Land Subsidence in the Tokyo Lowland

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INTRODUCTION

Resulting from long discussions on land subsidence in the Tokyo Lowland among specialists concerned, the following have been clarified.

1) Land subsidence has mainly been caused by the compaction of soft clayey layers because of over-pumping of ground water (Miyabe, 1962).
2) Compaction is progressing not only in Alluvium, but also in Pleistocene layers (Miyabe, 1967).
3) Generally, the amount of land subsidence is determined by the amount of compaction of Alluvium and that of the layers below Alluvium.
4) Relationship between the amount of land subsidence and the thickness of Alluvium is clear, particularly in the case of land subsidence due to pumping of ground water from the Alluvial and the upper Pleistocene aquifers.

Unfortunately, however, areal characteristics of land subsidence have not been fully understood in previous studies. In this respect, the authors intend to analyse the characteristics of areal differentiation of land subsidence in the Tokyo Lowland, and to consider the causes of such areal differentiation based on data of land subsidence since 1930 and geological and geomorphological studies.

MIGRATION OF THE CORE-AREA OF LAND SUBSIDENCE

The rate and mode of land subsidence in the Tokyo Lowland have changed annually and regionally. Such changes are thought to have been caused by both the areal difference of ground conditions and the areal difference of the rate of lowering of ground water level due to pumping.

In order to clarify the regionality of land subsidence, areal variation of land subsidence is analysed by using data from repeated levelings during the following periods : 1) 1930-1938, 2) 1951-1955, 3) 1961 and 4) 1966, each of which represents : 1) climax period of subsidence before the Second World War, 2) the recurring period after the war, 3) the climax period after the war, and 4) the declining period, respectively. In this analysis the area that subsided at a rate of more than 100 mm/year is defined as the core-area of land subsidence, because annual subsidence of 100 mm is thought to be an indicator showing the intensity of subsidence that corresponds approximately to the maximum annual compaction within the more shallow deposits, shallower than 35-70 m, most of which are Recent Deposits, as deduced from data obtained from the land subsidence recorder during the climax period after the war.

Area a)-h) are the core-areas of land subsidence in the Tokyo Lowland (Fig. 1), and are located in a limited part of the lowland. From Fig. 1 annual and areal differentiation of the core-areas are clearly pointed out as follows :

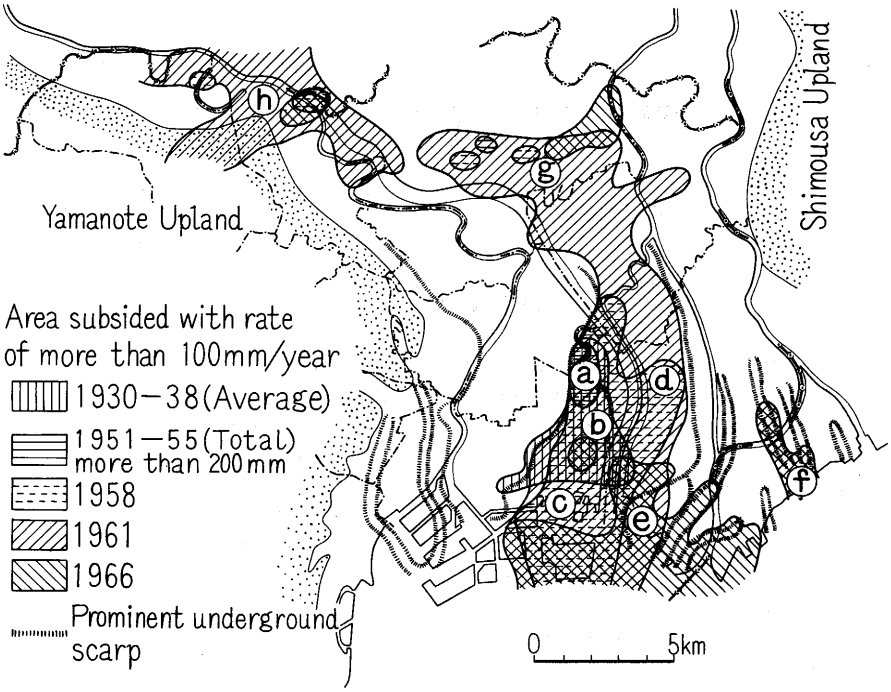

Fig. 1 Migration of core-area of land subsidence.

a : Azuma-Higashi, b : Central Joto, c : South Joto, d : Central-North Edogawa, e : Central-South Edogawa, f : East-South Edogawa, g : Adachi, h : Johoku.

1) The core-areas until 1955, the end of the recurring period, are found in the Koto District including the areas a), b) and c), and in the northern part g). Among those areas, a) is noted as the area of maximum subsidence.

2) After 1957, the beginning of the climax period of subsidence after the war, the main body of the core-area expanded rapidly not only over both the west and east bank areas of the Arakawa Discharge Channel, but also far to the northern part of the lowland.

3) During 1966, the maximum period of subsidence, the maximum annual subsidence exceeded 180 mm in areas a), b) and g), and the core-area occupied the widest extent, estimated to be 69 km^2.

4) In the Johoku area h) located in the northwestern part of the lowland, the area subsided at a rate of more than 100 mm/year has appeared since 1955, and extended even over the Yamanote Upland in the climax period.

5) Annual subsidence in the main body of the core-area has been decreasing since 1963, accompanying the decrease of the total area of the core-area. The cause of decrease of subsidence is due mainly to the regulation regarding the pumping of ground water in this area.

6) But, in the southeastern coastal area intensive subsidence at a rate of 100-180 mm/year has occurred since 1961. The southeastern coastal area located in the east bank area of the Arakawa Discharge Channel is noted as a representative area of subsidence in recent years.

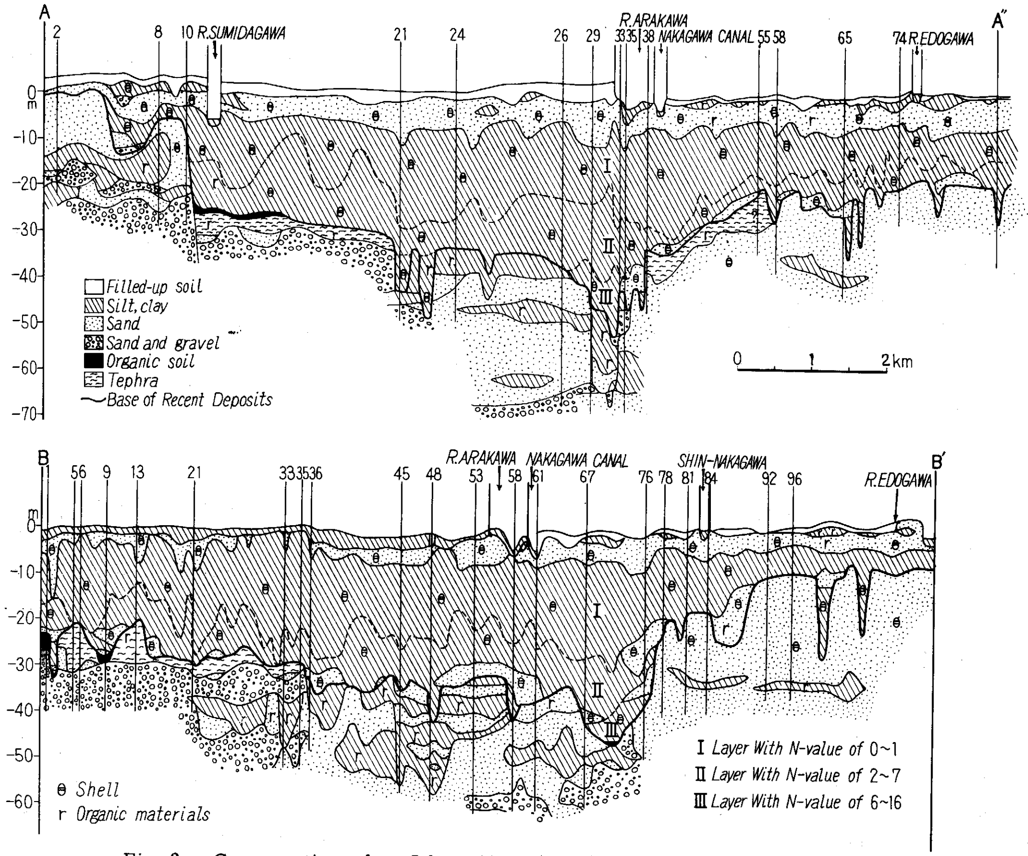

Fig. 2 Cross sections along Subway No. 5 (A-A'') and Metropolitan Expressway No. 7 (B-B'). Location of sections is shown in Fig. 5.

RESTORE OF BURIED LANDFORMS AND SIGNIFICANCE TO LAND SUBSIDENCE

Buried Landforms of the Tokyo Lowland

Generally speaking, the terraces and valleys are buried under the coastal lowlands, which have been formed as a result of eustatic change of sea level. These terraces and valleys consist of more consolidated layers than the layers covering them and an unconformity is formed between these two layers. The upper layer consists mainly of marine clayey sediments (AC : Alluvial Clay in Fig. 2) overlain by deltaic sandy sediments (US : Upper Sand in Fig. 2). These sediments with high water content and low N-value are soft and very compressible, and have played an important role in land subsidence (Miyabe, 1962). From such a standpoint, the upper loose sediments have been defined as Alluvium in this study, and it is practically coincident with Recent Alluvium employed in geological studies (e.g., Minato et al., 1965).

In order to investigate the distribution of the thickness of Alluvium, the authors attempted to restore the underground landforms buried by Alluvium, i.e., landforms expressed by the base of Alluvium. The corss sections along Subway No. 5 (A-A'') and Metropolitan Expressway No. 7 (B-B') have been analysed to be used as the datum profiles (Fig. 2). Then, other data of bore holes have been analysed with reference to the datum profiles to clarify the distribution of the buried landforms as shown in a geomorphological map of the underground landforms (Fig. 5).

According to these figures, the following can be pointed out as the bases of Alluvium.

1) Upper shallow terrace (Ia)

The terraces at about 10 m below sea level are found in the western end of the cross section A-A'' and in the eastern part of the cross section B-B'. They are the buried coastal terraces with a width of 2 to 4 km, being distributed along the fringe of the Pleistocene uplands, Yamanote and Shimousa Uplands (Hatori et al., 1962). The terrace distributed under the western part of the lowland has been divided into Nihonbashi Terrace (western part) and Asakusa Terrace (eastern part) (Kaizuka, 1964), by the underground valley, Showadori-dani (valley). The buried terrace distributed in the eastern part of the lowland, named Koiwa Terrace, inclines southward gently and reaches 13 m below sea level at southern end.

2) Lower shallow terrace (Ib)

There is a terrace with a depth of 20-30 m below sea level in the eastern part of the cross section A-A'' and the same terrace can be recognized only between Nos. 78 and 84 in the cross section B-B'. These are the buried coastal terraces deeper than Ia (Hatori et al., 1962). The terrace distributed under the southern part of the lowland is named Urayasu Terrace and that distributed under the line B-B' in Fig. 5 is named Nishi-Ichinoe Terrace respectively.

Both buried coastal terraces Ia and Ib consist of well consolidated Pleistocene sandy layers of Tokyo Formation.

3) Upper middle terrace (IIa)

The terraces with a depth of approximately 30 m below sea level are pointed out between Nos. 10 and 21 of the cross section A-A'' and in the western part of the cross section B-B', but they are the same terrace with a broad distribution under the western area of the lowland. This terrace can be regarded as a buried fluvial terrace formed during Pleistocene, because it consists of gravelly layers overlain by tephra, Kanto Loam, with a certain thickness (Kaizuka, 1964). This terrace was named Honjo Terrace by F. Tada (1961).

4) Lower middle terrace

This terrace, named Kasai Terrace, exists between Nos. 38 and 55 of the cross section A-A'', sloping westward from 20 to 30 m below sea level. The distribution of this terrace is restricted to the small area of the southern part of the lowland. It may be said that the terrace had been formed during Pleistocene, because the uppermost layer composing the terrace consists of tephra-like deposits and weathered Pleistocene sandy layers.

5) Deeper terrace

The lowest terrace distributed under the central part of the lowland appears in the middle of both cross sections A-A'' and B-B' at 30 to 40 m below sea level. The materials composing the terrace are the clayey and sandy sediments, alternating vertically and horizontally from place to place. They also vary in solidity, therefore it is often impossible to define the base of Alluvium. This terrace may be regarded as a fluvial one which was formed by rejuvenation due to the slight drop of sea level during the transgression after the maximum stage of Würm Ice Age. But the precise information about the age when the terrace was formed is not obtained.

6) Underground valley

Some valleys that dissected the above-mentioned terraces manifest themselves in both cross sections, and appear in several sizes. The greatest valley under the central part of the lowland, which reaches to a depth of 60 m below sea level in the southern

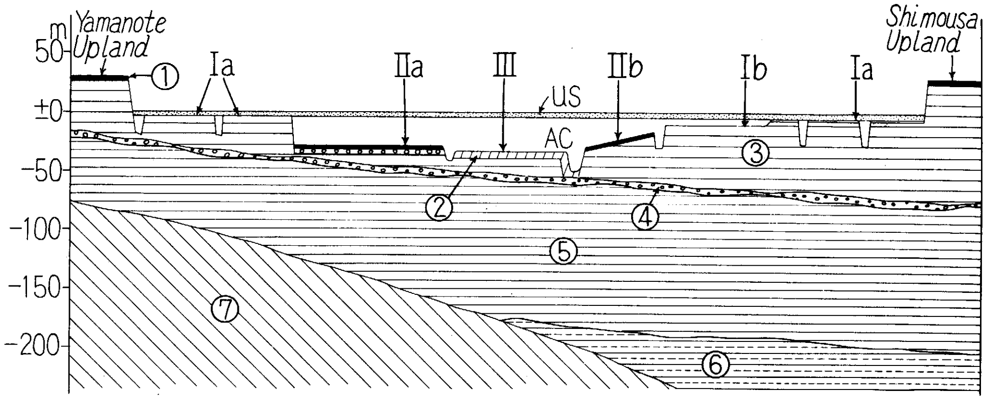

Fig. 3 Simplified geologic. l section of the Tokyo Lowland.

Buried terrace - Ia : Upper shallow, Ib : Lower shallow, IIa : Upper middle, IIb : Lower middle, III : Deeper.
Stratigraphy - Alluvium : US : Upper Sand, AC : Alluvial Clay;
Pleistocene and older : 1 : Tephra, 2 : Uppermost Clay, 3-5 : Tokyo F., 6 : Narita G., 7 : Miura G..

part, can be recognized as a main valley.

As mentioned above, the upper shallow, buried coastal terraces (Ia) composed of well consolidated materials are distributed under the both sides of the lowland. In the western part of the lowland, the upper middle, buried fluvial terrace (IIa), consisting of Pleistocene gravelly layers with tephra adjoins to the upper shallow terrace. In the southeastern part of the lowland, the lower shallow, buried coastal terrace (Ib) adjoins to the upper shallow terrace, and the lower middle terrace (IIb) adjoins to the former. In addition deeper terrace is found between the middle terraces and several valleys have modified these landforms.

The idealized schematic profile showing subsurface geology and landforms is demonstrated in Fig. 3.

As for the chronological studies on these landforms will be discussed in near future.

The Alluvial clayey layer (AC) can be divided into three layers by an N-value : I, II and III (Fig. 2). The layer I with an N-value of O-1, which occupies the main part of AC, is most compressible. The thickness of this layer increases toward south and middle of the lowland. The thickness of the layer II with an N-value of 2-7 is only 2-6 m except for the area over the deeper terrace and valley bottoms. Especially, the layer II is not found over the shallow terrace. The distribution of the layer III with an N-value of 6-16 is restricted within the valley bottoms and its thickness is not so large except for

Tab. 1 Depth of the buried landforms and thickness of Alluvium, in meters.

Buried landforms	Depth*	Upper Sand (US) (3-20)**	Alluvial Clay (AC)		
			I (0-1)	II (2-7)	III (6-16)
Upper shallow terrace	0-10	4-8	0- 6	0	0
Lower shallow terrace	20-30		5-10	2- 5	0
Upper middle terrace	30		6-16	4- 8	0
Lower middle terrace	30-40		10-20	2- 6	0
Deeper terrace	30-40		11-22	6-12	0
Valley bottom	30-60		11-22	6-12	0-12

* Depth means not only the elevation of each landform below mean sea level, but also the approximate total thickness of Alluvium, because the ground height of the studied area is +2 to -2 meters.
** Figures in the parentheses denote an N-value.

the southern part of the deep valley. Distribution and thickness of each layer of Alluvial Clay are determined primarily by the buried landforms. The depth of buried terraces and valleys and the thickness of Alluvium covering them are denoted in Tab. 1.

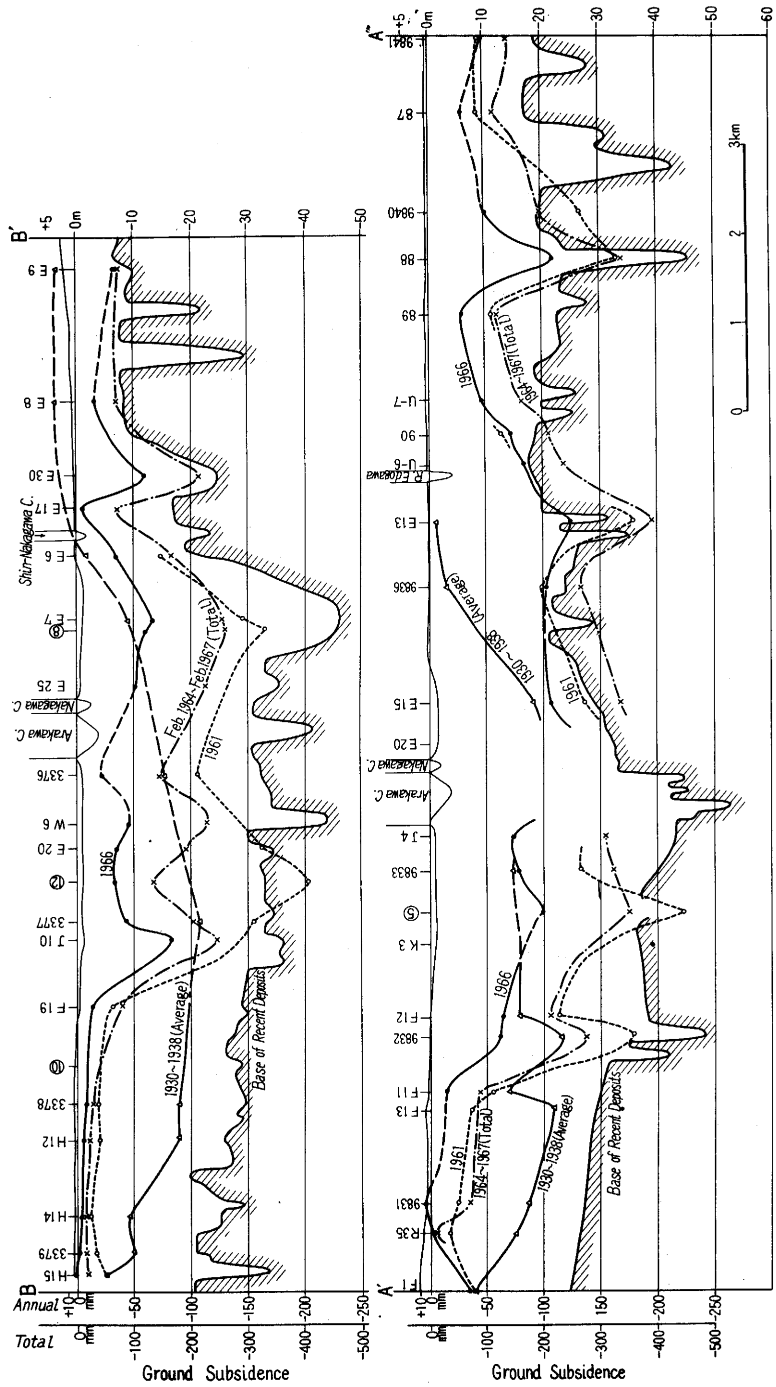

Fig. 4 Relationship between buried landforms and land subsidence along Metropolitan Expressway No. 7 (B-B') and Subway No. 5 (A'-A''). Location of sections is shown in Fig. 5.

The areas subsided at a rate of more than 100 mm/year, the core-area of land subsidence is limited to the central part of the Tokyo Lowland as discussed above. In order to explain such areal differentiation of land subsidence, the relationship between land subsidence and ground conditions is analysed annually and regionally by using restored buried landforms.

The relationship between cross sections of bruied landforms along Metropolitan Expressway No. 7 and Subway No. 5, and the amount of subsidence measured by bench marks near the sections during 1930-1938, 1961 and 1966 are noted in Fig. 4. The following apparent relationships can be recognized from this illustration :

1) Clear difference in the rate of subsidence is identified between areas over shallow buried terraces situated beneath both sides of the lowland and over the central part of lowland where Alluvium is more thickly deposited.

2) The eastern edge of the area subsided at a rate of more than 100 mm/year, i.e., the core-area of subsidence, has never gone beyond underground scarp limiting the western margin of the Koiwa, the Nishi-Ichinoe and the Urayasu Terraces. The western edge of core-area coincides approximately with the eastern scarp of the Honjo Terrace, and has never extended far over the terrace surface even in the climax period of subsidence. In the southern part of the Tokyo Lowland, in other words, the main

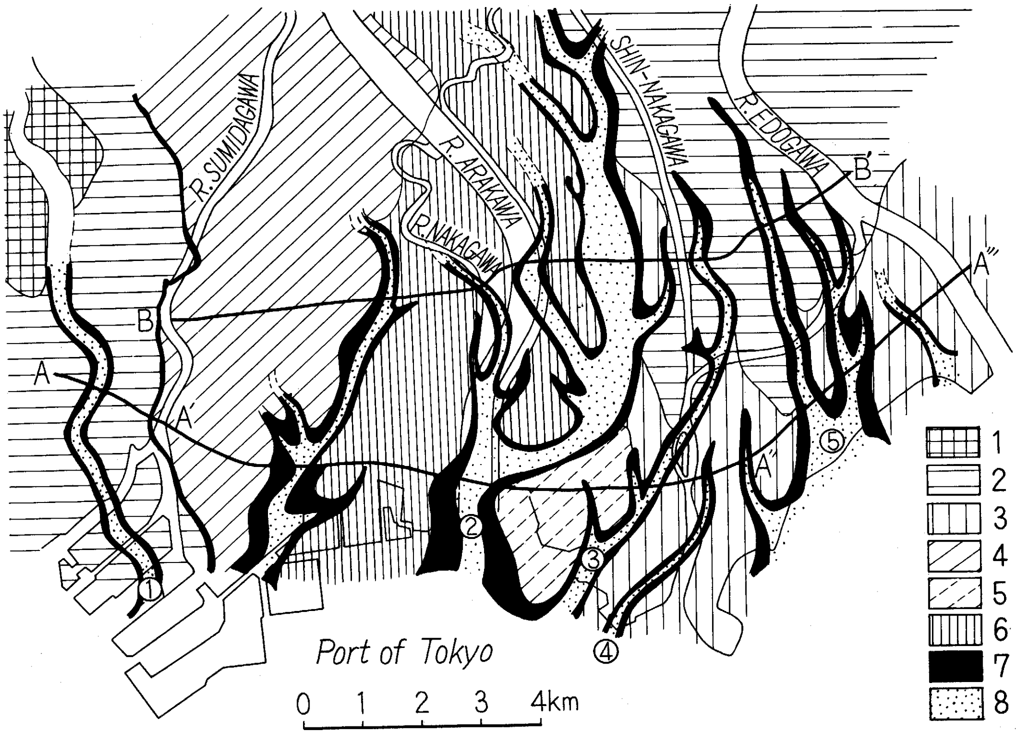

Fig. 5 Geomorphological classification of buried landforms in the southern Tokyo Lowland.

1 : Yamanote Upland; Buried terrace - 2 : Upper shallow (Ia), 3 : Lower shallow (Ib), 4 : Upper middle (IIa), 5 : Lower middle (IIb), 6 : Deeper (III), 7 : Buried scarp, 8 : Buried valley -①: Showadori-dani (valley), ②: Main valley, ③: Myokenjima-dani, ④: Urayasu-dani, ⑤: Maeno-dani; A-A''' and B-B' : Location of cross sections in Figs. 2 and 4.

body of the core-area of subsidence has almost always been limited to the central part of the lowland, and occupies the area over the lowest buried terrace and valleys of greater than 30 m below sea level, i.e., the area where the total thickness of Alluvium exceeds 30 m.

3) In the southeast part of the lowland, rapid subsidence at a rate of more than 100 mm/year has recently occurred on and around deep buried valleys in the Urayasu Terrace.

4) Comparing the rate of subsidence over the Honjo Terrace with that over the eastern shallow terrace group, the following contrast can be recognized: Although mean annual subsidence of 50-100 mm was observed over the Honjo Terrace during 1930-1938, a slight uplift of land surface was recorded over the Koiwa and the Urayasu Terraces during the same period. During 1961 and 1966, on the contrary, annual subsidence over the Koiwa and the Urayasu Terraces was 30 mm greater than that over the Honjo Terrace. This may indicate the annual variation of ground water level in those areas.

From the above mentioned, it is natural to consider that buried landforms which determine the areal variation of the thickness of soft compressible clayey layers has played an important role as a causative factor resulting in the regionality of land subsidence. But, in order to prove the exact role of buried landforms, it is necessary to clarify the relative amount of soil compaction from the surface to the base of Alluvium to the total amount of subsidence.

According to observed data on partial soil compaction deduced from measuring of standard iron tubes, more than 50 % of the total subsidence was caused by the compaction of soil layers within the shallow deposits, shallower than 35-70 m (Tokyo Metropolitan Government, 1969), which corresponds approximately to the thickness of Alluvium. Among the shallow deposits, marine clayey layer (AC), the distribution of which is governed by buried landforms, should be noted as the main compaction layer because of its physical properties and thickness (Figs. 2-3, Tab. 1).

Therefore, buried landforms may still be used as a significant indicator to explain the cause of the areal characteristics of land subsidence.

FORMATION OF LAND BELOW SEA LEVEL

As a result of progress of land subsidence in the Tokyo Lowland, the land below sea level, the so called Tokyo Zero Meter Region, occurred mostly coinciding with the core-area of land subsidence. The Zero Meter Line delimiting the land below sea level, is shifting outward. Although the eastern and western limits are almost fixed or shifting

Tab. 2 Growth of land below sea level, in square kilometers.

Year	Area	Source
1959	ca. 38	T. Nakano
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.

* Geographical Survey Institute.
** Tokyo Institute of Civil Engineering.

very slowly eastward and westward, the northern limit is moving northward and northwestward several kilometers annually. As a result, the area of land below sea level is expanding year by year.

According to the first figures obtained by T. Nakano in 1959, the area covered about 38 km^2. After a detailed survey of the Tokyo Lowland, the Geographical Survey Institute reported the area covered 35.2 km^2 in 1960. Since then, the Tokyo Institute of Civil Engineering reports land subsidence once a year. According to those reports, the area expanded as shown in Tab. 2. The deepest point is lower than 2.5 m below mean sea level. That is the result of land subsidence in more than a half century.

The expansion has, of course, occurred in the core-area mentioned above, and the limit of expansion is encroaching to the limit of the area of Alluvium more than 30 m in thickness. The expansion of the land below sea level brought various hazardous conditions to the Tokyo Lowland area. The representative one is the danger to high tide due to severe typhoons, and the other is the danger to flooding. More than 500,000 persons and various facilities of the urbanized area will be affected by disasters, if suitable facilities for disaster prevention are not prepared.

The most severe problem is thought to be disasters due to severe earthquakes. Because of land subsidence, dikes along rivers have been repaired several times and are insufficient in strength. Moreover, water level is higher than the surrounding ground level, and any break due to earthquake will result in flood disasters.

It must be emphasized that earthquake disasters in the land below sea level will be caused not only by destruction of structures and fire, but also by flood due to the break of dikes.

CONCLUSION

In conclusion, following facts should be mentioned.

a. Core-areas of land subsidence expanded northward in the earliest period of land subsidence and in the periods before and after the Second World War, and in the last several years several small core-areas of land subsidence were separated.

b. Five levels of buried terraces, scarps and dissected valleys were restored with reference to boring data. The core-areas of land subsidence coincide with high density areas of buried valleys.

c. Eastward expansion of core-area of land subsidence after the regulation of ground water use in the western section of the Tokyo Lowland can also be pointed out.

d. The land below sea level of over 50 km^2 occurred by land subsidence mostly in the core-area of land subsidence, original height of which was about 1-2 m.

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