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# Study on the Relation between Local Earthquakes and Minute Ground Deformation

## Part 3. On Effects of Diurnal and Semidiurnal Fluctuations of the Temperature and Atmospheric Pressure on Ground Tilts.

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### Abstract

The diurnal and semidiurnal effects of atmospheric temperature and pressure upon the ground tilt observed by tiltmeters in Wakayama, Japan are investigated with the use of one year's data. In the first half of the paper, monthly amplitudes and phases of $M_2$, $S_2$, $O_1$ and $S_1$ constituents have been calculated in respect of ground tilts, oceanic tides, atmospheric temperature and pressure by the Fourier transform method. Interrelation between ground tilts and meteorological disturbances have been examined by the amplitude and phase fluctuations. In the latter half of the paper, coefficients for the effects of temperature, atmospheric pressure and its time gradient upon the ground tilts have been determined from their mean daily variations by the least squares method. Two pairs of tiltmeters installed in the same direction on one concrete base behave in a different manner for diurnal and semidiurnal changes of temperature and pressure, 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 deformations of the ground, and in the evaluation of tidal constituents, especially in that of the $S_2$ constituent. An estimation of the effects of an atmospheric pressure gradient is attempted for atmospheric tidal waves, the obtained value being 7″ per 1 mb/km, but the direction of the ground tilt is opposite to that of the loading influence due to barometric pressure.


### Introduction

In the previous paper[1], the effects of the oceanic tides, atmospheric temperature, pressure and its time gradient upon ground deformation were examined under some simplified assumptions. As to the diurnal and semidiurnal changes of these disturbances, further attempts are made in this paper with the use of one year's data to investigate the effects of them on the tilting motion of the ground.

### Observational Data

Descriptions of the instruments are shown in Table 1. At Akibasan observation station, two sets of tiltmeters are installed in parallel but opposite directions, as seen in Fig. 1, on one concrete base, the width, length and height of which are about 50, 150 and 10 cm, respectively.

TABLE 1.
Observation stations and instruments.

| Station | Location | Instrument | | Type | Mark |
|---|---|---|---|---|---|
| Wakayama Harbor | 34°13′ N 135°09′ E | Tide Gauge | | Fuess | WT |
| Wakayama Meteorological Observatory | 34°13.6′N 135°10.0′E | Thermometer | | Bimetal | T |
| Akibasan | 34°11.8′N 135°10.4′E | Barometer | | Aneroid | PA |
| | | Tiltmeter | E-W | Horizontal Pendulum | Aa |
| | | | W-E | ,, | Aa′ |
| | | | S-N | ,, | Ba |
| | | | N-S | ,, | Ba′ |
| Oura | 34°11.3′N 135°09.5′E | Tiltmeter | E-W | Horizontal Pendulum | Ao |
| | | | S-N | ,, | Bo |

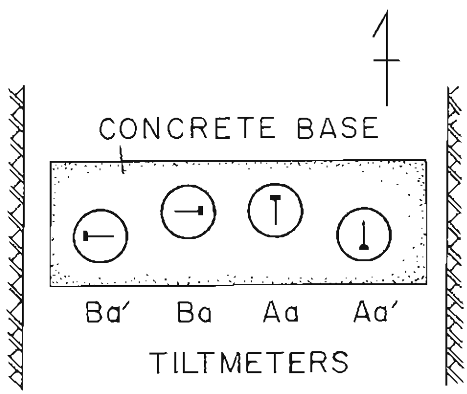


Fig. 1. Arrangement of tiltmeters at Akibasan.

One pair of tiltmeters is equipped with oil-dampers to suppress the free oscillations of pendulums due to traffic vibrations from the road near the observation station.

Hourly values of one year's data from August 1, 00h00m, 1960 to July 31, 23h00m, 1961 (Japanese Mean Time) are used for the present analysis.

The observations of ground tilting have been sometimes interrupted by heavy precipitations, failure of the electric power supply and instrumental troubles. The numbers of days monthly, for which data are lacking, are given in Table 2, for each tilting component.

Interpolating methods for missing data have been devised for the processing of gravimetric data by Longman[2] and Lecolazet[3]. In the case of gravimetric records, the instrumental drift is, generally speaking, linear, and the missing curves can be interpolated through a comparatively simple procedure.

However, estimations of the loss of data are very difficult to make when the drift is large and cannot be expressed by any simple functions. Meteorological changes cause the ground tilt at Akibasan and Oura because of the shallowness of the observation rooms, and these disturbances form the main part of the drift. Accordingly, it is necessary for good estimations of the missing data to know the response of the ground to the meteorological disturbances. In the present study, short intervals when data were lacking have been interpolated under the assumption that the drift was linear and that tidal oscillations proportional to those of the sea level at Wakayama Harbor were superimposed on the drift to the first

TABLE 2.
Monthly numbers of the days for which data are lacking.

| Month | | Instrument | | | | | |
|---|---|---|---|---|---|---|---|
| | | Aa | Aa′ | Ba | Ba′ | Ao | Bo |
| 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 |

approximation. Therefore it is to be noted that the obtained results include some degree of error from the loss of data.

## Fourier Analysis

As the first step, the amplitudes and phases of three major tidal constituents $M_2$, $S_2$ and $O_1$, and the meteorological constituent $S_1$ were calculated on the basis of one month's data of ground tilts, oceanic tides, atmospheric temperature and pressure by the Fourier transform, in order to examine the diurnal and semidiurnal changes of these disturbing factors including tidal variations. For practical calculation of the amplitudes and phases, numerical integrations have been performed following the trapezoid rule by giving their theoretical angular frequencies, after linear drift has been removed.[4),5)]

We can get information about tidal phenomena from the amplitudes and phases of $M_2$, $S_2$ and $O_1$ constituents, and about meteorological effects-temperature and pressure-from $S_1$ and $S_2$, since $S_1$ is entirely due to meteorological changes and $S_2$ is also disturbed by them. However, as the resolution of a spectrum is limited by the analyzed duration of data, adjacent constituents within the resolving power are not separable. When one month's data are analyzed by this method, the minimum separable frequency difference is estimated as 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 ($N_2$, $L_2$, $\nu_2$, $\lambda_2$), ($L_2$, $\lambda_2$, $T_2$, $R_2$, $K_2$), ($Q_1$, $M_1$, $\rho_1$) and ($M_1$, $J_1$, $P_1$, $K_1$), respectively. The amplitudes of these adjacent constituents are generally small compared with those of $M_2$, $S_2$ or $O_1$, and in the present circumstance the effects of cross contaminations may be left out of consideration except in the case of $S_1$ unless the absolute values of the amplitudes or phases are concerned. If there are no effects from the meteorological disturbances, the calculated amplitude and phase for the period of 24.000 hours are influenced by the $K_1$ constituent owing to the nearness of the angular frequency.

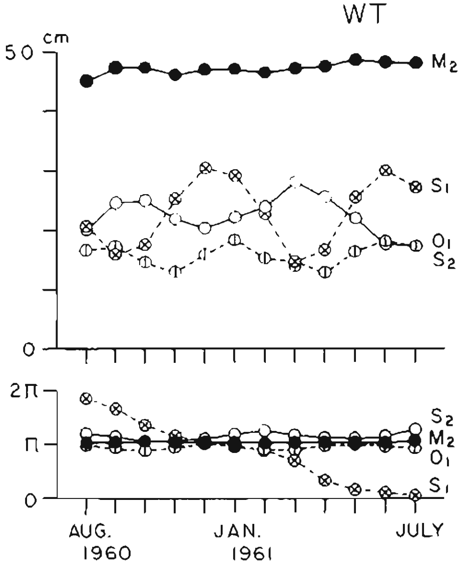


Fig. 2. Monthly amplitudes and phases of the oceanic tides observed at Wakayama Harbor.

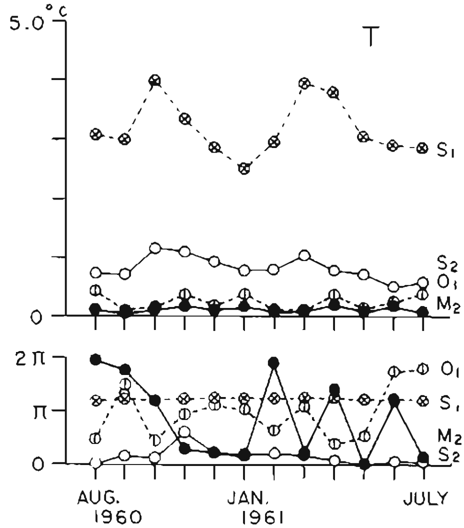


Fig. 3. Amplitudes and phases of the atmospheric temperature observed at Wakayama Meteorological Observatory.

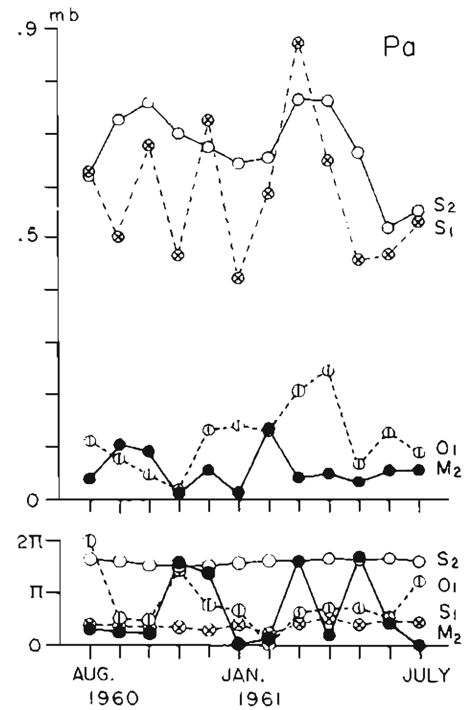


Fig. 4. Amplitudes and phases of the atmospheric pressure observed at Akibasan.

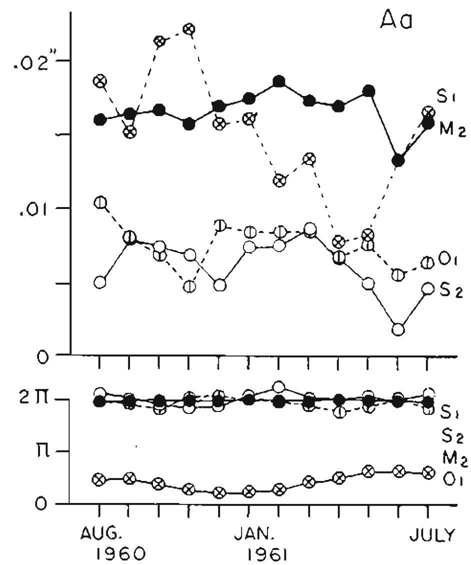


Fig. 5. Amplitudes and phases of the E-W component ground tilt observed at Akibasan.

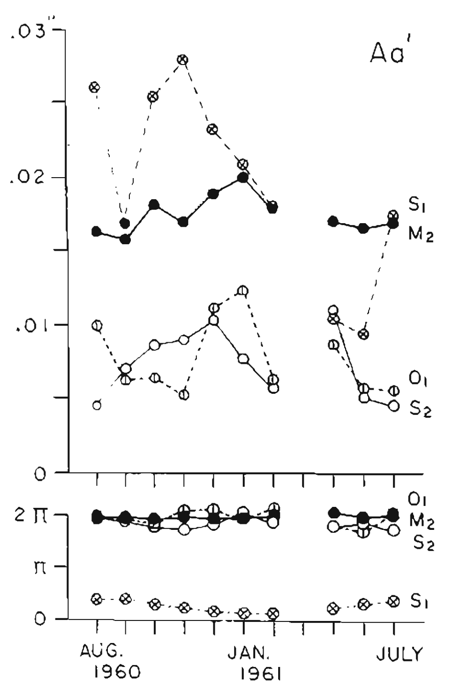


Fig. 6. W-E component ground tilt at Akibasan.

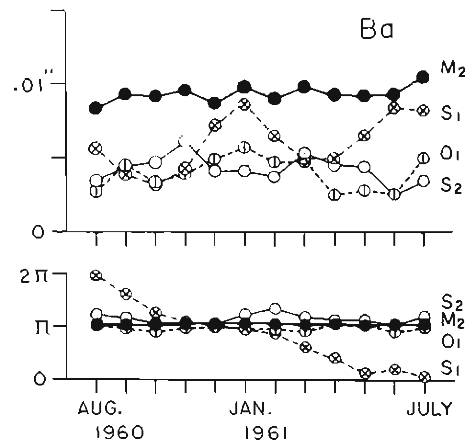


Fig. 7. S-N component ground tilt at Akibasan.

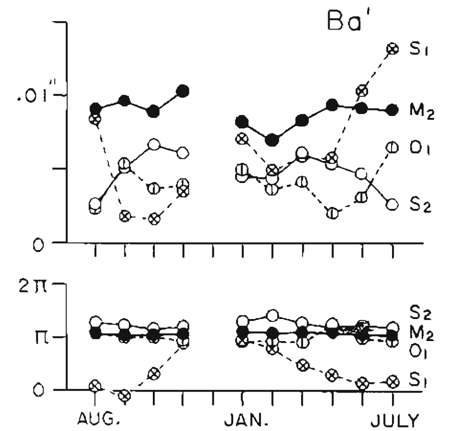


Fig. 8. N-S component ground tilt at Akibasan.

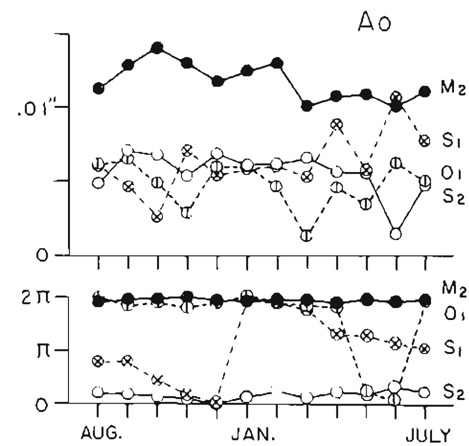


Fig. 9. E-W component ground tilt at Oura.

Obtained amplitudes and phases of the four constituents for one month's data are shown in Figs. 2 to, 10, where the positive deflection on the tiltmetric results means the south or eastward tilting, and the phase means the lag of the maximum value behind that of the theoretical maximum at the beginning

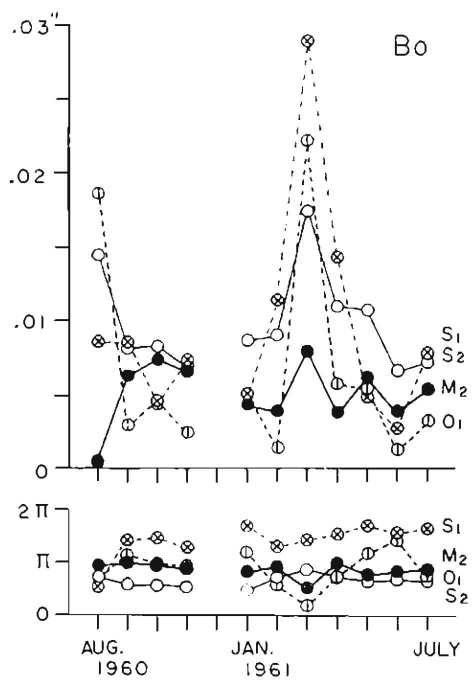


Fig. 10. S-N component ground tilt at Oura.

of each month.

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

(1) Oceanic Tides at Wakayama Harbor (WT).

The amplitudes and phases of the $M_2$ constituent are almost constant and show no remarkable changes. The maximum deviation of the amplitudes and phases are about 8% and 8°, respectively, in which errors from the effect of contamination of adjacent constituents and from numerical integrations are included together with the real fluctuation. Therefore the calculative error is smaller than those values.

Considerable fluctuations are seen as to the amplitudes of $S_1$, $S_2$ and $O_1$, which may be caused by the mixing of other constituents. A notable phase shift is that of $S_1$ which shifts $2\pi$ per year, signifying that the calculated amplitudes are those 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 phase of $M_2$ is nearly equal to those of $S_2$ and $O_1$.

(2) Atmospheric Temperature at Wakayama Meteorological Observatory (T).

The amplitude of $S_1$ is the largest, as expected. Amplitude variations of a period of 6 months are found in both $S_1$ and $S_2$, the maximum of which appear in the fall (September or October) and spring (March or April), although it is a question whether this phenomenon is an annual occurrence. The fluctuations having periods of 25.819 ($O_1$) and 12.421 hours ($M_2$) are very small compared with $S_1$ $S_2$, and their phases also show random scatterings as a matter of course. It may safely be deduced from this fact that we can disregard the effects of temperature fluctuations in respect of these lunar tidal oscillations.

(3) Atmospheric Pressure at Akibasan (PA).

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. The amplitudes corresponding to $M_2$ and $O_1$ are very small. Because their phases are not constant, these amplitudes are interpreted as merely apparent oscillations with periods of 12.421 and 25.819 hours.

(4) E-W Component Tilt at Akibasan (Aa and Aa').

It is obvious in Fig. 5 that there exists a periodic oscillation corresponding to $S_1$-meteorological constituent-which may be attributable to temperature change, since the phase of $S_1$ did not shift during one year. The amplitudes of this constituent varied remarkably and the phases shifted slightly within the one year period.

The amplitude of $M_2$ of the Aa component was small in June, 1961, but a similar tendency cannot be seen in the Aa′ component, so it is concluded that the diminution is not real but due to errors in the interpolation for the missing data.

(5) N-S Component Tilt at Akibasan (Ba and Ba′).

The pattern of the Ba 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 components. All the spectral features bear a resemblance to that of the oceanic tides, and we can conclude from this fact that the N-S component tilt at Akibasan consists mostly of the indirect effects of the oceanic tidal changes.

It is noted that the amplitude fluctuation of $S_1$ of the Ba′ component has a similar tendency as that of Ba, but the minimum value in October is smaller and the maximum in July is larger than those of Ba, respectively, from which an annual change of $S_1$ of the Ba′ component may be deduced.

(6) E-W Component Tilt at Oura (Ao).

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

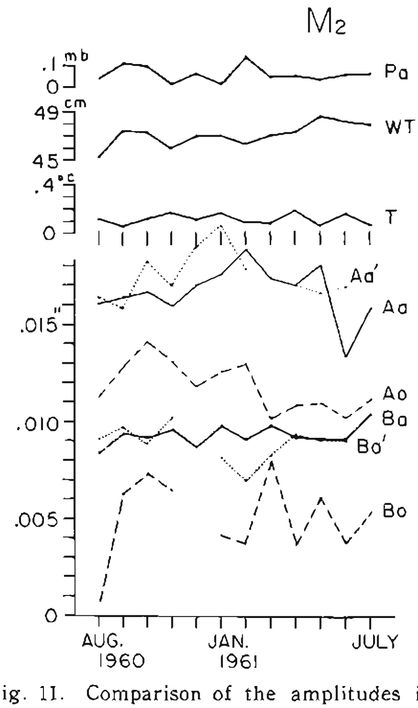


Fig. 11. Comparison of the amplitudes in respect of $M_2$.

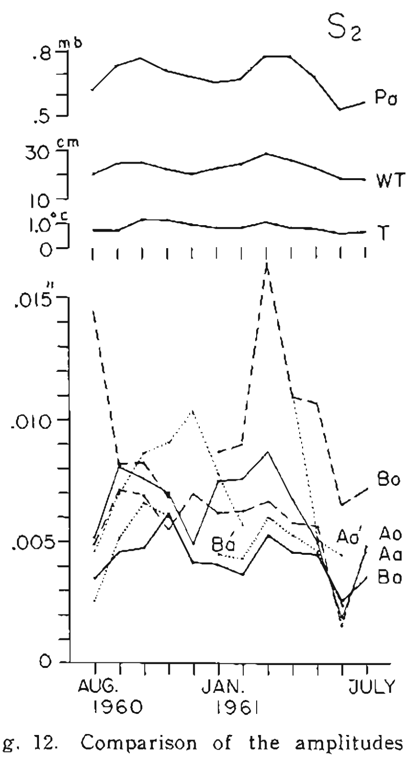


Fig. 12. Comparison of the amplitudes in respect of $S_2$.

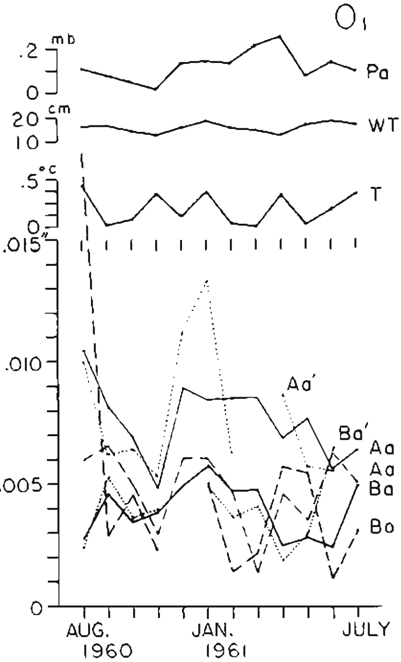


Fig. 13. Comparison of the amplitudes in respect of $O_1$.

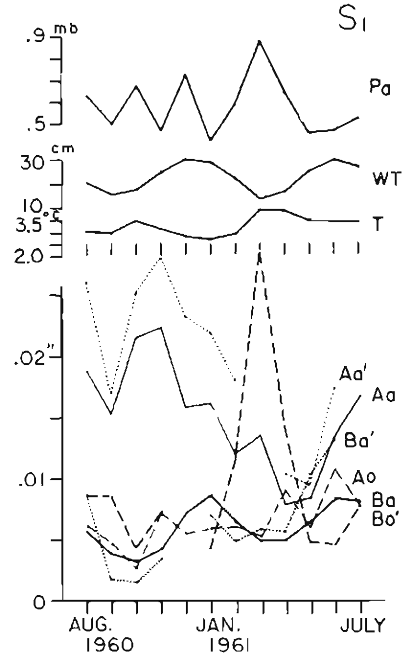


Fig. 14. Comparison of the amplitudes in respect of $S_1$.

(7) N-S Component Tilt at Oura (Bo).

The features of the amplitude and phase changes of this component are markedly different from the above-mentioned components of the ground tilt. The amplitude of $M_2$ is smaller than $S_1$ and $S_2$, and sometimes smaller than $O_1$. It is characteristic that the amplitudes of all constituents show a remarkable increase in March and decrease in June, 1961. Fluctuations of the phases are also large compared with those above-mentioned. As reported in the previous paper, this component is strongly affected by pressure changes and rainfall, so that the drift is very large. Thus it may be inferred that the amplitudes and phases obtained are heavily disturbed by such a large drift and so they are not true values for each constituent but some apparent resultant amplitudes and phases.

However, it should be mentioned that the practical fluctuations of the temperature and atmospheric pressure having the same periods as those of lunar tides $M_2$ and $O_1$ are so small that neither the temperature nor pressure change directly affects the ground tilting of the lunar constituents.

In Figs. 11 to 14, comparisons of the amplitude changes are given regarding each constituent.

No clear correlations are seen between the ground tilting and oceanic tides, temperature or atmospheric pressure in respect of $M_2$ and $O_1$. The amplitudes of $M_2$ and $O_1$ are not always equal for the two pairs of tiltmeters, Aa and Aa', and, Ba and Ba' (Figs. 11 and 13).

It appears clearly in Fig. 12 that the changes of pressure have more or less influence upon all the tilting components in $S_2$. Amplitudes of the oceanic tides seem to be also affected by pressure, although they are disturbed by the contamination of other constituents.

The correlation between the Bo component and pressure is remarkable for $S_1$, it is concluded that the abnormal increase in the amplitude in March is due to the effects of pressure changes. Besides, the amplitudes of Aa′ are always larger than those of Aa (Fig. 14).

Weighted mean amplitudes and phases in 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 3. The weights applied are inversely proportional to the numbers of the days shown in Table 2. In the table the mean values of the amplitudes and phases of the oceanic tides, Ba, Ba′ and the Ao component for $S_1$, and the phases of the temperature and pressure for $M_2$ and $O_1$ are not given because they are meaningless.

Now, let's compare the two pairs of tiltmetric results observed on the same concrete block at Akibasan.

The amplitude ratios and phase differences obtained by the two tiltmeters in the same direction are given in Table 4 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

TABLE 3.
Weighted mean amplitudes and phases.

| | $M_2$ | | $S_2$ | | $O_1$ | | $S_1$ | |
|---|---|---|---|---|---|---|---|---|
| | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase | Amplitude | Phase |
| WT | 47.1cm | 186.°2 | 22.3cm | 208.°1 | 15.8cm | 170.°1 | — | — |
| T | 0.12°C | — | 0.82°C | 22.6 | 0.25°C | — | 3.20°C | 223.°2 |
| PA | 0.058mb | — | 0.669mb | 284.8 | 0.118mb | — | 0.581mb | 70.5 |
| Aa | 0.01672″ | 355.8 | 0.00630″ | 4.6 | 0.00761″ | 346.1 | 0.01515″ | 75.2 |
| Aa′ | 0.01738 | 352.3 | 0.00723 | 330.0 | 0.00773 | 349.6 | 0.02006 | 50.4 |
| Ba | 0.00935 | 186.5 | 0.00429 | 207.3 | 0.00396 | 173.1 | — | — |
| Ba′ | 0.00391 | 190.4 | 0.00475 | 222.9 | 0.00390 | 178.1 | — | — |
| Ao | 0.01188 | 353.0 | 0.00571 | 32.4 | 0.00481 | 352.6 | — | — |
| Bo | 0.00493 | 144.1 | 0.00909 | 107.1 | 0.00595 | 151.6 | 0.00835 | 239.9 |

TABLE 4.
Amplitude ratios and phase differences for Aa′ to Aa and Ba′ to Ba component.

| | Amplitude Ratio | Phase Difference | Amplitude Ratio | Phase Difference |
|---|---|---|---|---|
| | (Aa′/Aa) | (Aa′-Aa) | (Ba′/Ba) | (Ba′-Ba) |
| $M_2$ | 1.04 | − 3.5 | 0.95 | 3.°9 |
| $S_2$ | 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 Ba and Ba′ components are corresponding to $K_1$.

large for the latter.

As seen in Figs. 3 and 4, periodic changes in the temperature and pressure corresponding to $S_1$ and $S_2$ are very predominant compared with those corresponding to $M_2$ and $O_1$. Therefore, it is concluded that the concrete blocks is not deformed but uniformly inclines owing to the indirect effect of the oceanic tides, while it is deformed by the effect of temperature or pressure changes. This means that the wave length of the deformation due to temperature or pressure changes is so short that the concrete block is deformed after the deformation of the observation room. Accordingly, such a deformation cannot be ignored when scales of topographical features or irregularities in heating are so small and the depth of the observation room is not as large as at Akibasan as has been shown theoretically and observationally by many researchers[6].

## Determination of the Effects of Atmospheric Temperature, Pressure and Its Time Gradient

As the method of determination of these effects is the same as that described in Part 1[1], the procedure is given briefly in the following.

First, mean daily variations (solar time) of the ground tilt, oceanic tides, temperature and atmospheric pressure have been obtained from one month's data, after eliminating the drift by Pertzev's method. They are shown by solid lines in Figs. 15 to 23. On the other hand, the ratios of the $M_2$ amplitude of

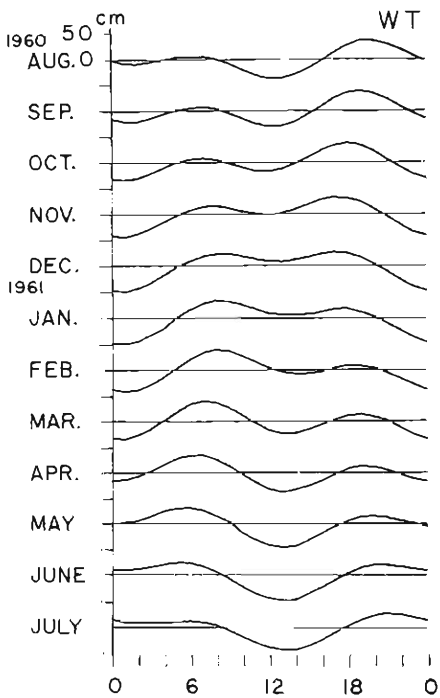


Fig. 15. Mean daily variations of the oceanic tides.

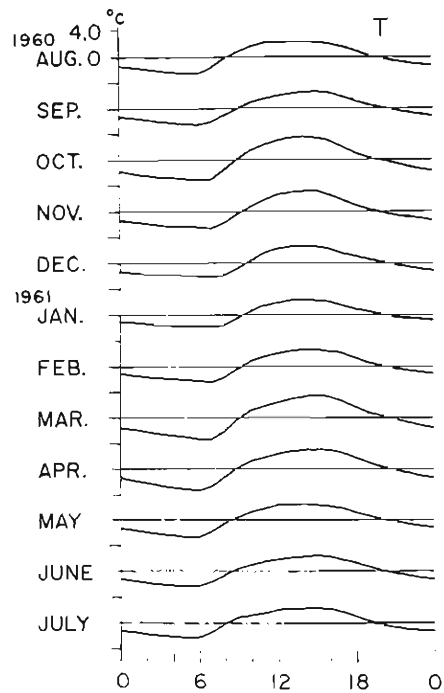


Fig. 16. Mean daily variations of the atmospheric temperature.

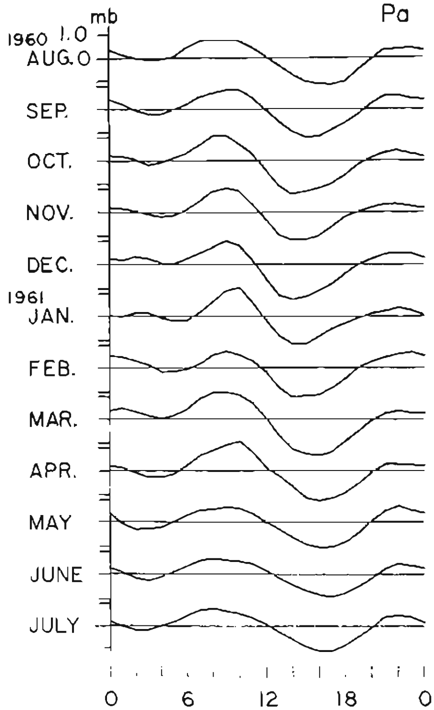


Fig. 17. Mean daily variations of the atmospheric pressure.

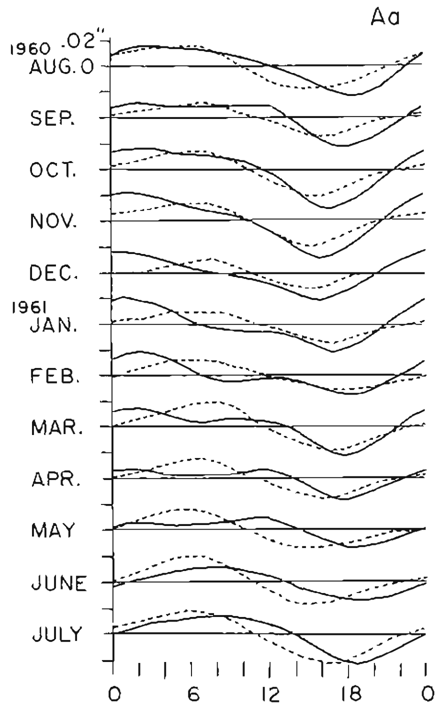


Fig. 18. Mean daily variations of the E-W component tilt at Akibasan.
Solid line: Original.
Dashed line: Corrected in respect of tidal change by oceanic tides.

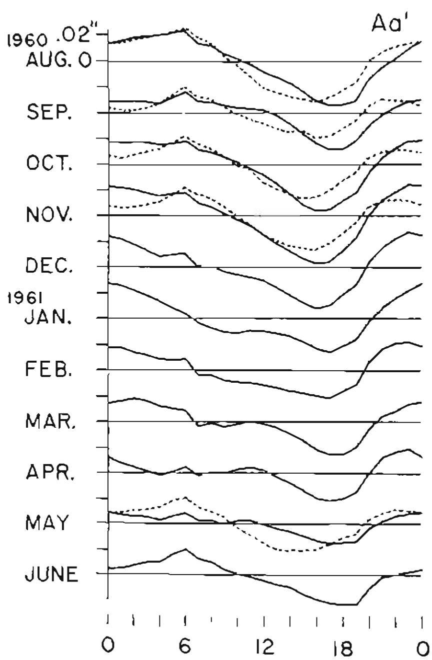


Fig. 19. W-E component tilt at Akibasan.

each tilting component to that of the oceanic tides have been calculated from the mean amplitudes given in Table 3. Multiplying each ratio by the hourly values of the mean daily variations of the oceanic tides (WT), we subtract the products from the corresponding components of tilt. As the phase of the Bo component differs by about one hour from that of the oceanic tides, the products have been slid one hour against the Bo component for phase adjustments.

On account of the small phase differences among $M_2$, $S_2$ and $O_1$ for the oceanic tides, as seen in the preceding paragraph, it may be permissible to use the phase of $M_2$ as a representative phase of the constituents as an approximation.

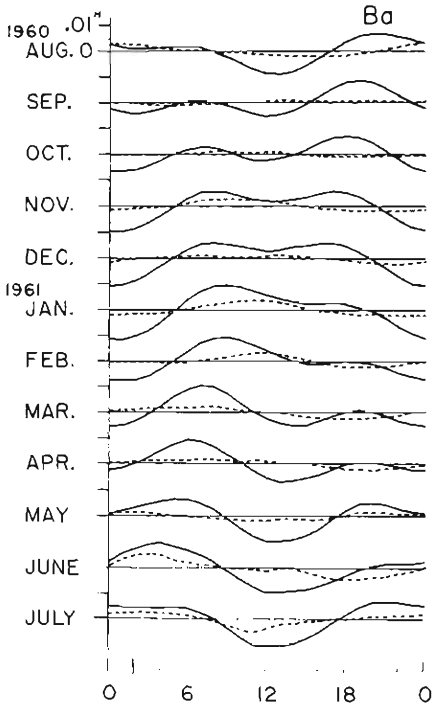


Fig. 20. S-N component tilt at Akibasan.

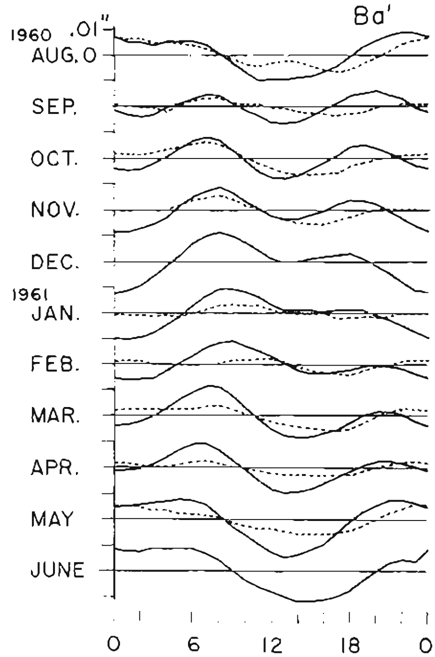


Fig. 21. N-S component tilt at Akibasan.

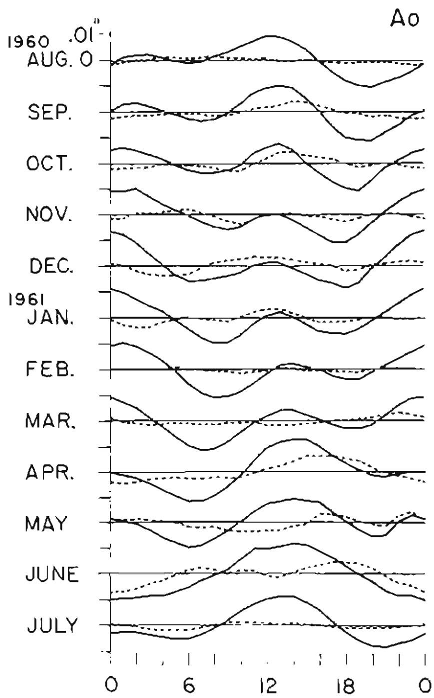


Fig. 22. E-W component tilt at Oura.

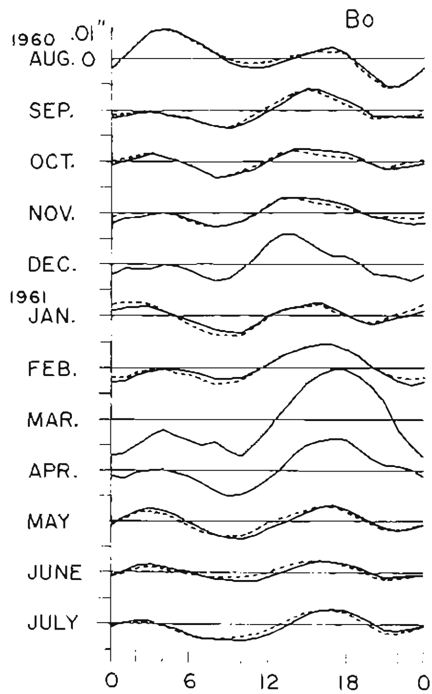


Fig. 23. S-N component tilt at Oura.

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 a long period analysis. For this purpose, we are now analyzing the data from a one year period. However, as the sea level fluctuates irregularly under the influence of meteorological changes and currents, and the ground might be deformed by the loading effects, adoption of the above-mentioned procedure is not necessarily meaningless as an approximation.

The obtained residuals are shown in the figures by dashed lines.

As expected from the results of the Fourier analysis, daily variations are clearly seen in the residuals of Aa and Aa′ components, which may be mainly caused by temperature changes. On the contrary, residuals of the Ba component show no regular changes but showed very small ones in September, October (1960), April and May (1961). The residuals of the Ba′ component are somewhat larger than Ba.

For the reason that the oceanic tidal effects are very small in the Bo component, the features of its residuals are scarcely different from the originals, and are very similar to the mean daily variations of pressure.

Assuming that these residuals are represented by linear combinations of the temperature (Fig. 16), pressure (Fig. 17) and its time differential, the coefficients for these disturbances have been determined by the method of least squares, where we defined the time differential of pressure as $dp/dt=(1/2)\cdot[p(t+1)-p(t-1)]$ (mb/hour), as in Part 1[1]. The coefficients obtained are summerized in Tables 5 to 10, together with the oceanic tidal effects determined by the Fourier analysis. As concluded in the previous paper,[1] the curves of the mean

TABLE 5.
Coefficients of the disturbing factors to the ground tilt of Aa component. (Unit. 0.001″)

| | Oceanic Tides (1cm) | | Temperature* (1°C) | Barometric Pressure (1mb) | Time Gradient of Pressure (1mb/hour) |
|---|---|---|---|---|---|
| 1960 | | | | | |
| Aug. | −0.357 | (12.7) | −5.55±0.27 | 1.64±0.88 | − 7.8 ±1.8 |
| Sep. | −0.348 | (11.5) | −3.09±0.23 | 2.15±0.79 | − 4.7 ±1.4 |
| Oct. | −0.353 | ( 8.4) | −3.55±0.26 | 1.3 ±1.0 | − 4.8 ±1.5 |
| Nov. | −0.345 | (13.4) | −4.14±0.13 | 0.72±0.49 | − 2.27±0.71 |
| Dec. | −0.363 | (11.9) | −2.09±0.43 | 2.2 ±1.3 | 0.7 ±1.6 |
| 1961 | | | | | |
| Jan. | −0.374 | ( 6.4) | −4.23±0.34 | −0.7 ±1.0 | − 6.4 ±1.6 |
| Feb. | −0.405 | ( 4.3) | −4.40±0.43 | −5.1 ±1.5 | − 7.3 ±2.4 |
| Mar. | −0.368 | (11.3) | −3.33±0.52 | 3.2 ±1.8 | − 8.2 ±2.7 |
| Apr. | −0.361 | ( 6.3) | −3.00±0.21 | 3.09±0.74 | − 0.8 ±1.6 |
| May | −0.372 | ( 9.1) | −4.15±0.29 | 0.8 ±1.0 | − 1.7 ±2.0 |
| June | −0.332 | (11.6) | −4.92±0.46 | 3.2 ±1.8 | 3.5 ±3.5 |
| July | −0.330 | (17.0) | −5.05±0.61 | 6.7 ±2.2 | −11.1 ±4.2 |

Values in the parentheses of the column of the oceanic tides are phase differences between the ground tilt and disturbing factor, positive signs meaning phase leads of the latter to the former.

(*: The phase of the temperature advances one hour compared with that of the ground tilt.)

TABLE 6.

Coefficients of the disturbing factors to the ground tilt of Aa' component. (Unit. 0.001'')

| | Oceanic Tides (1cm) | | Temperature (1°C) | Barometric Pressure (1mb) | Time Gradient of Pressure (1mb/hour) |
|---|---|---|---|---|---|
| 1960 Aug. | −0.364 | (17.5) | −7.15±0.28 | 10.91±0.87 | −5.8±2.2 |
| Sep. | −0.334 | (12.4) | −3.39±0.45 | 6.6 ±1.5 | 1.3±3.0 |
| Oct. | −0.385 | (22.3) | −3.65±0.36 | 7.4 ±1.4 | −4.4±2.6 |
| Nov. | −0.370 | (15.5) | −5.02±0.47 | 5.6 ±1.8 | −5.3±3.2 |
| Dec. | −0.403 | (22.0) | | | |
| 1961 Jan. | −0.426 | (17.1) | | | |
| Feb. | −0.385 | ( 6.9) | | | |
| Mar. | | | | | |
| Apr. | −0.360 | ( 1.1) | | | |
| May | −0.340 | (12.5) | −4.95±0.17 | 7.10±0.61 | 3.7±1.4 |
| June | −0.351 | ( 6.0) | | | |
| July | | | | | |

TABLE 7.

Coefficients of the disturbing factors to the ground tilt of Ba component. (Unit : 0.001'')

| | Oceanic Tides (1cm) | | Temperature (1°C) | Barometric Pressure (1mb) | Time Gradient of Pressure (1mb/hour) |
|---|---|---|---|---|---|
| 1960 Aug. | 0.186 | (−0.5) | −0.831±0.086 | 0.12±0.27 | −3.02±0.68 |
| Sep. | 0.198 | ( 1.0) | 0.240±0.061 | 0.16±0.20 | −7.67±0.40 |
| Oct. | 0.194 | ( 0.8) | 0.059±0.065 | 0.56±0.25 | −1.02±0.47 |
| Nov. | 0.210 | (−1.3) | 0.20 ±0.18 | 1.29±0.68 | −1.3 ±1.2 |
| Dec. | 0.186 | (−3.6) | −0.27 ±0.20 | −1.18±0.57 | −1.23±0.84 |
| 1961 Jan. | 0.209 | (−4.3) | 0.55 ±0.26 | 1.34±0.75 | −1.6 ±1.4 |
| Feb. | 0.196 | (−6.3) | 0.20 ±0.17 | 0.33±0.55 | −4.74±0.98 |
| Mar. | 0.209 | (−1.0) | −0.458±0.092 | 0.46±0.30 | −2.66±0.60 |
| Apr. | 0.196 | (−1.7) | −0.353±0.075 | 0.64±0.27 | −2.52±0.63 |
| May | 0.187 | ( 2.5) | −0.35 ±0.11 | −0.32±0.37 | 0.81±0.79 |
| June | 0.189 | ( 4.3) | −1.36 ±0.20 | −0.78±0.75 | −8.0 ±1.8 |
| July | 0.217 | ( 3.6) | −1.09 ±0.11 | −2.09±0.34 | 0.13±0.80 |

daily variations for the temperature have been delayed one hour in the process of determining coefficients of Aa component, because the mean square errors are smaller in this case than when there is no delay. But such a tendency could not be found in respect of the Aa' component and its coefficients have been determined under circumstances where there is no phase delay between the tilting motion and temperature change.

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

(1) Effects of the Atmospheric Temperature.

TABLE 8.
Coefficients of the disturbing factors to the ground tilt of Ba′ component. (Unit : 0.001″)

| | Oceanic Tides (1cm) | Temperature (1°C) | Barometric Pressure (1mb) | Time Gradient of Pressure (1mb/hour) |
|---|---|---|---|---|
| 1960 Aug. | 0.201 (− 7.1) | −2.19 ±0.15 | 0.46±0.47 | −7.9 ±1.2 |
| Sep. | 0.204 ( 1.4) | −0.22 ±0.14 | 2.06±0.44 | −1.14±0.86 |
| Oct. | 0.188 (− 0.3) | −0.80 ±0.12 | 2.47±0.42 | 0.27±0.81 |
| Nov. | 0.221 (− 4.0) | −0.45 ±0.14 | 2.37±0.54 | 0.40±0.95 |
| Dec. | | | | |
| 1961 Jan. | 0.173 (−13.2) | 0.35 ±0.19 | 2.10±0.54 | −0.43±0.96 |
| Feb. | 0.150 (−10.0) | −0.087±0.083 | 1.79±0.28 | −4.97±0.50 |
| Mar. | 0.176 (−10.0) | −0.758±0.084 | 1.72±0.27 | −1.20±0.55 |
| Apr. | 0.197 (− 5.8) | −0.553±0.036 | 1.01±0.23 | 0.35±0.56 |
| May | 0.187 ( 0.8) | −1.41 ±0.26 | 1.10±0.91 | 0.0 ±2.0 |
| June | 0.186 (− 1.6) | | | |
| July | | | | |

TABLE 9.
Coefficients of the disturbing factors to the ground tilt of Ao component. (Unit : 0.001″)

| | Oceanic Tides (1cm) | Temperature (1°C) | Barometric Pressure (1mb) | Time Gradient of Pressure (1mb/hour) |
|---|---|---|---|---|
| 1960 Aug. | −0.250 (14.8) | −0.03 ±0.13 | 0.54±0.38 | −0.54±0.93 |
| Sep. | −0.272 (11.7) | 0.37 ±0.11 | −1.61±0.36 | −1.78±0.71 |
| Oct. | −0.299 ( 9.0) | 0.16 ±0.12 | −2.14±0.42 | −0.26±0.81 |
| Nov. | −0.284 ( 6.3) | −0.52 ±0.12 | −1.89±0.45 | −0.99±0.80 |
| Dec. | −0.252 (15.8) | 1.09 ±0.29 | 1.93±0.81 | −2.0 ±1.2 |
| 1961 Jan. | −0.268 (17.4) | 0.41 ±0.19 | 0.11±0.54 | −2.65±0.95 |
| Feb. | −0.282 ( 8.5) | −0.244±0.079 | −0.62±0.27 | −0.89±0.48 |
| Mar. | −0.215 (11.5) | 0.15 ±0.17 | 0.48±0.53 | 2.3 ±1.1 |
| Apr. | −0.229 (23.5) | 1.040±0.078 | −2.24±0.27 | 3.32±0.66 |
| May | −0.226 (10.2) | −0.54 ±0.22 | −2.44±0.78 | −0.3 ±1.7 |
| June | −0.211 (17.0) | 1.46 ±0.24 | 0.21±0.90 | 11.4±2.1 |
| July | −0.233 (14.8) | 0.279±0.045 | 0.62±0.15 | −2.52±0.35 |

Effects of the temperature changes on ground tilting are very clear in Aa and Aa′ components, and the coefficients of Aa′ are larger than those of Aa. Moreover, the effects of the temperature may be found in Ba and Ba′ components too, 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 analyzed period, although the period is too short to permit one to ascertain such an annual variation.

The amplitude ratio $O_1/M_2$ of the oceanic tides is 0.336 and the ratios of the Aa and Ba components being 0.455 and 0.423, respectively. Therefore, effects

TABLE 10.
Coefficients of the disturbing factors to the ground tilt of Bo component. (Unit: 0.001″)

| | Oceanic Tides | Temperature | Barometric Pressure | Time Gradient of Pressure |
|---|---|---|---|---|
| | (1cm) | (1°C) | (1mb) | (1mb/hour) |
| 1960 Aug. | 0.025 (16.3) | −3.9 ±1.4 | − 9.7 ±4.4 | −19 ±11 |
| Sep. | 0.133 ( 8.9) | 0.49±0.21 | −10.55±0.69 | − 6.1± 1.4 |
| Oct. | 0.156 (20.6) | −1.31±0.16 | −10.28±0.60 | − 6.5± 1.2 |
| Nov. | 0.142 (31.5) | 0.40±0.19 | − 8.12±0.70 | − 4.0± 1.3 |
| Dec. | | | | |
| 1961 Jan. | 0.090 (39.2) | −1.56±0.85 | −11.0 ±2.5 | − 7.0± 4.4 |
| Feb. | 0.083 (20.4) | | | |
| Mar. | 0.170 (95.7) | | | |
| Apr. | 0.079 (10.5) | | | |
| May | 0.126 (47.3) | −0.92±0.19 | −13.23±0.67 | − 3.2± 1.5 |
| June | 0.079 (39.3) | −0.12±0.26 | −8.64 ±0.96 | − 7.2± 2.2 |
| July | 0.112 (36.8) | −0.29±0.22 | −13.58±0.73 | − 2.8± 1.8 |

of the diurnal tides have not been completely eliminated but still remain in the residuals to a small extent and disturb the obtained coefficients. However, it is concluded that the annual tendency above-mentioned is not due to the remnants of the tidal disturbances ($K_1$ constituent, for example) but due to temperature changes, because the tendency can also be seen in the changes of the $S_1$ constituents in Figs. 7 and 8, and the fluctuation of Ba′ is larger than that of Ba.

We could not recognize the phase delay between the temperature and thermal tilts except the Aa component (one hour). Because the variation of surface temperature is hardly propagated into the tunnel by heat conduction and the delay is so small, these tilting motions are not caused by heat conduction from the surface, but by the propagation of thermal deformation.[7] According to results obtained by Nakano,[8] the amounts of thermal tilts at Akibasan are satisfactorily explained by variations of surface temperature having a wave length equal to the topographical scale (about 100 m) and amplitude of several tenth of the mean daily variation, neglecting the term of heat conduction.

Fig. 24 shows a schematic diagram of the tilting motion observed by the two central tiltmeters Aa and Ba due to daily variations of the temperature. It is apparent in the figure that the daily tilting motion has the largest amplitude in the summer and the smallest in the winter, although the daily variation of the temperature shows larger amplitude in the spring and fall. This phenomenon is a general tendency in thermal deformations of the ground.[9] The northward tilting in the morning is remarkable in the summer, which might be attributable to increment of the declination of the sun in this season.

It is interesting that the features of the thermal tilts are very similar to those of buckling motions observed in a building of simple figure,[10] which may be caused by the simple topographical form of the hill in which the observation room is situated.

On the contrary, thermal tiltings at Oura are not so clear as at Akibasan

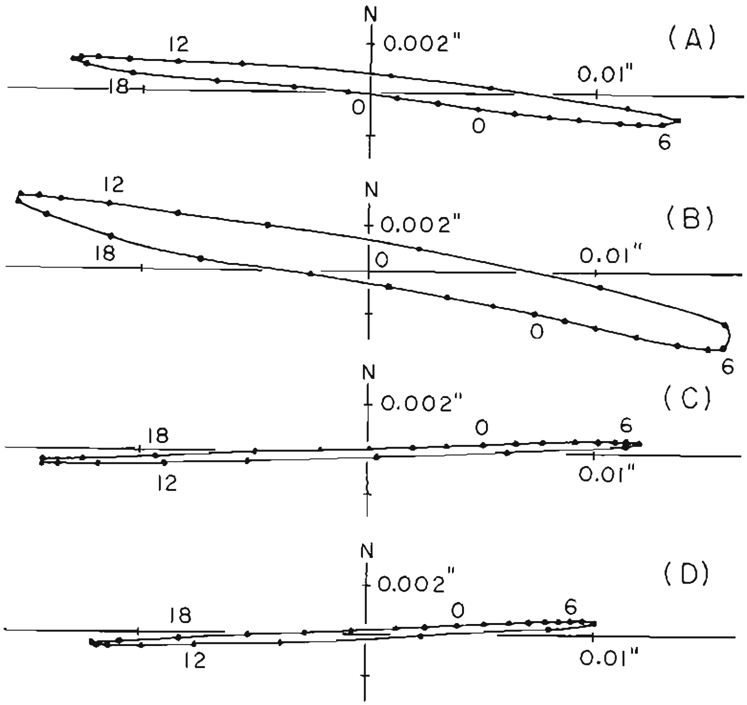


Fig. 24. Influence of atmospheric temperature on the ground tilt at Akibasan.
A : Spring (March-May)
B : Summer (June-August)
C : Fall (September-November)
D : Winter (December-February)

owing to the situation of the observation room and topographical conditions.

We have been obliged to use the atmospheric temperature as a provisional parameter of the thermal deformation, but it is necessary for further investigations to get more exact information about thermal boundary conditions through measurements of temperature on and near the surface of the ground.

(2) Effects of the Atmospheric Pressure.

As direct effects of atmospheric pressure on the ground are not likely to show seasonal changes, the signs of the coefficients may be considered as a clue in proving their validity. From this point of view, Aa and Ba components have positive coefficients, from which an east and southward inclination is deduced for the increase of pressure, while the values of the coefficients of Aa′ and Ba′ are about three times larger than those of Aa and Ba. It is inferred from this fact that the direct effects of pressure has strong local characteristics similar to the effect of temperature.

It is to be noted that these coefficients have opposite signs to those reported in the previous paper[1] except in the case of the Bo component. This conflict is probably caused by differences in the temperature data used as parameters. The present results are considered to be more reliable than those of the previous paper, but further investigations are required to elucidate this subject.

(3) Effects of the Atmospheric Pressure Gradient.

In general, the time differential of the barometric record observed at some fixed point is meaningless. However, we can substitute it for information about the pressure gradient, provided that the velocity and direction of propagation of the pressure waves are constant.

As seen in the preceding paragraph, the semidiurnal oscillation is most predominant among atmospheric components, the main term of which consists of a westward migrating semidiurnal solar wave.[11] The diurnal solar wave which is considered to have originated from solar radiation also migrates westwards with the sun, and the mean daily variations of the pressure shown in Fig. 17 are allowed to consist of westward propagating waves of constant velocity. Therefore, the time differential $dp/dt$ calculated from the mean daily variations 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 do not differ so much for corresponding components of both stations. Thus it is possible that the ground in the Wakayama region may incline uniformly north-westwards according to increasing pressures. The amount of ground tilt is roughly estimated as about 7″ per 1 mb/km of the pressure gradient in the E-W direction, assuming the velocity as 1400 km/hour. However, this seems to be contradictory to the theoretical result given by Darwin[12] and Khorosheva[13] that the ground will incline toward the barometric maximum, because of the westward migration of diurnal and semidiurnal pressure waves.

In the procedure of determining the coefficients, we have used the mean daily variations calculated from one month's data. Angular velocities of almost all tidal constituents being not equal to 15.000 or its multiples except $S_1$ and $S_2$, their phases at the beginning of each month shift gradually through one year. Therefore, the only constituent which gives consistent coefficients over one year is $S_1$, or $S_2$ in our case, and there is a possibility of entering the errors by the process of eliminating the tidal effects and adopting the temperature observed at Wakayama Meteorological Observatory as a parameter.

Tomaschek has reported similar phenomena in respect of the effects of the barometric pressure gradient at Winsford in England, and explained its behavior in connection with tectonic structure.[14] 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 analysis is longer than that in his investigation. This suggests that such behavior of the ground tilt might be intrinsic in the effect of the barometric pressure gradient.

## Summary

To establish a quantitative relation between the observed ground tilt and oceanic tides, atmospheric temperature and pressure changes, amplitudes and phases corresponding to $M_2$, $S_2$, $O_1$ and $S_1$ constituents were calculated from tiltmetric records, and compared with those for the oceanic tides, temperature and barometric pressure. Next, after eliminating the tidal influence by using the oceanic tides as an intermediary, the effects of the temperature, pressure

and its time gradient were determined by the method of least squares.

Obtained results show that temperature and pressure influence the ground tilt with short wave lengths which cause deformation in the floor of the observation room (In this case, pressure influence does not mean the effect due to pressure gradient but direct effect proportional to barometric changes.). It is concluded that observations of ground tilt can advantageously be carried out at the central position of the floor in an observation room where there is a lesser degree of influence from temperature and pressure, since these become larger as they approach the walls. 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 daily variations of the atmospheric pressure consist of westward migrating waves with a constant velocity. However, the ground inclines towards the barometric depression, which contradicts the loading effect of the pressure.

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