62. *On the Sinking of the Earth's Crust in the Eastern Part of the City of Tokyo.*

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1. As already reported[1], the surface of the earth's crust in Honzyô, Hukagwa, and neighbourhood, i.e., the eastern part of Tokyo, was found to have subsided considerably during the last ten years or so. The amount of sinking since 1923, was found to be 1·6 m at most. It might therefore be of interest to inquire into various causes that are believed to brought out this subsidence.

Before dealing with the causes of the sinking, the results of the preceding studies will be summarized briefly.

(i) The bench–marks in Tokyo and vicinity that have subsided

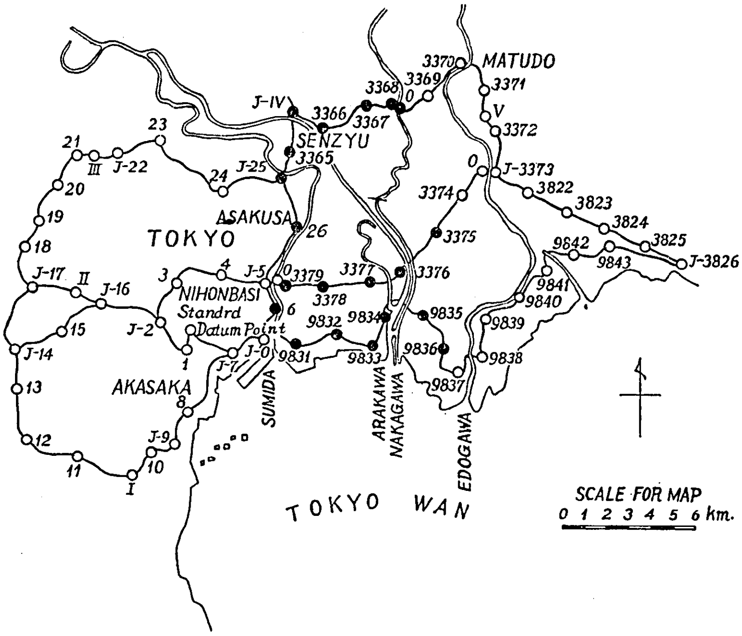

Fig. 1. Distribution of bench-marks.
Marks • denote the bench-marks subsided remarkably.

1) N. MIYABE, *Bull. Earthq. Res. Inst.*, **10** (1932), 844~857; **13** (1935), 587~591.

remarkably during these ten years are indicated in Fig. 1 by ●, from which it will be noticed that the region of greatest subsidence lies between the Sumidagawa and the Yedogawa, the northern boundary of which approximately coincides with the line connecting Senzyu and Matudo. The northern part of Asakusa, near Senzyu; the neighbourhood of Hama-tyô, Nihonbasi; the Tameike valley, Akasaka; and the zone from Marunouti to Kanda are also zones of subsidence, although the extent to which they have sunk are not so large as in Honzyô and Hukagawa[2].

(ii) From the vertical displacements[3] of bench-marks that are believed to have occurred during the period from Nov. 1929 to Feb. 1932, the earth's crust in Honzyô and Hukagawa which seems to consist of several crustal blocks, tilted and subsided considerably, as has been shown in the preceding paper[4].

(iii) The velocities of sinking of many of the bench-marks situated in this region have accelerated up to the present; several in fact appear to have reached maximum, although the general tendency of the velocity of sinking to increase does not seem to have stopped.

(iv) It is also noticed that, in general, the amounts of subsidence

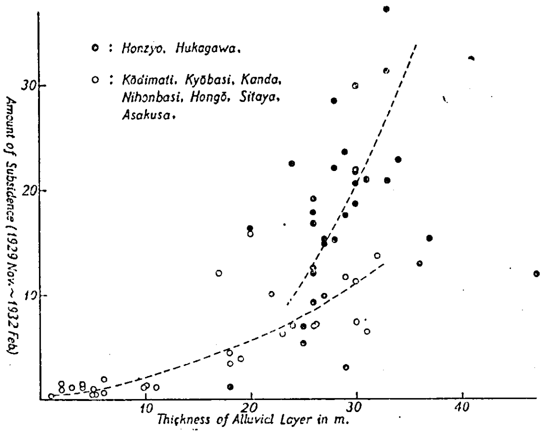

Fig. 2. Amounts of subsidence and thickness of alluvial layer.

are greater where the alluvial surface layer is thicker as shown in Fig. 2. This fact suggests that some change in the surface layer might have greatly affected to brought out the subsidence.

2. As to the explanation of this sinking phenomenon, it is regrett-

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2) N. MIYABE, *Proc. Imp. Acad.*, **9** (1933), 588~591.

3) The data of vertical displacements of bench-marks utilised in this study were obtained by relevellings made by the Tokyo municipality.

4) N. MIYABE, *loc.cit.* 1).

able that, with no other data in our possession expecting those relating to the deformation of the earth's surface, there is no means of deciding which is the most plausible one among the several possible causes of the subsidence, as will be discussed in the following paragraphs.

Some attribute the sinking merely to settling of the superficial layers of filling earth that was used in the reclamation of this district to a thickness of about 1~3 m. If so, then since the subsidence of the earth's crust in this district amounts to more than 1 m since the time of the Kwantô earthquake of 1923, the layer of filling earth should have compressed to about half its original thickness or it should have disappeared, which seems hardly possible.

A possible cause of sinking was dealt with in the preceding paper[5], wherein we calculated the probable extent of sinking for the case in which the surface layer of the earth's crust is regarded as an elastic substance and also for the case in which it is regarded as sandy material, due to surface load of the filling earth. The result was that the amount of sinking estimated in neither of the two cases was large enough to account for the remarkable extent of sinking that occurred. Moreover, the slow rate and particularly the acceleration of the sinking cannot be explained by elastic or plastic deformation due to surface load of reclamation earth.

We shall next consider other possible explanations of the remarkable crustal depression.

3. It was already noticed that there are several wells in Hukagawa charged with methane gas[6], which generally issued from depths of about 30 m or more, and which has continued with considerable pressure for the last ten years or so. As for some gas-charged wells, it was observed that the pressure of the gas diminished considerably since the time of the Kwantô earthquake of 1923 from what it was before the event.

This fact may suggest the existence of a component of sinking as the result of decrease in pressure of underground gas held between impermeable layers situated at a depth of several tens of metres.

In estimating the amount of sinking of ground surface as the result of reduction in pressure of the underground gas, certain calculations made by Drs. Sezawa and Nishimura may be used, the portion applying to this case being of the form

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5) N. MIYABE, *loc. cit.*

6) N. MIYABE, *Proc. Imp. Acad.*, **7** (1931), 344~347.

$$u=\frac{\Delta p}{\mu}\frac{b}{a}\frac{\vartheta_0}{\vartheta_0'},$$

for maximum displacement in the simplest form of deformation, and in which a, b, are the vertical and horizontal dimensions respectively, μ the rigidity of the disturbed surface layer, and Δp the change in pressure, the layer being assumed to be incompressible and elastic. We consider the case when the value of u for the case when $b \gg a$ or $b \doteqdot 100\ a$ is of the order of 1.

For an actual case, the change in pressure, Δp, of the underground gas may be estimated to be nearly 3/10 of the atmospheric pressure, which is derived from the fact that, before the earthquake, the underground water was discharged by the pressure of the gas to a height of about 12 feet above the ground. By substituting these numerical figures, the extent of ground sinking due to exhaustion of underground gas is estimated to be of the order of 1 mm, when μ is assumed to be of the order of 10^8 c.g.s., the result however is negligible when compared with the actual subsidence.

4. The residents of Honzyô, Hukagawa, Sunamati, etc., that is, in the Kôtô district of Tokyo, have noticed a remarkable drop in the level of the water of the wells.

Although the exact extent to which the water level has sunk cannot be estimated with sufficient accuracy, it seems to be of the order of several metres compared with the level before the earthquake of 1923. Since clay contracts when dried or unhydrated, the surface layer of the earth in this region, which is composed of clay and sand to a depth of about 30 m, might have suffered vertical contraction owing to lowering of the underground water level.

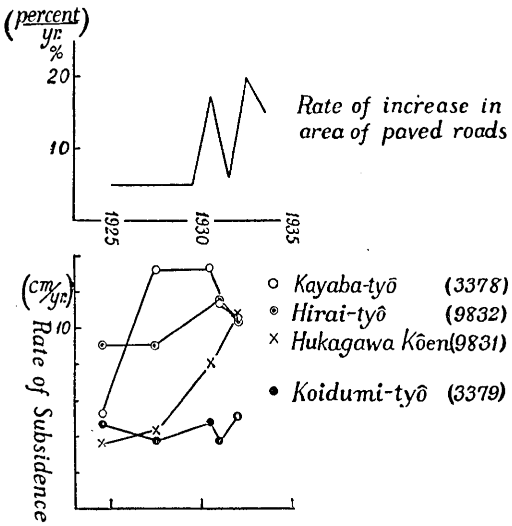

Fig. 3. Change in rates of subsidence and of increase in area of paved roads, in Tokyo.

In our laboratory experiments[8], the contraction in linear dimen-

7) K. SEZAWA and G. NISHIMURA, *Bull. Earthq. Res. Inst.*, 8 (1930), 13.

8) The method of the experiment very simple, that is, the volume and weight of the mass of clay contained in a meter glass are messured once a day.

sions of a mass of clay when unhydrated amounted to several tens percent as shown in Fig. 5, in which the percent contraction of the clay mass is plotted against the decrease in water contents. If this result could be applied without any modification to explain the actual extent of the crustal subsidence in Honzyô and Hukagawa, the lowering of the underground water level should be of the order of 10 m, which however seems to be too much.

The underground water level will naturally remain at constant depth so long as the supply and the outgo of the water are in equilibrium.

But with disturbance of water supply or increase in water consumption (plus seepage) the level of the underground water would sunk, resulting in another equilibrium level lower than before[9].

The disturbance in water supply would arise from congestion of houses as the result of city planning, the drainage system becoming more regular, and the roads becoming all paved, whereas consumption of the underground water would increase with increased industrial activities.

Hence, as the sinking of the ground surface is in positive correlation with the sinking of the level of the underground water, it may also be expected that the sinking will go on along with increase in the area of paved roads or with decrease in the area of unpaved roads, which may be taken as a measure of the development of the city. In Fig. 3, the changes in rate of vertical displacement of a

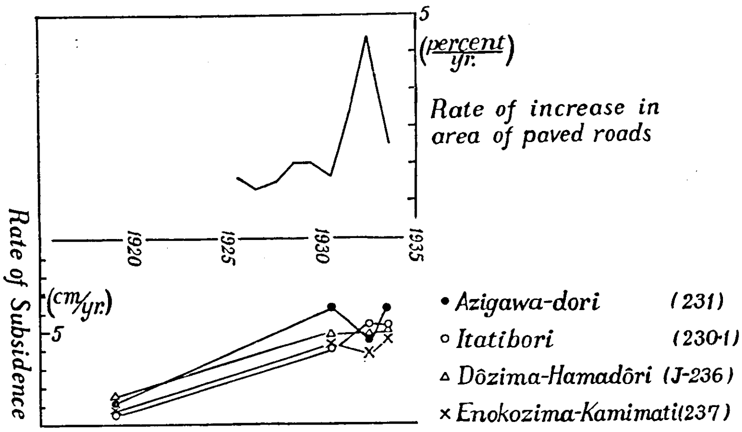

Fig. 4. Change in rates of subsidence and of increase in area of paved roads, in Osaka.

number of bench-marks, together with changes in the area of paved

9) When consumption increases and the level of the underground water is lowered, the gradient of the level increases. Hence, the supply of underground water will also increase so that the level stays at a lower position of equilibrium.

roads, in Honzyô and Hukagawa are shown. The two curves are fairly parallel to each other.

A similar relation is also shown between vertical earth movements and the areal percentage of unpaved roads in Osaka, as shown in Fig. 4.

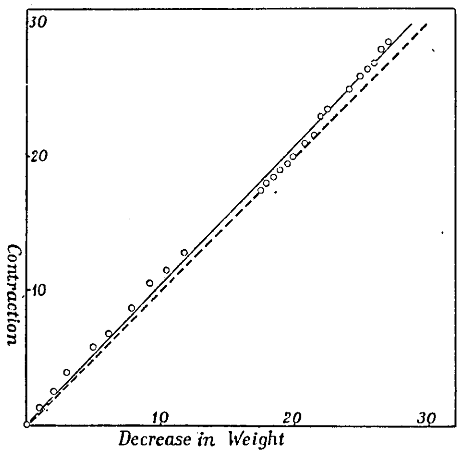

Fig. 5. Contraction of a mass of clay by being unhydrated.

5. From geological survey made by the Reconstruction Bureau[10] in which data obtained by borings were used, it was found that the surface layer of the earth's crust in Honzyô, Hukagawa and neighbourhood consists of alluvial deposits to a depth of about 30 m, which is very much thicker than the same layer in the region west of the Sumidagawa, as also that these layers of alluvial deposits are mostly sandy clays or clayey sands.

It also came to light that about 380 years ago the shore line in Hukagawa was about 1 km north of, but parallel to, the present shore line, all of which shows that the alluvial layers in this region were deposited only very recently. From these facts, it is suggested that the thixotropic property of the alluvial deposits, or the phenomena of quick sand, as pointed out by Prof. T. Terada[11], might have played an important part in causing the sinking of the earth's crust in the present case. The thixotropic property of a sand mass, according to H. Freundlich[12] is geratly affected by any increase in the amount of electrolyte held in the penetrated water.

Since the sandy clay layer of the alluvial deposits is regarded as thixotropic, the looseness of the sand pile in the water may also vary with the amount of electrolytes contained. A simple experiment was made to measure the looseness of a sand pile in water containing various quantities of $MgCl_2.6H_2O$. The looseness of the sand pile was measured by the extent to which it settled as the result of trains of feeble shooks given to it. The results are shown in Fig. 6, in which the extent of settling are plotted against the concentration of $MgCl_2.6H_2O$

10) Reconstruction Bureau, "The Results of Geological Surveys in Tokyo and Yokohama", (Tokyo, 1925), (in Japanese).

11) T. TERADA, *Bull. Earthq. Res. Inst.*, **13** (1935), 562~568.

12) H. FREUNDLICH, *Proc. Faraday Soc.*, **31** (1935), 769~773.

in the penetrated water.

From this figure, we notice that a very small quantity of electrolyte is sfficient to consideraby increase the looseness of the thixotropic sand clays.

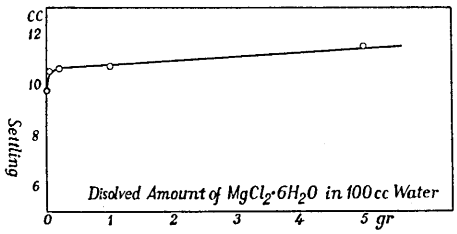

Fig. 6. Change in amount of settling of loosely piled sand mass in electrolytic solution due to concentration.

When the level of an underground water that has been kept in equilibrium with the sea water penetrates the sand layer in the manner shown schematically in Fig. 7, the level of the underground water is lowered by x m, that is to say, the boundary of the sea water AC′B′ in Fig. 7 will be elevated by y m, which is related to x so that

$$y=\frac{\rho_0}{\rho-\rho_0}x,$$

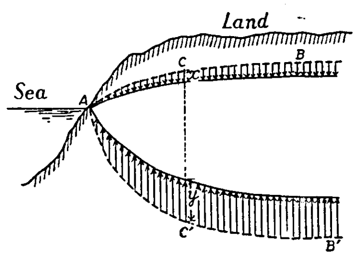

Fig. 7.

where ρ_0 is the density of plain water, that is, 1, and ρ is the density of sea water, which is slightly greater than 1.

Thus the average amount of electrolyte in the penetrated water may increase[13], in consequence of which the thixotropy of the layer of sandy clays may be affected. Thus the lowering of the level of

13) A sample of water taken from a well in Sunamati in the region under consideration was subjected to chemical analysis, with results as shown in the following table. Analysis by Mr. S. Tanaka.

Ions	Quantities in 1 litre water
K	0·0945 gr.
Na	1·1656
Ca	0·3594
Mg	0·1969
Cl	2·5262
SO_4	0·0658
HCO_3	0·8917
H_2SiO_3	0·0461
Total	5·5417
Oxygen required	0·0070

The depth of the bottom of the well is 3m and that of the surface of the water 22 cm from the ground surface. The temperature of the water was 17°C, while the open air temperature was 26°C.

The result of this analysis shows that the water of this well contains more ions of Na, Mg, Ca, etc. than those of ordinary underground water, which is regarded as owing to penetration of more sea water.

the underground water is instrumental in settling still further the surface layers.

Judging from the experiment, further settling (a few percent) due to changes in concentration of the electrolyte in the penetrated water is to be expected. As the thickness of the surface layer in Honzyô and Hukagawa is about 30 m, the sinking of the ground surface thus caused is expected to be several tens of cm. Actually, however, the amount of sinking expected from this cause may be reduced to a certain extent, for the reason that the underground water levels at various depths are found to be seperated by impermeable layers, so that the lowering of one of these underground water levels may not always permit the penetration of the sea water, that is, the average electrolyte content does not always increase, as shown in the schematical figure of Fig. 7.

6. The foregoing possible causes of sinking of the earth's crust in Honzyô and Hukagawa are now summarized.

(i) Surface load of reclamation earth.

(ii) Reduction in pressure of the underground gases.

(iii) Contracion of the surface layer of the soil caused by lowering of the underground water level.

(iv) Effects of increase in concentration of electrolytes in the underground water on the thixotropic sand layer, caused by penetration of the sea water.

These are all equally probable explanations of the phenomenon, and yet the extent of sinking that could be attributed to any one of them is insufficient to explain the actual subsidence. It is therefore my opinion that these four causes are operating jointly with the crustal deformation generally going on in much wider areas such, for example, as those recognized as block movements[14] and the general subsidence in the alluvial plains remarked by Dr. C. Tsuboi[15].

In conclusion, the writer wishes to express his sincere thanks to Professor Torahiko Terada for his valuable suggestions given through the present investigation.

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14) N. MIYABE, *loc. cit.*

15) C. TSUBOI, *Jap. Journ. Astr. Geophys.*, **9** (1933), 95.

62. 江東地域に於ける地盤の沈下

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本所深川等，所謂，江東方面に於いて，地盤の沈下の著しい事は既に知られてゐる所である．

本論文では，その沈下の理由について考へ得べきことを二三擧げてみたのであるが，要するに今日では，その何れの理由が勝つてゐるかを判定する事が困難である．

沈下の量と，表面の沖積層の厚さとの關係を調べてみると，今までのところでは，大體に於いて，沖積層の厚い場所程沈下量が大であるといふやうな傾向も見えるので，表面の沖積層の收縮などゝ言ふことも，無視し得ない沈下の理由の一つであらうと思はれるが，それ許りであるとも言へないやうである．

尙，研究が進められてゐるから，今後の成果に期待するより外はない．