LIQUEFACTION-INDUCED PIPELINE DAMAGE CONCENTRATION AND LANDFORM AND LAND USE CHANGES IN THE KASHIMA REGION

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\textbf{ABSTRACT}: The 2011 earthquake in Tohoku, Japan caused extensive liquefaction in the coastal area of the Tokyo Bay and the lower banks of the Tone River in the North Kanto region. Because small-diameter underground pipelines were subjected to ground deformation, the amount of pipeline damage can be considered an indicator of the severity of the liquefaction. An analysis of the pipeline damage in the Kashima region along the lower banks of the Tone River showed that the damage was concentrated in an area of 1 km\textsuperscript{2}. In this study, the reason for the concentration of damage in that small area was analyzed with respect to landform and land use changes that had occurred. The area in which the pipeline damage was concentrated was identified using old topographic maps compiled in the 1880s, as it was difficult to identify the area of concentrated pipeline damage using the current topographic map alone.

\textbf{Key Words}: The 2011 Tohoku earthquake, liquefaction, lower bank of Tone River, pipeline damage, landform and land use change

\textbf{INTRODUCTION}

The earthquake that occurred on March 11, 2011 off the Pacific coast of Tohoku, Japan (hereafter referred to as the Tohoku earthquake) and its aftershocks provoked ground shaking for a long duration and caused liquefaction in a large area around Tohoku and Kanto. Yasuda and Harada (2011) reported that the area of the Tokyo Bay’s shore in which liquefaction occurred was 42 km\textsuperscript{2}. Not only the area of liquefaction but also the levels of roadway subsidence and housing inclination induced by the liquefaction exceeded those caused by previous earthquakes in Japan. The number of locations at which liquefaction occurred during previous earthquakes as well as during this earthquake was confirmed to be 70 or more (Wakamatsu 2011). Because strong ground motion was observed in a large area of east Japan, the spatial range and extent of the liquefaction associated with this earthquake are not clear.

This study attempted to determine the spatial range of the liquefaction caused by the Tohoku earthquake on the basis of the distribution of water-pipeline damage in the cities of Kamisu, Kashima, and Itako in Ibaraki Prefecture and the city of Katori in Chiba Prefecture (hereafter referred to as the
In addition, this study attempted to clarify the relation between the area of concentrated pipeline damage and topographic characteristics.

**OBJECTIVE**

Liquefaction-induced subsidence and lateral flow cause damage to underground structures and housing foundations. Liquefaction-induced ground deformation provokes larger strains in underground structures, such as pipelines and cables, than does seismic ground motion. Thus, effective countermeasure for liquefaction on underground structures is useful in identifying locations with high potential for liquefaction and in evaluating underground strain magnitudes.

The Japanese seismic design practices for assessing the effects of liquefaction on underground pipelines, such as water and gas pipelines, installed over large areas at high densities were revised after the 1995 Kobe earthquake (JWWA 2009; JGA 2001). The seismic design guidelines for water supply facilities provides a method for judging liquefaction potential using an index based on the borehole profile and, if the potential is high, provides the ground displacement and strain based on values measured during the Kobe earthquake and the Niigata Chuetsu earthquake. For instance, the allowable tensile ground strain transverse to the shore protection was set to be 1.2% to 2.0%, and the allowable tensile ground strain in the reclaimed land and river basin was set to be 1.0% to 1.5%. Detailed seismic checks of liquefaction potential are necessary for major facilities and important trunk pipelines. On the other hand, effective seismic countermeasures for small-diameter pipeline networks installed over large areas at high densities involve identifying areas in which liquefaction occurs easily on the basis of spatial geological information available in topographic maps, rather than from point-wise borehole profiles, and then executing the measures, such as installing anti-earthquake pipes to resist liquefaction-induced ground strains or isolating the pipeline network in the liquefaction-prone area from the rest of the network to minimize the area to which service is cut. The guidelines identified the types of landforms with high liquefaction potential as old rivers, reclamation sites, and areas of soft subsoil. It is important to confirm the spatial range and landforms of the area in which liquefaction occurred during the Tohoku earthquake.

This study targeted the Kashima region, which is in the downstream portion of the Tone River, to determine the relation between pipeline damage and landforms in the liquefaction area. The target area was selected on the basis of the results of field reconnaissance conducted by the authors (Kuwata and Katagiri 2011), during which sand boiling (an indicator of liquefaction) was observed at many points; many houses were observed to be tilted and sunk unevenly, and the pipeline and ducts were found to be damaged. The surface of the roadway in the liquefied areas of the cities of Itako and Katori was found to be uneven, and the water pipelines in these areas were found to have been replaced with temporary above-ground pipelines as an emergency measure. Evidence of liquefaction was observed over an area of 1 km². The pipeline damage in this area was caused mainly by ground shaking or liquefaction, although the tsunami associated with the earthquake also flooded a small part of the area.

In this study, the area within which the amount of required pipeline repair was high was identified as the area of concentrated pipeline damage at first. Subsequently, the area of concentrated pipeline damage is identified by confirming that liquefaction occurs in the area and by examining the concentration of pipeline damage through a comparison between old and current topographic maps.

**PIPELINE DAMAGE IN THE KASHIMA REGION**

A database of the water-pipeline network in the Kashima region and the locations at which it was damaged was developed first. Paper maps of the water-pipeline network and the locations of damage, obtained from the local water supply authorities of the four cities, were digitized from scanned images. Data on the pipeline materials and diameters were inventoried in geographic information system (GIS) shape format by editing digital roadway maps from the Geospatial Information Authority of Japan.
Fig. 1 shows the pipeline network in the target region and the locations of the damage caused by the earthquake. The small water supply systems of old towns in the region, such as Ohno Town in Kashima City, Ushibori Town in Itako City and Omigawa Town in Katori City, are independent of the network that serves the downtown areas of these cities, and these small water supply system suffered less damage than the portions of the pipeline network in the downtown areas. Therefore, information on the small water-supply systems in the old towns mentioned was not included in the database developed for this study. The water-supply system in the south of old Sawara Town in Katori City was excluded for the same reason.

The composition ratios of the lengths of pipeline by pipe material in the target region are shown in Fig. 2, and damage statistics are listed in Table 1. The pipeline lengths and composition ratios in the target region are somewhat different from those indicated by the statistics (JWWA 2007) because of the inclusion of the transmission pipeline with the distribution pipelines and because of the date of publication of the map. The data set adopted in this study was based on the paper map. The number of damage locations was that recorded as of October 2011. There were some districts in which pipelines were replaced by temporary above-ground pipelines, and the number of locations at which damaged pipeline was replaced by new pipeline is not known. The amount of damage in these districts was accounted for separately in terms of the length of damaged lines.

The data on the composition ratios of pipeline length by pipe material indicate that ductile cast-iron pipes (DIP) accounted for 60 to 70% of the pipeline lengths in Kashima and Kamisu Cities and that polyvinyl chloride pipe (VP) accounted for approximately 60% of the pipeline lengths in Itako and Katori Cities. Pipes with diameters of 75 to 150 mm accounted for 66 to 85% of the pipeline lengths in all of the cities. The fragile material known as asbestos cement pipe (ACP) had been widely adopted for pipeline use in the Kashima region and was still present in significant proportions in older urban areas. On average, ACP accounts for approximately 20% of the pipeline length in several cities in the region. Kamisu and Itako Cities had been replacing ACP with earthquake-proof pipe to update their pipeline systems.

Kashima City had the highest pipeline repair rate of the four cities, with 0.64 locations per km
(hereafter expressed as No./km). This rate is almost equal to the rate of Kashiwazaki City after the 2007 Niigata Chuetsu-oki earthquake (Konagai et al. 2007). The other cities in the region had pipeline repair rates of 0.2 to 0.3 No./km, which are comparable to the rates in the area of strong ground motion in the northwest of Miyagi Prefecture following that earthquake (Kuwata and Okamoto 2012).

![Chart showing pipeline repair rates by city](chart.png)

(ACP: Asbestos cement pipe, CIP: Cast-iron pipe, DIP: Ductile cast-iron pipe, DIP-NS: Ductile iron pipe with seismic joints, PE: Polyethylene pipe, SP: Steel pipe, VP: polyvinyl chloride pipe)

**Fig. 2** Composition ratios of pipeline lengths by pipe material in the target region

**Table 1** Damage statistics in the target region

<table>
<thead>
<tr>
<th>City</th>
<th>Pipeline length (km)</th>
<th>Number of repair locations (No.)</th>
<th>Pipe repair rate (No./km) (% (km/km))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itako</td>
<td>247</td>
<td>80</td>
<td>0.32 (15.1 km)</td>
</tr>
<tr>
<td>Kamisu</td>
<td>718</td>
<td>211</td>
<td>0.29</td>
</tr>
<tr>
<td>Kashima</td>
<td>343</td>
<td>221</td>
<td>0.64</td>
</tr>
<tr>
<td>Katori</td>
<td>246</td>
<td>35</td>
<td>0.14 (17.9 km)</td>
</tr>
</tbody>
</table>

Note: Numbers in brackets reflect temporary pipelines

There are several areas in which the pipeline damage locations were more concentrated, as shown in Fig. 1. To express the pipeline-damage concentration quantitatively, a plot of the pipeline installation density vs. the pipeline repair rate is shown for each district in Fig. 3. A district unit is defined as an administrative division designated by the Ministry of Public Management, Home Affairs, Posts and Telecommunications. A pipeline repair rate of 0.3 No./km and a pipeline installation density of 10 km/km² were used as references to group the districts into four classes. The pipeline repair rate was 0.44 No./km in Kobe City after the 1995 Kobe earthquake, 0.30 No./km in Nagaoka City and 0.31 No./km in Ojiya City after the 2004 Niigata Chuetsu–oki earthquake, and 0.32 No./km in Wajima City after the 2007 Noto Peninsula earthquake (Kobe City Water Bureau 1996; The Ministry of Health, Labour, and Welfare 2005 and 2007). A pipeline repair rate of 0.3 No./km can be considered an average for a city that suffers earthquake damage due to ground shaking. A pipeline installation density of 10 km/km² corresponds to that of the populated area (DID, Densely Inhabited District) of
Kashiwazaki City, Niigata Prefecture, according to Kobayashi et al. (2011). To identify the districts in the area in which the pipeline repair rates were comparable, the districts that had abnormally high pipeline repair rates, because of small quantities of installed pipeline with respect to the population density, were excluded. Fig. 4 shows the districts grouped into four classes. Class 5 was defined as encompassing the districts with 80% or more of its pipeline length damaged or replaced with temporary pipeline. Two or more districts in Class 4 and Class 5 can be considered adjacent, as shown in Fig. 4. Seven zones, designated A through G, that matched two or more adjoining districts were extracted and considered to represent the pipeline-damage concentration area, as shown in Table 2. The districts in these zones were included in Class 4 and Class 5.

These zones correspond to the area in which sand boiling indicators of liquefaction were confirmed during the authors’ field reconnaissance. The damage in the pipeline-damage concentration area can be considered to have been caused by the liquefaction. This area is referred to as the “liquefaction-induced pipeline-damage concentration area” in this paper. Table 2 lists the area and pipeline length of each zone. The areas of the zones were limited in this study to 1 to 2 km² but were not necessarily delimited to correspond to administrative districts. However, it should be noted that there sand boiling caused by local liquefaction occurred even in the Class 2 area.

![Fig. 3](image3.png)

**Fig. 3** The plot of pipeline installation density vs. pipeline repair rate in each district

![Fig. 4](image4.png)

**Fig. 4** The pipeline-damage concentration area and the pipeline-damage classes of the districts
Table 2 Zones of liquefaction-induced pipeline-damage concentration area

<table>
<thead>
<tr>
<th>Zone</th>
<th>Name of zone</th>
<th>City</th>
<th>Area (km²)</th>
<th>Length of pipeline (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Horiwari</td>
<td>Kamisu and Kashima</td>
<td>1.18</td>
<td>22.7</td>
</tr>
<tr>
<td>B</td>
<td>Fukashiba</td>
<td>Kamisu</td>
<td>0.98</td>
<td>28.7</td>
</tr>
<tr>
<td>C</td>
<td>Shitte</td>
<td>Kamisu</td>
<td>2.23</td>
<td>30.4</td>
</tr>
<tr>
<td>D</td>
<td>Hirai</td>
<td>Kashima</td>
<td>1.28</td>
<td>19.1</td>
</tr>
<tr>
<td>E</td>
<td>Midorigaoka</td>
<td>Kashima</td>
<td>0.58</td>
<td>15.2</td>
</tr>
<tr>
<td>F</td>
<td>Hinode</td>
<td>Itako</td>
<td>1.94</td>
<td>33.5</td>
</tr>
<tr>
<td>G</td>
<td>Sawara</td>
<td>Katori</td>
<td>1.13</td>
<td>10.4</td>
</tr>
</tbody>
</table>

LANDFORM CHANGES IN THE LIQUEFACTION-INDUCED PIPELINE-DAMAGE CONCENTRATION AREA

To investigate the topographic characteristics of the liquefaction-induced pipeline-damage concentration area, a paleo-topographic map on a 1:20,000 scale made in the 1890s (Geospatial Information Authority of Japan) was compared with the current topographic map, which is on a 1:25,000 scale (Geospatial Information Authority of Japan 1978 & 1979). The current topographic map contains information on the landform classification by height and surface geological features, as well as the elevation at 1-m intervals and the presence of facilities such as disaster prevention facilities. The current topographic map was published in 1978 and 1979, but has not been updated since then. In the target region, the Wani River reclamation project was completed in 1928 (Kamisu City 1984), the Kashima Port opened in 1969, and the construction of the Kashima seaside industrial area was completed in 1973. The Sotosakaura reclamation project in Itako City was completed in 1950, and its land relocation project was completed in 1979 (Hashimoto and Yasuda 2011). The landform and land use has not changed since the large-scale reclamation projects of the Wani River and the Sotosakaura. Thus, the topographic map published in the 1970s is considered the current map, and landform changes were identified by comparing this map with the paleo-topographic map. The landform changes in the target region caused by sedimentation of the Tone River and artificial modifications are remarkable, even though they have occurred over a period of just 100 years.

Pipe fragility in the liquefaction-induced pipeline-damage concentration area was found to vary by pipe material and diameter. A substantial proportion of the pipe in Zone F is polyvinyl chloride (VP), whereas in Zones A through E, the majority of the pipeline length is ductile cast-iron pipe (DIP). There are also considerable proportions of asbestos cement pipe (ACP) and polyvinyl chloride pipe (VP) in Zone G, as shown in Fig. 5. According to the pipeline damage estimation method (JWWA, 1998), the fragility of DIP with typical mechanical joints is 0.3 times that of VP, whereas ACP is 2.5 times more fragile than VP. The pipelines in Zones F and G are thus more fragile than those in the other zones. In addition, in each zone, approximately 70% of the pipes have diameters of 100 mm or less, as shown in Fig. 5. The pipe diameter distributions of the zones are not very different.
Zone A: Horiwari

Fig. 6 shows the distribution of pipeline-damage locations in Zone A (the Horiwari District of Kamisu City and the Nagasu District of Kashima City), plotted on the current topographic map and the paleo-topographic map. The home foundations in Horiwari subsided more than the roads because of liquefaction and water having been supplied to 200 households was supplied by temporary above-ground pipelines as of October 2011. The eastern part of Nagasu was flooded by the tsunami. Although almost the entire area of Zone A is shown in the filled land on the current topographic map, the southern part of Horiwari District 2 did not have a high incidence of pipeline damage. The paleo-topographic map developed approximately 100 years ago indicates that the Wani River eroded to the inland of Horiwari and Ikiri Districts, where the liquefaction occurred and where the pipeline damage was concentrated. Pipeline damage was also concentrated in the northeastern part of the Nagasu District, which had been used for rice fields in the past. The southwestern part of the Nagasu District had been a bog where grass grew. Areas that had been in the river or on land with high groundwater levels, such as rice fields and bogs, were reclaimed. In addition, the west side of Zone A
was reclaimed from the Wani River in 1928, as mentioned previously. According to the borehole profile of the reclaimed land of the Wani River, fine sand (N=5) is present to a depth of 2 m from the surface (T.P+2.5 m), over a layer of silt mixed with fine sand (N=5 to 10) to a depth of 3 m and a layer of fine sand (N=40) to a depth of 25 m. Liquefaction of the ground seems to have occurred at a depth of 5 to 6 m from the surface.

The paleo-topographic map is useful in clarifying the hydrological environment and pipeline damage in the area of the old river. The northeastern area of the Nagasu District, which had been rice fields according to the paleo map and is filled land according to the current map, experienced liquefaction, and pipeline damage occurred at many locations. These two maps alone are not sufficient to describe the characteristics of the liquefaction damage. The paleo town map published in the 1600s (Kashima City 2005) indicates that there had been a moat in the Nagasu District derived from the river between the Horiwari and Ikiri Districts. The pipeline damage induced by the liquefaction occurred along the location of this moat.

**Zone B: Fukashiba**

Fig. 7 shows the distribution of pipeline-damage locations in Zone B (the Fukashiba District of Kamisu City), plotted on the current topographic map and the paleo-topographic map. The area in Zone B was developed as a residential area in conjunction with the development of the Kashima industrial area. Substantial evidence of sand boiling induced by liquefaction was observed in the schoolyard of the elementary school in Zone B. In addition, many of the houses in this zone were tilted.

Zone B is located on a sand bank that is known to be compacted, according to the current topographic map. The paleo-topographic map indicates the location of a Pine grove in this zone. It is difficult to identify the factor responsible for the liquefaction from these topographic maps. Tsukamoto et al. (2011) showed that gravel mining took place in Zone B and its surroundings during the 1960s. The borehole profile indicates that the top soil layer is 6 to 7 m of sand, with an N value less than 5. Therefore, the soil that was backfilled after the gravel mining is believed to have been liquefied. It is difficult to identify any artificial change in the subsurface ground from the current and paleo-topographic maps.

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![Fig. 7 Pipeline damage plotted on the topographic maps of liquefaction-induced pipeline-damage concentration area Zone B: Fukashiba](image)
Zone C: Shitte

Fig. 8 shows the distribution of pipeline-damage locations in Zone C (the Shitte District of Kamisu City) plotted on the current topographic map and the paleo-topographic map. Damage to the foundations of houses and subsidence of the roadway were confirmed. The area of Shitte-Chuo Districts 6 and 7 is a low hill, and liquefaction was concentrated in its vicinity. Pipeline damage locations are concentrated on the sand bank and open plain on the current topographic map and the Pine grove and sand bank on the paleo-topographic map. Examination of aerial photographs taken in the 1960s (Geospatial Information Authority of Japan) revealed that Zone C is not an area that has experienced rapid housing development but rather a gradual increase in housing density. The sand-gravel mix in Kamisu City is called Ikisu sand and is famous for being a good construction material. Zone C is similar to Zone B in that it was gravel mining took place in the zone and it is the backfilled soil that seems to have been liquefied. The geologic history of the zone has not been clarified, and it is necessary to review more information.

Zone D: Hirai

Fig. 9 shows the distribution of pipeline-damage locations in Zone D (the Hirai District of Kashima City), plotted on the current topographic map and the paleo-topographic map. Pipeline damage in Zone D was concentrated in the back swamp of the sand bank on the Pacific coast. Because the terrace is located on the west side of Zone D, the zone is a back swamp with poor drainage between the terrace and the sand bank on the sea side. Residential settlements have developed recently in Zone D under urban development planning; the zone had long been a wetland. Pipeline-damage was concentrated in the empty, shallow valley in the sand bank shown on the current topographic map. On the paleo-topographic map, this area is identified as a waste land. The height of the groundwater table in the weak soil is believed to have led to liquefaction.
Zone E: Midorigaoka

Fig. 10 shows the distribution of pipeline-damage locations in Zone E (the Midorigaoka District of Kashima City) along the Japan Railway, plotted on the current topographic map and the paleo-topographic map. The Midorigaoka District in Zone E is a residential settlement on the terrace, and a valley exists in the foothills, according to the current topographic map. In the area of Miyashita Districts 1 through 3, abundant evidence of sand boiling induced by liquefaction was observed in the...
area surrounding the bottom of a viaduct near the Kashima-Jingu station of the Japan Railway. This sand boiling is shown as being located in filled land in the valley on the current topographic map and as being located in a rice field on the paleo-topographic map. This ground was easily liquefied because of the high groundwater table in the area. Both the current and paleo-topographic maps show that the groundwater table is high in Zone E, and high groundwater is known to make soil susceptible to liquefaction.

**Zone F: Hinode**

Fig. 11 shows the distribution of pipeline-damage locations in Zone F (the Honode District of Itako City), plotted on the current topographic map and the paleo-topographic map. There were no pipeline damage locations identified in the south of Zone F (Hinode Districts 4, 5, 6, and 8) because the subsidence of the road was more severe than in the north and as a result, above-ground temporary pipelines were installed, without damage investigation and repair being conducted. Zone F is shown as being located in filled ground on the current topographic map and as being the location of an inland lake on the paleo-topographic map. Drainage of the lake began as part of farmland development, and reclamation of the land was completed in the 1950s. The zone was subsequently developed as a residential area in conjunction with the construction of the Kashima industrial area in the 1970s.

According to the borehole profile for Hinode District 3, under a layer of fill 0.5 m in thickness, a layer of fine sand (N=5 to 15) is present to a depth of 4 m from the ground surface. Beneath this layer is a layer of fine sand mixed with silt (N<5), present to a depth of 6 m, and a layer of fine sand (N>30) to a depth of 9 m or more. The cross section of the north–south line crossing Zone F identified by Hashimoto and Yasuda (2011) indicates that a diluvial sandy layer is present beneath the alluvial sandy layer in the north of Zone F, while an alluvial clay layer with a thickness of approximately 5 m exists between the alluvial sandy layer and the diluvial sandy layer in the south of the Zone F. The above-mentioned borehole profile represents conditions at the boundary between the north and the south. The fine sand mixed with silt is at the north border of the alluvial clay layer. The inland alluvial sandy layer is believed to have been liquefied. The liquefaction area could be estimated if a paleo-topographic map was available, but it is difficult to determine from the current topographic map alone.

![Filled land](image1) ![Reclaimed land](image2) ![Coastal plain](image3)

![Paddy field](image4) ![Water](image5)

(a) Current topographic map (b) Paleo-topographic map

Fig. 11 Pipeline damage plotted on the topographic maps of liquefaction-induced pipeline-damage concentration area Zone F: Hinode
Zone G: Sawara

Fig. 12 shows the distribution of pipeline-damage locations in Zone G (the Sawara District of Katori City), plotted on the current topographic map and the paleo-topographical map. Zone G is the area between the Tone River and the national roadway Route 356. Lateral spread induced by liquefaction occurred on the banks of canals and dammed them up. Extensive liquefaction occurred in Zone G, and the damaged pipeline was replaced with temporary above-ground pipes. Thus, most of the pipelines in this zone were assessed not as repair locations but as damaged lines.

While the same filled land is present in both Zone G and the inland area on the current topographic map, the paleo-topographic map clearly indicates the difference between the old riverside in Zone G and the inland area. The paleo-topographic map is helpful in understanding the zone’s liquefaction susceptibility.

Fine sand (N<5) is present to a depth of 6 m, and beneath that layer is a layer of silt present to a depth of 8 m and a fine sand layer (N=10) present to a depth of 13 m, according to the borehole profile for the location of the city office in Zone G. Liquefaction is believed to have occurred in this reclaimed sand.

GEOGRAPHIC CHARACTERISTICS OF THE LIQUEFACTION-INDUCED DAMAGE CONCENTRATION AREA

The pipeline repair rates, the current and past topographic characteristics, and the factors contributing to liquefaction in each zone are summarized in Table 3. The pipeline repair rates in the various zones of the liquefaction-induced pipeline-damage concentration area range from 1.0 to 3.0 No./km, whereas the rate is 0.19 No./km in areas other than these zones. The pipeline repair rates in the damage concentration area are 6 to 17 times higher than in other areas. The pipeline repair rate is considered to be influenced by the subsidence level of liquefaction rather than by the fragility of the pipeline materials used in the zones, even though the fragility of the pipeline materials used was not the same for all of the zones.
Table 3  Pipeline repair rates and landform changes in the liquefaction-induced pipeline-damage concentration area

<table>
<thead>
<tr>
<th>Zone</th>
<th>Name of zone</th>
<th>Length of pipeline (km)</th>
<th>No. of pipe damage [damaged length (km)]</th>
<th>Pipeline repair rate (No./km) [Damage rate (%)]</th>
<th>Topography (Present / Past)</th>
<th>Liquefaction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Horiwari</td>
<td>22.7</td>
<td>75</td>
<td>3.30 Filled land/ River</td>
<td>Reclaimed soil of old river was liquefied. Reclaimed soil of gravel mining place was liquefied.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Fukashiba</td>
<td>28.7</td>
<td>40</td>
<td>1.40 Sand bank/ Pine grove</td>
<td>Reclaimed soil of gravel mining place was liquefied (believed). Filled soil of back swamp between terrace and sand bank was liquefied</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Shitte</td>
<td>30.4</td>
<td>54</td>
<td>1.78 Sand bank/ Pine grove</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Hirai</td>
<td>19.1</td>
<td>43</td>
<td>2.25 Sand bank/ Waste land</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Midorigaoka</td>
<td>15.2</td>
<td>37</td>
<td>2.44 Back swamp, filled land/ Paddy field</td>
<td>Filled soil on the valley was liquefied.</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Hinode</td>
<td>33.5</td>
<td>38</td>
<td>1.13 Filled Lake</td>
<td>Reclaimed soil of old river was liquefied.</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Sawara</td>
<td>10.4 [8.4 km]</td>
<td>1 [8.4 km]</td>
<td>-- Filled land/ River</td>
<td>Reclaimed soil of old river was liquefied.</td>
<td></td>
</tr>
</tbody>
</table>

Subtotal in the zones 160 288 1.80
Subtotal outside the zones 1,379 259 0.19

Note) Unknown amounts of pipeline damage in Zones F and G are excluded from the list.

Of the seven zones, three (Zones A, F, and G) are areas in which the old river was reclaimed and the reclaimed soil was liquefied. Liquefaction-induced subsidence in these zones was extensive, and damaged water pipelines were replaced by temporary above-ground pipes. The filled ground in the back swamp and valley was also liquefied in two zones (Zones D and E), where many instances of pipeline damage occurred along a single line. The spatial range of the liquefaction-induced pipeline-damage concentration area can be specified by referring to the paleo-topographic map, although it is difficult to distinguish liquefied areas from non-liquefied areas for the same topographic categories using the current topographic map. For two zones (Zones B and C) in which soil that was backfilled after gravel mining was liquefied, it was not possible to identify the cause of the liquefaction from the current and paleo-topographic maps. Guidelines for compaction of backfill soil should be developed, and information on artificial modifications to the ground should be added to the topographical map.

In this study, areas where two or more adjacent districts with pipeline installation densities of 10 km/km² or more and pipeline repair rates of 0.3 No./km or more were defined as belonging to the pipeline-damage concentration area, and the occurrence of liquefaction in this area was confirmed. The soils in the liquefaction-induced pipeline-damage concentration area described in this study are highly susceptible to liquefaction, according to the information available from some borehole profiles. As well as the soil condition, the spatial distribution of such soils over areas of 1 km² or more formed a basin of weak soil, let the ground motion within it be amplified, and resulted in liquefaction causing extensive ground deformation and the large number of pipeline damage. Because permanent ground displacement by liquefaction is a severe type, it is necessary to clarify in the future the relation between permanent ground displacement in liquefied soil and pipeline damage.
CONCLUSIONS

In this study, the spatial distribution of water-pipeline damage in the Kashima region due to soil liquefaction that occurred during the 2011 off the Pacific coast of Tohoku earthquake was examined. In addition, the factors responsible for the liquefaction that occurred in the various zones of the liquefaction-induced pipeline-damage concentration area were analyzed using current and old topographic maps. The following conclusions can be drawn from the results of this study.

• Areas in which two or more adjacent districts with pipeline installation densities of 10 km/km² or more and pipeline repair rates of 0.3 No./km or more were defined as belonging to the pipeline-damage concentration area, and evidence of liquefaction in this area was confirmed. Seven zones within this area were identified. These zones have a spatial range of approximately 1 km².

• The soils in the zones of the liquefaction-induced pipeline-damage concentration area have been artificially modified by activities such as land reclamation from an old river, land reclamation in the back swamp and valley, and soil backfilling after gravel mining. The extent of the liquefaction area can be estimated from the paleo-topographic map but is difficult to determine from the current topographic map alone.

• The pipeline repair rates in the various zones of the liquefaction-induced pipeline-damage concentration area are 6 to 17 times higher than those of surrounding districts.

• The soils in the liquefaction-induced pipeline-damage concentration area are susceptible to liquefaction. As well as the soil condition, the spatial distribution of such soils over areas of 1 km² or more formed a basin of weak soil, let the ground motion within it be amplified, and resulted in liquefaction causing extensive ground deformation.

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