SOIL LIQUEFACTION IN THE TONE RIVER BASIN DURING THE 2011 EARTHQUAKE OFF THE PACIFIC COAST OF TOHOKU

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abstract

A brief report about the liquefaction damage in the Tone river basin, caused by the 2011 earthquake off the Pacific coast of Tohoku, is presented. It includes sand boiling, damage to river dikes, the settlement and tilt of superstructures, the uplift of light underground structures and lateral spreading. A history of land reclamation along the Tone river is briefly presented to understand why extensive liquefaction took place predominantly in reclaimed land. The recorded ground motions near the river were analyzed and compared to near-source ground motions. The effects of the site location and the ground conditions during the peak ground acceleration are discussed.

keywords

2011 earthquake off the Pacific coast of Tohoku, liquefaction, case history

1 INTRODUCTION

HISTORY OF TONE RIVER BASIN

The Tone river (in Japanese, Tone-gawa) originates in the volcanic area of the northwestern Kanto region and flows approximately 320 km southeast, crosses the Kanto Plain with the Tokyo Metropolitan area, and finally enters the Pacific Ocean at Choshi City. No other river in Japan has been so modified by human activity [1]. Its course has been altered and its entire length is confined by dikes. The ancient Tone river flowed to Tokyo Bay; however, its course was diverted to the Pacific Ocean during the 17th century (Fig. 1). Although the main purpose of the project was to protect the capital of Japan, Tokyo, from floods, there have been infinitely many floods in the rest of river basin since then.

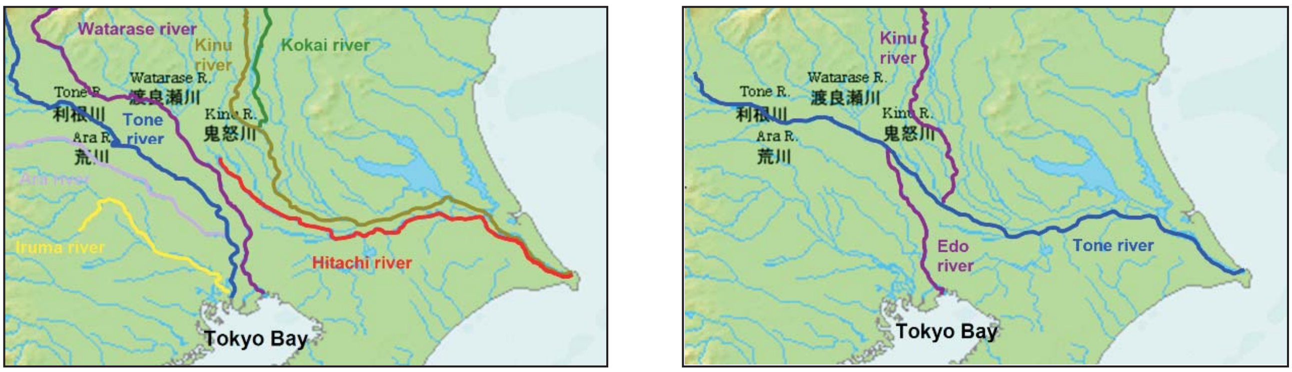

Figure 1. Eastward diversion of Tone river (modified from [2]): original course (left) and diverted course (right).

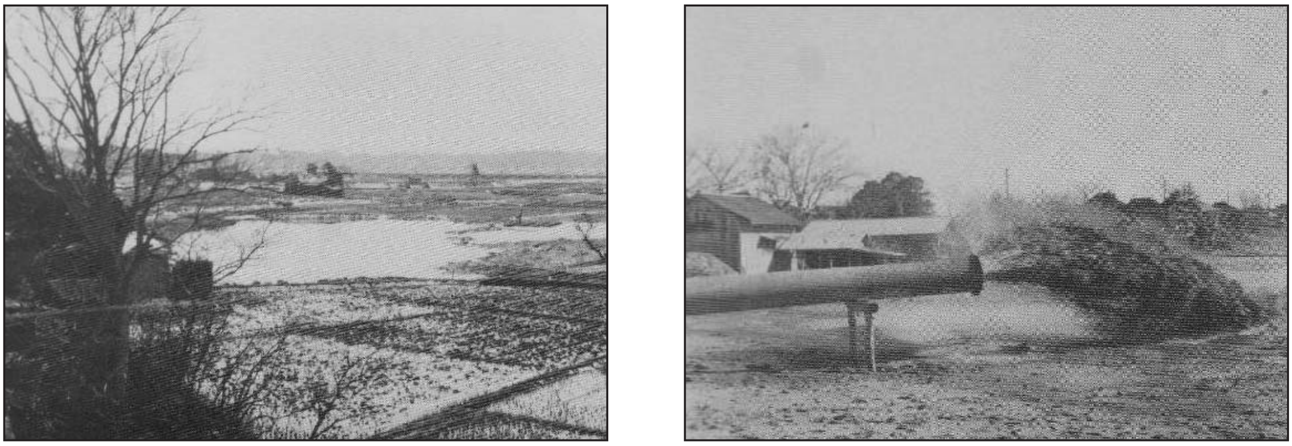

Figure 2. "Kirisho-numa" swamp (left) and its reclamation using dredged soils (right) [3].

One of the floods caused the breaching of the Tone river dike near Fusa, Abiko city in Chiba prefecture in 1870 [2]. The embankment for controlling the waters of the river collapsed over a length of more than 80 m and submerged the whole Fusa area. A large swamp called "Kirisho-numa" with an area of more than 5 ha was created. This area suffered from frequent flood disasters. Therefore, a project to improve the Tone river channel and the dike was initiated in 1952. The dredged soil was transported through pipes to reclaim the swamp. Finally, the reclaimed area was converted into a residential area. The "Kirisho-numa" swamp and the process of its reclamation using dredged soils are shown in Fig. 2.

2011 EARTHQUAKE OFF THE PACIFIC COAST OF TOHOKU

One of the world's largest recorded earthquakes in history, with a moment magnitude $M_w = 9.0$, occurred and affected the east part of Japan on the 11th of March 2011 at 14:46 local time. It was caused by tectonic movements of the North American plate and the Pacific plate. The Geospatial Information Authority of Japan [4] constructed a fault model using co-seismic, surface-displacement data observed by the GPS Earth Observation Network System. A fault model that consists of two rectangular faults with a uniform slip in an elastic half-space shows that the total major rupture length reached approximately 380 km with a fault width of 90-130 km. The slip amounts of the northern and southern segments were estimated to be ~25 m and ~6 m, respectively [4].

Fig. 3 shows the surface displacements caused by the main shock. A star indicates the epicenter of an earthquake. Two rectangular faults were assumed. The circles indicate the epicenters of the aftershocks determined until the 15th of March. There have been 408 aftershocks with a magnitude of 5.0 or above up until the 15th of March at 5 p.m. [5], indicating a tendency of tectonic plates and faults to stabilize ground conditions, which have been greatly altered by the earthquake.

The existence of two faults might be proved by the near-source acceleration waveforms. Two remarkable distinct phases of ground motion can be seen on the earthquake ground-motion records from seismographs in the north part of Honshu island [6], which are the closest to the epicenter, while on the acceleration waveforms recorded in the south, in the Tone river basin, the first phase is not visible at all (Fig. 6).

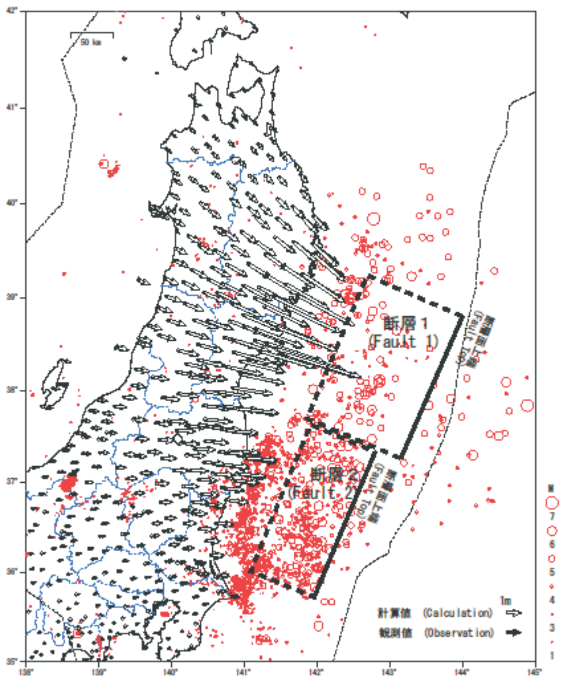

Figure 3. Calculated and observed co-seismic horizontal surface displacements [4].

2 GROUND-MOTION CHARACTERISTICS DURING THE 2011 EARTHQUAKE OFF THE PACIFIC COAST OF TOHOKU

THE EFFECT OF SITE LOCATION

Although the damage due to the great Tohoku earthquake occurred at many places on the east part of Honshu island, only five typical sites with liquefaction occurrence in the Tone river basin are presented in this paper. Their locations are shown in Fig. 4b. Fig. 4a presents the overall location of the earthquake's hypocenter, the Tone river basin and the seismographs, the records of which are discussed in this paper.

To understand the transfer of ground shaking from near-source to more distant sites, we compare the earthquake motion records from six sites of the Japanese seismograph network. The seismographs CHB004, IBR016, MYG004 and MYG010 are part of K-NET, a Japanese, nation-wide, strong-motion seismograph network. They are all installed on the ground surface. Seismograph CHBH13 is part of KiK-net, a Japanese, strong-motion, seismograph network, which consists of pairs of seismographs installed in a borehole as well as on the ground surface. Basic data about these seismographs are listed in Table 1. Their location is shown in Fig. 4a and Fig. 4b.

It is evident from Table 1 that the levels of ground shaking recorded during the 2011 earthquake off the Pacific coast of Tohoku were very high and the values of the peak ground accelerations (PGAs) at some seismograph locations, e.g., PGA≈3.0g at MYG 004, exceeded all reasonable expectations. It is difficult to explain such values, particularly as there was no extra damage observed on bridges or buildings in Tsukidate, where this record was made [8]. It is supposed that the design values of the PGAs less than 1.0g were used in the design. A detailed insight into the acceleration record shows a sharp spike. It might not be caused directly by seismic-induced ground motions, but by some other impacts that happened nearby (some banging) during the earthquake's

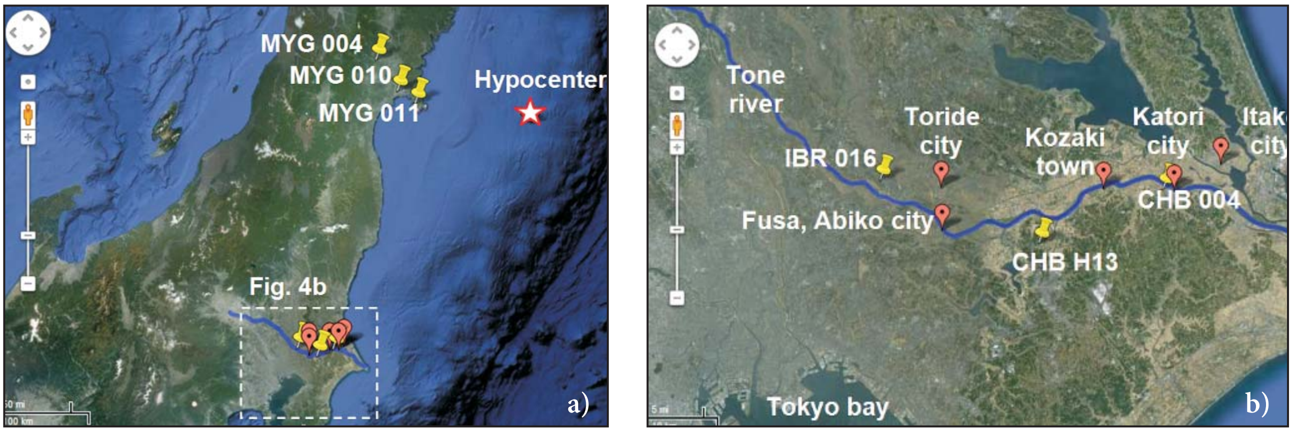

Figure 4. Map of the sites discussed in the paper (a) and their detailed locations (b) along the Tone river (modified from http://maps.google.com).

Table 1. Details about the K-NET and KiK-net seismographs [7].

Seismograph	Epicentral distance [km]	Altitude [m]	Peak acceleration* [cm/s^2]	Depth [m]	Base
CHB 004	323	13.9	300.7	surface	Ash clay, sandy soil
CHB H13	340	12	233.9	surface	sandstone, siltstone, mudstone and conglomerate (surface)
			56.9	1300	Chert (bedrock)
IBR 016	350	20.4	516.7	surface	Ash clay, sand
MYG 004	175	40	2699.9 (spike)	surface	Clay, rock
MYG 010	143	2	458.2	surface	Sand
MYG 011	121	13.2	921	surface	Rock

* maximum value of NS/EW components

duration. If this spike is eliminated the maximum PGA of this record is reduced by more than half.

The subsoil condition with a firm base in the cases of two extreme PGA values (MYG 004 and MYG 011) differs slightly from the subsoil conditions at the other discussed locations, where sandy soil is observed in the base. There is no evidence that this could be a reason for the sharp spike phenomenon in the case of MYG 004. Sharp spikes could also be caused by another kind of source, e.g., some banging near the instrument. In general, these kinds of spiky accelerations can be safely ignored as they do not allow sufficient time to cause large deformations. On the other hand, seismograph MYG 011 is located on a slope, suggesting possible topographical amplifications [9], while seismograph MYG 004 is located on flat ground.

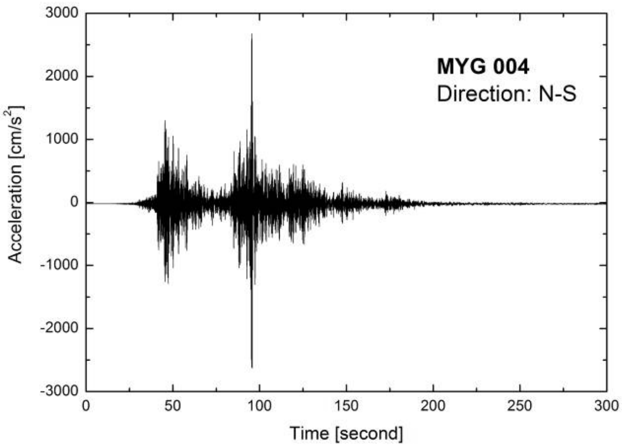

Figure 5. Ground-motion record with the largest observed peak ground acceleration PGA=2699.9 cm/s^2 during to the 2011 earthquake off the Pacific coast of Tohoku, K-NET seismograph MYG 004.

Nevertheless, we can also observe high PGA values at all the other listed locations, on average almost 0.4g. It should be noted that the PGA at the near-source location (Miyagi prefecture) is comparable to the PGA recorded at the locations in the Tone river basin, although the epicentral distance in the case of the latter is almost twice as large as in the case of the

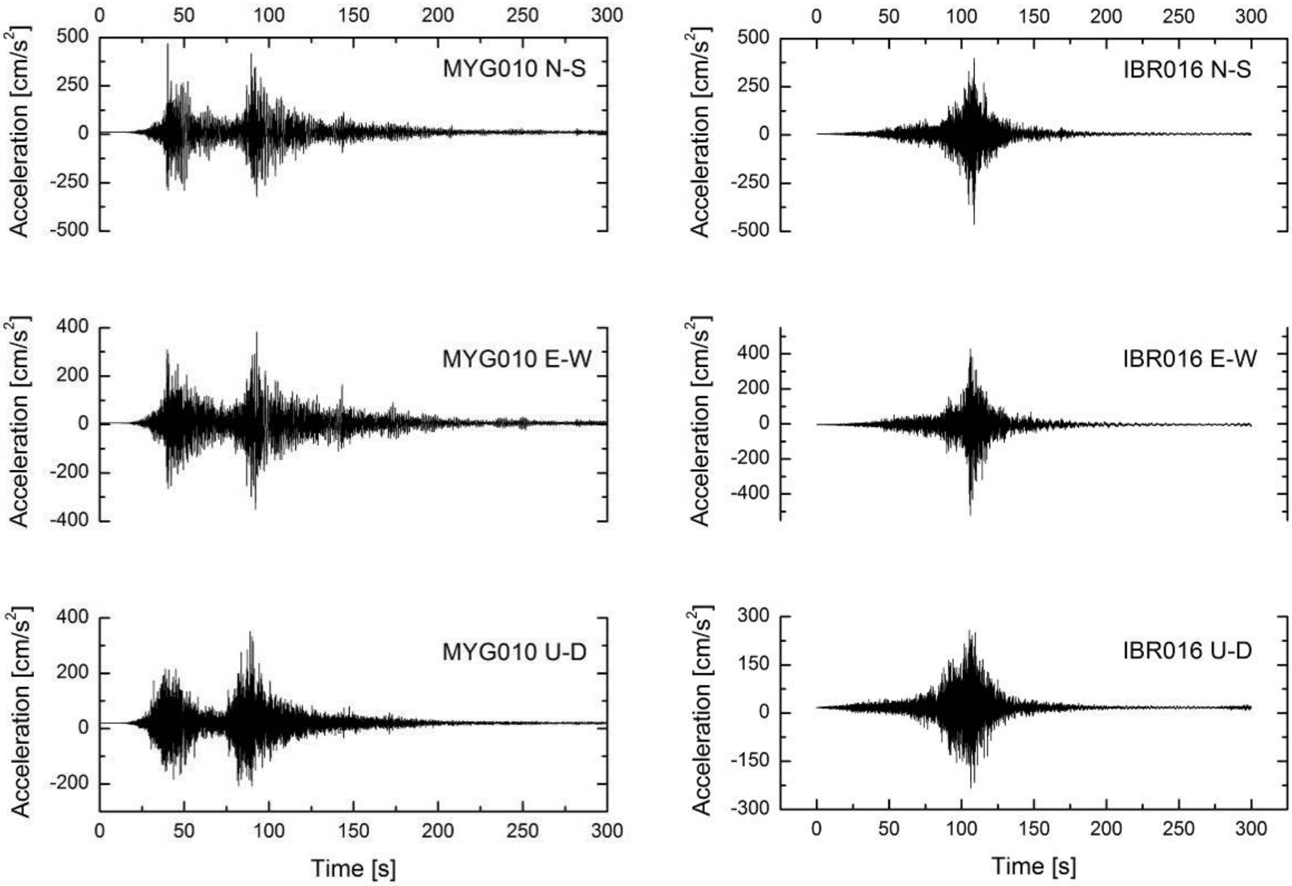

Figure 6. Ground-acceleration records at (left) the near-source K-NET seismograph (MYG 010) and (right) the K-NET seismograph near the Tone river (IBR 016).

Miyagi prefecture. One should refer to Fig. 3, where the assumed faults are shown. A similar distance to rupture is evident for both locations.

Spectral analyses of the ground acceleration records are shown in Fig. 7. It is clear that the dominant period ranges up to 2 s at the near-source sites in Miyagi prefecture, while the dominant frequency increases up to a period of nearly 0.2 s at sites near the Tone river.

THE EFFECT OF THE AMPLIFICATION OF MOTION IN THE SURFACE ALLUVIUM

Ground motion records at two selected K-NET stations and one selected KiK-net station near the Tone river do not differ a lot. The durations of the shakings were rather long, 100-200 s, suggesting that the soil was subjected to a large number of load reversals. The selected stations are located at soft alluvium soils with shear-wave velocities of less than 500 m/s in the upper 20 m. The soil profiles are similar, consisting of sand or sandy soil covered by volcanic ash clay (Fig. 8). Considering the high level of ground water, as the Tone river is near, these ground conditions combined with a large number of load cycles are sufficient for triggering the liquefaction.

The seismograph CHBH13 is part of the KiK-net network, and the motion records at the surface and at the bedrock (1300 m deep) are available. Soil profile from deep borehole of seismograph CHBH13 is presented in Fig. 9, while Fig. 10 shows the effect of surface alluvium layers on the wave propagation. A clear amplification of the acceleration in the top soft soil layers can be seen. Results of spectral analysis of ground motion records at bedrock and surface are compared on Fig. 11. Besides the amplification, one can observe that surface record results dominant period close to 0.2 s which is very similar to those obtained in other locations near Tone river (Fig. 7), while slightly smaller dominant period ranges of nearly 0.1 s is achieved at the bedrock.

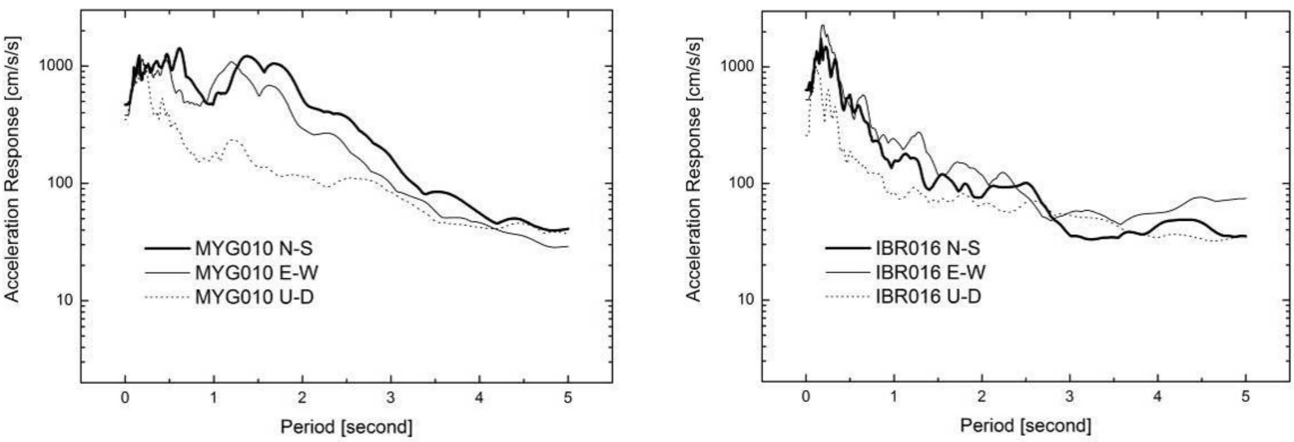

Figure 7. Spectral analysis of ground-motion data (5% damping) at (left) the near-source K-NET seismograph (MYG 010) and (right) the K-NET seismograph near the Tone river (IBR 016).

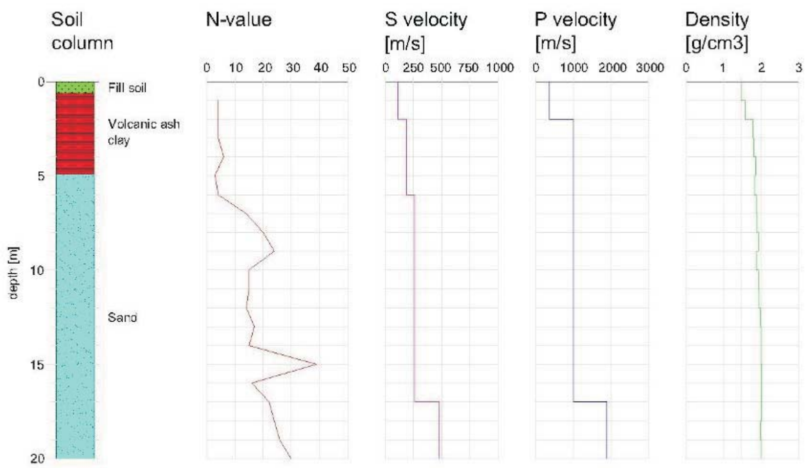

Figure 8. Typical shallow (20 m) soil profile along the Tone river, K-NET station IBR 016 (data from [7]).

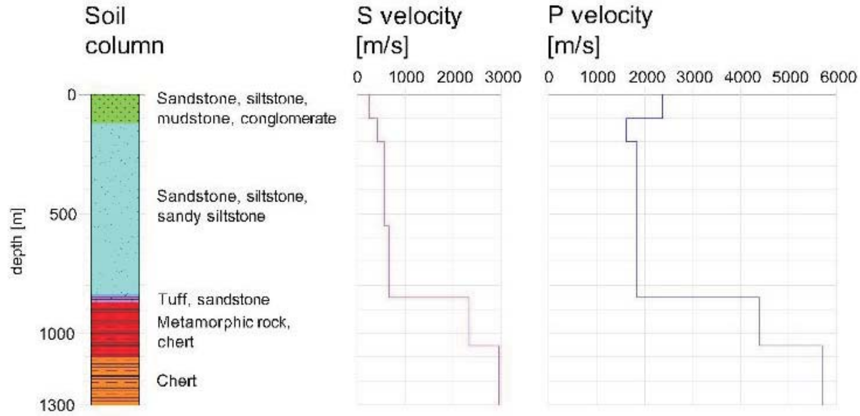

Figure 9. Soil profile from the deep borehole (1300 m) at the KiK-net station CHB H13 (data from [7]).

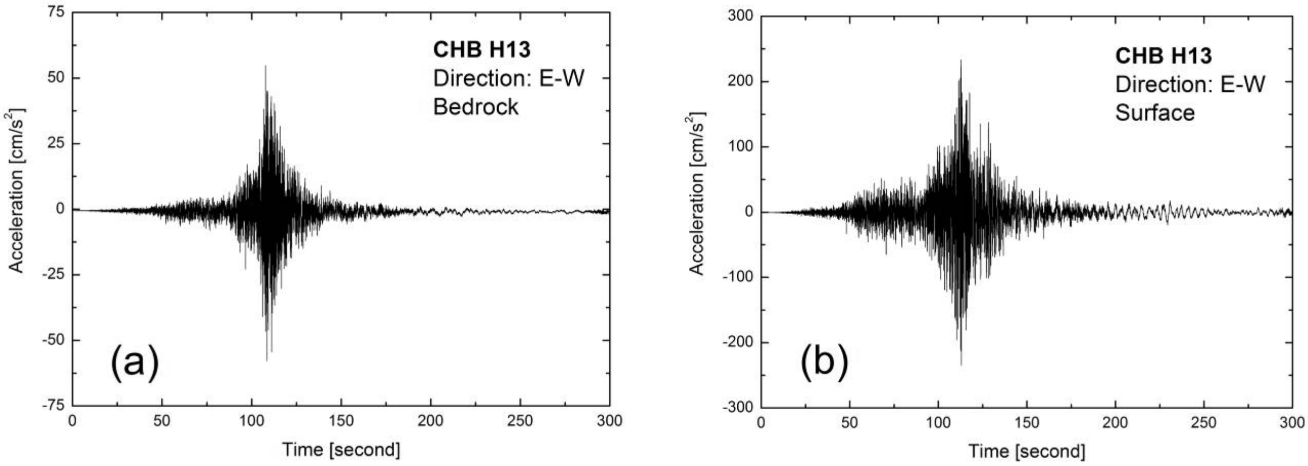

Figure 10. Amplification of ground motion as evidenced from (a) ground motion recorded at the bedrock and (b) ground motion recorded at the surface at CHB H13 location (KiK-net).

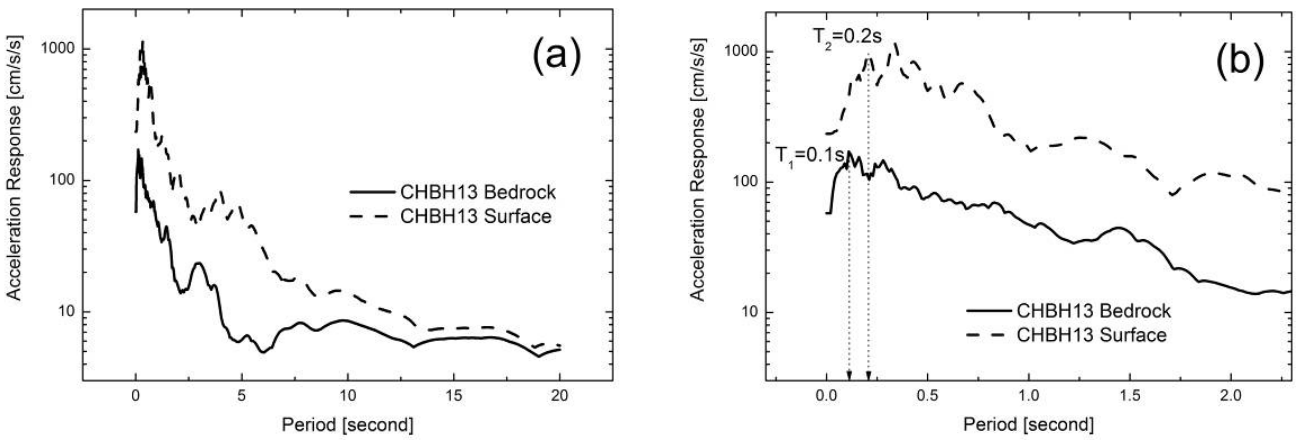

Figure 10. Comparison of the spectral analysis of ground motion data (5% damping) recorded at bedrock and surface at CHB H13 location: (a) overall and (b) close look (KiK-net).

3 LIQUEFACTION OCCURRENCE ALONG THE TONE RIVER AND ITS EFFECTS

The following photographs were taken during a post-earthquake survey [10, 11] at five sites (see Fig. 4) with liquefaction occurrence in the Tone river basin. The consequences of liquefaction are briefly described.

SAND BOILING

Sand boiling was observed almost everywhere that the liquefaction occurred. If the ground is covered by a less permeable layer, e.g., volcanic ash clay, small cracks or channels are formed to dissipate the seismically induced, excess pore-water pressure. The water velocity was sufficient in cases presented in Fig. 12 to carry fine sand to silt soil particles to the surface. The gradation curves of the samples from several locations of sand boiling are presented in Fig. 18.

DAMAGE TO RIVER DIKES

The settlement and cracking of the Tone river dike occurred at many places, mostly due to the shear failure of the slope itself or the liquefaction of subsoil layers and/or a submerged part of the dike itself. The damaged dikes were temporarily rehabilitated against possible high water and protected against rainfall infiltration (Fig. 13).

Figure 12. Extensive sand boiling (a) at the rice field in Toride city and (b) between residential houses in Abiko city.

Figure 13. Extensive protection of the damaged Tone river dike (Sakae town) against rainfall.

SETTLEMENT AND TILT OF HEAVY STRUCTURES

Liquefaction-induced ground-surface settlements are caused by the volumetric strain that develops as a consequence of sand boiling and the re-consolidation of the liquefied soil layers. As superstructures with shallow foundations are often of asymmetric self-weight or subsoil conditions are not perfectly uniform, settlements might be accompanied by tilt (Fig. 14b). The average range of settlements noticed at the described sites was between 10 and 30 cm, but might be up to 1 m in some extreme cases (Fig. 14a).

UPLIFT OF LIGHT UNDERGROUND STRUCTURES

Many manholes, sewerage pipelines and other underground structures with small self-weight were popped out of the ground due to the upward buoyancy force generated by the liquefaction of the surrounding soil (Fig. 15). Based on the observed damage, we can see that good backfill material is needed to avoid the uplift of light underground structures due to the liquefaction of backfill material. Other kinds of countermeasures should be taken if this is not possible. Some sewage manholes have been protected by adding a mass to increase the self-weight, or adding a drainage capacity, among others.

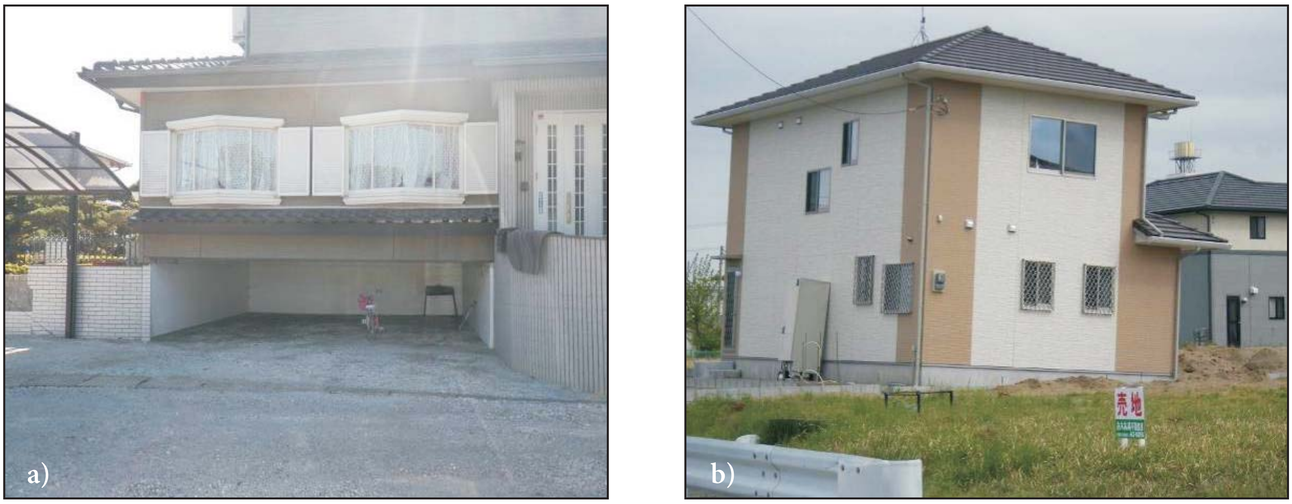

Figure 14. Residential houses in Itako city settled (a) evenly or (b) with tilting.

Figure 15. Uplift of (a) pipeline in reclaimed land of Itako city and (b) underground tank in Kozaki town.

Figure 16. Lateral spreading with a maximum horizontal displacement of about 1 m in Katori city.

LATERAL SPREADING

Lateral flow occurs in the case of very gently sloped ground underlain by a liquefied layer, or a liquefied soil layer at the back of a quay wall or a revetment that undergoes a residual outward displacement. It was observed to a limited extent in some areas facing towards a river or pond (Fig. 16).

DIFFERENTIAL SETTLEMENTS

In general, superstructures supported on deep foundations, e.g., a pile foundation, in the case of important infrastructure, e.g., viaducts, bridges, and multi-storey buildings, performed well, even when the subsoil liquefied. Many of these kinds of foundations were designed in Japanese practice by considering the possible effects of liquefaction. However, liquefaction-triggered uneven settlements of the surrounding ground caused a lot of damage to connecting pipes (Fig. 17).

Figure 17. Settlements of the ground around buildings with deep foundations in Katori city.

4 DISCUSSION

As stated above, samples from sand boiling at several places were collected and their gradation curves were defined. They were compared to three European soils with an estimated liquefaction potential [12, 13, 14]. The results are all presented in Fig. 18. It is clear that the gradation curve of the Bostanj silty sand [13] fits very well with the gradation curves obtained from the sand-boiling samples, while gradations of other two soils noticeable differ from the gradation of sand-boiling samples.

We do not know the initial state of the liquefied soil layers. By analyzing the exact location of the liquefied sites from past earthquakes the reoccurrence of liquefaction was noticed on the same sites during the recent earthquake. Wakamatsu [15] reports that liquefaction took place to limited extents along the Tone river basin in the 1987 Chibaken-Toho-oki earthquake with a moment magnitude $M_w = 6.7$. This earthquake had a much closer epicenter with much smaller magnitude than the 2011 earthquake off the Pacific coast of Tohoku, thus the strong motion records were in general smaller than the ones recorded in 2011. As far it is known to the authors, there are no other records of previous liquefaction through the natural soil deposites in this area.

It is difficult to understand the existence of a liquefied site just next to a non-liquefied site, as shown in Fig. 19a in the case of Abiko city. Both of liquefied sites and non-liquefied sites were confirmed by the survey [11] and located on recent aerial photo (Fig. 19a). Theirs location was transformed from a current map into an old map, that was compiled based on survey results conducted in 1928 before the time of the reclamation of the "Kirisho-numa" swamp (see Fig. 2) and the other swamps, the old river channels, etc., in the Tone river basin [2, 11]. The reclaimed land was later developed as residential area, where liquefaction occurred during the recent 2011 earthquake off the Pacific coast of Tohoku. From Fig. 19b it seems that the occurrence of liquefaction is greatly affected by the insufficient compaction of dredged soils during land reclamation.

5 CONCLUSION

The 2011 earthquake off the Pacific coast of Tohoku caused liquefaction, triggering on enormous number of sites along the Tone river. It induced damage to houses, lifeline facilities and river dikes. In general, good performance of the structures supported by deep foundations was observed.

Most of the sites affected by the liquefaction were reclaimed land, which used to be old river beds or swamps before the reclamation. Liquefaction reoccurrences were noticed during the recent earthquake on several sites when compared to the affected sites from previous earthquakes. The boiled sands were mostly fine sands, which could originate from the material dredged from the Tone river during the reclamation works.

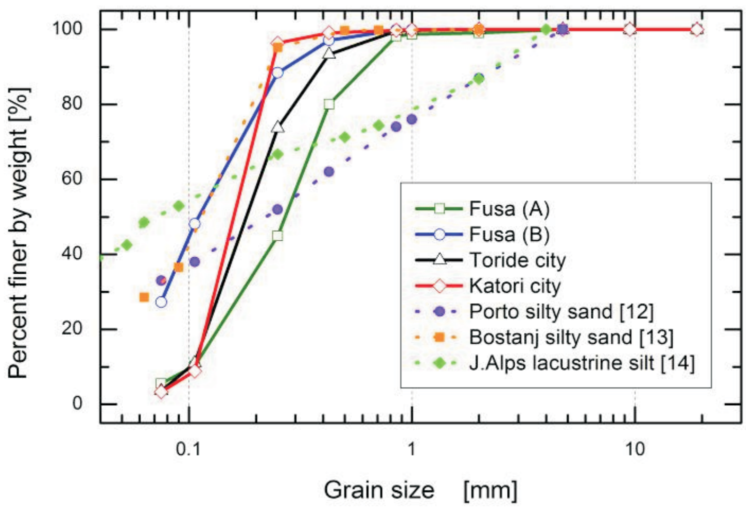

Figure 18. Gradation of samples retrieved from the sand-boiling sites near the Tone river.

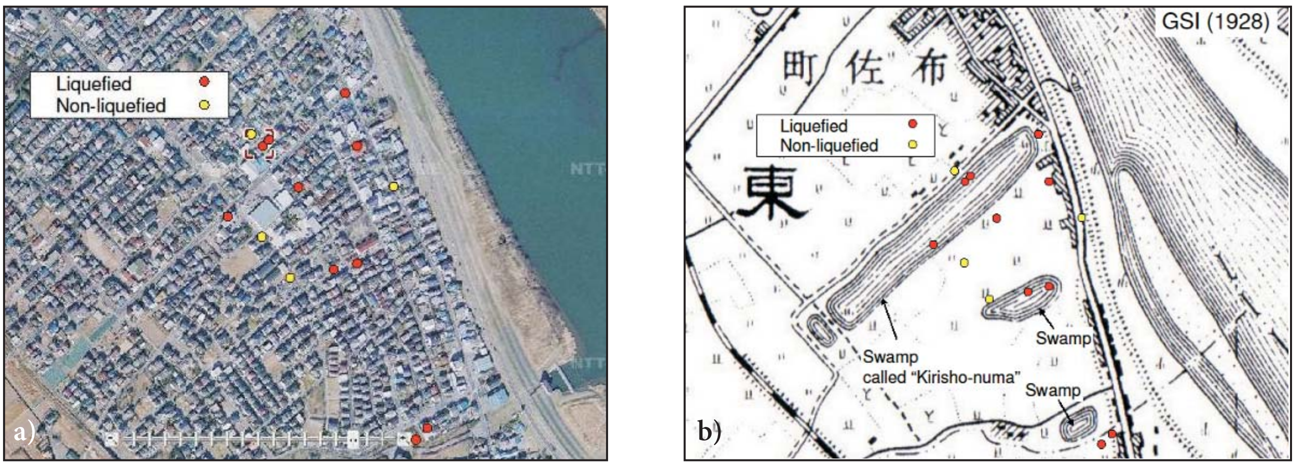

Figure 19. Location of liquefied and non-liquefied sites confirmed by the survey in Abiko city are plotted on (a) recent aerial photo and on (b) old map made by GSI in 1928.

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