Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 52 No. 4 December 2021 ISSN 0046-5828

Wide-area Land Subsidence of Kashiwazaki Plain due to the 2007 Niigata-ken Chuetsu-Oki Earthquake

S. Ohtsuka[1], K. Isobe[2], and Y. Fukumoto[1]
[1]*Department of Civil and Environmental Engineering, Nagaoka University of Technology, Nagaoka, Japan*
[2]*Division of Field Engineering for Environment, Hokkaido University, Sapporo, Japan*
E-mail: ohtsuka@nagaokaut.ac.jp

ABSTRACT: Wide-area land subsidence occurred across the Kashiwazaki Plain, Niigata, Japan after the 2007 Niigata-ken Chuetsu-Oki Earthquake. The stratified ground subsidence meter clearly showed that a thick clayey layer had caused this subsidence after the earthquake. To examine the ground conditions, a boring survey was conducted at the site and the physical and mechanical properties of the ground were tested. Although leveling surveys are insufficient for surveying the behavior of the ground, the measurement data obtained at various points from these surveys are meritorious for grasping the spatial distribution and the time-dependent property of the land subsidence. In this study, by analyzing the instantaneous and the long-term amounts of land subsidence at each point from the time-series observation data, the correlation between geology and topography is reported and the cause of the land subsidence of the clayey soils after the earthquake is discussed. It is clarified that the existence of a marine clay layer greatly affected the long-term subsidence of the land.

KEYWORDS: Land subsidence, Earthquake, Clayey soils, Terrain classification.

1. INTRODUCTION

The Niigata-ken Chuetsu-Oki Earthquake occurred on July 16, 2007, killing 11 people and damaging more than 6,000 residences. The epicenter of the earthquake was off the coast of the Kashiwazaki Plain in Niigata Prefecture, located north of Tokyo, and 13 km under the ground. The quake registered 6.8 on the magnitude scale of the Japan Meteorological Agency (JMA), and the Kyoshin Net (K-net) accelerograph measured a maximum ground acceleration of 813 Gal. The seismic intensity, defined in terms of the Japanese scale, was recorded as an upper 6 on the Kashiwazaki Plain. Figure 1 indicates the distribution of seismic intensity recorded in Niigata Prefecture. It shows the heavy earthquake excitation that struck a wide area of the Kashiwazaki Plain. The liquefaction of the ground, due to the earthquake, was widely observed along the Sabaishi River. It caused severe damage to the residences there, mostly due to the differential settlement of the ground caused by the liquefaction.

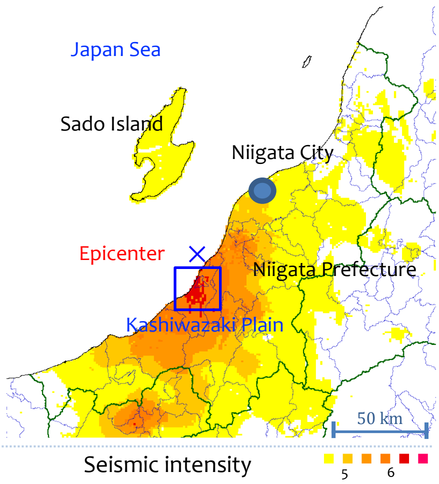

Figure 1 Distribution of seismic intensity

The land subsidence on the Kashiwazaki Plain has been accelerating due to the pumping up of underground water. The use of underground water is strictly controlled. In winter, however, underground water is commonly used to melt snow that has piled up on the ground. This causes seasonal non-negligible land subsidence. This subsidence has been keenly observed through measurements taken by the Niigata Prefectural Office. This measurement system was able to clearly capture the earthquake-induced land subsidence of 2007, as shown in Figure 2 (Isobe and Ohtsuka, 2013). The measurements taken by the stratified ground subsidence meter at Shimbashi indicated sharp increases in the subsidence of the clayey layer, the thickness of which was 23 m, after the earthquake.

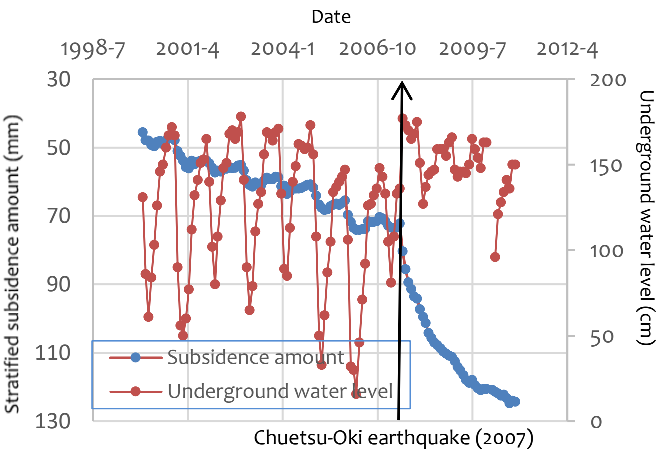

Figure 2 Stratified subsidence of clayey layer at Shimbashi

The subsidence of clayey soils has been observed in the past due to the Mexico City Earthquake (1985), the Great Hanshin-Awaji Earthquake (1995), the Off the Pacific Coast of Tohoku Earthquake (2011) and so on (Zeevaert, 1983; Hyodo, Yasuhara and Murata, 1988; Ohara and Matsuda, 1988; Yasuhara and Kazama, 2015). Subsidence has been commonly pointed out in measurements taken by leveling surveys. However, the subsidence of clayey soils cannot be proven by measurement data taken by leveling surveys since land subsidence cumulatively reflects the various behaviors of the ground from the base to the surface, and it is unclear which layer actually caused the subsidence. It is noted that this paper reports measurements by the stratified ground subsidence meter which can specify exactly which layer caused the subsidence after an earthquake. To survey the cause of the earthquake-induced long-term subsidence of clayey soils, a boring survey using standard penetration tests (SPTs) was conducted at Shimbashi.

Earthquake-induced land subsidence has commonly been investigated by many researchers by clarifying the mechanical properties of the clay sustaining a cyclic load, e.g., the generation of pore water pressure and compressibility (Suzuki, 1984; Yasuhara and Andersen, 1989; Matsuda, 1997; Sato, Nhan and Matsuda, 2018).

These studies have greatly contributed to clarifying the mechanism of earthquake-induced land subsidence from the viewpoint of the deformation property of a soil. It is possible to estimate the amount of post-earthquake land subsidence with the compression property of the soil obtained from indoor tests simulating the earthquake-induced land subsidence. However, it is still difficult to assess the amount of post-earthquake land subsidence since there are few cases with clear information on the stratum configuration of the ground and the mechanical properties of the soil in the relevant area of earthquake disasters. Even so, from the viewpoint of disaster mitigation, it is very important in practice to predict the amount of post-earthquake land subsidence, and it is useful if it can be predicted with the primary information, such as the commonly published terrain classification.

Moreover, past reports on the land subsidence induced by earthquakes were mostly point-wise. There have been few reports on the regional distribution of the land subsidence amount. Thus, it would be worthwhile to clarify the characteristics of the post-earthquake land subsidence amount based on disaster data. Consequently, this information would comprise valuable data for the field of disaster science. This study surveys the correlation of the post-earthquake land subsidence amount with the terrain classification using long-term observation data on land subsidence. Although leveling surveys are insufficient for capturing the behavior of the ground, the measurement data obtained from these surveys at various points are meritorious for grasping the spatial distribution and for discussing the difference in the time-dependent property of the subsidence in consideration of geology and topography. In this paper, by analyzing the instantaneous and the long-term amounts of land subsidence at each point from the observed data, the correlation among the geology, the topography and the post-earthquake land subsidence amount is discussed.

2. GEOLOGY AND TOPOGRAPHY

Figures 3 and 4 show the terrain classification map and the altitude distribution map, respectively, for the Kashiwazaki Plain. A dune is seen to have developed widely along the seacoast; it is the remarkable topographical feature of the area. It created a hilly terrain along the seacoast, as shown in Figure 4. A thick clayey layer later developed behind the dune and a delta formed. On the upper stream of this delta, a valley plain is distributed and a natural levee formed alongside the river. The geological cross section addressed in this research is illustrated with a dotted red line in the figures. It passes the measurement points of the land subsidence, such as Shimbashi, Yanagibashi and Motoshiro. The downtown area of Kashiwazaki City is distributed mainly in the dune and the delta. Shimbashi, where the stratified ground subsidence meter was set up, is located in the delta, as shown in Figure 4.

The geological cross section is illustrated in Figure 5. As seen in the figure, the soft clay is deposited thickly, in layers AC1, AC2 (marine clay) and AC2, from the ground surface to the base. The thickness of the soft clay layer reaches almost 50 m. The soft clay exists thickly below the dune. The wide distribution of soft clay is noted to have caused the long-term land subsidence after the earthquake. The stratified ground subsidence meter was set up at Shimbashi, as seen in Figure 5.

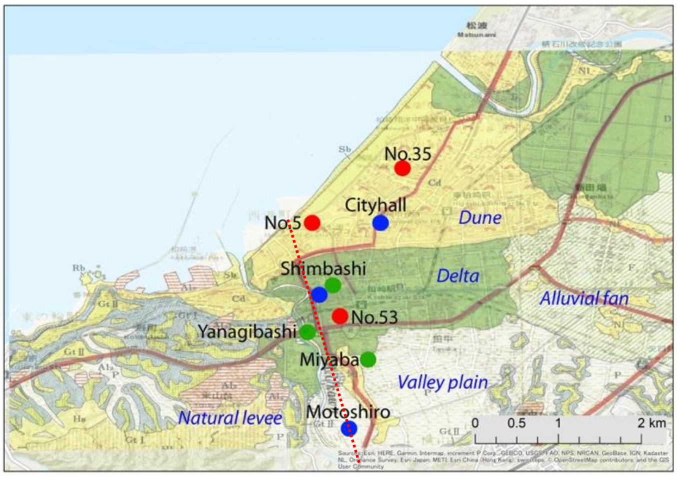

Figure 3 Terrain classification map

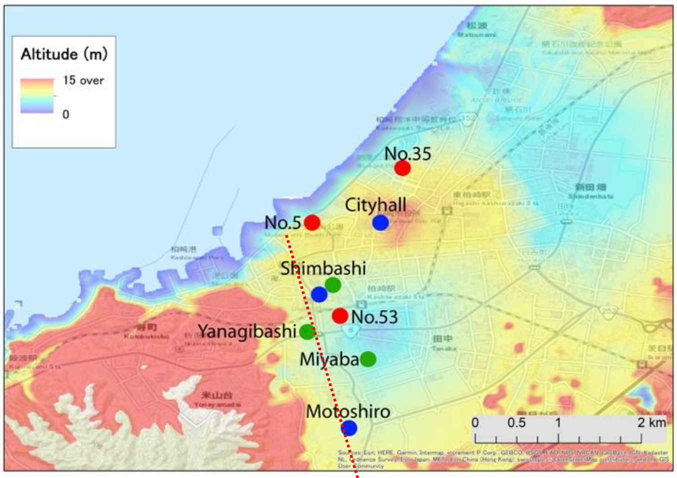

Figure 4 Altitude distribution map

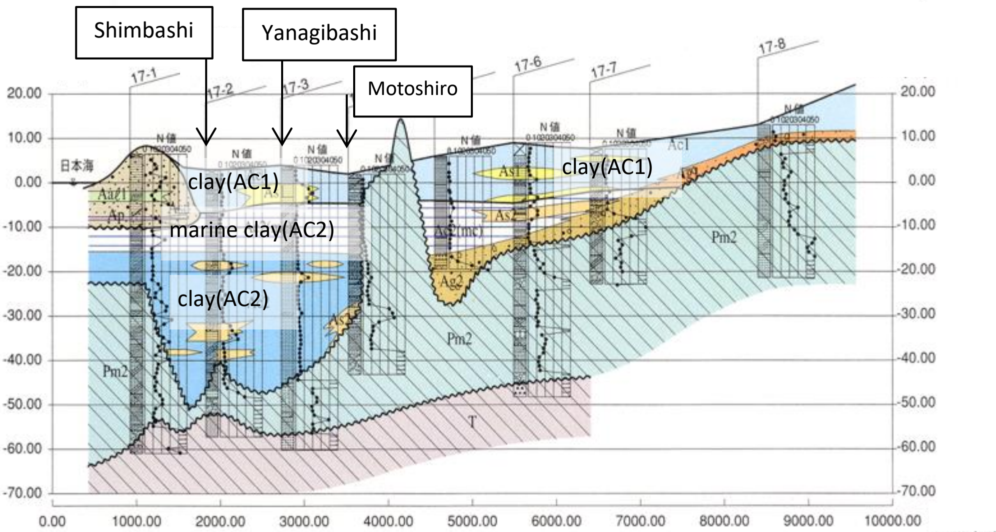

Figure 5 Geological cross section map (Location is exhibited in Figures 3 and 4)

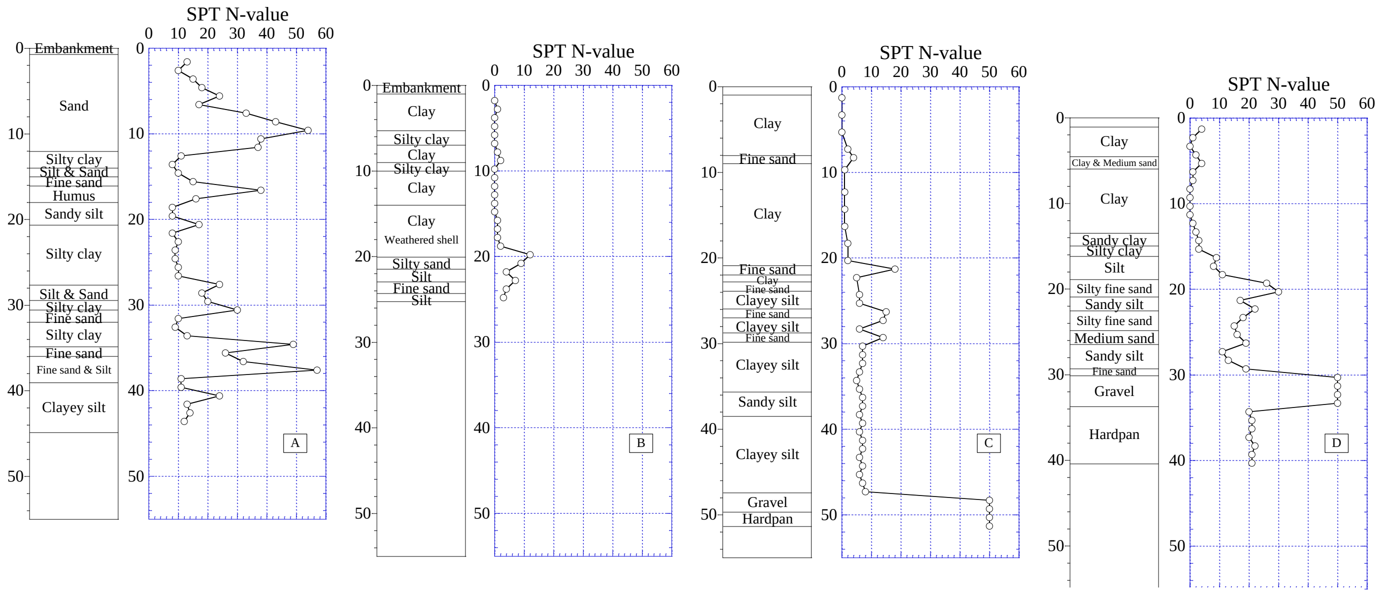

Figure 6 Geological columns and SPT-N values at four sites in typical terrain classification: (a) City hall in dune, (b) Shimbashi-A in delta, (c) Shimbashi-B in delta, and (d) Johtoh in valley plain.

Figure 6 displays the geological columns containing the SPT-N values at several points across the Kashiwazaki Plain. Some of the geological column data were obtained from the Hokuriku Geological System database in Japan (Council for Utilization of Hokuriku Geological Database System, 2018). Their locations are illustrated in Figure 4 as points A to D. Point A is located in the dune, points B and C in the delta and point D on the valley plain. The authors conducted a boring survey at Shimbashi (marked as B) and sampled undisturbed specimens directly from the clayey layers. From the boring survey, the ground at Shimbashi was confirmed to mainly consist of soft clay with N values ranging from 0 to 2. Small pieces of weathered shells were observed from around 11 m in depth and the presence of more significant shells was observed around 14 m. The soft clay layer extended to 21 m in depth and sat on a silt layer with an N value of approximately 10. These observations indicate that a marine clay layer exists from around 11 m to 21 m in depth in the Shimbashi district.

3. MEASUREMENT OF LAND SUBSIDENCE

3.1 Stratified Subsidence Measurement

The land subsidence measured by the stratified ground subsidence meter at Shimbashi is shown in Figure 2. This figure represents the fluctuation in the groundwater level at a depth of 23 m around 1999 to 2011 and a record of the amount of land subsidence of the clayey layer from a depth of 23 m to the ground surface. In the winter months, from January to March, the groundwater level dropped rapidly due to the pumping up of groundwater. After April, however, when the pumping up of water had ceased, the level was gradually restored. The groundwater level had completely recovered in a year, at around 170 cm from the reference point, and this recovery means the sustainable use of groundwater. However, when the amount of snowfall is heavy, the groundwater level drops significantly due to need for the accelerated pumping up of groundwater. In such cases, one year is insufficient for the recovery of the groundwater level. The amount of land subsidence is closely correlated with the fluctuation in the groundwater level. The subsidence occurs in winter, but the ground rebounds as the groundwater level recovers. Nevertheless, the figure indicates the land subsidence that accumulated at the nearly constant rate of 3 mm/year since 1999. Although the groundwater level is normally recoverable in a year, it can be seen that residual land subsidence has been generated.

In the figure, it is remarkable that the land subsidence has progressed rapidly, approximately 50 mm/3 years, since the 2007 earthquake. The fluctuation in groundwater level in the first 3 years following the earthquake is considerably small compared to that of the average year; and thus, the occurrence of the rapid land subsidence is thought to be due to the earthquake. The amount of land subsidence generated after the earthquake was large immediately after the earthquake and became moderate with the passage of time. This phenomenon may have been caused by the behavior whereby excessive pore water pressure was excited in the clayey layer due to the earthquake and dissipated with the passage of time, causing the land subsidence. Despite the land subsidence increasing after the earthquake, it almost settled around 2010 and proceeded at the same rate as in the past. This measurement clearly indicates that the clay layer caused the earthquake-induced land subsidence; however, it is still not clear which clay layer, AC1 or AC2 (marine clay), caused the greater amount of subsidence. The physical properties of the soils sampled from Shimbashi were obtained as seen in Tables 1 and 2. The tables additionally exhibit those of the other sites, the locations of which are shown in Figure 2, to grasp the properties of each clay layer. The clay layer of AC2 (marine clay) consists of marine clay which shows a higher natural water content and plasticity index than AC2. Moreover, the soil of AC2 (marine clay) consists of more than 50% clay and the void ratio is greater, as shown in Table 2.

Table 1 Physical properties of clayey layer

Layer	Location	Plasticity index I_p	Liquid limit w_L (%)	Natural water content w_n (%)
AC1	Miyaba	24.2	51.1	52.8
AC2 (marine clay)	Miyaba	42.9	78.2	76.3
	Shimbashi	48.6	87.0	73.5
AC2	Miyaba	25.1	59.1	53.2

Table 2 Void ratio and texture of clayey layers (Miyaba)

Layer	Void ratio	Sand (%)	Silt (%)	Clay (%)
AC1	1.393	16.0	62.9	21.1
AC2 (marine clay)	2.057	0.5	47.8	51.7
AC2	1.474	1.7	55.7	42.6

3.2 Leveling Measurement

Since the use of the stratified ground subsidence meter is limited, due to its high cost, this study focuses on a leveling survey to investigate the subsidence behavior of the land. The advantages of leveling surveys are their simplicity and cost efficiency. In addition, they can be applied to many locations on a plain. They are effective for schematically grasping the features of the land subsidence. Leveling surveys have been conducted by the Niigata Prefectural Office. They provide valuable information on the spatial distribution and time-dependent property of the land subsidence. Unfortunately, although a leveling survey was conducted every year before the earthquake, it has only been implemented every other year since the earthquake.

Figure 7 displays the typically measured relationships of land subsidence and time at three different points. The locations of the measurement points are given in Figure 4. They show the great drop in subsidence just after the earthquake in the same way as that of the stratified ground subsidence meter at Shimbashi. However, the trends in the land subsidence and time relationship are different among the three points. The land subsidence of No. 5, the location of the dune, was generated instantaneously and remained constant after the earthquake. On the contrary, the land subsidence of No. 35, also located in the dune, was generated not only instantaneously, but also continued to be generated for a long time. This difference in behavior may have been caused by the difference in soil profiles between the two points. The soil profile of No. 35 consists of the sandy soil of the dune and the clayey soil beneath the dune. The existence of a clayey layer is thought to affect the difference in the post-earthquake subsidence behavior. On the contrary, the land subsidence of No. 53, located in the delta, was mostly generated after the earthquake; the instantaneous subsidence occurring during the earthquake was comparatively small. As discussed above, these measured data indicate that the long-term subsidence was mainly generated in the clayey layer due to consolidation phenomena.

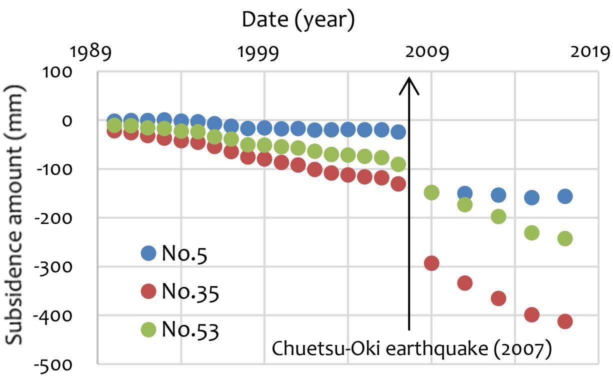

Figure 7 Land subsidence and time relationship at three points

4. ANALYSIS OF INSTANTANEOUS AND LONG-TERM SUBSIDENCE AMOUNTS

4.1 Analysis Method

By analyzing the obtained measurement data, this study proposes to define the instantaneous and the long-term subsidence amounts. Figures 8 and 9 show typical examples of determining the amounts using the measured data. In this procedure, the following three hypotheses are introduced:

1) The instantaneous subsidence is generated in a short time during and after the earthquake.
2) The land subsidence after the earthquake follows the hyperbolic curve in regards to time which is a general assumption in the consolidation behavior of clay.
3) The land subsidence basically proceeds at a specific rate at each point due to the pumping up of groundwater. Once the earthquake-induced subsidence settles, the rate of land subsidence coincides with that of the past trend.

Figures 8 and 9 illustrate that the amounts of instantaneous subsidence, d1, and long-term subsidence, d2, can be properly defined with the measured data for two different cases. Although it is not apparent whether the long-term subsidence has already converged, it is assessed by assuming that the long-term subsidence will not change greatly. These two subsidence indexes provide the valuable features of the land subsidence caused by the earthquake.

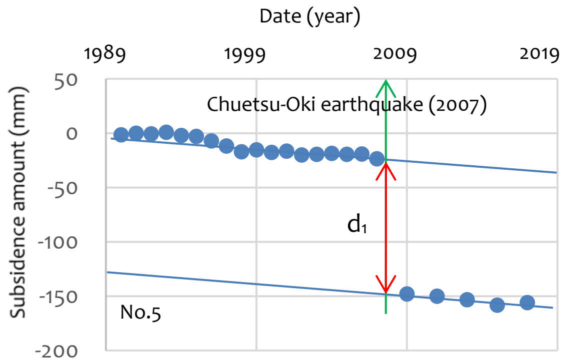

Figure 8 Typical examples of recorded land subsidence and time relationship (dune)

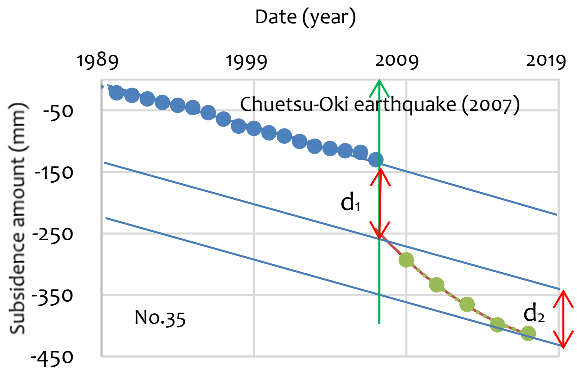

Figure 9 Typical examples of recorded land subsidence and time relationship (dune)

4.2 Spatial Distribution of Instantaneous and Long-term Land Subsidence Amounts

By analyzing the instantaneous and the long-term subsidence amounts at each point with the observed data, the spatial distributions of them in the Kashiwazaki Plain are investigated. Figures 10 and 11 show the results of the instantaneous and the long-term subsidence amounts. In these figures the terrain classification and altitude distribution are also indicated, respectively. In comparison with the terrain classification, it is clear that the instantaneous subsidence is dominant in the dune. However, it is still widely observed in both the delta and the valley plain, although the amount of subsidence is small. It is not clear why the instantaneous subsidence is observed in the delta and the valley plain, but the possible cause will be discussed in the following section.

On the other hand, the amount of long-term land subsidence is generally large in the delta, reflecting the thick layer of clay. However, in the valley plain, it is comparatively small although the clayey layer is thick, as shown in Figure 5. This phenomenon is very interesting and it will be discussed later in detail from the viewpoint of the mechanical properties of the soils. Long-term land subsidence is also observed in the dune. This is because a clayey layer is distributed under the dune, as shown in Figure 5 and noted previously. Although the correlation between the instantaneous or the long-term land subsidence amount and the terrain classification is observed in the figures, the quantitative examination is insufficient. It will be further discussed next.

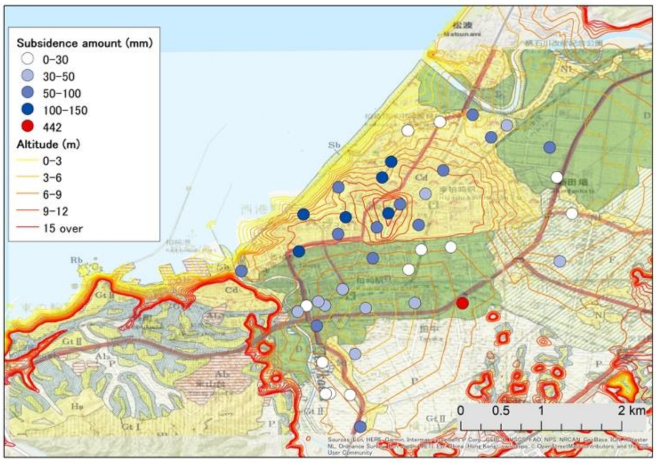

Figure 10 Distribution of instantaneous subsidence amounts

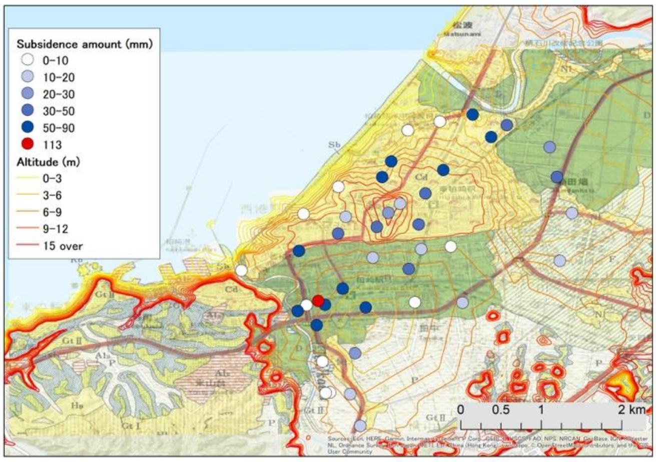

Figure 11 Distribution of long-term subsidence amounts

4.3 Terrain Classification and Land Subsidence Amounts

The features of the generation of instantaneous and long-term land subsidence amounts are closely analyzed against the terrain classification shown in Figures 12 and 13. The figures express the ratio of the instantaneous or the long-term land subsidence amounts to the total subsidence amount. Figure 12 indicates that the instantaneous land subsidence is dominant in the post-earthquake land subsidence. The ratio of the instantaneous subsidence to the total subsidence is seen to be comparatively higher in the dune and the valley plain. In the dune, this result is consistent with the deformation property of the sandy soil since the sandy soil is instantly compressed by a dynamic load, such as an earthquake, when it is deposited loosely. On the other hand, it is beyond expectations that the instantaneous land subsidence amount is also observed in the delta and the valley plain, although the instantaneous subsidence amount is comparatively smaller than that in the dune. Generally, clayey soil is not likely to be compressed instantly by a dynamic load due to the short time for draining. The reason for the instantaneous subsidence of the clayey soil is not clear. In the relevant area of the delta and the valley plain, the residential houses and infrastructures have commonly been built on the low-height sandy fill on the clayey soils. This sandy fill can be compressed instantly and it is one of the possible reasons why the instantaneous land subsidence was caused. However, when instantaneous land subsidence occurs in the low-height sandy fill, the subsidence amount becomes almost the same despite the terrain classification. The extent of the range in instantaneous subsidence amounts for the delta and the valley plain is seen in the figure. Thus, various factors, including the soundness of the measuring points and the accuracy of the estimation method for the instantaneous subsidence, need to be examined further.

Next, Figure 13 shows that the long-term land subsidence is dominant in the delta. It is likely to reflect a thick layer of clayey soils. From the mechanical properties of sandy soil, it can be inferred that long-term subsidence does not occur in the dune. However, it is seen in the figure that the long-term subsidence is still large in the dune. As shown in the geological cross section map in Figure 5, a thick clayey layer, about 15 m in height, exists below the dune and reaches about 30 to 40 m in height near the edge of the dune. It is possible that this clay layer caused the long-term subsidence in some parts of the dune despite it being difficult to prove this hypothesis since no stratified ground subsidence meter was installed. In the valley plain, long-term land subsidence is also generated due to the existence of a thick clayey layer. However, the subsidence amount is comparatively small compared to that in the delta. This is due to various factors such as the height in the clayey layer and the compression index of the soil. As shown in Figures 5 and 6, the deposited layers are macroscopically the same between the delta and the valley plain, and the height in the clayey soil is almost similar despite the variation in height that exists. Although this difference is very interesting, it is difficult to discuss the difference in the trends of the long-term land subsidence between the delta and the valley plain from the primary information. It is further discussed from the mechanical viewpoint in the next section.

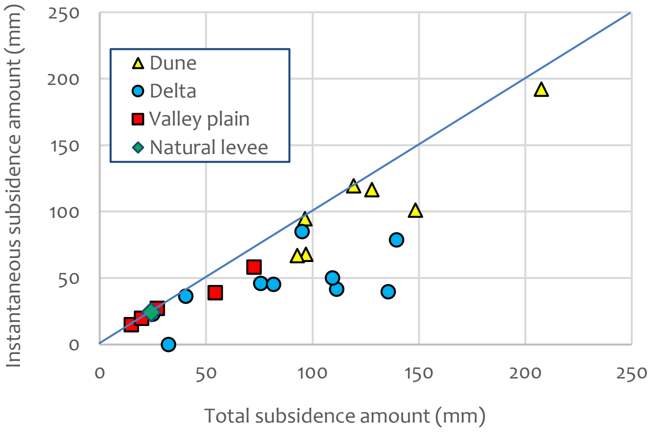

Figure 12 Instantaneous subsidence amounts and terrain classification

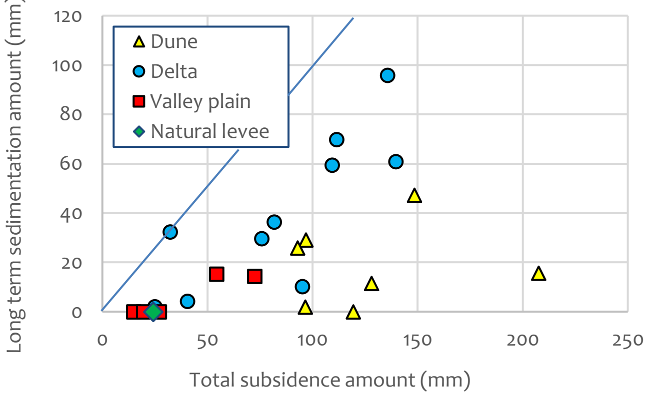

Figure 13 Long-term subsidence amounts and terrain classification

5. DISCUSSION ON LONG-TERM SUBSIDENCE

5.1 Effect of Topography by Hilly Terrain

The reason why the long-term land subsidence is large in the delta will be discussed further. One possible reason is the topography. Since the delta is distributed adjacent to the dune, which forms the hilly terrain, the soil in the delta, especially near the dune, is basically loaded by shear stress due to the irregularity in topography. It is well known from soil experiments that a greater amount of pore water pressure is generated for a repeated load when additional initial shear stress is applied to the soil element. In this study, the effect of the hilly terrain of the dune is investigated by organizing the ratio of the long-term land subsidence amount to the total subsidence amount against the distance from the dune, as shown in Figure 14. All plotted data belong to the terrain classification of the delta. Although the trend in the decrease of the ratio against the distance from the dune can be seen in the figure, it is not so clear. Moreover, it is possible to think the soil profile changes according to the distance from the dune, reflecting the change in the terrain classification from delta to valley plain. It is not feasible to instantly conclude the cause of the different subsidence trends between the delta and the valley plain as the effect of the topography seen in the results in the figure, but this issue needs to be examined further using other cases.

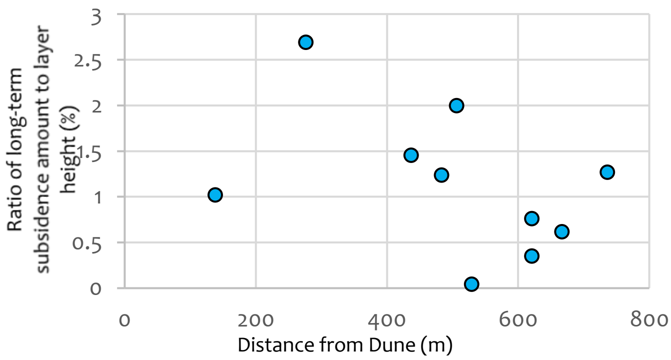

Figure 14 Long-term subsidence and distance from dune

5.2 Effect of Marine Clay Layer

The physical properties of the soils were surveyed for undisturbed samples taken from two sites, namely, Shimbashi and Miyaba. The basic physical indexes are shown in Table 1. The plasticity index of AC2 (marine clay) is higher than those of AC1 and AC2, and the liquid limit of AC2 (marine clay) is higher than that of AC2. The natural water content of AC2 (marine clay) is very high, 76.3%, and it shows that the clay layer of AC2 (marine clay) is thought to be highly compressible. Table 3 expresses the long-term land subsidence amounts in comparison with the layer thickness of AC2 (marine clay) at four points. It is seen that the long-term land subsidence amount can be correlated with the thickness of the marine clay of AC2 (marine clay).

Table 3 Long-term subsidence and marine clay

Location	Layer thickness of marine clay (m)	Long-term subsidence (mm)
Shimbashi	18.0	95.8
Yanagibashi	9.1	60.8
Miyaba	5.4	15.2
Motoshiro	6.15	23.0

Subsequently, oedometer tests were carried out to clarify the compression characteristics of the marine clay of AC2. Two specimen types were examined: (1) undisturbed specimens and (2) reconstituted specimens made from a slurry sample with water added. For the reconstituted specimens, the specimens for which the oedometer test of (1) had been done were reused. The purpose of these tests was to clarify the effect of the sedimentary environment on the mechanical properties of the undisturbed specimens. Figure 15 shows the e-logp' relationship observed in the oedometer tests for the samples from the shallow and deep layers. The figure indicates that the undisturbed specimens from each layer exhibited characteristics of high compressibility after the application of consolidation yield pressure (about 140 kPa) compared to those of the reconstituted specimens.

Inagaki et al. (2010) proposed a compression index ratio to represent the skeletal structure characteristics of the natural deposited clay. The compression index ratio was defined by the ratio of the compression indexes in the normal consolidation behavior of the compression curves of two samples, as Cc/Ccr, where Cc is the compression index of the undisturbed sample and Ccr is the compression index of the reconstituted sample which is prepared by kneading the same sample (destroying the skeletal structure) and consolidating it. From a survey of the post-service residual settlement of expressway embankments on cohesive soils, Inagaki et al. (2011) pointed out that the residual settlement tended to be greater than that by the design using Cc when Cc/Ccr > 1.5. The compression index ratio is similar in concept to the sensitivity ratio, but while the sensitivity ratio is defined using the strength, the compression index ratio is defined with respect to the deformation characteristics. Inagaki et al. (2010) and Tashiro et al. (2011) denoted that the clay, whose compression index ratio is greater than 1.5, is judged to have a highly skeletal structure and showed a remarkable deterioration in skeletal structure for application of an external load. According to Asaoka et al. (2000), the highly structured hilly clay tended to generate great land subsidence due to the degradation in its structure by the application of the load. The marine clay sampled at Shimbashi showed the compression index ratio as Cc/Ccr = 1.4 to 2.25; this proves that this marine clay has a highly skeletal structure. Therefore, it is possible that the plastic compression of the clay was caused together with the deterioration in the skeletal structure when subjected to cyclic shearing due to the earthquake. This feature indicates that the post-earthquake land subsidence was caused by the property of the highly skeletal structure of the marine clay.

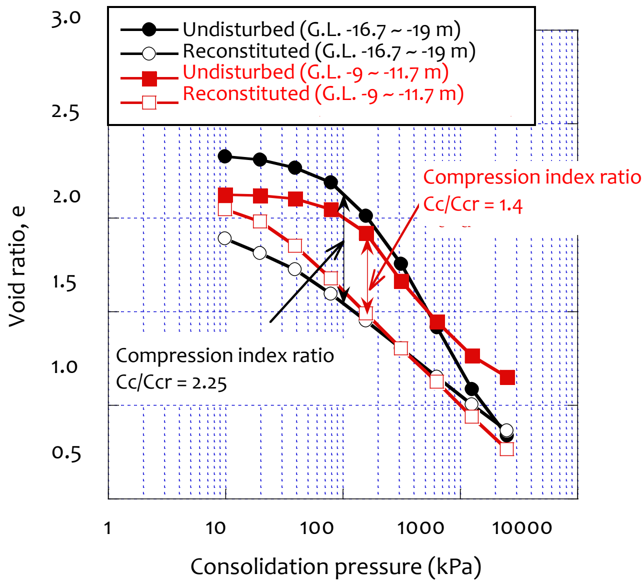

Figure 15 Compression characteristics of marine clay in undisturbed and reconstituted conditions

In the case of the highly structured soil, the sedimentary structure is progressively lost by a repeated shearing in the earthquake excitation. This causes the volumetric compression of the clay and resultantly generates excess pore water pressure during an earthquake (Asaoka, 2003). Yasuhara and Kazama (2015) reported that the sedimentary structure of clay was commonly observed from oedometer tests on clay sampled from the field where the earthquake-induced long-term subsidence had been generated in the 2011 off the Pacific coast of Tohoku Earthquake. This report supports the mechanism of the long-term subsidence induced by an earthquake and indicates the possibility that post-earthquake land subsidence is high in highly structured clay such as a marine clay. The sedimentary structure of the marine clay on the Kashiwazaki Plain is more developed than that of the terrestrial clay.

Although a post-earthquake settlement analysis of clayey soils was implemented based on the consolidation theory using the compression and consolidation coefficients of the soil, the magnitude of the pore water pressure generated by the earthquake is required in the computation. However, to assess the earthquake-induced pore water pressure, more tests for the dynamic deformation properties of the soil are needed. Due to the lack of experimental data, it is difficult in this study to assess the magnitude of the pore water pressure induced by the earthquake. The post-earthquake settlement analysis of clayey soils is a further target to be clarified.

6. CONCLUSIONS

The following conclusions were obtained from this study:

1) On the Kashiwazaki Plain, Niigata Prefecture, Japan, subsidence over a wide area occurred after the 2007 Chuetsu-Oki earthquake. By measurements taken with a stratified ground subsidence meter, it was clarified that the clayey layer caused long-term subsidence.
2) The amounts of instantaneous and long-term land subsidence were analyzed by a leveling survey at many points on the Kashiwazaki Plain. From the spatial distribution of the subsidence amounts, it was clearly shown that instantaneous land subsidence was generated in sandy soils, such as a dune, while long-term land subsidence was generated in clayey soils, such as a delta.
3) By investigating the correlation of the amount of land subsidence with the terrain classification, it was clearly shown that the amount of long-term land subsidence was large in the delta reflecting the thick marine clayey layer. On the contrary, the amount was very small on the valley plain even though the clayey layer was thick. Through physical tests, the distribution of marine clay was found to be the key when analyzing wide-area subsidence caused by the earthquake.
4) The physical characteristics of the marine clay were obtained as those commonly observed. However, the values for the compression index ratio (defined as the ratio of the compression index of the undisturbed samples to that of the reconstituted samples) were obtained as structured. This property was concluded as one of the possible causes of the earthquake-induced long-term subsidence of the marine clay.

7. ACKNOWLEDEMENTS

This work was supported by JSPS KAKENHI Grant Numbers JP16H02362 (K. Yasuhara). The authors are deeply grateful to Prof. K. Yasuhara for his valuable suggestions in the carrying out of this work. Moreover, the authors are grateful to Mr. T. Hasegawa, a former student in the graduate course at Nagaoka University of Technology, for his devoted support of this work.

8. REFERENCES

Asaoka, A., Nakano, M., Noda, T., and Kaneda, K. (2000) “Delayed compression/consolidation of natural clay due to degradation of soil structure”, Soils and Foundations, 40(3), pp75-85.

Asaoka, A. (2003) “Consolidation of clay and compaction of sand - An elasto-plastic description”, Keynote lecture, Proc. of 12th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Leung et al. Singapore, 2, pp1157-1195.

Council for Utilization of Hokuriku Geological Database System. (2018) Hokuriku Geological System database, http://www. jiban.usr.wakwak.ne.jp.

Hyodo, M., Yasuhara, K., and Murata, H. (1988) “Earthquake induced settlements in clays”, Proc. of 9th World Conference on Earthquake Engineering 1: III89 - III94.

Isobe, K. and Ohtsuka, S. (2013) “Study on long-term subsidence of soft clay due to 2007 Niigata Prefecture Chuetsu-Oki Earthquake”, Proc. of 18th International Conference on Soil Mechanics and Geotechnical Engineering, pp1499-1502.

Inagaki, M., Nakano, M., Noda, T., Tashiro, M., and Akira, A. (2010) “Proposal of a simple method for assessing the susceptibility of naturally deposited clay grounds to large long-term settlement due to embankment loading”, Soils and Foundations, 50(1), pp109-122.

Matsuda, H. (1997) “Estimation of post-earthquake settlement-time relations of clay layers”, J. of Japan Society for Civil Engineers, Div. C, 568(III-39), pp41–8. [in Japanese].

Ohara, S. and Matsuda, H. (1988) “Study on the settlement of saturated clay layer induced by cyclic shear”, Soils and Foundations 28(3), pp103-113.

Sato, H., Nhan, T., and Matsuda, H. (2018) “Earthquake-induced settlement of a clay layer”, Soil Dynamics and Earthquake Engineering 104, pp418–431.

Suzuki T. (1984) “Settlement of saturated clays under dynamic stress history”, J. of Japan Society of Engineering Geology 25(3), pp21–31. [in Japanese].

Tashiro M., Noda, T., Inagaki, M., Nakano, M., and Asaoka, A. (2011) “Prediction of settlement in natural deposited clay ground with risk of large residual settlement due to embankment loading”, Soils and Foundations, 51(1), pp133-149.

Yasuhara, K. and Andersen, K. H. (1989) “Post-cyclic recompression in clay”, Proc. of 4th International Conference on Soil Dynamics and Earthquake Engineering 1, pp159- 167.

Yasuhara, K. and Kazama, M. (2015) “Land subsidence of clay deposits after the Tohoku-Pacific Ocean Earthquake”, 9th International Symposium on Land Subsidence, Proc. of the International Association of Hydrological Sciences, 372, pp211–216.

Yasuhara, K., Konami, T., Hyodo, M., and Hirao, K. (1991) “Earthquake-Induced Settlement in Soft Grounds”, Proc. of 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics 3.9, pp365-370.

Zeevaert L. (1983) “Foundation engineering for difficult subsoil conditions”, New York: Van Nostrand.