ABSTRACT

The following facts should be mentioned:

a) Core area of land subsidence expanded northward in the earliest period of land subsidence and in the periods before and after the end of 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 dissecting valleys were restored based on boring data. The core areas of land subsidence coincid with high density areas of buried valleys.
c) Eastward expansion of core area of land subsidence after the regulation of groundwater use in the western section of the Tokyo Lowland can also be pointed out.

1. INTRODUCTION

As a result of long discussions on land subsidence in the Tokyo Lowland among the specialists concerned, the following have been clarified.

1. Land subsidence has been caused mainly by the compaction of soft clayey layers within aquifers subject to over-pumping of ground water.
2. Compaction is progressing not only in Alluvium, but also in Diluvium.
3. Generally speaking, the amount of land subsidence is shown 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 rather clear, particularly in case of land subsidence due to pumping of ground water from Alluvium and Upper Diluvium water bearing layers.

Unfortunately, however, areal characteristics of land subsidence have not been fully understood in previous studies. In this respect, the authors intended 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 land subsidence data since 1930 and geological and geomorphological studies.

2. 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 both by the areal difference
Land subsidence in the Tokyo deltaic plain

of ground conditions, above all by the areal variation in the thickness of soft compressible clayey layers, and by the areal difference of rates of lowering of groundwater levels due to pumping.

In order to make clear the regionality of land subsidence, areal variation of land subsidence is analyzed by using data obtained from repeated levelings during the following periods; 1930-1938, 1951-1955, 1961 and 1966, each of which represents 1) peak period of subsidence before the Second World War, 2) the recurring period after the war, 3) the peak period after the war, and 4) the declining period, respectively. In this analysis the area which 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, and corresponds approximately to the maximum annual compaction withing the shallower deposits—shallower than 35-70 m, almost all of which are the Recent Deposits, as deduced from data obtained from the land subsidence gauge during the peak period after the war.

![Figure 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

Areas a)–h) are the core-areas of land subsidence in the Tokyo lowland, and are located in the limited part of the lowland. As show on figure 1, annual and areal differentiations of the Core-areas are clearly pointed out as follows:

1. The core-areas until 1955, at 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 these areas a) is noted as the area of maximum subsidence.
2. After 1957, the beginning of the peak 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 to the far 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, about 69 km².

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

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

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

3. RESTORATION OF BURIED LANDFORMS AND THE SIGNIFICANCE TO LAND SUBSIDENCE

a) BURIED LANDFORMS OF THE TOKYO LOWLAND

Generally speaking, terraces and valleys are buried under the coastal lowlands, which were formed by rejuvenation due to eustatic change of sea level. These terraces and valleys consist of harder layers than the layers covering them and an unconformity is present between them. The soften sediments comprise the layers near the ground surface and are indication of their physical properties. From this standpoint, the upper loose sediments are defined as Alluvium in this study, and are essentially the same as the Recent Alluvium employed in geological studies. Alluvium consists mainly of marine clayey sediments (AC Alluvial clay in fig. 2) overlain by deltaic sandy sediments (US: upper sand). The clayey layer is divided into three parts according to N-value (fig. 2).

In order to investigate the distribution of the thickness of Alluvium, the authors tried to reconstitute the landforms buried by the Alluvium, that is, landforms expressed by the base of the Alluvium. In the first place, the cross sections along Subway No. 5 (A-A”) and Metropolitan Expressway No. 7 (B-B”) were drawn as the datum profiles (fig. 2). Then analysing other data obtained from borings, the distribution of buried landforms was clarified as shown on the geomorphological map (fig. 5).

According to these data, landforms have been identified:

1. Upper shallow terrace (Ia)

The terraces at about 10 meters depth below sea level are shown on the western end of the cross section A-A’” and along the eastern part of the cross section B-B’”. They are buried coastal terraces with a width of 2-4 kilometers and are distributed along the fringe of the Diluvium uplands, Yamanote and Shomosa Uplands. The eastern terrace named Koiwa Daichi inclines southward gently and reaches 13 meters below sea level at its southern end.

2. Lower shallow terrace (Ib)

There is a terrace at a depth of 20-30 meters below sea level as shown in the eastern part of cross section A-A’”. This buried coastal terrace named Urayasu Daichi is present under the southeastern part of the lowland. Ia and Ib consist of well consolidated sandy layers.
3. Upper middle terrace (IIa)

The terraces at a depth of approximately 30 meters below sea level are indicated between borings No. 10 and No. 21 of cross section A-A'' and along the western part of the cross section B-B'', but they are parts of the same terrace with broad distribution under the western area of the lowland. This terrace can be regarded as a buried river or fluvial terrace because it consists of gravelly layers overlain by tephra, Kanto Loam, of variable thickness.

![Cross section diagram](image)

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

4. Lower middle terrace (IIb)

This terrace is indicated between borings Nos. 38 and 55 of cross section A-A''. It slopes westward at about 20-30 meters below sea level, but its distribution is restricted to a small area in the southern part of the lowland and its origin remains unexplained.

5. Deeper terrace (III)

The lowest terrace under the central part of the lowland is shown in the middle of both cross sections A-A'' and B-B'', 30-40 meters below sea level. The materials comprising...
the terrace are clayey and sandy sediments, and vary both vertically and horizontally from place to place. They also vary in density, so it is often impossible to define the base of the Alluvium.

6. Underground valley

Several valleys dissect the terraces mentioned above and manifest themselves in both cross sections, though they are in different sizes. The largest is under the central part of the lowland at a depth of 60 meters below sea level and in the southern part of the lowland it is considered as a main valley.

As mentioned above, the upper shallow, buried terraces which are composed of well consolidated materials, are present beneath both sides of the lowlands. The upper shallow terraces are connected in the western part with the upper middle terrace, which is composed of Alluvial gravelly layers with tephra, and in the eastern part with the lower middle terrace. Also the lower terrace is present between the middle terraces where the several valleys modify these landforms.

The idealized schematic profile showing subsurface geology and landforms is presented in figure 3. The depths of buried terraces and valleys and the thickness of Alluvium covering them are given in table 1.


<table>
<thead>
<tr>
<th>Buried landforms</th>
<th>Depth</th>
<th>Upper sand (US)</th>
<th>Alluvial clay (AC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(3-20)</td>
<td>I (0-1)</td>
</tr>
<tr>
<td>Upper shallow terrace</td>
<td>0-10</td>
<td>0-6</td>
<td>0</td>
</tr>
<tr>
<td>Lower shallow terrace</td>
<td>20-30</td>
<td>5-10</td>
<td>2-5</td>
</tr>
<tr>
<td>Upper middle terrace</td>
<td>30</td>
<td>6-16</td>
<td>4-8</td>
</tr>
<tr>
<td>Lower middle terrace</td>
<td>30-40</td>
<td>10-20</td>
<td>2-6</td>
</tr>
<tr>
<td>Deeper terrace</td>
<td>30-40</td>
<td>11-22</td>
<td>6-12</td>
</tr>
<tr>
<td>Valley bottom</td>
<td>30-60</td>
<td>11-22</td>
<td>6-12</td>
</tr>
</tbody>
</table>

Figures in the parentheses denote N-value.
b) RELATIONSHIP BETWEEN LAND SUBSIDENCE AND BURIED LANDFORMS

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

The relationship between cross sections of buried 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 is shown in figure 4. The following apparent relationships can be recognized from this illustration:

1. The difference in the rates of subsidence is shown clearly between areas on both sides of the lowland which are underlain shallow buried terraces, and areas in the central part of lowland where Alluvium is thickest.

2. The eastern edge of the core-area of subsidence (subsidence rate of more than 100 mm/year) has never extended beyond the underground scarp limiting the western margin of the Koiwa, the Nishi-Ichinoe and the Urayusu Daichi. The western edge of the core-area coincides approximately with the eastern scarp of the Honjo Daichi, and has never extended far over the terrace area even in the peak period of subsidence. In the southern part of the Tokyo lowland, the main part of the core-area of subsidence almost always has been limited to the central part of the lowland, where the lowest buried terrace and valleys are deeper than 30 m below sea level—the area where the total thickness of the Alluvium exceeds 30 m.

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

4. Comparing the rate of subsidence over the Honjo Daichi with that over the eastern shallow terrace group, the following contrasts can be recognized: Although mean annual subsidence of 50-100 mm was observed over the Honjo Terrace during 1930-

![Figure 4. Relationship between buried landforms and ground subsidence, in cases of bench marks, along Metropolitan Expressway No. 7 (B-B') and Subway No. 5 (A'-A'). Location of sections is shown in figure 5](image-url)
1938, slight uplift of land surface was recorded over the Koiwa and the Urayasu Daichi during the same period. However, during 1961 and 1966, annual subsidence over the Koiwa and the Urayasu Daichi was 30 mm greater than that over the Honjo Daichi. This may reflect the annual variation of ground-water level in these areas.

From the above, it is natural to conclude that buried landforms which determine the areal variation in the thickness of soft compressible clayey layers has played an important role in the magnitude regionality of land subsidence. But, in order to prove the exact role of buried landforms, it is necessary to determine the ratio of 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 using standard iron tubes, 60-100% of the total subsidence has been caused by the compaction of soil layers within the shallow deposits, shallower than 35-70 m, which corresponds approximately to the thickness of Alluvium. Among the shallower deposits, the marine clay layer (Ac), the distribution of which is governed by buried landforms, is the main compaction layer because of its engineering properties and thickness. (figs. 2-3, tab. 1).

Therefore, buried landforms are significant indicators of the areal characteristics of land subsidence.

FIGURE 5. Geomorphological classification of buried landforms in the south Tokyo Lowland.
1: Yamanote Upland; Buried terrace - 2: Higher upper (Ia); 3: Lower upper (Ib); 4: Higher middle (IIa); 5: Lower Middle (IIb); 6: Lower (III); 7: Buried scarp; 8: Buried valley - (1): Showadori-dani; (2): Main valley; (3): Myokenjima-dani; (4): Urayasu-dani; (5): Maeno-dani; A-A' & B-B': Location of cross sections in figure 2 and figure 4
4. CONCLUSION

In conclusion, the following facts are presented:

a) Core-areas of land subsidence expanded northward in the earliest period of land subsidence and in the end periods before and after the end of the Second World War. In the last several years several additional small core areas of land subsidence have been identified.

b) Five levels of buried terraces scarps and dissecting valleys were recognized based on boring data. The core-areas of land subsidence coincided with high density areas of buried valleys.

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

REVIEWS OF LAND SUBSIDENCE RESEARCHES IN TOKYO

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ABSTRACT

The present paper deals with an historical review of development of land subsidence research in Tokyo during about thirty years. Three periods are distinguished; the purposes, methods and results of the research in each period are briefly summarized in relation to advancement of the land subsidence phenomena in Tokyo.

RÉSUMÉ

Une revue historique des recherches sur les affaissements à Tokyo au cours des 30 dernières années est présentée. Trois périodes peuvent être distinguées ; les buts, méthodes et résultats des recherches dans chaque période sont brièvement résumés en relation avec l'avancement de la subsidence à Tokyo.

1. INTRODUCTION

The land subsidence in the lowland of Tokyo was discovered as a result of repeated precise levelling which had been carried out in 1924, in order to study the post-seismic crustal disturbance associated with the Kwanto Earthquake of 1923. The recognition of such an abnormal subsidence of land is said to be the first one in Japan or elsewhere.

The present paper is a historical review of the progress of the land subsidence phenomena in Tokyo and of the related investigations.

The writers' acknowledgements are given to Dr. Naomi Miyabe for his kind supervision and for reading this manuscript, and to the members of our Institute for their valuable assistance in the preparation of this manuscript.