A NOTE ON LAND SUBSIDENCE IN JAPAN

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PREFACE

There are many causes making the land surface subside. Tectonic movements of the earth such as earthquakes and basin making movements, and underground solution or erosion of calciliferous rocks are natural ones. On the other hand, there are many artificial causes, e.g. compaction of sediments by loading over soft clayey deposits or drainage from deposits with high water contents, underground mining of solid minerals, withdrawal of fluids etc. Among these processes, land subsidence is defined in Japan as a phenomenon of making the land surface subside due to withdrawal of ground water and natural gas. Withdrawal of oil is also taken for one of the causes of land subsidence, but such process has not been reported in Japan.

The areas where are likely to subside due to withdrawal of ground water and natural gas are the plains composed in general of thick unconsolidated materials such as the Alluvium and the Upper Diluvium. About 70% of Japanese population is living in the plains and almost all industrial regions stand there. Especially, the deltaic lowlands are densely inhabited as well as a number of the industrial facilities are concentrated. It is estimated that population density per km^2 in the deltaic lowlands exceeded 1,000 in 1970, and more than 90% of the national product of Japan is yielded in the deltaic lowlands. The reasons why land subsidence is one of the serious social problems in Japan are reflected in intensive land use of the deltaic lowlands. Also, it increases seriousness of the influences of land subsidence that the Japanese Islands are used to be attached by the typhoons bringing the heavy rains and the storm surges.

OUTLINE OF HISTORY OF LAND SUBSIDENCE IN JAPAN

Before the Second World War

Since the first precise levelling was carried out in Tokyo and its vicinity in 1883, a precise relevelling was often repeated. As a result, it was clarified in the begining of the 1900's that the ground height in the deltaic lowlands is lowering gradually. Lowering rate, however, was too small to regard the phenomenon as land subsidence. Conspicuous fall of the ground height with the rate of more than several ten mm per year was found by the precise relevelling after the Kanto Earthquake of 1923. But several geophysicists interpreted that such land subsidence was occurred by crustal movement associated with the earthquake (for example, Imamura, 1925).

A precise levelling which was carried out several years later revealed that extraordinary fall of the ground height had continued in the Tokyo Lowland (Imamura, 1931). In addition, obvious land subsidence was pointed out in the deltaic part of the Osaka Plain by A. Imamura, too. But he regarded these phenomena as acute crustal movement concerning a fault or seismic activity.

As the land subsidence continued, the iron pipes of wells, the foundations of long bridges and big buildings began to protrude from the land surface. Some geophysicists became conscious of the fact that a cause of land subsidence consists in decrease in thickness of the sediments within the casing depth of wells. N. Miyabe (1937) set up an observation well recording the magnitude of protrusion of an iron pipe. In the deltaic part of the Osaka Plain, K. Wadachi and T. Hirono (1939) tried to observe the amount of land subsidence on the basis of same method as used by N. Miyabe. They clarified that land subsidence, which is caused by compaction of the soft clayey deposits, is a quite different phenomenon from crustal movements. Analysing a relation existing between the amount of fall of ground water level and that of land subsidence, they also came to an opinion that the soft clayey deposits are forced to compact due to withdrawal of ground water. But social disruption with the Second World War made the studies be impossible to be continued, before the valuable outcomes were supported wholly.

After the Second World War

Withdrawal of ground water was forced to stop in the industrial regions of both Tokyo and Osaka, where were destroyed by bombing during the last period of the Second World War. As a result, land subsidence came to a sudden stop and land surface even upheaved slowly in some areas. When the causes of land subsidence were discussed again later, this fact supported solidly an opinion that main cause of land subsidence is withdrawal of a large volume of ground water. As the industrial regions were reconstructed, land subsidence resumed the activity and became to progress faster since 1950.

As for a casing depth of wells, it was generally shallower than 50 m until about 1950, but it became deeper and deeper, for much more ground water was needed to satisfy water demand for industrial uses at a low price. Most of wells were likely to have the casing depth of more than 100 m in 1955. It was pointed out in 1952 that the iron pipes of observation wells, which were set in the Tokyo Lowland before the Second World War, began to subside. That demonstrates an increase of the depth within which the deposits were forced to be compacted.

Since adoption of the policies for industrial development of Japan in 1955, land subsidence has occurred in such areas as Niigata in the Niigata Plain, Chiba in the southern part of the Tokyo Lowland, some paddy fields of Saga Prefecture in the Shiroishi Plain etc. For instance, the deltaic part of the Niigata Plain, in where existence of land subsidence was detected in 1956, subsided 540 mm from September 1959 to next September.

In connection with a countermeasure of land subsidence in the Niigata Plain, a cause of land subsidence was discussed again. The discussion concluded that the cause of land subsidence in the Niigata Plain consists in withdrawal of natural gas and the associated water (Nakano and Takehisa, 1960). It means that the land surface was forced to subside due to withdrawal of the fluids laying at the depth of more than several hundred or thousand meters.

At that time, existence of the land below sea level was mentioned in some deltaic lowlands. The first figure which was obtained by T. Nakano, one of the authors, in 1959 showed that the area of the land below sea level covered approximately 38 km^2 in the Tokyo Lowland. After the deltaic part of the Nobi Plain was inundated vastly by the destructive Isewan Typhoon of 1959, the ground heights were surveyed precisely. The levelling in the inundated area proved that there exists the land below sea level with the area of more than 200 km^2. Not only in the Tokyo Lowland and the Nobi Plain, but also in the Plains of Niigata, Osaka and Kochi the lands below sea level were detected one after another.

On the other hand, control of uses of ground water has begun to be taken into account. A law on industrial water supply was enforced in 1956 to execute the official regulation of withdrawal of ground water for industrial uses on the legal basis. After that, a law concerning the regulation of withdrawal of ground water which is used in the buildings for a purpose of cooling or heating became operative in 1962. Based on these laws, regulation of withdrawal of ground water was enforced in several cities, e.g. Kawasaki City located in the deltaic lowland of the River Tama in the southern part of the Kanto Plain, Cities of Osaka and Amagasaki located in the Osaka Plain, Kawaguchi City located in the northern part of the Tokyo Lowland and Tokyo Metropolis.

Land subsidence in the last decade

The main cause of land subsidence before 1960 was withdrawal of ground water for industrial uses. Withdrawal of ground water used in the buildings in the business districts or the shopping districts was the secondary cause of land subsidence. Withdrawal of natural gas in the Niigata Plain and of ground water for agricultural uses in the Shiroishi Plain was known as the heterogeneous causes of land subsidence.

Economic growth in Japan was noteworthy in the 1960's. Population has been concentrated into the large cities and the urbanized areas have spread into the rural areas around the large cities such as Tokyo and Osaka. But development of surface water did not keep pace with the growth of the industrial regions or the spread of the urbanized areas. Accordingly, water supply even for domestic uses should be depended on ground water as well as for industrial uses. Moreover, ground water has begun to be used to melt snow on the roads and the rails in some of heavy snowy districts along the coast of the Japan Sea. Though there was an example of land subsidence due to withdrawal of natural gas in the Niigata Plain, the magnitude of land subsidence was increased conspicuously in the coastal region of Chiba Prefecture due to withdrawal of a large quantity of natural gas and the associated water (Nakano, 1974).

Uses of ground water were of many sorts and amount of demand was far increased in the 1960's. Also, occurrence of land subsidence was not limited in the industrial regions, but was extended into the agricultural regions, the residential districts etc.

Based on the results of the first order levelling carried out in the whole country, the Geographical Survey Institute, the Ministry of Construction, manifested 32 areas in 1971, in where the land surface has been subsided more than the supposed amount of the crustal movement. According to a research which was performed by the authors and their collaborators in 1972, existence of land subsidence was confirmed in 46 areas in number. The authors added two areas by a complementary research of 1975. These areas are shown in Fig. 1.

The lands below sea level were discovered newly in the Ise Plain, the Shiroishi Plain and the coastal lowland of Chiba Prefecture. The lands below sea level in the Tokyo Lowland and in the Plains of Nobi and Osaka continued to extend at that time. According to the report of the Environmental Agency of Japan, the area of land below sea level in Japan covers 1,168 km^2 in 1975, among which the area of 478 km^2 exists in the Nobi Plain. The report stated that land subsidence spreads over the area of 6,680 km^2, and population living there is estimated to exceed 38 millions.

Thus, land subsidence is progressing in many plains of Japan. If the plains in where the ground water level is falling are taken into consideration, most of all plains and basins of Japan require a proper scientific care.

Concerning the countermeasures of land subsidence, it is important to decrease the volume of water supply relying on ground water. But development of surface water is not

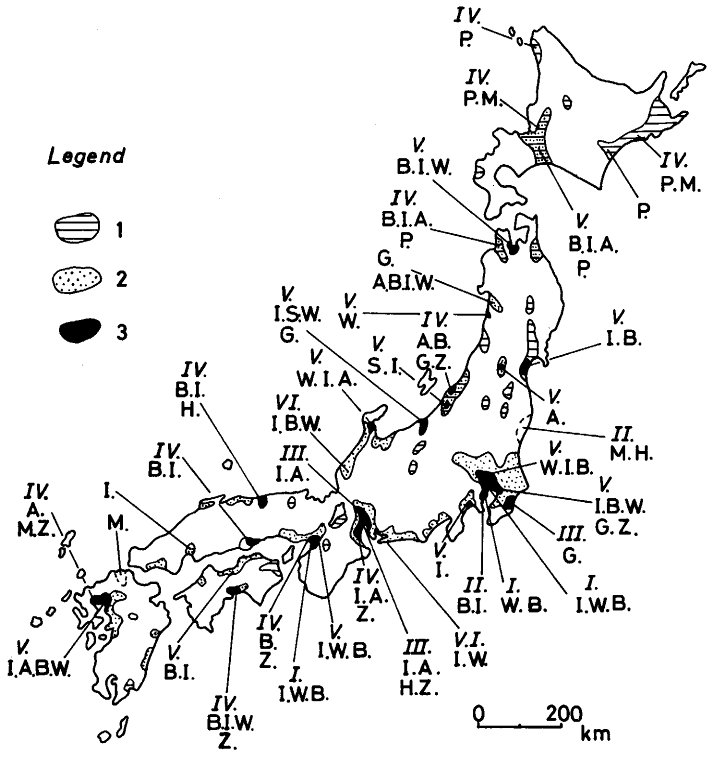

Fig. 1 Distribution and some characteristics of areas in where land subsidence have occurred.

Situation of land subsidence : 1:Plains and basins where proper scientific care is required, 2:Plains and basins in where land subsidence have occurred, 3:Areas in where more than several ten milimeters of land subsidence have occurred;
The year when land subsidence occurred : I:Before 1935, II:Before 1945, III:Before 1950, IV:Before 1960, V:Before 1970, VI:After 1970;
Purpose of ground water use : I:Industrial use, A:Agricultural use, W:Supply through waterwork (mainly domestic use), B:Using in building, S:Melting snow;
Other characteristics : Z:Land below sea level distributes, G:Natural gas is withdrawn, P:Peaty land exists, H:Hotspring exists, M:Influenced by mining of coal.

likely to catch the magnitude of water demands. Moreover, concentration of the industries and population are restricted obstinately in the metropolitan regions of Tokyo, Chukyo and Kinki, in where land subsidence is progressing and the land below sea level is stretching. Accordingly, increase of water demands is so conspicuous in these regions that an absolute volume of surface water is thought to be insufficient to satisfy water demands.

LAND SUBSIDENCE IN THE TOKYO LOWLAND

Landform and subsurface geology of Tokyo

A landform of Tokyo located in the southwestern part of the Kanto Plain is classified roughly into the Musashino Upland and the Tokyo Lowland. The former borders on western frontier of the latter (Fig. 2).

The Musashino Upland with the height of 20 to 50 m consists of the terraces originating in the coastal plains and the alluvial fans formed during the end of the Pleistocene. The upland is composed of the marine sandy deposits and the fluvial gravels covered with tephra named Kanto Loam with the thickness of 3 to 9 m. An eastern frontier of the Tokyo Lowland is bordered by the Shimousa Upland which has same origin as the Musashino Upland (Fig. 2).

The Tokyo Lowland was one of the inlets opening to Tokyo Bay at about 5,000 to 6,000 years B.P. or at the highest stage of sea level of the Yurakucho transgression which is related to the Flandrian transgression in Europe (Fairbridge, 1961). The inlet was buried with the deltaic deposits with the pace of gradual falling of sea level during these several thousand of years. In addition, the southern part of the Tokyo Lowland was emerged by reclamation and filling-up since sixteenth century. Most of all parts of the Tokyo Lowland have originally the ground height of only less than 2 m.

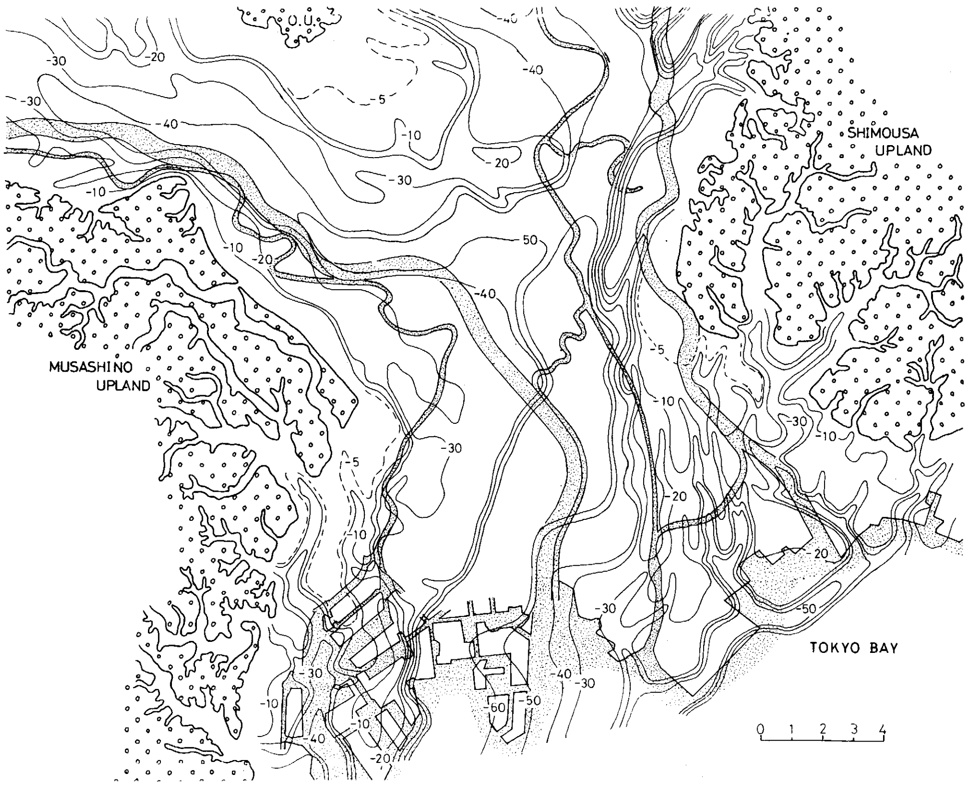

Fig. 2 Basal landform of the recent deposits (heights in meters).
O.U. : Omiya Upland.

The upper part of the deposits distributed in the Tokyo Lowland is the recent ones. The recent deposits are defined in this paper as the deposits which were formed since the maximum stage of Würm Ice Age of 18,000 to 20,000 years B.P. and were composed of the latest formation. They include, therefore, a part of the late Pleistocene deposits as well as the Holocene ones.

A basal landform of the recent deposits was reconstructed by scrutinizing many bore hole records in the Tokyo Lowland (Fig. 2). Three distinct buried platforms are detected in Fig. 2. The lowest platform is a buried valley floor with a height of lower than –60 m in the southern part of the Tokyo Lowland and of –50 m in the northern part. The buried valley floor which was formed by the maximum stage of Würm Ice Age is able to be traced into Tokyo Bay and is named the Paleo Tokyo River. It continues to a continental shelf in the Pacific Ocean through a submarine canyon in the Uraga Strait connecting Tokyo Bay to the ocean.

The middle platform of approximately –30 m in height is pointed out in the central part of the Tokyo Lowland. Small distribution of the middle platform with somewhat lower height can be seen in the vicinity of river mouth of the Ara River. They can be regarded as the buried fluvial terraces formed during the late Pleistocene, because they consist of gravelly deposits overlain by tephra, Kanto Loam, with certain thickness.

The upper platforms are distributed along the periphery of the Uplands of Musashino, Shimousa and Omiya. They are believed as the buried abrasion platforms which are able to be classified into two parts; the lower with the height of about –20 m was formed at about 10,000 years ago when an oscillation of sea level occurred during the transgression stage after the maximum stage of Würm Ice Age, and the upper of 0 to –10 m in height was formed at around the highest stage of sea level of the Yurakucho transgression.

The recent deposits of the Tokyo Lowland are classified into two members, the upper and the lower, as in the other deltaic lowlands of Japan.

The lower member consists of the gravelly deposits and an alternation of sandy layers and clayey ones over them. The gravelly deposits are the river bed gravel accumulated in the buried valley bottom of the Paleo Tokyo River and its branches. The alternation seems to be composed of two parts. The lower comprises well consolidated sandy deposits with the N-value of standard penetration test of 50 to more than 100 and the consolidated clayey deposits with the N-value of 10 to 20. The upper consists of the layers of somewhat looser sand and soft clay. The top of the lower member has a height of –30 to –40 m in the Tokyo Lowland. Accordingly, thick distribution of the lower member is limited in the buried valley bottom.

The upper member of the recent deposits is divided into two parts, too. The lower part is composed of clayey or silty deposits accumulated in the bay bottom. They are of high water content and very soft with the N-value of 0 to 3 and have 20 to 30 m in thickness. They distribute broadly in the Tokyo Lowland except on the upper platform developing higher than –5 m in height. The upper part is the deltaic sandy deposits with the maximum thickness of about 8 m and with the N-value of 3 to 20. It occupies the uppermost part of the deposits in the Tokyo Lowland except artificial filling.

A further detailed analysis on distribution and evolution of the recent deposits in the Tokyo Lowland was referred previously by I. Matsuda (1974), one of the authors.

Vicissitude of land subsidence of Tokyo

Vicissitude of land subsidence of the Tokyo Lowland is able to be read in Fig. 3 showing the accumulated amount of land subsidence recorded by the precise relevellings of the bench

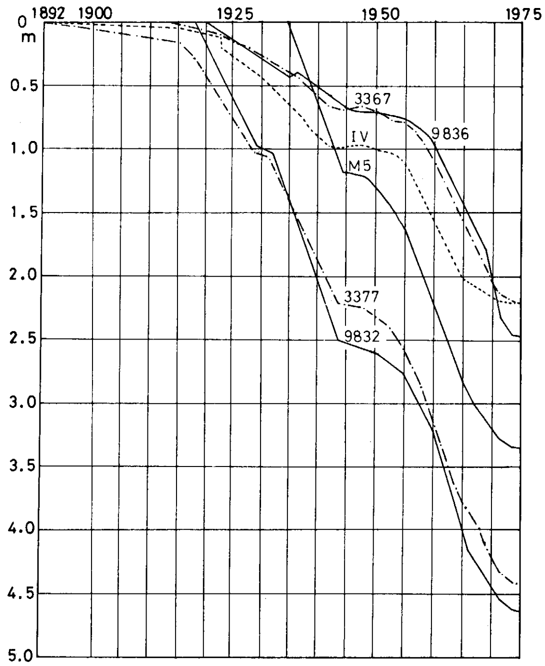

Fig. 3 Integrated land subsidence in the Tokyo Lowland.

marks. The location of the bench marks are exhibited in Fig. 4. Land subsidence with the total amount of about 170 mm was recorded on the bench mark of no. 3377 from 1892 to 1916. An annual mean value of land subsidence, therefore, was only about 7 mm during this period, most of which is thought to be the result of natural compaction of soft recent deposits and partly due to downward crustal movement.

It was one of the result of a precise relevelling carried out after the Kanto Earthquake of 1923 that conspicuous land subsidence was detected first. The fact, however, was regarded as the crustal movement concerned with the earthquake. An area with the subsiding ratio of more than 150 to 170 mm per year appeared in the beginning of the 1930's. Land subsidence became more rapidly in the end of same decade when the largest value of land subsidence before the Second World War was recorded. Based on the fact that the accumulated amount of land subsidence exceeded 2 m in the end of the 1930's, it can be pointed out that the land below sea level was borne by that time because of the existence of broad area with the original height of lower than 2 m in the southern part of the Tokyo Lowland.

Land subsidence continued to be of much amount until the end of the Second World War. Magnitude of land subsidence was less in the northern part than in the southern part of the Tokyo Lowland during these days (Nakano et al., 1969 and Nakano, 1970).

Tokyo suffered bombing during the end of the Second World War and the industrial regions were destroyed. Then, land subsidence was stopped, for the amount of withdrawal of ground water was forced to decrease due to destruction of the factories.

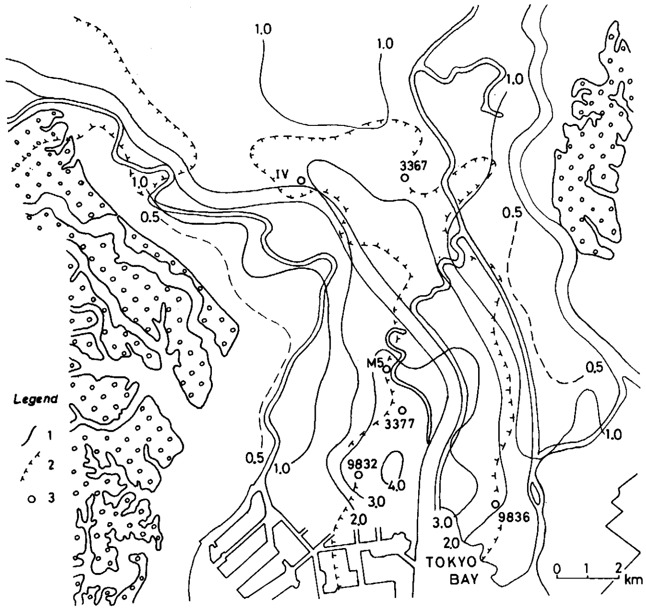

Fig. 4 General outlook of accumulated amount of land subsidence in the Tokyo Lowland since 1929.
1:Accumulated amount (in meters) of land subsidence since 1929, 2:Boundary of area subsided more than 100 mm in 1961, 3:Location of bench marks shown in Fig. 3.

As the industrial regions were reconstructed after the Second World War, land subsidence was resumed and progressed faster than before the war. Land subsidence was recorded almost all-over the Tokyo Lowland in 1961 when the area of 74 km^2 was subsided more than 100 mm (Tab. 1). Conspicuously, the region with such amount of subsidence was not only extended south to north along the both banks of the Ara River in the Tokyo Lowland, but also invaded into the Musashino Upland (Fig. 4).

The amount of land subsidence decreased in the Tokyo Lowland except the southernmost part after 1961 when regulation of withdrawal of ground water was started. A ground water level began to rise in 1966.

A horizontal distribution of the accumulated amount of land subsidence only since 1929 is able to be drawn, for many new bench marks were set in this year in order to extend the area to be measured. Accordingly, though the large accumulated value of more than 4 m was recorded on the bench marks of nos. 3377 and 9832 (Fig. 3) which were set in the southern part of the Tokyo Lowland before 1929, their values read from the isoplethes in Fig. 4 are less than 4 m. In addition, Fig. 4 only shows a general situation of land subsidence, because many bench marks were destroyed by bombing in the Second World War and the amount of land subsidence during the periods lacking the records of relevelling were estimated. In spite of the fact, it can be pointed out that the area in where much amount of land subsidence was recorded coincided with the area over the buried lower platform. On the other hand, land subsidence of the total amount of only less than 0.5 m was recorded over the shallower part of the buried upper platforms with the height of higher than –10 m.

Further study on the migration of the core-areas of land subsidence of more than

Table 1 The area of subsided land in Tokyo

Year	More than 50 mm	More than 100 mm
1959	121 km^2	43 km^2
1960	146	53
1961	173	74
1962	156	64
1963	160	69
1964	167	42
1965	131	24
1966	127	12
1967	121	18
1968	164	30
1969	133	20
1970	165	33
1971	109	16
1972	50	4
1973	24	15
1974	33	6
1975	0	0

100 mm per year, was reported previously by the authors and H. Kadomura (Nakano et al., 1969).

Regulation of withdrawal of ground water

Materialization of some plans to prevent land subsidence became possible with a help of establishment of the law on industrial water supply in 1956. In 1961, drilling of new well to pump up ground water for industrial uses was subject to restriction on the depth of the strainers and an area of a bore of iron pipe in the southern part of the Tokyo Lowland.

In accordance with the establishment of the law concerning regulation of withdrawal of ground water used in the buildings, drilling of new well to pump up ground water for such purpose was restricted in 1962. The application of this restriction was extended in 1965 to the wells which were constructed before 1962. As a result, withdrawal of ground water used in the buildings from the aquifers laying within the depth of 550 m or 650 m has been prohibited in Tokyo.

When withdrawal of ground water for industrial uses is subject to restriction, it is legislated to supply substitutive water by the law on industrial water supply in 1956. In order to regulate withdrawal of ground water for industrial uses, two industrial water-works were constructed. One is the Koto Industrial Waterwork which was accomplished in 1964 to supply water to the factories located in the south-central part of the Tokyo Lowland. The another is the Johoku Industrial Waterwork constructed in 1971 for the purpose of supplying water to the factories of the northern part of the Tokyo Lowland. Following the commencement of water supply through these industrial waterworks, withdrawal of ground water for industrial uses has been prohibited within the depth of 550 m both in the northern part and south-central part of the Tokyo Lowland.

There is no law or ordinance to regulate withdrawal of natural gas and the associated water and that is another cause of land subsidence in the Tokyo Lowland. Thus, the Tokyo Metropolitan Government bought the mining right in 1972 in order to stop withdrawal of natural gas and the associated water.

INFLUENCES OF LAND SUBSIDENCE

If it is regarded as direct damage that the buildings, bridges etc. have gone out of repair due to compaction of the deposits within the depth of piles, the problems with decreasing of the ground height may be taken for indirect damage caused by land subsidence. The latter is more serious than the former.

As mentioned above, the land below sea level of the Tokyo Lowland came into existence by about 1935. It continued to expand gradually in the central part of the Tokyo Lowland under where the lower buried platform was located. Its area reached to 38 km^2 according to the first figure obtained by T. Nakano, one of the authors, in 1959. After a detailed survey of 1960, the Geographical Survey Institute, the Ministry of Construction, reported the land below sea level covering 35.2 km^2 in area. Since then, the Tokyo Institute of Civil Engineering has added a record on the area of the land below sea level to his annual report on land subsidence. According to these reports, the area has spread as denoted in Tab. 2.

The areas in every 50th cm of the ground height of lower than T.P. +1 m (T.P., Tokyo Peil, means the mean sea level of Tokyo Bay.) in 1974 are given in Tab. 3. The land below flood tide level of about T.P. +1.0 m which invades about 13 km inlandward from the coastal region, has 124.3 km^2 in area. The land even below ebb tide level of about T.P. −1.0 m reaches 31.5 km^2.

Population in every meter of the ground height was calculated on the basis of the population census report in 1970 (Tab. 4). About one million peoples live in the region with the height of lower than mean sea level. As the area of the land below sea level was 64.1 km^2 in 1970 (Tab. 3), population density in this region was about 14,700 per km^2. Supposed the banks were broken by an earthquake or an accident at the time of flood tide level, an inlet with the area of as much as 124.3 km^2 would appear and about one and a half million

Table 2 Expansion of land below sea level in the Tokyo Lowland

Year	Area	Data Source
1959	ca. 38 km^2	Nakano, T.
1960	35.2	G. S. I.
1961	36.3	T. I. C. E.
1962	37.1	T. I. C. E.
1963	41.2	T. I. C. E.
1964	44.2	T. I. C. E.
1965	45.3	T. I. C. E.
1966	50.2	T. I. C. E.
1967	57.6	T. I. C. E.
1968	57.8	T. I. C. E.
1969	60.0	T. I. C. E.
1970	64.1	T. I. C. E.
1971	64.8	T. I. C. E.
1972	66.0	T. I. C. E.
1973	66.7	T. I. C. E.
1974	67.6	T. I. C. E.

G. S. I. : the Geographical Survey Institute, the Ministry of Construction.
T. I. C. E. : the Tokyo Institute of Civil Engineering.

Table 3 Area in every 50th cm of the ground height of lower than T.P. +1.0 m in the Tokyo Lowland on Jan. 1, 1974.

Ground height (T.P.)		Area	Accumulated area
lower than −2.5 m		2.1 km^2	2.1 km^2
−2.5	−2.0	7.1	9.2
−2.0	−1.5	9.6	18.8
−1.5	−1.0	12.7	31.5
−1.0	−0.5	18.6	50.1
−0.5	0	17.5	67.6
0	+0.5	29.8	97.4
+0.5	+1.0	26.9	124.3

Table 4 Population in every meter of the ground.height of lower than T.P. + 1.0 m in the Tokyo Lowland in 1970.

Ground height (T.P.)		Population	Accumulated population
lower than −2.0 m		80,000	80,000
−2.0	−1.0	250,000	330,000
−1.0	0	610,000	940,000
0	+1.0	570,000	1510,000

peoples would suffer from inundation. Most of 330 thousand peoples who live in the land below ebb tide level would be exposed to danger of being drowned.

The further the land subsidence progresses, the more a degree of danger of flood disaster increases. Three types of flood disaster can be thought in the Tokyo Lowland.

The first is a flood caused by a storm surge, an influx of high water driven by a typhoon. Looking through a record only since 1900, the damaging storm surges were brought to the Tokyo Lowland eight times by the typhoons of 1911, 1917, 1921, 1927, 1938, 1949, 1953 and 1958. Among them, the highest tide level of T.P. +2.99 m recorded in 1917, when the southern part of the Tokyo Lowland of 86.8 km^2 in area was inundated. The number of casualities reached to 1,542 and that of damaged houses was 189,310.

The Tokyo Metropolitan Government has constructed the embankments along the coast of Tokyo Bay and of the rivers to prevent disasters caused by the storm surge and the river flood. Also, many canals have been walled. The embankments and walls, however, have been forced to decrease their heights due to land subsidence and they have been raised several times. Accordingly, they became insufficient in strength and new anti-flood countermeasure was planned in 1957. Construction of high embankments along the coast of Tokyo Bay and of the Rivers of Sumida and Ara was incorporated in this plan to safeguard the areas where have been lowered by land subsidence. The design level of high tide adopted in the plan was T.P. +2.99 m which was recorded by the storm surge brought by the typhoon of 1917. Meanwhile, when the coastal region of the Nobi Plain was damaged extremely by the storm surge driven by the Isewan Typhoon of 1959, the recorded level of high tide was equivalent to T.P. +3.97 m. Thus, the design level of high tide in Tokyo Bay was altered to T.P. +3.97 m.

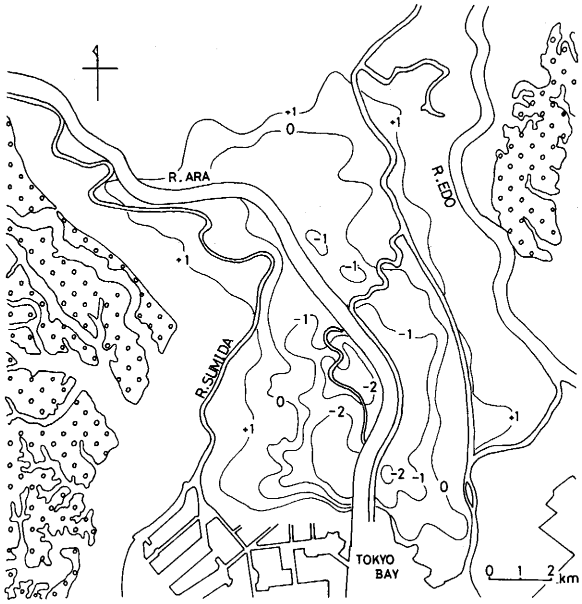

Fig. 5 Ground height (in meters) of the Tokyo Lowland on July 1, 1973.

Water in the deltaic lowland drains off only very slowly. Especially, drainage is impossible at the time of flood tide, because the water level of the rivers and the canals is higher than the land surface. When it rains heavily, rain water stays on the land without draining to the waterways and inundation occurs. That is the second type of the flood disaster supposed in the Tokyo Lowland, especially in the area below sea level. The pumping stations and the water gates, therefore, are constructed in company with construction of the embankments.

The last type of flood disaster, which is most severe, will be caused with a strong earthquake. When the Niigata Plain was striken by the earthquake with the magnitude of 7.5 in 1964, the dikes were destroyed due to liquefaction of the ground, which occurred extensively in the deltaic lowland composed of the loose sandy deposits. As a results, the area below sea level, where had been borne with land subsidence, was inundated immediately after the earthquake, and the inundated water stagnated there until pumped out. Possible occurrence of such disaster must be mentioned in the Tokyo Lowland, too. If a severe earthquake occurred in the vicinity of the Tokyo Lowland, several parts of the embankments would be broken. Water would invade into the land below sea level and an inlet would be formed in the central part of the Tokyo Lowland. The area and the position of the inlet and the number of peoples suffered from inundation can be read from Tab. 3, Fig. 5 and Tab. 4 respectively.

PRICE OF GROUND WATER

On the case of ground water used in the factories, its cost composes of construction expenses of the facilities to withdrawal and to supply it, maintenance expenses of these facilities and expenditures for electric power consumed to pump up. Though it is not the latest value calculated from these expenditures, the cost of ground water was 1 to 3 yen per m^3 in 1960 according to the Ministry of International Trade and Industry. Converting the value into the current one, it is 2 to 5 yen per m^3. In addition, expenses for ground water take only less than 1 to 2% of production cost (for example, Hida, 1969). Thus, ground water has been used at almost free of cost.

Utilization of ground water, however, went generally with land subsidence and the associated losses. It is thought as one of the important topics to be examined that how much has been economically lost by land subsidence and whether ground water use can take an economical balance or not on a different point of view from production cost.

In order to clear completely the increased unsafe conditions for the flood disasters, it is indispensable to restore the ground height to the same height as before land subsidence was caused. Expenses for restoration of the ground height may be regarded as one of the losses resulted from ground water use.

Table 5 Area in every 50th cm of the ground height of lower than T.P. +2.0 m in the Tokyo Lowland on Feb. 1, 1961.

Ground height (T.P.)		Area	Accumulated area
lower than −1.5 m		2.3 km^2	2.3 km^2
−1.5	−1.0	6.4	8.7
−1.0	−0.5	10.8	19.5
−0.5	0	9.7	29.2
0	+0.5	11.2	40.4
+0.5	+1.0	32.2	72.5
+1.0	+1.5	27.2	99.7
+1.5	+2.0	25.0	125.3

The areas in every 50th cm of the ground height on Feb. 2, 1961 and on Jan. 1, 1974 are shown in Tabs. 3 and 5 respectively. The land with the ground height of lower than +2.0 m in 1961 has the area of 125.3 km^2, which covers almost the same area as the land lower than +1.0 m in 1974. These lands are located in the central part of the Tokyo Lowland (Fig. 5), and their locations coincide mostly with each other. Mean ground height in this region is +0.65 m in 1961 and −0.36 m in 1974. Thus, it is estimated that the accumulated amount of land subsidence of about 1 m was recorded over the area of about 125 km^2 in the central part of the Tokyo Lowland from 1961 to 1974. That is to say, filling of 1.25×10^8 m^3 in volume is needed to restore the ground height to the same height as in 1961. Though estimating low, the price of filling may be supposed more than 5×10^3 yen per m^3. Accordingly, the total price of necessary fillings exceeds 6.25×10^{13} yen.

Meanwhile, total volume of ground water withdrawn in the area of about 238 km^2 in the central part of the Tokyo Lowland and its vicinity is able to be calculated at about 2.1×10^9 m^3 on the basis of the figures given by the Research Group of Land Subsidence in the Southern Kanto (1974). The price of filling per 1 m^3 of ground water is able to be obtained by dividing 6.25×10^{13} yen by 2.1×10^9 m^3. That is 3×10^3 yen per m^3 (about 10 dollars per m^3). Such a large value of net benefit is not supposed to be reaped through ground water use.

Actually, the increased danger from the flood disasters due to land subsidence is not cleared by filling over the subsided area, but such measures as construction of the embankments, the pumping stations and the water gates and improvement of the sewers are adopted generally. Construction expense of these facilities is much less than that for filling up to restore the ground height. Nevertheless, the price of ground water calculated by the Tokyo Metropolitan Research Institute for Environmental Protection on the basis of expenses for construction and repair of these facilities exceeded 200 yen per m^3.

The ground water utilization is very profitable for the enterprises who are not responsible for the economical losses resulted from land subsidence. But national and local governments have borne huge financial burden in order to prevent the flood disasters in the deltaic lowlands subsided by withdrawal of ground water. If the casualities and the property losses due to the flood disasters are taken into account, ground water use as land subsidence is caused is not economical. This fact is detected not only in the Tokyo Lowland, but also in the deltaic part of the Plains of Osaka, Nobi, Niigata etc.

CONCLUDING REMARKS

It is beyond doubt that land subsidence is caused due to overwithdrawal of ground water. If withdrawal of ground water is stopped, the land surface ceases from subsiding. When withdrawal of ground water is intended to stop, supply of substitutive water is indispensable and required by law. Surface water is sought as a source of substitutive water and it becomes necessary to take a measure to meet the situation of water uses on macroscopic view. But surface water is being used in large quantities for industrial uses as well as domestic uses in the regions such as the metropolitan regions of Tokyo, Chukyo and Kinki in where the population and the industries are concentrating and land subsidence is progressing. Moreover, much water is needed for agricultural uses in the districts behind these metropolitan regions. It is required urgently to make a macroscopical plan of rearrangement of the industries and the population based on the distribution of the water resources.

Though land subsidence was interrupted, the ground height can not naturally be restored to the former state. It is impossible to raise the ground height of the subsided areas where have been densely inhabited. These areas are exposed to great danger of the flood disasters for any length of time.

It can be said that land subsidence is progressing in all of the plains of Japan. Behind the fact, there exists an easy-going way of thinking satisfying water demand with ground water which can be taken in hand without large investment in development. Though there are many difficulties in developing surface water, an attitude of using ground water easily without consideration on possible volume of supply must be altered.

The authors would like to dedicate this paper to Prof. Taiji Yazawa in commemoration of his retirement from Tokyo Metropolitan University, and to Prof. Martin Schwind, who is famous among Japanese geographers for his intensive studies on geography of Japan and has continuously encouraged us to extend such studies as present topic.

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