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Long-term Settlement of Holocene Clay Induced by the 2011 off the Pacific Coast of Tohoku Earthquake

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ABSTRACT

The aim of the study reported in this paper is to reveal the long-term settlement of Holocene clay ground after the 2011 off the Pacific coast of Tohoku earthquake. The authors took level readings six times across Urayasu City, Chiba Prefecture, during the period from April 2011 to April 2013. The result is a chronological record of changes in settlement of first-order benchmarks and survey points showing that settlement is taking place due to the earthquake. In the Phase I reclaimed land (which was constructed between 1968 and 1975), the settlement rate is shown to be approximately 6 mm/year, more than twice the rate of settlement before the earthquake. In the Phase II reclaimed land (which was constructed between 1978 and 1980), the settlement behavior is found to differ according to whether the reclaimed land had been improved or not. Further, natural alluvial lowland has not settled since the earthquake.

Introduction

According to several settlement observations after earthquakes, ground starts to settle strongly and subsidence occurs over a long period of time following an earthquake, particularly in soft cohesive ground. Such phenomena have been reported in Japan; for example, the 1978 off the coast of Miyagi Prefecture earthquake (Towhata (2008)), the 1995 southern Hyogo Prefecture earthquake (Matsuda and Nagira (2000)) and the 2007 Niigataken Chuetsu-oki Earthquake (Koishi et al. (2012)). In all cases that occurred in Japan, the foundation ground consisted of soft Holocene clay.

Previous studies by centrifuge model tests (e.g., Hotta et al. (1998); Fiegel et al. (1998)) and numerical simulation (Noda et al. (2009)) have shown that settlement of ground can be induced by earthquakes. This is probably because some amount of excess pore water pressure develops during the shaking in cohesive soil, as well as in sandy soil, and its dissipation induces volume contraction. In addition, unlike in the case of sandy soil, it has been reported that settlement starts a few months or a few years after an earthquake takes place (Towhata (2008)). This means the post-disaster situation cannot be understood by simply conducting a damage survey just after an earthquake. Reports (e.g. Yasuhara et al. (1998); Towhata (2008)) indicate that long-term settlement after an earthquake may occur in ground formed mostly in soft cohesive sediments. However, these reports were based on observations of settlement monitoring points, not on area-wide surveys. Thus, no precedent exists for continuously monitoring subsidence following an earthquake over a large area where soft cohesive soils are deposited.

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Since the 2011 off the Pacific coast of Tohoku earthquake (hereafter referred to as the "Tohoku Earthquake"), the authors have taken six level readings across Urayasu City in Chiba Prefecture, where there is a thick layer of Holocene clay. In this paper, the data collected from April 2011 to April 2013 are first presented, and the settlement trends are then discussed.

Geological Conditions

The location and landform classification of Urayasu City (GSI, 2015a) are shown in Figures 1 and 2. The city was formed by reclaimed land along the shores of Tokyo Bay, and three-quarters of the city stands on reclaimed land (Chiba Prefecture, Urayasu City, 2015). Reclamation began in 1968 and was completed in 1980, with the work taking place in phases: Phase I ran from 1968 through 1975, with the rest of the reclamation taking place in Phase II from 1978 through 1980. Figure 3 shows the history of this land reclamation as well as two geological sections through Urayasu City (Chiba Prefecture (2015a); Chiba Prefecture, Urayasu City (1986)). The data in this figure were obtained on the basis of borehole investigations (locations plotted in Figure 2). The vertical axis shows the elevation relative to the mean sea level of Tokyo Bay (elevation 0 m); this elevation value is commonly referred to as Tokyo Peil (T.P.) (GSI, 2015b). Buried valleys and buried terraces are present below Urayasu City, causing complex variations in the thickness of the Holocene clay.

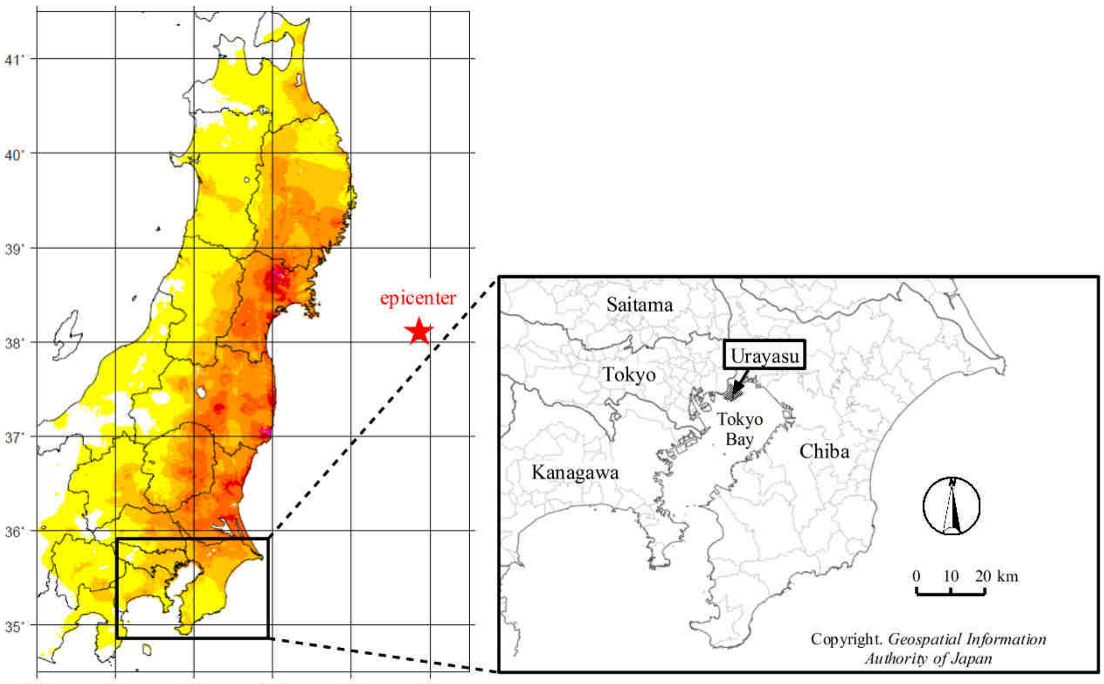

Figure 1. Location of Urayasu City, Chiba Pref.

In this paper, a clay layer with an SPT *N*-value less than 3 is defined as the "Ac" (Holocene clay) layer. Along line A-A' the Ac is 25 to 40 m thick, while along B-B' it is 10 m thick near the old coastline to the northern end and 30 m thick at the seaward end, with a marked thickening towards the sea (in the southeast direction). Given the situation, there were concerns about

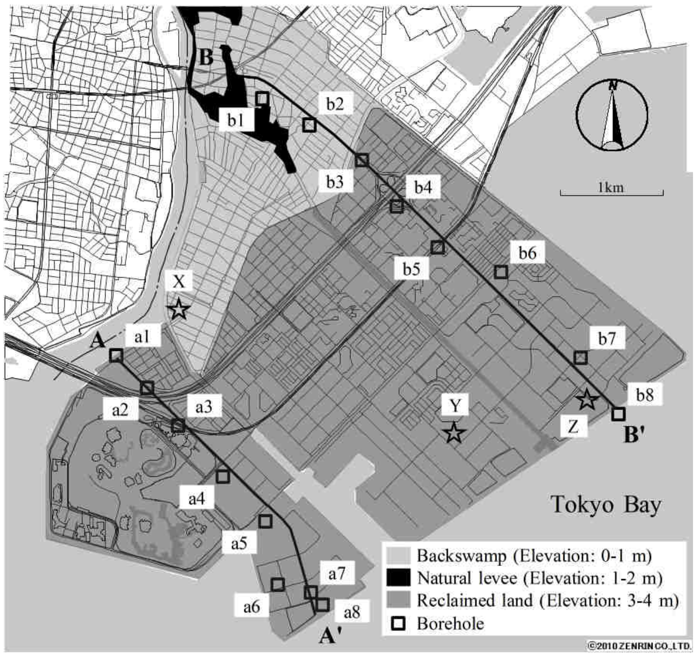

Figure 2. Landform classification and borehole map of Urayasu City (Chiba Prefecture, 2015a; GSI, 2015)

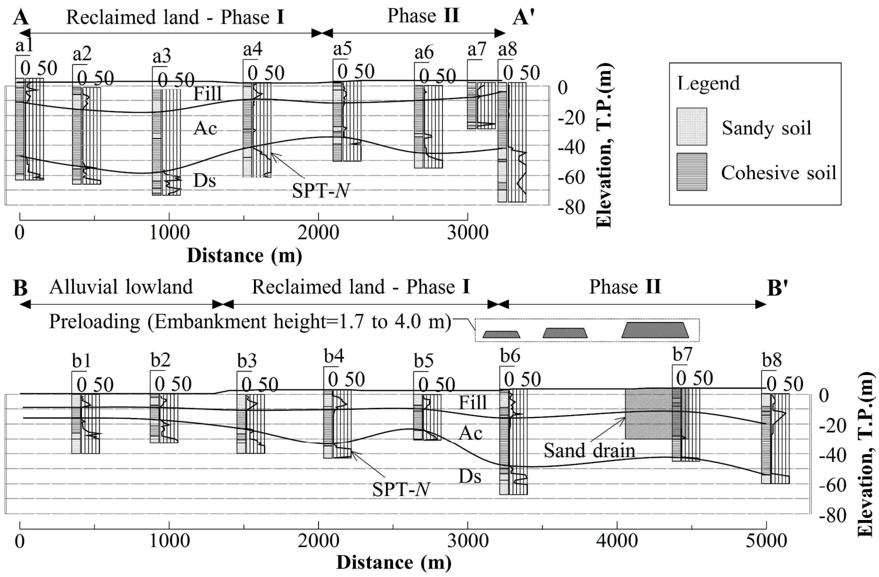

Figure 3. History of land reclamation and geological cross-sections through Urayasu

consolidation of the reclaimed ground from the beginning of the reclamation work. According to a contemporary report on foundation improvement work (Jinbo and Kimura (1994)), the eastern side of the area reclaimed in Phase II was improved using sand drain (SD) and/or fill preloading (PL) methods as a solution to this problem. The improved area is indicated in Figure 3.

Additionally, natural sand deposits required liquefaction countermeasures because the ratio of safety to liquefaction (FL value) was less than 1.0. In consideration of economics and applicability, the sand compaction pile method was chosen (Jinbo and Kimura (1994)). The liquefaction countermeasures were used only at the location of roads.

The depth profiles of consolidation yield stress of Holocene clay derived from sites X, Y and Z are shown in Figure 4. Locations of X, Y and Z are plotted in Figure 2. Site X is located in the alluvial lowland, and OCR values of 1.0 to 2.7 were observed with soil samples from layer Ac at site X. Site Y is located in the reclaimed area, and OCR values of layer Ac range from 1.5 to 2.4. Site Z is also located in the reclaimed land. At site Z, layer Ac is lightly overconsolidated at the depth less than GL-30 m. In addition, normally consolidated clay lies at a depth ranging from GL-30 to -55 m.

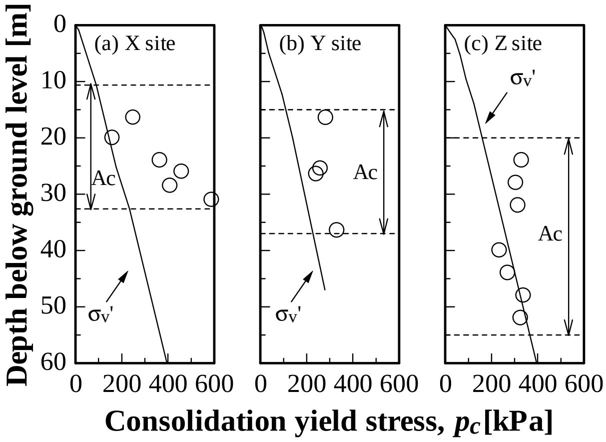

Figure 4. Depth profiles of consolidation yield stress (adopted from Murakami et al., 2013)

Outline of Level Surveys

Level surveys were performed on two survey lines across Urayasu City. Figure 5 shows the locations of the survey lines, survey points, and first-order benchmarks (as managed by Chiba Prefecture) (Chiba Prefecture (2015a)). Line-A connects Maihama with Chidori. It has a total length of about 3 km. Line-B, taking Urayasu Station (on the Tozai subway line) as its starting point, links Kitazakae and Nekozane with Hinode and Akemi. It has a total length of about 5 km. These lines were chosen to cross the alluvial lowland and reclaimed land from northwest to southeast in order to look squarely at the relation between long-term settlement after the Tohoku Earthquake and the reclamation history. Neighborhoods toward the southern ends of these lines lie on comparatively new land. Ten survey points were selected on Line-A and eleven on Line-B. The interval between these points ranges from 150 to 800 m. The points were selected as having a small chance of being redeveloped, demolished, removed, or suffering local subsidence due to road construction work since the intention is to obtain accurate level data over a long period. The same points were surveyed in each set of level readings. All reference marks, so as not to be affected by ground level fluctuation, were set up on structures supported by bearing piles or on elevated bridge piers. The type of foundation was identified by company or public records of construction (Japan Railway Construction Public Corporation (1991)).

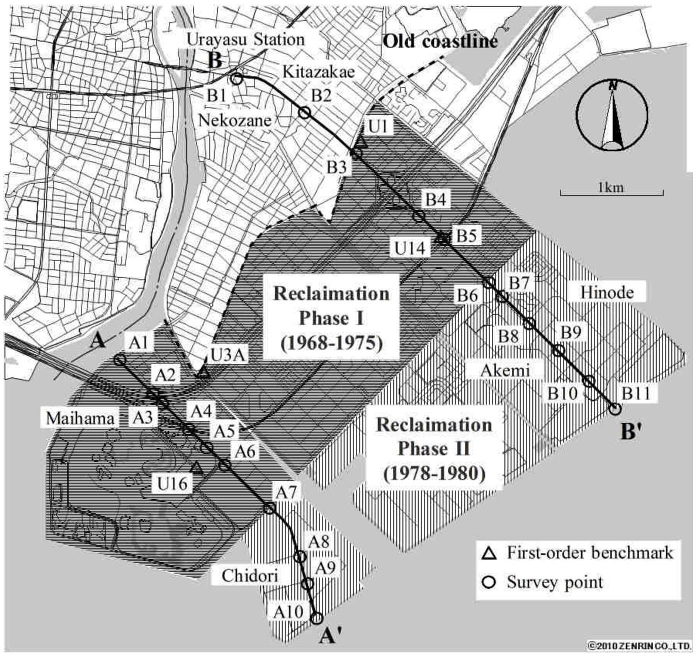

Figure 5. Location of survey lines, survey points, and first-order benchmarks

To control the accuracy of the measurements, two-direction observations were conducted between three or four survey points. The tolerance of misclosure is defined by the following formula:

$$C = m\sqrt{S} \quad (1)$$

in which *C* is misclosure, in mm; *m* is constant; and *S* is the total length leveled, in km. This definition is given in the rules for public surveying established by the Ministry of Land, Infrastructure, Transport and Tourism (GSI, 2015c). In this survey, the observational accuracy is classified as first-order leveling by setting the constant m to 2.5:

$$C = 2.5\sqrt{S} \quad (2)$$

Because S ranges from 0.3 to 1.4 km, C ranges from 1.3 to 2.9 mm.
Measurements began in April 2011 and survey point levels have been taken six times, as of April 2013 (including measurement of the initial levels). In addition, the first-order benchmarks were measured each time.

Survey Results and Discussion

Subsidence Trend after the Tohoku Earthquake

Figure 6 and 7 shows the chronological changes in settlement along the two survey lines. Leveling data affected by disaster-relief work, such as a survey point being significantly displaced, is removed (survey points A8, A9, A10 and B8).

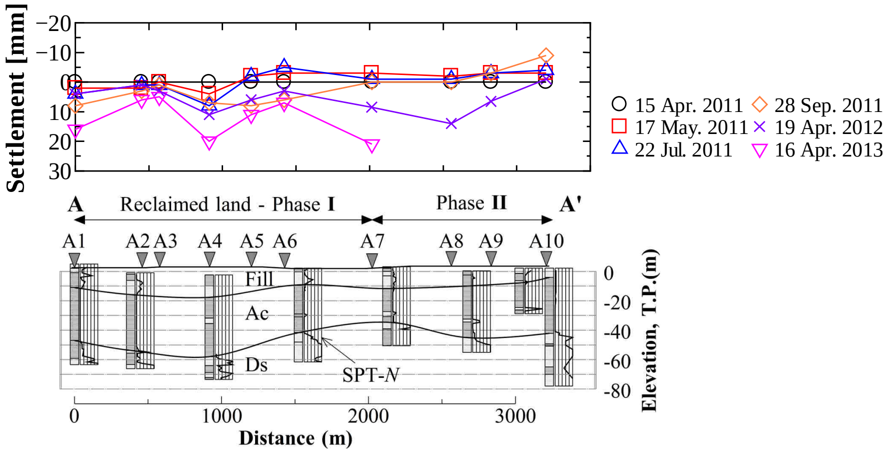

Figure 6. Chronological changes in settlement along the survey line: Line-A

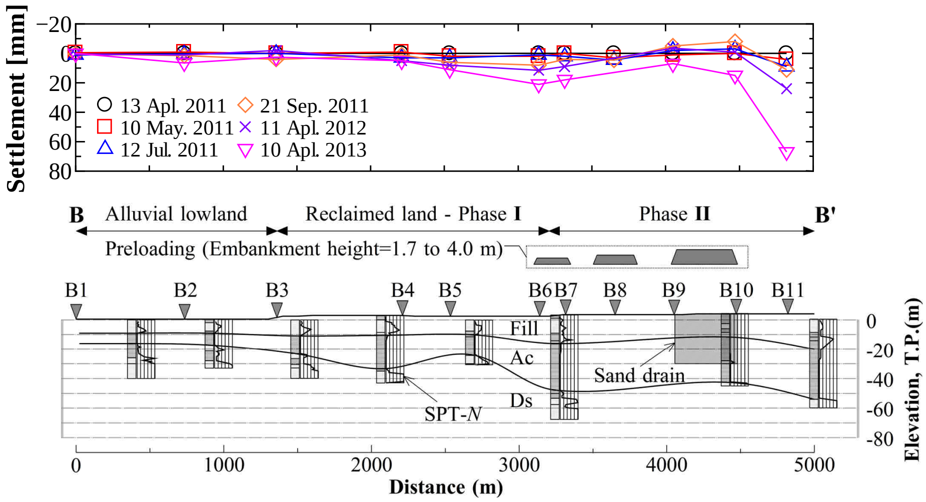

Figure 7. Chronological changes in settlement along the survey line: Line-B

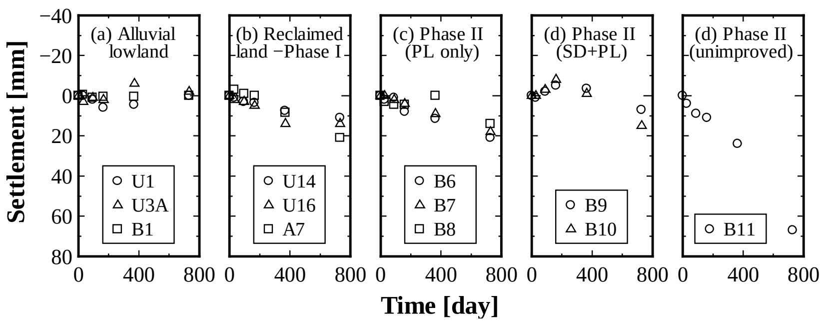

Figure 8. Typical time history of settlement by area

Figure 8 shows the measured settlement of the survey points and first-order benchmarks with respect to the initial April 2011 elevations recorded after the Tohoku Earthquake. In the time history of the settlement of the points located in alluvial lowland shown in Figure 7(a), none of these points have settled significantly. As seen in Figure 5 previously, these three points lie near the alluvial lowland ground which was deposited over ten thousand years ago (Japan Railway Construction Public Corporation (1991)) and therefore compacted more than reclaimed ground.

Moreover, as seen in Figure 4, layer Ac in this ground is overconsolidated as compared to reclaimed land. From these it is considered that the post-earthquake settlement rate at these points is not greater than before the earthquake. Figure 8(b) shows the settlement of the points located in the Phase I reclaimed land. In contrast, settlement induced by the Tohoku Earthquake was observed on this reclaimed ground. Figure 8(c), (d) and (e) show the settlement of survey points B6 to B11 after the Tohoku Earthquake. These points are all located on the Phase II reclaimed land. Nevertheless, the ground settlement behavior of each point is different. As already noted, eastern areas of the Phase II reclaimed land were improved using the SD and PL methods. Survey points B9 and B10 lie within this improved area using both SD and PL, so they showed the least settlement. On the other hand, survey point B11 is located in an unimproved area, so it has seen significant settlement. These results demonstrate that the long-term settlement behavior of the Holocene ground since the earthquake differs according to whether the area was reclaimed or reclaimed and then improved.

Comparison of the Settlement before and after the Tohoku Earthquake

Figure 9 shows the overall time history of the settlement of benchmarks (Chiba Prefecture (2015b)). It describes the vertical displacement of the ground surface, which includes the following components: consolidation settlement following reclamation before the earthquake; immediate post-earthquake settlement caused mainly by liquefaction of fill layers; and long-term settlement of the Holocene clay following the earthquake. Fukutake and Jang (2013) calculated the ground settlement after the earthquake by obtaining the volumetric strain from the maximum shear strain using the equation of Ishihara and Yoshimine (1992). Their result indicated that the amount of settlement in the liquefaction layer should be 10 to 20 cm, which is roughly in accordance with the value (15 cm) found in Figure 9. For the purpose of investigating the long-term settlement trend following the earthquake, fitted lines obtained by the method of least squares are shown. Figure 9(a) and (b) shows the vertical displacement of benchmarks U1 and U3A, situated above the alluvial lowland of the old coastline. As mentioned above, these points have not settled. On the other hand, benchmarks U14 and U16 located centrally in the Phase I reclaimed land show a monotonic downward settlement after the Tohoku Earthquake (Figure 9(c) and (d)). In the case of benchmark U14, consolidation settlement by reclamation had been finished before the earthquake. However, subsidence has re-occurred since the earthquake. The two lines have almost the same gradient and the settlement rate is 5.4 to 6.6 mm/year. As for benchmark U16, the post-earthquake settlement rate is 2.2 times its value before the earthquake. According to the results of soil element tests on cohesive soil (Tamura et al. (2006)), the volumetric strain after cyclic shear is dependent on the maximum shear strain developed during the cyclic shear. It seems that post-earthquake settlement in in-situ ground occurs by same mechanism as seen in the laboratory tests. Certain parts of reclaimed land in Urayasu (e.g. the area around benchmark U16) have settled since reclamation. Then, the cyclic shear stress generated by the earthquake acted on this ground, and increased the rate of subsidence.

Conclusions

The authors carried out level surveys with the aim of observing the long-term settlement of Holocene clay in Urayasu City, Chiba Prefecture, following the 2011 off the Pacific coast of Tohoku earthquake. Two survey lines were set, crossing the alluvial lowland and re-claimed land from northwest to southeast, and level readings have been taken six times since the earthquake. The results of the investigations so far can be summarized as follows:

1) Long-term settlement of Holocene clay following the earthquake was observed at the first-order bench-marks and the survey points on reclaimed ground. The alluvial lowland has not settled since the earthquake.
2) In the Phase I reclaimed land, settlement observed after the earthquake was linear at a rate of approximately 6 mm/year. This is more than twice the settlement rate observed before the earthquake. That is, the earthquake has increased the rate of subsidence of Holocene clay ground.
3) In the Phase II reclaimed land, settlement behavior differs according to whether the reclaimed land had been improved or not. Vertical displacement was relatively little in improved areas, both where sand drain and fill preloading methods had been used, and was significant in the unimproved area.

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