Lowland Technology International 2017; 19 (3): 165-174
International Association of Lowland Technology (IALT): ISSN 1344-9656
Special Issue on: Kumamoto Earthquake & Disaster

Research Paper

Water supply damage caused by the 2016 Kumamoto Earthquake

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ARTICLE INFORMATION

Article history:

Received: 06 March, 2017
Received in revised form: 25 November, 2017
Accepted: 27 November, 2017
Publish on: 08 December, 2017

Keywords:

Water distribution network
Kumamoto Earthquake
Lifeline damage
Pipeline failure rates
Kumamoto water supply

ABSTRACT

Widespread damage to lifeline systems occurred as a result from the Kumamoto Earthquakes that initiated on April 14, 2016. Interruption to the water, gas, and electric power supply affected thousands of people. Landslides and surface rupture caused significant damage to transportation systems, especially roads and bridges. This paper provides an overview of observations and information gathered by US researchers (sponsored by Geotechnical Extreme Events Reconnaissance Association), Japanese researchers, and others regarding water supply damage. Emphasis is placed on the largest water authority in the region of the earthquake, Kumamoto City, including damage metrics for various pipe materials and diameters. The greatest damage occurred at valves and other fundamental mechanisms of large diameter pipelines. Pipelines constructed of ERDIP and HDPE performed most favorably while steel and cast iron pipelines were shown to be the more vulnerable. A liquefaction-induced lateral spreading site at which pipeline damage occurred is identified for further study.

1. Introduction

Seismically induced damage to lifeline systems occurred in many areas within the Kumamoto region as a result of significant earthquakes that occurred during April 14-16th, 2016. Landslides and surface rupture caused damage to transportation systems, especially roads and bridges. Widespread interruption to the water, gas, and electric power supply affected thousands of people. Heavy rainfall during the two days following the earthquake sequence hindered lifeline recovery and repair efforts.

The Kumamoto Earthquakes are a series of earthquakes including a foreshock of moment magnitude (M_W) 6.2 (local Japan magnitude M_j 6.5) at 21:26 JST on April 14, 2016, another foreshock of M_W 6.0 (M_j 6.4) on April 15th, and the mainshock M_W 7.0 (M_j 7.3), which struck at 01:25 JST on April 16, 2016. **Figure 1** provides a map

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Note: Discussion on this paper is open until June 2018.

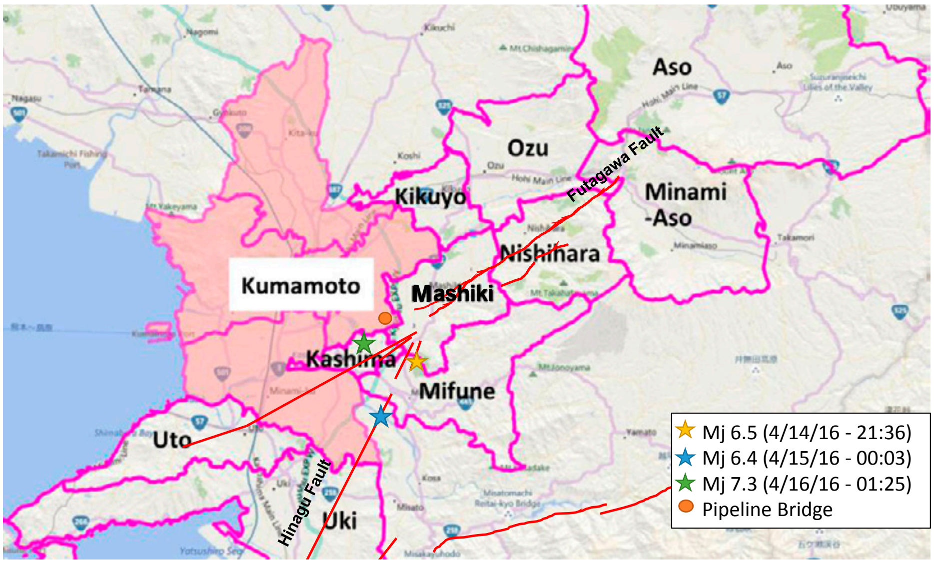


Fig. 1. Kumamoto City and surrounding districts.

Table 1. Water Supply Pipelines in Kumamoto Region (JWWA, 2014).

	Raw Water Main (km)	Transmission Main (km)	Distribution Main (km)	City Totals (km)
Kumamoto City	44.4	57.5	3,208	*3,310*
Mashiki Town	2.1	2.9	97.6	*102*
Ozu-Kikuyo Water Supply Authority	7.6	8.0	380	*395*
Uto City	4.9	4.6	128	*137*
Uki City (misumi area)	13.4	8.2	54.3	*75.8*
Uki City (matsubase area)	14.7	7.8	183	*205*
Aso City	7.9	13.7	202	*223*
Minamiaso Village	0.0	3.2	15.3	*18.5*
Pipeline Total	*95.0*	*105.7*	*4,268*	*4,469*

of the region, boundaries of impacted districts, and the location of the Kumamoto Earthquakes. The earthquakes struck just east and south of relatively densely populated Kumamoto City.

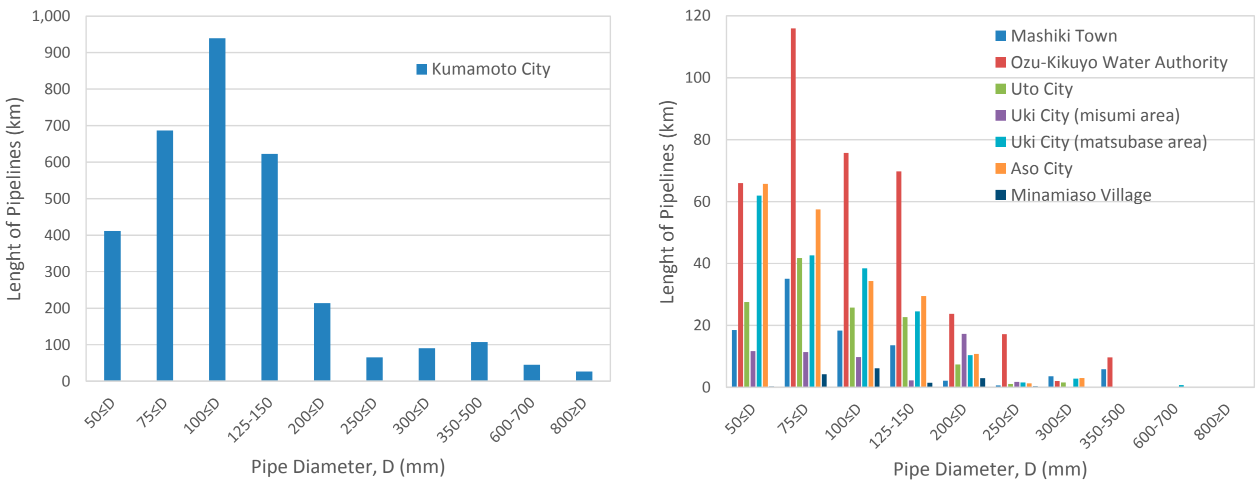
This paper focuses on performance of the water supply system and includes information obtained from briefings by the Japan Water Works Association (JWWA) Director of Engineer Department & General Institute Yasunori Kimura on May 9th 2016 and Kumamoto City Waterworks and Sewage Bureau (KWSB) Director of Water Technologies Administration Hirofumi Nakashima on May 12th 2016. Focus will be placed on Kumamoto City, the only district that has released damage statistics as of the time of this writing.

2. Water supply

The region's geology includes deep pyroclastic flow deposits more than 100 meters thick that accumulated during a series of Mount Aso volcanic eruptions 270,000 to 90,000 years ago. These naturally porous deposits serve as deep underground aquifers for the fourteen municipalities in the region.

Kumamoto City supplies its 670,000 citizens with clean drinking water from these underground aquifers. It is the only city in Japan with greater than 500,000 residences to source water solely from groundwater. It is the largest district in the affected area serving 320,000 customers.

Under typical operating conditions, little treatment of groundwater is necessary due to natural purification. Only mild chlorination is typically used as treatment. For shallow wells, some minor UV and flocculation systems are necessary, and a few wells require manganese and iron treatment. For most deep wells, no treatment is necessary. In general, use of groundwater is believed to have improved the pace of water supply recovery in Kumamoto, compared to a scenario where water treatment plants or dams need to be repaired.



(a) Kumamoto City (b) All other Districts

Fig. 2. Pipeline diameter distribution for affected districts.

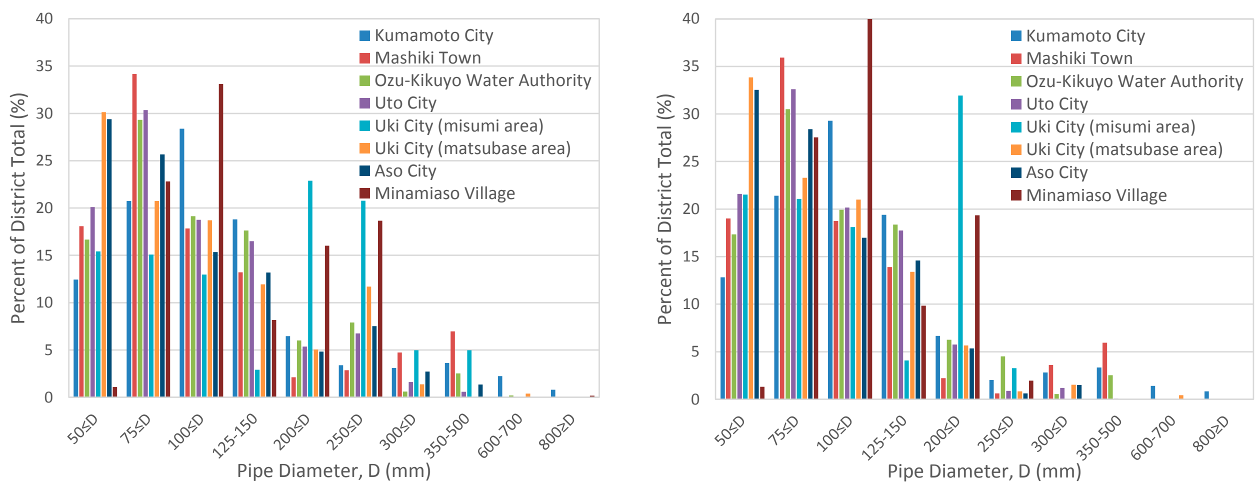
3. Water distribution system

The region is supplied by about 4,469 km of water pipelines, 75% of which are within Kumamoto City. **Table 1** provides the 2013 year end statistics for length of untreated (raw), transmission, and distribution mains in districts that were affected by the earthquakes (JWWA, 2014). The data show that distribution mains account for the vast majority of the system. Transmission mains are minimal due to the distribution of groundwater well points throughout the region.

Figure 2 summarizes pipeline diameter statistics for Kumamoto City and the surrounding districts. About 80% of all pipelines have diameters of 150 mm and less. Pipelines of diameters greater than 300 mm account for less than 6% of the total system length. The most widely used diameter pipeline in Kumamoto City is 100 mm, accounting for over 28% of the total system. Binned raw water and transmission main data was not available for pipeline diameters less than 300 mm. The reported lengths of raw and transmission mains in this range were included under the 250≤D label, resulting in a minor peak at 250≤D in the figure.

Figure 3 provides the pipeline diameter statistics normalized by the total length of pipeline in each district. **Figure 3**(a) shows the diameter distribution for the summation of raw, transmission, and distribution mains while **Fig. 3**(b) includes distribution mains only. The artificial increase for diameters of 250≤D is reduced when considering distribution main statistics alone. A generally consistent trend can be recognized across the water authority districts in which smaller diameter distribution mains comprise the majority of these systems.

Conduits of various materials are used to transport water in the region. **Figure 4** presents an overview of water supply pipelines for the region and Kumamoto City as the summation of conduit (raw water), transmission, and distribution mains. Comprising 61% of the regional total, ductile iron is the most widely used material in the region, followed by various types of polyvinyl chloride



(a) All mains included (b) Distribution mains only

Fig. 3. Pipeline diameter as percentage of district totals.

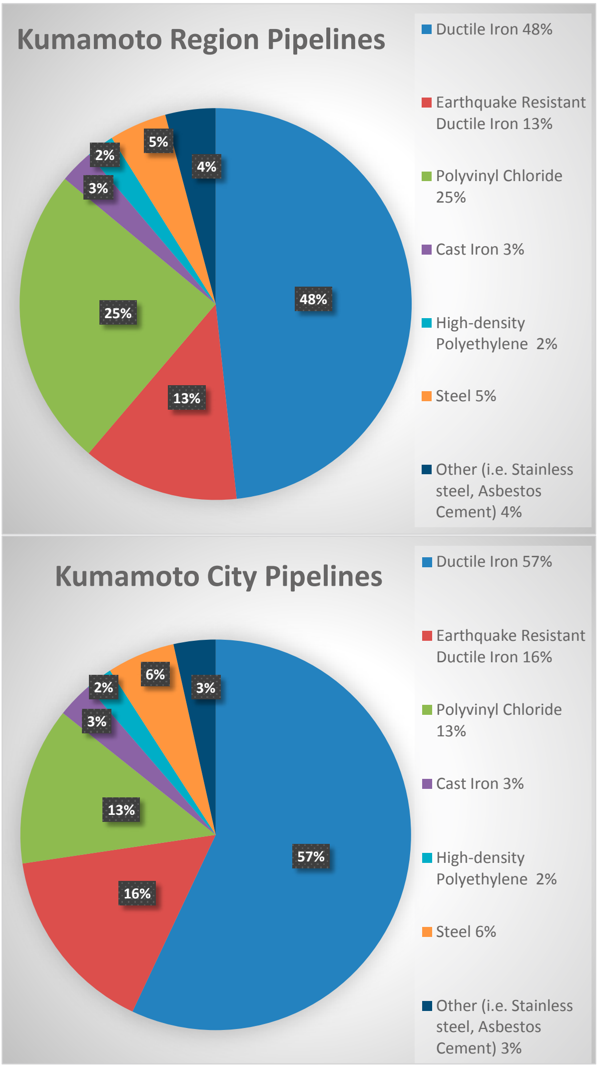


Fig. 4. Distribution of water supply pipelines (untreated, transmission, and distribution mains) in Kumamoto Region and Kumamoto City (data from JWWA, 2014).

(PVC), cast iron pipe (CIP), fusion and mechanically bonded high-density polyethylene (HDPE), and steel (welded and non-welded). The data, provided by a JWWA 2013 report, also reports totals for asbestos cement, stainless steel, other types of polyethylene pipe, and other less common materials, the summation of which are grouped in the figure under the title “other”.

Figure 4 reports the percentage of both typical ductile iron pipe (DIP), where segments of pipe are joined by bell and spigot joints, and earthquake resistant ductile iron pipe (ERDIP). Typical DIP joints have limited capacity to accommodate bending and axial movement imposed by ground deformation (Wham & O’Rourke, 2015). In some cases they may be fitted with mechanical restraints to resist pullout. ERDIP are assembled with bell and spigot joints that provide the pipeline additional joint deflection capacity and allow axial pullout to occur prior to engagement of axial resistance (Pariya-Ekkasut et al., 2016). To address water supply vulnerability to natural hazards, over the past 10 years ERDIP has been used for almost all newly installed water pipelines in Kumamoto City.

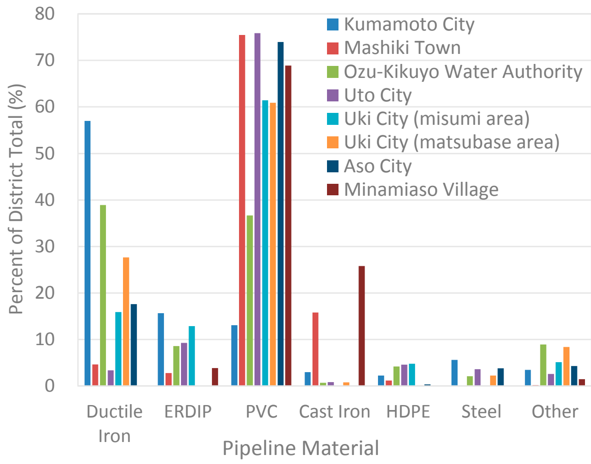


Fig. 5. Percentage of existing pipe material per district.

The regional numbers are highly influenced by the largest district, Kumamoto City. **Figure 5** provides a breakdown of percentage of pipeline composition relative to each district. DIP accounts for the largest components of pipeline length for Kumamoto City and Ozu-Kikuyo Water Authorities, the two largest districts considered in this study. In contrast, the other six districts use 60% or greater PVC pipelines. There are several possible explanations for this discrepancy. For instance, older networks will be composed of materials available at the time of installation. Water authorities are also likely to favor system continuity and prefer using materials and procedures with which their crews are most familiar. Initial material cost may have a more significant impact on projects undertaken by smaller, rural communities than those of larger urban water departments.

To provide perspective to damage statistics presented in the following section it is useful to consider the percentage of material used for each range of pipeline diameter. **Figure 6** provides a comparison of materials used for each diameter bin in Kumamoto City. While DIP accounts for the largest percentage of the Kumamoto’s water system, it is not used for smaller service connections 50mm or less. It is also notable that steel pipe accounts for significant percentages of both the largest (36%) and smallest (25%) pipe diameter ranges. The figure also shows that ERDIP is more widely used for large diameters greater than 300mm).

4. Water supply damage

As of 2014, Kumamoto City water facilities consist of 3,366 km of pipeline, 19 transmission facilities, 67 distribution facilities, and 96 operational well points. Distributed across the city are a series of above and below

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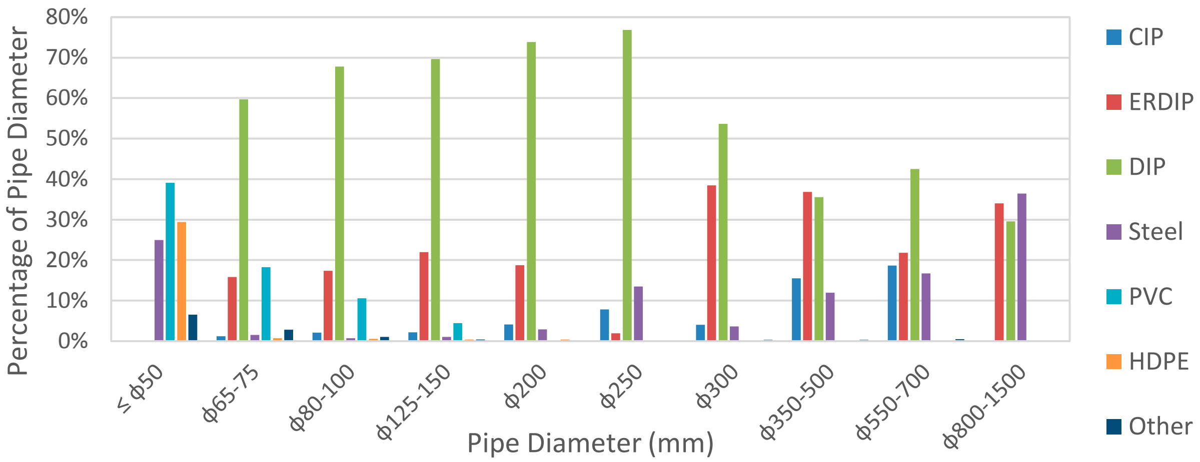

Fig. 6. Percentage of pipe by diameter used in Kumamoto City.

ground storage tanks for use as disaster recovery water reservoirs.

The April 14th M_W 6.2 earthquake caused 69 of 96 wells in Kumamoto City to stop pumping due to water turbidity. The relative proximity of the earthquake focus to the aquifer led to suspended particles in the water and associated reduction in water quality, resulting in suspension of water supply to about 85,000 households.

During the April 16th M_W 7.0 event, all 96 supply wells were stopped due to water quality concerns (turbidity). Water service to all 326,000 households in Kumamoto City and over 400,000 customers throughout the region was suspended to avoid depleting limited emergency reservoir supplies though damaged pipes. It took 1.5 days for particulates to settle and groundwater to return to acceptable quality levels. During this time, the water bureau worked closely with fire and emergency service providers to ensure adequate supply for life safety and emergency needs. It was fortunate that fire was not a significant issue, due largely to the time of day the earthquakes occurred (at night). The City considers this relatively rapid recovery of the water supply to be a success and that recovery may have taken longer if their water supply was sourced differently and required multifaceted treatment procedures.

Leakage occurred in significant pipelines including a 900-mm steel conduit and a 1350-mm steel distribution main, as well as multiple ruptures of an 800-mm steel transmission main discussed later. Damage to larger transmission pipelines affected the speed of restoration. Repairs and circumventing damaged mains reduced the number of customers without water to 90,000 by April 19, and to about 30,000 by April 22. Required pipe repairs in Kumamoto City were concentrated along the east side of the city near Mashiki.

On a typical day, Kumamoto City consumes about 220,000 m^3 of water. The demand on the system following the April 16 event was 270,000 to 280,000 m^3, a 30% increase in pumping by volume. Leaking of damaged pipelines is considered the primary cause of demand increase. By May 16, 2016 the demand remained 10% higher than typical operating volume, demonstrating the need for repairs that continued to take place during the proceeding several months.

4.1 Water Distribution System Damage: Kumamoto City

Kumamoto City Water and Sewer Bureau submitted a report to the Ministry of Health, Labor and Welfare, the central government agency in charge of water supply, summarizing water supply damage resulting from the Kumamoto Earthquakes (KWSB, 2016). The publicly available report summarizes pipeline damage statistics gathered by the agency and includes description of repair efforts conducted at critical locations.

Figure 7 summarizes the repair data for various diameters and materials. **Figure 7**(a) includes the total damage for each diameter range as well as the damage attributed to valves and other mechanisms necessary for system functionality. The figure shows that valves and other accessories account for the majority of damage repairs for larger diameter pipes (greater than 300 mm). This may be a function of additional mechanisms necessary to safely manage larger diameter pipes. **Figure 7**(b) shows the distribution of damages relative to pipe material. Valves account for the greatest percentage of the total damages, followed by steel pipe.

As of May 12, 2016, 165 pipe repairs were required in Kumamoto City. Approximately one year following the event the City reported 447 total incidents of pipeline damage requiring repair, 296 of which were damage to pipes or pipe joints, and not attributed to valve or mechanical system damage. These data suggest a pipeline damage ratio and overall system damage ratio of 0.09 and 0.14 damages/km, respectively, for Kumamoto City. **Figure 8** provides damage ratios for various pipe

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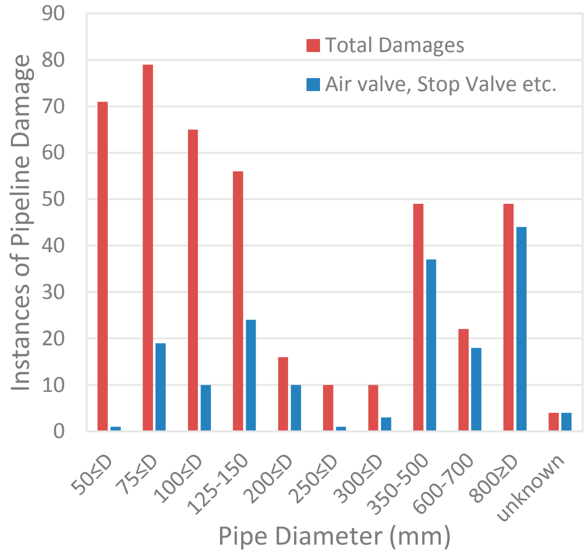
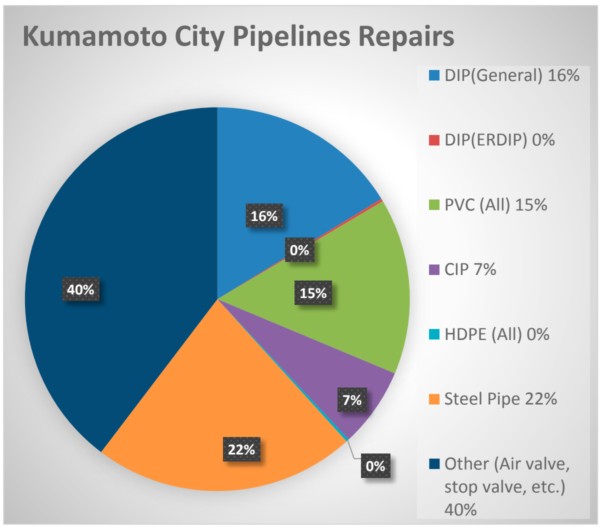
diameters. **Figure 8**(a) suggests that larger diameter pipelines are more susceptible to damage, especially pipelines of 800 mm or greater. The significant damage ratio of large pipes is a direct result of necessary repairs to valves and other mechanical components of pipelines greater than 350 mm in diameter. **Figure 8**(b) provides a magnified look at damage ratios for pipelines only, excluding valves and other components. The figure suggests that, while smaller diameter pipes required the greatest number of repairs per pipeline length, damage ratio for pipelines alone is relatively independent of diameter.

Figure 9 provides damage metrics for various materials, as well as the overall damage ratio for Kumamoto City. The two right columns in **Fig. 9**(a) are normalized by the total pipeline length reported for Kumamoto City in 2014, 3,366 km. Steel is shown to have the largest damage ratio requiring greater than 0.5 repairs/km. As expected, brittle cast iron pipelines performed poorly relative to more ductile systems. Of the 578 km of Earthquake Resistant Ductile Iron Pipe (ERDIP), there were no reported breaks, and only a single repair required to address improper assembly. There was a single HDPE repair required for a small-diameter, mechanically-jointed line.

Figure 9 (b) shows a diameter breakdown for damage ratios of the mostly poorly performing materials. The steel pipe statistics, which included both screw and welded connections, show that various diameters performed poorly. The largest damage ratio, 3.7 repairs/km which is not shown on the plot for clarity purposes, occurred in 300 mm diameter steel pipe. Although specific data was not available, the authors hypothesize that the substantial

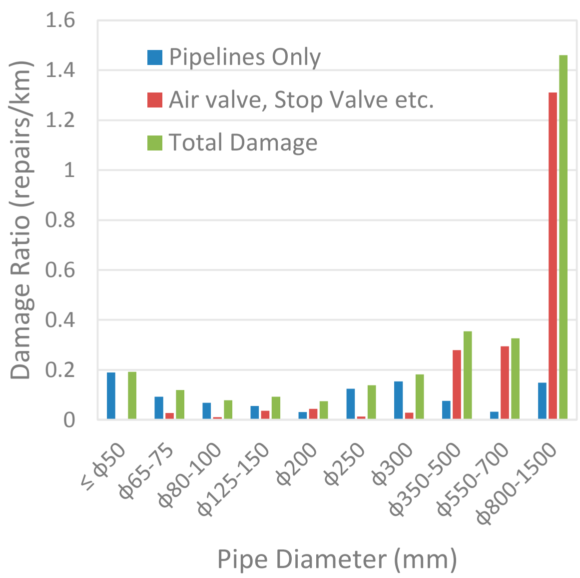


(a) Damage per pipe diameter

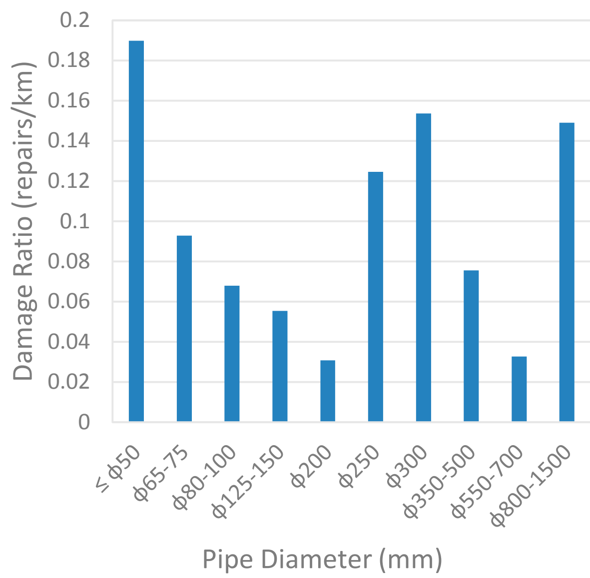


(b) Damage per pipe materials

Fig. 7. Pipeline damage/repairs in Kumamoto City

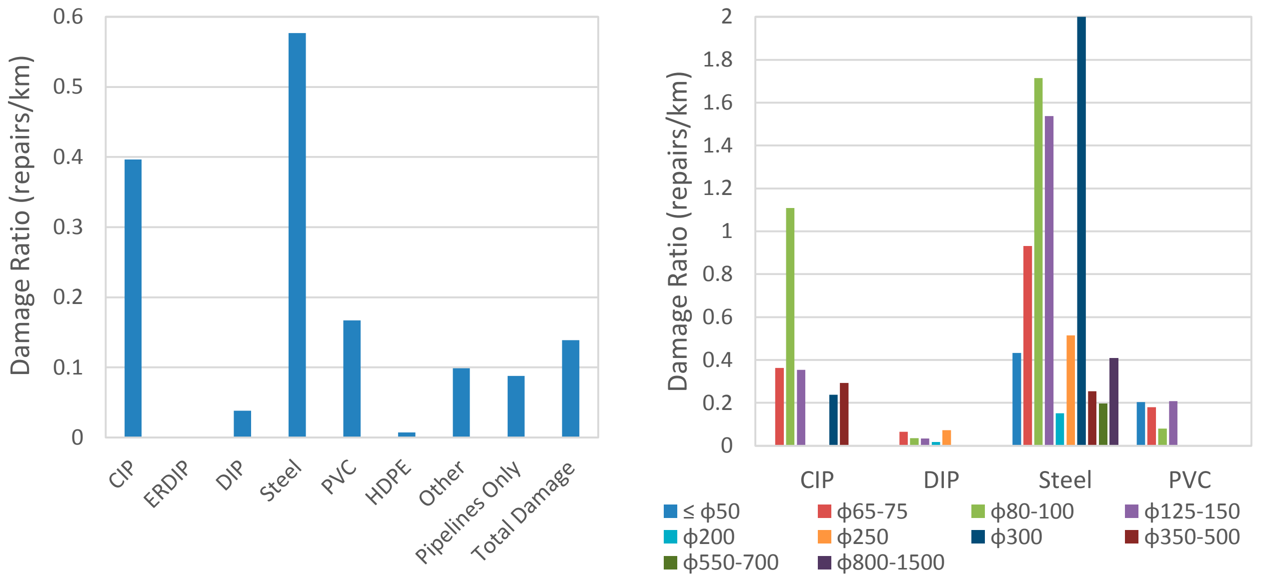


(a)



(b)

Fig. 8. Damage ratios for (a) all pipelines and system components and (b) pipelines excluding valves and other mechanisms.



(a) (b)

Fig. 9. Damage ratios for (a) all pipeline diameters and (b) select material and diameters in Kumamoto City (Note: not shown is ϕ300mm steel with damage ratio=3.7).

number of failures for this size and material may correlate with a specific pipe with poor construction quality, aggressive deterioration with age, or located in an area of significant ground deformation. The data suggest that, in general, steel and cast iron (CIP) pipelines performed poorly across many diameters.

4.2 Multiple Repair Site

One site of particular interest is a lateral spread event located in Akisumachi Nuyamazu, adjacent to parallel pipeline and traffic bridges along Route 232 crossing a tributary of the Midorikawa River at the east Kumamoto City limits (identified in **Fig.1**). Site observations (liquefaction, ground cracking) and data (e.g., LiDAR) collected at the site can be found in the GEER reconnaissance report (Kayen, et al., 2016). **Figure 10**(a) shows a Google Earth satellite image of the site dated April 14, 2016 (US date). Significant ground cracking can be seen in the field to the northwest of the bridges. **Figure 11**(a), taken May 7, 2016, shows the lateral spread and pipeline bridge in the background. **Figure 10**(b) shows a survey map and **Table 2** provides a summary of pipeline breaks in the area as reported by KWSB (2016).

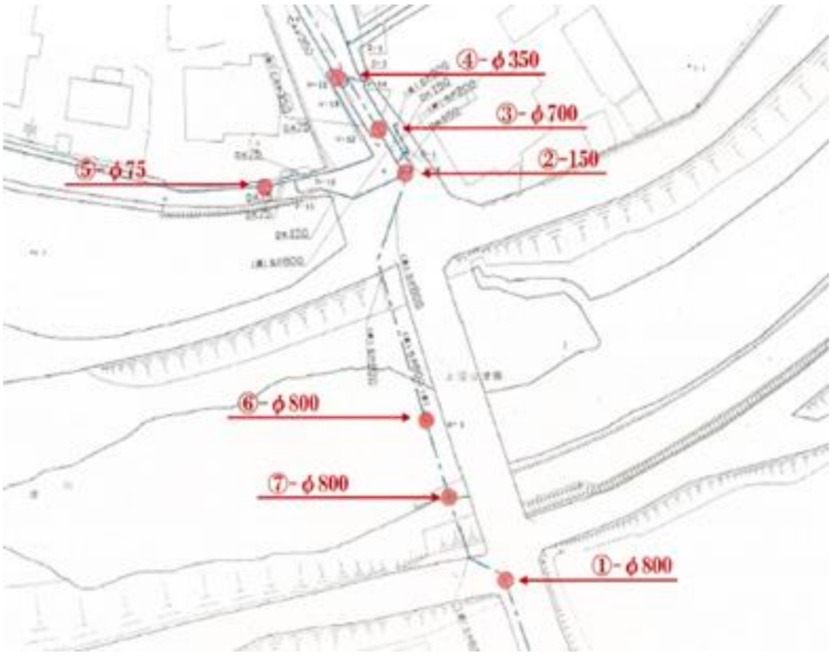
Table 2. Description of pipeline damages.

No.	Dia. (mm)	Material (description)
1	800	Steel (rupture near abutment)
2	150	DIP (K-type) Leakage at joint
3	700	Steel (fracture at gate valve flange)
4	350 x 75	CI or DI (rupture of Flange Tee, FT)
5	75	Ductile Iron (A-type) Leakage at joint
6	800	Steel (leakage at air valve)
7	800	Steel (rupture at expansion/contraction joint)

The 800-mm steel pipeline carries emergency water supply to 57,000 people from reservoir tanks located in the agricultural field to the south over the river to populated residential districts. The pipe isFf equipped with slip joints to account for expansion/contraction (typical range of ±50 mm) near both the north and south abutments. During the April 14th event, leakage occurred at the slip joint close to the south abutment (**Figure 11**(b), repair No.7). Observations suggest leakage occurred due to over insertion of the joint, an indication that the banks of the river displaced as a result of the April 14 foreshock. It is likely a component capable of larger compressive displacements, such as the seismically-resilient inclusions tested by Wham et al. (2017), would have survived the imposed deformation and continued uninterrupted conveyance of emergency water supply across the river.

A total of seven repairs were required in the vicinity of the pipeline bridge, including four repairs to valves and joints of the large diameter steel pipeline. Further investigation of this site is suggested owing to the general lack of liquefaction induced lateral spreading that occurred in the region as a result of the Kumamoto Earthquakes.

(a) Google Earth image of site



(b) Drawing of site and pipeline repairs (KWSB, 2016)

Fig. 10. Google earth image and layout of the site and pipeline repair work.

Comparisons of well-performing pipelines in the area can help address vulnerabilities.

5. Summary and conclusions

The water supply was interrupted to thousands of residents as a result of the Kumamoto Earthquakes. The largest percentage of pipelines by length in the region are smaller diameter pipes composed of ductile iron or polyvinyl chloride. However, the largest repair ratios determined from available data occurred at valves and other fundamental mechanisms of large diameter pipelines, especially those greater than 800 mm diameter. The statistics suggest the importance of incorporating the resiliency of connections and mechanisms when assessing the seismic performance of distribution systems.

(a) Lateral spreading, pipeline bridge in distance (Kayen, et al. 2016)

(b) Leakage of 800 mm diameter bridge pipeline at expansion joint (KWSB, 2016)

Fig. 11. Location of significant lateral spread and pipeline repairs (32.77326, 130.78428).

When considering only damage to pipelines, the data shows that expected damage is largely independent of diameter, but that smaller diameter service lines are most vulnerable to damage. In Kumamoto City, pipelines constructed of ERDIP and HDPE performed most favorably while steel and CI pipelines were shown to be the more vulnerable materials to earthquake-induced damage.

Additional statistics and repair documentation will help determine which factors (i.e., location, embedment soil, age, deterioration) are most influential in predicting pipeline susceptibility to seismic hazards. A liquefaction induced lateral spreading site requiring multiple pipeline repairs is identified and recommended for further study.

Further information regarding water supply damage in areas outside of Kumamoto City is expected to be made public by JWWA in the future. The GEER reconnaissance report (Kayen et al. 2016) includes observations and information collected about other lifeline system damage resulting from the Kumamoto Earthquake. Additional information on utility restoration and recovery is provided by Nojima & Maruyama (2016).

Acknowledgements

Thanks are extended to Yasunori Kimura (Japan Water Works Association) and Kumamoto City Waterworks and Sewage Bureau representatives Hirofumi Nakashima and Hitoshi Fujimoto for providing information about municipal utility damage and recovery efforts. Colleagues at Kubota Corp, including Toshio Toshima, Satoshi Suenaga, Takeshi Hara, Mitsuo Hayashi, Kohei Ikeda, and Keita Oda are acknowledged for providing valuable guidance and information.

This work was made possible by funding from the Geotechnical Extreme Events Reconnaissance (GEER) Association, which is supported in part by the National Science Foundation through the Geotechnical Engineering Program under Grant No. CMMI-1266418. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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