SHORT PERIOD VARIATION IN LAND SUBSIDENCE

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ABSTRACT

On the records of compaction obtained at several stations in and near Tokyo, we notice fluctuations with nearly diurnal and semidiurnal periods superimposed with secular advancement of subsidence. These short period fluctuations are separated by taking deviations from the 24 hours' moving averages of the hourly values of compaction read on the records, and subjected to detailed study.

Of these, the diurnal change is characterized with particularly remarkable daytime swelling of surface soil layer. The swelling of the soil layer appears to be very nearly parallel to the change in barometric pressures, also to the change in the heights of the ground water level, though the latter is slightly out of phase (with a lag of 2-3 hours). We then studied in some detail the relation between the changes in the barometric pressures and the diurnal variation in land subsidence, taking into consideration the changes in the heights of the ground water level, which may have been influenced by the barometric pressure changes.

The terms of tidal changes are also taken out, of which the $M_2$ term is most remarkable, though the amplitude is far less than that of the diurnal fluctuations.

1. In the land subsidence area of Tokyo and its vicinity, a number of compaction recorders stations have been installed to obtain continuous records of compaction of the surface soil layer which has considerable thickness. In the records thus obtained, various interesting features may be noted, among which the oscillatory fluctuations with approximate diurnal and semi-diurnal periods are rather conspicuous. These oscillatory fluctuations may be caused by periodic external disturbances, such as direct and indirect effects of tidal force and atmospheric pressure changes.

The land subsidence is undoubtedly due to the lowering of the ground water pressure resulting from excessive withdrawal of ground water. The soft surface soil layer, the compaction of which accounts for the main part of the observed land subsidence, may also undergo oscillatory movements in response to external periodic disturbances. These movements may be characterized by the physical properties of the soil layer which may control the development of continuing land subsidence in response to the lowering of the ground water pressure. An explanation of the mechanism of land subsidence may be developed through a detailed study of the periodic variations observable in the compaction records.

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2. The following procedures were used to analyze short period variations in the compaction records.

On the actual graphs from the compaction recorders and those from ground water hydrograph recorders operated simultaneously at a particular station, hourly values were read and their deviations from the twenty-five-hour moving average were calculated. These procedures were followed with regard to the records obtained from the stations at Todabasi, Kameido, and Minami-sunamati, for the years 1956, 1961, and 1966. The locations of these stations are given in figure 1.

![Figure 1. Locations of observation stations in Tokyo](image)

At Todabasi station are four observations wells, each equipped with compaction recorders and two of them also equipped with hydrographs recorders. For the present analyses, the compaction and hydrograph records that were obtained at No. 1 well were used. The reference tube at No. 1 well is at a depth of 290.0 metres. At the No. 2 well, the reference tube reaches a depth of 113.0 metres. Because the observations at No. 1 well began in the beginning of 1961, and those at No. 2 well began in the end of 1961, it was possible to work with the records obtained during 1961 and 1966 at No. 1 well, but only with those of 1966 from No. 2 well.

At each of the Kameido and Minami-sunamati stations, there are two observation wells, deep and shallow, both equipped with compaction and hydrograph recorders. The reference tubes of the compaction recorders at Kameido station are fixed at the depths of 143.0 metres (deep) and 65.0 metres (shallow), while those at Minami-sunamati station are fixed at depths of 130.0 metres (deep) and 70.0 metres (shallow). Because the operation of the compaction recorders at these stations began in 1954 on the shallow wells and in 1961 on the deep wells, we have available compaction records for 1956, 1961 and 1966 from the shallow wells, and records for 1961 and 1966 from the deep wells, for the present analyses.
3. Attention was first focussed on the component of variation with the exact diurnal period for the short period fluctuations in the land subsidence records because of a conspicuous apparent swell of the surface soil layer which appears late in the morning and decays before evening. Since the hourly deviations of the compactions, computed as mentioned above, may include the components of variations with tidal periods, that is, 12.42 hours ($M_2$), 12.00 hours ($S_2$), 25.82 hours ($O$), 23.93 hours ($K_i$), and so on, average values of the deviations at each hour of successive days are taken over a period of a year to eliminate the effect of tidal components. In the present report, these average values were taken over 55 days (about two months) for elimination of the most effective component, the $M_2$ component.

Examples of the average diurnal variations in the land subsidence (strictly, the diurnal variation in the height of the land surface) obtained from the compaction records at the Kameido station are shown in figure 2. Those demonstrate the apparent daytime swell of the surface soil layer.

![Figure 2. Mean diurnal variation of compaction at Kameido. (Negative values represent swelling)](image)

The apparent daytime swell of the surface soil layer should be attributed neither to the temperature effect, nor to the mere changes in the height of the ground water level. The atmospheric temperature is relatively high during the period when the swell of the surface soil layer reaches its maximum, and the thermal expansion coefficient of the reference tube of the compaction recorder may not be smaller than that of the soil layer. Hence, the temperature effect on the compaction records, if any, should be apparent contraction of the surface soil layer, in contrast with the swelling observed in the actual records. The change in the height of the ground-water level may not be the only cause of this swelling, because it is quite out of phase with deviations of the compactions. It also was noted that this swelling commences late in the morning and recovers in the evening.

Fortunately, it was found by chance that in the barograph records taken at the compaction recorder station of Sin-edogawa, there was a fluctuation, though with small amplitude, that just was in phase with the fluctuations in the compaction records. Both the barograph records and the compaction records are plotted in figure 3. The similarity of these two fluctuating curves is obvious. Thus it may be concluded that there is a leading component of fluctuation in the compaction records that is caused by the barometric fluctuations.
Another question that then arises is whether the similar relation holds between the smoothed curve of the compaction records and that of the barograph records. The smoothed barograph curves show quasi-periodic change with an approximate period of several days, and the smoothed compaction records show fluctuations with a similar period. However, the latter fluctuation is more or less out of phase with the former. On the other hand, the fluctuations in the smoothed compaction records seem to be linearly related with those in the smoothed curve showing the gradual change in the positions of the ground water level, observed at the corresponding compaction recorder station.

In order to make this relation clear, the hourly values of compaction, with the short period variations and the secular variation term linearly proportional to time eliminated, are plotted against the corresponding values of the smoothed ground water pressure. The results are shown in figure 4. Since the plot does not cover a sufficiently long period
the relation revealed in figure 4 may not be decisive. So far as the curve shown in figure 4 is concerned, the dependency on the relation of the compaction and decreasing ground water pressure is different from that of the swelling and increasing ground water pressure. If this relation is found in other cases, it is presumable that there may be retardation of strain yielded in the soil layer under the influence of alternate applications of positive and negative stresses. The soil mass under consideration may then be of the nature of a rheological substance.

4. The analyses were carried out using compaction records from the Kameido, Minami-sunamati, and Todabasi station in Tokyo, for the years 1956, 1961 and 1966, and using compaction records from Tidori-tyo (Kawasaki) in 1968. However, because the operation of the compaction recorders at No. 2 wells of the Kameido and Minami-sunamati stations began in the beginning and fall of 1961, the analyses of compaction records from these stations for the years 1956 and 1961 were impossible.

The average diurnal variations of compaction at these stations thus determined are approximately the same in their phases, but generally different in their amplitudes. The curves of average diurnal variation of compaction at these stations for the year 1961 are shown in figure 5.

![Figure 5. Mean diurnal variations of compaction at Todabasi (A), No. 2 well of Minami-sunamati (B), No. 1 well of Minami-sunamati (C), and No. 1 well of Kameido, for the year 1961. (Negative values represent swelling)](image-url)

The amounts of apparent swelling in the diurnal variation of compaction thus obtained for the stations mentioned above are given in table 1, together with the data of annual subsidence (annual amounts of compaction), thicknesses of soil layer, the heights of the ground water level (annual mean values), and annual fall of the ground water level, at respective observation stations.

As for the time variation, if any, of the apparent swelling of the soil layer, refer to the curves in figure 2. In this figure, the average diurnal variations of compaction at Kameido station are given referred to an arbitrary datum, and are converted into actual
TABLE 1. Apparent Swelling and Reference Data

<table>
<thead>
<tr>
<th>Amount of swelling</th>
<th>Thickness of layer</th>
<th>Annual Compaction</th>
<th>Height of G.W.L. (Annual Mean)</th>
<th>Fall of G.W.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kameido No. 1 Well</td>
<td>0.11 mm 64 m</td>
<td>74.4 mm</td>
<td>-37.9 m</td>
<td>3.9 m</td>
</tr>
<tr>
<td>Minami-sunamati No. 1 Well</td>
<td>0.12 mm 70 m</td>
<td>121.5 mm</td>
<td>-32.2 m</td>
<td>2.9 m</td>
</tr>
<tr>
<td>Minami-sunamati No. 2 Well</td>
<td>0.053 mm 130 m</td>
<td>109.0 mm</td>
<td>-33.1 m</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

amounts of swelling of about 0.06 mm in 1956, 0.11 mm in 1961, and 0.09 mm in 1966. In 1961, the annual compaction at Kameido station reached nearly a peak value and then declined. The amounts of apparent swelling seem to have followed the rise and fall of the amounts of yearly compaction.

5. If the apparent swelling is, caused mainly by the depression in the atmospheric pressure, it also may be influenced by the change in the height of the ground water level which too is affected by the change in the barometric pressure.

An analysis in this direction was made with the compaction records obtained at Tidori-tyo (Kawasaki) and at Sin-edogawa observation stations. On analyzing the compaction records obtained at Tidori-tyo station, for the sake of simplicity, the diurnal variation curve of compaction is worked out by taking average values of each hourly readings over a two month period, from September to October of 1968. This is done by putting the value of the 0-hour reading of each day equal to zero, in order to eliminate the effect of secular variation of compaction. The curve thus obtained is compared with the mean diurnal variation in barometric pressure and with the height of the ground water level observed at the same station. From the results, we notice discrepancies between the minima of these three types of curves. Therefore, the compaction, or strictly speaking, the height of the land surface, \( u \) may be expressed, as a function of atmospheric pressure and the height of the ground water level, by

\[
u = a h + b p + u_0,
\]

where \( u, h, p \) are respectively the hourly values of the height of the land surface recorded, those of the ground water level and the atmospheric pressure, and \( u_0, a, b \) are the constants to be determined statistically, using the data from the compaction records obtained at the Tidori-tyo station. The values of constants thus determined are \( u_0 = 104.89, a = 0.81, \) and \( b = -3.68, \) where the negative sign of \( b \) designates that the land surface moves upwards in response to the depression of the atmospheric pressure. The estimated compaction curve calculated on the basis of equation (1) is given by filled circles in figure 6. The empty circles in figure 6 show the actual observed diurnal variations in the height of the land surface.

Similar analysis was made of the compaction records obtained at the Sin-edogawa observation station. The compaction records used were obtained during October 1968, and the results are expressed by

\[
u = 2.54 h - 1.91 p,
\]

where the fluctuation in the height of the ground water level, \( h, \) is measured in cm. and those in the barometric pressure, \( p, \) in milli-bars. Although the magnitudes of the coefficients are different from those obtained with the compaction records in Tidori-tyo, Kawasaki, the phenomena of apparent swelling observed at stations in Tokyo and in Kawasaki are thus recognized as of similar nature.
Short period variation in land subsidence

FIGURE 6. Observed (empty circles) and estimated (filled circles) mean diurnal variations of compaction at Tidori-ryo, Kawasaki, during September to October, 1968. (Negative values represent swelling)

7. Apparent swelling of the surface soil layer is generally observed at various observation stations in Tokyo and Kawasaki, as previously described and is caused in the main by the fluctuation in the atmospheric pressure. However, several exceptional cases also are notable. One of them is the mean diurnal variation curve obtained from the compaction records from No. 1 well of the Minami-sunamati station for the 55-day period in the beginning of 1961. The curve is shown in figure 7a, in which the curves for different periods also are shown for reference. Another example is given in figure 7b, which shows

FIGURE 7a. Anomalous mean diurnal variation of compaction at No. 1 well of Minami-sunamati station, obtained for the first 55 day period of 1961. (Negative values represent swelling)
FIGURE 7b. Anomalous mean diurnal variation of compaction at No. 2 well of Kameido station, obtained for the first and second 55 day period of 1966. (Negative values represent swelling)

FIGURE 7c. Mean diurnal variation in the height of ground water level at No. 2 well of Kameido station
the diurnal variation curves deduced from the compaction records obtained at No. 2 well of the Kameido station for the first and second 55 day period of 1966. For reference, the curves designating the diurnal variation of compaction for similar periods of 1961 also are shown in the figure.

These exceptional diurnal variations seem to be more or less affected by the diurnal change in the heights of the ground water level. But there is a considerable phase difference between these two kinds of curves. The difference may be noted by comparing the curves in figure 7b with those of figure 7c, which show the curves of diurnal changes in the heights of the ground water level at No. 2 well of the Kameido station for the corresponding periods.

The diurnal variation in the compaction of the surface soil layer may then be regarded as having occurred under the influences of change both in barometric pressure and in the heights of the ground water level. This assumption, however, may not be a satisfactory approach to the solution of the problem in that the soil layer occasionally is unresponsive to the change in the barometric pressure. Because this assumption does not imply the source of change in the response characteristics of the soil layer, the problem should therefore be reserved for future investigations.

8. Lastly, additional remarks should be made on the results of tidal analyses in association with the compaction records. Among a number of tidal components, the $M_2$ component only is determined, and the results are given in the table below.

**Table 2. $M_2$ Component in Compaction**

<table>
<thead>
<tr>
<th>Station</th>
<th>Time Interval</th>
<th>Amplitude</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 Well, Minami-sunamati</td>
<td>January 1-February 27, 1961</td>
<td>0.0024 cm</td>
<td>208</td>
</tr>
<tr>
<td>No. 2 Well, Kameido</td>
<td>January 1-February 15, 1961</td>
<td>0.0019 cm</td>
<td>271</td>
</tr>
<tr>
<td>No. 2 Well, Minami-sunamati</td>
<td>May 23-September 4, 1961</td>
<td>0.0010 cm</td>
<td>271</td>
</tr>
</tbody>
</table>

The results show no remarkable change from those worked out with the compaction records obtained at the observation stations in the Yokkaiti land subsidence area [1], and those with the compaction records obtained at stations in Tokyo in 1934 [2]. The amplitudes of the tidal components in the compaction thus obtained are of lower order of magnitude in comparison with those which are recognized as caused by the fluctuations in the barometric pressure.

Tidal analyses on the compaction records obtained at stations in Tokyo, however, are in progress, and the further results will be published when the analyses have been completed.

In conclusion, the authors would like to express their sincere thanks to the members of the Tokyo Institute of Civil Engineering for their kind assistance in the preparation of this paper.

**Références**