Special Contributions, Geophysical Institute, Kyoto University, No. 9, 1969, 29-90

STUDY ON METEOROLOGICAL AND TIDAL INFLUENCES UPON GROUND DEFORMATIONS

By

Torao TANAKA

(Received October 7, 1969)

Abstract

Observational results of the ground deformations obtained by means of tiltmeters and extensometers at two stations in Wakayama City in Kinki District, Japan, are presented and discussed with particular emphasis on the relation to meteorological and oceanic phenomena. The ground at the Oura station inclines gradually to the north-westward and a similar tendency is also discernible at the Akibasan station. It is shown that the annual changes observed are due to the thermal deformation of the ground by the temperature change on the ground surface and that their wave lengths and mode are nearly equal to those of the daily changes, depending mainly on the local topography near the stations. Drift, that might be caused by initial disturbances on the instruments and their surroundings, lasted for several years on a record at Akibasan, which suggests that every discretion is required as to the interpretation of secular changes from conventional tiltmetric or extensometric results. From a concurrent observations by two pairs of tiltmeters of the horizontal pendulum type, it is ascertained that tiltmeters of this type may be used for observations of secular tilting motions with certain qualifications. The diurnal and semidiurnal changes observed by each pair of the two tiltmeters are affected by the atmospheric pressure and air temperature, and each behaves in a different manner, from which it is concluded that these effects have very local characteristics detectable even when the tiltmeters are placed so close to each other. This should be given due consideration in an observation of minute ground deformations and in the evaluation of tidal constituents, especially in that of the S_2 constituent. An estimation of the effect of the atmospheric pressure gradient on the ground tilt is attempted as to the atmospheric tidal waves, the obtained value being about 7″ per 1 mb/km, but the direction of the ground tilt is oppose to that of the loading influence due to the barometric pressure. From the spectral structures of the tiltgram at Akibasan it is shown that the change in the periodic range from 1 to 33 days in the the ground tilt at the station is scarcely influenced by the changes of the air temperature, atmospheric pressure, its time derivative and loading of the water in the neighboring sea. It is also shown that the effect of precipitation is, on the contrary, very remarkable and that the ground tilt caused by an impulsive precipitation is tentatively represented by $\alpha t \cdot \exp(-\beta t)$ with equal values of β for the E-W and N-S components of the tilt. Corrected spectra for the disturbances are given, which suggest predominance of several oscillatory tilting motions. Comparisons of the spectral structures of the tiltmetric and extensometric records with those of the barograms show that the amplitude ratio of the ground tilt or strain to the pressure increases and the phase difference between them also varies slightly with the frequency. This frequency dependence of the spectral ratios can be apparently expressed as the sum of the two parts proportional directly to the change of the pressure and proportional to the time derivative of the pressure change, respectively. A tentative method for elimination of the disturbances due to the oceanic and meteorological changes from the tiltgrams is introduced. Digital filterings of the tiltgrams by several types of filters are also attempted to detect small anomalous ground tilts. There can be seen in these results that peculiar ground tilts of the magnitude of about 0.02″ or smaller existed at the two stations shortly before and after the three local earthquakes occurred on Nov. 14, 1960, in this district. Although these phenomena may be related to the occurrence of these earthquakes, further investigations are needed to verify the relation between them.

Contents

Introduction
Chapter I. Secular Changes of Ground Tilts and Strains
  1. Observation stations and instruments
  2. Secular ground tilts and strains
  3. Summary
Chapter II. Spectral Structures of Tiltmetric and Extensometric Records
  1. Continuous observations of the ground deformations
  2. Data
  3. Fourier spectra
  4. Amplitudes and phases of principal tidal constituents obtained from one year's data
  5. Effects of diurnal and semidiurnal fluctuations of the atmospheric pressure and air temperature on the ground tilts
  6. Spectral structure of the tiltgrams at Akibasan
  7. Mean diurnal changes of the ground tilts and effects of the atmospheric pressure and air temperature upon them
  8. Another consideration about the effect of the atmospheric pressure upon the ground tilts and strains
  9. Some considerations about the spectral structures of the ground tilts
  10. Summary
Chapter III. Detection of Anomalous Deformations of the Ground and an Application of the Digital Filtering
  1. Detection of anomalous deformations of the ground by tiltmeters and extensometers
  2. A way to reduce the effects of oceanic tides and meteorological changes
  3. Digital filtering for detection of minute anomalous changes of the ground tilts
  4. Summary

Introduction

It is a well known fact that characteristic ground deformations are often found after the occurrence of destructive earthquakes near their epicentral regions. In Japan, since geodetic survey such as levelling and triangulation were carried out shortly after the great Nobi Earthquake in 1891, much work has been done in order to investigate the relation between earthquake occurrences and ground deformations. Particularly, recent results of the Niigata Earthquake on June 16, 1964 and the Matsushiro Earthquake Swarm which began in August 1965 are worthy of special mention by virtue that a characteristic crustal movement before and after the earthquake has been revealed by repetition of level surveyings at the epicentral region in the case of the Niigata Earthquake (Tsubokawa, Ogawa and Hayashi [1964]), and that the crustal tilts and strains observed by levelling surveys and electro-optical measurements have been related to the seismicity of the swarm and interpreted to elucidate the mechanism of earthquakes in the case of the Matsushiro Earthquake Swarm (Dambara [1966], Kasahara et al. [1967]). Besides, the elasticity theory of dislocations has been applied to the analysis of the displacements, strains and stresses associated with faulting, and much work has been done to make clear the focal mechanism of earthquakes (for example, Maruyama [1964], Press [1965], Chinnery and Petrak [1967], Wyss and Brune [1968]). In addition, highly sensitive tiltmeters of the horizontal pendulumtype and linear strainmeters were devised and employed as station instruments in study of earth-tides and crustal deformations. In 1943, K. Sassa and E. Nishimura [1951] detected a peculiar tilting motion of the ground that appeared about six hours before the occurrence of the Tottori Earthquake at Ikuno, using tiltmeters of this type. Thereafter, similar phenomena have been frequently observed, supposedly connected with destructive earthquakes (for example, Nishimura [1953], Caloi [1958], Takada [1959], Karmaleeva [1963], Tanaka [1964], Ozawa [1965]), and worth of note is the fact that the geodetic measurement of the crustal movements by triangulation and levelling and continuous observation of them by tiltmeters and extensometers at some fixed stations are some of the promising ways to elucidate the mechanism of earthquake occurrences and further to predict their occurrences.

Continuous observations of the crustal deformations by tiltmeters and extensometers are generally carried out in deep tunnels to avoid the effect due to meteorological disturbances. However, it is not adequate to carry out observations in very deeply situated rooms below the surface, because the rooms are deformed by the great rock-pressure and the observations of real ground deformations of the area concerned are disturbed. With observational results from many observing stations, K. Hosoyama [1957] concluded that the depth of the observation room adequate to the present purpose is about 100-200 m below the surface. However, such an ideal room is not always obtainable for such observations in certain regions, and moreover, it is thought to be almost impossible that the observations of crustal deformations are perfectly free from the meteorological and locally restricted disturbances. Consequently, discrimination of real crustal movements from other disturbances is indispensable for the investigations by tiltmeters and extensometers, and many papers have been published as to the relation between the ground deformations and meteorological disturbances. Treatments about removal of annual variations of the ground deformations due to air temperature change and precipitation have been shown by I. Ozawa [1956], M. Takada [1958] and V. V. Popov et al. [1960] and crustal deformations due to the atmospheric pressure have been treated by R. Tomaschek [1957], D. Simon et al. [1967] and others (Khorosheva [1958], Bonchkovskii [1963]).

In Wakayama District, local earthquakes have occurred very frequently since about 1920, and the seismological and geodetical study has been made by A. Imamura et al. [1932], S. Miyamura [1959] and T. Mikumo [1959]. At present, routine seismological observations are being carried out by the Wakayama Microearthquake Observatory belonging to the Earthquake Research Institute of University of Tokyo. In 1965, the third cooperative observation of ultra-microearthquakes was practiced by the Research Group for Ultra Microearthquakes in this district for the purpose of clarifying the nature of the local earthquakes and seismicity (Hori and Matsumoto [1967], Watanabe and Kuroiso [1967]). Since large earthquakes rarely occur in certain restricted areas where the crustal deformations have been continuously kept under observations, it is difficult to collect sufficient data on anomalous crustal deformations related to earthquakes, and observations of these phenomena in such an active region of local earthquakes as Wakayama District would give us a sufficient amount of data in a relatively short period of time, in the case that local earthquakes are also accompanied by correspondingly small deformations of the ground near the epicenters. For the purpose stated above, observations of the ground deformations by tiltmeters and extensometers have been kept up at Oura and Akibasan in Wakayama City. However, since the both observation rooms are shallowly seated and near the sea, the ground deformations observed are considerably affected by not only meteorological changes but also by oceanic tides. Accordingly, elimination of these disturbing factors from observed records is necessary to obtain substantial crustal deformations which might be related to the occurrence of local earthquakes.

In this paper we discuss mainly the ground deformations observed at the two stations in Wakayama caused by meteorological changes and the methods of elimination of these obstructive deformations, and present the resultant deformations in relation to the occurrence of local earthquakes. In Chapter I, observational settings and the secular deformations including annual changes are presented. Chapter II is concerned with the determination of each disturbing factor such as the atmospheric pressure, air temperature and oceanic tides, based on the spectral structure of the tiltmetric and extensometric records. A way to reduce meteorological and oceanic tidal disturbances and the digital filtering of the records for the purpose of detection of anomalous ground deformations are presented in Chapter III.

Chapter I. Secular Changes of Cround Tilts and Strains

1. Observation stations and instruments

The observation of the ground deformation was commenced on March 26, 1960 at Oura in Wakayama City. It is shown by S. Miyamura [1959] that the foci of local earthquakes are distributed mainly from 3 to several km under the surface near Wakayama City, where the depth of the foci is shallowest in this district. The Oura station is on the northern slope of Mt. Takatsushi and located at 34°11.′3 N latitude and 135°09.′5 E longitude. The observation room is about 50 m above sea level and 5 m below the ground surface, and the bed rock is weathered crystalline schist. The instruments with which the Oura station is equipped are shown in Table 1.

Table 1. List of instruments at Oura.

Instrument	Type	Azimuth	Sensitivity	Mark	Recording speed
Tiltmeter	Horizontal pendulum	E-W N-S	0.007″/mm 0.005″/mm	A_0 B_0	180mm/hour ; Mar. 26~Aug. 12, 1960
Extensometer	Benioff (Bow-string)	E-W N-S	2.8×10^{-9}/mm 5.0×10^{-9}/mm	E_{eo} E_{no}	30mm/hour ; Aug. 12, 1960 ~Sept. 15, 1961
Barometer	Aneroid		0.18 mb/mm	P_0	7mm/hour ; Sept. 15, 1961 ~Apr. 5, 1968
Thermometer	Bimetal		0.01°C/mm	T_0	

Table 2. List of instruments at Akibasan.

Instrument	Type	Azimuth	Sensitivity	Mark	Recording speed
Tiltmeter	Horizontal pendulum	E-W W-E N-S S-N	0.004″/mm 0.007″/mm 0.004″/mm 0.007″/mm	A_a A_a' B_a B_a'	180mm/hour ; July 15~Aug. 12, 1960 30mm/hour ; Aug. 12, 1960 ~Sept. 15, 1961
Extensometer	Benioff (Bow-string)	E-W N-S	3.1×10^{-9}/mm 2.3×10^{-9}/mm	E_{ea} E_{na}	7mm/hour ; Sept. 15, 1961 ~Apr. 2, 1965
Barometer	Aneroid		0.11 mb/mm	P_a	
Thermometer	Bimetal		0.01°C/mm	T_a	

The Akibasan station was set up at the western foot of a small hill called Akibasan on July 14, 1960, being about 1 km distant from Oura, in order to complete and verify the results observed at Oura, and the observation was continued until April 2, 1965. The location was 34°11.′5 N latitude and 135°10.′4 E longitude, and the depth of the room was about 10 m. The bed rock was also crystalline schist. As will be discussed later, this station was considered to be more suitable for observation of ground deformations than Oura, probably because of its deeper situation. Table 2 shows the instruments used at Akibasan. Two sets of tiltmeters of horizontal pendulum type were operated in order to examine the instrumental error. The geographical situation of the stations and configurations of instru-

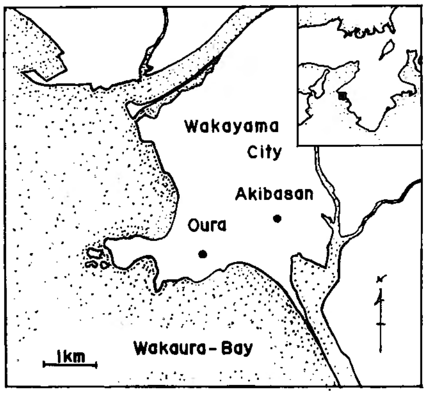

Fig. 1. Geographical situation of the stations, Oura and Akibasan.

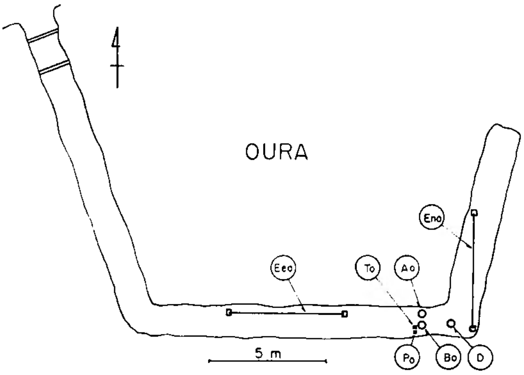

Fig. 2a. Configuration of instruments at the Oura station.

A_o ; E-W component tiltmeter
B_o ; N-S component tiltmeter
E_{eo} ; E-W component extensometer
E_{no} ; N-S component extensometer
P_o ; Barometer T_o ; Thermometer
D ; Declinometer

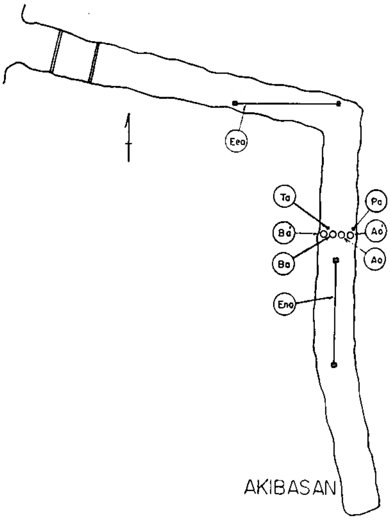

Fig. 2b. Configuration of instruments at the Akibasan station.

A_a ; E-W component tiltmeter (with damper)
A_a' ; W-E component tiltmeter
B_a ; N-S component tiltmeter (with damper)
B_a' ; S-N component tiltmeter
E_{ea} ; E-W component extensometer
E_{na} ; N-S component extensometer
P_a ; Barometer T_a ; Thermometer

ments are shown in Figs. 1 and 2. Two extensometers with double bow-string optical magnifiers devised by H. Benioff [1959] have been used at both stations. 5 m super-invar rods of 1 cm diameter were used as the length standard. Thermometers and barographs are of the bimetal and aneroid types respectively, and their deflections have been recorded optically on photographic papers together with those of tiltmeters and extensometers.

2. Secular ground tilts and strains

Because the tiltmeters and extensometers were operated under high sensitivity in order to detect small deformations of the ground, observations were sometimes interrupted by heavy precipitations, which caused large deformations of the rooms because of their shallowness. Accordingly, we shall discuss only the annual changes and general tendencies of the secular deformations in the following so far as circumstances permit.

(1) Case of Oura

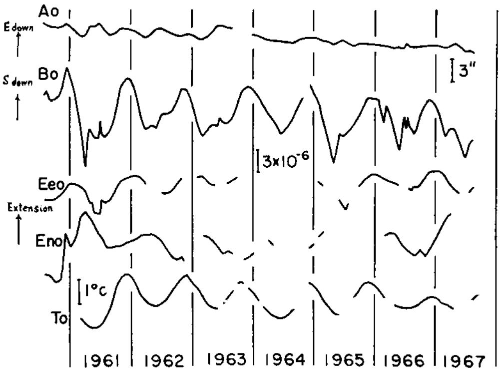

Fig. 3. Secular changes of the ground tilts and strains at Oura.

A_o ; E-W component tilt E_{eo} ; E-W component strain
B_o ; N-S component tilt E_{no} ; N-S component strain
T_o ; room temperature

Ground tilts, strains and room temperature observed at the Oura station are shown in Fig. 3. The symbols A_o and B_o mean the E-W and N-S components of the ground tilt and E_{eo} and E_{no} the E-W and N-S components of the strain, respectively. The room temperature is represented by T_o. Upward traces of A_o and B_o correspond to the east- and southward inclinations of the ground, and those of E_{eo} and E_{no} correspond to the extension. Large annual changes are apparent in the N-S component of tilt and both components of strain, the double amplitudes of which are estimated to be about 6″ and 5×10^{-6}, respectively. While, the annual change is obscure on the E-W component tilt. Short-period fluctuations that appeared in both the tiltmetric and extensometric records are mainly due to heavy precipitations. As to the ground tilts, the secular changes are comparatively small contrary to the large annual changes, and this agrees with the general tendency pointed out by K. Hosoyama [1957] thatannual changes and meteorological influences are large and secular changes small in shallow observation rooms, while the former is small and the latter large in deep rooms. The room temperature shows a regular annual change, the amplitude of which are estimated to be about 1°C and the maximum and minimum occur in November and June, respectively. The mean room temperature is about 15°C and monthly mean of the air temperature passes over this value at the end of October and from April to May in this district. Therefore, it can be said that the maximum and minimum values of the room temperature appear about one month after the outdoor temperature has passed over the room temperature. Since the phase of the large annual change on the N-S component tilt coincides fairly well with that of the room temperature change, the annual change of this component tilt is concluded to be caused by the thermal deformation due to the room temperature change. Meanwhile, on the E-W component strain the maximum and minimum extension seem to appear at February and August respectively, the mode of which agrees with that of the air temperature, and the N-S component strain shows a phase lag of about three months compared with the E-W component. Accordingly, it may be concluded that these annual changes of the strains are not directly due to the thermal deformation by the room temperature but due to the annual change of the air temperature and generated by thermal effect near the ground surface. At Oura, fluctuations of the room temperature of the period of several hours which are supposedly due to the temperature change of the underground water are sometimes observed, when the tiltmetric and extensometric records are disturbed. In such cases, the tiltmeters show west- and southward inclinations respectively, and both extensometers show contractions as the temperature rises. This response of the extensometers to the room temperature is opposite to that of the annual changes of the room temperature, and from this it is also ascertained that the annual change of the strain is independent of the room temperature. On the contrary, the response of the N-S component tilt is in accord with that of the annual change. These facts certify the above conclusions to be valid.

In Fig. 4, yearly vectorial diagrams of the ground tilt at Oura are shown including the annual change. In this figure, a slow monotonic secular change of about 0.7″ per year is seen to the northwestward direction. This secular change of the ground tilt shows qualitative agreement with the recent results of the geodetic survey made by A. Okada et al [1968].

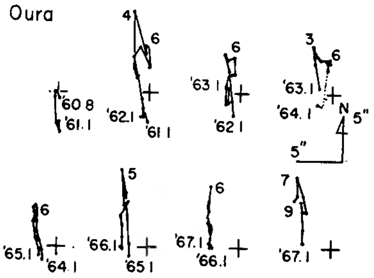

Fig. 4. Yearly vectorial diagrams of the ground tilt at Oura.

(2) *Case of Akibasan*

Observational results from July 1960

to April 1965 are shown in Fig. 5. In this figure, the symbols A_a and A_a', and B_a and B_a' mean the E-W and N-S component tilts, the upward traces of which correspond to the east- and southward inclinations, respectively. Similarly, E_{ea} and E_{na} mean the E-W and N-S components of the ground strain, and the upward traces show the extension. At Akibasan, the two sets of tiltmeters A_a, B_a, A_a' and B_a' were installed in parallel but opposite directions as seen in Fig. 2 b on one concrete base, the width, length and height of which are about 50, 150 and 10 cm, respectively. One pair of tiltmeters was equipped with oil-dampers to suppress the free oscillations of pendulums by traffic vibrations from the road near the observation station.

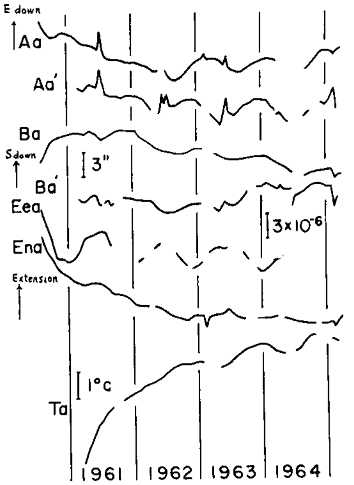

Fig. 5. Secular changes of the ground tilts and strains at Akibasan.
A_a, A_a' ; E-W component tilt
E_{ea} ; E-W component strain
B_a, B_a' ; N-S component tilt
E_{na} ; N-S component strain
T_a ; room temperature

Now, in Fig. 5, gradual rise of the room temperature continuing for several years is very characteristic. It seems to be almost impossible that such a long-term rise of the room temperature was real, and the phenomenon might be caused by the drift of the bimetals or strings which suspended the mirror of the thermometer. However, a very similar drift to it is apparently seen on E_{na}, the N-S component of strain, and therefore it may be rash to conclude that the phenomenon is nothing but instrumental drift of the thermometer. In February 1965, the double doors at the entrance of the observation room were broken by someone roguish, and thereupon the room temperature fell considerably, when the tiltmeters A_a and A_a', and B_a and B_a' showed apparently east- and southward inclinations respectively, and the both extensometers contractions. However, the amounts of inclinations observed by the tiltmeters A_a' and B_a' which were placed on both corners of the concrete base reached about ten times of those observed by A_a and B_a placed on the central part of the base, and this means that the inclinations observed at sudden fall of the room temperature might have a very short wave length and perhaps mainly due to the deformation of the concrete base. Similar tendencies were observed when men entered the room to change the recording papers. At any rate, because the exponential contraction appeared on E_{na} is reverse to the changes on the small fluctuations of the room temperature, it cannot be explained simply as the effect due to the rise of the room temperature. Hitherto, it is said that initial drift of the exponential form supposedly due to the instrumental and environmental disturbances is usually seen, which continues about one year or less long after the commencement of observations. For example, such drift is observable on the B_a component of tilt and E_{ea} component of strain in Fig. 5. Although we cannot draw any definite conclusion about the origin of the long-term drift in the E_{na} component strain and the room temperature in the present stage, it is to be noted that observational results of the ground tilts or strains by tiltmeters or extensometers must be interpreted taking the possibility into the consideration that there may exist long-term initial drift continuing for several years, especially when we are concerning ourselves with secular ground deformations.

Now we shall discuss briefly the annual changes appearing on the tiltmetric and extensometric results.

The amplitude of the annual change of the room temperature is about 1°C or less and its maximum and minimum appear in November and May, which coincides fairly well with the tendency at Oura. The annual changes that appeared on the two tiltmeters in the same direction are in good accord with each other. By the reasons that the amplitudes of A_a and B_a are nearly equal to those of A_a' and B_a' respectively, that the directions of the ground tilts to the change of the room temperature are reverse to those in the case of short-period changes, and that the phases of the tilts are thought to agree with that of the air temperature, the annual change of the ground tilt at Akibasan is concluded to be caused by the temperature change at the ground surface. Furthermore, the phase of A_a' seems to be ahead of that of A_a, and the former amplitude is slightly larger than the latter. This tendency is identical with that for the diurnal change as to the A_a and A_a' components as will be shown later, and therefore it is concluded that both the annual and diurnal changes of the ground tilt are caused by the air temperature and generated by the same mechanism depending on the surface topography and geological circumstance near the station and also depending on the shape of the observation room.

As to the ground strain, there can be seen a large annual change on the E-W component in spite of the considerable data lacking, while it is not so remarkable on the N-S component. Because the relation between the annual changes and room temperature is reverse to that regarding to the short-period changes, and because the phase difference of about three months is seen between the two perpendicular components as well as in the case of Oura, the annual change of the ground strain at Akibasan is considered to be caused by the temperature change at the ground surface.

It has often been pointed out before now that secular changes observed by tiltmeters of the horizontal pendulum type are not generally in accord with those observed by water-tube tiltmeters or those expected from the results of level surveyings, and one of the reasons for the discrepancy between them is assigned to the shift of zero lines due to the instrumental drift of tiltmeters of the horizontal pendulum type. Comparing the secular change appeared on the tiltmeter A_a with that on A_a' which was installed in parallel direction to A_a, good resemblance between them can be observed on the whole, although slight discrepancy is seen in the beginning of 1963. Similarly, the change of B_a is in accord with that of B_a' except 1963. If there exist instrumental effects on secular changes, it is hardly possible that such a good resemblance can be obtained by the two parallel tiltmeters. Therefore it is deduced that the discrepancies between secular changes observed by tiltmeters of the horizontal pendulum type and those observed by water-tube tiltmeters or geodetic methods are not due to the zero shift of the instruments but due to very local tilting motions supposedly connected to the deformations of tunnels themselves, likewise in the case of the diurnal and annual changes. It is also possible as pointed out by T. Hagiwara [1947] that the discrepancies are due to the difference of the dimensions of the spans across which the observations of the ground inclinations are measured. Accordingly it can be said that tiltmeters of the horizontal pendulum type record true inclinations of the tripods of the instruments at least, which are attributable to the crustal inclination extending over a wide area, its transformed inclination of the ground depending on local conditions and entirely local inclination characteristic to the observing points.

Vectorial diagrams of the ground tilt composed from the tiltmeters A_a and B_a at Akibasan are shown in Fig. 6. As seen in the figure, the annual change at Akibasan is far smaller than that at Oura, and not only the direction but

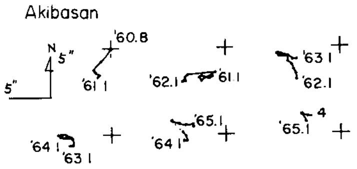

Fig. 6. Yearly vectorial diagrams of the ground tilt at Akibasan.

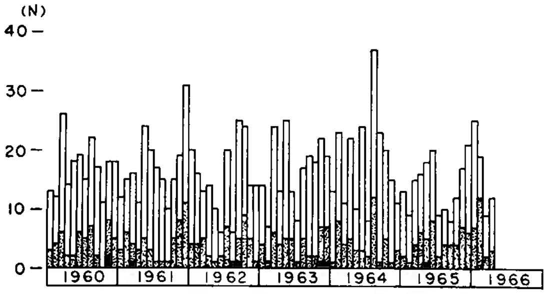

Fig. 7. Monthly numbers of earthquakes occurred near Wakayama City reported on the Seismological Bulletins of the JMA.
□ ; unfelt ▨ ; felt ■ ; small felt area

the rate of the secular inclination at Akibasan agrees satisfactorily with those at Oura.

Finally, monthly numbers of local earthquakes reported on the Seismological Bulletins of the Japan Meteorological Agency as events occurred near Wakayama City are given in Fig. 7. S. Miyamura et al. [1966] have reported that the seismicity in this region tended to dwindle since 1963. Vicissitudes of the seismicity, however, seem not to be remarkable on this figure, and we will not take up the discussion about the relation between the secular ground inclinations and seismicity of local earthquakes in this region.

3. *Summary*

Some results from the tiltmetric and extensometric observations at the two stations in Wakayama City have been described and discussed especially regarding to the annual and secular changes in this chapter. They are summarized in the following.

1) Since the two observation rooms are not so deep below the ground surface, annual changes are observed on both tiltmetric and extensometric records. It is deduced from the similarity of the mode of the annual changes with that of the diurnal changes that they are mainly due to the change of the outdoor temperature and that their mechanism of appearance is identical depending possibly on the shapes of the tunnels and surface topography near the observation rooms.

2) Gradual northwestward tilting of the ground can be seen at both stations, which does not seem to contradict the result from the levelling survey in the neighboring region. Shallowly seated observation rooms may be advantageous for observations of secular changes, although annual and other meteorological disturbances are large, because they are eliminated without difficulty.

3) Long-term drift which was probably caused by initial disturbances and continued several years after the commencement of observations is observable on an extensometric record at Akibasan. This suggests that it is dangerous to presume that the initial drift may settle down within one or a half-year as is now generally accepted.

4) From comparison of the records by the four tiltmeters installed on one concrete base, it is concluded that tiltmeters of the horizontal pendulum type record correctly the tilting motions at the sites without instrumental drift even in long term observations, and they are able to be used for observations of secular changes under some qualifications.

Chapter II. Spectral Structures of Tiltmetric and Extensometric Records

1. *Continuous observations of the ground deformations*

The ground deformations observed by tiltmeters or extensometers generally consist of very complicated factors. They are, for instance, deformations by the earth tides, meteorological changes such as rainfall, atmospheric pressure and air temperature, insolation, and underground water, local ground deformations near observation sites (including artificial disturbances), instrumental errors and substantial crustal deformations, some of which might be related to the occurrence of earthquakes. A schematic representation is proposed in Fig. 8, showing a view about the ground deformations and their observations.

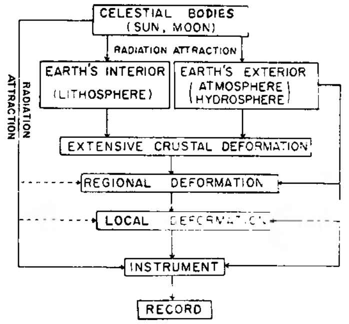

Fig. 8. A schematic representation about ground deformations and their observations.

The gravitational attraction from celestial bodies, mainly from the Sun and Moon, acts on the Earth and gives rise to the earth tides, the global deformation of the Earth. At the same time, the attraction acts on some kinds of observing instruments such as those of tiltmeters of the horizontal pendulum type. Moreover, the attraction acting on the earth's air mass and ocean water generates the atmospheric and oceanic tides which deform the earth's crust and change the potential field of gravity. In addition, instruments of some types may be directly affected by the air and water mass.

The earth's crust may be deformed extensively or regionally by the stress originating from the earth's interior, and naturally the ground in the vicinity of the observing instruments is also deformed. However, the mode of the two deformations are not always thought to coincide with each other, and the strain pattern observed at one fixed point by the continuous observations would not represent the strain pattern of a large area which might be related more directly to the internal stress of the crust. Thus it may be interpreted that the extensive or regional deformations are transformed into some different local deformations by the surface topography of the ground, geological circumstances near the observational sites, and positions and shapes of the observing rooms.

Similarly, the ground deformations due to the origins of the Earth's exterior may not only be extensive or regional ones but can also be expected to be very local. In this case, there may also be some transformations in mode when the extensive or regional stress causes the local deformations at the observational sites. Additionally instruments are directly influenced by the external origins such as room temperature, pressure, humidity and so forth.

Characteristic deformations indigenous to each observational site are usually observed, which are mainly generated by the rock pressure near the underground rooms, and they become larger as the depth of the rooms is greater.

Finally, instrumental drift may also be inevitable under highly sensitive operation.

Thus the tiltmetric or extensometric records are thought to consist of ground deformations and instrumental deflections by the many factors mentioned above. However, because it is not ascertained whether these factors affect independently on the obtained results and their influences are recorded as a simple superposition of them or not, it is an important problem to elucidate the interaction between the influences due to each factor.

Conversely, if we want to get the extensive or regional crustal deformations caused by the earth's internal origins from tiltmetric or extensometric observations, it is necessary to know not only the transformation formulae from the substantial deformations to the deflections of tiltmeters or extensometers, but also to know how other deflections are caused by the earth's external origins such as meteorological changes, and pursuit of the inverse transformation and elimination of these obstructive deformations and deflections are required. Accordingly, it is essential to practice the procedure mentioned above and to direct our efforts to this purpose. However, we cannot know directly the stress pattern within the earth's crust which causes the crustal deformations, and so characteristics of the input signals of the substantial crustal deformations can hardly be obtained; this makes processing of the obtained data difficult.

As to the investigation of the deformations due to the external origins, we cannot help taking some approximate methods under simplified assumptions in the present stage, since it is difficult to collect a large quantity of information about the disturbing factors such as meteorological changes and oceanic level and to carry out the observations of the crustal deformations of different spatial extents from narrow to wide ones.

Now, we may analogize the above mentioned relations as follows. There is a black box, input of which is the substantial crustal deformations originated from the internal stress of the earth and output is tiltmetric or extensometric records. If we want to know the substantial crustal deformations from the records, it is necessary to clarify the nature of the transformation in the black box. For example, in order to investigate its spatial characteristic, concurrent observations such as array observations, small and large scale measurements by the geodetic methods are necessary. For the purpose of identification of the signals corresponding to the substantial deformations, check of the reproducible nature of the phenomena by continuous observations, study of the spectral structures, use of the instruments with some appropriate frequency responses and so forth are also needed according to the viewpoint of time. Because the proper instrumental drift may also be contained in the output, we must use different kinds of instruments in order to distinguish them from real deformations near the observation sites. As to the disturbances from the external origins, we may obtain the output corresponding to the disturbing deformations from the box or the instrumental response by applying the external factors such as meteorological changes as input. In this case, we must observe the phenomena which are considered to be the factors causing the ground deformations and regarded as the input to the black box as far as possible, and investigate the relation between the input factors and output records.

According to the reasons mentioned above, it is important to investigate the ground deformations caused by the external origins of the earth. Among them, the meteorological influences are the largest and most important for the analysis and interpretation of the data. In this chapter, the relations between them are discussed as to the tiltmetric data obtained at the two stations in Wakayama City, mainly based on the Fourier spectra of them.

2. *Data*

The atmospheric pressure, air temperature and precipitation are considered as the most important factors among the meteorological disturbances on the tiltmetric and extensometric records. In addition, since the two stations are situated at points about 0.7 and 1.5 km from the nearest sea coast of Wakaura Bay, the tidal changes of the ground tilts and strains observed are large and chiefly caused by the bending action of the loading mass of the near sea water upon the ground. Accordingly, in the present study we assume that the original factors which disturb the tiltmetric and extensometric records are the atmospheric pressure, air temperature, precipitation and oceanic tides. In this case, the effects of the primary earth tides and oceanic tides are lumped together, because the magnitude of the latter is far larger than that of the former. The tiltmetric data observed at the two stations, Oura and Akibasan, have been used in the present study, and the duration of the analysis is the one year from July 31, $15^{h}00^{m}$, 1960 to July 31, $14^{h}00^{m}$, 1961 (UT). The readings were made up to 0.1 mm on the records at intervals of one hour. The tidal record of the Fuess type tide gauge observed at the Wakayama Harbor Tidal Station (34°13′N, 135°09′E) were used as the data of the oceanic water height. The data of the air temperature and precipitation are those observed at the Wakayama Meteorological Observatory (34°13.′6N, 135°10.′0E). The barogram used in the present study is that observed by an aneroid type barometer at

Akibasan. The duration and reading intervals of the tidal records, thermogram and barogram are of course the same as those of the tiltmetric record, namely from July 31, 15^h00^m, 1960 to July 31, 14^h00^m, 1961 (UT), and every hour, respectively. In the present study we have provisionally adopted the intensity of precipitation, mm per one hour, to represent its pattern, which is considered as the time derivative of the precipitation. It is to be noted that since the distances from Akibasan and Oura to the Wakayama Meteorological Observatory are about 3 and 4 km respectively, the air temperature and precipitation observed there would not be, strictly speaking, identical with those at Akibasan and Oura. However, we have not carried out meteorological observations at these stations and could not use these data, although it is desirable to use data observed at the same place where observations of the ground deformations are carried out.

The tiltmetric observations have been sometimes interrupted by heavy precipitations, failure of the electric power supply and instrumental troubles. The monthly numbers of days, for which the data are lacking are given in Table 3 for each tilting component. Interpolating methods for missing data have been devised for processing the gravimetric records, for example, by I. M. Longman [1960] and R. Lecolazet [1961]. In the case of gravimetric records, the instrumental drift is generally linear or of simple form, and the missing curves can be interpolated through comparatively easy procedures. However, estimation of the lack of data is very difficult to make when drift is large and cannot be expressed by any simple functions. As to tiltmetric and extensometric records, meteorological disturbances are generally

Table 3. Monthly numbers of the days for which the data are lacking.

Month		Instruments					
		A_a	A_a'	B_a	B_a'	A_o	B_o
1960	Aug.	0	1	0	0	3	6
	Sep.	0	1	0	0	0	2
	Oct.	2	4	1	3	0	1
	Nov.	0	2	0	0	0	1
	Dec.	10	11	10	11	4	13
1961	Jan.	1	9	1	4	3	7
	Feb.	0	7	1	6	1	7
	Mar.	0	14	0	3	1	8
	Apr.	4	10	4	4	6	7
	May	0	8	0	1	0	0
	June	5	5	3	4	3	5
	July	6	16	2	13	5	2

observed on them when the observation room is shallowly seated like the cases at Akibasan and Oura, and the drift are mainly due to these disturbances. Accordingly, it is necessary for ideal estimations of the missing data to know the response of the ground to the meteorological disturbances. This forms a vicious circle in the present case, and at the first step we have interpolated the short periods without data under the assumption that the drift was linear and the tidal oscillations proportional to those of the sea level at Wakayama Harbor were superimposed on the linear drift to the first approximation in the present study.

3. *Fourier spectra*

Let $f(t)$ be an arbitrary time function, and then its Fourier transform $F(\omega)$ is given by

$$F(\omega)=\int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt=a(\omega)-i\cdot b(\omega), \tag{1}$$

where

$$a(\omega)=\int_{-\infty}^{\infty} f(t)\cos\omega t dt, \tag{2}$$

$$b(\omega)=\int_{-\infty}^{\infty} f(t)\sin\omega t dt. \tag{3}$$

On the other hand, when the amplitude and phase spectra, $F(\omega)$ and $\phi(\omega)$, are given, then $f(t)$ is expressed by the formula,

$$\begin{aligned} f(t)&=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}d\omega,\\ &=\frac{1}{\pi}\int_{0}^{\infty} |F(\omega)|\cos[\omega t+\phi(\omega)]d\omega. \end{aligned} \tag{4}$$

The amplitude and phase spectra, $|F(\omega)|$ and $\phi(\omega)$, should be obtained by

$$|F(\omega)|=\sqrt{[a(\omega)]^2+[b(\omega)]^2}, \tag{5}$$

$$\phi(\omega)=\tan^{-1}[-b(\omega)/a(\omega)]. \tag{6}$$

Because the duration of records to be analysed is not infinite, the practically obtained spectrum is not equal exactly to $F(\omega)$, but the Fourier transform of a truncated function $f(t)$ which is zero outside the finite interval $T\geqq|t|$, is defined by the convolution $\int_{-\infty}^{\infty}\{F(\tau)\sin T(\omega-\tau)/[\pi(\omega-\tau)]\}d\tau$ (Papoulis [1962]). However, when the duration of the observation, $2T$, is long enough for the angular frequency considered, namely $\omega T\gg1$, the convolution may well be approximated as $F(\omega)$. Numerical integrations to obtain $a(\omega)$ and $b(\omega)$ in the present study were performed following the trapezoidal rule, after linear drift of the data has been removed. Neither data window nor frequency window has been applied to get the amplitude and phase spectra, because it is one of the present purposes to determine the absolute amplitudes for specific frequencies. It is to be remarked that $F(\omega)$ was multiplied by the coefficients inversely proportional to the period, $1/T$, for its normalization in order to estimate the amplitudes of tidal constituents and diurnal changes of the meteorological factors.

4. Amplitudes and phases of principal tidal constituents obtained from one year's data

Following the procedure mentioned above, the amplitudes and phases of 8 principal constituents of the tidal changes of the E-W and N-S component tilts at Akibasan have been calculated from the one year's data. The extensometric results at Akibasan and both extensometric and tiltmetric results at Oura have not been calculated because of lacking data of long periods. The results obtained are tabulated in Table 4. Simultaneously, the tidal record at Wakayama Harbor WT, atmospheric pressure P_a, air temperature Y and the intensity of precipitation P have been analysed and the results are also given in the table. As is expected, only the amplitudes of the pressure and temperature of the S_2 constituent, the period of which is 12.000 hours and equal to half of the mean solar day, are remarkably large compared with other constituents. It is to be noted that the M_2 constituent of the pressure is small as about 5 % of that of S_2 and we can regard the S_2 constituent as the only one among the atmospheric tidal constituents to be taken into consideration.

Comparing the amplitudes and phases of the tiltmetric constituents with

Table 4. Amplitudes and phases of 8 principal tidal constituents.

Constituent		E-W Tilt (A_a)	N-S Tilt (B_a)	Oceanic tides (WT)	Temperature (Y)	Pressure (P_a)	Precipitation (R)
M_2	$\|F(\omega)\|$	0.01662″	0.009332″	47.07 cm	0.04542°C	0.0381 mb	0.05044 $^{mm/}_{hour}$
	$\phi(\omega)$	190°.28	21°.33	20°.68	187°.07	214°.03	283°.34
S_2	$\|F(\omega)\|$	0.005736	0.003951	21.86	0.7921	0.656	0.02552
	$\phi(\omega)$	4.13	207.86	207.42	25.52	283.95	268.34
N_2	$\|F(\omega)\|$	0.003523	0.001863	9.663	0.02948	0.00154	0.04428
	$\phi(\omega)$	132.56	321.59	324.39	50.96	288.17	203.42
K_2	$\|F(\omega)\|$	0.002148	0.0009572	4.409	0.08878	0.0738	0.07104
	$\phi(\omega)$	170.95	328.36	309.08	168.43	57.95	247.39
K_1	$\|F(\omega)\|$	0.006888	0.005761	22.17	0.1449	0.0503	0.05099
	$\phi(\omega)$	136.40	334.33	335.13	133.73	111.62	355.54
O_1	$\|F(\omega)\|$	0.007191	0.003952	15.65	0.02633	0.0745	0.05216
	$\phi(\omega)$	35.34	220.06	218.07	192.73	156.06	347.33
Q_1	$\|F(\omega)\|$	0.001249	0.0007158	3.356	0.1040	0.0858	0.03787
	$\phi(\omega)$	350.25	136.36	150.68	265.10	205.39	344.05
P_1	$\|F(\omega)\|$	0.001945	0.002407	8.034	0.1207	0.0801	0.03684
	$\phi(\omega)$	230.78	43.04	48.23	109.44	217.74	125.28

Remarks: The phases of each constituent are referred to the origin time of the analysis, namely July 31, 15^h00^m, 1960 (UT).

Table 5. Amplitude ratios and phase differences of the tiltmetric constituents to the oceanic tidal height.

Constituent	Amplitude ratio (F_{Aa}/F_{WT})	Phase difference ($\phi_{Aa}-\phi_{WT}$)	Amplitude ratio (F_{Ba}/F_{WT})	Phase difference ($\phi_{Ba}-\phi_{WT}$)
M_2	0.000354	169.60	0.000198	0.65
S_2	0.000262	156.71	0.000180	0.44
N_2	0.000365	168.17	0.000193	−2.80
K_2	0.000538	161.87	0.000220	19.28
K_1	0.000310	161.27	0.000260	−0.80
O_1	0.000459	177.27	0.000252	1.99
Q_1	0.000372	199.57	0.000214	−14.32
P_1	0.000242	182.55	0.000300	−5.19

those of the oceanic tidal height, it is clear that the two tilting components are heavily affected by the tidal height of the nearby sea, Wakaura Bay. This may be seen in Table 5, in which the amplitude ratios of the E-W and N-S component tilts to the water height and phase differences between them are given for each constituent. Regarding the comparison of the E-W component with the water height, the ratio and phase difference may be estimated as about 0.00030~0.00040″/cm and 160°~180°, respectively, although the amplitude ratio of K_2 shows fairly large value which is possibly due to the errors from the smallness of the amplitude. The small amplitude ratio and phase difference of S_2 may be caused by the meteorological disturbances which we shall discuss later.

On the amplitude ratios and phase differences of the N-S component to the water height, slight discrepancy can be seen between the diurnal and semidiurnal tidal constituents, which might be caused by the difference of the distribution pattern of the loading of water between the two. A similar tendency may also be inferred from the large amplitude ratio of the O_1 constituent regarding to the E-W component.

As is a matter of course, no apparent large values in amplitude can be seen for the frequencies corresponding to the 8 principal constituents in the case of the intensity of precipitation. The effect of the precipitation on the tidal ground tilts can be estimated to be of the magnitude of the order of 0.0001″, at most, by multiplying the above mentioned amplitudes of precipitation and the spectra of the impulse response of the ground tilts to the precipitation which will be shown later, taking $\omega=0.52$ and 0.26 for semidiurnal and diurnal constituents respectively, and thus its effect may be considered to be sufficiently small to be neglected regarding the constituents.

5. *Effects of diurnal and semidiurnal fluctuations of the atmospheric pressure and air temperature on the ground tilts*

Next, the amplitudes and phases of the three major tidal constituents M_2, S_2 and O_1, and the meteorological constituent S_1 were calculated on the basis of monthly data of the ground tilts at Akibasan and Oura, oceanic tides, atmospheric pressure and air temperature by the Fourier transform, in order to estimate the relations between the diurnal and semidiurnal terms of these disturbing factors and their effects on the ground tilts. We can get informations as to the tidal phenomena from the amplitudes and phases of M_2, S_2 and O_1 constituents, and as to the meteorological effects -temperature and pressure- from S_2 and S_1, since S_1 is entirely due to meteorological changes and S_2 is also disturbed by them. However, since the resolution of a spectrum is limited by the analysed duration of the data, adjacent constituents within the resolving power are not separable. When one month's data are analysed by this method, the minimum separable frequency difference is estimated as about 0.0028 c/h. Hence the components corresponding to the frequencies of M_2, S_2, O_1 and S_1 are affected mainly by $(N_2, L_2, \nu_2, \lambda_2)$, $(L_2, \lambda_2, T_2, R_2, K_2)$, (Q_1, M_1, ρ_1) and (M_1, J_1, P_1, K_1), respectively, although the amplitudes of these adjacent constituents are generally small compared with those of M_2, S_2 or O_1 in Japan except in the case of S_1. The effects of this contamination may be reduced to some degree by a comparison between the results obtained from the same data interval by the same procedure. If there are no effects from meteorological disturbances, the calculated amplitude and phase for the period of 24.000 hours are mainly influenced by the K_1 constituent owing to the nearness of the angular frequency.

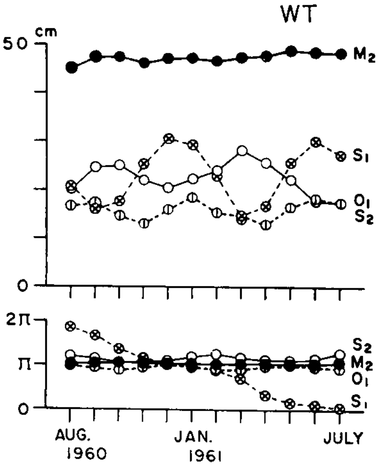

Fig. 9 a. Monthly amplitudes and phases of the oceanic tides observed at Wakayama Harbor.

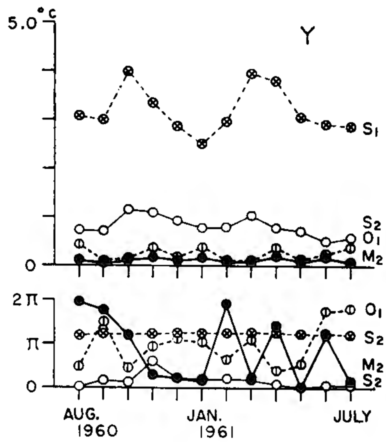

Fig. 9 b. Air temperature observed at the Wakayama Meteorological Observatory.

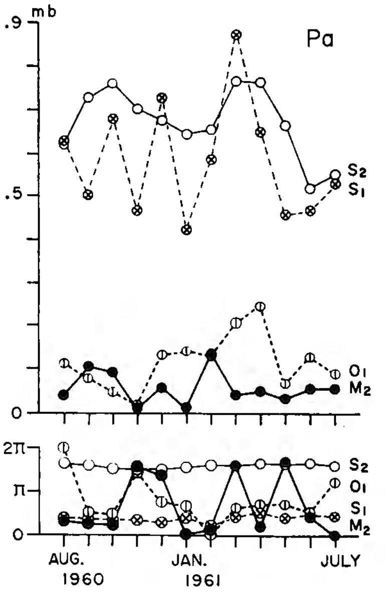

Fig. 9 c. Atmospheric pressure observed at Akibasan.

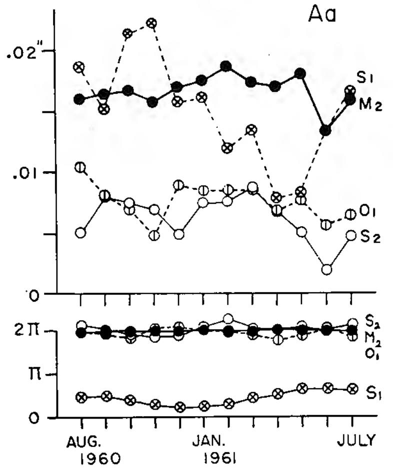

Fig. 9 d. E-W component tilt at Akibasan.

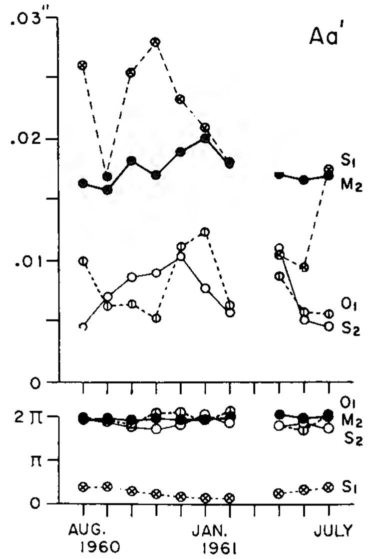

Fig. 9 e. E-W component tilt at Akibasan.

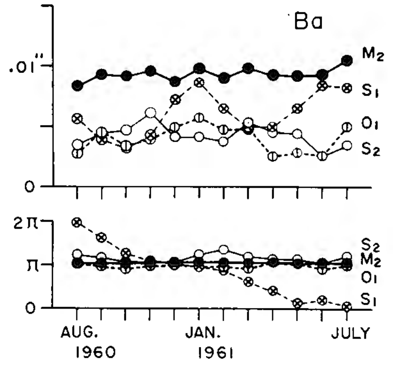

Fig. 9 f. N-S component tilt at Akibasan.

Obtained amplitudes and phases of the four constituents for monthly data are shown in Fig. 9, where the positive trace of the tiltmetric records means the east- or southward tilting, and the phases of M_2, S_2 and O_1 in this case

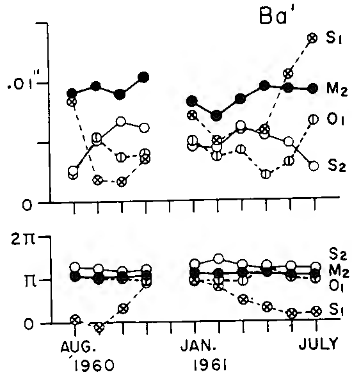

Fig. 9g. N-S component tilt at Akiba-san.

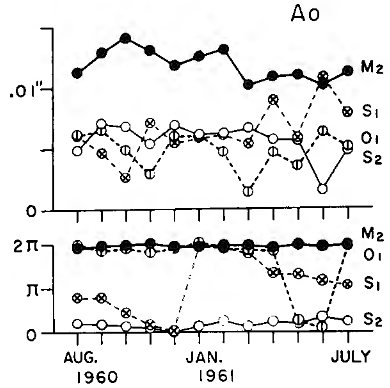

Fig. 9h. E-W component tilt at Oura.

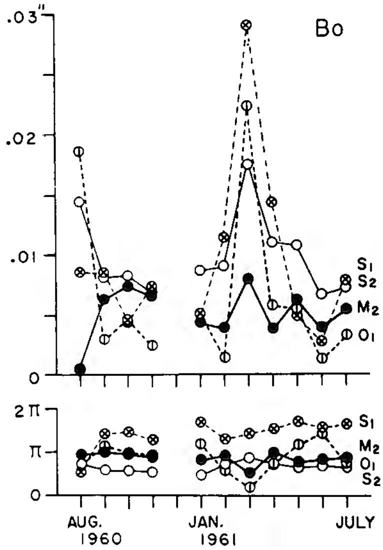

Fig. 9i. N-S component tilt at Oura.

mean the lag of the maximum values behind the theoretical maximum at Wakayama at the beginning of each month.

We shall discuss their features in some detail in the following.

(1) *Oceanic tides at Wakayama Harbor (WT)*

The amplitude and phase of the M_2 constituent are almost constant and show no remarkable changes. The fluctuations of the amplitude and phase are about 8% and 8°, respectively, this may be due to not only the real fluctuation of them but also to the errors from the effect of the adjacent constituents and numerical integration. Considerable fluctuations are seen as to the amplitudes of S_2, O_1 and S_1 which may be mainly attributable to the mixing of other constituents. A notable phase shift is that of S_1 which shifts 2π during one year, signifying that the calculated amplitude is that corresponding to K_1, and that S_1 itself, namely the diurnal meteorological disturbance, is very small compared with the amplitude of K_1. The amplitude and phase at July 31, 15^h00^m, 1960 of K_1 obtained from the one year's data, which are shown in Table 4, coincide with the mean amplitude and the phase of S_1 of the August in the present result, respectively. The phase of M_2 is nearly equal to those of S_2 and O_1, this means that the three constituents have nearly equal lag from the theoretical phases.

(2) *Air temperature at the Wakayama Meteorological Observatory (Y)*

The amplitude of S_1 is the largest, as expected. Amplitude changes of the 6 month period are observed in both S_2 and S_1, the maxima of which appear in autumn (September or October) and spring (March or April), although it is a question whether this phenomenon is an annual event. The amplitudes having periods of 25.819 (O_1) and 12.421 hours (M_2) are very small compared with those of S_2 and S_1, and their phases also show random scatterings as a matter of course. It may be safely deduced from this fact that we can disregard the effect of the temperature fluctuation in respect of the lunar tidal oscillations.

(3) *Atmospheric pressure at Akibasan (P_a)*

As is well known, diurnal and semidiurnal solar oscillations (atmospheric tides) are predominant, and their phases are almost constant on the whole. An abnormally large amplitude of S_1 is noticeable for March 1961. Because the amplitudes corresponding to M_2 and O_1 are very small and because their phases are not constant, they may be interpreted as merely apparent oscillations with periods of 12.421 and 25.819 hours.

(4) *E-W component tilt at Akibasan (A_a and A_a')*

It is obvious in Fig. 9 d that there exists a periodic oscillation corresponding to S_1 which may be attributable to the temperature change, since the phase of S_1 did not vary during the one year period. Its amplitude, however, fluctuates remarkably and the phase shifts slightly during the year. Although the amplitude of M_2 of the A_a component was extraordinarily small in June 1961, a similar tendency cannot be seen in A_a', from this it is concluded that the diminution is not real but may be due to errors in the interpolation for the missing data.

(5) *N-S component tilt at Akibasan (B_a* and *B_a')*

The pattern of the result of the B_a component is the most satisfactory among all the tilting components including those of Oura. The meteorological constituent S_1 is small compared with K_1, unlike the E-W component. All the spectral features bear a resemblance to that of the oceanic tides (WT), and we can conclude that the N-S component tilt at Akibasan consists mostly of the direct effect of the oceanic tidal changes. It is to be noted that although the amplitude fluctuation of S_1 of the B_a' component has a similar tendency as that of B_a, the minimum value in October is smaller, and the maximum in July larger than those of B_a, respectively. Therefore contamination of some existing constituent with K_1 in regard to the B_a' component may be deduced.

(6) *E-W component tilt at Oura (A_o)*

Since the phase of S_1 shows the shift relating to K_1, the diurnal effect of meteorological changes is not so large compared with the tidal phenomena. A noticeable decrease of the amplitude of S_2 is seen in June 1961.

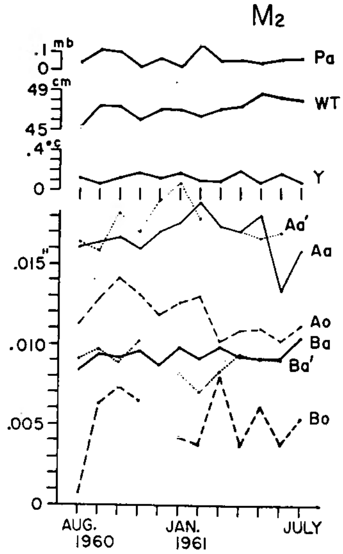

Fig. 10 a. Comparison of the amplitudes in respect of the M_2 constituent.

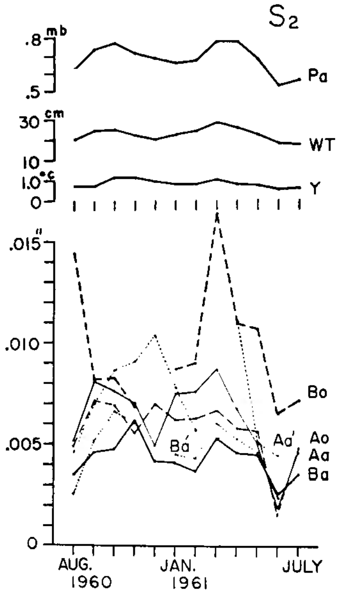

Fig. 10 b. Comparison of the amplitudes in respect of S_2.

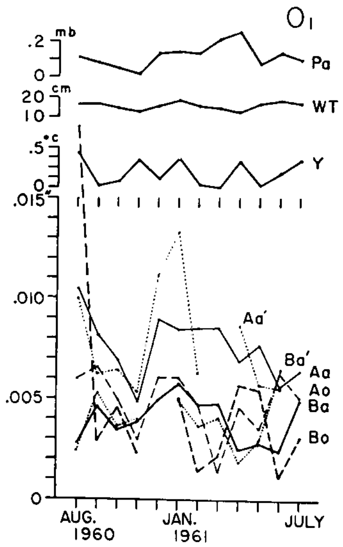

Fig. 10 c. Comparison of the amplitudes in respect of O_1.

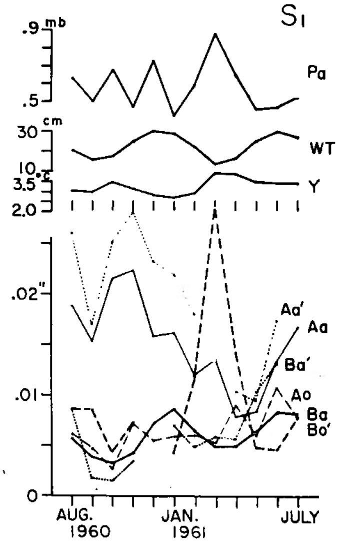

Fig. 10 d. Comparison of the amplitudes in respect of S_1.

(7) *N-S component tilt at Oura* (B_o)

The feature of the amplitude and phase changes of this component are remarkably different from the above mentioned components of the ground tilts. The amplitude of M_2 is smaller than S_2 and S_1, and at times smaller than O_1. It is characteristic that the amplitudes of all constituents show a remarkable increase in March and decrease in June 1961.

In Fig. 10, comparisons of the amplitude changes are given in regard to each constituent. In respect of M_2 and O_1, no clear correlations are seen between the ground tilts and oceanic tides, air temperature or atmospheric pressure. The amplitudes of M_2 and O_1 are not always equal to each other for the two parallel pairs of tiltmeters at Akibasan, A_a and A_a', and B_a and B_a', respectively (Figs. 10 a and 10 c). It appears clearly in Fig. 10 b that the change of the pressure has more or less influence upon all the tilting components of S_2. The amplitude change of S_2 of the oceanic tides is very similar to that of the pressure which suggests that the oceanic tides are affected by the pressure prevailingly as to the S_2 constituent. The correlation between the B_o component and pressure is remarkable for S_1, from which it is concluded that the abnormally large amplitude in March 1961 is attributable to the effect of the pressure change. Besides, the amplitude of A_a' is always larger than that of A_a, as seen in Fig. 10 d.

Weighted mean amplitudes and phases of the one year period have been calculated for each tilting component, for oceanic tides, temperature and pressure, the results of which are given in Table 6. The weights applied are inversely proportional to the numbers of the days shown in Table 3. In Table 6 the mean values of the amplitudes and phases of the oceanic tides, B_a, B_a' and A_o components for S_1, and the phases of the temperature and pressure for M_2 and O_1 are not given because they are meaningless. The results agree

Table 6. Weighted mean amplitudes and phases.

	M_2		S_2		O_1		S_1	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
WT	47.1 cm	186°.2	22.3 cm	208°.1	15.8 cm	170°.1	—	—
T	0.12°C	—	0.82°C	22.6	0.25°C	—	3.20°C	223°.2
P_a	0.058 mb	—	0.669 mb	284.8	0.118 mb	—	0.581 mb	70.5
A_a	0.01672″	355.8	0.00630″	4.6	0.00761″	346.1	0.01515″	75.2
A'_a	0.01738	352.3	0.00723	330.0	0.00773	349.6	0.02006	50.4
B_a	0.00935	186.5	0.00429	207.3	0.00396	173.1	—	—
B'_a	0.00891	190.4	0.00475	222.9	0.00390	178.1	—	—
A_o	0.01188	353.0	0.00571	32.4	0.00481	352.6	—	—
B_o	0.00493	144.1	0.00909	107.1	0.00595	151.6	0.00835	239.9

Table 7. Amplitude ratios and phase differences of A_a' to A_a, and B_a' to B_a.

	Amplitude ratio (A_a'/A_a)	Phase difference ($A_a'-A_a$)	Amplitude ratio (B_a'/B_a)	Phase difference ($B_a'-B_a$)
M_2	1.04	−3°.5	0.95	3°.8
S_2	1.15	−34.6	1.11	15.6
O_1	1.01	3.5	0.98	5.0
S_1	1.32	−24.8	1.04*	−4.8*

* S_1 constituents of B_a and B_a' components correspond to K_1.

fairly well with those obtained from the one year's data analysis, except apparent constituents such as M_2 and O_1 for the temperature and pressure.

Now, let's compare the two pairs of the tiltmetric results observed on the same concrete base at Akibasan. The amplitude ratios and phase difference obtained by the two tiltmeters in the same direction are given in Table 7 for each constituent. It is apparent that the ratios are nearly equal to 1 for M_2 and O_1, but considerably larger than 1 for S_2 and S_1. Similarly the phase differences are small for the former and larger for the latter. As seen in Figs. 9 b and 9 c, periodic changes in the temperature and pressure corresponding to S_2 and S_1 are very predominant compared with those corresponding to M_2 and O_1. Therefore it is concluded that the concrete base is not deformed but uniformly inclines owing to the loading effect of the oceanic tides, while it is deformed by the effect of the temperature and pressure changes. This means that the wave length of the deformation due to the temperature and pressure changes is so short that the concrete base is deformed according to the deformation of the observation room. Thus, such a deformation cannot be ignored when scales of topographical features or irregularities in heating and cooling at the ground surface are so small and the depth of observation rooms are not so large as at Akibasan, as shown theoretically and observationally by many researchers (for example, Kabuzenko [1959], Nakano [1963]).

6. *Spectral structure of the tiltgrams at Akibasan*

In order to investigate the spectral structure as to the periodic range within about one day, amplitude and phase spectra of the tiltgrams at Akibasan have been calculated according to (2), (3), (5) and (6). The duration of the analysis is fifty days from May 5, 15^h00^m to June 24, 14^h00^m, 1961 (UT). The results are shown in Figs. 11 and 12. As seen in the figures, not only the amplitudes of tidal changes of M_2, O_1, N_2 and S_2, but those of the diurnal changes of the period of 24.000 hours are predominant, although the contaminations are unavoidable between adjacent constituents because of the shortness of the analysed data interval. It can be seen in the figures that the amplitudes corresponding to tidal terms in the E-W component are larger than those in the

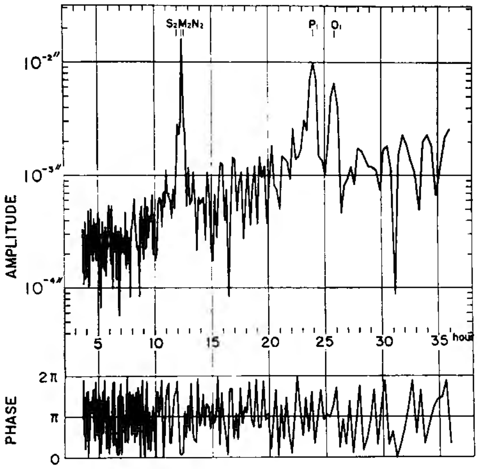

Fig. 11. Amplitude and phase spectra of the E-W component tilt (A_a) at Akibasan.

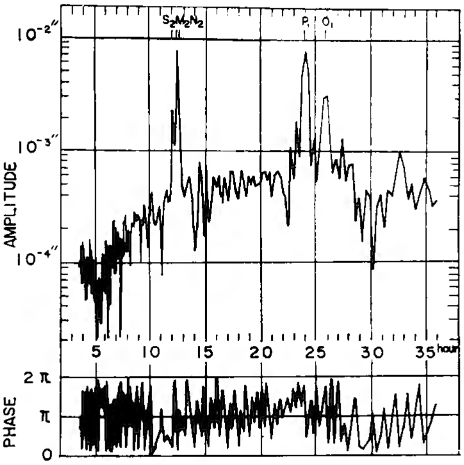

Fig. 12. Amplitude and phase spectra of N-S (B_a) at Akibasan.

N-S component, and that the noise level of the former is also higher than that of the latter. This may be explained by the influence of the meteorological and oceanic tidal changes which appear more noticeably in the E-W component than in the N-S.

The spectral features of the tilting motions as to the periodic ranges from 1 to 11 days and from 11 to 34 days are shown in Figs. 13 and 14. The duration of the analysis is one year from July 31, 15^h00^m, 1960 to July 31, 14^h00^m,

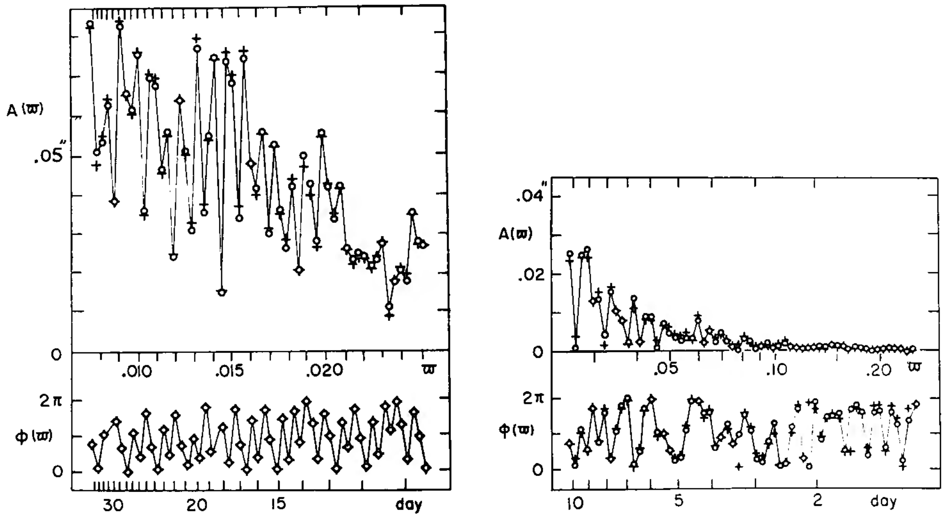

Fig. 13. Spectral amplitude $A(w)$ and phase $\phi(w)$ of the E-W component tilt at Akibasan. The cross represents the corrected values for the oceanic tides, air temperature, atmospheric pressure and its time derivative.

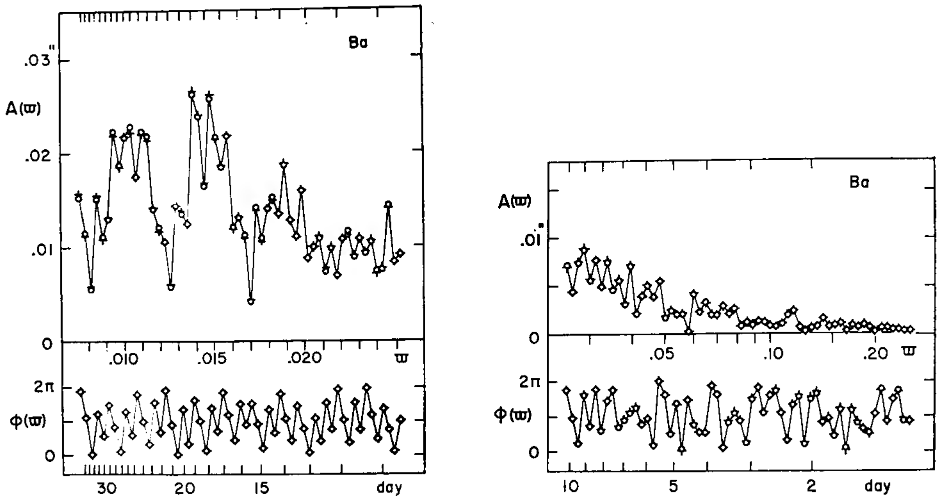

Fig. 14. Spectral amplitude and phase of the N-S component tilt at Akibasan. The cross represents the corrected values for the oceanic tides, air temperature, atmospheric pressure and its time derivative.

1961 (UT). In these figures the angular frequency and period are given in cycle per 2π hours and day, respectively. The absolute values of the amplitude spectrum of the E-W component are generally larger than those of the N-S as well as the case of the shorter periodic range mentioned above. The amplitudes and periods for apparent peaks are summarized in Table 8. The fortnightly constituents Mf (13.66 days) and MSf (14.77 days) cannot be ob-

Table 8. Periods and Amplitudes of apparent peaks on the tiltmetric spectra at Akibasan.

A_a (E-W component)		B_a (N-S component)	
Period (day)	Amplitude (second of arc)	Period (day)	Amplitude (second of arc)
28.7	0.0833	27.8	0.0222
26.0	0.0759	25.3	0.0228
24.5	0.0699	23.8	0.0222
19.9	0.0779	18.9	0.0263
18.5	0.0750	17.7	0.0258
17.7	0.0742	16.7	0.0217
16.7	0.0750	13.9	0.0186
13.2	0.0556	13.2	0.0159
10.7	0.0349	10.7	0.0142
9.1	0.0265	9.1	0.0088
7.8	0.0153	6.7	0.0070
6.7	0.0140	5.5	0.0054
4.4	0.0081	4.4	0.0041
		2.3	0.0023

served on the spectra, this may be due to the smallness of the amplitudes of the oceanic constituents and the highness of the background noise level.

7. *Mean diurnal changes of the ground tilts and effects of the atmospheric pressure and air temperature upon them*

Since the diurnal (24.000 hours) and semidiurnal changes (12.000 hours) are predominant in the case of the atmospheric pressure and air temperature as seen in Figs. 9 b and 9 c, it may be effective to investigate their influence upon the ground deformation in regard to the characteristic changes. For this purpose monthly mean diurnal changes (as to the solar time) of the ground tilts, oceanic tides, atmospheric pressure and air temperature have been obtained from one month's data, after eliminating the drift by the Pertzev's method. On the other hand, the amplitude ratios of M_2 of each tilting component to that of the oceanic tides have been calculated from the results given in Table 6. Multiplying each ratio by the hourly values of the mean diurnal changes of the oceanic tides, we subtracted the products from the corresponding components of the ground tilts (Tanaka [1967]). As the phase of the B_o component differs by about one hour from that of the oceanic tides, the product has been slid one hour against the B_o component for phase adjustment and subtracted from it. Although small phase discrepancies can be seen among the diurnal and semidiurnal groups as seen in Table 5, it may be permissible to use the phase of M_2 as a representative phase of the constituents as an approximation. Properly speaking, it is the right course of procedure to eliminate the tidal effects by the subtraction of theoretical curves synthesized according to the results obtained from the long term analysis, for example according to the results in Table 4. However, it is difficult in this case to distinguish the changes due to the tidal components from those due to the meteorological disturbances in the case of the S_2 constituent. Moreover, the sea level is influenced irregularly under the meteorological changes and currents, according to which the ground is deformed, and adoption of the above mentioned procedure is not necessarily meaningless as an approximation.

As expected from the results of the Fourier analysis, diurnal changes are clearly seen in the residuals of A_a and A_a' components which may be mainly caused by the temperature change. On the contrary, residuals of the B_a component show no regular changes except very small deviations in September, October in 1960, and April and May in 1961. The residuals of the B_a' component are somewhat larger than those of B_a. Because the oceanic tidal effect is very small in the B_o component, the features of its residuals are scarcely different from the originals, and are very similar to the mean diurnal changes of the pressure (Tanaka [1967]).

Assuming that these residuals are represented by linear combinations of the air temperature, atmospheric pressure and its time derivative, each coefficient for these disturbances has been determined by the method of least squares, where we defined the time derivative of the pressure as $dp_a/dt=(1/2)\cdot[p_a(t+1)-p_a(t-1)]$, (mb/hour), and calculated it from the curves of the mean diurnal changes of the pressure. The monthly coefficients obtained are summarized in Tables 9 and 10. The curves of the mean diurnal change for the temperature have been delayed one hour in the process of determining coeffi-

Table 9. Coefficients of disturbing factors to the ground tilts at Akibasan (Unit : 0.001″).

	A_a (E-W component)			B_a (N-S component)		
	Temperature* (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)	Temperature (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)
1960 Aug.	−5.55±0.27	1.64±0.88	−7.8 ±1.8	−0.831±0.086	0.12±0.27	−3.02±0.68
Sep.	−3.09±0.23	2.15±0.79	−4.7 ±1.4	0.240±0.061	0.16±0.20	−7.67±0.40
Oct.	−3.55±0.26	1.3 ±1.0	−4.8 ±1.5	0.059±0.065	0.56±0.25	−1.02±0.47
Nov.	−4.14±0.13	0.72±0.49	−2.27±0.71	0.20 ±0.18	1.29±0.68	−1.3 ±1.2
Dec.	−2.09±0.43	2.2 ±1.3	0.7 ±1.6	−0.27 ±0.20	−1.18±0.57	−1.23±0.84
1961 Jan.	−4.23±0.34	−0.7 ±1.0	−6.4 ±1.6	0.55 ±0.26	1.34±0.75	−1.6 ±1.4
Feb.	−4.40±0.43	−5.1 ±1.5	−7.3 ±2.4	0.20 ±0.17	0.33±0.55	−4.74±0.98
Mar.	−3.33±0.52	3.2 ±1.8	−8.2 ±2.7	−0.458±0.092	0.46±0.30	−2.66±0.60
Apr.	−3.00±0.21	3.09±0.74	−0.8 ±1.6	−0.353±0.075	0.64±0.27	−2.52±0.63
May	−4.15±0.29	0.8 ±1.0	−1.7 ±2.0	−0.35 ±0.11	−0.32±0.37	0.81±0.79
June	−4.92±0.46	3.2 ±1.8	3.5 ±3.5	−1.36 ±0.20	−0.78±0.75	−8.0 ±1.8
July	−5.05±0.61	6.7 ±2.2	−11.1±4.2	−1.09 ±0.11	−2.09±0.34	0.13±0.80

	A_a' (E-W component)			B_a' (N-S component)		
	Temperature (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)	Temperature (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)
1960 Aug.	−7.15±0.28	10.91±0.87	−5.8 ±2.2	−2.19 ±0.15	0.46±0.47	−7.9 ±1.2
Sep.	−3.39±0.45	6.6 ±1.5	1.3 ±3.0	−0.22 ±0.14	2.06±0.44	−1.14±0.86
Oct.	−3.65±0.36	7.4 ±1.4	−4.4 ±2.6	−0.80 ±0.12	2.47±0.42	0.27±0.81
Nov.	−5.02±0.47	5.6 ±1.8	−5.3 ±3.2	−0.45 ±0.14	2.37±0.54	0.40±0.95
Dec.						
1961 Jan.				0.35 ±0.19	2.10±0.54	−0.43±0.96
Feb.				−0.087±0.083	1.79±0.28	−4.97±0.50
Mar.				−0.758±0.084	1.72±0.27	−1.20±0.55
Apr.				−0.553±0.066	1.01±0.23	0.35±0.56
May	−4.95±0.17	7.10±0.61	3.7 ±1.4	−1.41 ±0.26	1.10±0.91	0.0 ±2.0
June						
July						

---

* The phase of the temperature advances one hour compared with that of the ground tilt of the A_a component.

Table 10. Coefficients of disturbing factors to the ground tilts at Oura (Unit: 0.001″).

	A_o (E-W component)			B_o (N-S component)		
	Temperature (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)	Temperature (1°C)	Pressure (1 mb)	Time derivative of pressure (1mb/hour)
1960 Aug.	−0.03 ±0.13	0.54±0.38	−0.54±0.96	−3.9 ±1.4	− 9.7 ±4.4	−19 ±11
Sep.	0.37 ±0.11	−1.61±0.36	−1.78±0.71	0.49±0.21	−10.55±0.69	− 6.1± 1.4
Oct.	0.16 ±0.12	−2.14±0.42	−0.26±0.81	−1.31±0.16	−10.28±0.60	− 6.6± 1.2
Nov.	−0.52 ±0.12	−1.89±0.45	−0.99±0.80	0.40±0.19	− 8.12±0.70	− 4.0± 1.3
Dec.	1.09 ±0.29	1.96±0.81	−2.0 ±1.2			
1961 Jap.	0.41 ±0.19	0.11±0.54	−2.65±0.95	−1.56±0.85	−11.0 ±2.5	− 7.0± 4.4
Feb.	−0.244±0.079	−0.62±0.27	−0.89±0.48			
Mar.	0.15 ±0.17	0.48±0.53	2.3 ±1.1			
Apr.	1.040±0.078	−2.24±0.27	3.32±0.66			
May	−0.54 ±0.22	−2.44±0.78	−0.3 ±1.7	−0.92±0.19	−13.23±0.67	− 3.2± 1.5
June	1.46 ±0.24	0.21±0.90	11.4 ±2.1	−0.12±0.26	− 8.64±0.96	− 7.2± 2.2
July	0.279±0.045	0.62±0.15	−2.52±0.35	−0.29±0.22	−13.58±0.73	− 2.8± 1.8

cients of the A_a component because the mean square errors are smaller in this case than when there is no delay. However, such a tendency could not be found in respect of the A_a' component, and its coefficients have been determined under the circumstance that there is no phase delay between the temperature change and the consequent tilting motion.

Some considerations will be given for the coefficients of each disturbing factor in the following.

(*1*) *Effects of the air temperature*

Effects of the temperature change on tiltgrams are very clear in A_a and A_a' components, and the coefficients as to A_a' are larger than those as to A_a. The effect may also be found in B_a and B_a' components, where the coefficients of the former tend to be positive in the winter and negative in the summer, and those of the latter to be negative throughout the analysed period, although there remains some uncertainty due to the approximate method used to eliminate the oceanic tidal effects and the period is too short to permit one to ascertain such an annual change. However it is suggested that the annual tendency is not due to the remnants of the tidal disturbances, for example K_1 constituent, but due to the temperature change, because the annual tendency can also be observed in the changes of the S_1 constituent and the fluctuation of B_a' is larger than that of B_a, as seen in Fig. 10 d, while such a tendency cannot be seen in the result of the oceanic tides.

We could not recognize the phase delay between the temperature and thermal tilts except the one hour delay in the case of the A_a component.

Since the change of the temperature at the ground surface is hardly propagated into the tunnel by heat conduction within such a short time interval, these tilting motions are not caused by heat conduction from the surface, but by the propagation of the thermal deformation. According to results obtained by S. Nakano [1963], the amount of the thermal tilt at Akibasan is satisfactorily explained by the change of the surface temperature having a wave length nearly equal to a topographical scale of about one hundred meters and amplitude of several tenth of the mean diurnal change of the temperature, neglecting the term of heat conduction.

Fig. 15 show a schematic diagram of the tilting motion due to diurnal change of the temperature, which was obtained by averaging the coefficients of respective three months as to the two central tiltmeters A_a and B_a. It is apparent in the figure that the diurnal tilting motion has the largest amplitude in the summer, and the smallest in the winter, although the diurnal amplitude of the temperature is larger in the spring and autumn. This phenomenon is considered as a general tendency in the thermal deformations of the ground (Kabuzenko [1959]). It is interesting that the features of the thermal tilts are very similar to those of buckling motions observed in a building of simple design (Ito [1960]), which may be caused by the simple topographical form of the hill in which the observation room was situated.

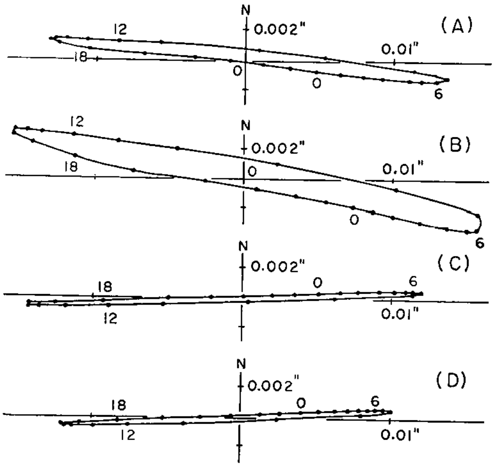

Fig. 15. Influence of the air temperature on the ground tilt at Akibasan.
A; Spring (March-May)
B; Summer (June-August)
C; Autumn (September-November)
D; Winter (December-February)

Thermal tilting at Oura is not so remarkable as at Akibasan owing possibly to the situation of the observation room and topographical conditions. Although we have been obliged to use only the air temperature as a provisional parameter of the thermal deformation, it is necessary for further precise investigations to get more exact information about thermal boundary conditions through measurements of temperature on, near, and beneath the surface of the ground.

(2) *Effects of the atmospheric pressure*

As the direct effect of the atmospheric pressure on the ground is not likely to show seasonal changes, the consistency of the obtained coefficients through the one year period may be considered as a clue in proving their validity. From this point of view, the A_a and B_a components at Akibasan are recognized to have positive coefficients, and this means east- and southward inclination for high pressure. The coefficients of A_a' and B_a' are larger about three times than those of A_a and B_a, and from this it is inferred that the direct effect of the pressure has strong local characteristic similar to that of the air temperature. It is clear that the B_o component at Oura is heavily influenced by the pressure change.

(3) *Effects of the time derivative of the atmospheric pressure*

It is, in general, impossible to get spatial informations about the distribution pattern of the atmospheric pressure by the time derivative of the barometric record observed at some fixed point. However, we may substitute it for information about the pressure gradient, provided that the velocity and direction of propagation of the pressure waves are constant. Moreover, it may be possible that the time derivative of the pressure itself is related to the tiltgrams through the instrumental disturbances, for example. As seen in the result of the Fourier analysis, the semidiurnal oscillation is most predominant among atmospheric components, the main term of which consists of a westward migrating semidiurnal solar wave (Siebert [1961]). The diurnal solar wave which is considered to have originated from the solar radiation also migrates westwards with the sun, and the mean diurnal change of the pressure is allowed to consist of westward propagating waves of constant velocity. Therefore, the time derivative dp/dt calculated from the mean diurnal change may be substituted for the pressure gradient in the present case. As seen in the tables, the signs of the coefficients for terms dp/dt seem to be consistent and the values also do not differ so much for corresponding components of both stations. Thus it is possible that the ground in the Wakayama region inclines uniformly north-westwards according to increasing pressure. The amount of the ground tilt is roughly estimated as about 7″ per 1 mb/km of the pressure gradient in the E-W direction, assuming the velocity to be 1400 km/hour. However, this seems to be contradictory to the theoretical results given by G. H. Darwin [1882] and V. V. Khorosheva [1958] that the ground will inlcine toward the barometric maximum, since the diurnal and semidiurnal pressure waves migrate westwards. In the procedure of determining the coefficients, we have used the mean diurnal changes calculated from one month's data. Angular velocities of almost tidal constituents being not equal to 15.000° or its multiples except S_2 and S_1, their phases at the beginning of each month should shift gradually through one year. Therefore, the constituents which give consistent coefficients over one year are considered to be S_2 and S_1 in the present case, and there is a possibility of entering the errors by the process of eliminating the tidal effects and adopting the temperature observed at the Wakayama Meteorological Observatory as a parameter. R. Tomaschek [1957] has reported similar phenomena in respect of the effects of the barometric pressure gradient at Winsford in England, and explained their behavior in connection with tectonic structure. It is very interesting that not only qualitatively but quantitatively as well, the present result is not so different from his, although the wave length which we have used for the analysis is longer than that in his investigation. This suggests that such behavior of the ground tilt may be intrinsic in the effect of the barometric pressure gradient.

Table 11. Coefficients of disturbing factors to the ground tilt at Akibasan.

Disturbing factor		Ground tilt	
		A_a (E-W component)	B_a (N-S component)
Sea level at the Wakayama Harbor	; $w(t)$	−0.00035 (second/cm)	0.00020
Air temperature at the Wakayama Meteorological Observatory	; $y(t)$	−0.0039 (second/°C)	−0.00029
Atmospheric pressure at Akibasan	; $p_a(t)$	0.0014 (second/mb)	0.000047
Time derivative of the pressure at Akibasan	; $p_a'(t)$	−0.0038 (second/mb/hour)	−0.0028

In Table 11, coefficients of disturbing factors to the ground tilts A_a and B_a at Akibasan obtained by averaging the monthly values are given together with those of the oceanic height.

8. *Another consideration about the effect of the atmospheric pressure upon the ground tilts and strains*

On the tiltmetric and extensometric records at both stations, small fluctuations which correspond fairly well with the change of the atmospheric pressure are observed. Plotting the amplitudes of deflection on the tiltmetric and extensometric records versus those on the barogram, and assuming the relations between them to be linear, the ratios of the ground tilts or strains to the pressure change are obtained, the results of which are summarized in Table 12 (Tanaka [1964]). In order to find the relations between them in more detail, the Fourier transforms of the tiltmetric, extensometric and barometric data have been obtained and compared with each other. Several data intervals in which the change of the atmospheric pressure was especially large have been picked

Table 12. Ground tilts and strains by the atmospheric pressure.

Station	Instrument	Tilt and strain per one mb change of the pressure
Oura	A_o (E-W component tilt)	$-0.0058''$
	B_o (N-S component tilt)	$-0.015''$
	E_{eo} (E-W component strain)	-6.6×10^{-9}
	E_{no} (N-S component strain)	-1.8×10^{-8}
Akibasan	A_a (E-W component tilt)	$-0.0054''$
	E_{na} (N-S component strain)	6.6×10^{-9}

out and the Fourier transforms have been calculated according to (2), (3), (5) and (6). Under the assumption that the pressure disturbance is represented by a transformation through a linear system and expressed as the convolution of the pressure and proper weight functions, amplitude ratios and phase differences have been calculated for each tilt and strain components. It is needless to say, however, that the disturbances caused by the pressure on the tiltmetric and extensometric data cannot be fully represented by the convolution of the pressure change at one fixed point and weight function, but spatial information about the pressure distribution is necessary to depict the response to the pressure change. Although we have been obliged to use only the barometric data at Oura and Akibasan in the present case, the above assumption will require some modification when more extensive materials are available.

Since meteorological effects other than those due to the pressure and earth tides also distort the spectra obtained, the amplitude ratios and phase differences have been calculated only in regard to the amplitude spectral peaks for which

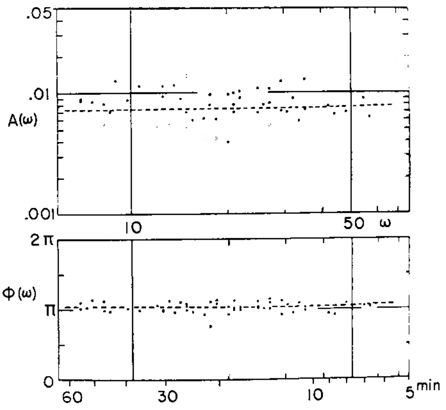

Fig. 16 a. Amplitude ratio and phase difference of the E-W component tilt at Oura to the atmospheric pressure. Unit of the ordinate of the ratio is second of arc/mb.

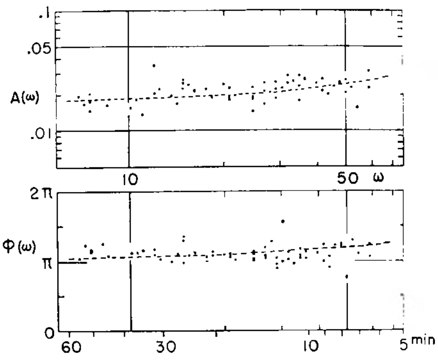

Fig. 16 b. N-S component tilt at Oura.

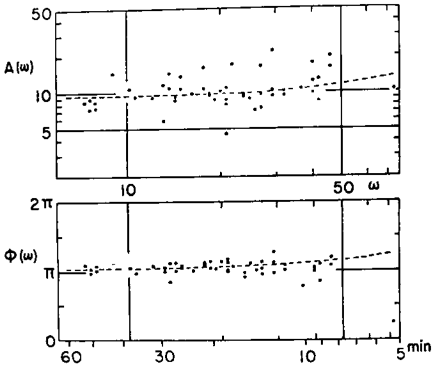

Fig. 16c. E-W component strain at Oura. Unit of the ordinate of the ratio is $\times 10^{-9}$/mb.

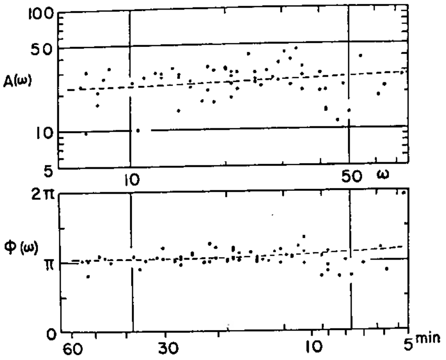

Fig. 16d. N-S component strain at Oura.

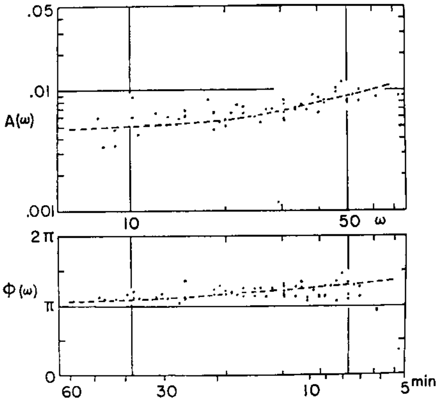

Fig. 17a. Amplitude ratio and phase difference of the E-W component tilt at Akibasan to the atmospheric pressure. Unit of the ordinate is second of arc/mb.

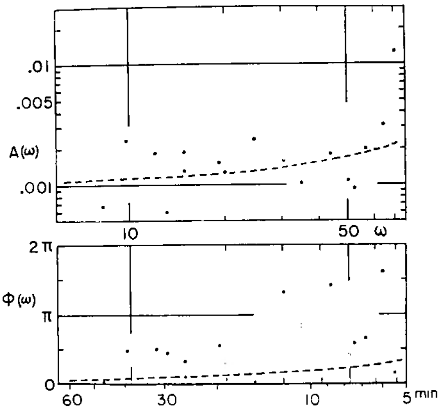

Fig. 17b. N-S component tilt at Akibasan.

good correspondence is seen between the spectra of the tiltmetric or extensometric records and barograms. The amplitude ratios and phase differences thus obtained are shown in Figs. 16 and 17. As seen in the figures, all components of tilts and strains at Oura and the E-W component tilt at Akibasan show fairly systematical aspects. In the cases of the E-W component tilt and N-S component strain at Oura, the amplitude ratios are almost constant and independent of the frequency in the present periodic range, and the phase differences are also constant and nearly equal to π. Therefore it is concluded that the disturbances due to the atmospheric pressure which appeared on the records of these components are almost proportional to the barometric change at Oura and can be expressed as the curves multiplied by some constants to the barogram at Oura within the present periodic range. On the other hand, the spectral ratios of the N-S component tilt and the E-W component strain at Oura and E-W component tilt at Akibasan show some different aspects from those mentioned above, namely that in these components the amplitude ratios increase gradually as the frequency increases, and the phase differences deviate slightly from π. A similar tendency is also seen in the N-S component tilt at Akibasan, although the calculated values of the phase difference show considerable scattering. By introducing the tiltmetric or extensometric change proportional to the time derivative of the atmospheric pressure, the frequency dependence of the spectral ratios can apparently be interpreted; namely by assuming the atmospheric disturbance $f_p(t)$ on the tiltmetric or extensometric records to be given as

$$f_p(t)=\alpha\cdot p(t)+\beta\cdot dp(t)/dt,$$

where $p(t)$ is the sequence of the observed atmospheric pressure, and α and β are constants. By the values of α and β given in Table 13, we can obtain the amplitude ratios and phase differences shown by dashed lines in Figs. 16 and 17. As seen in the figures, the curves favorably satisfy the observed values and from this it is concluded that the atmospheric disturbances appeared on the records of tiltmeters or extensometers have a common property of the frequency dependence that the spectral ratios of the disturbances on the tiltmetric or extensometric records to the atmospheric pressure change increase as the frequency increases within the periodic range from several minutes to about one hour, and that this can be apparently explained by considering the sum of the direct effect proportional to the change of the pressure and the indirect effect proportional to the time derivative of it as the first approximation (Tanaka [1968 b]).

Table 13. Values of α and β at Oura and Akibasan.

Station	Instrument	α	β
Oura	A_o (E-W component tilt)	$-0.0074''$/mb	$0.000040''$/mb/hour
	B_o (N-S component tilt)	-0.019	0.00033
	E_{eo} (E-W component strain)	-9.4×10^{-9}/mb	0.12×10^{-9}/mb/hour
	E_{no} (N-S component strain)	-24×10^{-9}	0.23×10^{-9}
Akibasan	A_a (E-W component tilt)	$-0.0050''$/mb	$0.00015''$/mb/hour
	B_a (N-S component tilt)	0.0011	-0.000027

9. *Some considerations about the spectral structures of the ground tilts*

In the sixth section of this chapter, Fourier spectra of the tiltgrams at Akibasan have been calculated from the one year's data. However, these spectra are thought to be distorted by various disturbing factors such as loading by sea water, atmospheric pressure, air temperature, precipitation and so forth. Hence, an attempt has been made to estimate the distortion of the spectra by some known disturbing factors.

Thereupon, in order to examine the loading effect of sea water on the spectra of the tiltmetric records, we have calculated the Fourier spectra of the tidal record observed at the Wakayama Harbor Tidal Station. Similarly Fourier spectra of the atmospheric pressure, air temperature, time derivative of the pressure and the intensity of the precipitation have also been obtained. The analysis is of course identical in length to that of the tiltgrams, namely being from July 31, 15h00m, 1960 to July 31, 14h00m, 1961 (UT). Comparing the precipitation spectrum with that of the ground tilt, it is obvious that they bear a striking resemblance to each other, not only as to the coincidence of the spectral peaks but also as to whole aspects of the amplitude and phase spectra (Tanaka [1968a]). From this we can deduce that the deformation of the ground due to the precipitation has an important influence on the tiltmetric results at Akibasan in the present frequency range.

Now, let $f(t)$ be a sequence of observed values which relates to the ground deformation, for example, an observed ground strain or tilt in an arbitrary direction obtained from an extensometer or tiltmeter. Since $f(t)$ is usually disturbed by meteorological and oceanic influences, it is reasonable to consider $f(t)$ as a function including these disturbances as parameters. Thus $f(t)$ is represented as

$$f(t)=f\{t, a(t), b(t), c(t), \cdots\cdots\},$$

where $a(t)$, $b(t)$, $c(t), \cdots\cdots$ are sequences of the disturbing factors which bring about the ground deformation. It may be assumed that they affect it independently of one another, so that we can then express the deformation $f(t)$ as the sum of the respective deformation caused by each factor. Accordingly, the above equation may be rewritten as follows;

$$f(t)=g(t)+[a(t)]+[b(t)]+[c(t)]+\cdots\cdots,$$

where $g(t)$ represents the sequence of the ground deformation due only to internal origins within the earth, and the bracket means the sequence corresponding to the deformation caused by each disturbing factor. When the deformations $[a(t)]$, $[b(t)]$, $[c(t)], \cdots\cdots$ are proportional to the amount of changes of the disturbing factors $a(t)$, $b(t)$, $c(t), \cdots\cdots$ respectively, we get

$$f(t)=g(t)+c_1\cdot a(t)+c_2\cdot b(t)+c_3\cdot c(t)+\cdots\cdots. \tag{7}$$

Strictly speaking, this is not always the case but the coefficients c_1, c_2, $c_3, \cdots\cdots$ are regarded as variables with time and frequency of the changes of the factors. For example, the pressure disturbances on the ground tilts at Oura and Akibasan seem to depend on the frequency as shown in the preceding section, in which we have tried to express the pressure disturbance as the sum of the two terms proportional to p and dp/dt, respectively, in order to represent the disturbance as a linear combination of the known factors. However, we assume that the equation (7) holds as an approximation for simplification in the present stage. Then, according to the results shown in Table 11, the ground tilts to be observed at Akibasan may be written as

$$f_E(t) = -0.00035w(t) - 0.0039y(t) + 0.0014p_a(t) - 0.0038p_a'(t) + [r(t)]_E + g_E(t),$$

$$f_N(t) = 0.00020w(t) - 0.00029y(t) + 0.000047p_a(t) - 0.0028p_a'(t) + [r(t)]_N + g_N(t),$$

where $[r(t)]$ is the ground tilt caused by the precipitation, and $g(t)$ the residual term including the substantial tilting of the ground. The suffix E or N means the tilting component of the east-west or north-south, respectively. The reason we particularly discriminate only the ground tilt due to the precipitation from the other disturbances is that the relation between the precipitation and the ground tilt due to it is not so simple as to be represented by a proportional expression, which will be discussed later in some detail.

In order to evaluate the influences due to the changes in the sea level $w(t)$, air temperature $y(t)$, atmospheric pressure $p_a(t)$ and its time derivative $p_a'(t)$, we have calculated the Fourier transforms $F_E'(\omega)$ and $F_N'(\omega)$,

$$\begin{aligned} F_E'(\omega) &\equiv \Re_E(\omega) + G_E(\omega) \\ &= F_E(\omega) + 0.00035W(\omega) + 0.0039Y(\omega) - 0.0014P_a(\omega) + 0.0038P_a(\omega), \end{aligned}$$

$$\begin{aligned} F_N'(\omega) &\equiv \Re_N(\omega) + G_N(\omega) \\ &= F_N(\omega) - 0.00020W(\omega) + 0.00029Y(\omega) - 0.000047P_a(\omega) + 0.0028P_a'(\omega) \end{aligned}$$

using the respective Fourier transform of each factor, where $F(\omega)$, $W(\omega)$, $Y(\omega)$, $P_a(\omega)$, $P_a'(\omega)$, $\Re(\omega)$ and $G(\omega)$ are the Fourier transforms of $f(t)$, $w(t)$, $y(t)$, $p_a(t)$, $p_a'(t)$, $[r(t)]$ and $g(t)$, respectively. The results obtained are shown in Figs. 13 and 14 by the crosses. As seen in these figures, the corrected spectra $F_E'(\omega)$ and $F_N'(\omega)$ show only slight differences in comparison with the original ones. Even though they must contain errors due to the approximations, it is unlikely that the magnitudes of the distortions of the spectra exceed two or three times those of the present results, and from this it is concluded that the observed ground tilts in the periodic range from 1 to 33 days are scarcely influenced by the loading effect of the nearby sea, air temperature, atmospheric pressure and its time derivative, if the relation between these disturbing factors and consequent ground tilts determined from the periodic range within one day is assumed to be extrapolated to the phenomena of the present range with which we are concerned.

It is well known that heavy rainfalls bring about ground deformations near the surface, and Akibasan is no exception. The disturbances remain even after the rainfalls have ceased, and it generally needs two or three weeks before the disturbances fade away. At Ide Observatory, M. Takada [1958] observed that the effects of rainfalls on the ground tilt and strain generally appeared when the amount exceeded 15 mm, reached their peaks two days after the rainfalls commenced and lasted two or three weeks. He thereupon adopted triangles with their vertices at two days after rainfalls and the bases of 15 or 20 days long as an approximation of the effects. S. Takemoto [1967] showed that the ground tilt and strain due to rainfall were given by the sum of the two exponential functions, namely by $\alpha t\cdot\exp(-\beta t)+\gamma t\cdot\exp(-\sigma t)$ at Iwakura Observatory, Kyoto. As to the extensometric record at Osakayama Observatory, I. Ozawa [1950] calculated the weighting function of precipitation according to the method proposed by C. Tsuboi [1940], under the assumption that the rate of the change of the strain $F(t)$ caused by precipitation is expressed as

$$F(t)=\int_0^{2\pi}f(t+\alpha)\phi(\alpha)d\alpha,$$

where $f(t)$ and $\phi(t)$ are the daily precipitation and weighting function, respectively, and that $F(t)$ and $f(t)$ are both expansible into the Fourier series within the interval $0\leqq t\leqq 2\pi$. Taking these instances into account, it is conceivable that the phenomenon is equivalent to that of a transformation through a transducer, where its input and output are time series corresponding to precipitation and ground deformation, respectively. Therefore, we put the relation between the intensity of the precipitation $r(t)$ and consequent ground tilt $[r(t)]$ as

$$[r(t)]=\int_{-\infty}^{\infty}r(t-\tau)h(\tau)d\tau,$$

where $h(t)$ is an impulse response of the ground tilt to the precipitation. In this case, the Fourier transform $\Re(\omega)$ of $[r(t)]$ is given by

$$\Re(\omega)=R(\omega)\cdot H(\omega),$$

where $R(\omega)$ and $H(\omega)$ are the Fourier transforms of $r(t)$ and $h(t)$, respectively. Hence in order to estimate the impulse response, we divide $F_E'(\omega)$ and $F_N'(\omega)$ by $R(\omega)$, although they consist not only of the effect of the precipitation but also of the substantial crustal tilting and errors due to approximation. The results are shown in Fig. 18, where the spectral amplitudes were smoothed.

Now, if we assume that the response of the ground tilt to an impulsive rainfall is expressed by

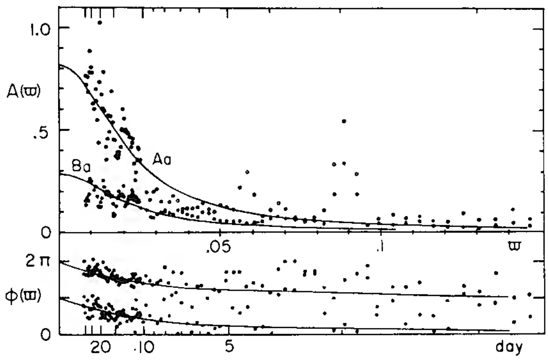

Fig. 18. Ratios of the corrected spectra of the ground tilts to the spectrum of intensity of precipitation. Open and solid circles are the results for the E-W and N-S component tilts respectively. Solid curves denote the amplitude and phase spectra of the impulse responses, $h_E(t)$ and $h_N(t)$.

$$h(t)=\begin{cases}\alpha t\cdot\exp(-\beta t), & (t\geqq 0)\\ 0, & (t<0)\end{cases}$$

then its amplitude and phase spectra, $A(\omega)$ and $\phi(\omega)$, are given as

$$A(\omega)=\frac{\alpha}{\beta^2+\omega^2}, \tag{8}$$

$$\phi(\omega)=\tan^{-1}\left(\frac{2\beta\omega}{\beta^2-\omega^2}\right), \tag{9}$$

respectively. It is observed from the figure that the frequency corresponding to $\phi=\pi/2$ or $3\pi/2$ is 0.021, and we get $\beta=1/48$ by (9), considering the spectral phase shift of π in the case of B_a. Therefore, it is concluded that the ground tilt attains its maximum about 48 hours after an impulsive rainfall. With $\alpha=$ 0.00036 and 0.00013 for the E-W and N-S components, respectively, we obtain

$$A_E(\omega)=\frac{0.00036}{(0.021)^2+\omega^2}, \qquad A_N(\omega)=\frac{0.00013}{(0.021)^2+\omega^2},$$

$$\phi_E(\omega)=\tan^{-1}\frac{0.042\omega}{(0.021)^2-\omega^2}, \qquad \phi_N(\omega)=\tan^{-1}\frac{0.042\omega}{(0.021)^2-\omega^2}-\pi.$$

These are shown by solid curves in Fig. 18, from which it is deduced that the impulse responses of the ground tilts to precipitation, $h_E(t)$ and $h_N(t)$, are given as

$$h_E=+0.00036t\cdot\exp(-0.021t),$$

$$h_N=-0.00013t\cdot\exp(-0.021t),$$

respectively. In Fig. 19, the curves of $h_E(t)$ and $h_N(t)$ are shown schematically. From this we can see that the ground inclines north-eastwards after precipitation. Since the observation site was in the tunnel at the foot of the west side on the hill, the tilting motion contradicts apparently the tendency pointed

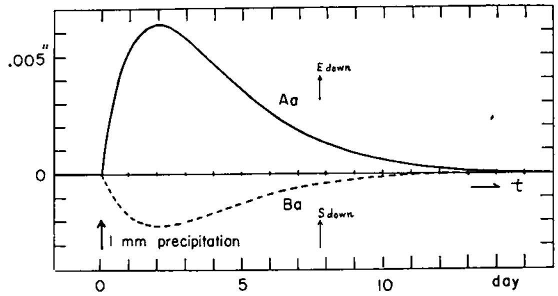

Fig. 19. Response of the ground tilts at Akibasan by an impulsive precipitation.

out by K. Hosoyama [1957] that mountains and hills bulge due to precipitations. It must be noticed that $h_E(t)$ and $h_N(t)$ obtained above may be put as average through the year and vary to some degree on each event, according to such conditions as the temperature of the rain and surface of the ground, humidity of the air, the moisture content of the ground and so forth.

Finally, using these impulse responses, namely by subtracting the products $H_E(\omega)\cdot R(\omega)$ and $H_N(\omega)\cdot R(\omega)$ from $F_E'(\omega)$ and $F_N'(\omega)$ respectively, we eliminate the effects of the precipitation on the Fourier spectra. The results are shown in Figs. 20 and 21. We can see several peaks in these amplitude spectra; they are for the periods of 29.8, 25.2, 20.3, 17.7, 15.2 and 9.4 days in the E-W component and 32.1, 29.8, 25.2, 21.4, 19.8, 15.2, 11.1, 9.4 and 7.5 days in the N-S component. Those for the periods of 15.2, 11.1 and 9.4 days in the latter component are especially conspicuous. However, some ambiguity remains due to the simplified assumptions in the results, and not only should the method used be further investigated but more observational data must also be employed to

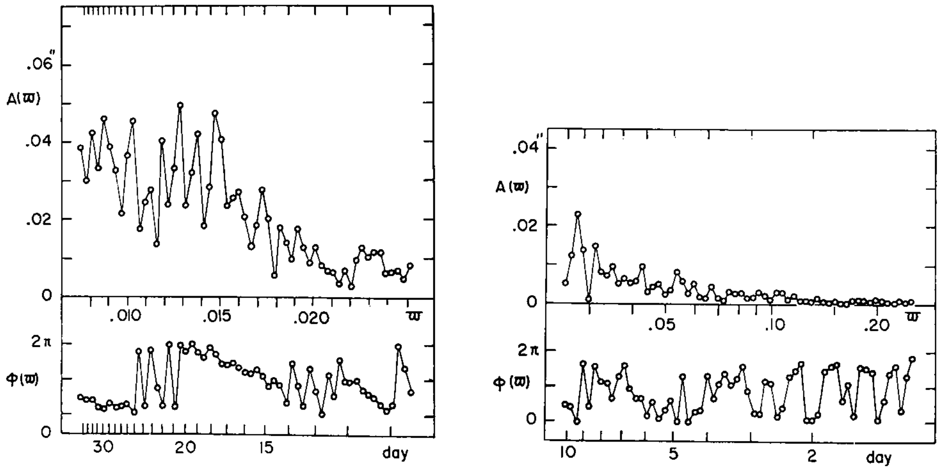

Fig. 20. Corrected amplitude and phase spectra of the E-W component tilt at Akibasan.

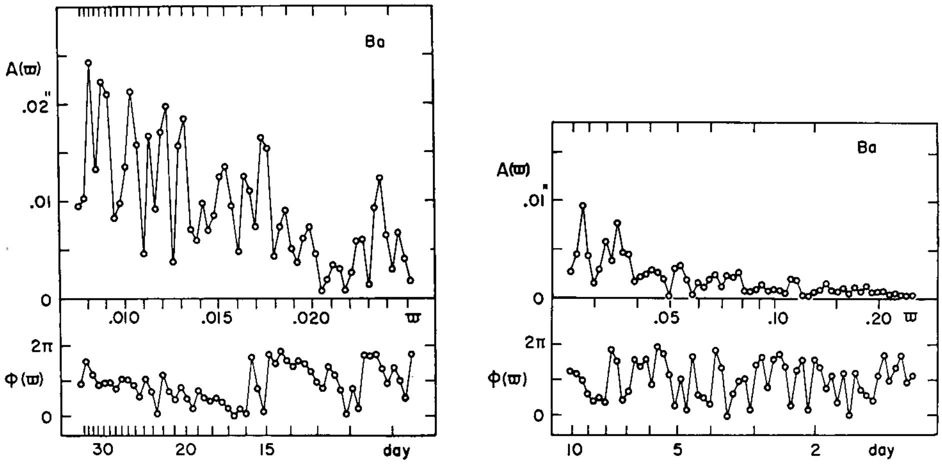

Fig. 21. Corrected amplitude and phase spectra of the N-S component tilt at Akibasan.

clarify general aspects of the long periodic deformations of the ground and bring their origins to light.

In the above procedure, we have substituted the time derivative of the pressure for the spatial gradient of it. In order to reconsider the effect of the spatial gradient of the pressure, we have calculated the Fourier transforms of the space differences of the atmospheric pressure. Barometric data at intervals of six hours at Tokushima, Owase, Kyoto and Shionomisaki Meteorological Observatories were used for the present analysis. The locations of the Observatories are shown in Fig. 22. For the E-W component of the pressure gradient, the difference of the barometric values at Owase and Tokushima was taken. Similarly the difference between Kyoto and Shionomisaki was taken for the N-S component. Obtained results are shown in Figs. 23 and 24. There can be seen no similarity between the spectra of the spatial difference of the pressure and original or reduced spectra of the ground tilt at Akibasan shown in Figs. 13, 14, 20 and 21, from which it is concluded that the ground tilt at Akibasan, Wakayama City, is scarcely influenced by the spatial

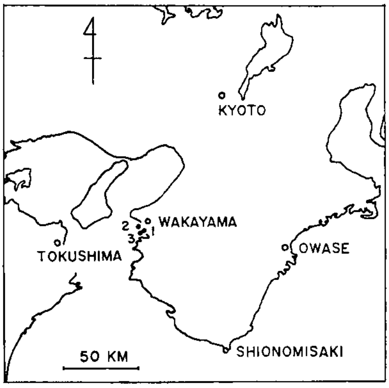

Fig. 22. Location of the Tokushima, Owase, Kyoto and Shionomisaki Meteorological Observatories for which the spatial pressure gradients were calculated (open circles), and epicenters of local earthquakes occurred on Nov. 14, 1960 (solid circles).

1. Epicenter of the earthquake at $07^{h}47^{m}$, Nov. 14.
2. Epicenter of the earthquake at $11^{h}08^{m}$, Nov. 14.
3. Epicenter of the earthquake at $13^{h}31^{m}$, Nov. 14.

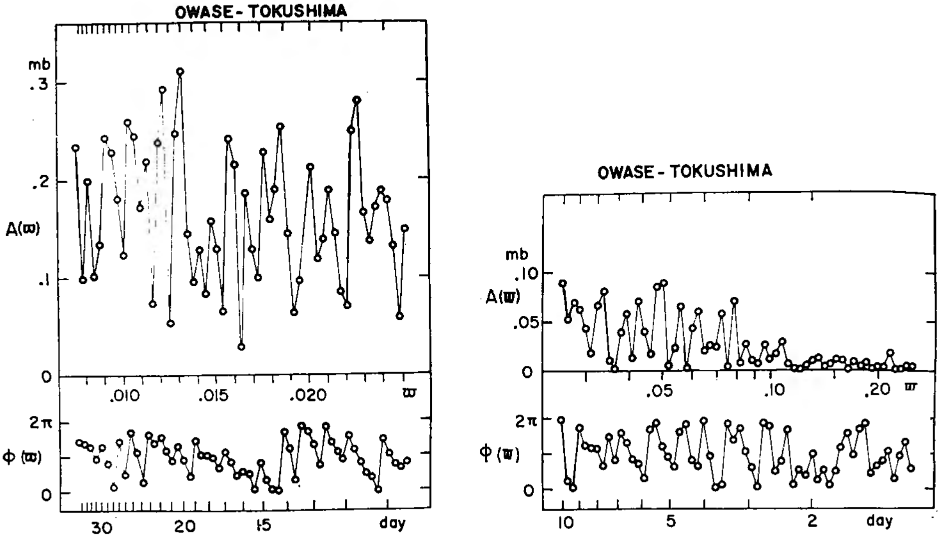

Fig. 23. Spectral amplitude $A(\omega)$ and phase $\phi(\omega)$ of the pressure gradient (E-W direction) obtained from the difference of barometric values at Owase and Tokushima.

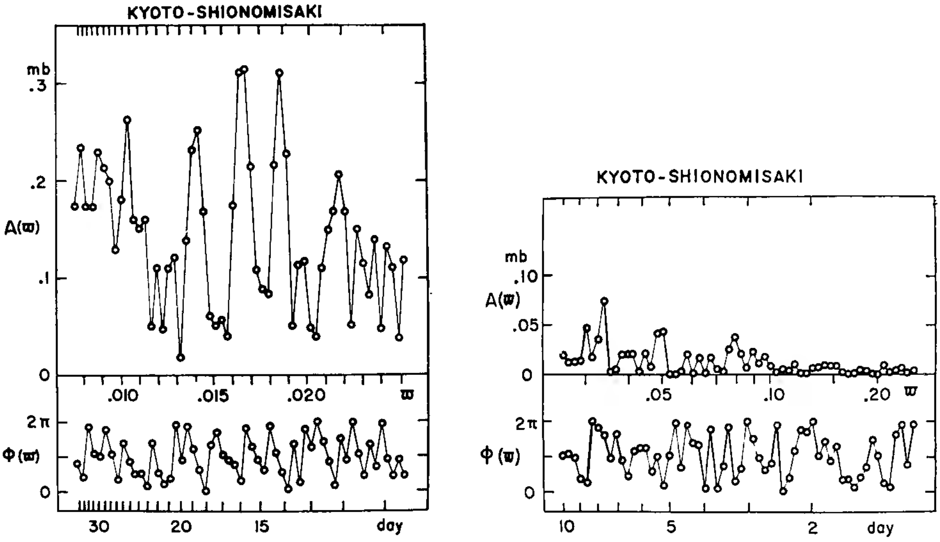

Fig. 24. Spectral amplitude $A(\omega)$ and phase $\phi(\omega)$ of the pressure gradient (N-S direction) obtained from the difference of barometric values at Kyoto and Shionomisaki.

gradient of the pressure of the extent of several tens kilometers in the present frequency range.

It is to be noted that the disturbing ground tilt due to precipitation can be eliminated by convolving the impulse response with the intensity of precipitation. As an example, the calculated results and observed ground tilts are

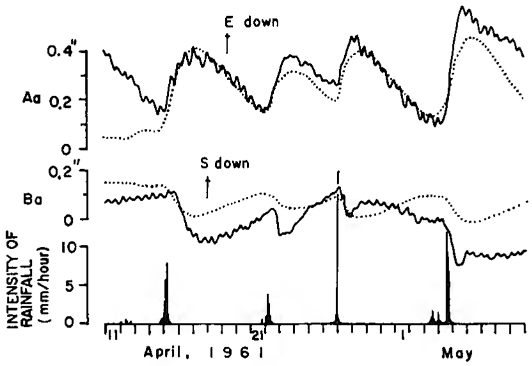

Fig. 25. An example of comparison of the observed ground tilts caused by precipitations with calculated values (dotted lines) by convolving the impulse response obtained from Fourier spectra and intensity of precipitation. In this figure a linear change has been removed in A_a for convenience of comparison.

compared in Fig. 25, where a linear drift of the ground tilt observed in the E-W component has been removed for convenience of comparison. Fair coincidence is seen between the two for both components, and from this it is concluded that we can approximately eliminate the disturbances caused by precipitation by this procedure, which is thought to be of good use for identifying small anomalous ground deformations.

10. Summary

In this chapter, meteorological influences and tidal phenomenon that appeared on the tiltmetric and extensometric records at Wakayama have been investigated mainly on the basis of their spectral structures. Amplitudes and phases of the 8 principal tidal constituents at Akibasan have been obtained from the one year's data and compared with those of the oceanic tides. To establish quantitative relations between the observed ground tilt and oceanic tides, atmospheric pressure and air temperature, the amplitudes and phases of the four major constituents were determined from monthly tiltmetric data, and compared with those for the oceanic tides, temperature and pressure. Obtained results suggest that the temperature and pressure affect on the ground tilt with comparatively short wave length which causes deformations of the floor of the observation room. A trial was made to determine the effect of the barometric pressure gradient. The coefficient was estimated as 7″ per 1 mb/km under the assumption that mean diurnal change of the pressure consists of westward migrating waves with a constant velocity.

The spectral structures of the ground tilt in the periodic range from 1 to 33 days are mainly distorted by precipitation near the observational site, and the changes in meteorological factors other than precipitation and in the height of the nearby sea have not so much influence on the ground tilt. The disturbance by precipitation has been determined under the assumption that it is expressed as a function of the intensity of precipitation. The results show that at Akibasan the ground inclines towards the northeast by impulsive rainfall and reaches the maximum two days afterwards. Corrected spectra of the ground tilt for the disturbing factors above mentioned are also given, in which some prominent oscillating motions of the ground tilt are observed, the origins of which, however, remained unknown.

Comparison of the spectra of the ground tilts with the atmospheric pressure shows that the amplitude ratio of them increases as the frequency increases and that the phase difference between them also varies slightly with the frequency. This phenomenon may be apparently explained by the sum of the direct change of the pressure and its time derivative, which suggests that this expression can be used for the elimination of the pressure disturbance from tiltmetric or extensometric record for first approximation, when the spatial distribution of the pressure are not known.

Since the data used are not sufficient, we have only introduced some tentative treatments about the disturbances on the tiltmetric and extensometric records at the present stage, and there are many points which are uncertain and more extensive investigations of this problem are required in the future.

Chapter III. Detection of Anomalous Deformations of the Ground and an Application of the Digital Filtering

1. *Detection of anomalous deformations of the ground by tiltmeters and extensometers*

As is discussed in the preceding chapters, records of the ground deformations observed by tiltmeters or extensometers consist of many factors such as earth tides including effects of the oceanic tides, changes caused by meteorological disturbances, deformations peculiar to the observation stations, instrumental drift and so forth. When observations are carried out for the purpose of detecting anomalous ground deformations relating to the occurrence of earthquakes, they would be successfully accomplished if the magnitudes of the anomalous deformations are sufficiently larger than those of the disturbances. On the contrary, it would be difficult to identify these deformations if they are of the same magnitudes as those of the disturbances or smaller. Of course it is necessary to use highly sensitive instruments in order to observe small deformations of the ground. However, the above mentioned disturbances are also magnified simultaneously so far as these instruments have flat responses with frequency of the phenomena. Accordingly it is necessary to eliminate these disturbances from our observational results in some adequate way.

Two methods can be considered for this purpose; one is by determining quantitatively the magnitude of the deformation caused by each disturbing factor, eliminating the disturbances from the observational results, and the other is by extracting aimed deformations relating to the occurrence of earthquakes alone by suppressing the disturbing noise using appropriate filters, which may be attainable by either data-processing or some technical devices at the stage of observations such as the introduction of instruments having some specific responses, grouping of many instruments, selection of the observation sites and so forth.

In the first half of this chapter an attempt is made to reduce the disturbances using the relations between major meteorological ones and oceanic tides and the consequent ground tilts, which were obtained in the preceding chapters. In the latter half, an application of digital band-pass and high-pass filters is shown in order to detect small anomalous tilts.

2. *A way to reduce the effects of oceanic tides and meteorological changes*

In the preceding chapter, we have discussed the major disturbing factors and consequent ground deformations at the two stations in Wakayama, and obtained some approximate relations between them. We use these relations for the reduction of their effects on the tiltmetric records in order to investigate whether there exist anomalous ground tilts before and after the occurrence of local earthquakes or not.

On November 14, 1960, four local earthquakes occurred at 07h47m, 11h08m, 13h31m and 23h28m in this district, the last one being smaller than the others (Intensity in JMA Scale at Wakayama was II). The epicenters and depths of these earthquakes except the last were reported as (34°.1 N, 135°.0 E, 0-10 km), (34°.25 N, 135°.1 E, 0-10 km) and (34°.25 N, 135°.1 E, 10 km), respectively, on the Seismological Bulletin of the Japan Meteorological Agency. The S-P duration times and intensities at the Wakayama Meteorological Observatory were 0.8 sec, II, 1.0 sec, II and 1.2 sec, III, respectively. The locations of the epicenters of the three earthquakes determined graphically from the S-P times at the network stations of the Earthquake Research Institute, University of Tokyo, are shown in Fig. 22. From this figure these epicenters are estimated to be situated very near the two stations, and their magnitudes, especially of the third, were of the greatest class in this district. Therefore, we have made a trial to reduce disturbances from the original records with respect to the occurrence of these earthquakes under the assumption that the equation (7) holds. The coefficients used are summarized in Table 14. In this example we have

Table 14. Coefficients used for the reduction of disturbances.

Disturbing factor	Akibasan		Oura	
	A_a (E-W component tilt)	B_a (N-S component tilt)	A_o (E-W component tilt)	B_o (N-S component tilt)
Oceanic tides (Wakayama Harbor, cm)	−0.0035″ (+20 min.)	0.00020″	−0.00025″ (+20 min.)	0.00011″ (+80 min.)
Air temperature (Wakayama Meteorological Obs., °C)	−0.00414 (+60 min.)	0.00020	−0.00052	0.00040
Atmospheric pressure (Akibasan, mb)	−0.0050	0.0011	−0.0074	−0.019
Time derivative of pressure (Akibasan, mb/hour)	0.00015	−0.000027	0.000040	0.00033

Remarks: The time in the parentheses is the phase lag considered for the reduction. Positive sign means the advancement of a disturbing factor.

aimed at detecting peculiar changes of a comparatively short interval within several hours, and left the effect due to the precipitation out of consideration because it did not rain within the three days interval. The result is shown in Fig. 26. The jumps appearing on the records of the A_0 and B_0 components at Oura at the occurrence of earthquakes have been adjusted to be lines because they might be attributable to instrumental errors. As seen in the figure, the

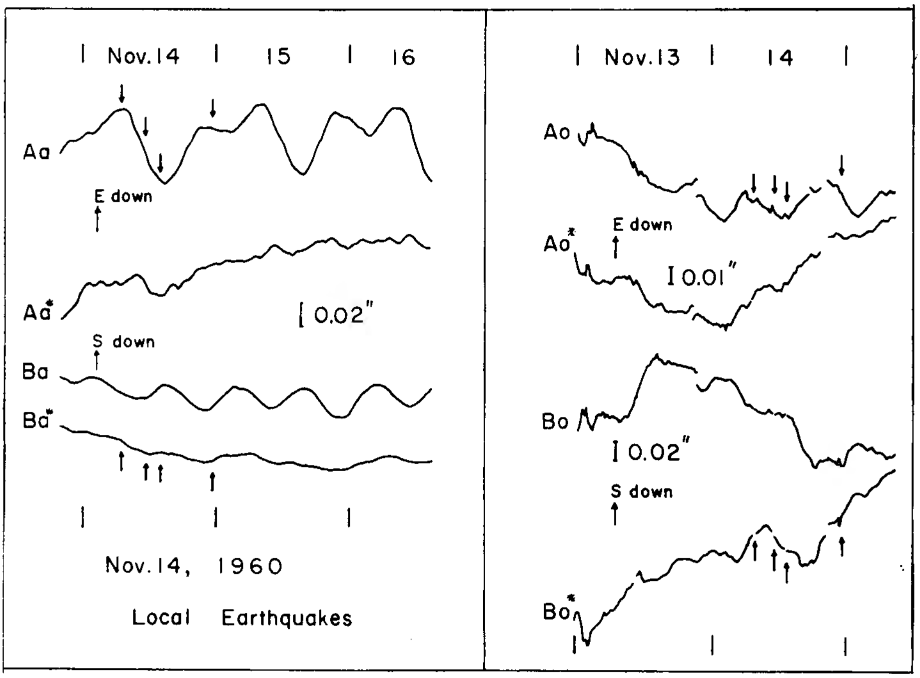

Fig. 26. Tilting motions before and after the remarkable local earthquakes on Nov. 14, 1960. (※; corrected curves, ↓; local earthquake)

tidal and the thermal disturbances have been fairly well reduced on the corrected curves. Small fluctuations which might be caused mainly by the atmospheric pressure have not been eliminated sufficiently and become conspicuous on the corrected curves of the A_a components at Akibasan, and A_0 and B_0 at Oura, according to the reduction of changes with long periods. On the corrected curve of A_a there can be seen a rapid westward inclination in the interval from the occurrence of the second earthquake to that of the third. Although there remains some uncertainty due to the processing of the jumps of the data, it may be right to consider that the direction of the tilting motion reversed about five hours before the occurrence of the first earthquake on the corrected curve of the E-N component tilt at Oura, and that the direction in the N-S component also reversed about three hours before the first earthquake and thereafter the tendency of the northward tilting continued until about three hours after the occurrence of the third, then the direction reversing again. On the other hand, any marked anomalous tilting motions cannot be observed on the corrected curve of the N-S component at Akibasan. Since meteorological disturbances on this component are smallest compared with the other components in the figure, there may be a suspicion that the above mentioned peculiar tiltings before and after the occurrence of the earthquakes were accidental events and might be caused by meteorological origins, notwithstanding the tentative reduction of the major disturbances. Further, in the present correction for the atmospheric pressure we have used the coefficients obtained from the spectral ratios of the pressure and the consequent ground tilts in the periodic range within a few hours, and there remains a question whether these coefficients may or must not be used directly for the reduction of the disturbances of such a long period as one day or more. Actually the coefficients to the pressure changes in Tables 9 and 10 are, generally speaking, smaller than those in Table 13 regarding the respective components, and the frequency dependence of the pressure disturbances should be investigated in more detail for the present purpose. However, since the epicentral distances of the local earthquakes from Oura station are smaller than those from Akibasan as seen in Fig. 22, it is not irrational that the magnitude of the anomalous tilting motion at Oura which might be related to these earthquakes was larger than that at Akibasan. Consequently, it is not concluded immediately in the present stage whether there have been any peculiar ground deformations connected with these local earthquakes or not, and this means, conversely speaking, that the ground deformations connected with the local earthquakes, if existing, are too small to be detected apparently by the present measurements, namely of the magnitude less than 0.02″ for the ground tilt. In order to proceed to more precise discussions, not only the investigations of the disturbances upon the ground deformations and the methods of reduction of them must be improved as well as using more sensitive instruments, but also the crustal deformations due to the stress release by local earthquakes must be investigated quantitatively under the consideration about their focal mechanism.

3. *Digital filtering for detection of minute anomalous changes of the ground tilts*

A sequence of quantitative data of the ground deformation, assigned to a specific moment in time-for example, the tilting motion of the ground in some direction-is a time series. When we consider the deformation relating only to the occurrence of an earthquake as a signal, and the disturbing deformations due to the meteorological changes, earth tides and so forth as noise, then the detection of anomalous deformations of the ground concerning earthquakes is identical with the procedure of picking out signals from a time series containing noise. In general, it is thought that the disturbances to be considered as noise are periodic and anomalous deformations as signals are transient, unless the occurrence of earthquakes is periodic. If we know the characteristic of the signal, namely the spectral structure of the signal, it might be possible to take out the signal by using some suitable filters which are able to pass the signal only. However, unfortunately, we have not the knowledge about the characteristics of the signal of the deformations related to small earthquakes, and moreover, it is uncertain at the present stage whether such minute deformations can be observed. Therefore we cannot avoid adopting the procedure whereby, making digital filters of many kinds and applying them to the time series, and we identify the signal by examining the correlation between the output and the occurrence of earthquakes by trial and error. In other words, it means that we must look for a filter that makes S/N of the output larger than that of the original time series. Thus we must decide which filter is most effective for this purpose.

Hitherto, such filters of weight functions as the 25 hours running mean, the Pertzev's method and so forth, have been used for the analysis of tidal phenomena, and these low-pass filters and simple band-pass filters have been used for detection of secular changes of the crustal deformations (for example, Inoue [1932], Ozawa [1962]).

We have designed some types of band-pass filters on the basis of the Fourier spectra shown in the preceding chapter, and applied them to the tiltgrams. When the center frequency and the band-width of a rectangular filter is denoted by ω_0 and $2\omega_c$, respectively, and its amplitude characteristic $A(\omega)$ is

$$A(\omega)=\begin{cases}0, & (\omega<\omega_0-\omega_c)\\ A(\omega), & (\omega_0-\omega_c\leqq\omega\leqq\omega_0+\omega_c)\\ 0, & (\omega_0+\omega_c<\omega),\end{cases}$$

then the impulse response of this filter $h(t)$ is given as

$$h(t)=\{2A(\omega_0)/\pi\}\cdot\{\sin[\omega_c(t-t_0)]/(t-t_0)\}\cos\omega_0 t.$$

We can get the output $g(t)$ for the band-pass filtering of $f(t)$ by taking the convolution between $h(t)$ and $f(t)$, namely

$$g(t)=\int_{-\infty}^{\infty}h(\tau)f(t-\tau)d\tau.$$

In order to calculate the impulse response of an arbitrary filter, we divide it into n rectangular sections. Then the impulse response of the filter is given as the summation

$$h(t)=\sum_{j}^{n}h_j(t),\quad (\omega_c\rightarrow\Delta\omega_j,\ \omega_0\rightarrow\omega_j,\ \omega_{j+1}-\omega_j=\Delta\omega_{j+1}+\Delta\omega_j),$$

where $h_j(t)$ is the impulse response of each small rectangular filter, ω_j lies in the band of the filter and $\Delta\omega_j$ is the width of it (Mikumo and Aki [1964]).

Examples of comparison of the amplitude characteristics of the digital filters used with those of designed are shown in Fig. 27, where the former and the latter are illustrated by dashed and solid lines respectively. The difference of their shapes is probably due mainly to the errors in the integration caused by the limited time length of $h(t)$. We limited the time interval of calculation

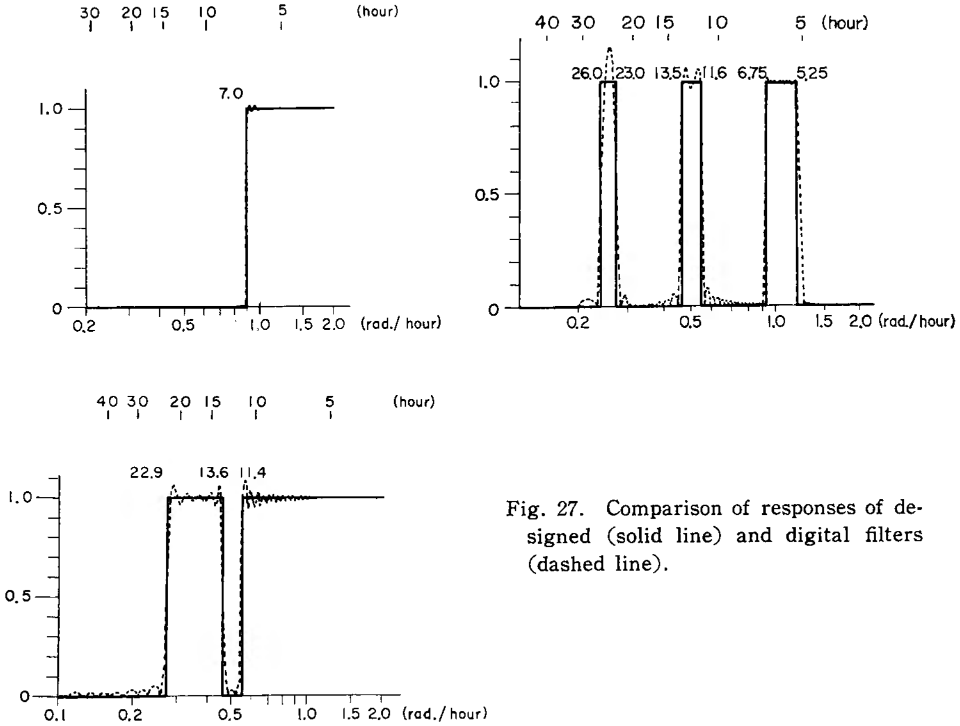

Fig. 27. Comparison of responses of designed (solid line) and digital filters (dashed line).

of the convolution within 360 hours and there is an indication that the more complex the shape of the filter is, the more the response is distorted. However, these digital filters are considered to be satisfactory for our present purpose.

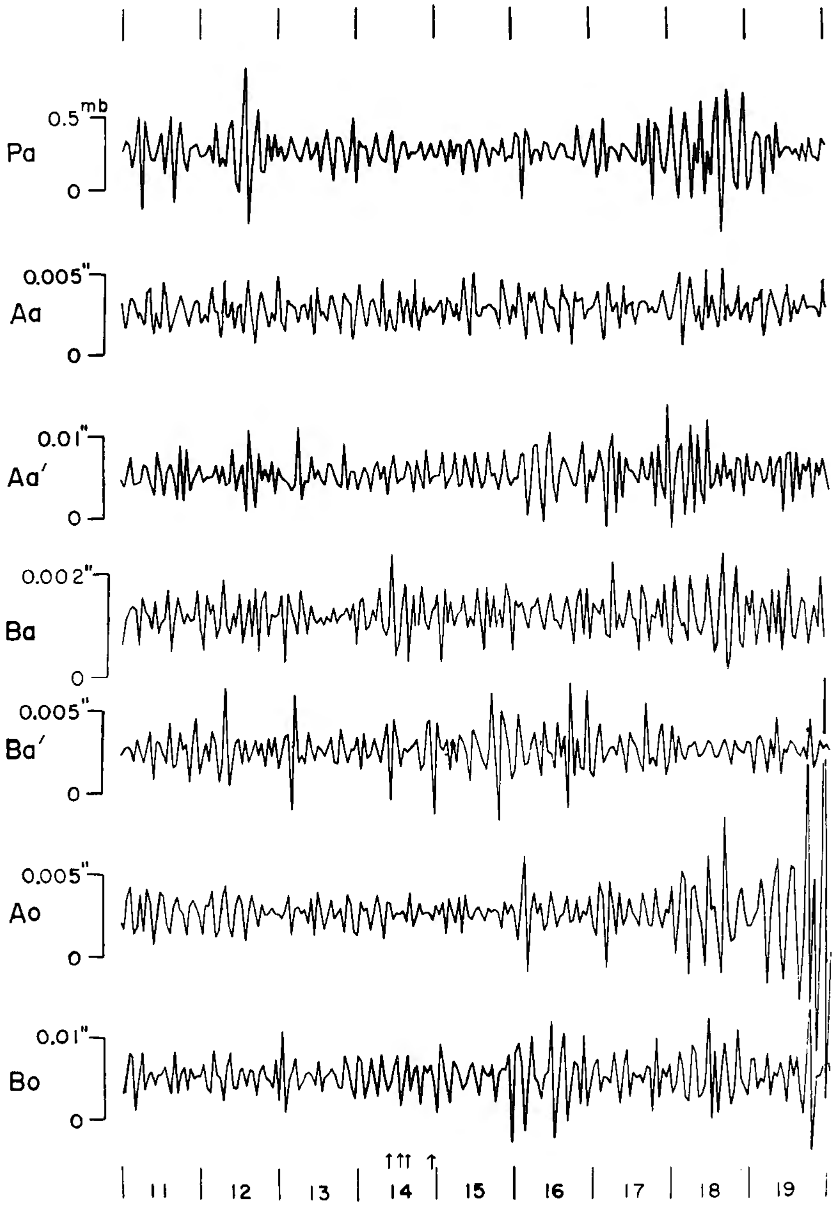

Fig. 28. Filtered records of the atmospheric pressure P_a and ground tilts by 0.200 c/h high-pass filter.

The examples of the practical filtering are now described. From the Fourier spectra of the tiltmetric records, it is obvious that the amplitudes near the diurnal and semidiurnal terms are especially predominant, we designed one

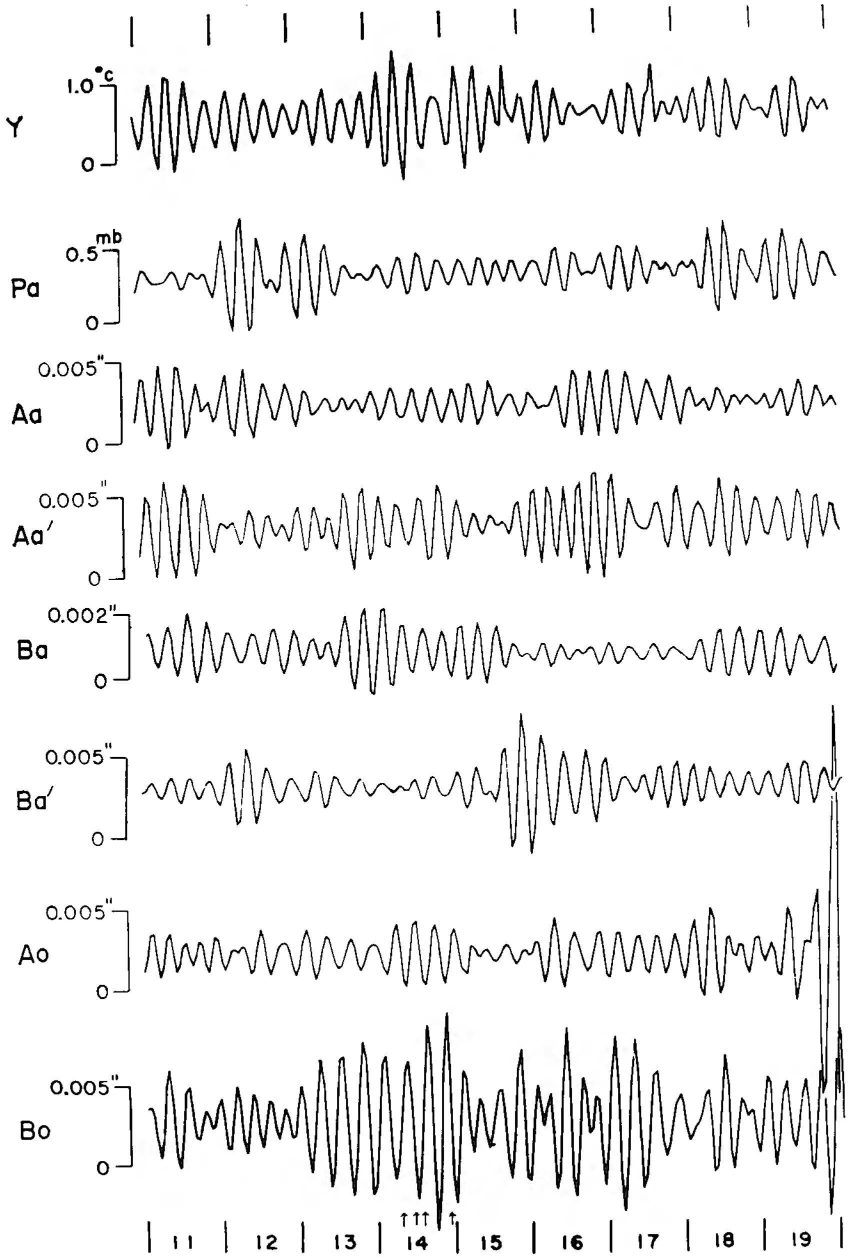

Fig. 29. Filtered records of the air temperature Y, atmospheric pressure P_a and ground tilts by 0.200-0.143 c/h band-pass filter.

high-pass and three band-pass filters, and applied them to the tiltgrams in order to investigate the changes in the periodic ranges shorter than one day. Examples of obtained results from November 11 to 19, 1960 are shown in Figs. 28 to 31. In order to examine the effect of the atmospheric pressure and air temperature, the barogram at Akibasan and the thermometric record at the Wakayama Meteorological Observatory have been filtered by the same filters incidentally. The high-pass filtering of the thermometric record was omitted. We shall discuss the results in the following.

Generally speaking, the correspondence is not so remarkable between the outputs of the filtered barograms or thermometric records and those of the ground tilts in the present frequency ranges shown in the examples. Fair correspondence is not found even on the B_0 component, although it is confirmed in the previous chapter that this component of tilt was heavily affected by the atmospheric pressure change. However, the phase of the high-pass filtered pressure corresponds with that of the high-pass filtered of the B_0 component when the amplitude of the pressure change was large as seen in Fig. 28. Accordingly it is deduced that the relation between the pressure change and the consequent ground tilt cannot be fully represented by the barometric data at

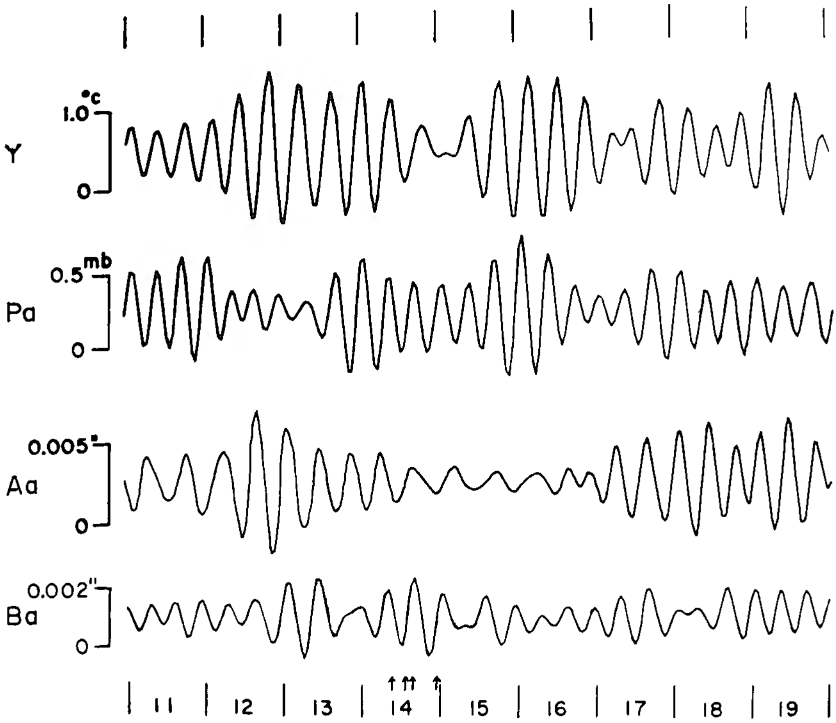

Fig. 30. Filtered records by 0.143-0.0910 c/h band-pass filter.

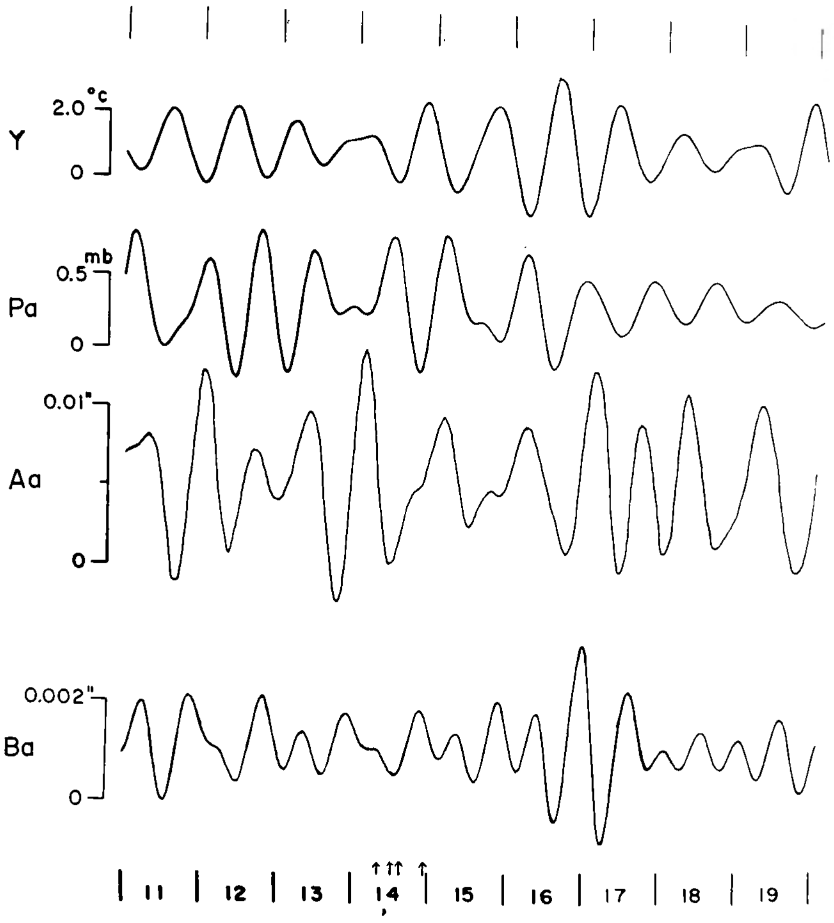

Fig. 31. Filtered records by 0.0770-0.0430 c/h band-pass filter.

one fixed station without adding spatial information about the pressure distribution, although approximate relations averaged in rather long time intervals can apparently be expressed by the summation of the direct and indirect effect proportional to the pressure and to its time derivative respectively, as discussed in the preceding chapter.

As is expected from the fact that the disturbances due to the pressure and temperature on the two tiltmeters A_a' and B_a' situated near the corner of the concrete base at Akibasan are larger than those on A_a and B_a situated near the central part of the base, the amplitudes of the outputs of A_a' and B_a' are generally larger than those of A_a and B_a, respectively. It is to be noted, however, that any distinct correlations can hardly be seen between the amplitude changes of the two pairs of the tiltmeters, in other words one is not a simple magnification or reduction of the other, and this suggests an extremely

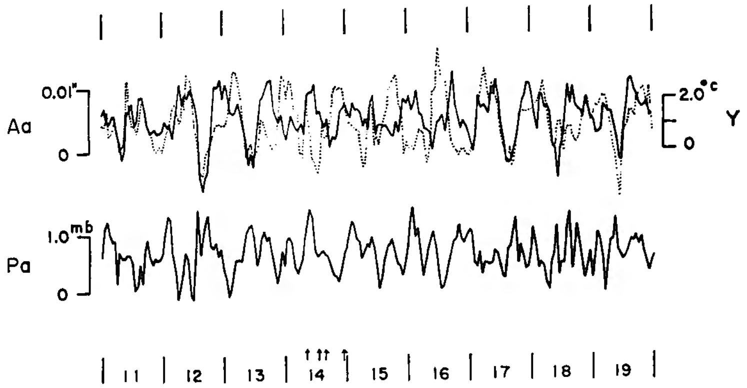

Fig. 32. Comparison of the filtered results of the E-W component tilt at Akibasan (A_a) with those of the air temperature (Y, dashed line) and atmospheric pressure P_a. The response of the used filter is 1 in the periodic ranges from 1 to 11.5 hours and from 13.6 to 22.5 hours.

local nature of the disturbances in the present frequency range.

Another example of filtering is shown in Fig. 32, in which the filtered barogram and thermometric record are also shown. Correspondence between the ground tilt and the temperature change can be partly seen in this case, in contrast to the poor correspondence to the pressure. Comparing this result with the former it may be concluded that rectangular band-pass filters with narrow band-width are more adequate than complex filters with broad bandwidth for the present purpose.

A peculiar tilting motion which seems to be related to the occurrence of the earthquake on November 14 is seen only on the high-pass filtered tiltgram of the N-S component at Akibasan (Fig. 28), probably because of the low noise level. This peculiar change is connected to the occurrence of the earthquake at 11h08m, and a question arises whether it is due to the true ground tilting or the shift of the equilibrium position of the tiltmeter by the shock of the seimic waves as is often seen on the tiltgrams of this type of instrument. In order to ascertain this, we have shifted artificially the zero line of the tiltgram at the time of the earthquake occurrence and filtered these modified records, the results of which are shown in Fig. 33. As seen in the figure, the peculiar change is not reduced by the steps of the record. Since a similar tilting is also detectable on the B_a' component corresponding to that of B_a, it may be inferred that this phenomenon is not due to the instrumental effect but to the true creep-like ground tilting at the time of the event. It is expected from these results that although it is not concluded directly that this tilting motion is undoubtedly connected to the crustal deformation at the occurrence of the earthquake, high-pass filtering of the B_a component may be effective to detect

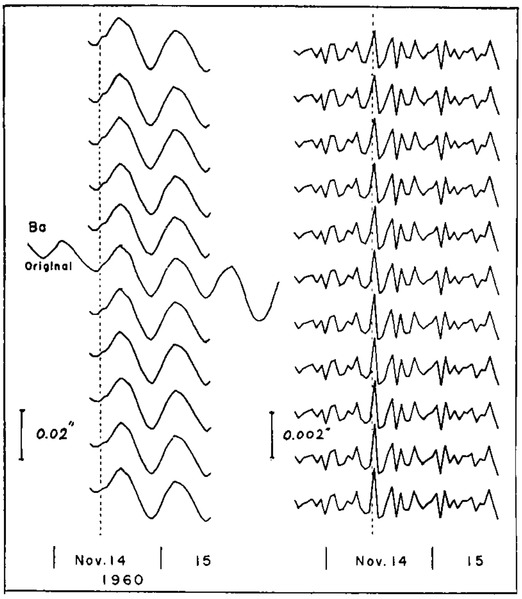

Fig. 33. Stepped tiltgrams at the time of the earthquake occurrence at 11^h08^m on Nov. 14, 1960, and their filtered results. Curves on the left are the original (center) and stepped tiltgrams, and curves on the right are filtered tiltgrams. The dashed line indicates the time of the earthquake occurrence and accordingly the time when the step was given.

this kind of tilting motions continuing over several hours, and the tiltgrams of A_a and B_a at Akibasan before and after the occurrence of other earthquakes have been filtered by using the same high-pass filter. The obtained examples are shown in Figs. 34 to 36. On the filtered B_a components of these examples there can be observed some peculiar tilting motions at the occurrence of local

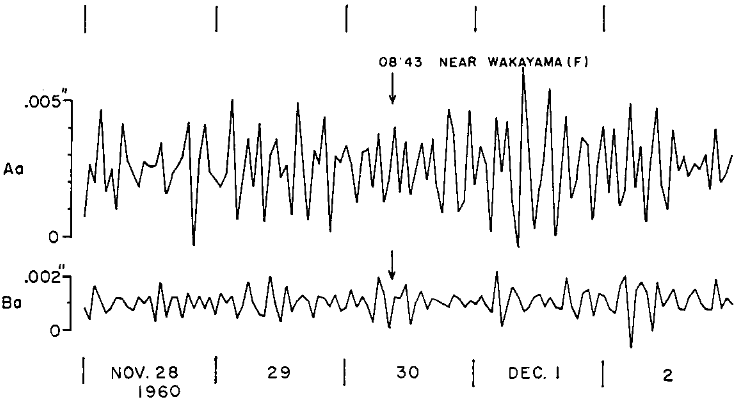

Fig. 34. Examples of filtered tiltgrams before and after the local earthquake at 08^h43^m on Nov. 30, 1960.

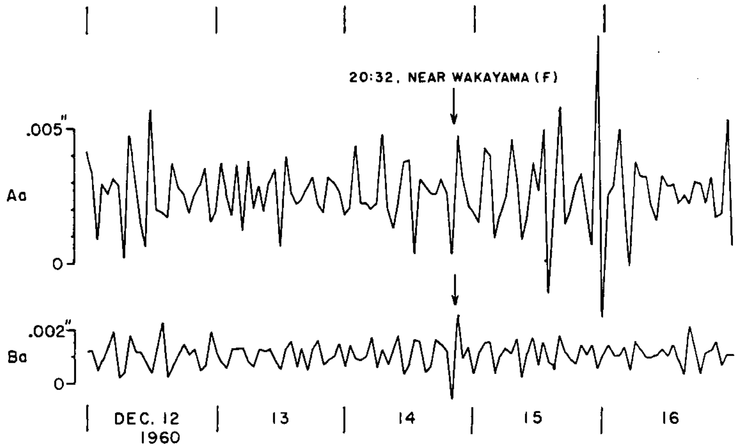

Fig. 35. Examples of filtered tiltgrams before and after the local earthquake at 20^h32^m on Dec. 14, 1960.

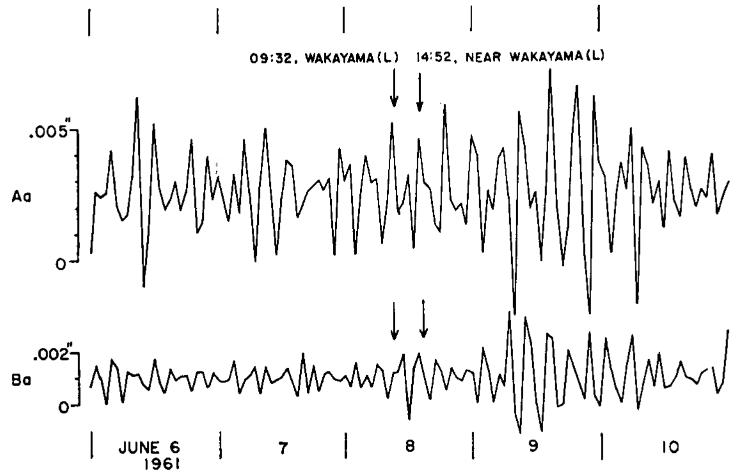

Fig. 36. Examples of filtered tiltgrams before and after the local earthquakes at 09^h32^m and 14^h52^m on June 8, 1961.

earthquakes. In common with the previous result, the background noise of the A_a component due to the meteorological origins are too large to disclose characteristic tilting motions on this component. Although it is not concluded immediately that these tilting motions are connected to the occurrence of local earthquakes, these results show an upper limit of the magnitude of the tilting motions so long as we consider such rapid changes of the tilting motions lasting several hours.

4. Summary

Two methods for the reduction of disturbances due to the oceanic tides and meteorological changes have been introduced in this chapter. In the former half we have tried to eliminate the disturbances by a tentative procedure from the tiltgrams at the two stations. On the E-W and N-S components at Oura and E-W component at Akibasan, peculiar tilting motions amounting to about 0.02″ are observable before and after three local earthquakes occurred in November 14, 1960, although they cannot be immediately related to the crustal deformation at the occurrence of these earthquakes. In the latter half some examples of digital filtering have been shown as an attempt to detect minute ground deformations hidden behind the disturbances, and it is concluded that the high-pass and band-pass filters of simple shapes suitably designed may serve the present purpose and especially those with the narrow frequency band are more effective. Accordingly, as well as digital filtering of the records, observations of the ground deformations by instruments with some appropriate frequency responses are also thought to be effective, and the observation systems should be improved under this point of view.

Peculiar tilting motions of the ground of the amount of about 0.002″ are seen on the high-pass filtered tiltgram of the N-S component at Akibasan in connection with the occurrence of some local earthquakes. Although these phenomena cannot be directly related to the occurrence of the earthquakes, it is suggested from this that the crustal tiltings connected with the local earthquakes in this district may not exceed 0.002″, granted that these tilting motions exist and continue a few hours.

Acknowledgments

I wish to express my sincere thanks to the late Professor Eiichi Nishimura for his kind guidance. I also thank Professors Tokio Ichinohe and Michio Takada for their generous advice and Dr. Takeshi Mikumo and Mr. Yutaka Tanaka for their valuable suggestions and encouragement throughout this work. My thanks are due to Mr. Masaru Yamada of our Institute and the members of the Earth Science Institute of Wakayama University for their kind help concerning the observations. I am much indebted to the Wakayama Meteorological Observatory for permission to use the meteorological and tidal data, and the Osaka District Central Meteorological Observatory and Kyoto and Owase Meteorological Observatories for kindly offering data of the atmospheric pressure. I am also indebted to Professor Setsumi Miyamura of the Earthquake Research Institute, University of Tokyo, for kindly offering the seismometric data. The numerical calculations in this study have been carried out mainly by a HITAC 5020E at the Computer Centre of University of Tokyo.

References

Benioff, H., 1959; Fused-Quartz Extensometer for Secular, Tidal, and Seismic Strains, Bull. Geol. Soc. Amer., **70**, 1019-1032.

Bonchkovskii, V. F., 1963; A Specific Case of Connection between the Variations of Tilts and Linear Deformations and Distribution of Atmospheric Pressure, Izv. Akad. Nauk., SSSR, **9** (English Translation), 832-836.

Caloi, P., 1958; About Some Phenomena Preceding and Following the Seismic Movements in the Zone Characterized by High Seismicity, *Contributions in Geophysics in Honor of Beno Gutenberg*, **1**, 44-56.

Chinnery, M. A. and J. A. Petrak, 1967; The Dislocation Fault Model with a Variable Discontinuity, Tectonophysics, **5**, 6, 513-529.

Dambara, T., 1966; Vertical Movements of the Earth's Crust in Relation to the Matsushiro Earthquake, Jour. Geod. Soc. Japan, **12**, 1, 18-45.

Darwin, G. H., 1882; On Variations in the Vertical Due to Elasticity of the Earth's Surface, *Scientific Papers* (*Oceanic Tides*), **1**, 444-459.

Hagiwara, T., 1947; Observation of Changes in the Inclination of the Earth's Surface at Mt. Tsukuba (Third Report), Bull. Earthq. Res. Inst., **25**, 27-29.

Hori, M. and H. Matsumoto, 1967; Observation of Ultra Microearthquakes by Seismometer array method in the Vicinity of Wakayama, Central Japan, Zishin, **II**, **20**, 41-49.

Hosoyama, K., 1957; On the Observation of Secular Phenomena of the Tilting Motion of the Ground, Mem. Coll. Science, Kyoto Univ., A, **28**, 3, 253-282.

Imamura, A., T. Kodaira and H. Imamura, 1932; The Earthquake Swarms of Nagusa and Vicinity, Bull. Earthq. Res. Inst., **10**, 636-648.

Inoue, W., 1932; On Earth-tiltings Observed at Mt. Tukuba, Bull. Earthq. Res. Inst., **10**, 1, 130-144.

Ito, Y., 1960; On the Daily Variation of Tilting Motion of the Ground and the Structure (1), Kantogakuin Univ., Kenkyu Hokoku, **5**, 39-44.

Kabuzenko, S. N., 1959; The Theory of Thermal Deformations of the Earth's Surface, Izv. Akad. Nauk., SSSR, **8** (English Translation), 300-303.

Karmaleeva, R. M., 1963; On a Certain Coincidence between Anomalous Tilt and the Occurrence of Earthquakes, Izv. Akad. Nauk., SSSR, **10** (English Translation), 970-972.

Kasahara, K., A. Okada, M. Shibano, K. Sasaki and S. Matsumoto, 1967; Electro-Optical Measurement of Horizontal Strains Accumulating in the Swarm Earthquake Area (3), Bull. Earthq. Res. Inst., **45**, 225-239.

Khorosheva, V. V., 1958; Effect of the Atmospheric Pressure on the Tilting of the Earth's Surface, Izv. Akad. Nauk., SSSR, **1** (English Translation), 77-79.

Lecolazet, R., 1961; Sur la Reconstitution des Observations par Interpolation, IV me Symposium International sur les Marées Terrestres, Communications de l'Observatoire Royal de Belgique, **188**, Série Géophysique, **58**, 267-272.

Longman, I. M., 1960; The Interpolation of Earth-Tides Records, Jour. Geoph. Res. **65**, 11, 3801-3803.

Maruyama, T., 1964; Statical Elastic Dislocations in an Infinite and Semi-infinite Medium, Bull. Earthq. Res. Inst., **42**, 289-368.

Mikumo, T., 1959; A Consideration on Generation Mechanism of Local Earthquakes, Mem. Coll. Science, Kyoto Univ., A, **29**, 221-240.

Mikumo, T. and K. Aki, 1964; Determination of Local Phase Velocity by Intercomparison of Seismograms from Strain and Pendulum Instruments, Jour. Geoph. Res. **69**, 4, 721-731.

Miyamura, S., 1959; Local Earthquakes in Kii Peninsula, Central Japan. Part III. Temporary Seismological Network in the Neighbourhood of Wakayama, Bull. Earthq. Res. Inst., **37**, 609-635.

Miyamura, S., M. Hori and H. Matsumoto, 1966; Local Earthquakes in Kii Peninsula (Part 5), Bull. Earthq. Res. Inst., 44, 2, 709–729.

Nakano, S., 1963; The Effect of Surface Temperature on the Crustal Deformations, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 12, 60.

Nishimura, E., 1953; Study on Some Phenomena Foretelling the Occurrence of Destructive Earthquakes, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 6.

Okada, A., S. Izutuya, Y. Ito and K. Kadono, 1968; Results of Levelling Resurvey between Wakayama and Kainan, Wakayama Prefecture, Bull. Earthq. Res. Inst., 46, 413–416.

Ozawa, I., 1950; On the Observations of Strains of the Ground Surface Using by Invar-wire and Invar-bar Extensometer, and Effect of the Rain-fall to the Change of the Ground Surface, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 3, 69–74.

Ozawa, I., 1956; On the Observation of Crustal Deformation at Osakayama, Memorial Issue of the Fifth Anniversary, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 14–19.

Ozawa, I., 1962; On the Combined Observation of the Crustal Deformations at Some Observatories inside a Small Area (at Osakayama), Zishin, II, 15, 3, 157–168.

Ozawa, I., 1965; On the Observations of the Abrupt Change of the Elastic Energy in the Crust in the Remarkable Earthquakes, Spec. Contr. Geoph. Inst., Kyoto Univ., 5, 125–137.

Papoulis, A., 1962; *Fourier Integral*, McGraw-Hill, New York, 55 pp.

Popov, V. V. and M. K. Chernyavkina, 1960; Several Results of Observations of Deformations of the Earth's Surface at the Geophysical Station "Yalta", Izv. Akad. Nauk., SSSR, 7 (English Translation), 671–676.

Press, F., 1965; Displacements, Strain, and Tilts at Teleseismic Distances, Jour. Geoph. Res., 70, 2395–2412.

Sassa, K. and E. Nishimura, 1951; On Phenomena Forerunning Earthquakes, Trans. Amer. Geoph. Union, 32, 1, 1–6.

Siebert, M., 1961; Atmospheric tides, Advances in Geophysics, 7, 105–187.

Simon, D. and M. Schneider, 1967; Zum Auftreten luftdruckbedingter Störungen in Horizontalpendelaufzeichnungen auf drei verschiedenen Erdgezeitenstationen, Marées Terrestres, Bull. d'Inform., 49, 2218–2225.

Takada, M., 1958; On the Observation of the Crustal Deformation and Meteorological Effect on It at Ide Observatory and on the Crustal Deformation Due to Full Water and Accumulating Sand in the Sabo-Dam, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 23.

Takada, M., 1959; On the Crustal Strain Accompanied by a Great Earthquake, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 27, 29–46.

Takemoto, S., 1967; The Observation of Crustal Deformations at Iwakura, Kyoto (I) –On the Influence of the Precipitation on Extensometers and Tiltmeters–. Annuals, Dis. Prev. Res. Inst., Kyoto Univ., 10A, 157–164.

Tanaka, Y., 1964; Relation between Crustal and Subcrustal Earthquakes Inferred from the Mode of Crustal Movements, Spec. Contr. Geoph. Inst., Kyoto Univ., 4, 19–28.

Tanaka, T., 1964; Study on the Relation between Local Earthquakes and Minute Ground Deformation (Part 1), Bull. Dis. Prev. Res. Inst., Kyoto Univ., 14, 1, 55–77.

Tanaka, T., 1967; Study on the Relation between Local Earthquakes and Minute Ground Deformation (Part 3), Bull. Dis. Prev. Res. Inst., Kyoto Univ., 16, 2, 17–36.

Tanaka, T., 1968a; Study on the Relation between Local Earthquakes and Minute Ground Deformation (Part 4), Bull. Dis. Prev. Res. Inst., Kyoto Univ., 17, 3, 7–20.

Tanaka, T., 1968b; On the Effect of Atmospheric Pressure upon Ground Tilt, Bull. Dis. Prev. Res. Inst., Kyoto Univ., 18, 2, 23–36.

Tomaschek, R., 1957; Tides of the Solid Earth, Encyclopedia of Physics (Handbuch der Physik), 48, Geoph. II, 838–839.

Tsubokawa, I., Y. Ogawa and T. Hayashi, 1964; Crustal Movements before and after the Niigata Earthquake, Jour. Geod. Soc. Japan, 10, 3–4, 165–171.

Tsuboi, C., 1940; A Problem of Weighted Mean, Bull. Earthq. Res. Inst., 19, 458–475.

Watanabe, H. and A. Kuroiso, 1967; Some Properties of Microearthquakes in the West of Kii Peninsula, Central Honshu, Japan, Zishin, II, 20, 180–191.

Wyss, M. and J. N. Brune, 1968; Seismic Moment, Stress, and Source Dimensions for Earthquakes in the California-Nevada Region, Jour. Geoph. Res. 73, 4681–4694.