Liquefaction Hot-Spot Based on Pipeline Damage and Topographical History in the Kashima Region during the 2011 off the Pacific Coast of Tohoku Earthquake

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SUMMARY:
The Tohoku, Japan earthquake occurring on March 11, 2011 caused huge liquefaction to the coastal area of the Tokyo Bay and to the Valley of Tone River in North Kanto region. Since small-diameter water pipeline densely buried near the surface is pulled out at the joint part due to the liquefied ground deformation, the number of pipeline damage would be an indicator of the liquefaction severity. Referring to the analysis of pipeline analysis in the Kashima region in the Tone River, the pipeline damage was not homogeneously distributed but concentrated locally in the size of 1 km^2. This study calls this concentration area as liquefaction hot spot and analyzes the liquefaction factor from the topographical history. The factor of the hot spot was able to be clarified by using the paleo-topographical map though it was difficult to specify the liquefaction hot spot only by a present topographical map.

Keywords: Tohoku earthquake, Liquefaction, Hot spot, Pipeline damage, Topographic history

1. INTRODUCTION

The 2011 off the Pacific coast of the Tohoku earthquake that occurred on March 11, 2011 and its aftershocks provoked the ground motion with long duration and induced liquefaction in large area. Yasuda and Harada (2011) reported that the liquefaction area of the Tokyo Bay shore is 42 km^2. Not only the liquefied area but also roadway subsidence induced by the liquefaction exceeds those experienced in the past earthquakes in Japan. Since the strong ground motion was observed in a large area of the east Japan, it is not clarified the area and extent of liquefaction in this earthquake. This study attempts to specify the spatial distribution of liquefaction from the distribution of water pipeline damage for the Kamisu, Kashima and Itako Cities in Ibaraki Prefecture and the Katori City in Chiba Prefecture (hereafter, referred as to Kashima region), in the mouth of Tonegawa River, and to clarify the relation of liquefaction concentrated area and topographical characteristics.

2. SELECTION OF LIQUEFACTION HOT SPOTS

The database of water pipeline network and its damage locations in the Kashima region were developed at first. The paper maps of the water pipeline network and its damage location offered by the local water supply authorities of four cities were digitalized by scanning. The dataset with pipeline material and diameter was inventoried in the shape format of the GIS by editing the roadway digital maps of the Geospatial Information Authority of Japan. Fig. 1 shows the pipeline network and pipeline damage locations due to the earthquake in the target region. The small water-supply systems for old towns; old Ohno Town in Kashima City, old Ushibori Town in Itako City and old Omigawa Town in Katori City, are independent from the downtown of the cities, and they had slight damage rather than the downtown areas. Therefore, the above-mentioned small water-supply systems of the old towns were not used in the database in this study.

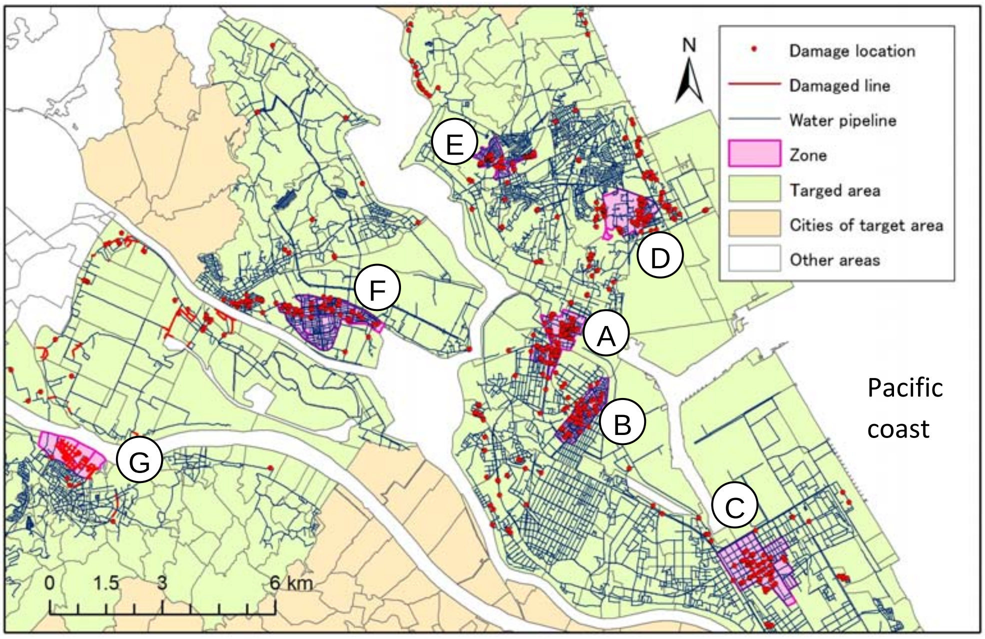


Figure 1. Location of water pipeline damage location and liquefaction hot spots

Among four cities in the Kashima region, Kashima City has the highest pipeline damage rate as 0.64 locations per pipeline length in km. This level of pipeline damage rate is almost equal to that of Kashiwazaki City in the 2007 Niigata Chuetsu-oki earthquake. The other cities has the pipeline damage rate of 0.2 to 0.3 locations per km, which are the same of the strong ground motion area in the northwest Miyagi Prefecture in this earthquake.

There are several areas on which the pipeline damage locations have concentrated more locally as shown in Fig. 1. These areas correspond to the area where the sand boiling of liquefaction was confirmed in the reports. The concentration area of the pipeline damage locations can become a key indicator of liquefaction. Seven areas from Zone A to Zone G were set as the liquefaction hot spot in this study as shown in Table 1. The liquefaction factor is considered from the relation to topographical characteristics. The range of each Zone has been extracted by units of several administrative blocks. The area of each zone becomes 1-2 km^2.

Table 1. Zone of liquefaction hot spots

Zone	Name of zone	Cities	Area (km^2)	Length of pipeline (km)
A	Horiwari	Kamisu and Kashima	1.18	22.7
B	Fukashiba	Kamisu	0.98	28.7
C	Shitte	Kamisu	2.23	30.4
D	Hirai	Kashima	1.28	19.1
E	Midorigaoka	Kashima	0.58	15.2
F	Hinode	Itako	1.94	33.5
G	Sawara	Katori	1.13	10.4

3. CASE STUDY OF LIQUEFACTION HOT SPOT

In order to investigate the topographical characteristic of the zones of the liquefaction hot spot, the paleo-topographical map made in 1890's and the present topographic map on 1: 25,000 scale were used. Because the targeted region is in the mouth of Tonegawa River, the topographical transition with the stream sediment is remarkable.

On the other hand, the attribute of the pipeline in the liquefaction hot spot is deferent in terms of pipe material and diameter. There are a lot of polyvinyl-chloride pipes (VP) in Zone F while ductile cast-iron pipe (DIP) has the majority of the pipeline from Zone A to Zone E as shown in Fig.2, and there are a lot of asbestos cement pipe (ACP) and polyvinyl-chloride pipes (VP) in Zone G. Moreover, each Zone has about 70 % in the ratio of pipeline with 100mm or less in diameter as shown in Fig. 3.

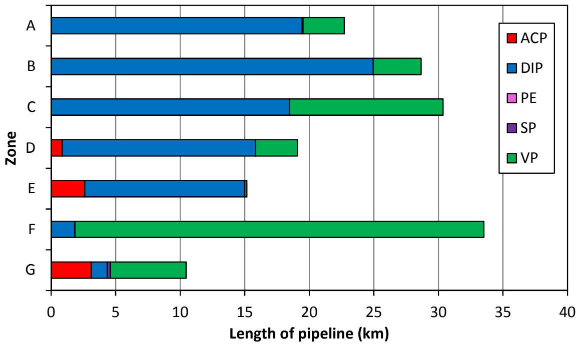


Figure 2. Pipeline length by material in the Zone

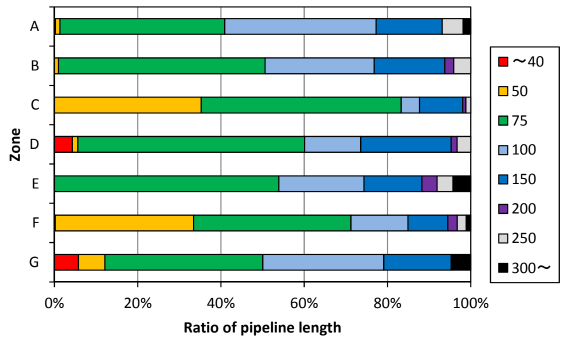
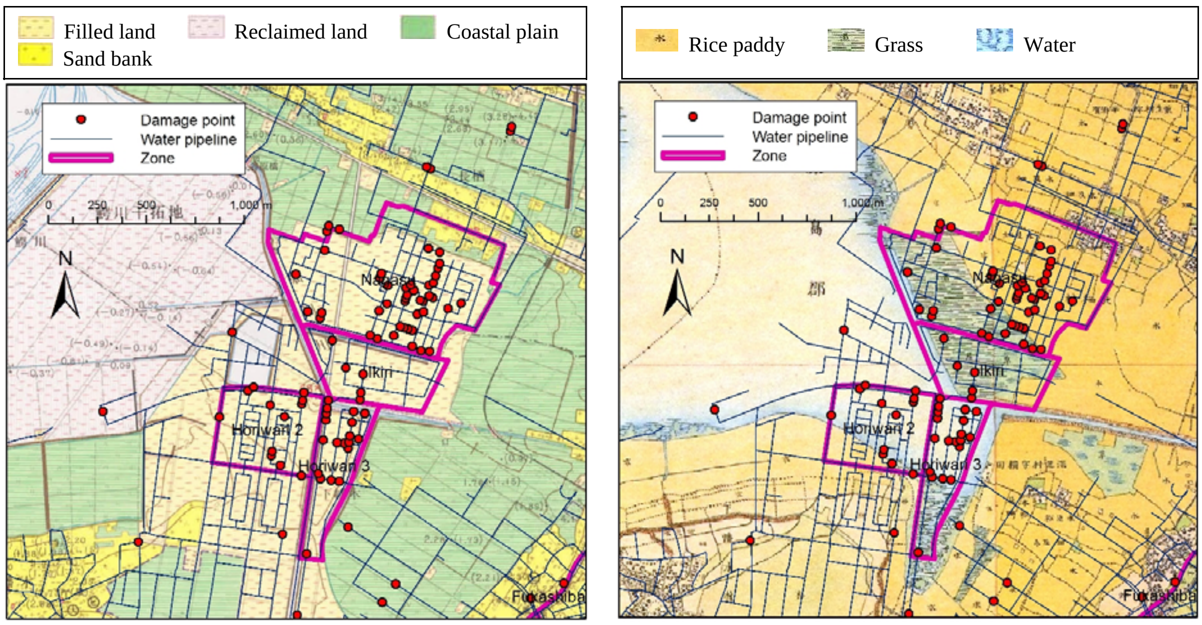


Figure 3. Ratio of pipeline length by diameter

3.1 Zone A: Horiwari

Fig.4 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone A (Horiwari district of Kamisu City and Nagasu district of Kashima city). Housing lots in Horiwari subsided more than roads due to the liquefaction and water was supplied to 200 households by the temporary above-ground pipelines when investigating in October, 2011. The east past of Nagasu was flooded by the tsunami. The Zone A is the filled land in the present topographical map. In the same category of topography, the Horiwari 2 had the large number of pipeline damage whereas its southern part did not. The paleo-topographical map about 100 years ago indicates that the Wanigawa River eroded to the inland of Horiwari and Ikiri, where the liquefaction occurred and the pipeline damage was concentrated. The part of the Wanigawa River in the past was reclaimed as the filled or reclaimed lands. Referring to the borehole profile at the reclaimed land of the Wanigawa River, the fine sand (N=5) piles up with thickness of 2m from the surface (T.P+2.5m), then in the subordinate layers the silt mixing fine sand (N=5-10) with 3m and the fine sand (N=40) with 25 m piles up. Liquefied ground seems to be the ground of 5-6 m from the surface.



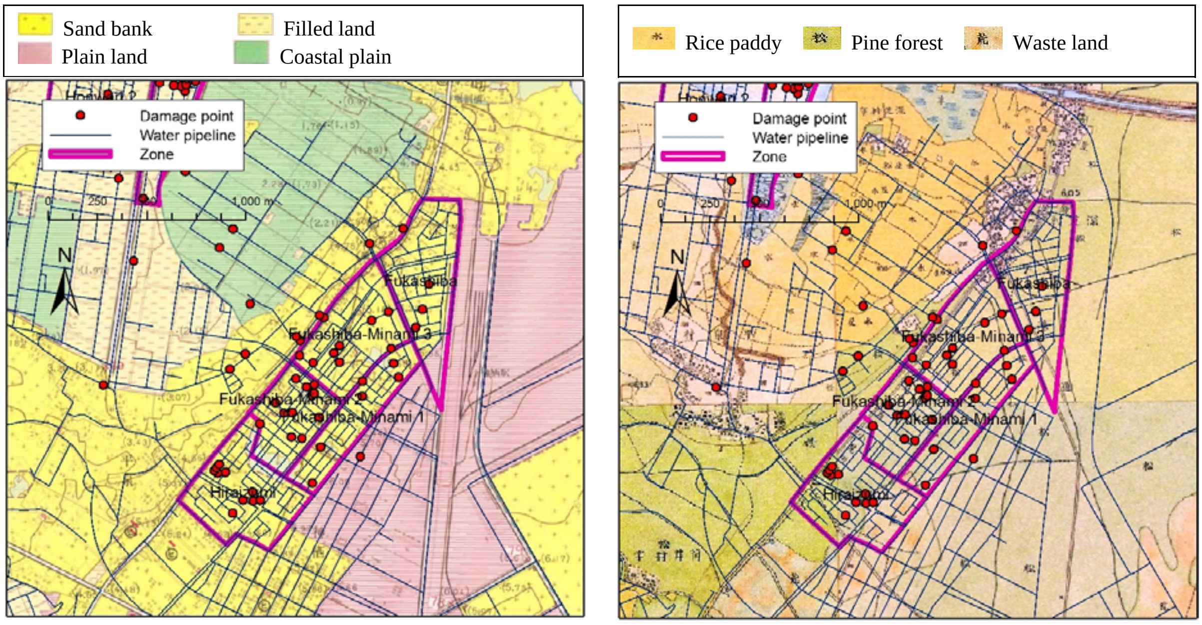
(a) Topographical map (b) Paleo-topographical map

Figure 4. Pipeline damage and topographical map in liquefaction hot spot Zone A: Horiwari

3.2 Zone B: Fukashiba

Fig.5 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone B (Fukashiba district of Kamisu City). The area of Zone B was developed as the housing lot according to the development of the Kashima industrial area near it. The large sand boiling induced by the liquefaction was seen in the schoolyard of elementary school in the Zone B. Many houses inclined. The Zone B is the sand bank in the topographical map, which is generally known to be compacted. The paleo-topographical map also indicates the pine forest. It is hard to find the factor causing the liquefaction hot spot from these topographical maps.

Tsukamoto et al. (2011) shows that Zone B and its surrounding were the gravel mining place in 1960's and the sand layer with the thickness of 6-7 m and N value less than 5 piles up. Therefore, it is thought that the back-filling soil after the gravel mining was liquefied. It is hard to find the liquefaction factor from the present and old topographical map.

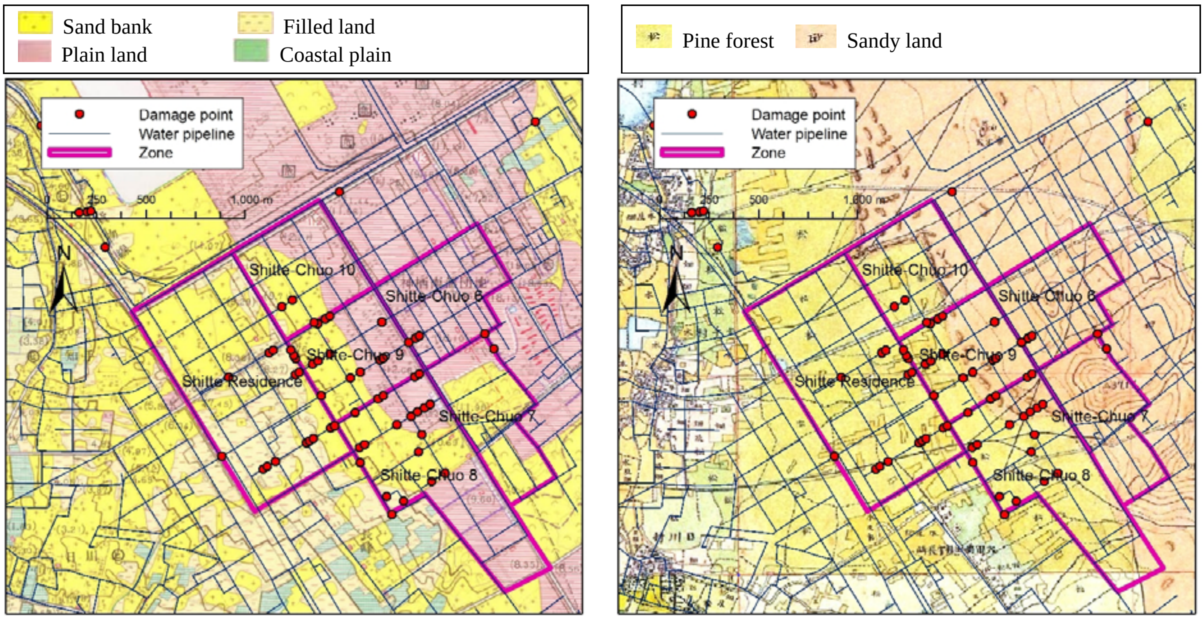


(a) Topographical map (b) Paleo-topographical map

Figure 5. Pipeline damage and topographical map in liquefaction hot spot Zone B: Fukashiba

3.3 Zone C: Shitte

Fig.6 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone C (Shitte district of Kamisu City). There are a lot of houses and fields in the region of Zone C. The damage to the housing lot and the subsidence of the road were confirmed. The area of Shitte-Chuo 6 & 7 is the low hills, and the liquefaction concentrated in the back ground. The Zone C concentrated by the pipeline damage locations is the sandy bank and plain land in the present topographical map and the pine forest and sandy bank in the paleo-geographical map. Furthermore the Zone C is not the area with a rapid housing land development but the area houses gradually increased, as referring to the aero-photograph in 1960's. It is said that the Zone C is similar to Zone B and was used as the gravel mining place and the back filling soil seems to be liquefied. The factor of liquefaction could not be distinguished from the topographical maps.

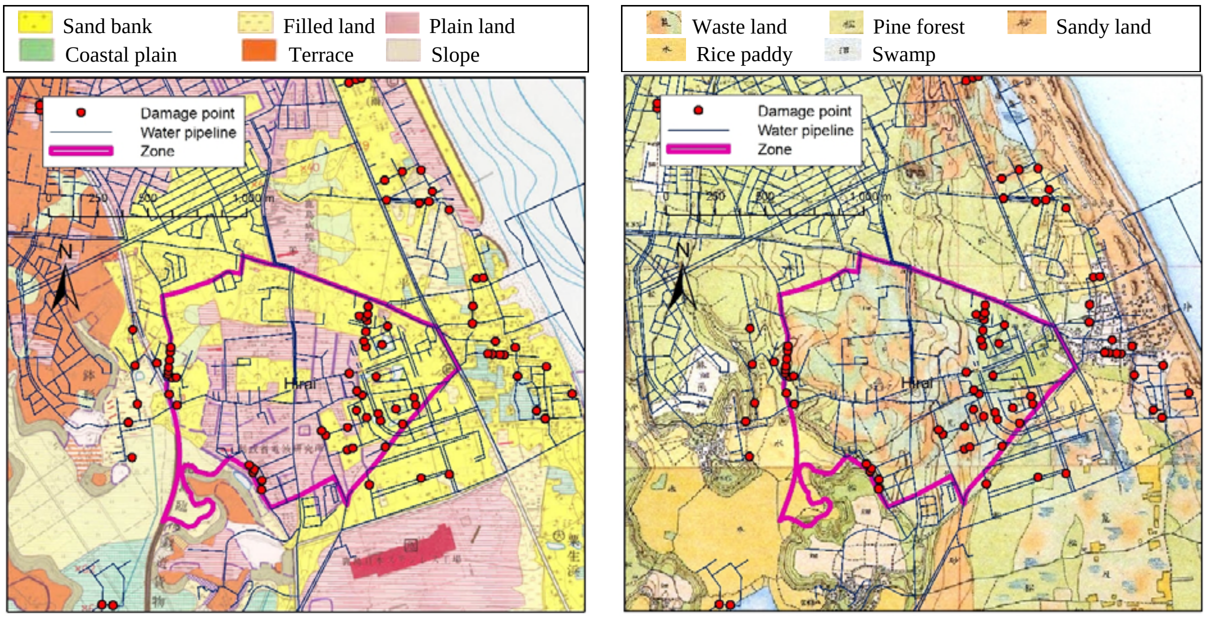


(a) Topographical map (b) Paleo-topographical map

Figure 6. Pipeline damage and topographical map in liquefaction hot spot Zone C: Shitte

3.4 Zone D: Hirai

Fig.7 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone D (Hirai district of Kashima City). The pipeline damage concentrates in the back swamp of sandy bank on the side of the Pacific Ocean as well as Zone D. Because the terrace is located on the west side of Zone D, the Zone D is a back swamp where the drainage between the terrace and the sandy bank on the sea side becomes bad. The housing land was developed recently in Zone D under the urban development planning thought it was wetland for a long time. The pipeline damage locations concentrate in the place of the hollow and shallow valley in the sand bank in the present topographical map. In the paleo-topographical map, it is in the waste land. It is thought that the height of the ground water table in the weak ground led to liquefying.

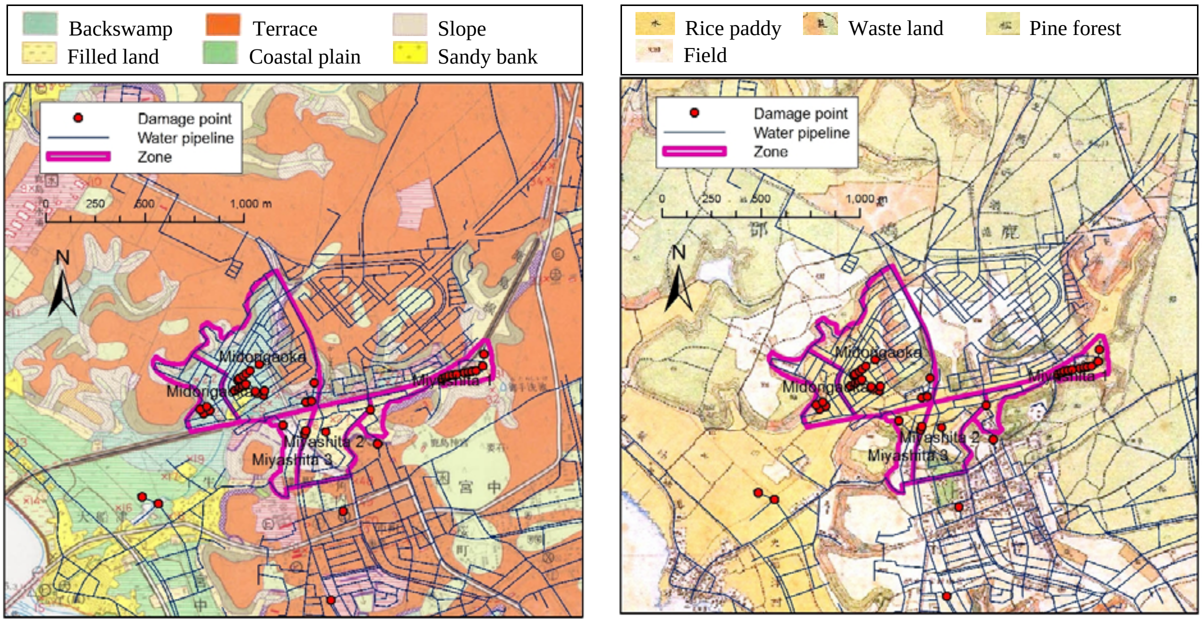


(a) Topographical map (b) Paleo-topographical map

Figure 7. Pipeline damage and topographical map in liquefaction hot spot Zone D: Hirai

3.5 Zone E: Midorigaoka

Fig.8 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone E (Midorigaoka district of Kashima City) along the Japan railway. The Midorigaoka in the Zone E is the residential settlement on the terrace and the valley is formed in the foothill from the present topographical map. On the other hand, in the area of Miyashita 1-3, a lot of sand boiling induced the liquefaction was seen under the ground surrounding the bottom of elevated bridge near the Kashima-Jingu station of the Japan Railway. It is the filled land on the valley in the present topographical map and the rice paddy in the paleo-topographical map. Its ground was easy to be liquefied because of high ground water table. The both present and old topographical maps shows that the Zone E is the high ground water table near the geological boundary. This condition is known well so far to be liquefied easily.

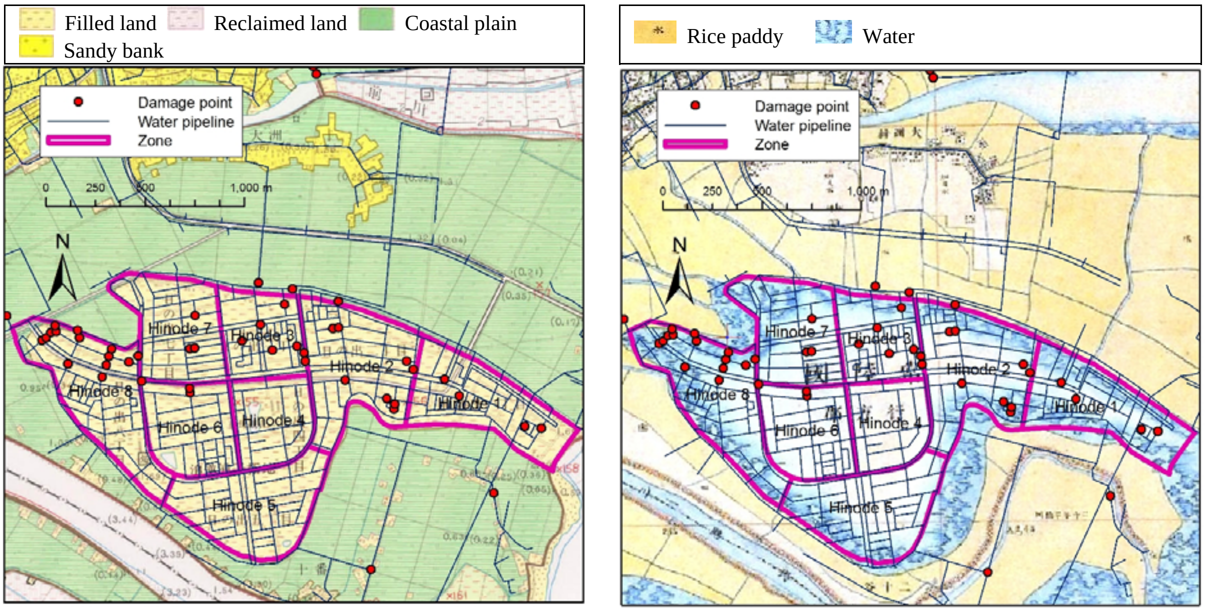


(a) Topographical map (b) Paleo-topographical map

Figure 8. Pipeline damage and Topographical map in liquefaction hot spot Zone E: Midorigaoka

3.6 Zone F: Hinode

Fig.9 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone F (Honode district of Itako City). There is no pipeline damage location in the south of Zone F (Hinode 4, 5, 6 and 8) since the subsidence of road was severe and the pipeline was installed above the ground as the temporary pipeline without no damage investigation. The Zone F was the filled ground in the present topographical map and the inland lake in the paleo-topographical map. The drain work of the lake began as the farmland development and it completed as reclaimed land in the 1950's. Afterwards it was developed as housing lot in order to supply houses with the construction of the Kashima industrial estate in the 1970's. According the borehole profile in the place of Hinode 3, under the fill of 0.5m in thickness, the fine sand (N=5-15) piles up until GL-4m, then fine sand mixing silt (N <5) piles up until GL-6. It becomes the fine sand of N>30 at GL-9m or less. The reclaimed layer of the inland lake has about 10m in thickness in the north part of the Zone F and it considers to be liquefied. The liquefaction area would be estimated if the paleo-topographical map is used though it is difficult to forecast becoming the liquefaction hot spot only by the present topographical map.

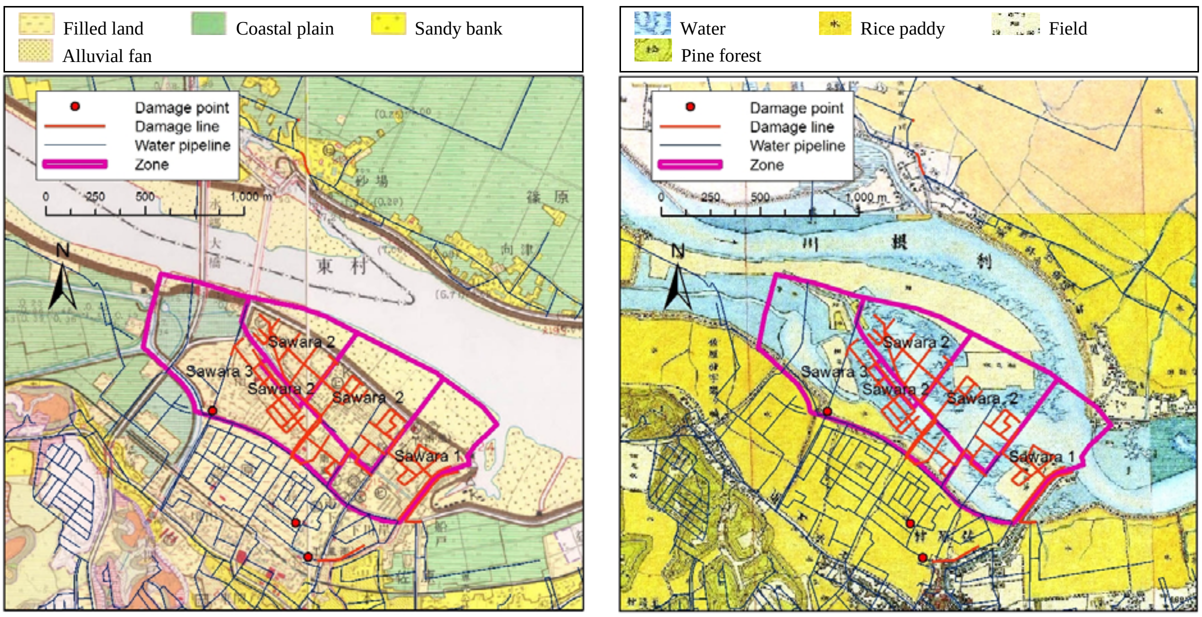


(a) Topographical map (b) Paleo-topographical map

Figure 9. Pipeline damage and topographical map in liquefaction hot spot Zone F: Hinode

3.7 Zone G: Sawara

Fig.10 shows the distribution of water pipeline damage locations over the present topographical map and paleo-topographical map near Zone G (Sawara district of Katori City). The Zone G is the area between the Tonegawa River and the national roadway Route 356. The lateral spread induced by the liquefaction occurred on the bank of canals and dammed up the canal. The extensive liquefaction in the Zone G let the pipeline restoration to be done by temporary aboveground pipeline. Most part of pipeline was assessed not in the damage point but as the damaged pipeline. The fine sand of N<5 piles up with thickness of 6m in GL-6m, and the silt is placed at the subordinate position by the thickness of 2m. The fine sand of about N=10 piles up in addition in GL-13m according to the borehole profile at the city office in the Zone G. It is thought that liquefaction was generated in this reclaimed sand. While the same filled land is drawn both in the Zone G and in its inland in the present topographical map, the paleo-topographical map clearly indicates the difference between the old riverside in the Zone G and the inland. The paleo-topographical map is helpful to understand liquefaction possibility.



(a) Topographical map (b) Paleo-topographical map

Figure 10. Pipeline damage and topographical map in liquefaction hot spot Zone G: Sawara

4. GEOGRAPHICAL FEATURES FACTOR OF LIQUIDIZING HOT SPOT

The result of the pipeline damage rate, the present and past topographical characteristics, and liquefaction factors in each Zone is summarized in Table 2. The pipeline damage rate in the Zones of liquefaction hot spot is 1.0 to 3.0 locations per length in km while 0.19 locations per length in the area other than the Zone. The damage rate in the hot spot is 6 to 17 times high compared with the other area. The damage rate is considered to be influenced by the subsidence level of liquefaction rather than by the vulnerability of pipeline materials between the Zones, though the vulnerability is not the same between the Zones.

As for the topographical characteristics in the Zones, three zones (Zones A, F and G) out of seven zones are the area where the old river was reclaimed and the reclaimed soil was liquefied. Their liquefaction-induced subsidence was extensive and the water pipeline was restored by temporary aboveground pipeline without replacing. The filled ground on the back swamp and valley is also liquefied in two zones (Zones D and E), where pipeline damage locations concentrate on a certain span of the pipeline. The range of the liquefaction hot spot can be specified by referring to the paleo-topographical map though it is hard for the present topographical map to distinguish the liquefied area and the surrounding not-liquefied area from the same topographical categories. Moreover, two zones (Zones B and C) where the back fill soil of the gravel mining place had been liquefied were not able to be identified from the present and past topographical maps. It is necessary to make the standard or guideline of compaction for back fill soil and to add information on artificial modification ground in the topographical map.

The ground of the liquefaction hot spot zones presented in this study is the ground possible to be liquefied as far as some borehole profiles are referred. Furthermore, what the similar ground distributes spatially in the range of 1 km^2 made the extensive ground deformation by the liquefaction. That caused the concentration of underground water pipeline damage.

Table 2. Pipeline damage rate and geographical history in the liquefaction hot spot

Zone	Name of zone	Length of pipeline (km)	No. of pipe damage [damaged length (km)]	Pipe damage rate (No./km) [Damage rate (%)]	Topography (Present / Past)	Liquefaction factor
A	Horiwari	22.7	75	3.30	Filled land/ River	Reclaimed soil of old river was liquefied.
B	Fukashiba	28.7	40	1.40	Sandy bank/ Pine forest	Reclaimed soil of gravel mining spot was liquefied.
C	Shitte	30.4	54	1.78	Sandy bank/ Pine forest	Reclaimed soil of gravel mining spot was liquefied.
D	Hirai	19.1	43	2.25	Sandy bank/ Waste land	Filled soil of back swamp between terrace and sandy bank was liquefied
E	Midorigaoka	15.2	37	2.44	Back swamp, filled land/ Rice paddy	Filled soil on the valley was liquefied.
F	Hinode	33.5	38	1.13	Filled land/ Lake	Reclaimed soil of old river was liquefied.
G	Sawara	10.4	1 [8.4km]	— [80.6%]	Filled land/ River	Reclaimed soil of old river was liquefied.
Subtotal in the Zones		160	288	1.80		
Subtotal outside the Zones		1,379	259	0.19		

Note) Pipeline which is unknown damaged pipeline in the Zones F and G is excluded from the list.

5. CONCLUSIONS

This study clarified a spatial distribution of liquefaction from the damage distribution of water pipeline damage in the Kashima region during the 2011 off the Pacific coast of Tohoku earthquake. In addition, the factor of liquefaction in the zones of the liquefaction hot spot was analyzed from present and old topographical maps. Followings can be summarized as the conclusions of this study.

- When the area on which pipeline damage location concentrated was defined as the liquefaction hot spot, there are seven zones of the liquefaction hot spot in the targeted region. They have the area of about 1 km^2.

- The ground in the zones of the liquefaction hot spot is classified into three types: the reclaimed land from an old river, the reclaimed land on the back swamp and valley, and the back fill land after the gravel mining places.

- The range of the liquefaction hot spot can be specified by referring to the paleo-topographical map though it is hard for the present topographical map to distinguish the liquefied area and the surrounding not-liquefied area from the same topographical categories.

- It has been understood that the conduit damage rate grows by 6-17 times in the liquidizing hot spot compared with other districts in the surrounding.

- What the similar ground distributes spatially in the range of 1 km^2 made the ground deformation by the liquefaction extensive. That caused the concentration of underground water pipeline damage.

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