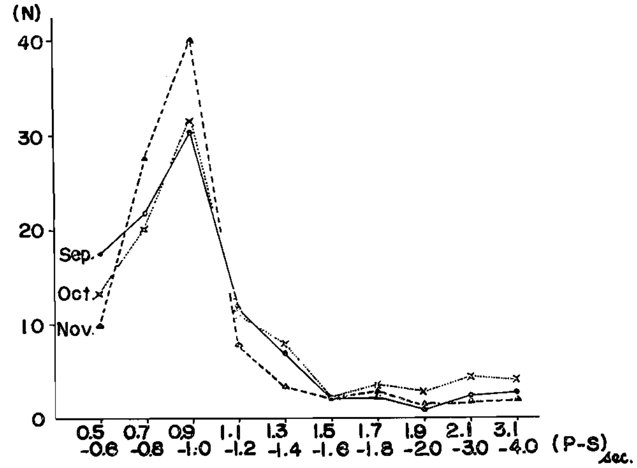

Fig. 2. Frequency distribution of P-S duration time at Oura. (Sept.-Nov., 1960)

In the following examinations, we treat the local earthquakes, P-S duration times, or the durations of the shock, if S waves are not so clear, shorter than 2 sec.. Figure 3 shows the relation between the maximum trace amplitudes and numbers of earthquakes. It is concluded that Ishimoto-Iida's coefficient is about 1.9 in this district, which is in accord with Miyamura's result[33]. The number of local earthquakes at Oura in one day, which might be considered to represent approximately the activity of the local earthquakes in this area, varied considerably as shown in Figure 4, even though some of the earthquakes were probably overlooked by the instrumental and observational errors. The numbers of the earthquakes appear to take smal-

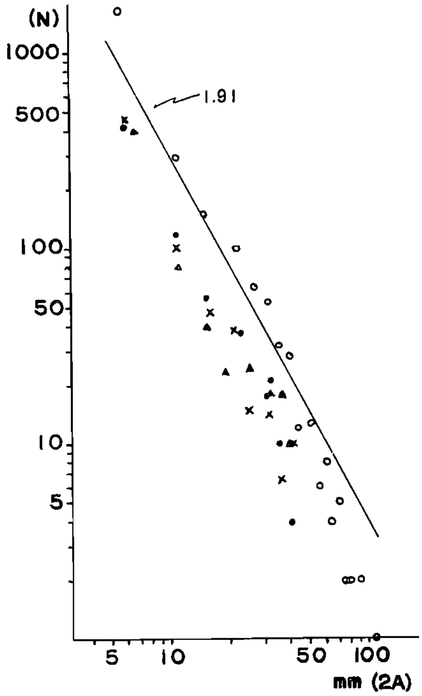

Fig. 3. Frequency distribution of the maximum trace amplitude at Oura.
(○ : Sept.-Nov., ● : Sept., × : Oct., ▲ : Nov., 1960)

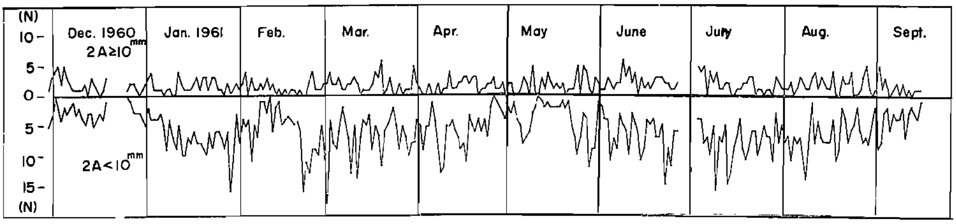

Fig. 4. Changes of the local earthquakes in one day at Oura.
(A : Maximum trace amplitude)

ler values in February and May, but J. Kinoshita reported that unfelt earthquakes tended to occur generally more in summer than in winter and felt earthquakes reached the maximum in February and August, and the minimum in May and October in this district[34]. We cannot conclude whether the tendency which appears in the Figure is an annual variation of earthquake-occurrence or a temporary behavior because of the shortness of the period of observation.

Next, in order to investigate the daily variation of earthquake-occurrence, we carried out harmonic analysis about the mean numbers of the earthquakes per one hour for the solar and lunar time, the period of the analysis being from November 25, 1960 to September 15, 1961 and from December 27 to May 31, 1961 for solar and lunar time variation, respectively. Now, when y_i is the number of earthquakes which occurred from i (o'clock) to $i+1$ in a fundamental period, we represent y_i as

$$y_i = a_0 + \sum_{\nu=1}^{q} \{a_\nu \cos \nu x_i + b_\nu \sin \nu x_i\} \quad (i=1, 2, \cdots\cdots, p)$$

and then the harmonic coefficients a_0, a_ν and b_ν are obtained from the following equations by the method of least square,

$$a_0 = \frac{1}{p} \sum_{i=1}^{p} y_i, \quad a_\nu = \frac{2}{p} \sum_{i=1}^{p} y_i \cos \nu x_i, \quad b_\nu = \frac{2}{p} \sum_{i=1}^{p} y_i \sin \nu x_i,$$

where

$$x_i = i\left(\frac{2\pi}{p}\right), \quad 2q+1 \leqslant p.$$

If the total number of the earthquakes is distributed at random in the refering intervals, the mean of the relative amplitudes $c_\nu' = \sqrt{a_\nu'^2 + b_\nu'^2}/a_0'$ obtained from a_ν', b_ν' and a_0' by harmonic analysis for this distribution is defined as "expectancy" and presented by the following equation,

$$\varepsilon = \sqrt{\frac{\pi}{n}},$$

where ε is independent of ν. Then, the probability $W(k)$ that the relative amplitude c_ν' becomes smaller than $k\varepsilon$ is given by

$$W(k) = e^{-\frac{\pi}{4} k^2}.$$

Hence, we can estimate the probability that c_ν arises by chance, from the

TABLE 3.
Result obtained from harmonic analysis of the numbers of the local earthquakes.

	Solar daily variation $n=1788$ $\varepsilon=0.0419$ $a_0=74.5$		Lunar daily variation $n=1371$ $\varepsilon=0.0478$ $a_0=57.125$	
ν	C_ν	W	C_ν	W
1	0.06712	0.1	0.12184	0.007
2	0.05409	0.3	0.01138	1.0
3	0.04631	0.4	0.01085	1.0
4	0.01463	0.9	0.05812	0.3
5	0.04664	0.4	0.05532	0.3
6	0.05664	0.3	0.07300	0.2
7	0.03852	0.5	0.07965	0.1
8	0.01961	0.9	0.02941	0.8
9	0.02604	0.8	0.02958	0.8
10	0.10000	0.01	0.02433	0.8
11	0.02550	0.8	0.04674	0.5

n : Total number of earthquakes, ε : Expectancy, $C_\nu = \sqrt{a_\nu^2 + b_\nu^2}/a_0$, $W = e^{-\frac{\pi}{4}\kappa^2}$

ratio of the relative amplitude $c_\nu = \sqrt{a_\nu^2 + b_\nu^2}/a_0$ to the "expectancy" ε. We show the values of c_ν and $W(k)$ obtained in Table 3. Although the values of $W(k)$ are rather large, it may be said that the amplitude of the period of lunar 24- and 3.4-hours and solar 24- and 2.4-hours are somewhat predominant. The effect of the oceanic tides on occurrence of the earthquakes seems to be negligible order, since the probability of the period of lunar 12-hours nearly equals zero. We cannot explain, at present, whether the reason of the predominance of lunar 24- and 3.4-hours is due to accident or to some significant phenomena such as the atmospheric pressure change. It is interesting that solar 2.4-hour period is predominant. The same fact was reported by J. Kinoshita and he did not decide the cause of this phenomena[35]. It is noteworthy that the same phenomena have been found in the different period and the magnitude of the objective earthquakes. Investigation of this problem of whether this result was introduced by the process of analysis or is a substantial phenomena related to the occurrence of the earthquakes, will be made in the near future. Finally, we report the distribution of the time interval of occurrence of the earthquakes at Wakayama. It is a matter of common knowledge that the time interval distribution of destructive earthquakes and the felt earthquakes near Japan have the frequency distribution of the form of $f(\tau) = be^{-\lambda t}$ generally. Y. Tomoda has shown that the volcanic earthquakes and aftershocks of a great earthquakes take the distribution curve represented by the function of $f(\tau)d\tau = k\tau^{-p}d\tau$, where k and p are constants[36]. But K. Mogi has concluded that the time interval distribution of occurrence of earthquakes followed the exponential distribution in a

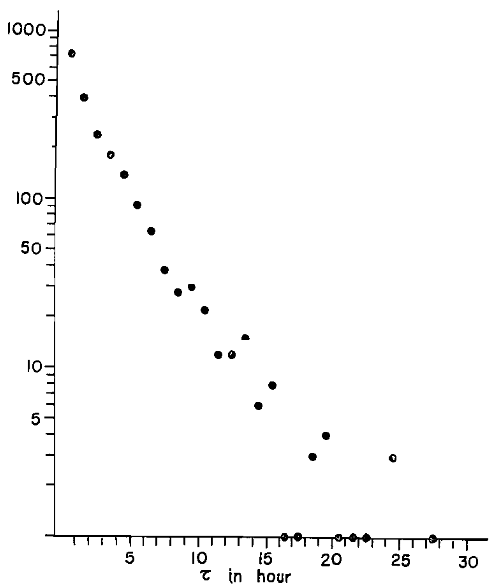

Fig. 5a. Time interval distribution of local earthquake observed at Oura.

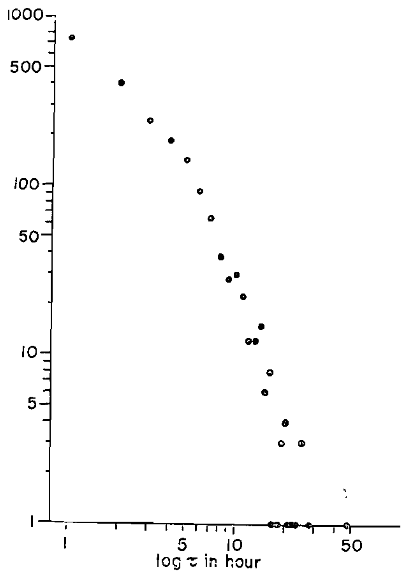

Fig. 5b. Time interval distribution with logarithmic scale of τ, for the same data used in Fig. 5a.

stationary state, and even in an arbitrary process by dividing the process into appropriate stationary states, too, namely the time of occurrence of an earthquake was independent of the passage of time of occurrence of the former earthquake[37]. We show the time interval distribution curves plotted on semi-logarithmic and logarithmic coordinates in Figure 5a and 5b, which have been obtained about the earthquakes observed in a period from December 1, 1960, to September 15, 1961, except the intervals which contained the time of exchanges of the seismograms. It seems that the curvature of the frequency distribution presented by the semi-logarithmic coordinate has a tendency toward a downward convex (Fig. 5a) and the distribution is represented by two straight lines when abscissa is the function of log t (Fig. 5b). Although it is venturesome to decide immediately the distribution of the time interval of occurrence of earthquakes at Wakayama District, it appears that the earthquakes have a tendency that the shorter intervals between them arise more frequently than in case of random occurrences.

4. The ground deformations observed at Oura and Akibasan observation stations

The ground deformations observed at both observation stations, local felt earthquakes and the precipitation at Wakayama City are shown in Figure 6.

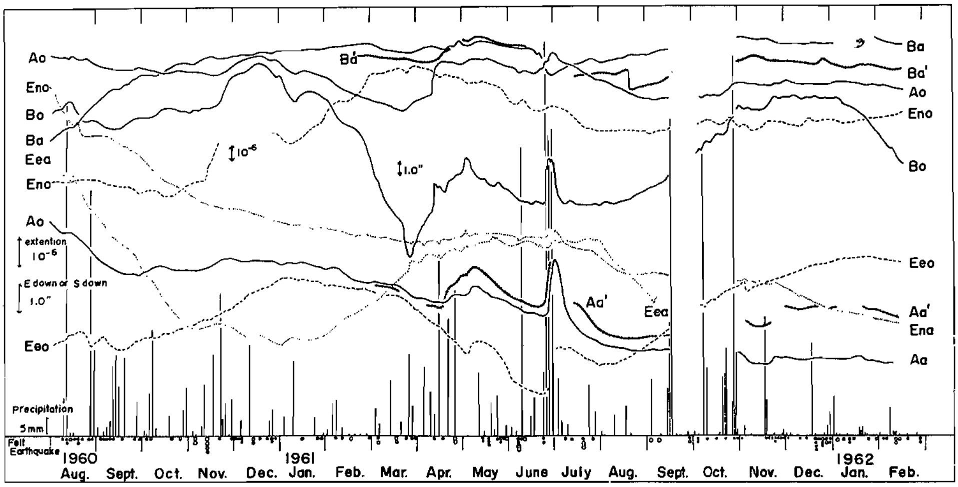

Fig. 6. Tilting motion and variation of linear strain observed at Oura and Akibasan. (○ : Remarkable local earthquakes, ● : Felt local earthquakes, Vertical line : precipitation)

As is seen in the Figure, they are considerably affected by meteorological changes, mainly of rainfall, because of the shallowness of the observation rooms. The deformation of the ground by precipitation is attributed to the load of the rain, increase of the undergound water, and inflow of the water into the observation room, which causes the conditions, such as room temperature, to change. Tilting motion and strain observed at Akibasan had been affected by the influence of the setting up of the equipment up to November 1960, and thereafter the instruments have become stable and observational data of Akibasan are less affected by meteorological changes than Oura.

The amplitudes and the phases of annual variations of each component of ground-tilt and ground-strain obtained from the observation of two years are as follows:

Mark	Amplitude	Phase	
A_0	12″	Max. (E-down) Dec.	Min. (W-down) May
B_0	> 5″	(S-down) Dec.	(N-down) June
E_{e0}	4×10^{-6}	(Extension) Jan.	(Contraction) June
E_{n0}	2×10^{-6}	(Extension) Mar.	(Contraction) Oct.
A_a	1.0″>	(E-down) Dec.	(W-down) June
B_a	1″		
E_{ea}	3×10^{-6}	(Extension) May	(Contraction) Dec.

These values were very roughly estimated and the period of the observation is too short to discuss the annual variation. When the variations of the period of a few days are under consideration, the annual variation may be assumed to be linear. If the annual variation of the ground deformation is caused mainly by the atmospheric temperature, there are phase differences of a few months between the tilting or strain of the ground and the maximum or minimum of the variation of the atmospheric temperature. On the other hand, the phase difference is a few hours in the case of the daily variation. This difference may be explained by the deformation elastically transmitted from the surface in the case of the daily variation, while by the deformation resulted from heat transmission from the surface in case of the annual variation. Both stations are also affected by precipitation, when it exceeds 10 mm. This effect may be somewhat reduced for the secular ground deformation, but it is very defficult to decide the form and amount of the deformation in each case. Therefore, we cannot help omitting the data observed on rainy days in case of the investigation of the minute but anomalous ground deformation for a short period, especially when the observation room is shallowly situated. Reduction of the effect of the precipitation for a period longer than several months is possible by treatment of the total precipitation or the flux of the underground water coming into the observation room. The relation between the precipitation and the maximum deformation of the ground is shown in Figure 7. E_{no} and E_{eo} sometimes showed the opposite sense of the deformation and the form was very different from one another. The values of the maximum tilting and strain obtained from the Figure are

A_a $0.5''\times10^{-2}$ per 1 mm precipitation
A_0 $0.25''\times10^{-2}$
B_a $-0.35''\times10^{-2}$
E_{na} -6.5×10^{-9}

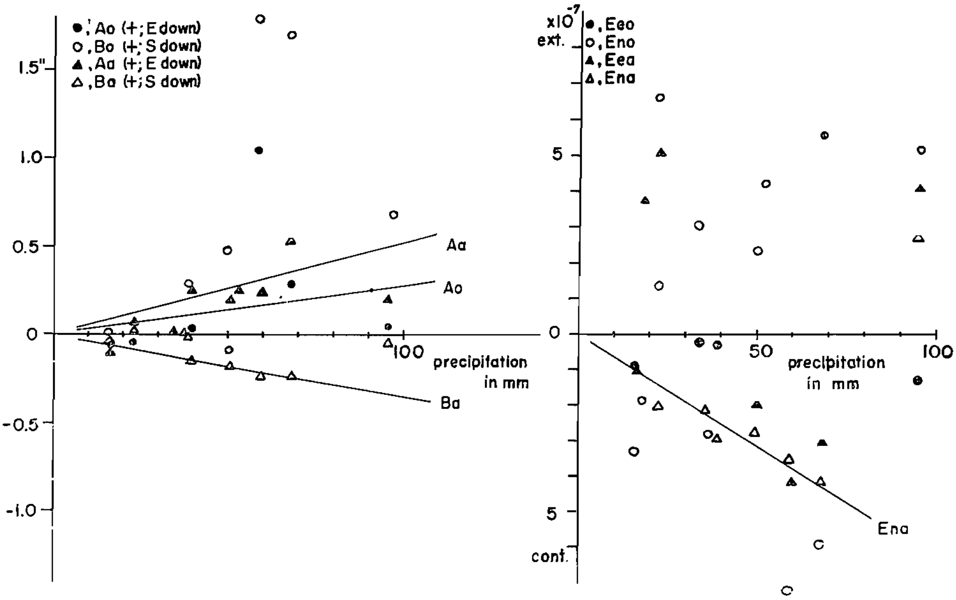

Fig. 7. Relation between the ground tilt and strain and precipitation.

5. Effects of the oceanic tides and meteorological change and an approximation of reduction of them

The ground deformation observed by tiltmeters or extensometers consists of very complicated factors generally. These are, for example, the deformation by earth and oceanic tides, meteorological changes such as rainfall, atmospheric pressure and temperature, insolation, underground water, local ground deformation near the observation station (including artificial disturbances), instrumental error and the substantial crustal deformation, some of which may be related to occurrence of earthquakes. The observation room is ordinarily established in a deep adit to avoid the effect of meteorological disturbances, but we could not get such a suitable situation at Wakayama, so both observation stations are very much affected by them, because of their shallowness of depth, which is less than 10 m. In addition, they are disturbed by the change of the load of sea water because of their nearness to sea. On the other hand, the crustal deformation related to the local earthquakes is presumed to be in magnitude of an order of less than 0.001″ for the ground tilt and 10^{-8} for strain, and it is necessary to eliminate these above-stated disturbances from the observational data. But, since it is impossible to carry out the elimination strictly, we cannot help adopting an adequate approximation under simplified assumptions. We assume that the following equation holds;

$$A(t)=\Sigma f_i(t),$$

where $A(t)$ and $f_i(t)$ are the ground deformation observed by tiltmeters or extensometers and the constituents of the ground deformation by each factor stated above, respectively. If $f_i(t)$ is represented by the equation

$$f_i(t) = c_i(t) \cdot g_i(t),$$

where $g_i(t)$ is a disturbring factor such as oceanic or meteorological change, we can represent the ground deformation as

$$A(t) = \sum c_i(t) \cdot g_i(t).$$

It is an interesting problem to decide the function of $c_i(t)$. We are carring out estimation of $c_i(t)$ for the data of one year and this will be treated in the near future. Assuming $c_i(t)$ to be independent of time for a short period, we get the following equation

$$A(t) = \sum c_i \cdot g_i(t). \tag{1}$$

Then it is formally possible to decide c_i by the method of undetermined multiplier, when all disturbing factors and the values of A as many as i or more are known.

For investigation of the minute ground deformation connected with the local earthquakes, we consider the reduction of the disturbances from observational data of two or three days. Some of these disturbing factors and their reduction are described in the following section with respect to such a short period.

(1) *Oceanic tides*

Since Oura and Akibasan station are situated at a point of 0.7 and 1.5 km distance from the nearest sea (Wakaura Bay), the tidal changes of the ground tilt and strain are chiefly caused by bending action of the loading mass of near sea water upon the ground. The amplitudes and plase of M_2 obtained by harmonic analysis of tilting components of Oura and Akibasan and those of the water height at the Wakayama Harbour Tidal Station from May 10 to June 8, 1961, are as follows :

Oura	A_0	0.0114″	50°20′
	B_0	0.0049″	9°30′
Akibasan	A_a	0.0168″	47°00′
	B_a	0.0087″	57°00′
Water height at the Wakayama Harbour Tidal Station		45.9 cm	60°00′

The same results for components of strain from August 9 to September 8, 1961, are as follows :

Oura	E_{e0}	0.58×10^{-9}	234°31′
	E_{n0}	1.93×10^{-8}	117°43′
Akibasan	E_{ea}	1.06×10^{-9}	306°08′
	E_{na}	3.72×10^{-9}	283°42′
Water height		44.34 cm	115°49′

These are the same order to the values observed at Beppu from 1937 to 1938[38].

The greater part of these amplitudes is mainly attributed to the oceanic tidal effect. Accordingly, we assume that the centre of the load of sea water does not move and the height of the water is equal to the sea level at the Wakayama Harbour Tidal Station in all effective area. If the observed amount of the ground tilt or strain is proportional to the oceanic tidal height at Wakayama Harbour, the tidal change of the ground deformation observed at Oura and Akibasan can be corrected by the ratio of M_2 component of the ground tilt or strain to that of the water height. In this case, the ratio of the amplitudes and the phase differences of each tidal constituent are presumed to be equal to one another in order to simplify the calculation. The amplitude and the phase difference to the tidal water height are as follows :

Station	Direction of tilt or strain		Ground tilt or strain per 1 cm change of tidal water height	Phase difference (hour)
Oura	Tilt	A_0	0.000294″	0.64
		B_0	0.000107″	3.4
	Strain	E_{e0}	-1.31×10^{-11}	4.08
		E_{n0}	4.31×10^{-10}	−0.12
Akibasan	Tilt	A_a	−0.000366″	0.86
		B_a	0.000190″	0.20
	Strain	E_{ea}	-2.39×10^{-11}	−0.68
		E_{na}	-8.40×10^{-11}	0.40

where positive signs of the ground tilt and strain mean E-down or S-down tilt and extension, positive signs of phase difference mean advancement of disturbing factors (water height). Accordingly, A_0, B_0, E_{e0} and A_a are subjected to elimination of the oceanic distrubance by procedure of advancement of 1, 3, 4 and −1 hours to the water height at Wakayama Harbour, respectively. But, the ratio of the amplitude of M_2 contains that of earth tides and both effects are eliminated together by this procedure, while the phases of the other constituents are different from that of M_2 and errors of earth tides are introduced conversely. Although it is possible to estimate the coefficients by the method of least square as stated later without using the amplitude ratio of M_2, we adopted the above-stated method, at present, for reasons of simplicity of the calculation and the greatness of the amplitude of the M_2 constituent.

Tilting diagram of M_2 component at Oura and Akibasan shows that the amplitude of Oura is smaller than that of Akibasan, though Oura station is nearer to the sea than Akibasan (Figure 8). This difference may be attributed to the canceling effect of the load of sea water nearly surrounding the Oura station which situated on a point justing into Wakayama Bay.

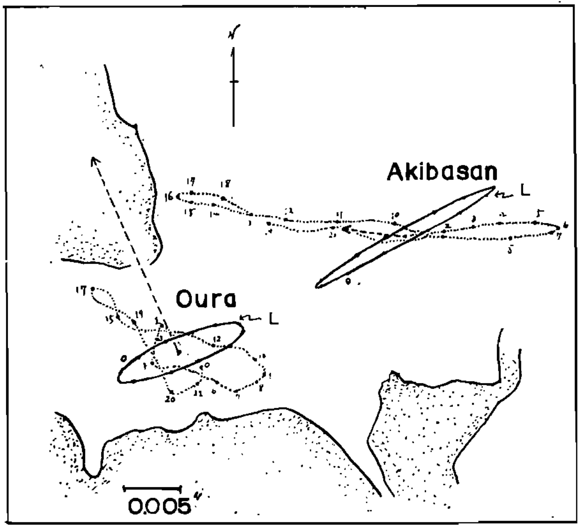

Fig. 8. Tilting diagram for M_2-component, pressure change and daily variation at Akibasan and Oura.
—●— : Tilt for M_2-component (L : Time of low tide of M_2-component at Wakayama Harbour Tide-station)
···●··· : Tilt for daily variation
←······ : Tilt for 1 mb pressure change

(2) *Atmospheric pressure and pressure gradient*

Tilting motion and strain observed at Oura and Akibasan show changes similar to the atmospheric pressure changes of amplitude of less than 1 mb and the phase difference between them is not recognized. Relations between comparatively large deformations by the atmospheric pressure and corresponding pressure changes are shown referred to tilting and strain in Figures 9a, 9b, 9c and 9d.

Assuming that the relation between them is linear, the coefficients of the tilting and the strain to the pressure changes are obtained from the Figures as follws :

Oura	Tilt	A_0 B_0	$-0.0058''$/mb. $-0.015\ ''$/mb.
	Strain	E_{e0} E_{n0}	-6.6×10^{-9}/mb. -1.8×10^{-8}/mb.
Akibasan	Tilt	A_a	$0.0054''$/mb.
	Strain	E_{na}	6.6×10^{-9}/mb.

For the pressure changes of a period of a few days, we have estimated the coefficient of the pressure about B_0 component of Oura at $-0.0165''$/mb..

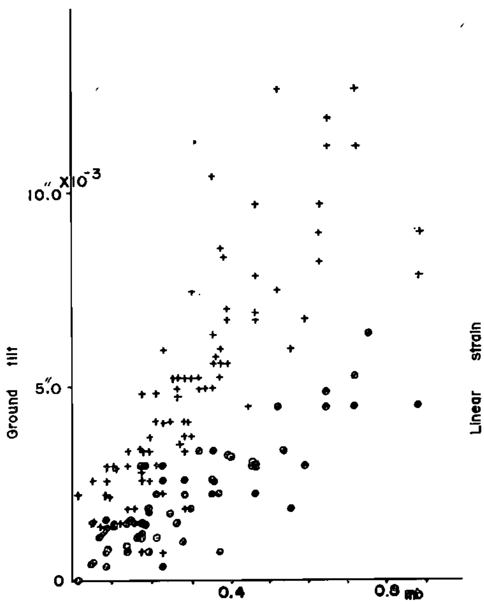

Fig. 9a. Relation between the ground tilt and the pressure change.
⦿ : Ao-component tilt of Oura
+ : Bo-component tilt of Oura

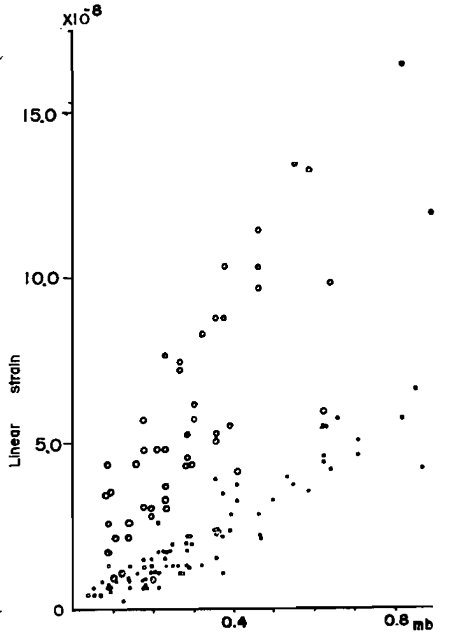

Fig. 9b. Relation between the linear strain and the pressure change.
○ . *Eno*-component strain of Oura
● : *Eeo*-component strain of Ousa

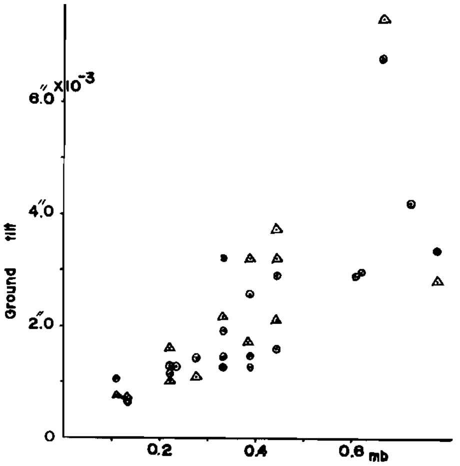

Fig. 9c. Relation between the ground tilt and the pressure change.
⦿ : *Aa*-component tilt of Akibasan
▲ : *Aa′*-component tilt of Akibasan

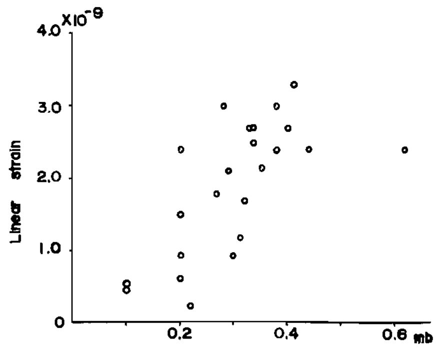

Fig. 9d. Relation between the linear strain and the pressure change.
○ : *Ena*-component strain of Akibasan

This is consistent with the above mentioned value referred to that of a period of an hour or less. From this fact, the relation between the tilting motion of the ground and the changes of the atmospheric pressure is assumed to be linear. B_0-component of Oura is most affected by changes of the atmospheric pressure and B_a of Akibasan is hardly affected by that of the order of 1 mb., being within the reading error. Hence, B_a component of Akibasan is most favorable as to the atmospheric pressure. Since a couple of tiltmeters at Akibasan displayed nearly equal deformation among each other by pressure changes, as seen in Figure 9c, and the tiltmeters at Oura were air tight for the change of the pressure of a period of a few days, it is concluded that this phenomenon is not the instrumental error but the true deformation due to the pressure change, even if it is the local deformation near the observation station.

It has been pointed out by K. Ishimoto[39] and R. Tomaschek[40] that the gradient of the atmospheric pressure gave rise to tilting motion of the ground. As will be mentioned later, we have investigated the effect of time gradient of the pressure in place of the gradient of the pressure and concluded that the time gradient had scarcely influenced the deformation

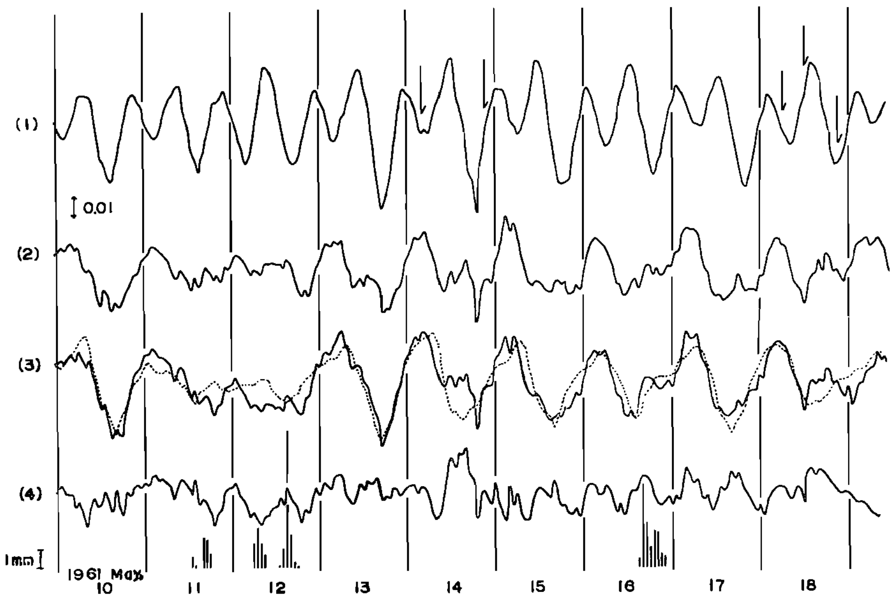

Fig. 10. An example of correction for the tidal and meteorological effects.
(1) Original record of *Aa*-component tilt of Akibasan
(2) *Aa*-component tilt of Akibasan corrected for the oceanic tides
(3) *Aa*-component tilt of Akibasan corrected for the oceanic tides and pressure
(4) *Aa*-component tilt of Akibasan corrected for the oceanic tides, pressure and daily variation

Dotted line : Atmospheric temperature at Oura
↓ : Felt local earthquakes
Vertical line : Precipitation

and was of negligible order in the present approximate level. But the scattering of the points in Figures 9a, 9b, 9c and 9d might be explained by the gradient of the pressure which was not represented enough by the time gradient, and more detailed investigation will be made in the future.

(3) *Daily variation due to meteorological causes (atmospheric temperature)*

The residual obtained by elimination of effects of the oceanic tides and the atmospheric pressure from the ground tilting and strain by using the coefficients above-stated, contains a distinct daily variation which is large in fine weather and small on rainy days. For example, A_a-component of Akibasan shows good correspondence to the atmospheric temperature (dotted line), as seen in Figure 10. Therefore, the deformation of the ground seems to be affected to a certain extent by change of the atmospheric temperature and the atmospheric temperature at Oura has been provisionally adopted as effective temperature on the daily deformation of the ground in the present case, though the daily variation is attributable not only to temperature, but to insolation, underground water level, and other factors.

(4) *Temperature of the observation room*

The temperature of the observation room has sometimes changed irre-

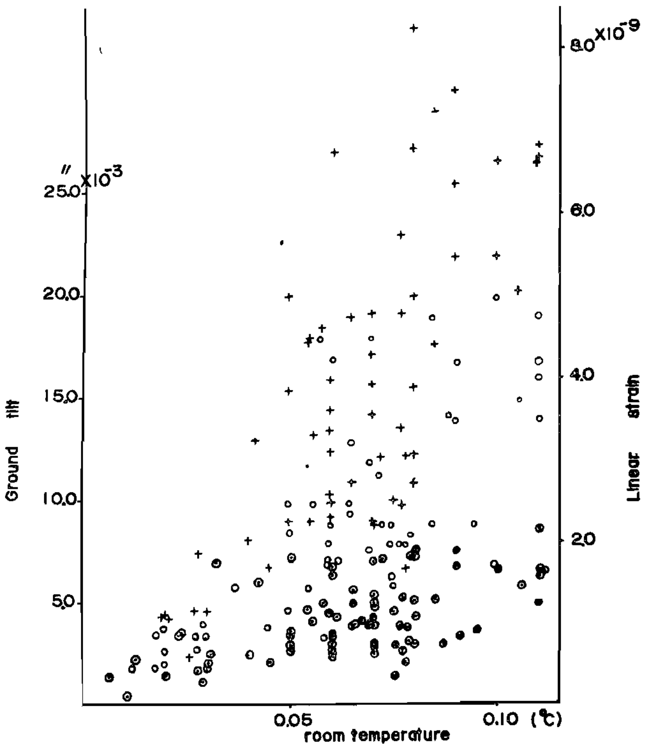

Fig. 11. Relation between the ground the tilt, linear strain and the room temperature.
⊙ : Ao-component tilt Oura
+ : Bo-componnt of Oura
○ : Eno-component strain of Oura

gularly to the degree of about one-tenth at Oura station, which seemed to come from a change of the temperature of the underground water. The relations between the change of the temperature and the ground tilt and strain are shown in Figure 11, for A_0-and B_0-component tilt and E_{n0}-component strain of Oura. Their coefficients are as follows :

Oura	Tilt	A_0 B_0	$6.0'' \times 10^{-2}$ $25.0'' \times 10^{-2}$ per 1°C change of the room temperature
	Strain	E_{e0} E_{n0}	-3.5×10^{-8} 33.0×10^{-8}

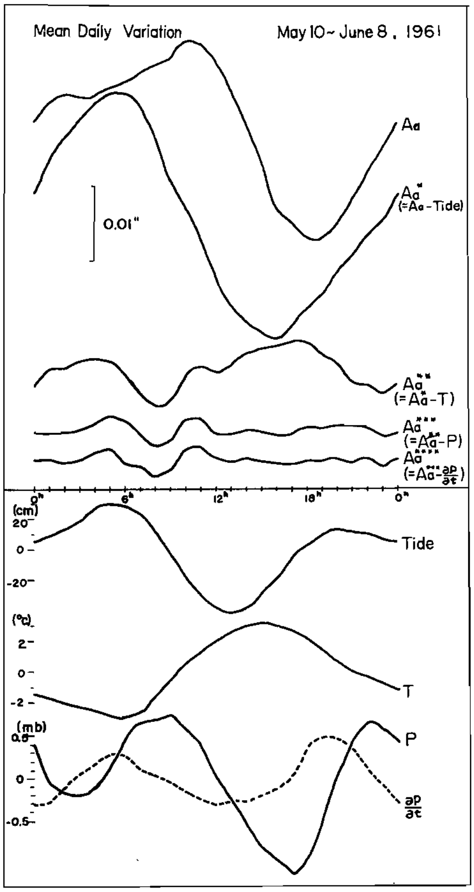

Fig. 12. Elimination of the meteorological and the oceanic tidal disturbances about *Aa*-component tilt of Akibasan.

Aa : Original record of *Aa*-component tilt of Akibasan
Tide : The water height at Wakayama Harbour
T : The atmospheric temperature at Oura
P : The atmopheric pressure at Oura
$\partial P/\partial t$: Time gradient of the atmospheric pressure at Oura (mb/hour)

Using these coefficients, the effect of the room temperature can be reduced according to the change of temperature. At Akibasan station, neither the daily variation nor the irregular change of the room temperature have been observed and no reduction for the room temperature is required.

About the practical data, we have decided the disturbing coefficients under the assumption that the equation (1) holds. Analyzed data were of a period from May 10 to June 8, 1961, for the ground tilt, and from August 9, to September 7, 1961, for the ground strain, In the first place, the mean daily variations of the ground tilt and strain were obtained from the period of one month above-mentioned. Then the mean daily variation of the oceanic tidal height was subtracted from the mean daily variation of the ground tilt or strain, when the amplitude and the phase of the oceanic tide were corrected by the ratio and the phase difference which had been decided from the result of the analysis of M_2 given in (*1*). Secondarly, we decided the disturbing coefficients from the residual by the method fo least square. Disturbances of the atmospheric pressure, its time gradient which was tentatively defined as $\partial p/\partial t|_{t=t_0}=1/2\cdot\{p_0(t_0+1)-p_0(t_0-1)\}$, (mb/hour) and the atmospheric temperature were accepted as the disturbing factors in the present case. The phase difference between the atmospheric tempera-

TABLE 4.
Coefficients of the disturbing factors to the ground tilt and strain.

Instrument \ Disturbance	Water height change of 1 cm	Atmospheric temperature change of 1°C	Atmospheric pressure change of 1 mb	Time gradient of pressure, mb/hour	Room temperature change of 1°C
A_a	$-0.0366'' \times 10^{-2}$ (+0.43 hour)	$(-0.544''\pm 0.014)\times 10^{-2}$ (−1 hour)	$(-0.346''\pm 0.048)\times 10^{-2}$	$(0.098''\pm 0.076)\times 10^{-2}$	
B_a	$0.0190''\times 10^{-2}$ (+0.10 hour)	$(-0.115''\pm 0.015)\times 10^{-2}$	$(0.0781\pm 0.053)\times 10^{-2}$	$(-0.032''\pm 0.098)\times 10^{-2}$	
E_{na}	-0.084×10^{-9} (+0.40 hour)	$(0.95\pm 0.23)\times 10^{-9}$ (−1 hour)	$(3.28\pm 0.83)\times 10^{-9}$	$(7.5\pm 1.4)\times 10^{-9}$	
E_{ea}	-0.024×10^{-9} (−0.34 hour)	$(-4.24\pm 0.34)\times 10^{-9}$ (−1 hour)	$(0.3\pm 1.2)\times 10^{-9}$	$(1.3\pm 1.5)\times 10^{-9}$	
A_0	$-0.0249''\times 10^{-2}$ (+0.32 hour)	$(-0.008''\pm 0.010)\times 10^{-2}$	$(-0.426''\pm 0.035)\times 10^{-2}$	$(0.000''\pm 0.065)\times 10^{-2}$	$6.0''\times 10^{-2}$
B_0	$0.0107''\times 10^{-2}$ (+1.68 hour)	$(0.008''\pm 0.017)\times 10^{-2}$	$(-1.367''\pm 0.059)\times 10^{-2}$	$(-0.11\pm 0.11)\times 10^{-2}$	$20.0''\times 10^{-2}$
E_{n0}	0.436×10^{-9} (−0.06 hour)	$(7.61\pm 0.43)\times 1.0^{-9}$	$(1.4\pm 2.2)\times 10^{-9}$	$(1.4\pm 2.2)\times 10^{-9}$	12.0×10^{-9}
E_{e0}	-0.0131×10^{-9} (+2.04 hour)	$(0.527\pm 0.030)\times 10^{-9}$	$(-6.4\pm 1.1)\times 10^{-9}$	$(-2.74\pm 0.16)\times 10^{-9}$	-35×10^{-9}

Positive signs of the ground tilt and strain mean *E*-down or *S*-down tilt and extension. Positive signs of phase difference mean advancement of the disturbing factor.

Time gradient of atmospheric pressure is defined as $\frac{\partial P}{\partial t}\Big|_{t=t_0}=\frac{1}{2}\{P_0(t_0+1)-P_0(t_0-1)\}$, (mb/hour).

ture and ground deformation was adopted from which minimized the mean error. An example of this procedure of reduction is shown in Figure 12.

From above we obtained coefficients for the disturbing factors which are listed in Table 4, together with these for the oceanic tidal effect and the room temperature. Comparing the result, with respect to effect of the atmospheric pressure, obtained by the method of least square with that of (2), it seems that the longer the period of change of the atmospheric pressure is, the smaller becomes the coefficient of the pressure about some of the components of the ground tilt and strain.

On November 14, 1960, four local earthquakes occurred at 07^h47^m, 11^h08^m, 13^h31^m and 23^h28^m, the last being smaller than the others (intensity II). Epicenters and the depth of the three earthquakes except the last were reported as (135.°0 E, 34.°1 N, 0--10 km), (135.°1 E, 34.°25 N, 0—10 km) and (135.°1 E, 34.°25 N, 10 km) on the Seismological Bulletin of the Japan Meteorological

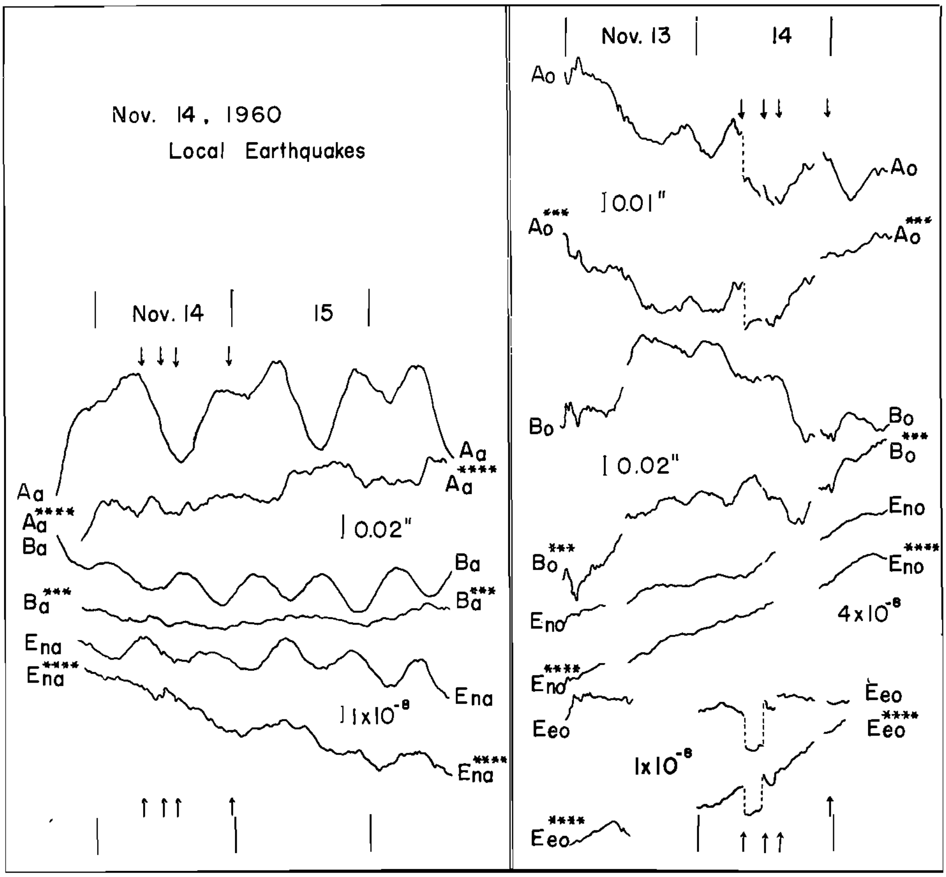

Fig. 13. Tilting motions and variations of linear strain before and after the remarkable local earthquakes on Nov. 14, 1960. (××××: corrected curve, ↑ : local earthquake)

Agency, respectively. P-S duration time and intensity at Wakayama Meteorological Observatory were 0.8 sec., II, 1.0 sec., II and 1.2 sec., III respectively. The epicenters of these earthquakes were situated near the vicinity of Wakayama City, and the magnitudes, especially of the third, were of the greatest class in this district. We have made a trial to reduce the above-mentioned disturbances from the data with respect to occurrence of these earthquakes. The result is shown in Figure 13. E_{ea}-component of strain of Oura could not be recorded then. Correction for the atmospheric temperature of A_0-, B_0- and B_a-components was omitted because of smallness of the coefficients. The jumps of the record at the time of occurrence of the earthquakes, which might be attributable to instrumental errors, have been left as they were. As is seen in the Figure it is not concluded immediately whether there have been any peculiar crustal movements connected with these local earthquakes or not, because the disturbances have not been subtracted sufficiently, calling, therefore, for a more precise method of elimination for this purpose. Conversely speaking, the ground deformations connected with local earthquakes, if existing, are of a smaller order than of the precision of measurement at present, namely less than 0.02″ for the ground tilt and 10^{-8} for the ground strain.

6. Summary

For the purpose of study of the minute ground deformation connected with small local earthquakes, some observations have been carried out in the seismically active area in Wakayama District, where the average number of small or micro-earthquakes in one year exceeds several thousand.

The results obtained are summarized as follows :

1) The P-S time distribution of the local earthquakes recorded at Oura observation station shows the peak on 0.9 sec. – 1.0 sec., and the coefficient of Ishimoto-Iida's formula was estimated as about 1.9. It seems that the periodic change of occurrence of the local earthquakes is predominant at periods of solar 24-and 2.4- hour and lunar 24- and 3.4-hour, and not related to tidal change of a period of lunar 12-hour. The time interval distribution of occurrence of the earthquakes is shown in Figure 5a and 5b. It appears that local earthquakes have a tendency that the shorter intervals between them arise mose frequently than in case of random occurrences, in this district.

2) A tentative method of reduction of disturbing factors such as oceanic tides and meteorological changes, has been introduced. The coefficients of the disturbances upon the ground deformation have been determined as show in Table 4. We have carried out the elimination of the disturbances for the data before and after the occurrence of some remarkable local earthquakes. But, as is seen in Figure 10 and 13, it is not concluded whether any peculiar ground movement relating to the local earthquakes exists or not, because of insufficient reduction of those obstructive disturbances, at present. An improvement of the method is considered necessary for study of the relation between the local earthquakes and the minute deformation of the ground. This problem will be treated in a more precise way

on the basis of further accumulated data in Wakayama District in the near future.

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