Review of an Equation to Estimate Seismic Damage to Water Mains in Light of the 2016 Kumamoto Earthquake

Yuko Tsuruda, Yuichi Ishikawa, Fumio Sasaki, and Masakatsu Miyajima

ABSTRACT

In 2011, the Japan Water Research Center established an equation to estimate (predict) the number of pipe failures in earthquakes. The equation estimates relative damage to mains per 250-meter grid cell of a service area. It was developed based on an analysis of major seismic disasters in the past. As the equation aims to facilitate an efficient seismic reinforcement of water supply facilities by water utilities, it needs to be reviewed and updated properly based on new knowledge and findings from relevant seismic disasters. Most recently, in April 2016, the Kumamoto Region of Japan was hit directly by two earthquakes of magnitude greater than Mw 6.0 that occurred consecutively over a three-day period. In the wake of the Kumamoto Earthquake, we reviewed the equation to see whether it needs an update to improve its accuracy for damage estimation.

The review result showed that overall, the correction factors of the equation and its reference damage rate have similar tendencies to the characteristics of the actual damages although the total number of estimated pipe damages in Kumamoto City was about 4.1 times larger than the number of the actual pipe damages, this can be partly explained from the fact that the equation is designed to estimate on the safe side. From these results, we decided that the equation is valid, requiring no immediate modifications to the correction factors and the reference damage rate. One concern remains, however, that the equation might have estimated a little too far on the safe side. Therefore, this aspect would need a further consideration.

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INTRODUCTION

In FY2011, the Japan Water Research Center ("JWRC") made an equation to estimate (predict) the number of pipe failures in earthquakes ("equation") [1]. The equation was developed based on the analysis of major seismic disasters in the past, including the 1995 Kobe Earthquake. In FY2013, the equation was revised upon the 2011 Great East Japan Earthquake in order to improve its accuracy for damage estimation and to incorporate newly obtained knowledge from the earthquake [2].

In April 2016, the Kumamoto Region of Japan was hit directly by two earthquakes of magnitude greater than Mw 6.0 that occurred consecutively over a three-day period. In the wake of the Kumamoto Earthquake, JWRC reviewed the equation to see if it would need a further update to improve its damage estimation.

THE EQUATION AND ITS CORRECTION FACTORS

Figure 1 and Table I show the procedure of estimating pipe damage using the equation and its correction factors as updated upon the 2011 Great East Japan Earthquake [3]. The equation is to estimate pipe damage per 250-meter grid cell of a service area. The estimation is carried out using the information on pipe material/joint, diameter, microtopography, peak ground velocity (PGV) of earthquakes, as well as liquefaction data (if applicable). The result is expressed in the number of damaged locations per kilometer. Another characteristic of the equation is that it is designed to estimate on the safe side to avoid an underestimate of seismic impact.

The reference damage rate of the equation refers to the damage rate of the pipe that has a reference material/joint, diameter, and microtopographic data, and is obtained using PGV. As for liquefaction, if a target area has liquefaction data, the reference damage rate will be calculated with a reference liquefaction damage rate set to 5.5 uniformly for all the relevant estimations.

The equation has a set of correction factors for different pipe materials/joints, diameters, and microtopographies. The reference correction factor is 1.0 with DIP (A) as the reference pipe material/joint while the reference diameter is 100-150 mm and the reference microtopography is either a valley lowland, alluvial fan, humid lowland plain, delta, or coastal lowland. Each correction factor was determined based on a comparison between the damage rate of DIP (A) and the damage rate of other pipe materials/joints, diameters, and microtopographies in major earthquakes in the past.

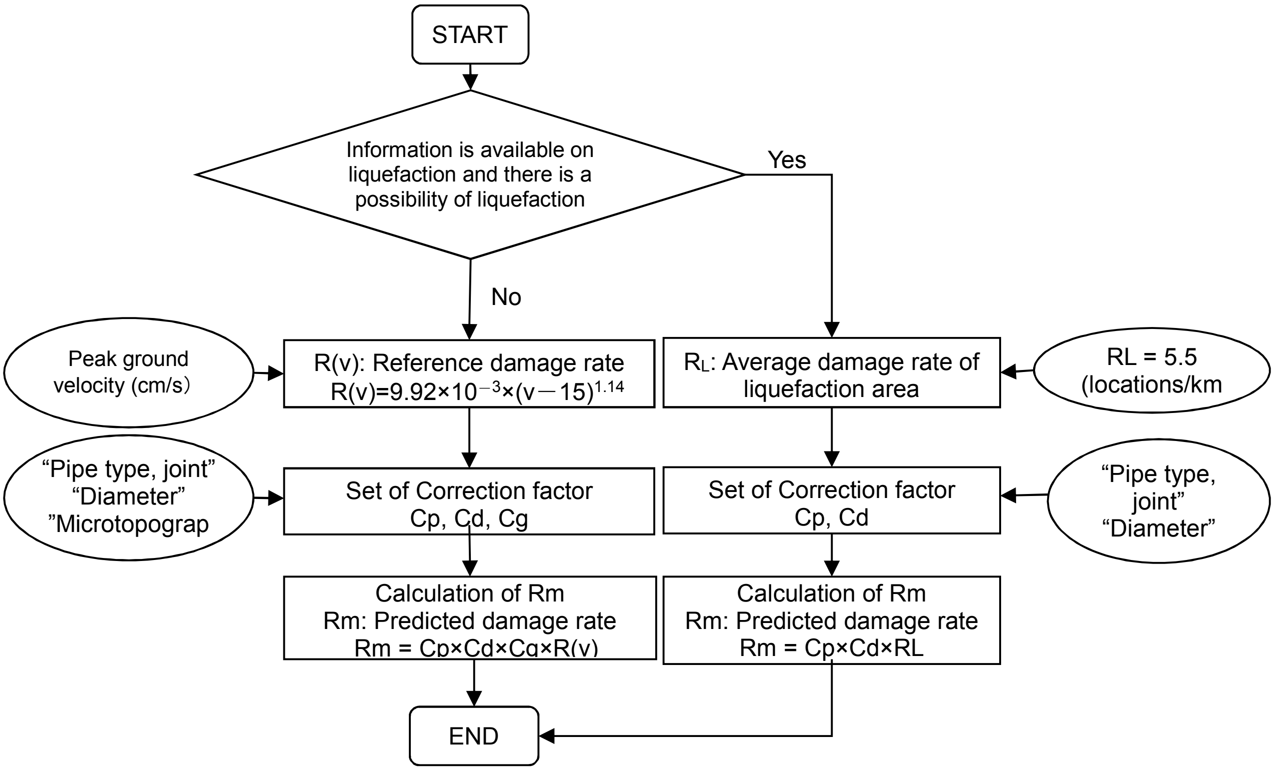


Figure 1. Process of estimating the number of pipe failures in earthquakes

TABLE I. EQUATION AND ITS CORRECTION FACTORS

If there is no information available on liquefaction or there is no possibility that liquefaction occurs	If there is an information available on liquefaction and there is a possibility that liquefaction may occur
$\boldsymbol{R_m = C_p \times C_d \times C_g \times R(v)}$ R_m: Estimated damage rate [locations/km] C_p: Correction factor for pipe and joint type C_d: Correction factor for pipe diameter C_g: Correction factor for microtopography R(v): Reference damage rate[locations/km] $R(v)=9.92\times10^{-3}\times(v-15)^{1.14}$ v: Peak ground velocity (cm/s) $(15 \leqq v < 120)$	$\boldsymbol{R_m = C_p \times C_d \times R_L}$ R_m: Predicted damage rate [locations/km] C_p: Correction factor for pipe and joint type C_d: Correction factor for pipe diameter R_L: Average damage rate of liquefaction area [locations/km], R_L = 5.5

Correction factor					
Pipe and joint type	Cp	Diameter (mm)	Cd	Microtopography where pipes are installed	Cg
DIP (A)	1.0	φ50－80	2.0	Mountain, mountain foot, hill, volcanic area, volcanic mountain foot, volcanic hill	0.4
DIP (K)	0.5				
DIP (T)	0.8				
DIP (disengagement prevention)	0	φ100－150	1.0	Gravel upland, loam upland	0.8
CIP	2.5	φ200－250	0.4	Valley lowland, alluvial fan, humid lowland plain, delta, coastal lowland	1.0
VP (TS)	2.5				
VP (RR)	0.8	φ300－450	0.2		
SP (welding)	0.5/0			Natural levee, former river channel, sandbar, gravel bar, dune	2.5
SP (non-welding)	2.5	φ500－900	0.1		
ACP	7.5			Reclaimed land, drained land, lakes and marshes	5.0
PE (electrofusion)	N/A				

REVIEW OF THE EQUATION UPON 2016 KUMAMOTO EARTHQUAKE

Review Process

Figure 2 shows the review process of the equation. The validity of the equation was tested using the data on pipe damage in the 2016 Kumamoto Earthquake. The assessment covered and considered the transmission, conveyance and distribution mains with over 50 mm diameter that sustained damage (but excludes those used for water pipe bridges as well as other above-ground, exposed mains).

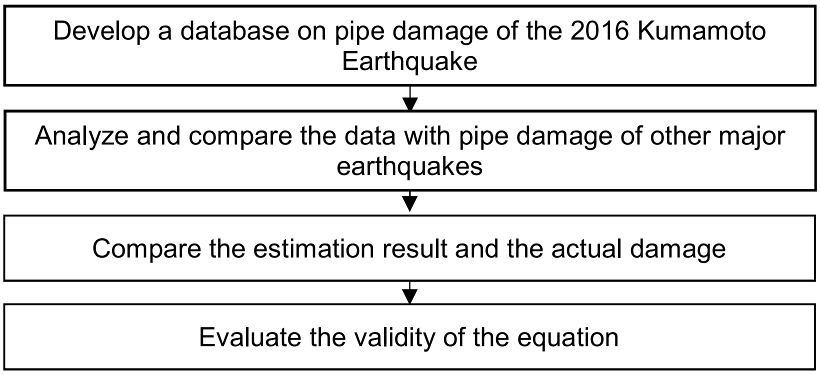


Figure 2. Review process of the equation.

Development of a Database on Pipe Damage

First, regarding the 2016 Kumamoto Earthquake, we collected related data on pipe damage, ground motions, ground conditions, and the distribution of the liquefaction that occurred. Next, a GIS-based database was produced out of these data. As for the pipe damage, Kumamoto City provided relevant data from their mapping system. Based on the provided data, we plotted the location of the pipe damage on GIS. Further, to produce a database, we entered the data on pipe material, joint, diameter, year of installation, the level of ground motions in each 250-meter grid cell of the service area as well as their ground conditions. Table II shows a list of the items in the database.

TABLE II. ITEMS OF THE DATABASE

Item	Details	Shape on GIS	Source
Pipe attributes	Pipe material/joint, diameter, year of installation	Line	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Location of pipe damage	Plot on GIS	Point	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Damage attributes	Damage type and level, pipe material/joint, diameter, year of installation	Point	Mapping data provided by Kumamoto City Water and Sewerage Waterworks Bureau
Ground motion	PGV per grid cell on GIS	Grid cell (250 m)	Mesh data of PGV distribution in the main shock of the 2016 Kumamoto Earthquake at 1:25 pm on April 16th, 2016. Available from the website of the National Research Institute for Earth Science and Disaster Resilience

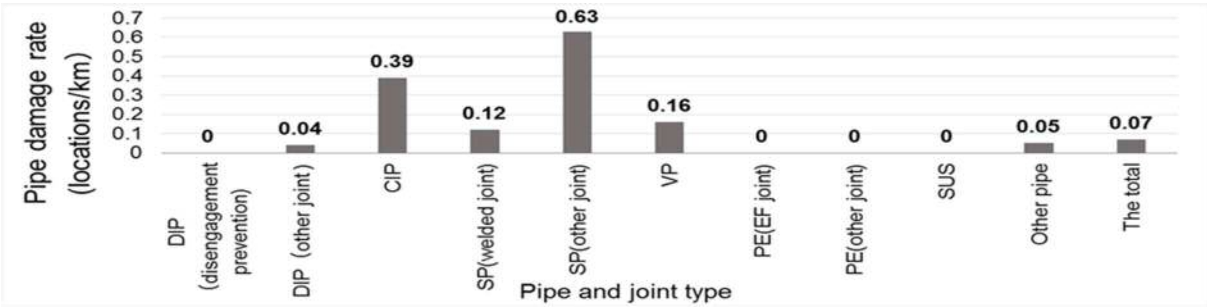
Ground condition	Microtopography per grid cell on GIS	Grid cell (250 m)	Database of topography and ground classifications [5]. Available from the website of the National Research Institute for Earth Science and Disaster Resilience
Distribution of liquefaction	Locations of liquefaction shown per grid cell as well as plotted on GIS	Grid cell (250 m) & Point	Mesh and point data of liquefaction distribution in the 2016 Kumamoto Earthquake [6]. Available from the website of the National Research Institute for Earth Science and Disaster Resilience available

CHARACTERISTICS OF PIPE DAMAGE IN 2016 KUMAMOTO EARTHQUAKE AS COMPARED WITH PIPE DAMAGE IN OHER MAJOR EARTHQUAKES

Pipe Damage in Kumamoto City

The pipelines in Kumamoto City stretches 3,238 km. The total number of pipe damages was 233, which translates into 0.07 per kilometer. As Figure 3 shows, the number of damage by pipe material was 0.63/km for SV (other joint), 0.39/km for CIP, 0.16/km for VP, 0.12/km for SP (welded joint), and 0.04/km for DIP (other joint). Overall, the damage rate was lower for larger diameter pipes (Figure 4).

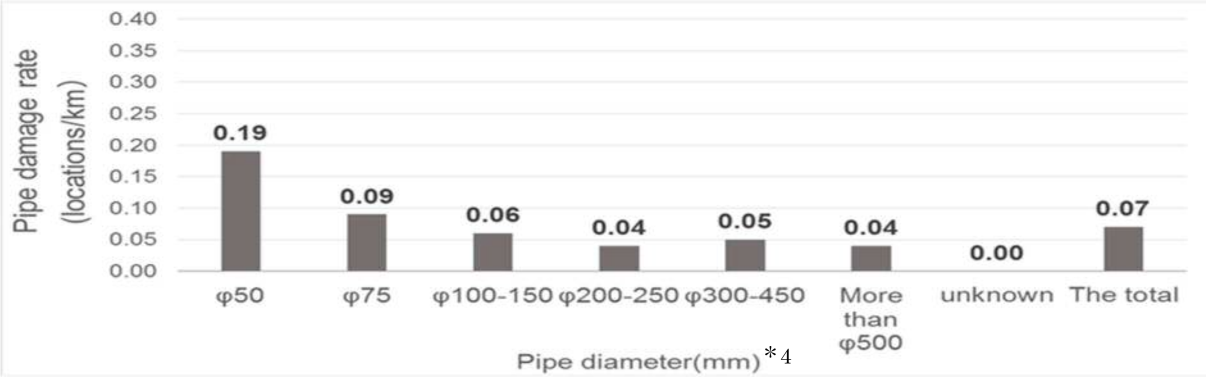
Figure 5 shows the pipe damage rate by microtopography. As it shows, the former river channel shows the highest damage rate. We consider this is partly because the mains installation lengths along the former river channel is only 5 km, which is shorter compared to other locations. In average, weaker gronds showed larger damage rates.



Pipe material*1	DIP (disengagement prevention)	DIP (other joint)	CIP	SP (welded joint) *2	SP (other joint)*3	VP	PE (EF joint)	PE (other joint)	SUS	Other pipe
Pipe damage (no. of locations)	0	72	36	8	59	55	0	0	0	3
Pipe Installation length (km)	583	1882	92	68	93	346	97	8	5	63

*1: Covers only mains with over 50 mm diameter
*2: SP (welded joint) does not include SP with expansion/flange joint. The latter is included in SP (others).
*3: SP (others) includes SP with threaded joint and others but excludes SP with welded joint.

Figure 3. Pipe damage rate by pipe material in Kumamoto City



*4: Covers only mains with over 50 mm diameter

Figure 4. Pipe damage rate by pipe diameter in Kumamoto City

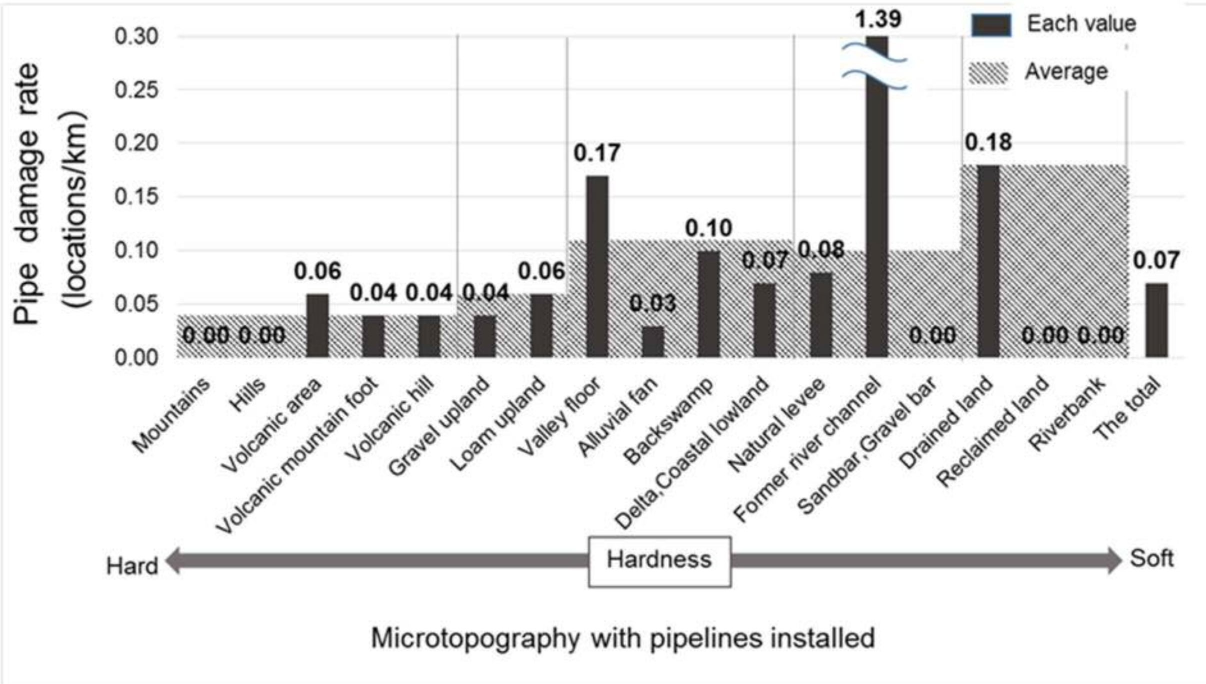


Figure 5. Pipe damage rate by microtopography in Kumamoto City

PGV and Pipe Damage Rate

Figure 6 shows the PGV distribution and pipe damage in the main shock of the 2016 Kumamoto Earthquake. And Figure 7 shows the pipe damage rate by PGV. As is shown in Figure 7, the pipe damage rates are larger where PGVs are greater. And this tendency corresponds to the current reference damage rate curve of the equation.

Also, some of the damaged areas show a PGV of over 120 cm/s. This value is beyond the maximum PGV covered by the equation, which considers the range of $15 \leqq v < 120$ (cm/s). However, since the mains installation lengths in Kumamoto City in the areas that recorded a PGV of over 120 cm/s was as short as 20 km in total, we were not able to collect sufficient amount of data as to reconsider the current PGV range of the equation.

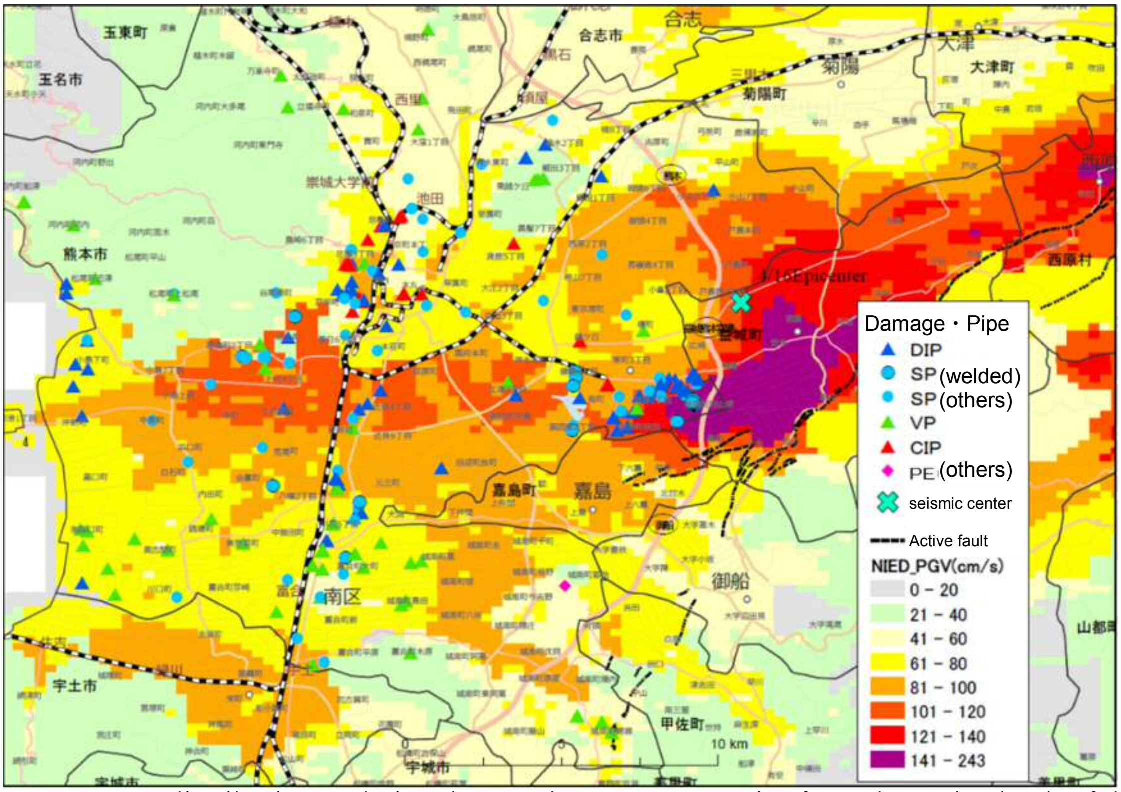
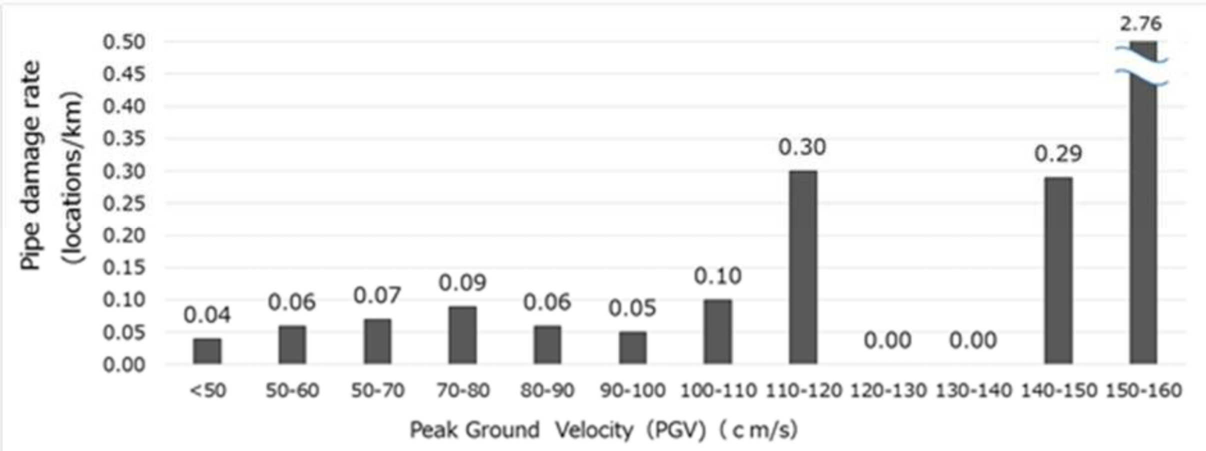


Figure 6. PGV distribution and pipe damage in Kumamoto City from the main shock of the 2016 Kumamoto Earthquake

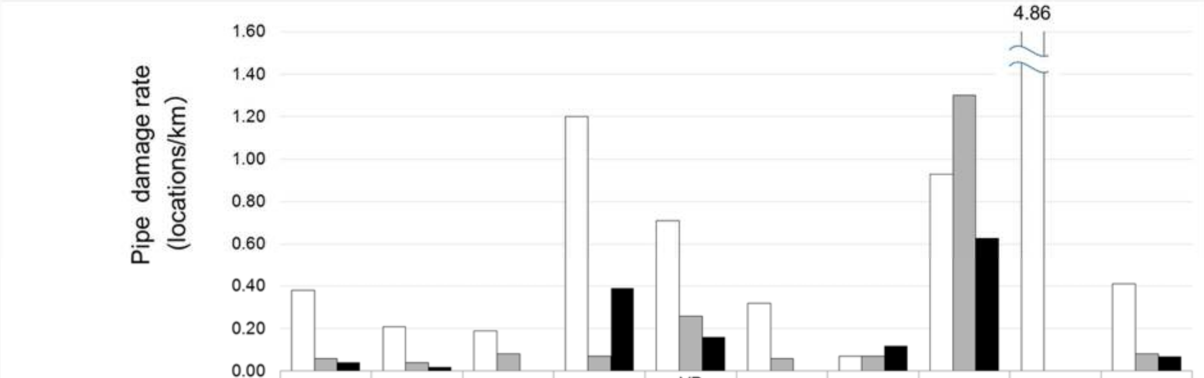


PGV (cm/s)	<50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	150-160
Pipe damage (no. of locations)	32	15	33	46	33	13	37	15	0	0	1	8
Pipe Installation length (km)	750	254	452	519	568	268	358	50	6.9	5.5	3.4	2.9

Figure 7. Pipe damage rate by PGV

Comparison between Kumamoto Earthquake and Other Major Earthquakes

Figure 8 shows the pipe damage rates in the 2016 Kumamoto Earthquake and some of the other major earthquakes that occurred in the past in Japan. The damage rate in the Kumamoto Earthquake was about 1/10 compared to the 1995 Hanshin Awaji Earthquake, 2004 Niigata Prefecture Chuetsu Earthquake, and 2007 Niigata Prefecture Chuetsu-oki Earthquake [7] while it was about the same as Sendai City in the 2011 Great East Japan Earthquake [3].



Pipe and joint type	DIP (A)	DIP(K)	DIP(T)	CIP	VP (TS)	VP(RR)	SP(welded)*5	SP(other)	ACP	The total
□ Hyogo pref and Nigata pref*6	0.38	0.21	0.19	1.20	0.71	0.32	0.07	0.93	4.86	0.41
■ Sendai city	0.06	0.04	0.08	0.07	0.26	0.06	0.07	1.30		0.08
■ Kumamoto city	0.04	0.02		0.39	0.16		0.12	0.63		0.07

*5: SP (welded joint) does not include SP with expansion/flange joint.
*6: For Hygo Pref., we analyzed the damage rate in Kobe City, Nishinomiya City and Asiya City in the 1995 Hanshin Awaji Earthquake; for Niigata Pref., we analyzed the damage rate in former Nagaoka City and Ojiya City in the 2004 Niigata Prefecture Chuetsu Earthquake and in Kashizawaki City and Kariwa Village in the 2007 Niigata Prefecture Chuetu-oki Earthquake.

Figure 8. Comparison of pipe damage rate between Kumamoto Earthquake and other major earthquakes

ASSESSMENT OF ESTIMATION ACCURACY OF THE EQUATION

Evaluation of Validity of the Correction Factors

To see the appropriateness of the correction factor Cp for pipe material/joint, we compared the damage rates of the reference pipe material/joint (DIP (A)) and other pipes that have the reference diameter (φ100-150) and are installed in the reference microtopography (valley lowland, alluvial fan, humid lowland plain, delta, or coastal lowland). Also, to see the appropriateness of the correction factor Cd for pipe diameter, we compared the damage rate of the reference diameter and other diameters in relation to the reference pipe material/joint. Further, to see the appropriateness of the correction factor Cg for microtopography, we compared the damage rate of the reference microtopography and other microtopographies in relation to the reference pipe material/joint as well as the reference diameter.

Table III shows the evaluation result of Cp in Kumamoto City. It shows that the actual damage rate of CIP is 12.5 times the rate of DIP (A) when the CIP's correction factors is 2.5, which shows a large gap between the two. On the other hand, the actual damage rate of DIP (K) is 0.8 times the rate of DIP (A) when the DIP (K)'s correction factor is 0.5. And the actual damage rate of VP is 2.9 times the rate of DIP (A) when the VP's correction factor is 2.5. Therefore, it can be said that for DIP (K) and VIP, their actual damage rates in relation to DIP (A) are close to the correction factors. As for why there is a large gap between the CIP's correction factor and its damage ratio to DIP (A), we consider CIP's damage rate was more susceptible to the number of pipe damages than other pipes since its installation length is shorter.

Table IV and Table V show the evaluation result of Cd and Cg, respectively. The result shows that overall, the actual damage rates are close to the correction factors.

TABLE III. DAMAGE RATE BY PIPE MATERIAL/JOINT FOR THE REFERENCE DIAMETER AND REFERENCE MICROTOPOGRAPHY (KUMAMOTO CITY)

	CIP	DIP(K)	DIP(A)	SP (welded)	SP (other)	VP
Pipeline length(m)	26,124	211,508	515,753	3,981	1,664	63,678
Pipe damage (no. of locations)	14	7	22	1	10	8
Pipe damage rate (locations/km)	0.536	0.033	0.043	—	—	0.126
Ratio to the damage rate of DIP (A)	12.50	0.80	1.00	—	—	2.90
Correction factor(Cp)	2.5	0.5	1.0	0.8/0	2.5	2.5

TABLE IV. DAMAGE RATE BY PIPE DIAMETER FOR THE REFERENCE MATERIAL/JOINT (DIP (A)) (KUMAMOTO CITY)

	<φ50	φ75	φ100-150	φ200-250	φ300-450	More than φ500
Pipeline length(km)	0	313	765	160	72	9
Pipe damage (no. of locations)	0	23	30	6	0	0
Pipe damage rate (locations/km)	0	0.073	0.039	0.038	—	—
Ratio to the damage rate of DIP (A)	—	1.9	1.0	1.0	—	—
Correction factor(Cd)	2.0		1.0	0.4	0.2	0.1

TABLE V. DAMAGE RATE OF THE REFERENCE MATERIAL/JOINT (DIP (A)) WITH THE REFERENCE DIAMETER (Φ100-150) BY CORRECTION FACTOR CG FOR MICROTOPOGRAPHY (KUMAMOTO CITY)

Microtopography	Mountain, Mountain foot, Hill, Volcanic area, Volcanic mountain foot, Volcanic hill	Gravel upland, Loam upland	Valley floor, Alluvial fan, Backswamp, Delta, coastal lowland	Natural levee, Former river channel, Sandbar,Gravel bar, Dune	Reclaimed land, Drained land, Lakes and marshes
Pipeline length(km)	157	310	205	69	24
Pipe damage (no. of locations)	3	14	8	2	3
Pipe damage rate(locations/km)	0.019	0.045	0.039	0.029	0.125
Ratio to the damage rate of DIP (A)	0.5	1.2	1.0	0.7	3.2
Correction factor(Cd)	0.4	0.8	1.0	2.5	5.0

Evaluation of Validity of the Equation

To evaluate the accuracy of the equation, we compared the number of estimated pipe damage with the number of actual pipe damage in Kumamoto City for each grid cell of the service area. The damage was compared for the reference pipe material/joint (DIP (A)) with the reference diameter (φ100-150).

The equation estimated a total of 251 grid cells to have one or more than one pipe damage (Figure 9). On the other hand, the number of pipe damages that actually occurred was 30 in 19 grid cells out of these 251 ones (Figure 10). The estimate was on the safe side, which corresponds to the design principle of the equation*.

*as for the comparison of all kinds of pipes with over 50 mm diameter, the total number of estimated pipe damages in Kumamoto City was about 4.1 times larger than the number of actual pipe damages.

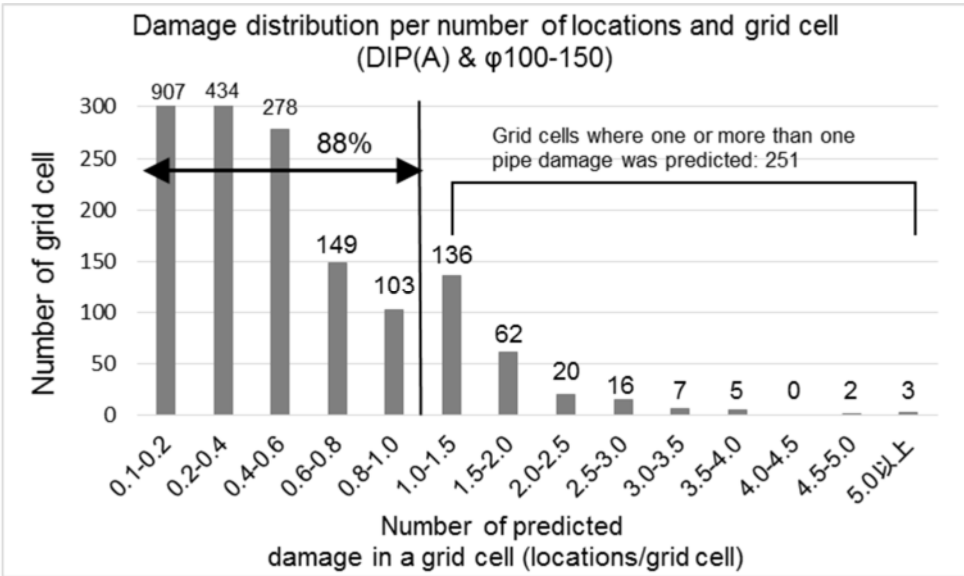


Figure 9. Number of pipe damage estimated by the equation for the reference pipe material/joint with the reference diameter

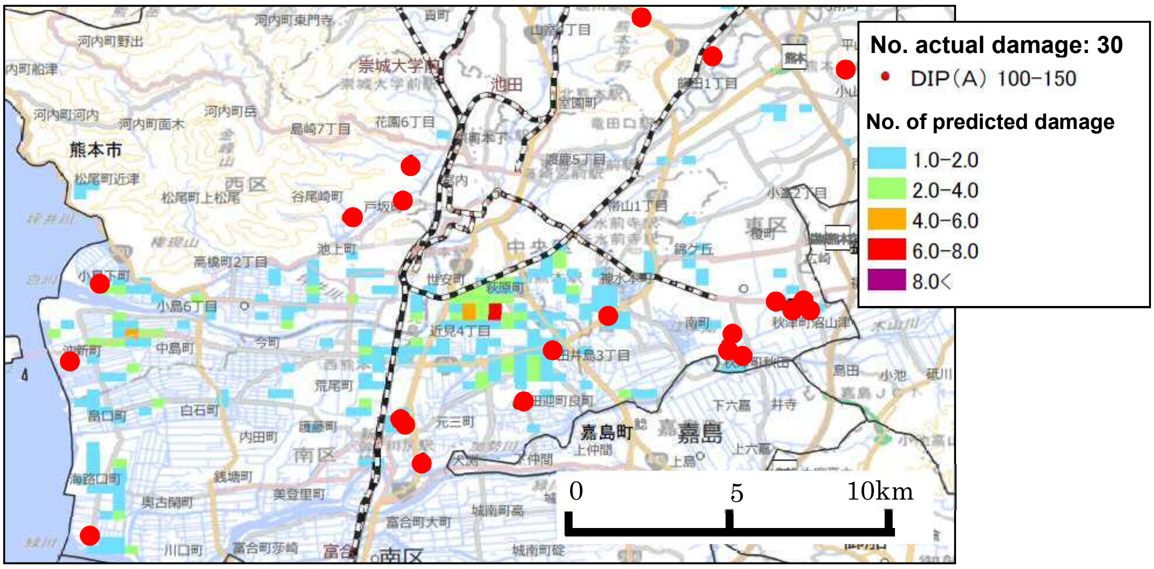


Figure 10. Locations of actual pipe damage and the distribution of estimated pipe damage for the reference pipe material/joint with reference diameter

In addition, for DIP (A) with 100-150 mm diameter, we also compared its damage rate in the 2016 Kumamoto Earthquake with the damage rate in other major earthquakes. Figure 11 shows the result by PGV levels along with the reference damage rate curve obtained from this comparison. It shows that the distribution of pipe damage is similar between the Kumamoto Earthquake and the other earthquakes.

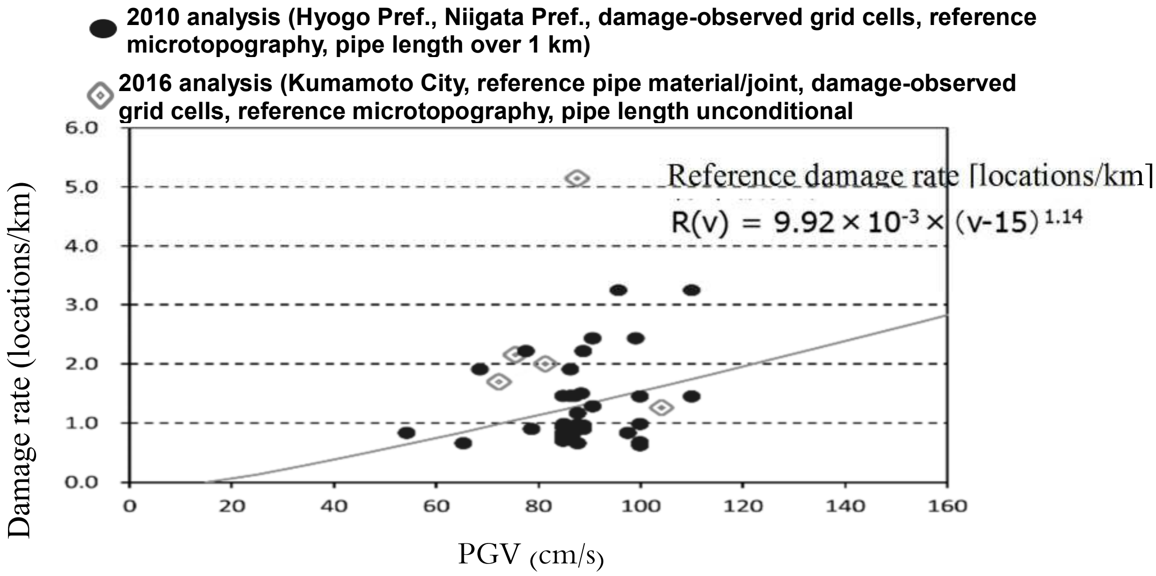


Figure 11. Damage rate of DIP (A) with 100-150 mm diameter in the 2016 Kumamoto Earthquake and in other major earthquakes along with the reference damage rate curve

CONCLUSION

The pipe damage analysis in Kumamoto City shows that for some pipe with short installation lengths, there a gap between the damage rates when compared to past earthquakes as well as between the correction factor and its damage ratio to the reference pipe material/joint. Overall, however, the correction factors of the equation and its reference damage rate had similar tendencies to the characteristics of the actual pipe damage. Also, the estimate given by the equation was on the safe side, which corresponds to its design principle.

From these results, we decided that the equation is still valid and requires no immediate modifications to the correction factors and the reference damage rate. One concern remains, however, that the equation might have estimated a little too far on the safe side, providing the number of estimated pipe damage a few times larger than the actual number of damage. Therefore, this aspect would need more considerations to further increase the accuracy of the equation.

We expect this equation will be utilized by more utilities to help an effective pipe renewal and replacement for an improved preparedness against future seismic risks.

ACKNOWLEDGMENTS

We would like to extend our gratitude to the Kumamoto City Water and Sewerage Waterworks Bureau for their data provision as well as to the water utilities and private companies that participated in this review process.

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