SEISMIC DAMAGE ESTIMATION PROCEDURE FOR WATER SUPPLY PIPELINES

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SUMMARY

This paper presents a practical procedure for estimating damage to water pipes when an earthquake occurs. The procedure considers the pipe material, pipe diameter, ground condition and liquefaction condition as well as earthquake ground motion intensity. The standard fragility curve (damage ratio) is proposed as a function of peak ground acceleration based on the strong ground motion observation data of the 1995 Hyogoken-nanbu (Kobe) Earthquake and the damage data around the observation points. This standard fragility curve is modified by factors such as pipe material, pipe diameter, ground condition and liquefaction condition. These modification factors were determined mainly from a detailed analysis of damage to Ashiya and Nishinomiya cities caused by the 1995 Hyogoken-nanbu Earthquake. A 50-meter square mesh or grid system was adopted in this analysis in order to consider the micro land classification such as narrow valleys.

INTRODUCTION

This paper presents a practical seismic damage estimation procedure for water supply mains. The procedure is established based on the results obtained by the preliminary analysis for the water pipe damage caused by the 1995 Hyogoken-nanbu Earthquake[1],[2] and the detailed damage analysis for Ashiya and Nishinomiya cities. The GIS analysis was made using the database of the water supply networks and damage to water mains caused by the 1995 Hyogoken-nanbu Earthquake prepared by the Japan Water Works Association (JWWA) for Kobe, Ashiya and Nishinomiya cities. The proposed damage estimation procedure considers not only the peak ground motions (acceleration and velocity) but also pipe material, diameter, topography (ground condition) and degree of liquefaction.

DAMAGE ESTIMATION PROCEDURE

With damage data obtained during the 1971 San Fernando Earthquake and the 1923 Kanto Earthquake, Kubo et al.[3] correlated damage rate of water pipes to peak ground acceleration, ground condition and pipe diameter. They applied this relationship to the damage estimation of Tokyo in 1978. Isoyama and Katayama[4] later improved the procedure and proposed a seismic damage estimation formula for buried pipes as shown below.

$$R_m(\alpha) = C_1\, C_2\, C_3 \cdot\cdot\cdot C_n\, R(\alpha) \tag{1}$$

where, $R_m(\alpha)$ is a modified damage rate (failures/km), C_i represents various correction factors (i =1 to n), $R(\alpha)$ is a standard damage rate (failures/km), and α is the maximum acceleration of seismic ground motion (cm/sec^2).

The standard damage rate $R(\alpha)$ is assumed to be the rate of damage to cast-iron water supply pipes of diameter 100 to 200 mm buried in alluvial soil at a shallow depth of about 1 m. The following standard damage rate was

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obtained from the relationship between the maximum acceleration and damage rate of cast-iron water pipes, based on the study for the 1971 San Fernando Earthquake.

$$R(\alpha) = 1.698\times10^{-16}\alpha^{6.06} \tag{2}$$

The conceivable correction factor C_i varies with pipe material, pipe diameter, soil condition, the degree of liquefaction, and so on. Various combinations have been adopted according to the condition of the city, and specific values of correction factors have been fixed based on the latest data at a particular point in time.

Equation (1) is used in this paper also. A standard damage rate curve and correction factors are established based on the results of a damage analysis of the 1995 Hyogoken-nanbu Earthquake. The correction factors used in this study are limited to pipe material, pipe diameter, topography (ground condition) and the degree of liquefaction, due to the availability of data and in view of their use for general purposes.

CORRECTION FACTORS

Area covered by analysis and database

In order to determine the correction factors, a detailed analysis was made for Ashiya and Nishinomiya cities. The database of water supply networks and the damage to the mains caused by the 1995 Hyogoken-nanbu Earthquake in Kobe, Ashiya and Nishinomiya cities, was used in this analysis[1]. This database includes all distribution pipes with diameter greater than 75 mm, locations of damage and types of damage. Topographical information was digitized from the map sheets for Ashiya and Nishinomiya prepared by the Geographical Survey Institute[5]. An analysis is made of the area shown in Figure 1 for which the above information is available. The liquefaction distribution and seismic intensity scale distribution given in reference [1] are used.

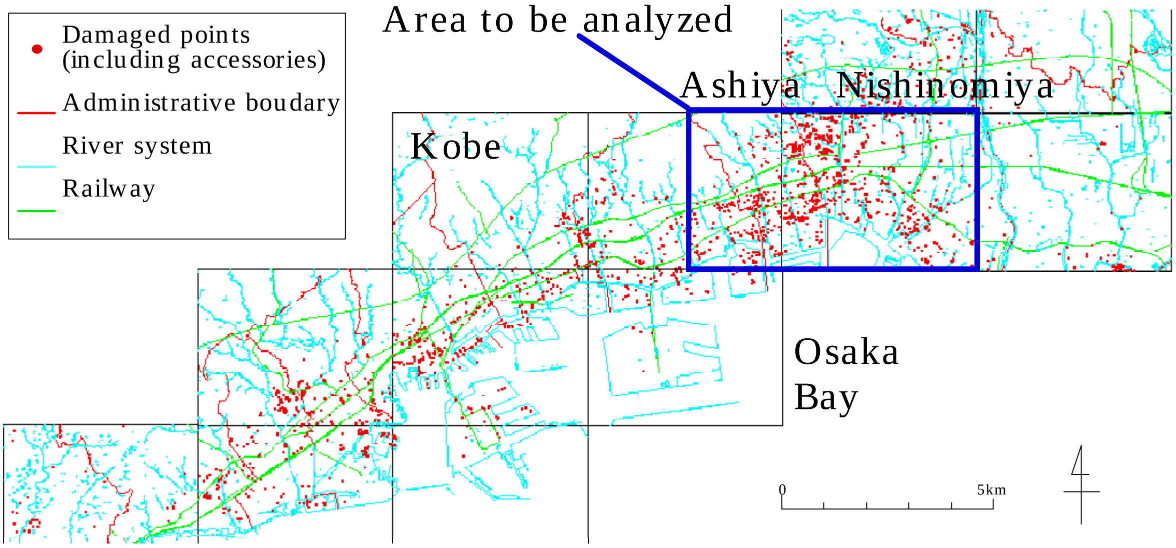


Figure 1: Analysis area

The water distribution network and damaged points in the analysis area are shown in Figure 2. Abbreviations used in this paper are DIP (ductile cast-iron pipe), CIP (cast-iron pipe), VP (polyvinyl chloride pipe), SP (steel pipe with welded joints), SGP (steel pipe with screwed joints) and ACP (asbestos cement pipe). Additional objects such as air valves, sluice valves and hydrants are collectively referred to as accessories.

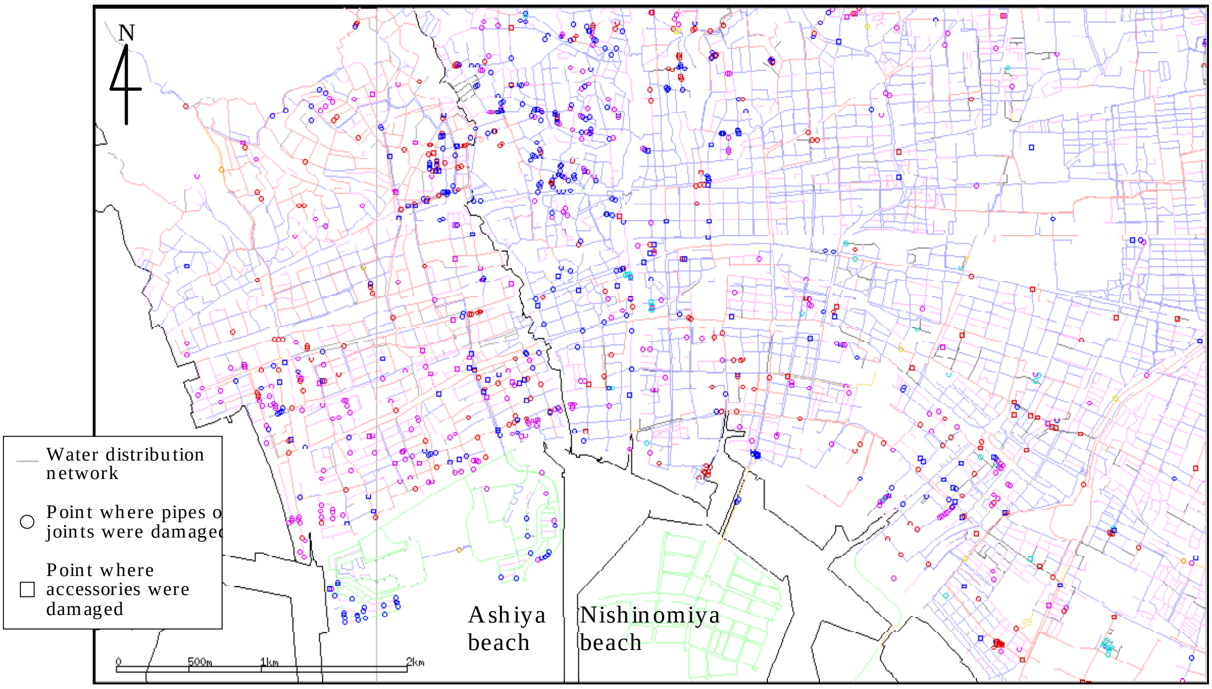


Figure 2: Water distribution network and damaged to water mains

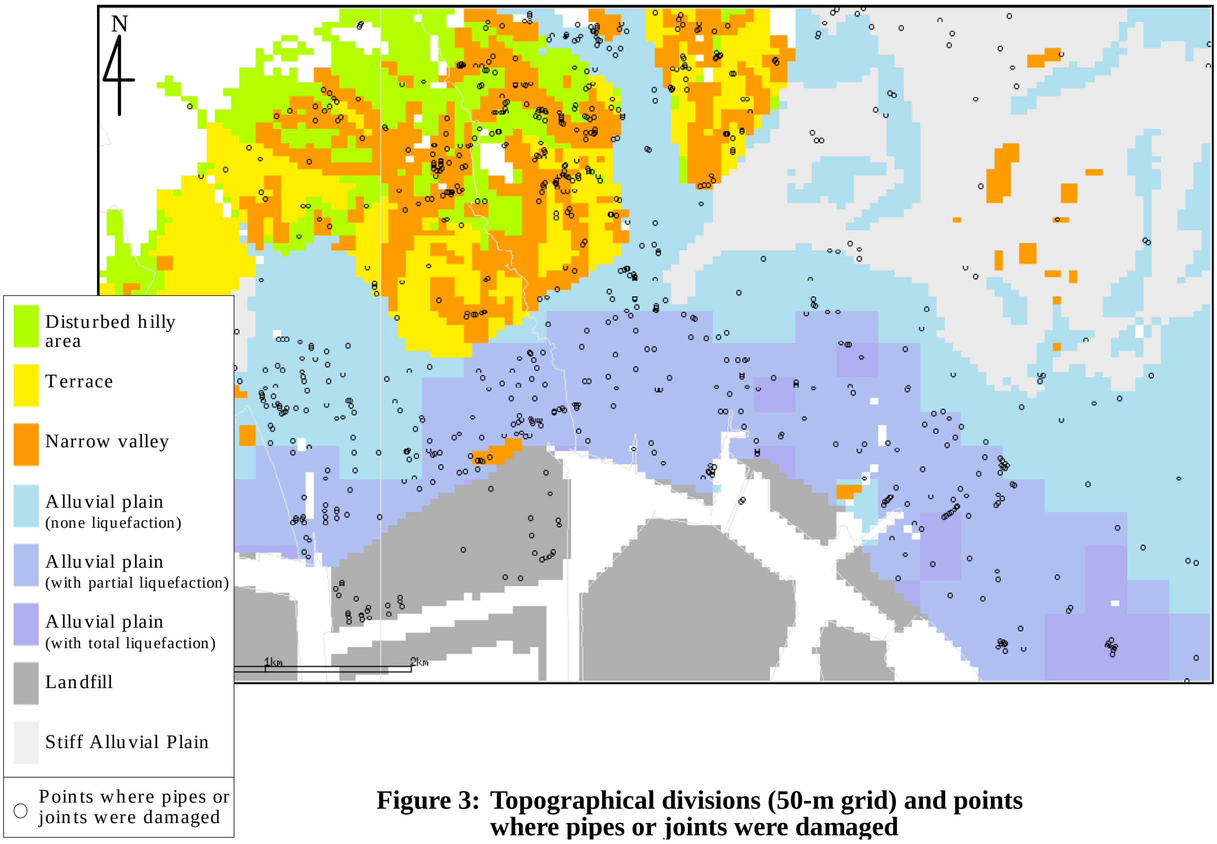


Figure 3: Topographical divisions (50-m grid) and points where pipes or joints were damaged

Grouping of topographical divisions

The topographical divisions of reference [5] are too many and detailed to use for defining coefficients, so topography is classified into five groups: “(artificially) disturbed hilly area”, “terrace”, “narrow valley”, “alluvial plain” and “stiff alluvial plain”. The results of classification are shown in Table 1 and Figure 3. It should be noted that the “terrace” and “narrow valley” divisions have been substantially disturbed by humans in this area. “Stiff alluvial plain” has experienced only minor damage owing to good soil conditions, and can virtually be regarded as consolidated alluvial plains with little artificial disturbance[1]. Most of the area of this classification corresponds to the flood plains in this area.

While valley bottom plains and flood plains are not separated in the topographical map by the Geographical Survey Institute[5], these two types of plains are treated separately in this analysis because the characteristics of damage to water supply pipes greatly vary between the two. The topographical map is transformed to a grid to facilitate analysis. 50-m grid cells are used to fully represent narrow valleys and other types of topography. In the subdivision of alluvial plains according to the degree of liquefaction, “none”, “partial” and “total” liquefaction correspond to “0%”, “50%” and “100%” in reference [1], respectively. This classification is made based on the liquefaction map of Hamada et al.[6] Figure 3 shows failure points of water mains on the 50-m grid cells topographical map. It is clear that most of the damage in hilly areas has occurred in the division of narrow valley. It should be noted that coastal landfill is excluded from this analysis.

Table 1: Topographical Group

Group	Topography
Disturbed hilly area	Cut slope, mudflow deposit, man-made hilly region
Terrace	Lower terrace surface, middle terrace surface, upper terrace surface
Narrow valley	Valley bottom plain, including former water space / pond
Alluvial plain	Alluvial fan, gentle frontage of fan, natural levee, sand bank or sand bar, hightened bank along tenjo-gawa, coastal plain, hinterland, former river bed
Stiff alluvial plain	Flood plain, fundamentally an alluvial plain but relatively stiff ground

Multivariate analysis

Summary values of number of failures, length of pipe and damage rate (failures/km) for various combinations of pipe material, pipe diameter and topographical division in the analysis area are shown in Table 2. Pipe materials are classified into five, specifically, DIP, CIP, VP, SP and Other (including SGP, ACP, and unidentified pipes). Four classes of pipe diameter, 75 mm, 100 to 150 mm, 200 to 400 mm, and 500 mm or larger, are used. Degree of liquefaction is divided into two categories, “without” (0%) and “with” (50 or 100%) liquefaction in this analysis because the coastal landfill area is excluded, where “total (100%)” liquefaction occurred. The table shows summary values of damage for pipes and joints without accessories. Accessories are excluded from the analysis.

Based on Table 2, a multivariate analysis is made using a quantification theory (Class I) at the logarithmic. The explanatory variables are pipe material, pipe diameter and topographical division, and a criterion variable is the damage rate R. The weight is considered according to the length of pipes. The basic formula is shown below.

$$R = C_p \, C_d \, C_g \, R_0 \qquad (3)$$

Table 2: Summary values for combinations of pipe material, pipe diameter and topographical division

Upper : Number of points (failures)
Middle : Length (km)
Lower : Damage rate (failures/km)

	All Materials of Pipe					DIP					CIP					VP					SP					Unidentified				
	All ϕ	75-75	100-150	200-450	500-800	All ϕ	75-75	100-150	200-450	500-800	All ϕ	75-75	100-150	200-450	500-800	All ϕ	75-75	100-150	200-450	500-800	All ϕ	75-75	100-150	200-450	500-800	All ϕ	75-75	100-150	200-450	500-800
All Types of Topography	616	174	344	98	0	234	32	151	51	0	196	37	114	45	0	150	82	68	0	0	2	1	0	1	0	34	22	11	1	0
	521	88.4	314	108	10.2	291	30	198	53.2	9.74	122	10.3	61.1	50.3	0.21	83.3	40.4	42.9	0	0	3.11	0.32	0.54	2.25	0	21.8	7.33	11.7	2.53	0.22
	1.18	1.97	1.09	0.91	0	0.8	1.07	0.76	0.96	0	1.61	3.59	1.87	0.89	0	1.8	2.03	1.58	-	-	0.64	3.11	0	0.45	-	1.56	3	0.94	0.4	0
Disturbed Hilly Region	40	9	23	8	0	26	3	16	7	0	4	0	3	1	0	10	6	4	0	0	0	0	0	0	0	0	0	0	0	0
	27.1	6.21	15.7	4.81	0.38	12.7	2.39	7.25	2.79	0.26	9.81	1	6.94	1.75	0.12	2.65	1.7	0.95	0	0	0	0	0	0	0	2	1.12	0.6	0.28	0
	1.47	1.45	1.46	1.66	0	2.05	1.26	2.21	2.51	0	0.41	0	0.43	0.57	0	3.77	3.54	4.2	-	-	-	-	-	-	-	0	0	0	0	-
Terrace	50	11	33	6	0	26	5	17	4	0	14	2	11	1	0	9	4	5	0	0	1	0	0	1	0	0	0	0	0	0
	39.7	8.89	22.4	7.98	0.5	20.1	3.6	13.1	2.98	0.5	14	1.88	7.67	4.49	0	4.25	3.04	1.21	0	0	0.49	0	0	0.49	0	0.8	0.37	0.41	0.02	0
	1.26	1.24	1.48	0.75	0	1.29	1.39	1.3	1.34	0	1	1.06	1.43	0.22	-	2.12	1.31	4.12	-	-	2.03	-	-	2.03	-	0	0	0	0	-
Narrow Valley Space	156	26	94	36	0	84	12	52	20	0	54	7	31	16	0	18	7	11	0	0	0	0	0	0	0	0	0	0	0	0
	57.2	10	30.6	13.5	3.14	29.7	4.4	15.2	7.01	3.04	19.3	1.73	11.3	6.13	0.09	5.78	3.09	2.69	0	0	0.15	0.1	0	0.05	0	2.36	0.67	1.39	0.29	0.01
	2.73	2.6	3.07	2.67	0	2.83	2.73	3.42	2.85	0	2.8	4.04	2.74	2.61	0	3.11	2.26	4.1	-	-	0	0	-	0	-	0	0	0	0	0
Alluvial Plain (None Liquefaction)	134	55	67	12	0	43	5	32	6	0	38	13	19	6	0	40	27	13	0	0	1	1	0	0	0	12	9	3	0	0
	163	30.5	104	26.8	2.09	89.7	9.59	63.5	14.5	2.09	30.3	3.36	14.9	12	0	36.6	15.7	20.9	0	0	0.5	0.23	0.23	0.04	0	6.09	1.65	4.26	0.18	0
	0.82	1.8	0.65	0.45	0	0.48	0.52	0.5	0.41	0	1.25	3.87	1.27	0.5	-	1.09	1.72	0.62	-	-	1.99	4.43	0	0	-	1.97	5.44	0.7	0	-
Alluvial Plain (with Liquefaction)	194	60	104	30	0	43	5	26	12	0	71	12	42	17	0	64	33	31	0	0	0	0	0	0	0	16	10	5	1	0
	118	16.7	73.2	27.5	0.87	61.4	3.41	45.1	12	0.87	28.1	0.92	13.5	13.7	0	19.7	9.98	9.74	0	0	1.24	0	0.16	1.09	0	7.7	2.38	4.6	0.73	0
	1.64	3.6	1.42	1.09	0	0.7	1.47	0.58	1	0	2.53	13.1	3.11	1.24	-	3.25	3.31	3.18	-	-	0	-	0	0	-	2.08	4.2	1.09	1.38	-
Stiff Alluvial Plain	42	13	23	6	0	12	2	8	2	0	15	3	8	4	0	9	5	4	0	0	0	0	0	0	0	6	3	3	0	0
	116	16.1	68.5	27.7	3.2	77.2	6.64	53.7	13.9	2.99	20.4	1.42	6.73	12.3	0	14.4	6.94	7.41	0	0	0.72	0	0.15	0.57	0	2.85	1.14	0.46	1.04	0.21
	0.36	0.81	0.34	0.22	0	0.16	0.3	0.15	0.14	0	0.73	2.11	1.19	0.33	-	0.63	0.72	0.54	-	-	0	-	0	0	-	2.11	2.63	6.48	0	0

where, C_p, C_d and C_g represent weights for pipe material, pipe diameter and topography relative to the respective bases (value=1), namely, CIP, 100 to 150 mm, buried in alluvial plain without liquefaction, respectively. R_0 indicates the standard damage rate, which is the damage rate for a standard combination represented in failures/km. Coefficients obtained as a result of regression are shown in Figure 4. Resulting standard damage rate R_0 is 0.96 failures/km in this analysis. The coefficient of correlation between estimated and actual number of failures is 0.87.

Establishment of correction factors

In the analysis up to the previous section, quantifications are carried out for local areas, and the population is not sufficient for some classifications. There may exist a danger of representing local characteristics of damage. In establishing correction factors for the damage estimation formula, the damage rate of each category for the entire region including Kobe shown in references [1] and [2] is considered.

Table 3 lists values of correction factors. Corresponding values by Table 2 and by "entire region" analysis are also shown in Table 3. The expression “Entire Area” is used when cross tabulation for Kobe, Ashiya and Nishinomiya in references [1] and [2] refers to the damage rate for the entire damaged area.

As described in Section 3.2 above, it is necessary to assume that “terrace” and “narrow valley” topographical divisions have undergone substantial artificial disturbances. The divisions excluded from the analysis such as coastal landfill, DIP with earthquake-proof joints and pipes of 75 mm or smaller diameter should be reviewed separately. The values listed in the table for divisions for which length is insufficient are not necessarily valid.

STANDARD DAMAGE RATE CURVE

Regression analysis by observed data

Damage to water supply pipes around points where strong motion was observed in the Hanshin (Osaka and Kobe) district is investigated and a fragility curve is formed based on the relationship between the damage rates and observed peak ground motions. Damage rate in the area around the strong motion observation point was investigated, and correlated to the peak ground motion value[7]. Figures 5 and 6 show the relationship between maximum acceleration and damage rate for CIP and DIP, respectively. Curves to which the following function is fitted by the least squares method are marked on these figures.

$$R(\alpha) = c\,(\alpha - A)^{b} \qquad (4)$$

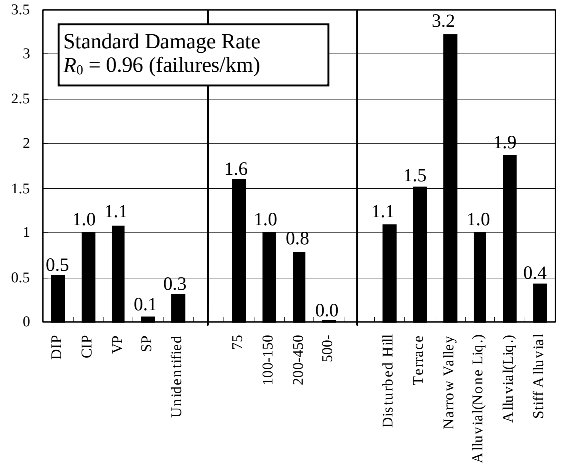
where, R(α) is damage rate (failures/km) based on the observed data, α is the maximum acceleration of the seismic ground motion (cm/sec2), and b and c are variances for regression. A indicates the acceleration at which damage starts to occur. A value of 100 cm/sec2 was shown to be valid after a review by varying the acceleration from 0 to 300 cm/sec2 in 50 cm/sec2 increments. Since a curve is formed here to identify a standard damage rate, the points with substantial liquefaction in the surrounding area or those for which damage rate may have increased due to topographic features are omitted. These points are represented by empty rectangles and circles in the figures. The results of regression are shown in the following equations.

$$\text{CIP:}\quad R(\alpha) = 2.88\times10^{-6}\,(\alpha-100)^{1.97} \qquad (5)$$
$$\text{DIP:}\quad R(\alpha) = 4.58\times10^{-7}\,(\alpha-100)^{1.93} \qquad (6)$$

For reference, equation (2), which used to be adopted in many cases of damage estimation in Japan, is also plotted on Figure 5. It is clear that equation (2) produced an extremely high damage rate in the zone where acceleration was 400 cm/sec^2 or more.

Similarly, damage rate curves are formed in relation to maximum velocity. The results of regression are shown in the following equations.

$$\text{CIP:}\quad R(v) = 3.11\times10^{-3}\,(v-15)^{1.30} \qquad (7)$$
$$\text{DIP:}\quad R(v) = 7.03\times10^{-6}\,(v-15)^{2.19} \qquad (8)$$



(a) Pipe Material (b) Pipe Diameter (c) Topography

Figure 4: Coefficients obtained as a result of quantification analysis

Table 3: List of correction factors

Item / Category		Factor	Regression (Fig.4)	TABLE 2	Entire Area[1],[2]
Pipe Material	DIP	0.3	0.5	0.5 (0.80/1.61)	0.3 (0.44/1.52)
	CIP	1.0	1.0	1.0	1.0
	VP	1.0	1.1	1.1 (1.80/1.61)	0.9 (1.46/1.52)
	SP	(0.3)	0.05	0.4 (0.64/1.61)	0.3 (0.47/1.52)
	ACP	(1.2)	-	-	1.2 (1.78/1.52)
Pipe Diameter	ϕ75	1.6	1.6	1.8 (1.97/1.09)	2.2 (1.90/0.93)
	ϕ100-150	1.0	1.0	1.0	1.0
	ϕ200-450	0.8	0.8	0.8 (0.91/1.09)	1.0 (0.94/0.93)
	ϕ500-	(0.5)	0.008	0.0 (0.00/1.09)	0.5 (0.51/0.93)
Topography	Disturbed Hill	1.1	1.1	1.8 (1.47/0.82)	-
	Terrace	1.5	1.5	1.5 (1.26/0.82)	-
	Narrow Valley	3.2	3.2	3.3 (2.73/0.82)	-
	Alluvial	1.0	1.0	1.0	-
	Stiff Alluvial	0.4	0.4	0.4 (0.36/0.82)	-
Lique-faction	None Liq.	1.0	1.0	1.0	1.0
	Partial Liq.	2.0	1.9	2.0 (1.64/0.82)	2.0 (1.46/0.82)
	Total Liq.	2.4			2.3 (1.67/0.72)

Values in parentheses have not yet been fixed due to insufficient length.

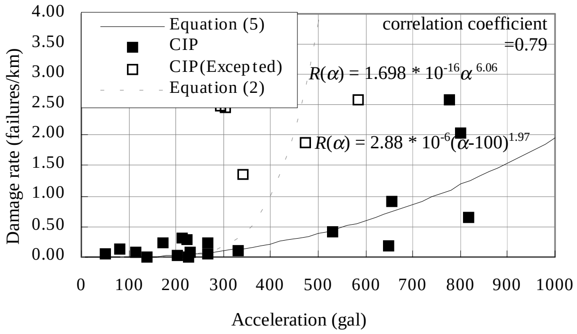


Figure 5: Relationship between PGA and damage rate of CIP

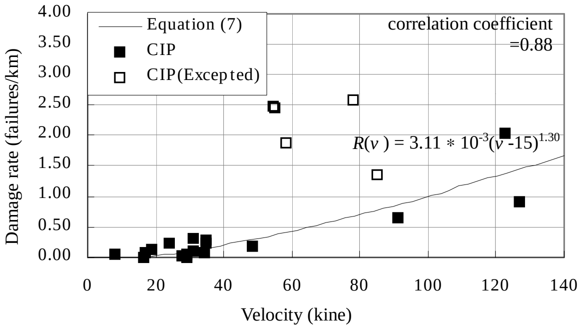


Figure 7: Relationship between PGV and damage rate of CIP

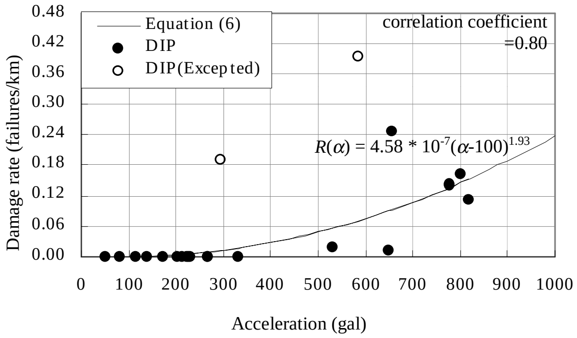


Figure 6: Relationship between PGA and damage rate of DIP

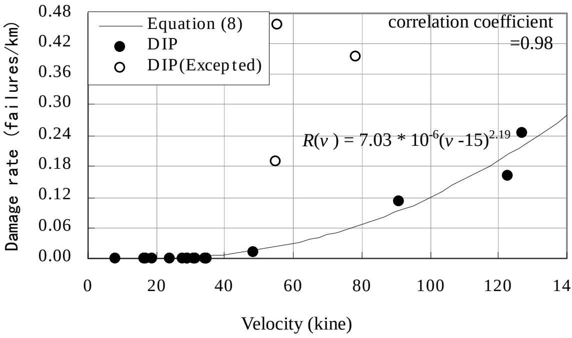


Figure 8: Relationship between PGV and damage rate of DIP

where, $R(v)$ is damage rate (failures/km) and v is the maximum velocity (cm/sec). As the velocity at which damage starts to occur, 15 cm/sec is considered valid by a review in which velocity was varied from 0 to 30 cm/sec in 5 cm/sec increments. Figures 7 and 8 show the relationship between the maximum velocity, and CIP and DIP damage rates, respectively.

Proposed standard damage rate curve

The damage rate obtained in Section 4.1 above is an average rate in the entire damaged area, but is not a standard damage rate for a standard combination. Here, equation (7) is used as an example to verify the relationship between the damage rate obtained in Section 4.1 and the standard damage rate, on the intensity scale in reference [1]. It is first assumed that maximum velocities 20, 60, 100, 140 and 180 cm/sec correspond to seismic intensities “4 or below”, “5”, “6”, “7” and “more than 7” on the scale in reference [1], respectively. Then damage rates are calculated by equation (7) at 0.0, 0.03, 0.12, 0.28 and 0.51 failure/km. Lengths for different intensity levels for a standard combination of CIP, ϕ100 to 150 mm, and alluvial plain without liquefaction are 0, 4.39, 5.46, 3.54 and 1.51 km. An average damage rate for the standard combination, obtained from the above values, is 1.17 failures/km. The standard damage rate R0 obtained as a result of a quantification analysis is 0.96 failure/km, which is on the 20% safe side. In view of the assumptions used for verification, however, the variance is considered to be within the error range. Therefore, for CIP, equations (5) and (7) are used without any modification as standard damage rate curves.

In a similar verification for DIP, lengths for different intensity levels for the standard combination of DIP, ϕ100 to 150 mm, and alluvial plain without liquefaction are 0, 21.9, 31.7, 8.6 and 1.34 km. An average damage rate calculated by equation (8) is 0.12 failure/km, which is 0.1 times the average damage rate for CIP obtained above by equation (7). The factor is far different from the correction factor of 0.3 for DIP as compared to CIP. This may be because relatively consolidated sound alluvial plains exist around the observation points where large seismic motion was registered. While all of the large seismic motions are found in the city of Kobe, non-liquefied alluvial plains in the city consist of relatively consolidated soil and have undergone little disturbances. As reported in reference [1], damage to DIP tends to start occurring when the soil strain exceeds 0.2 to 0.4%. The damage to DIP in the alluvial soil in the city of Kobe is small for the strength of seismic motion. If a more precise estimate is to be made, a damage rate estimation formula considering soil strain should be established. At present, however, estimation of soil strain is difficult. Therefore, a damage estimation formula in the form of equation (1) is established for the sake of simplicity and practicability. For DIP, equations (6) and (8) can be applied to sound alluvial plains as they are, but lead to underestimates in hilly areas with substantial soil disturbances or in liquefied areas. Thus, adjustments are made with coefficients to maintain compatibility with a correction factor of 0.3 for DIP defined in Section 3.4 above. The results are shown in the following equations.

$$\text{DIP:}\quad R(\alpha) = 1.32\times10^{-6}\,(\alpha-100)^{1.93} \qquad (6')$$

$$\text{DIP:}\quad R(v) = 2.03\times10^{-5}\,(v-15)^{2.19} \qquad (8')$$

When applied only to sound alluvial plains, equations (6) and (8) are acceptable. When applied to a whole area with substantial topographic variations, however, equations (6’) and (8’) are preferable. Equation (5) multiplied by a correction factor of 0.3 for DIP defined in Section 3.4 is almost identical to equation (6’). For other types of pipe, equations (5) and (7) are used by combining correction factors for pipe material.

CONCLUSIONS

This paper analyzed the characteristics of damage to water supply pipes during the 1995 Hyogoken-nanbu Earthquake, focusing on Ashiya and Nishinomiya cities where topography had significant effects on the damage. The relationship between topography and damage rate was analyzed qualitatively using GIS, and topography was classified into several typical groups and quantification was carried out. Based on the quantification results, correction factors were defined for pipe material, pipe diameter, topography and liquefaction, taking overall tabulation results for the damaged area into consideration. Standard damage rate curves were formed based on the peak values of seismic ground motion obtained at observation points, and on the rate of damage to water supply pipes in the surrounding area.

The database on water supply pipelines and on the damage on which the analysis was based is available from the Japan Water Works Association on CD-ROM under the same title as that of reference [1]. For details of the discussions presented in this paper, refer to reference [7].

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