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Kuraoka, S.; Rainer, J.H.

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Damage to water distribution system caused by the 1995 Hyogo-ken Nanbu earthquake

S. Kuraoka and J.H. Rainer

Abstract: The Hyogo-ken Nanbu earthquake on January 17, 1995, inflicted severe damage to the water distribution system, not only disrupting daily life activities and industrial operations but also causing major problems in fighting fires which destroyed 7377 homes. Disruption of water service is largely due to abundant water main breaks rather than failures of treatment plants, pumping stations, or the reservoirs. The total number (3300) of pipe breaks of the seven cities within 40 km east of the epicentre is one of the largest recorded among the strong earthquakes that occurred in the past 20 years. The major damage that led to the lack of water in Kobe City is described, and damage trends of water mains are compared with those found in past earthquakes. Important factors identified from these trends are noted for the study of estimation and mitigation methods of water main damage for the Greater Vancouver area.

Key words: earthquake, Hyogo-ken Nanbu, water mains, transmission line, reservoirs, fires, restoration.

Résumé : Le tremblement de terre de Hyogo-ken Nanbu, survenu le 17 janvier 1995, a gravement endommagé le réseau de distribution d'eau; il en est résulté non seulement une perturbation des activités de la vie quotidienne et du secteur industriel mais aussi des problèmes sérieux sur le plan de la lutte contre les incendies, qui ont détruit 7377 habitations. L'interruption de l'alimentation en eau a été causée en grande partie par les nombreuses ruptures de conduites d'eau principales plutôt que par des défaillances au niveau des usines de traitement, des stations de pompage ou des réservoirs. Le nombre total de bris de conduites, 3300, dans les sept villes situées dans un rayon de 40 km à l'est de l'épicentre, est l'un des plus élevés qui aient été enregistrés lors de séismes de forte intensité, au cours des 20 dernières années. Les auteurs de ce document décrivent les dommages sérieux causés aux conduites d'eau et qui ont provoqué le manque d'eau dans la ville de Kobe, et ils comparent les observations faites à ce niveau à celles qui l'ont été lors de séismes antérieurs. Ils font état des facteurs importants cernés grâce à ces observations, en vue de l'étude des méthodes d'estimation et de réduction des dommages qui pourraient être causés aux conduites d'eau principales de la région métropolitaine de Vancouver.

Mots clés : tremblement de terre, Hyogo-ken Nanbu, conduites d'eau principales, ligne de transmission, réservoirs, incendies, canalisations.

[Traduit par la rédaction]

Introduction

On January 17, 1995, Hyogo-ken Nanbu earthquake, also known as Hanshin Awaji Great Earthquake, inflicted severe damage to the Hanshin area, which is a narrow populated area extending roughly 50 km from Kobe City towards Osaka City (Fig. 1). The earthquake, with a magnitude of 7.2 on the Japan Meteorological Agency scale, had its epicentre near the northern tip of Awaji Island, with rupture lines extending eastward through Kobe City and on to Nishinomiya City (Fig. 2). The earthquake resulted in over 5500 deaths and 35 000 injuries, and destroyed or severely damaged 160 000 buildings, as well as bridges, industrial facilities, and harbour installations. The total damage to constructed facilities is estimated at over \$100 billion.

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S. Kuraoka and J.H. Rainer, Institute for Research in Construction, National Research Council Canada, Ottawa, ON K1A 0R6, Canada.

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This report mainly evaluates the impact of the effect of the earthquake on the water distribution system. While other lifelines such as gas, sewers, electricity, communications, and transportation facilities also suffered extensive damage, it is the water supply that is arguably the most important component for sustaining life and fighting the fires that can accompany an earthquake.

The following assessment is a result of the authors' visit to the affected areas about 10 days after the earthquake as a part of the Canadian reconnaissance team (Canadian Association for Earthquake Engineering 1995). Field observations of water main damage by the reconnaissance team were difficult, since the pipes are underground and communication with the city officials was limited owing to the crisis situation. Therefore, important damage data were later obtained through the courtesy of city officials of the seven cities in the Hanshin area and other agencies: Hanshin Water Supply Authority, Japan Ductile Iron Pipe Association, and Japan Water Works Association.

Disruption of water service imposed severe constraints on fire fighting, industrial operations, and daily life activities. In particular, lack of water was a major problem in fighting fires. More than 7377 homes were destroyed by fire in Kobe City (Kobe Municipal Water Works Bureau 1995). Another

Fig. 1. Interruption of water service to cities in Hanshin area with estimated iso-acceleration contours of peak ground motion (data as of February 1995).

critical problem was the water supply to hospitals. A hospital on Port Island, the reclaimed land off the coast of Kobe City, received only 5% of the normal amount of water as a result of failure of the major distribution main from the mainland. A number of heavy industries in the Hanshin area were also severely affected. For example, ship building operations at Mitsubishi Heavy Industry and Kawasaki Heavy Industry were interrupted for more than 1 month. The extent of the interruption to the water services in this area is illustrated in Fig. 1, with estimated isoacceleration contours derived from peak strong motion data (courtesy of Kyoto University). Immediately after the earthquake, 1.23 million consumers in the Hanshin area lost water service. The economic loss of the water distribution system is estimated to be in excess of 60 billion yen (approximately \$900 million Canadian) according to the report by Hanshin Water Supply Authority (1995a).

The major objective of this paper is to identify the critical failures which lead to the lack of water for fire fighting in Kobe City and to examine discernible trends of the water main breaks in comparison with those found in the past strong earthquakes. The first two sections of this paper describe the water distribution system of Kobe City under normal operating conditions and the damage to the system as

a result of the earthquake. This is followed by an assessment of pipe damage characteristics, restoration status, and performance of earthquake-proof pipes based on data from cities in the Hanshin area. Finally, important factors identified from these assessments are noted for the future study of estimation and mitigation methods of possible water main damage in the Greater Vancouver area. Analysis of the mechanisms of pipe failure due to large ground deformation and travelling ground waves is beyond the scope of this paper. Such analyses may be performed in the future as more quantitative data become available.

Water distribution system of Kobe City

Water mains

Kobe City is the centre of industries and government administration of the Hyogo Prefecture. The majority of the city is 100 m above sea level and rises towards the northern mountains with elevations in the range of 400 to 1000 m. The highly populated residential and industrial area is situated in a narrow strip along the coast about 4 km wide and 30 km long. The number of consumers, population, and water consumption of Kobe City are given in Table 1.

Fig. 2. Damage to transmission line from Yodo River to Kobe City. (DIP, ductile iron pipe; JMA, Japan Meteorological Agency.)

Table 1. Water service of Kobe City.

Population	1 500 000
Number of services	650 000
Length of distribution main (km)	3 963
Mean daily consumption (m ³ /d)	600 000
Maximum supply capacity (m ³ /d)	830 000
Supply from outside city (%)	75
Supply within city (%)	25

Since no major sources of water exist within Kobe City, 75% of the water is imported from the Yodo River 30 km east of Kobe City and 25% is supplied by the three major reservoirs within the city as illustrated in Fig. 2. Water from the Yodo River is carried primarily by two transmission lines through additional pumping stations and treatment plants. The transmission and treatment of water from the Yodo River are operated by the consortium, Hanshin Water Supply Authority (HWA), consisting of four cities: Kobe, Ashiya, Nishinomiya, and Amagasaki. Water from the Yodo River and the major reservoirs is distributed to the consumers through distribution reservoirs, pumping stations, distribution mains, and service lines.

The distribution mains are installed and managed by the city. The service lines are those connecting the distribution mains and homes. The service line within the consumer property is installed by the consumers. Pipe materials and joint types of distribution mains are shown in Table 2, where an earthquake-proof joint refers to a particular joint which can absorb relatively large ground deformation. The mechanisms and performance of the earthquake-proof joint will be

described later. Most of the distribution mains are ductile iron pipes as shown in Table 2. The cast iron and PVC pipes are in the process of being replaced with the ductile iron pipe.

Reservoirs, distribution reservoirs, and treatment plants

Three major reservoirs with a total capacity of 13 million m³ are constructed with dams in three locations as shown in Fig. 2. Water for the residential area in the northern mountain region of the city is supplied by the Sengari reservoir located in the northeast corner of the city in the Rokko Mountains. There are 119 distribution reservoirs and 44 pumping stations, controlling pressure and flow of the region whose elevation rises up to 300 m. Seven treatment plants purify about 310 000 m³/d of the water received from the three reservoirs in the city. This amount is equivalent to 50% of the daily water consumption of the city. More than 90% of this water is produced by the three major treatment plants: Uegahara, Okuhirano, and Sengari. The remaining 50% of the water supply is mostly purified by the treatment plants of the Hanshin Water Supply Authority located along the transmission lines from the Yodo River.

Distribution reservoirs with emergency shutoff valves

The city is currently in the process of installing emergency water-saving systems to 31 of 119 distribution reservoirs to be ready for the effects of strong earthquakes. Current distribution reservoirs with two storage units are selected so that one of the units can be equipped with automatic shutoff valves, which are designed to save daily water of 3 litres per person for a week. The city had completed 21 distribution reservoirs with this system before the earthquake. The cen-

tion of Water Distribution va line, 23 breaks occurred reed concrete pipe near the the Yodo River (point A in pair this pipe. On the same station, 15 km west from the is disabled owing to heavy system (point B in Fig. 2). his pumping station was dis- of a mechanical joint of the pipe. In the Daido transmis- ed in five mechanical joints e (point C in Fig. 2). Also, th the 1700 mm prestressed 2). The ruptured fault lines likely moved in strike-slip (jita 1995). The locations of mission line failures are not lting during the earthquake. due to transmission failures e is shown in Table 3. The ble 3 indicate that nearly all r was lost immediately after o a loss of 75% of the total e half of the remaining 25% d to the northern part of the f normal demand was avail- coastal region of the city. ost of the pumping and treat- quake, it was restored within

service lines

istribution mains and service ere the break rate for the dis- dividing the total number of istribution mains in kilometres he unit of the break rate will eaks per kilometre or breaks ity is large, the break rate will ences in the ground condition . Thus, locally, a higher break by the break rate of the entire age to pipes is much lower in than in the southern coastal differences in the ground con- ward (a small administrative

Fig. 3. Areas of damage concentration and local break rate (breaks per kilometre) of water distribution mains in Kobe City.

district of a large city such as Kobe) was obtained from Kobe City officials and is given in Fig. 3, which clearly indicates that break rate is higher in the southern coastal region than in the northern region. Clusters of highly damaged areas are also plotted in Fig. 3, showing that the damage was concentrated near the zone classified as intensity 7 (Japan Meteorological Agency) and the liquefied reclaimed land. Ruptured fault lines are also shown in Fig. 3 (Hujita 1995). The distribution mains on the Rokko Island performed remarkably well even though significant portions of the island had liquefied. The good performance is attributed to the extensive use of earthquake-proof joints, which will be described later. In general, 60% of the damage to the distribution mains is attributed to slip-out of joints and 20% is due to fracture and bending. Since 86% of the pipes used in the city are ductile iron pipes, the trend of break mode is expected to reflect that of the ductile iron pipe rather than that of other types of pipe. However, the break data with respect to different types of pipe were not available.

Critical failures to be noted are those sustained by the distribution mains supplying water to the reclaimed lands, mainly Rokko Island and Port Island shown in Fig. 2. The water to Port Island is supplied by two 600 mm diameter steel pipes with welded joints, carried over the Kobe Bridge. Both pipes were completely severed at location about 50 m from the bridge footing on the island side with gaps of approximately 100 mm. Consequently, water service to the entire 7000 residents on the island was lost. The damage may be attributed to the fact that the soils around the pipe settled

much more than the bridge footing on pile foundations. It took 23 days before water supply could be restored to the central hospital in the island.

The water to Rokko Island is supplied by steel pipes carried by the Rokko Bridge. The supply was disrupted not only due to failures to the pipe hangers under the bridge but also due to a number of breaks in the buried portion through the heavily damaged city. It took more than 3 weeks for the residents on this island to receive water.

Distribution reservoirs and treatment plants

Water from the Yodo River and the three major reservoirs flows to 119 distribution reservoirs in Kobe City, normally acting as a buffer to compensate for the daily fluctuation of consumption. As stated earlier, 21 of 119 reservoirs had emergency shutoff valves which are triggered by a telemetry system. Eighteen of the valves were activated by the earthquake, saving 33 000 m³ of water. Water in the remaining 101 distribution reservoirs, located at relatively high elevations, was lost in a short time owing to a significant number of breaks in the distribution mains and service lines. No major damage to the treatment plants and the three major reservoirs were reported except for the Uegahara treatment plant which was temporarily inoperable because of structural damage to the filtration and sedimentation systems. No major damage to the transmission line was found between the reservoirs and the distribution reservoirs. Therefore the damage to the reservoirs and the treatment plants was not directly responsible for the severe disruption of the water service.

Fig. 4. Joint failure of 800 mm ductile iron pipe in slip-out mode (courtesy of Kobe Municipal Water Works Bureau).

Fig. 5. Failure of 800 mm cast iron pipe in fracture mode (courtesy of Kobe Municipal Water Works Bureau).

Figure 4 shows a joint failure of a 800 mm ductile iron pipe in slip-out mode. Figure 5 shows the failure of a 800 mm cast iron pipe in fracture mode. The break rates with respect to the break modes for all types of distribution mains were obtained for Kobe City and Nishinomiya City as shown in Fig. 6, which shows that most breaks are slip-out of joints. Since more than 70% of the pipes are ductile iron pipes for both cities, it is suggested that the joint is the weakest part of the ductile iron pipe. This trend can be further confirmed with the data of Nishinomiya City, for which it was possible to differentiate the breakage data in terms of pipe material

and break mode. Figure 7 shows that the majority of the ductile iron pipes failed in slip-out mode, whereas for the cast iron pipes, more failures occurred in the fracture or bending mode than in slip-out mode. This might be expected, since a cast iron pipe is more brittle than a ductile iron pipe.

Correlation between break rate and pipe diameter

Correlation between the break rate and the pipe diameter may be indicative of the break mechanism of the pipe. Katayama (1980) examined the correlation for the 1978 Off-Miyagi earthquake in northeast Japan and O'Rourke et al.

Fig. 6. Break rate with respect to break mode of all types of pipe for Kobe City and Nishinomiya City.

Fig. 7. Break mode for ductile iron pipe (DIP) and cast iron pipe (CIP) for Nishinomiya City.

(1992) examined the correlation for the 1989 Loma Prieta earthquake. The trend shown by Katayama indicates a decrease in the break rate as the diameter increases for steel and asbestos cement pipes. However, no discernible trend could be found for the ductile iron or cast iron pipes. O'Rourke examined the effect of diameter on the repair rate of the cast iron pipes in the Marina District of San Francisco, which is an area about 4 km² that suffered from extensive liquefaction. There, the degree of damage is given by "repair rate," which is the number of repairs per unit length of pipe. In this paper, the repair rate and the break rate are assumed as the same and are used interchangeably. O'Rourke showed that the repair rate is a linear function of the logarithm of a nomi-

Fig. 8. Break rate of cast iron pipe versus pipe diameter for Nishinomiya City.

nal diameter, where the slope of the linear regression line is approximately -3 . This means that the break rate is inversely proportional to the cube of the pipe diameter. Since the moment of inertia of a thin-walled pipe is a function of the cube of the diameter multiplied by the thickness and since the variation in thickness is smaller than that of the diameter, the major mechanisms of the breakage may thus be attributed to longitudinal bending.

The correlation between the break rate and the pipe diameter for the Hyogo-ken Nanbu earthquake is examined for Kobe City and Nishinomiya City. For Kobe City no discernible trend was found, which may be due to the fact that the break rate could not be differentiated in terms of material types of pipe, mode of break, nor the intensity of ground deformation. For Nishinomiya City it was possible to differentiate the breakage data in terms of pipe material and break mode. A relatively clear trend can be seen in Fig. 8 between the pipe diameter and the break rate for the fractured or bent cast iron pipe. The slope of the linear regression curve is -3.1 , which is similar to that found by O'Rourke. However, no significant trend can be seen for the cast iron pipe or the ductile iron pipe damaged in slip-out mode, as shown in Figs. 8 and 9. This can be explained by the fact that these joints are not rigidly connected with bolts and basically do not carry axial load. Therefore, the slip-out is likely controlled by the magnitude of the ground deformation. In the case of the ductile iron pipe, the number of breaks due to bending and fracture is considered to be too low to determine a correlation with the diameter.

Correlation between break rate and pipe material

Types of pipe materials used in the four cities are shown in Fig. 10, where it is shown that the majority of the pipe is ductile iron pipe. The break rates for the three cities with respect to pipe material are compared in Table 6. Data from other cities were not available. It should be noted that the comparison ignores differences in the degree of ground deformation. Therefore, further data reduction is required as

Fig. 9. Break rate of ductile iron pipe versus pipe diameter for Nishinomiya City.

more detailed data of ground deformation and locations of pipes become available. Bearing this in mind, Table 6 indicates that the ductile iron pipe has performed better than other types of pipe. This trend is consistent with the findings of Katayama (1980), O'Rourke et al. (1985), and Laughlin (1995), indicating distinctively higher break rates with the cast iron pipe than with the ductile iron pipe. Significant differences in breakage of asbestos cement pipe among the cities may be due to localized large ground deformations.

Correlation between break rate and peak horizontal acceleration

The correlation between the break rate and the peak acceleration was established for the 1971 San Fernando earthquake (Richter magnitude 6.6) by Katayama et al. (1977), as shown in Fig. 11. The break rate was taken by dividing the 15 km by 7 km area into a uniformly sized narrow strip of 480 m by 15 km (7.2 km²). In the case of the 1978 Off-Miyagi earthquake, however, no significant correlation was identified between the break rate and the peak acceleration (Katayama 1980). A similar correlation is examined for the damage that occurred in the 1995 Hyogo-ken Nanbu earthquake. From the approximate iso-acceleration contours of peak horizontal acceleration data shown in Fig. 1, the break rate of each city is plotted against the range of peak accelerations of the corresponding city as shown in Fig. 11. The results show a trend of increase in break rate as the peak acceleration increases. Since the break rates fall below the curve given by Katayama et al. (1977) for the 1971 San Fernando earthquake, it is implied that the damage, in terms of the break rate, resulting from this earthquake is less severe than that of the 1971 San Fernando earthquake. However, it must be noted that for the same peak acceleration and the same pipe, different break rates may result depending on the size of the damage assessment area.

Restoration of water service

Not only mitigation of damage but also efficient restoration

Fig. 10. Type of pipe used in four cities in Hanshin area.

Table 6. Break rate with respect to pipe material.

Pipe material	Break rate (breaks/km)		
	Amagasaki	Itami	Nishinomiya
Ductile iron	0.08	0.07	0.45
Cast iron	0.49	1.07	2.22
Asbestos cement	14.24	0.19	3.27
Steel	0.42	—	0.21
Plastic	0.57	—	1.67

of the water supply is crucial in crisis situations. The restoration of water service took significant time and personnel. Approximately 6–7 weeks were needed for the service to be fully restored in Kobe City and Nishinomiya City. During the course of outage, water was distributed to the consumers by water trucks. The number of water trucks deployed in Kobe City and Nishinomiya City reached a maximum of 420 and 160, respectively, 1–3 weeks after the earthquake.

Repair of water mains

Repair of water mains was performed by initially supplying water to a block of the network near the distribution reservoirs. According to the city officials, the methods of leak detection were based on observation of water to the surface or by detection of noise. Once the block was examined and minimum repair jobs were completed, the process was repeated further downstream from the distribution reservoirs. By early February, Kobe City had investigated the damage to water mains by supplying water to 40% of the consumers, finding 2200 breaks in the distribution mains and service lines and leakage rate of 200 000 m³/d.

A number of factors complicated the progress of restoration. It was difficult to use acoustic-detection methods owing

Fig. 11. Break rate of cities in Hanshin area versus peak acceleration.

Fig. 12. Restoration of water service of Kobe City and Nishinomiya City.

Table 7. Personnel help received from other cities.

City	Total No. of breaks	Person-days	Person-days/break
Kobe	15 443	8 730	0.57
Nishinomiya	68 024	36 048	0.53

to significant noise of repair and demolition of other structures. Numerous pipe breaks lowered the water pressure that is required for the leak detection. Communication between city officials at different stations, government offices, and repair crews was difficult, since the emergency telecommunication system could not be used because of the collapse of the head office in the City Hall and the saturated use of tele-

Fig. 13. Restoration status of water, gas, and power services.

phones (Kobe Municipal Water Works Bureau 1995). Transportation of repair crews was difficult, since roads were blocked by debris of collapsed buildings and houses, toppled telephone and power poles, and electric wires. Even after the roads became passable in a few days, they were clogged with traffic since other main highways and expressways were damaged, diverting the traffic to the local roads. Access to valves was difficult owing to damage of residential houses. Because of time limitation and difficulties in the repair jobs, minor damages have likely not yet been found even though the service is fully restored. The recovery rates of service for Kobe City and Nishinomiya City are shown in Fig. 12.

For Kobe City and Nishinomiya City, the number of repair crews received from other cities reached a maximum of 1000 and 300, respectively, 3–5 weeks after the earthquake. The approximate total personnel and labour (person-days) per break is shown in Table 7, assuming 6 working days per week. It is found that the labour per break is approximately the same for the two cities.

The rates of restoration of three public utilities in the Hanshin area are presented in Fig. 13. The figure shows that the restoration of water service is time consuming compared to that of power lines. Restoration of the power line is relatively fast, since power cables in Japan are aboveground on utility poles, and therefore damage can be readily identified and accessed. Restoration of the gas lines is the slowest, since no leak is permitted for safety reasons, and at a number of locations water and soil were found inside the pipe which must be thoroughly cleaned. It is reported that 9800 personnel worked over 2 months to restore the gas system.

Performance of earthquake-proof pipes and joints

An earthquake-proof joint refers to a joint designed to absorb relatively large ground deformations by permitting extension, contraction, and rotation. This type of joint is used in series to act as a flexible chain rather than by single segment. The joints are classified as S, S-II, and US types according to the

The liquefaction threat exists mainly for the thick layer of sand. For a design acceleration of 0.2g, sand layers and silty sand layers with mean strength in this area may liquefy to a depth of 8 and 5 m, respectively. Hence, relatively high break rates may be expected for water mains in this area.

Flexibility of joints is also an important factor. Many stiff joints, such as cement caulking joints, failed in the 1994 Northridge earthquake, whereas ductile iron pipes with rubber gasket performed better (Laughlin 1995). In the Hyogo-ken Nanbu earthquake, no damage was found to earthquake-proof pipes which provide flexibility at the joints and a locking mechanism to prevent slip-outs. Use of such joints or modification of current joints may be valuable in the critical lines.

Summary

The major significance of this study is to raise awareness of the potential problems due to disruption of water service and to promote studies to improve understanding of what may happen and what can be done to mitigate the damage and optimize restoration of the service.

In the 1995 Hyogo-ken Nanbu earthquake, lack of water was a serious problem in fighting fires, supplying homes and industries, and treating patients in hospitals in Kobe City. This is largely due to the failure of the two transmission lines from Yodo River and due to the extensive water main damage within the city. Power outage and damage to reservoirs and treatment plants were less severe and are not the direct cause of the widespread loss of water service. Restoration was hampered by the loss of water pressure required to find the location of damage. Failures of other lifeline systems such as communication system and transportation roads caused delay in the restoration of the water service as well.

Approximately 15% of the distribution reservoirs had emergency shutoff valves which performed successfully in saving water. However, water in the other distribution reservoirs quickly drained through the leaking pipes because the reservoirs are located at relatively high elevations. The earthquake-proof pipes used in the three cities did not sustain any damage and were shown to be effective.

Although a quantitative assessment of pipe damage was subject to limitations arising from lack of local break data and ground condition details, damage characteristics in terms of pipe material, pipe diameter, break modes, and peak acceleration appear to be consistent with those found in the past earthquake studies. Also, the severity of damage observed in this earthquake is not particularly high in terms of the break rate.

Performance of water service in the case of a strong earthquake may be measured in terms of serviceability immediately after the earthquake and the efficiency of restoration. As is understood from the past earthquake experiences, it is important to prioritize the different needs of water supply and develop an integrated fail-safe system which ensures service to critical needs immediately after the earthquake. Efficiency of the restoration depends not only on the water distribution system, but also on telecommunication, electric power, and transportation systems. Dependence of restoration of water service on other lifeline systems must also be assessed. Critical water mains which govern the service to many consumer blocks should be resistant to strong earth-

quakes. It is especially necessary to carefully consider the seismic behaviour of collateral systems such as soil liquefaction and settlement of structures to which the pipes are attached.

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Fig. 14. S-type earthquake-proof joint (Japan Ductile Pipe Association 1995). **Table 8.** Earthquake-proof joints and pipes used in three cities.

City	Total length of distribution mains (km)	Length of earthquake-proof joint and pipe (km)	Percentage of earthquake-proof joint and pipe (%)	Location of usage
Kobe	3963	237	6	Reclaimed land
Ashiya	184	13	7	Reclaimed land
Nishinomiya	966	23	2	Reclaimed land

Japanese Industrial Standard. For example, allowable displacements of S-type joint is 40–80 mm (1 % of a single pipe segment) and the rotation is 7° for pipes less than 1200 mm in diameter. The cross section of the S-type joint is illustrated in Fig. 14, which shows a locking ring to prevent slip-out failure (Japan Ductile Iron Pipe Association 1995). The extent of usage of these pipes is shown in Table 8 for the three cities, Kobe, Ashiya, and Nishinomiya. In all three cities, no damage was found to these pipes and joints.

Implications for seismic damage to water mains in Canada

The seismicity in Canada, as specified in the National Building Code of Canada (NBCC 1990, Commentary J), stipulates a maximum design peak ground acceleration of 0.4g for portions of British Columbia, although higher peak accelerations can be expected. Seismic damage assessment of the Vancouver area is of particular importance, since it is highly populated and industrialized. While the NBCC design acceleration for Vancouver is 0.2g, locally higher accelerations up to possibly 0.4g can be expected under certain soil and site conditions. The acceleration, 0.4g, is comparable to the lower range of peak accelerations measured in the Hanshin area during the Hyogo-ken Nanbu earthquake. The break rate found in this earthquake for 0.4g acceleration is between 0.1 and 1.0 breaks/km.

It has been found in this earthquake and in the past earthquakes (Katayama 1980; O'Rourke et al. 1985; Laughlin

1995) that the break rate of brittle pipes such as cast iron pipes is distinctively higher than that of ductile iron pipes. The break rate of cast iron pipes found in the Hyogo-ken Nanbu earthquake varies from 0.5 to 2.2 breaks/km. However, past data of break rate indicate that the break rate of cast iron pipes can exceed 10 breaks/km in areas where large ground deformations have occurred. Since approximately 1000 km (73% of the total) of Vancouver city's distribution mains are relatively old cast iron pipes (McDonald et al. 1994), special attention must be paid to these vulnerable pipes in assessing seismic damage.

Pipe damage due to liquefaction, land slides, or settlement due to earthquakes have been studied in the past. High correlation between settlement and the number of pipe repair was found in the case of the 1989 Loma Prieta earthquake (O'Rourke et al. 1992). Based on the past four earthquakes (1964 Niigata, 1971 San Fernando, 1983 Nihonkai Chubu, and 1989 Loma Prieta), local break rates in liquefied areas are between 3.0 and 5.0 breaks/km (Eguchi 1983; Miyajima and Kitaura 1991; O'Rourke et al. 1992). Although local break rates in the liquefied areas in the Hyogo-ken Nanbu earthquake are unknown, pipe breaks tended to concentrate in these areas. For the Greater Vancouver area, liquefaction potential in the Fraser River delta was assessed based on results of standard penetration tests (Rainer et al. 1990). Typical deposit layers of this delta are a surficial thin layers of clays silts, sand deposits about 45 m, silt clay deposits about 200 m, glacial deposit about 100 m, and bedrock. The water table in this area is within 1 m of the ground surface.