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# EFFECTS OF ARTIFICIAL LANDFORM CHANGE TO WATER PIPELINE DAMAGE IN SENDAI CITY DURING THE 2011 TOHOKU OFFSHORE JAPAN EARTHQUAKE

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**Keywords:** Water supply pipe, Earthquake damage, The 2011 Tohoku Offshore Japan Earthquake.

**Abstract.** *Sendai City was severely affected by the Mw9.0 Tohoku Offshore Earthquake of March 11th, 2011. A system of 4458-km water supply network in the city had extensive damage, with 1064 locations seriously affected, resulting in cuts off water supply of 2.3 hundred thousand houses just after the earthquake. About 60 percent of locations of the damaged pipelines were found to be located not on low-lying land consisting of soft soils but on hilly residential lands developed by cutting and leveling the hills and then filling the valleys for the past several ten years. In this study, the old topographic maps surveyed before the land development were digitized and normalized for superimposing on locations of pipeline damage to analyze the effects of landform change to pipelines damage. As a result, the followings were reached: more than a half of pipe breaks in the developed areas occurred in the former hillside slope and one third of the breaks occurred in the former valleys in the hill; The heaviest concentration of the pipe breaks observed within the boundary area between cutting and filling with a thickness ranging from -2.5 m to 2.5 m; and the higher concentration of pipe breaks is found in the area of ground failures but the greater numbers of breaks also occurred outside of the areas.*

# 1 INTRODUCTION

Sendai City is the most densely-inhabited city in the Tohoku region, northern part of Japan's main island, Honshu, which was severely affected by the $M_W$ 9.0 Tohoku Offshore Japan Earthquake of March 11th, 2011. A system of 4458-km water supply network in the city had extensive damage, with 1064 locations seriously affected, resulting in cuts off water supply of approximately 2.3 hundred thousand households just after the earthquake. The damage to water supply network includes 437 of transmission and distribution pipes, 522 of water supply pipes, and 105 of auxiliary equipment, i.e. air valve, hydrant, pressure reducing valves, etc. About 60 percent of locations of the damaged pipelines were found to be located not on low-lying land consisting of soft soils but on hilly residential lands developed by cutting and leveling the hills and then filling the valleys for the past several ten years. There is no precedent for so many pipelines damaged in hilly land in Japan, possibly no other country in the world. It is important to analyze the conditions at the damaged sites especially effects of the artificial landform change and relation with occurrence of ground failures to prepare for future earthquakes, because there are great many similar residential lands in Tokyo and its suburbs, and other metropolitan areas in Japan such as Nagoya and Osaka.

In this study, the old topographic maps surveyed in 1928 and 1964 before the land development were digitized and normalized for superimposing on the locations of pipeline damage to analyze the effects of landform change to pipelines damage.

# 2 IMPACT OF THE 2011 TOHOKU OFFSHORE JAPAN EARTHQUAKE ON THE SENDAI WATER SUPPLY DISTRIBUTION NETWORK

The City of Sendai with a population of over one million and with an area of approximately 78,800 hectares is the biggest city in the Tohoku region, Japan. About 66% of the total area of the city is land covered with forests and farmland and only 16% of the area is used for residential land [1].

On March 11, 2011 at 2:46 PM local time a $M_W$ 9.0 earthquake struck along the subduction zone interface plate boundary between the Pacific and North America plates. The earthquake was immediately followed by a large tsunami that inflicted wide-spread damage to modern urban infrastructure extending from northern Tohoku to southern Kanto regions including Sendai and Tokyo.

Recorded horizontal ground motion accelerations ranged from 254 to 1869cm/s$^2$ and velocities ranged from 31 to 145cm/s with JMA Intensities reaching 5 upper and 6 minor over large populated areas in Sendai [2], [3]. Water supply was suspended to approximately 2.3 hundred thousand households (affected populations of 5 hundred thousand and 50% of water outage rate) in Sendai: it required eighteen days to restore water to all habitable service areas except tsunami- and severe ground failure-affected areas [4]. This is a relatively short recovery-period in the earthquake-affected areas.

The Sendai water system is consists of eight water treatment plants and fourteen water distribution plants, two pumping stations and 4458-km water pipeline network. Although there was considerable damage to drainage facilities and civil engineering facilities such as retaining walls and slopes in the yards, there was a little functional damage at two water distribution plants [4].

In contrast, there was significant damage to water distribution pipelines. Figure 1 shows the locations of water pipe breaks in Sendai following the 2011Tohoku Offshore Japan Earthquake, which is overlaid to the map of the water distribution network. A system of 4458-km water pipeline network in the city had extensive damage, with 1064 locations seriously affected: the damage to the pipeline network includes 437 of transmission and distribution pipes

(Photo 1), 522 of water supply pipes, and 105 of auxiliary equipment. No damage was found in ductile cast-iron: pipes with earthquake-proofing joint (Photo 2).

Table 1 presents summary of damage to transmission and distribution pipes and water supply pipes, and auxiliary equipment, showing that more than 90% of the breaks for the water pipes were in pipelines of VP and DIP with a diameter less than 150mm, and approximately 99% of the breaks for the water supply pipes addressed damage to VP, LP, PP and GP with a diameter less than 75mm [4].

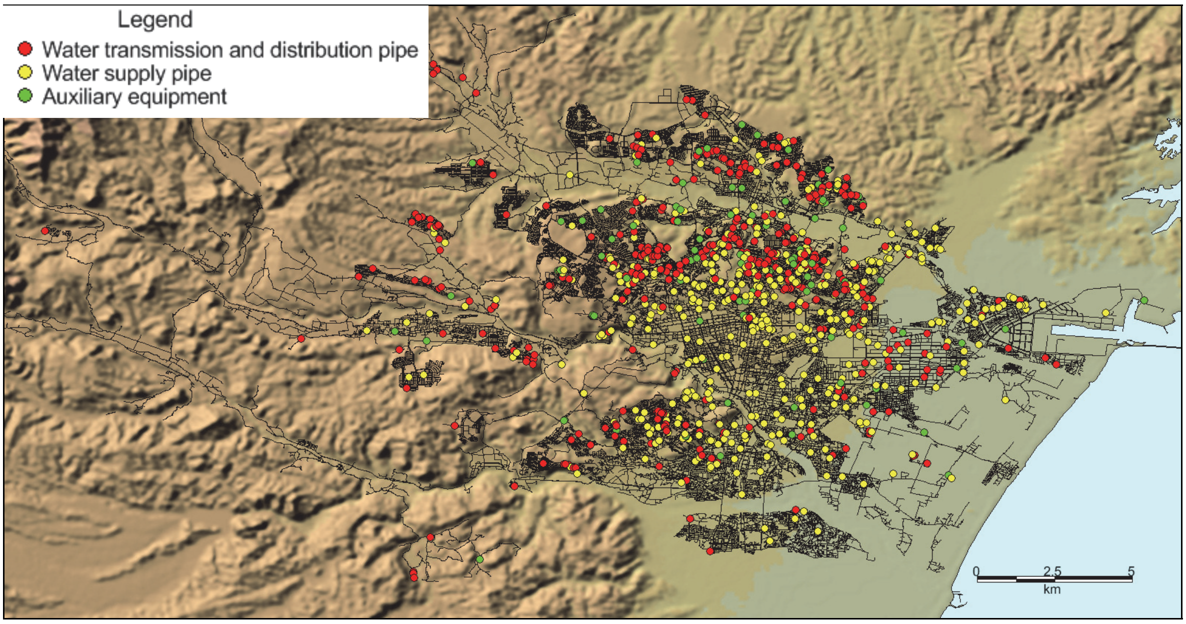



Figure 1: Locations of water pipeline breaks in Sendai following the March 11th 2011 Tohoku Offshore Japan Earthquake

Photo 1: Repair of water distribution pipe with a diameter of 800mm [4]

Photo 2: Earthquake-proofing water pipe with a diameter of 150 mm survived the tsunami [4]

Table 1: Summary of pipeline damage in Sendai water supply distribution network [4]

| | Diameter (mm) | Pipe material and number of Breaks | | | | | | | Total | Length (km) | breaks/km |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CIP | DIP | SP/SU | VP | LP | PP | GP | | | |
| Water transmission and water distribution pipes | <ϕ75 | 0 | 0 | 3 | 147 | 2 | 3 | 6 | 161 | 695.6 | 0.23 |
| | ϕ75 | 0 | 17 | 1 | 77 | – | – | – | 95 | 439.1 | 0.22 |
| | ϕ100-150 | 0 | 74 | 6 | 73 | – | – | – | 153 | 2236.4 | 0.07 |
| | ϕ200-450 | 0 | 23 | 1 | – | – | – | – | 24 | 861.6 | 0.03 |
| | ϕ500≤ | 0 | 3 | 1 | – | – | – | – | 4 | 225.5 | 0.02 |
| | Subtotal | 0 | 117 | 12 | 297 | 2 | 3 | 6 | 437 | 4458.0 | |
| Water supply pipes | <ϕ75 | 0 | 0 | 11 | 113 | 249 | 97 | 45 | 515 | 164.57 | 3.13 |
| | ϕ75 | 0 | 1 | 0 | 5 | 0 | 0 | 0 | 6 | 6.70 | 0.90 |
| | ϕ100-150 | 0 | 0 | 0 | 1 | 0 | | 0 | 1 | 4.54 | 0.22 |
| | Subtotal | 0 | 1 | 0 | 119 | 249 | 97 | 45 | 522 | 175.81 | |
| Auxiliary equipment | Fire hydrant | 0 | 4 | 0 | 3 | 0 | 0 | 0 | 7 | | |
| | Air valve | 0 | 38 | 16 | 2 | 0 | 0 | 0 | 56 | | |
| | Sluice valve | 0 | 6 | 2 | 11 | 0 | 0 | 0 | 19 | | |
| | Diversion valve | 0 | 12 | 0 | 10 | 0 | 0 | 0 | 22 | | |
| | Water shutoff valve | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | | |
| | Subtotal | 0 | 60 | 18 | 27 | 0 | 0 | 0 | 105 | | |

CIP: Cast-iron; DIP: Ductile cast-iron; SP: Steel; SU: Stainless-steel; VP: Vinyl chloride; LP: Lead; PP: Polyethylene; GP: Galvanized-iron plating

Table 2 represents number of breaks, length and break rate (breaks/km) in Sendai water distribution network differentiated per pipe material. Figure 2 shows the break rate for water distribution network to different pipe material. The break rate for GP is the highest among the other material and followed by LP, whereas no damage was found in CIP. The break rate for DIP is fairly-low although it has the longest pipe length of 2723.1km, which corresponds to 61% of the total length of the overall water pipes.

Table 2: Number of breaks, length and break rate (breaks/km) in Sendai water supply distribution network to different pipe material [4]

| Material | N. of breaks | Length(km) | Break rate |
|---|---|---|---|
| Cast-iron | 0 | 14.4 | 0 |
| Ductile cast-iron | 117 | 2723.1 | 0.04 |
| Steel/ Stainless-steel | 12 | 137.3 | 0.09 |
| Vinyl chloride | 297 | 1514.5 | 0.20 |
| Lead | 2 | 3.4 | 0.59 |
| Polyethylene | 3 | 52.7 | 0.06 |
| Galvanized-iron plating | 6 | 4.9 | 1.22 |
| Total | 437 | 4458.0 | 0.10 |

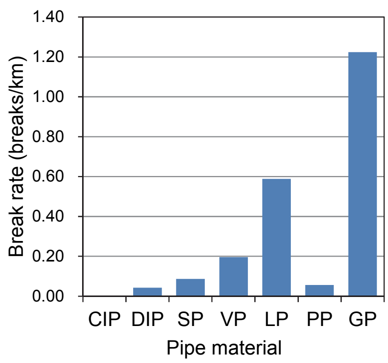



Figure 2: Break rate for water distribution network to different pipe material [4]

## 3 RELATIONSHIP BETWEEN GEOMORPHOLOGIC CONDITION AND LOCATIONS OF PIPE BREAKS

Figure 3 shows locations of pipe breaks and the water distribution network superimposed on the 7.5-sec Japan Engineering Geomorphologic Land Classification Map (JEGM) which is a nationwide site-condition map based on geomorphologic classification for various kinds of hazard mapping [5]. The damage to pipes was spread across hill (moss green), gravelly terrace (orange) and lowlands such as alluvial fan (yellow-green), delta and coastal lowlands (sky blue).

Figure 4 shows the break rate (breaks/km) for the Sendai water pipelines according to the geomorphological units in Figure 3, in which the units for lowlands such as alluvial fan, natural levee, back marsh and delta and coastal lowlands are combined into "lowland". The break rate for the pipes installed in "hill" is the highest among all geomorphologic units, which is more than 1.7 times than that for "other lowlands". This implies that the pipe break rate is higher in steep and hard ground than that in relatively flat ground containing soft soils. In order to investigate the causes of the concentration of the damage on the steeper hillsides, the history of land reclamation and former landform before the development in Sendai was investigated using old topographic maps.

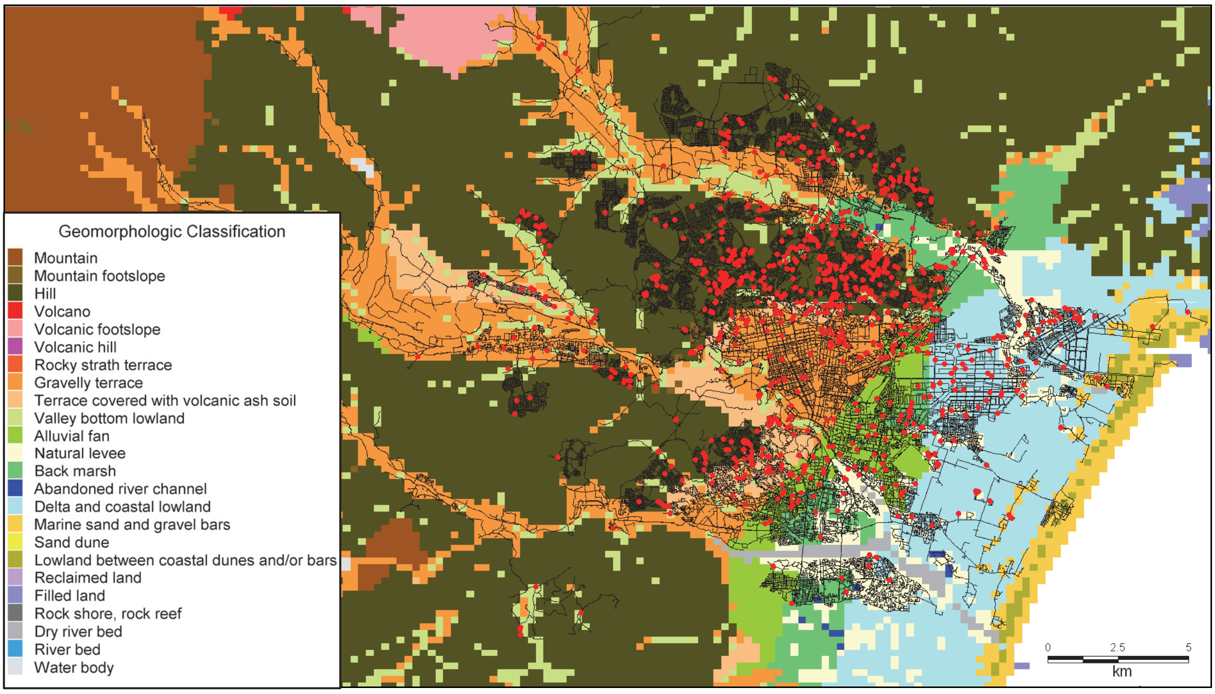



Figure 3: Locations of pipe breaks (red dots) and the water distribution network (black lines) superimposed on the 7.5-sec Japan Engineering Geomorphologic Classification Map

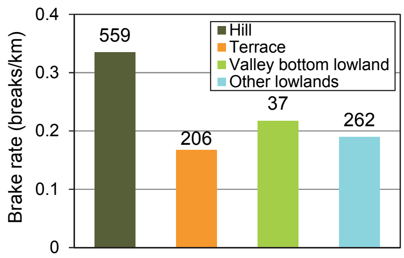


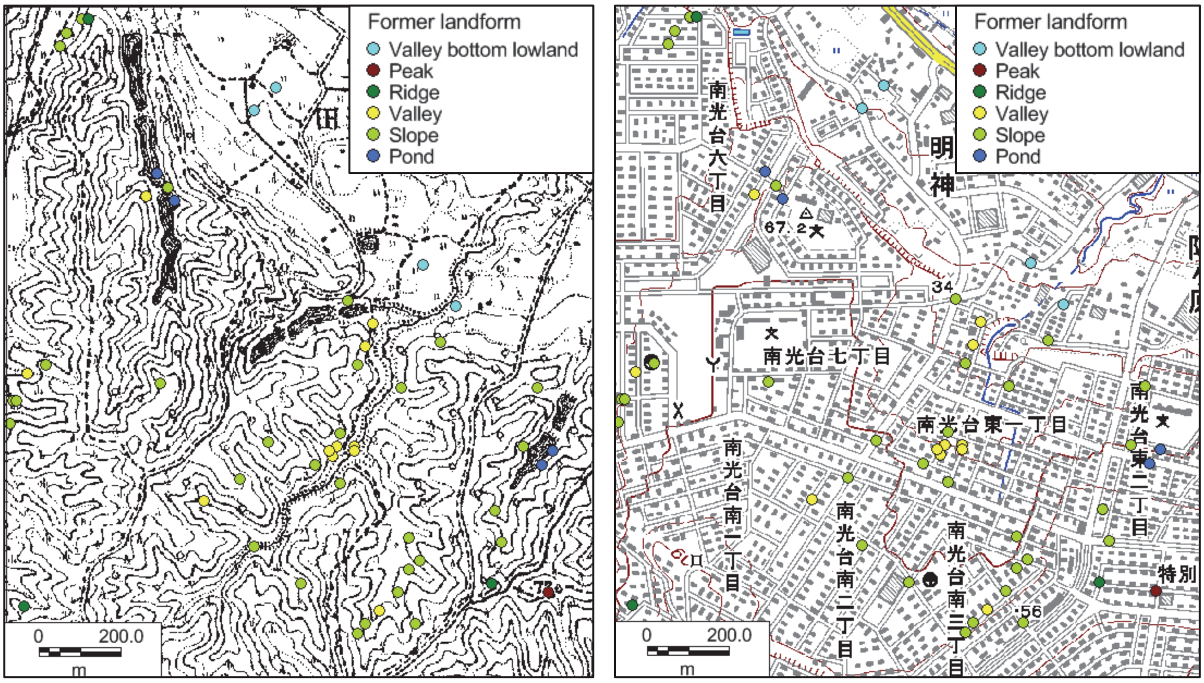

Figure 4: Break rate for water distribution network differentiated per geomorphologic land classification shown in Figure 3 (number on the bar graph shows the number of pipe breaks)

## 4 EFFECTS OF THE ARTIFICIAL LANDFORM CHANGE TO PIPE DAMAGE

Figure 5(a) is an old topographic map surveyed in 1928. It should be noted that the hill is dissected by many small valleys and streams in the hill. The development of the hills started in the early 1950s and gradually extended toward surrounding areas of the old urban district of Sendai. Figure 5(b) shows the topographic map after the land development for housing. The area was developed typically by cutting and leveling the hill and then filling the valleys with soils from the excavated areas in the hill. Therefore there are two general types of subsurface conditions in hilly land in Sendai: 1) natural soils of the original or excavated surface of the hill; it associated with the volcanic pumice flow deposit overlying Neocene sedimentary or volcanic bedrocks and 2) fills consisting mainly with the volcanic pumice flow deposit placed on the valleys and hollow parts in the hill. Areas underlain by these different profiles might to behave differently during the earthquakes.

In this study, we interpreted whether the landform change was done or not for the locations of the 1064 pipe breaks by comparing the present topographic maps with old maps before land development. Then, surface elevation before land development was evaluated by reading out of the counter lines in the old topographic maps, as well as interpreting of the former landforms: peak, ridge, slope, valley, pond and valley bottom lowland by means of interpretation of the old topographic maps.

Figure 6 presents pie chart of the percentages of landform change for the locations of a total of 1064 pipe breaks, indicating that more than 60% of the pipe breaks took place in the pipelines installed in the developed areas where landform change was done by cutting and filling. Figure 7 shows pie chart of the percentages of geomorphological units for 663 pipe break points where landform change was done. More than 80 % of the pipe breaks occurred in the pipelines installed hill. Consequently the two figures suggest that about 60% of the 1064 pipe breaks occurred within developed land of hill or terrace.




(a) Before land development (1964) (b) After land development (2008)

Figure 5: Locations of pipe breaks (red dot) superimposed on 1:25,000-scale topographic map set surveyed before and after land development in Sendai

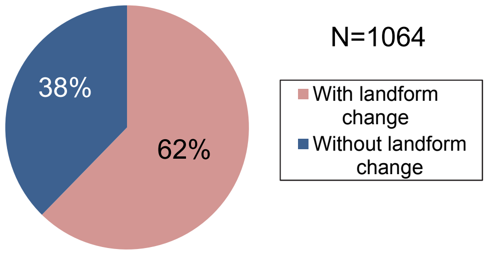



Figure 6: Percentage of pipe breaks according to landform change for all 1064 location

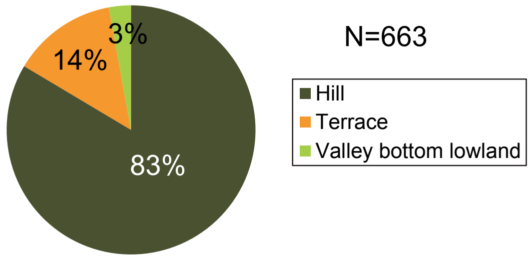



Figure 7: Percentage of pipe breaks according to geomorphologic land classification for 663 pipe break points located on the developed area

## 5 EFFECTS OF THE FORMER LANDFORM BEFORE LAND DEVELOPMENT TO PIPE DAMAGE

Figure 8 presents pie chart of the percentages of pipe breaks according to former landform before development. More than a half of the pipe breaks occurred in slope (yellow green in Figure 8) and one third of the breaks occurred in valleys in hillside (yellow). It should be noted that the breaks were found within former ponds (blue) although the numbers are small.

Figures 9 and 10 present bar charts summarizing the number of water pipe breaks of different pipe materials and different failure mode to different landforms before development, respectively. Figure 9 shows similar trends for different pipe materials: the percentages of slope are roughly 55-60% in spite of different types of pipe material and those of valley are around 30%, although number of the breaks for Vinyl chloride (VP) is the largest. The same trends with Figure 9 are found in Figure 10: the percentages of slope roughly 55-60% and those of valley are approximately 25-30% in spite of different failure mode, although number of pipe break with failure of pipe body is the largest.

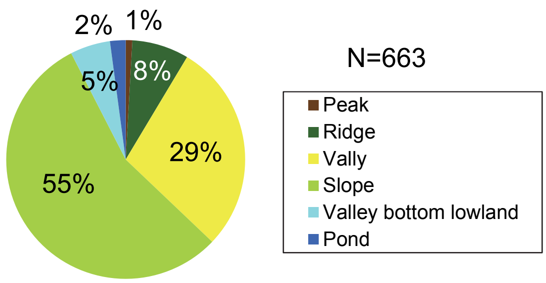



Figure 8: Percentage of pipe breaks according to former landform before land development

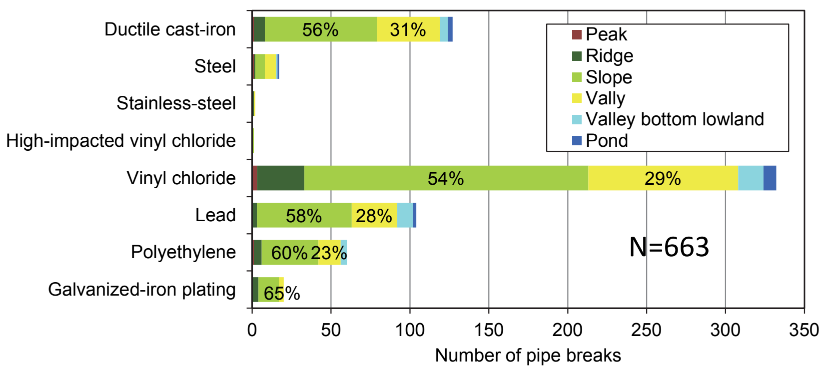



Figure 9: Number of water pipe breaks of different pipe materials to different landforms before development

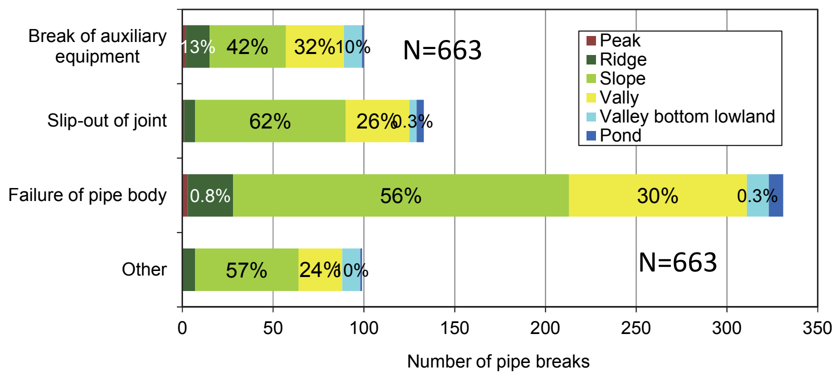



Figure 10: Number of water pipe breaks of different failure mode to different landforms before development

## 6 EFFECTS OF FILL THICKNESS TO PIPE DAMAGE

Subsurface ground conditions in the developed areas of the hilly land are primarily depend on whether the site was developed by filling the relatively low area such as valley or cutting and leveling the relatively high area such as hill ridge. Therefore, thickness of the cutting and filling at a total of 663 locations of pipe breaks was investigated in the developed area.

The surface elevation before land development was evaluated by reading out of the counter lines in the old topographic maps based on aerial photographic survey and current one was obtained from 5-m grid digital elevation model based on aerial laser survey [6]. In general, the leveling accuracy for this type of survey is roughly ±3 m and ±15 cm, respectively. The locations where current elevation is higher than that before the land development were considered to be fill areas in the hill, whereas the locations where it is lower than that before the development were considered to be cut areas. Thus the thickness of the filling and cutting were estimated by the difference of surface elevations between before and after the development.

Figure 11 shows relationship between thickness of the cut and fill and number of pipe breaks to different original (before-development) landforms, in which minus values represent thickness of cutting and plus values represent that of filling. In this figure, the number of pipe breaks is plotted according use of pipelines. It can be seen from the figure the heaviest concentration of the damage observed within the boundary area between cutting and filling with a thickness ranging from -2.5 m to +2.5 m. Damage to pipelines, in general, is observed many in fill areas whose original landforms are mainly slope or valley but very small number in cut areas whose original landforms are mainly slope and ridge, which implies that the performance of the fills placed on the natural ground of hilly areas is directly concern of the pipeline damage.

Figure 12 represents relationship between thickness of the cut and fill and number of pipe breaks to different type of pipe material. There are higher concentration within the boundary area between cutting and filling and fill areas regardless of the type of pipe material.

Figure 13 shows relationship between thickness of the cut and fill and number of pipe breaks to different failure mode. The breaks with every failure modes can be seen in the boundary area between cutting and filling and fill areas.

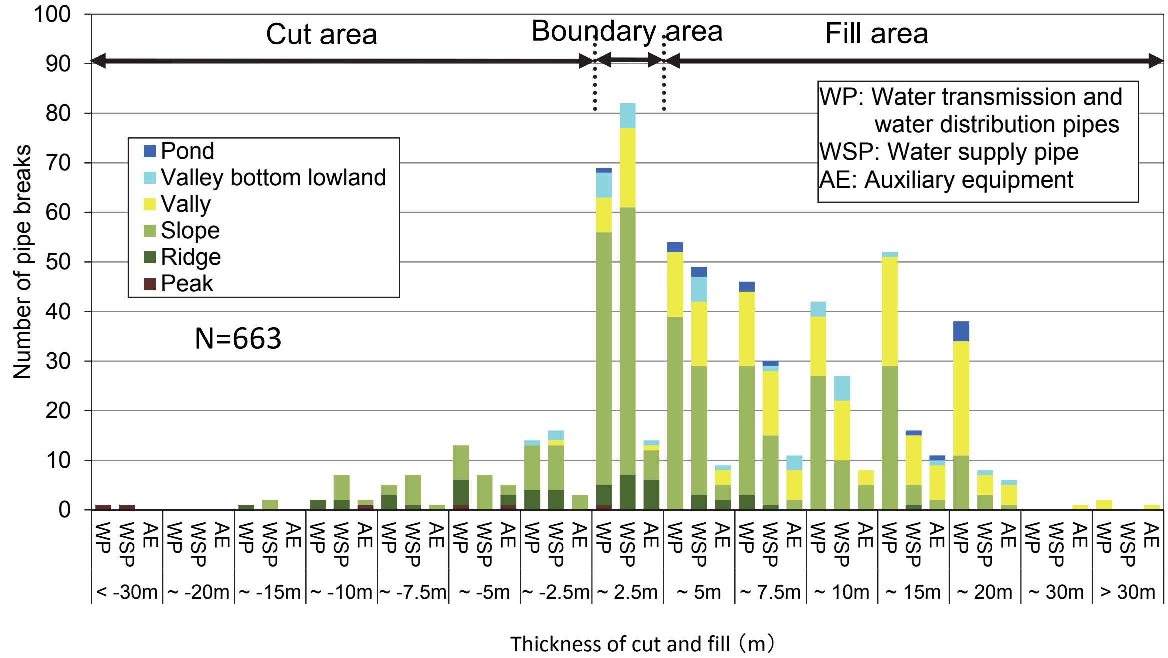



Figure 11 Relationship between thickness of the cut and fill and number of pipe breaks to different landforms before land development

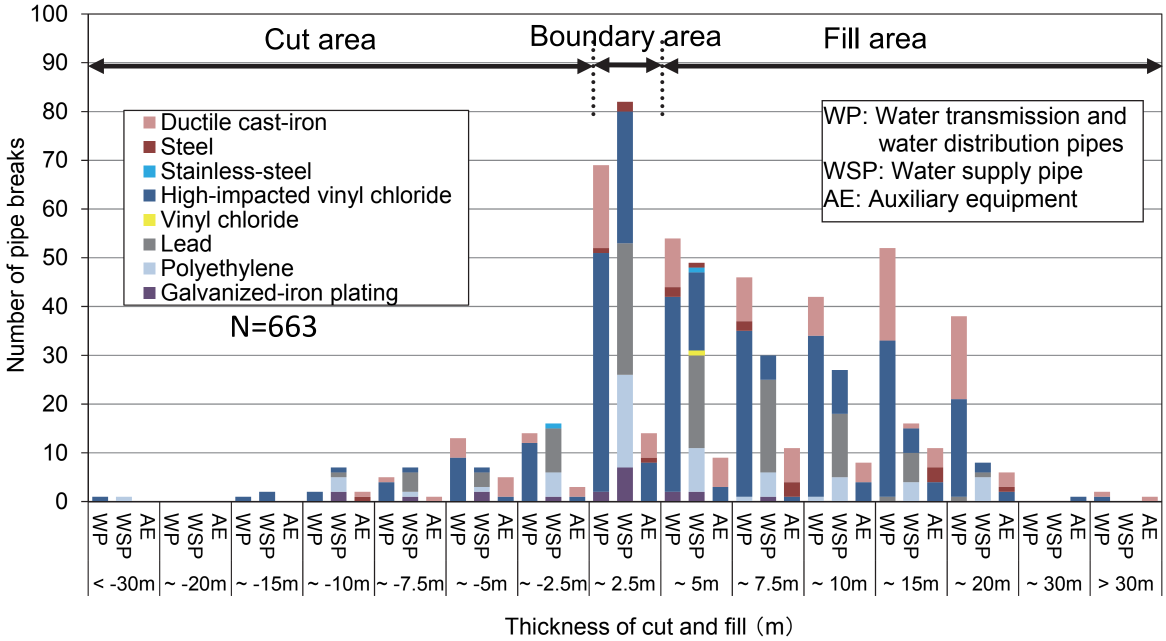



Figure 12 Relationship between thickness of the cut and fill and number of pipe breaks to different type of pipe material

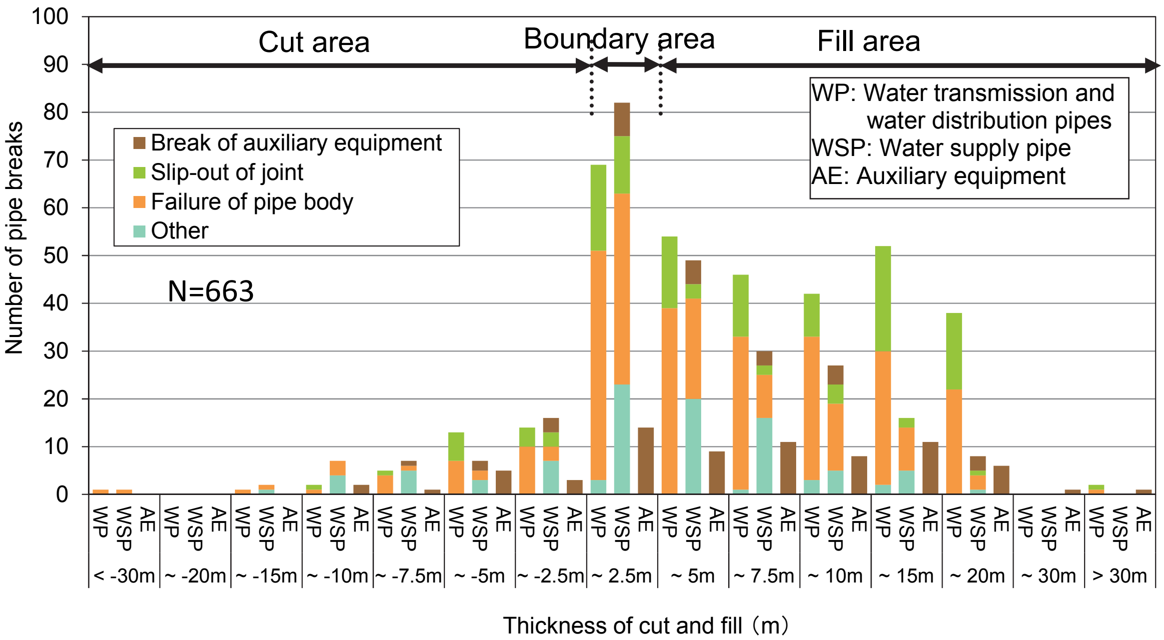



Figure 13 Relationship between thickness of the cut and fill and number of pipe breaks to different failure modes

## 7 EFFECTS OF GROUND FAILURES TO PIPE DAMAGE

Significant ground failures occurred in many place in developed areas in hilly land in Sendai: ground failures include landslide, slope failure, collapse of retaining wall and liquefaction-induced lateral spreading (Photos 3 and 4). The number of damaged lots due to ground failures reached 5080 [7]. Figure 14 shows the locations of water pipeline breaks and superimposed on a map of ground failures. The higher concentration of pipe breaks is found in the area of ground failures but the greater numbers of breaks are also plotted outside of the areas.

Photo 5 shows an example of pipe break location where no ground failure was reported. The current surface elevation is around 60 m from the sea level and thickness of the fill was estimated to be 70 cm. A vinyl chloride pipe with a 75-mm-diameter for water distribution pipelines was broken along the street in the photo. The ground surface is gently sloping and wavy deformation was found when we visited (one and a half years after the earthquake) as

Photo 3 Large crack due to landslide in Midorigaoka (courtesy of Sendai City)

Photo 4 Collapse of retaining wall in Asahigaoka

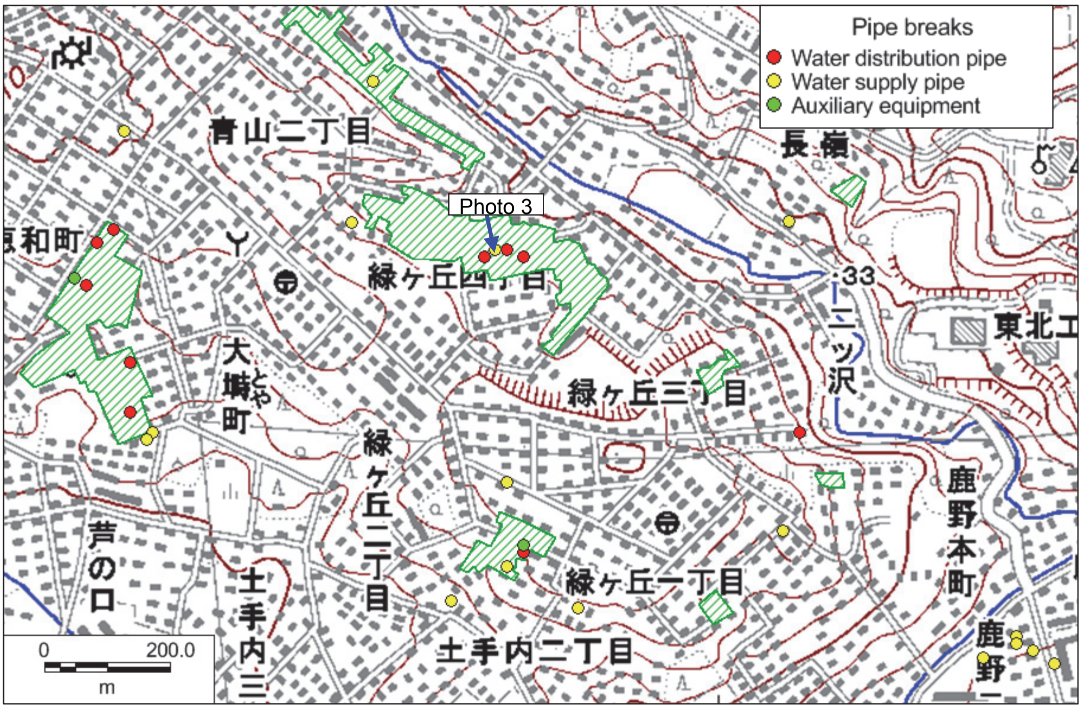



Figure 14 Locations of water pipeline damage and areas of ground failures (green polygons) caused by the 2011 Tohoku Offshore Japan Earthquake (areas of ground failure is adapted from [8] and geographic map is adapted from [9])

Photo 5 Location of pipe break in Anyouji

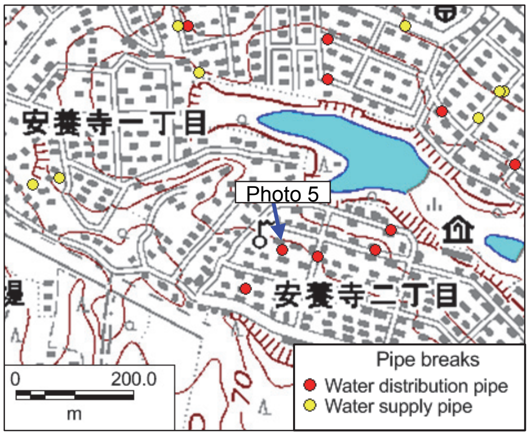



Figure 15 Map of pipe break locations in Anyouji (geographic map is adapted from [9])

shown in the photo. The pattern of ground deformation suggests that lateral spreading of the fill took place. The pipeline along the road was assumed to be ruptured in tension and compression in the tensile and compressive ground deformation zones.

## 8 CONCLUDING REMARKS

Based on an analysis of the damage to water pipelines in Sendai City associated with the 2011 Tohoku Offshore Japan earthquake, focusing on the landform change in the developed area of hilly land, the following conclusions have been reached:

- The break rate according to different geomorphologic units is the highest for pipes installed in “hill”, which is more than 1.7 times than that for “lowland”.
- Approximately 60% of the 1064 pipe breaks occurred within developed land of hill or terrace where landform change was done by cutting and filling.
- More than a half of pipe break in the developed areas occurred in the former hillside slope and one third of the breaks occurred in the former valleys in the hill.
- Concerning thickness of the cutting and filling in the developed land, the heaviest concentration of the pipe breaks observed within the boundary area between cutting and filling with a thickness ranging from -2.5 m to +2.5 m.
- The higher concentration of pipe breaks is found in the area of ground failures but the greater numbers of breaks also occurred outside of the areas.

## ACONOWLEGEMENT

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