Paper No. M-1

DAMAGE DUE TO LIQUEFACTION DURING THE 2011 TOHOKU EARTHQUAKE

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SUMMARY

The 2011 Tohoku earthquake caused a devastating damage to the eastern part of Japan. The Tokyo metropolitan area that is located more than 300 km away from its hypocenter suffered from strong ground shaking followed by extensive liquefaction damage along the coastal area. The authors have conducted an exhaustive investigation of damage due to liquefaction in Chiba city immediately after the quake. The resulted damage map has shown an extreme maldistribution. This article describes some of the liquefaction damage and then examines the damage distribution by looking into boring logs, aerial photography and microtremor measurement results. It was found from the study that the extreme maldistribution of liquefaction damage is mainly due to the very complex and varying soil profiles of the reclaimed ground along the coast.

INTRODUCTION

The 2011 Tohoku earthquake (M_W 9.0) that struck the eastern part of Japan on March 11 caused a devastating damage to this area resulting in about 20,000 fatalities. The Tokyo metropolitan area, that is located more than 300 km away from its hypocenter, was no exception. The areas along the Tokyo bay and the Tone river valley have suffered from not only strong shaking but also extensive liquefaction damage due to the main and after shocks (Figure 1). The authors have carried out an exhaustive survey on the damage due to liquefaction in Mihama ward of Chiba city, that is located about 50 km east of Tokyo, immediately after the quake for about ten days. The survey was conducted for all the public roads and most of the parks as well as some of the private properties. This survey revealed that due to liquefaction a huge amount of sand boiling, ground deformation and inclination and subsidence of the buildings were found in almost all areas of Mihama ward, which is entirely a reclaimed ground. Photograph 1 shows some of the typical damage found in this area.

Although small sand boiling was found on the main road, narrower streets inside a city block were almost completely covered with sand boiling as thick as 45 cm. One of the interesting phenomena, however, is that there are some no-damage blocks right next to heavily damaged blocks, in other

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words, the liquefaction damage map has shown an extreme maldistribution.

The objective of this study is to evaluate the effects of the local site conditions on the liquefaction damage distribution in Mihama ward of Chiba city due to the 2011 Tohoku earthquake based on the damage survey immediately after the earthquake, the existing soil investigation data and the soil exploration conducted after the quake [1].

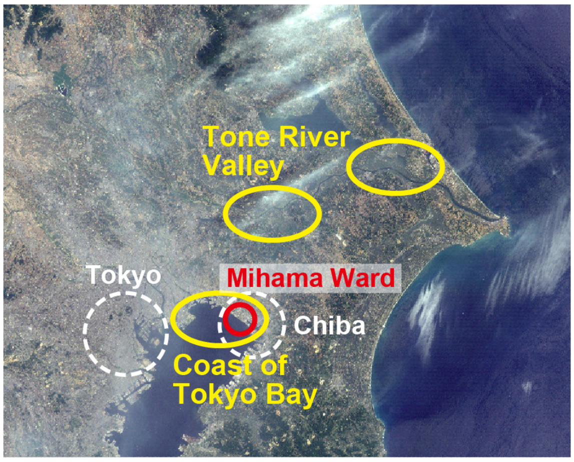

Figure 1 Target area

(a) Residential area

(b) Business/industrial area

Photo 1 Typical liquefaction damage in Mihama ward, Chiba city

LIQUEFACTION DAMAGE DISTRIBUTION

Figure 2 shows the map of Mihama ward with the constitution of districts. Mihama ward is located in the western part of Chiba city along the coast of Tokyo Bay and consists entirely of the reclaimed ground. It was reclaimed by dredge soil consisting of sand or sandy silt taken from the sea bed of Tokyo Bay. Reclamation was carried out from the southern part of the ward toward north from 1960s until mid-1980s.

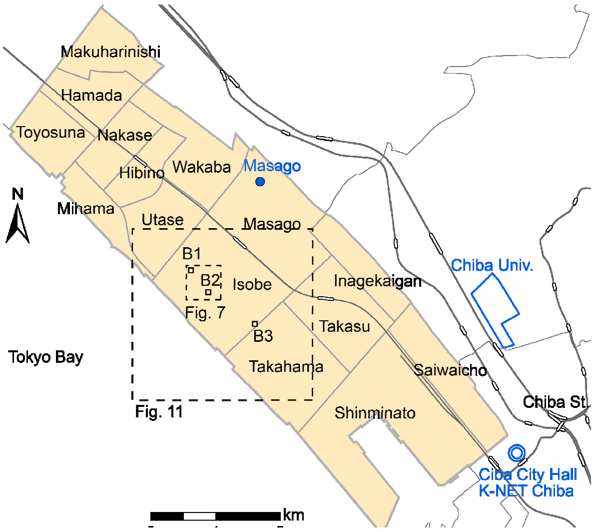

Figure 2 Map of Mihama ward

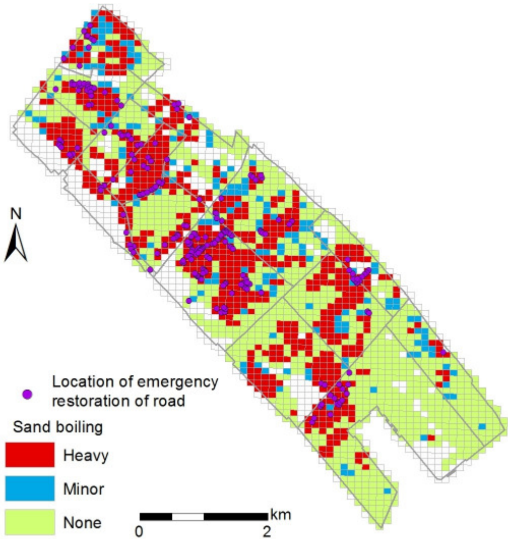

Figure 3 Distribution of sand boiling

A huge amount of sand boiling due to soil liquefaction occurred in almost all areas in Mihama ward during the earthquake. Sand boiling was hardly found on the main road and small sand boiling was found at the edge of the asphaltic pavement or on the sidewalk of the main road. On the other hand, some narrower streets inside a city block were almost completely covered with sand boiling as thick as 45 cm.

The sand which spouted out on the roads was removed by Chuo-Mihama civil engineering office of Chiba city within one week right after the quake. According to the office, the amount of the removed sand reached 8,500 m^3.

The liquefaction damage distribution was surveyed on public roads in Mihama ward immediately after the earthquake from March 12 to 20. The target of the survey includes all the public roads, most of the parks and some of the private properties situated in Mihama ward, which could be entered at that time. The severity of sand boiling is classified into three levels ; heavy, minor and none. The case in which the overflow area of sand boiling found in the spot is more than about 1 m is classified as 'heavy'. The case in which the overflow area is less than about 1 m is classified as 'minor'. The case in which no sand boiling was found is classified as 'none'.

Figure 3 shows the distribution of sand boiling using 100 m square grids together with the locations of emergency restoration of roads conducted by the Chuo-Mihama civil engineering office. White grids indicate the areas which could not be entered. Heavy sand boiling and road restoration locations are densely distributed in the coastal area when compared to the inland area. A number of spots associated with minor sand boiling are found in the inland area. The districts where widespread heavy sand boiling was found include Nakase, Hibino, Isobe, Takasu, Takahama and western part of Shinminato as shown in Figure 3. On the other hand, there are some districts, where only small sand boiling was found, namely Utase, the area between Isobe and Takahama and the inland part of Shinminato.

Figure 4 shows the distribution of liquefaction during the 1987 Chibaken-toho-oki earthquake [2] in addition to contour lines of the basement depth of an alluvial deposit [3]. Most of the past liquefaction areas are inclusive to the damage area shown in Figure 3. It is also seen from these figures that the liquefaction damage area of the 2011 earthquake is more widespread than that of the

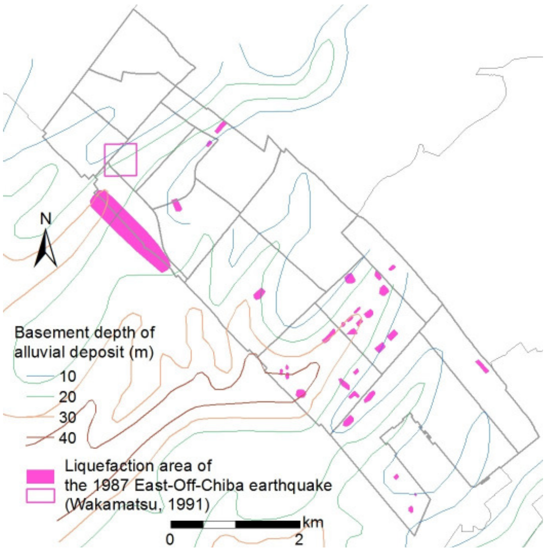

Figure 4 Historical liquefaction sites and alluvial deposit basement

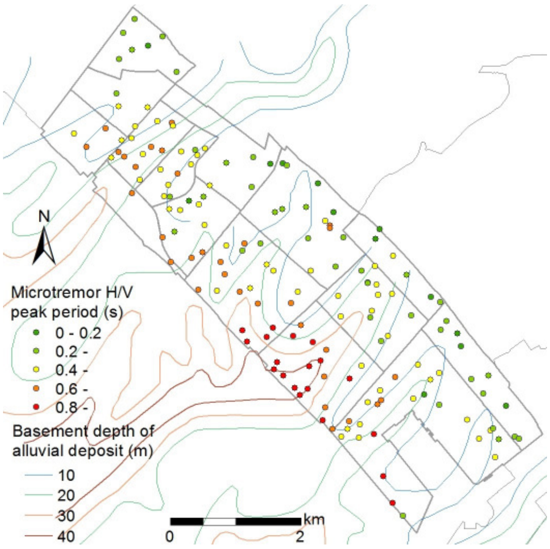

Figure 5 Peak period distribution obtained from microtremor measurements

past earthquake.

In the districts of Nakase, Hibino, Takasu and Takahama where heavy sand boiling was found, the basement depth of the alluvial deposit is deep compared to other districts, meaning that these districts are located on the so-called alluvial valley where thick alluvial deposits are accumulated. The areas in the northern part of Isobe and the western part of Shinminato where heavy sand boiling was also found, however, are situated on the ridge in the old times which is covered with thinner alluvial deposits in the present time.

PRELIMINARY ANALYSIS AND DISCUSSIONS

Microtremor Measurements

In order to estimate the natural period of the surface soil, microtremor measurements with a three-component sensor were conducted at 163 sites in Mihama ward. Figure 5 shows the peak periods of H/V spectra calculated from the three component motions of observed microtremors. The peak periods of microtremor H/V spectra are in fairly good agreement with the basement depth of alluvial deposits. The peak periods in the coastal area tend to be longer than those in the inland area. The peak periods in the districts such as Nakase, Isobe, Takahama and the western part of Shinminato, where heavy sand boiling was observed, tend to be longer than those in other districts. In addition the peak periods in Utase where only a small sand boiling was observed are shorter. However, in the area where small sand boiling was found such as the area between Isobe and Takahama, the long peak periods of microtremor H/V spectra are observed. This indicates that the severity of sand boiling cannot be explained only by the thickness of alluvial deposits.

Soil Profiles

Figure 6 shows the borehole logs at site B1 where heavy sand boiling was observed and site B2 where no sand boiling was observed. Site locations are shown in Figure 2. The thickness of the reclaimed soil is estimated to be 5 to 10 m at these sites. At site B1 whose natural period from microtremor measurements is estimated to be longer compered to other areas, fine sand and silt with low SPT-*N* values are found to accumulate alternately. At site B2 whose natural period is also estimated to be longer, the surface soil, in contrast, consists of fills with *N* values of about 10 and silts with low *N* values with the thickness of 11 m, which is underlain by fine sands with *N* values of more than 10. It seems that this is the reason why liquefaction damage is different between the two sites despite the similar peak periods of microtremor H/V spectra.

A series of cone penetrometer tests (CPT's) were conducted along a line crossing the border between heavily and less damaged areas in Isobe district as shown in Figure 7 in which the areas where sand boiling was observed are also shown. Figure 8 shows the estimated profiles of soil types obtained from CPT loggings at 6 locations. At the locations C1 and C2 near the damaged area by sand boiling, sand prevails to the depth of about 10 m. At the locations C3, C5 and C6 where no sand boiling was observed, silt and clay are predominant to the depth of 20 m.

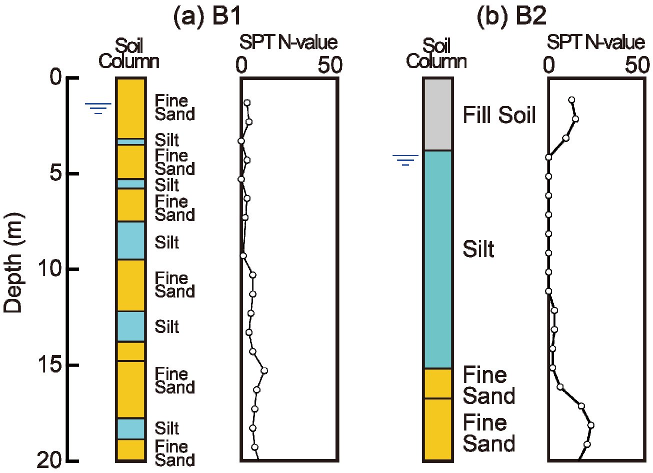

Figure 6 Boring logs in Isobe district

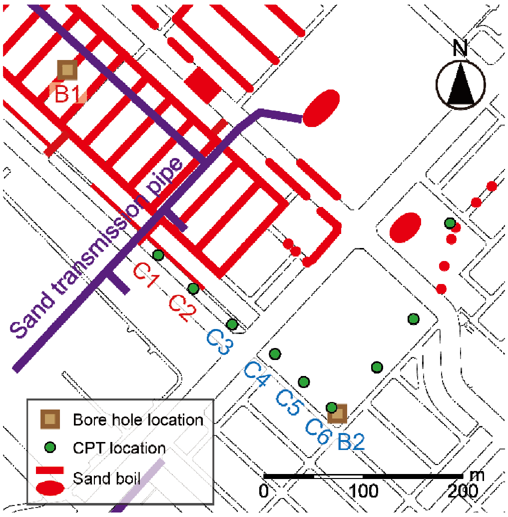

Figure 7 CPT locations

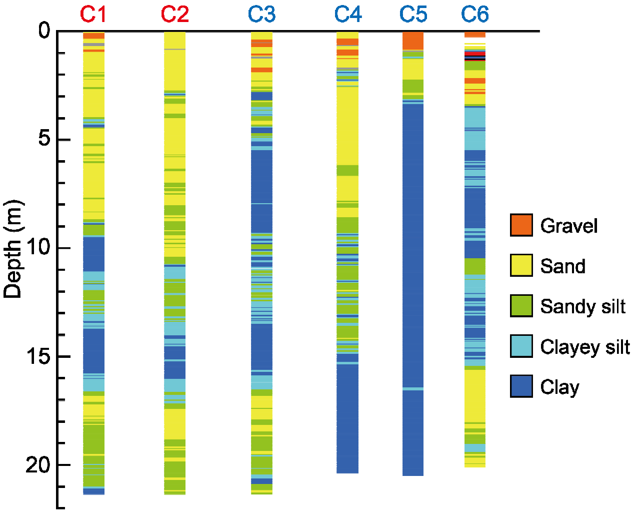

Figure 8 CPT logs

The above findings and discussions indicate that the difference in type of surface soil as well as the soil amplification characteristics significantly affected the difference in liquefaction damage in Mihama ward during the 2011 Tohoku earthquake.

Estimation of Maximum Strain during Earthquake

The previous discussions can lead to a tentative conclusion that liquefaction damage is severe in the area in which two conditions are met: there exists a thick layer of soft alluvial soils where the ground motion gets amplified significantly, and sand prevails in the soil profile especially in the shallow part. Based on this assumption, the authors have conducted a preliminary analysis [4] to estimate the maximum shear strain distribution of the target area during the earthquake and compared the results with the liquefaction damage distribution shown in Figure 3.

We have collected a total of about 600 boring logs in this area, as shown by the dots in Figure 9. Based on these data, three-dimensional soil model of this area has been constructed in the following way:

- The target area is partitioned into a number of small areas, each of which has the size of 100 m by 100 m.
- The soil profile for each subdivided area is determined by the weighted average of surrounding eight boring logs nearest to the area.

The ground motions during the main shock were recorded at a number of locations in the target area, among which the recorded ground motion at Masago, where no sand boiling was observed, has been used to obtain the input motion to the bedrock by the deconvolution process. This input motion to the bedrock was then applied to each of the soil model constructed above. Since liquefaction occurs in a sand layer, the maximum shear strain of sand layers up to the depth of 20 m from the ground surface was selected for each subdivided area. Figure 10 shows the distribution of maximum shear strain of sands. By the comparison of Figures 3 and 10, it can be pointed out that the assumption of two main factors for liquefaction damage being amplification due to soft soil deposits and dominance of sands in its profile explains well about the damage distribution.

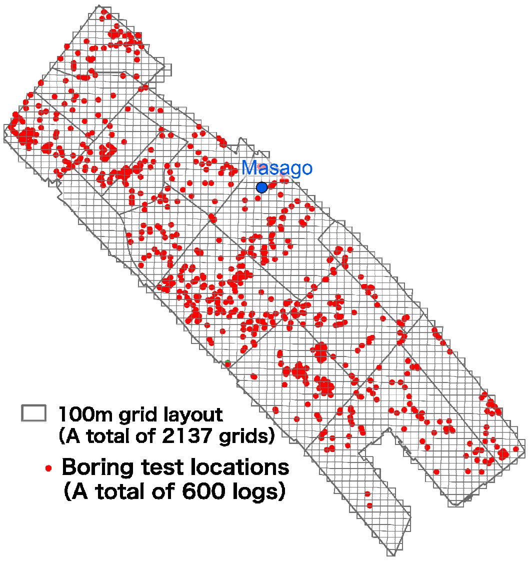

Figure 9 Boring test locations

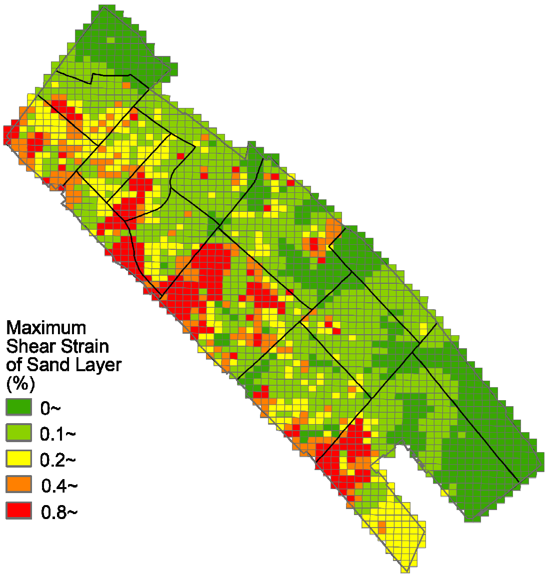

Figure 10 Maximum shear strain distribution

Effect of Land Reclamation Process

The sand pumping process was used for reclaiming the land in Mihama ward [5]. In the process, the soil consisting of sand and sandy silt accumulated on the sea bed of Tokyo bay was dredged, transmitted through sand pipes to another sea bottom surrounded by an embankment and then discharged from outlets. In this process, sand with low fine-grain content accumulates near the outlets of the sand transmission pipes, and silty sand with high fine-grain content accumulates in the area which is far from the outlets. In addition, accumulated soils tend to be loose and soft because of the sedimentary environment. This land reclamation process may explain why the soil profile varies in a short distance and liquefaction damage shows an extreme maldistribution.

Figure 11 shows the aerial photography of Isobe and Takahama districts shown in Figure 2 at the time of land reclamation back in 1972. The sand transmission pipes are found in this photography and are indicated by the purple lines. The pipe layout is indicated also in Figure 7. Sand boiling is found near the pipes such as CPT locations C1 and C2. CPT locations C3, C5 and C6 where surface soils mainly consist of silt are situated between the pipes, as can be seen in Figure 11.

There is a drainage canal called Kusano canal that runs between Isobe and Takahama districts crossing the reclaimed ground from inland to Tokyo Bay as shown in Figure 11. The surplus water contained in pumped dredge soils was drained away through Kusano canal to Tokyo Bay. There used to exist storage reservoirs in the both sides of Kusano canal that were used to precipitate fine grains in the drained water. It is understood from Figure 11 that site B3 where the surface soil mainly consists of silt is situated in this reservoir.

From the above findings and discussions, it is possible to suggest that the distance from the outlet of sand transmission pipes affected the distribution of liquefaction damage in Mihama ward due to the 2011 Tohoku earthquake.

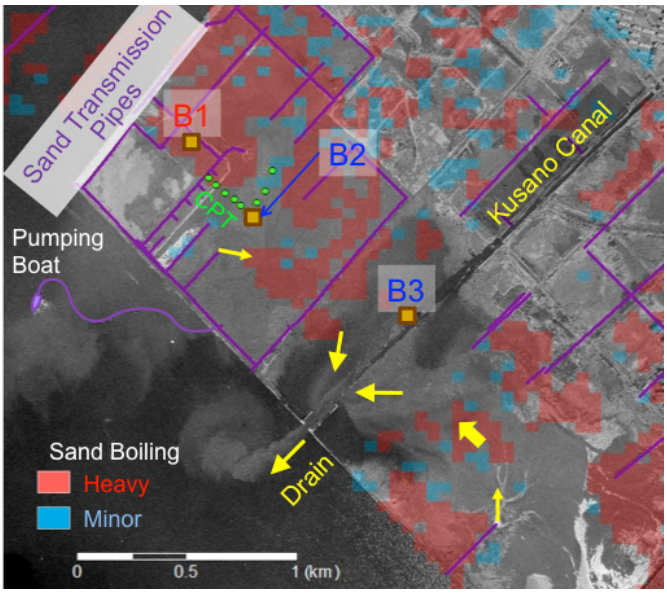

Figure 11 Aerial photography of Isobe and Takahama districts at the time of reclamation in 1972

CONCLUSIONS

The distribution of liquefaction damage in Mihama ward of Chiba city during the 2011 Tohoku earthquake was investigated by conducting an exhaustive search for all the public roads and parks. The effects of local site conditions on the damage distribution in the region were examined based on the field survey, microtremor measurements, analysis based on the boring logs and the aerial photography. From the results and discussions, the following conclusions are made:

1. Liquefaction damage in Mihama ward of Chiba city showed an extreme maldistribution.
2. The soil type of the surface soil as well as its amplification characteristics are the major factors that affected the severity of liquefaction damage.
3. The variation of soil profiles in a short distance may be resulted from the ground reclamation process.

ACKNOWLEDGMENTS

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