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650-km Long Zone of Liquefaction during the 2011 off the Pacific Coast of Tohoku, Japan Earthquake

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ABSTRACT

The off the Pacific Coast of Tohoku Earthquake of March 11, 2011 was associated with widespread damage in the eastern part of Japan. Our continuing surveys nearly four years from soon after the earthquake revealed that the earthquake induced liquefaction at a significant number of locations within a 650-km long zone that extended in the eastern part of Japan. Significant damage was caused to residential houses, pipelines, levees, agricultural facilities, and port facilities as a result of the liquefaction. Counting the numbers of approximately 250-m square grid cells containing any liquefaction site, more than 8600 grid cells were defined as liquefied. Examining the intensities of the ground motion of liquefaction grid-cells, approximately 94 % of liquefaction grid-cells are distributed in the areas where the I_{JMA} exceed "5 upper". The liquefaction occurrence ratio for artificial fills is the highest among all geomorphologic units in Kanto region.

Introduction

The M_w9.0 Tohoku Earthquake of March 11, 2011 (officially named the 2011 off the Pacific Coast of Tohoku Earthquake by the Japanese Meteorological Agency), Japan caused extensive and widely-spread liquefaction in the eastern part of Japan. Our continuing surveys nearly four years from soon after the earthquake revealed that this earthquake induced liquefaction at a significant number of locations in 193 municipalities (cities, special wards, towns, and villages) within a 650-km long zone that extended in Tohoku and Kanto regions. This paper first presents the distribution liquefied sites during the earthquake and typical land conditions of liquefied sites where damage is severe and widespread, with emphasis on land use change and land reclamation. The intensities of the ground motion that caused liquefaction are next discussed and finally liquefaction susceptibilities are discussed based on the geomorphological classification.

Geology and Geomorphology of Affected Area

Figures 1 and 2 show the geological and geomorphological futures for the Tohoku (Aomori, Iwate, Miyagi, Akita, Yamagata and Fukushima prefectures in the Figures) and Kanto (Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo and Kanagawa prefectures), regions respectively. The land futures in the eastern Tohoku region are characterized by mountain ranges running north-south and depression zones between these mountains. The geology consists mainly of: pre-tertiary sedimentary rock in Pacific side of Iwate and Fukushima Prefectures and tertiary

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sedimentary rock and quaternary volcanic rocks in the inland areas of Tohoku region. Plains consisted of quaternary soils and soft rocks are distributed limited areas: mainly in Pacific side of Miyagi Prefecture and in the inland areas along Kitakami River and Abukuma River.

In contrast, features of the Kanto region are characterized by the Kanto Plain which is a large subsidence area depressed more than 1000 m during the Quaternary. The plain mainly consist of two parts; terraces and lowlands. The terraces are covered with thick Pleistocene sediments including a large amount of volcanic ash derived from volcanoes to the southwest and to the northwest of the plain. The lowlands are composed of Holocene soft soils and fills.

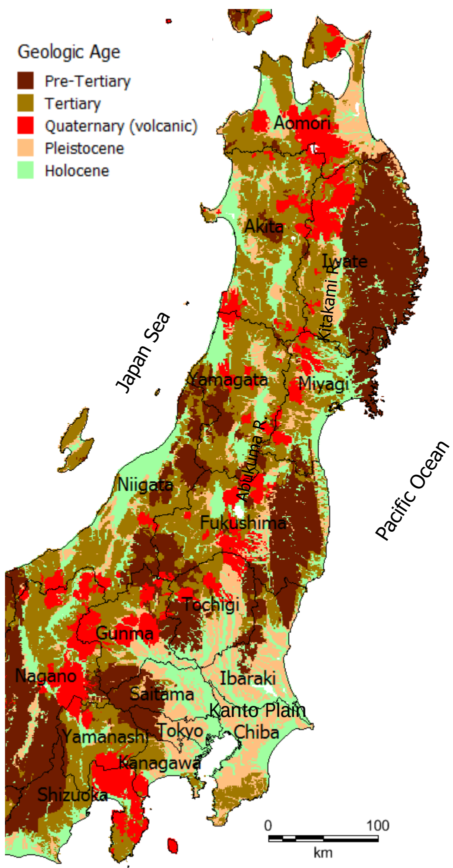


Figure 1. Surface geology (Wakamatsu et al., 2005)

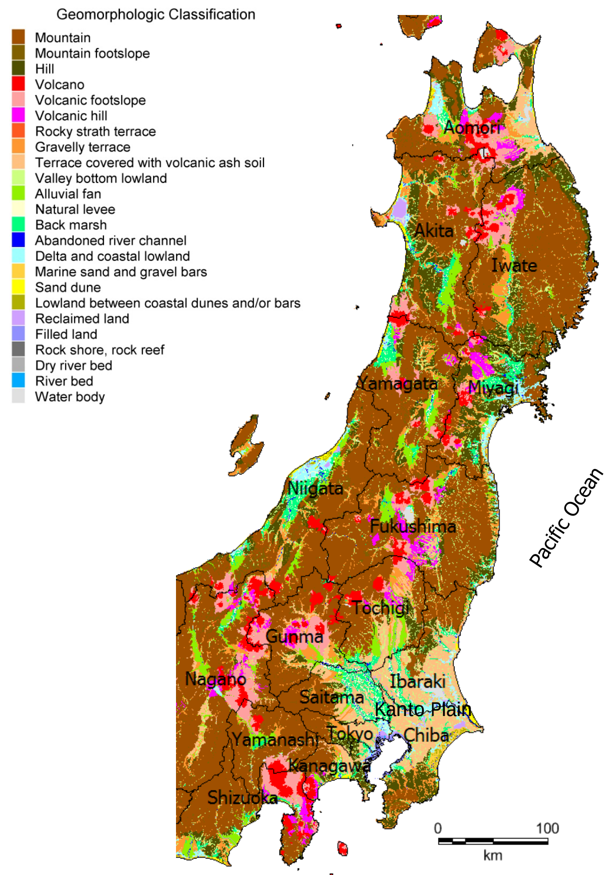


Figure 2. Geomorphological land classification map (Wakamatsu and Matsuoka, 2013)

Observed Liquefaction during the 2011 Tohoku Earthquake

Figure 3 shows the sites where liquefaction effects were observed during the 2011 Tohoku Earthquake. In our investigations, occurrences of liquefaction were identified by observed sand and water boiling during reconnaissance survey by authors and other researchers, and an interpretation of aerial photos taken immediately after the earthquake. Information on liquefaction-induced house damage provided by local governments was also included. However, liquefaction of backfill soil (e.g., sewage pipelines, manhole and levee body material) was excluded from this study because it was not ground-condition related liquefaction.

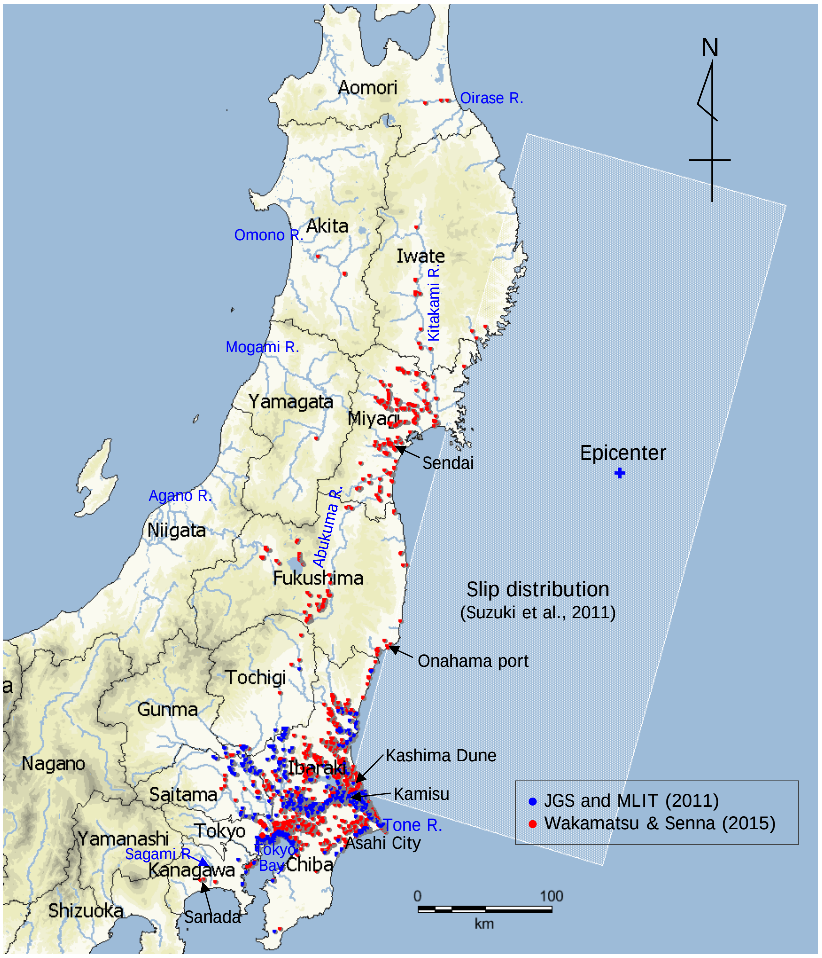


Figure 3. Liquefied sites during the 2011 Tohoku Earthquake

Huge numbers of large aftershocks and induced earthquakes including M_{JMA}7-class earthquakes have occurred. The liquefied sites during these earthquakes are combined as liquefaction during the main shock of March 11, 2011 at 2:46 p.m., because it is impossible to identify which shock triggered the occurrence of the liquefaction in all but a few cases.

Blue dots in Figure 3 show the liquefied sites which were identified immediately after the earthquake by cooperative survey of the Japanese Geotechnical Society (JGS) and the Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), whereas red dots show the liquefied sites which were supplemented by our investigation for 4-years following the earthquake. The additional liquefied sites in Kanto region are as much as 2.4 times than that by JGS and MLIT (2011).

Liquefaction took place in 193 municipalities (cities, special wards, towns, and villages) in all thirteen prefectures in Tohoku and Kanto regions within a 650-km long zone that extended from Aomori to Kanagawa Prefectures. Sanada, Hiratsuka City, southwest of Tokyo, is the farthest site of liquefaction, located in a valley bottom lowland in the lower reaches of Sagami River. This site is located 440 km from the epicenter and 134 km from the closest edge of the slip distribution of the 2011 earthquake evaluated by inversion analysis (Suzuki et al., 2011).

Serious damage was caused to residential houses, pipelines, levees, agricultural facilities, and port facilities as a result of the liquefaction. It can be seen from Figure 3 that liquefied sites are heavily concentrated in eastern part of Kanto region; in contrast, they are sparsely-distributed in Tohoku region including Sendai area. Differences in degree of density of liquefaction occurrence are probably due to the differences in geologic and geomorphological conditions of both region shown in Figures 1 and 2: Liquefiable low-lying lands covered with Holocene deposits and artificially artificial fills were limited in Tohoku region as compared to the Kanto region.

Land Conditions of Liquefied Sites with Emphasis on Land Use Change and Land Reclamation

Typical land conditions where severe liquefaction was induced during the 2011 earthquake will be discussed in this section with emphasis on change of land use and land reclamation. It is noteworthy from the practical viewpoint that the land conditions described in the following correspond with conditions in which liquefaction most likely to occur under smaller ground shaking based on the approximately 16,500 liquefaction case histories in Japan in 150 earthquakes from 745 to 2008 (Wakamatsu, 2011). In fact, second time and fourth time liquefaction was observed at 90 sites during the 2011 earthquake in the Kanto and Tohoku regions, at exactly the same places as those where liquefaction had occurred during the previous earthquakes (Wakamatsu, 2012).

Recent Artificial Fills along Tokyo Bay

Along the coastline of Tokyo Bay, land reclamation has been performed since 1592. Extensive violent sand boils occurred in artificial fills along the Tokyo Bay, particularly in the areas from Koto ward, Tokyo to Mihama ward, Chiba City. In order to investigate the ageing effect for the all Tokyo Bay areas, we interpreted the coastlines of the bay by aerial photos taken in 1947. The most of the liquefied sites located within the areas constructed after 1947 with 9 sites exceptions in Koto and Chuo wards. The oldest area where liquefaction observed is Toyo 1-chome, which was filled-up between 1887 and 1913, although no liquefaction effects were observed in Tsukishima constructed in 1887 and the other old lands filled-up between 1592 and 1834. This probably implies that the age of soil increases the liquefaction resistance though the intensity of the ground motion is out of consideration in this study.

In Tohoku region artificial fills are limited to small areas around several major ports. All of these ports were inundated by Tsunami immediately after the main shock; however, distinct sand boils were found in the wharfs of Onahama port, Fukushima Prefecture, which were completed in 1966, 1968 and 1980, respectively.

Filled-Up Land on Former River Channel and Flood-Prone Area

The severe liquefaction in the filled-up land on former river channel and flood-prone areas was observed in the areas along the large rivers in Tohoku and Kanto regions. The most severe and widespread damage was caused in the area along the Tone River, which is the second longest river and has the largest drainage area in Japan. Along the banks of the lower reaches of the river, numerous ponds and abandoned river channels were found along the Tone River and its tributaries, which were created as a consequence of the shortcut channeling projects which were conducted from the 1900s to the 1930s. These ponds and abandoned meanders channels were sequentially filled up with the dredged sand of the Tone River from the 1950s to the 1960s in order to increase rice production.

Violent sand eruptions and numerous large sand craters were observed with diameters of 1 to 3 meters in the paddy fields and residential lots, and single-family houses, water pipes, telephone poles and farm road and levees were damaged due to liquefaction during the 2011 earthquake. These effects predominantly developed within the filled channels and ponds. However, it is worth mentioning that liquefaction effects also occurred in the areas of the native ground along the rivers, which correspond to what we call flood-prone area. This implies that the ground surface of these areas is covered with loose fluvial deposits and poor drainage condition.

Skirt of Coastal Sand Dune

There has been many case history of liquefaction in the skirt of coastal sand dunes in Japan, including in the earthquakes of the 1964 Niigata, the 1983 Nihonkai-chubu and the 2004 Niigata-ken Chuetsu. The liquefaction in the sand dunes took place once again during the 2011 earthquake in Kashima Dune, Ibaraki Prefecture. A number of residential houses, pipelines, and agricultural lands were severely damaged by liquefaction.

Backfilled Land after Digging

Liquefaction-induced damage was extensive and severe in Asahi City which is located in the south-easternmost part of Chiba Prefecture facing the Pacific Ocean, where 773 houses were damaged due to liquefaction. In and around the city, iron sand mining had been in operation on a large scale up to the 1970s: excavation was done by open cuts to depths ranging from 5 to 10 m. Iron was extracted by iron concentrators from excavated sand at the site; the remaining sand was backfilled into the excavated ground. According to interviews with city government officials and local residents, the most of the liquefied areas were within the areas formerly excavated and backfilled for iron mining.

Liquefaction-induced damage to residential houses was also extensive and severe in Kamisu and Kashima cities located downstream on the left bank of the Tone River. In some areas of both cities, sand and gravel mining had been in operation from the 1960’s to the present to obtain the materials for construction and gardening: excavation was done in the same manner as the iron sand mining described above, and backfilled by poor quality sands. Many single-family houses built on the backfill ground settled and tilted perceptibly.

Developed Areas on Hill and Terrace

Liquefaction took place not only in low-lying land consisting of loose liquefiable soils but also in hilly residential land far from the coast and rivers. More than 2000 residential houses built on Pleistocene terrace were damaged in Kanto region as a result of liquefaction. The areas where the liquefaction was induced are developed lands on the terraces where landform change was made by cutting and filling over the past several decades. The damaged houses were located on fills placed on small stream valleys. The liquefaction-induced damage in this type of land also occurred in several cities and towns in Miyagi and Fukushima prefectures.

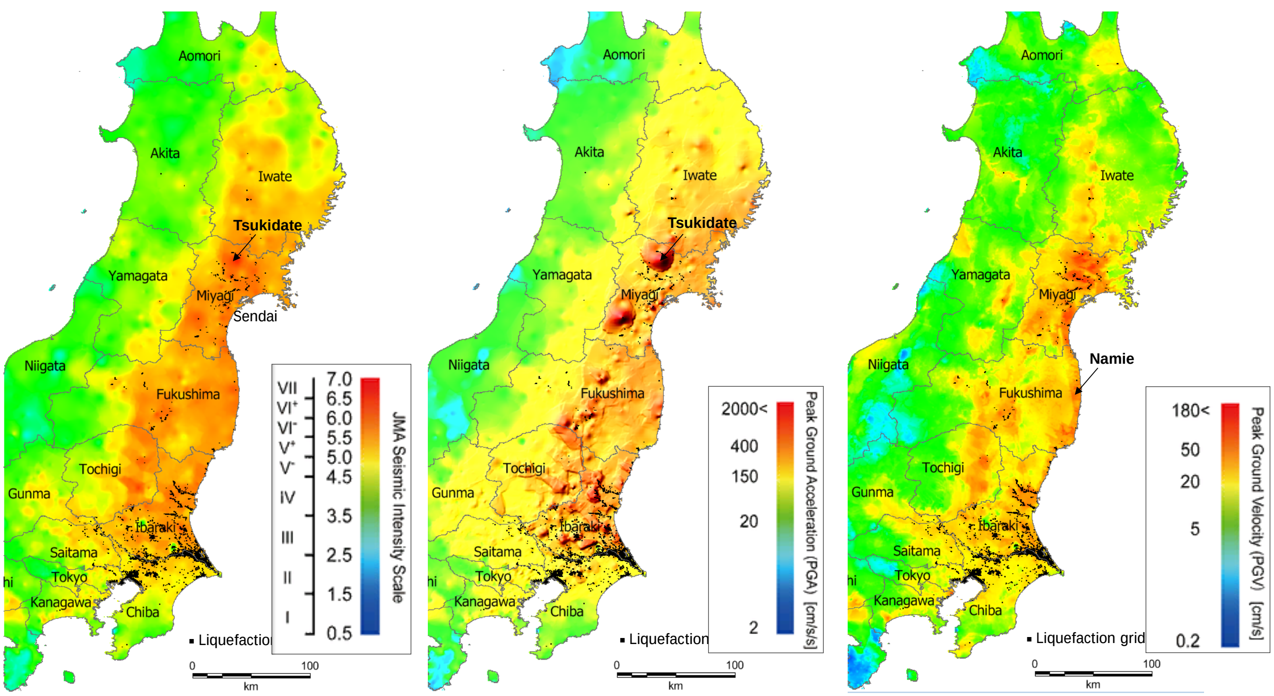
Discussion on the Liquefied Sites

Effects of Intensity of Ground Motion

Many strong motion records were obtained from the 2011 Tohoku Earthquake. The authors collected records at 1480 observation stations in Tohoku and Kanto regions. The observed peak horizontal ground acceleration (PGA) exceeded 1G at twenty sites and the maximum PGA is 2933 cm/s^2 (Gal) at the K-NET Tsukidate station, Miyagi Prefecture. The maximum peak velocity (PGV) observed is 113.5 cm/s (kine) at KiK-net Namie station, Fukushima Prefecture. The maximum JMA seismic Intensity is 6.7 at Tsukidate station.

Figures 4(a), (b), (c) show distributions of Japan Meteorological Agency (JMA) seismic intensity (I_{JMA}), peak horizontal acceleration (PGA) and velocity (PGV) with 250-m spatial resolution for main event of the March 11, 2011 earthquake, respectively, which were estimated by means of the spatial interpolation procedure (Matsuoka et al., 2015) using the strong ground observation records at 1480 seismic stations.

Counting the numbers of grid cells containing any site of liquefaction, which were determined by superimposing a 250-m grid cells, more than 8600 grid cells could be designated as “liquefaction grid-cell”. Examining the relationship between ground motion intensity and liquefaction occurrence, it can be found that 94 % of liquefaction grid-cells are distributed in the areas where the I_{JMA} exceed “5 upper”, 90 % are in the areas where the PGAs exceeded 150 cm/s^2 (Gal), and 95 % are in the areas where the PGVs exceeded 15 cm/s (kine), respectively. The threshold intensities for I_{JMA} and PGV that induced liquefaction coincided with those derived from the previous earthquakes (Wakamatsu, 2011; Midorikawa and Wakamatsu, 1988).



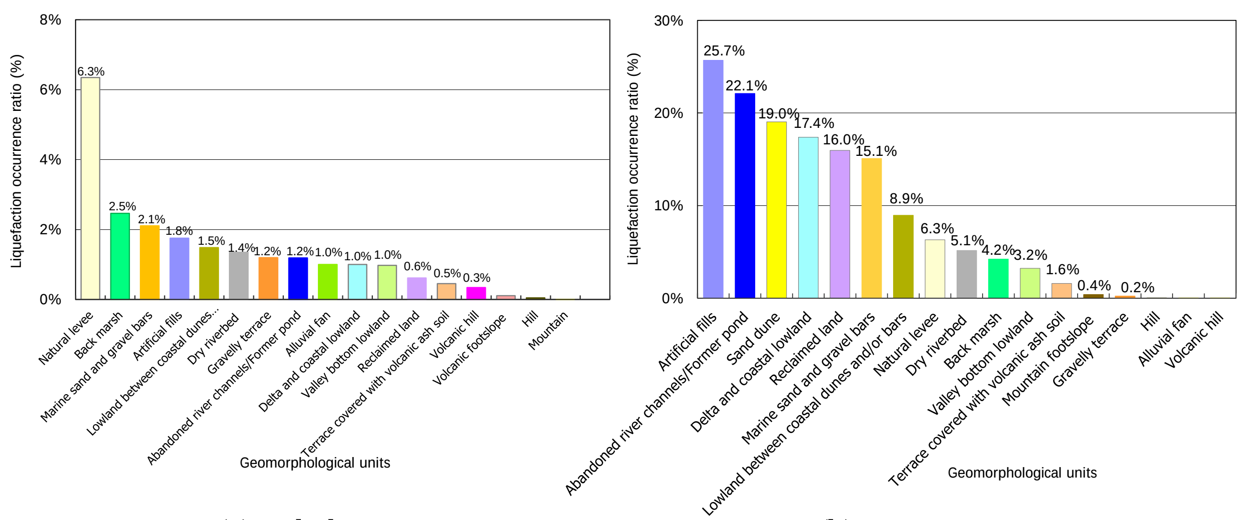
(a) JMA seismic intensity (b) PGA (cm/s^2) (c) PGV(cm/s)

Figure 4. Distribution of intensity of ground motion (Senna et al. 2014) and liquefaction grid-cells

Effects of Geomorphological Condition

It has been discussed that liquefaction potential is closely related with surface geological and geomorphological conditions (e.g. TC4 of ISSMGE, 1998; Matsuoka et al., 2015). In this viewpoint, geomorphological classification of liquefied sites during the 2011 earthquake was examined based on the Japan Engineering Geomorphological Land Classification Map (JGEM) (Wakamatsu and Matsuoka, 2013), which utilizes 250-m grid cells, employs a unified approach to classify landforms and ground conditions throughout Japan.

Figure 5 presents bar charts summarizing the liquefaction occurrence ratio (number of liquefaction grid cells divided by total number of grid cells) of different geomorphological unit for Tohoku and Kanto regions where I_{JMA} exceed 5 upper, respectively. It should be noted that the liquefaction occurrence ratios for artificial fills and former river channel in Kanto region are remarkably large, around 25%, respectively, among all twenty-one geomorphological units of the JGEM. Trends obtained from the field performance in Kanto region during the 2011 earthquake agree with the existing geomorphology-based criteria (e.g.TC 4, 1998). In contrast, the liquefaction occurrence ratio for any geomorphological unit in Tohoku region is lower than those in the Kanto region, which corresponds to 6% for natural levee at a maximum. It can be thought of two reasons for these differences between Kanto and Tohoku regions: first, the liquefaction susceptibility for each geomorphological unit differs depending on the geomorphological settings in the area; and second, the differences in the ground motion characteristics in each area.



(a) Tohoku region (b) Kanto region

Figure 5. Liquefaction occurrence ratio for each geomorphological unit of the JEGM

The March 11, 2011 Tohoku earthquake was characterized by the long duration of ground motion accompanied several successive events of the source area. In order to identify the difference in liquefaction occurrence ratio between the Tohoku and the Kanto regions, we have examined the relationship between liquefaction occurrence ratio and an accumulated real-time seismic intensity, *ΔIs*, where *ΔIs* is defined as the integral of the measured real-time seismic intensity exceeded a preset level (Senna et al., 2014). As a result, the *ΔIs* has a strong impact on the liquefaction occurrence ratios. We will also consider the effect of the regional characteristics of the ground conditions based on the longitudinal gradient of rivers running in the two regions, as well as borehole data.

Concluding Remarks

Widespread and severe liquefaction occurred within a 650-km long zone in the eastern part of Japan during the March 11, 2011 earthquake. The land conditions where severe liquefaction was induced were the same as those obtained from the previous 150 Japanese earthquakes. More than 90 % of the liquefaction during the 2011 earthquake occurred in the areas where I_{JMA} exceeded 5 upper, the PGAs exceeded 150 cm/s^{2}and PGVs exceeded 15 cm/s, respectively. These thresholds for I_{JMA} and PGV that induced liquefaction also coincided with those derived from the previous earthquakes, despite unprecedented extent and severity of liquefaction among the Japanese liquefaction case histories. The liquefaction occurrence ratios for filled land and former river channel in Kanto region are remarkably large, but those in Tohoku region are fairly low regardless of geomorphological classification units. The further investigation is needed to identify the cause of the differences in the liquefaction occurrence ratios between the Tohoku and Kanto regions

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References

The Japanese Geotechnical Society (JGS) and the Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Report on Reconnaissance Survey of Comprehensive Information about Liquefaction during the 2011 Off the Pacific Coast Of Tohoku, Japan Earthquake in Kanto Region (in Japanese). http://www.ktr.mlit.go.jp/bousai/bousai00000061.html, 2011.

Matsuoka M, Wakamatsu K, Hashimoto M, Senna S and Midorikawa S. Evaluation of liquefaction potential for large areas based on geomorphologic classification, Earthquake Spectra, in press, 2015.

*Midorikawa S and Wakamatsu K. Intensity of earthquake ground motion at liquefied sites, Soils and Foundations, 1988; **28**(2): 73-84.*

TC4 (Technical Committee No. 4) of ISSMGE. Manual for Zonation on Seismic Geotechnical Hazards. Japanese Geotechnical Society: Tokyo, 1998.

Senna S, Matsuoka M, Wakamatsu and Midorikawa S. K Liquefaction occurrence ratio estimation considering strong ground motion duration and regional characteristics, Proc., the 14th Japan Earthquake Engineering Symposium 2014; 2291-2300 (in Japanese with English Abstract).

Suzuki W, Aoi S and Sekiguchi H. Fault model and strong-motion observation station used in the source inversion analysis, http://www.kyoshin.bosai.go.jp/kyoshin/topics/TohokuTaiheiyo_20110311/inversion/, 2011.

Wakamatsu K, Kubo S, Matsuoka M, Hasegawa K and Sugiura M. *Japan Engineering Geomorphologic Classification Map with CD-ROM Database,* University of Tokyo Press: Tokyo, 2005. *(in Japanese with English abstract and manual).*

Wakamatsu K. Maps for Historic Liquefaction Sites in Japan 745–2008 with DVD-ROM Database, University of Tokyo Press: Tokyo, 2011 (in Japanese with English abstract and manual).

Wakamatsu K. and Matsuoka M. Nationwide 7.5-Arc-Second Japan Engineering Geomorphologic Classification Map and Vs30 Zoning Journal of Disaster Research 2013; ***8****(5): 904-911. Datum are available on line: http://www.j-shis.bosai.go.jp/JSHIS2/download.html?lang=en.*

Wakamatsu K. Recurrence of liquefaction at the same site induced by the 2011 Great East Japan Earthquake compared with previous earthquakes, Proc., the 15th World, Conference on Earthquake Engineering, Lisboa, 2012; No. 4572.