SEISMIC VULNERABILITY INDEX FOR LIFELINE FACILITIES

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ABSTRACT :

A simple index, vulnerability factor (V-factor), is introduced for evaluation of seismic vulnerability of lifeline network facilities. In widely-used statistical models for estimation of number of pipe breaks and joint failure in the event of earthquakes, correction factors are defined to represent relative vulnerability with respect to various pipe diameters, pipe materials, and joint types. Such correction factors are averaged over the entire networks on the basis of extended length of pipelines classified by pipe diameter, pipe material, and joint type. Applications are shown for water delivery systems in Japan. The nation-wide distribution of the V-factor demonstrates a significant diversity in terms of seismic vulnerability. Reduction of vulnerability in the ten-year period after the South Hyogo prefecture (Kobe) Earthquake in 1995 is also quantified. On the average, pipe damage is expected to be reduced by 20-25% compared to pre-Kobe event situation when exposed to the same level of ground motion.

KEYWORDS: lifeline, vulnerability factor, pipe breaks, pipe material, joint type, diameter

1. INTRODUCTION

In large cities, several thousands kilometers of lifeline network facilities spread over expanded urban areas. Because of the huge stock, the majority of lifeline network facilities remain non-seismic resistant and therefore highly vulnerable to strong ground motions and large ground deformation. In major events, repair works of a number of pipe breaks and joint failures are always the main cause of time-consuming restoration process. From the viewpoint of seismic risk management and asset management, it is of great importance to evaluate seismic vulnerability of existing lifeline network facilities. However, unlike building structures whose seismic design code was dramatically changed in 1981 in Japan, there are almost no distinctive criteria to address overall vulnerability of lifeline networks.

With this background, this study introduces a simple index, vulnerability factor (V-factor) for convenient evaluation of seismic vulnerability of lifeline network facilities. The proposed method is based on statistical models for estimation of number of pipe breaks and joint failure in the event of earthquakes. The estimation formulas define correction factors representing relative vulnerability with respect to pipe diameters, pipe materials, and joint types. Section 2 describes the common concept of the statistical model and a specific set of correction factors employed in this study. Section 3 describes the detailed and simplified methods to evaluate the V-factor. The correction factors are averaged over the entire networks on the basis of extended length of pipelines classified by pipe diameter, pipe material, and joint type. Section 4 presents practical applications for water delivery systems in Japan. Statistical distributions, ranges, and central values of the V-factors are shown. The nation-wide spatial distribution of the V-factors is also shown to demonstrate a significant gap in seismic vulnerability. Section 5 examines the annual change of the average V-factors all across Japan, in other words, the progress of seismic improvement in terms of reduced V-factors.

2. STATISTICAL MODEL FOR ESTIMATION OF PIPELINE DAMAGE

Statistical method is widely used for estimation of damage to lifeline networks subjected to strong ground shaking and ground deformations. Typical method for estimating number of pipe breaks and joint failure is to multiply extended length of pipeline by damage rate representing the average number of pipe breaks and joint failure per unit length.

$$N = L \cdot R_{fm}(x) \tag{2.1}$$

where N : number of pipe breaks and joint failure, L : extended length of pipeline (km), x : ground motion parameter such as PGA (peak ground acceleration), PGV(peak ground velocity), or SI (spectral intensity), and $R_{fm}(x)$: damage rate (breaks/km). Damage rate $R_{fm}(x)$ is given by the following equation.

$$R_{fm}(x) = C_d \cdot C_p \cdot C_g \cdot R_f(x) \tag{2.2}$$

where $R_f(x)$: standard damage rate (breaks/km) as a function of ground motion parameter x , C_d : correction factor for pipe diameter, C_p : correction factor for pipe material/joint type, C_g : correction factor for ground and liquefaction. As mentioned later, standard damage rate $R_f(x)$ (breaks/km) is defined for a combination of a particular type of pipe material, joint, and pipe diameter on the basis of damage statistics from past earthquakes.

Although the framework of Eqns. (2.1) and (2.2) are common to various models of statistical estimation methods, different models have different sets of correction factors and standard damage rate function. Table 2.1 shows an example of the correction factors suggested by Takada et al. (2001) on the basis of damage data from the Kobe event. In this study, Eqns. (2.1) and (2.2) and Table 2.1 were employed to show practical examples in sections 4 and 5.

The base case, to which the correction factor=1 is assigned, is cast iron pipe (CIP) with diameter of ϕ100-150mm. As for pipe diameter, seven categories are considered. The least value of the correction factor for pipe diameter C_d is 0.20 for ϕ1100mm or larger, and the largest value is 1.60 for ϕ75mm or smaller. As for pipe material/joint type, seven categories are considered. The least value of the correction factor for pipe material/joint type C_p is 0.0 for ductile cast iron pipe (DIP) with aseismic joint (type S and S-II equipped with mechanics to prevent pulling-out due to large ground strain and/or deformation), and the largest value is 4.0 for screw joint steel pipe (SGP).

Table 2.1 Correction factors C_d and C_p for water delivery pipeline (modified from Takada et al. (2001))

Diameter (mm)	Factor C_d
-ϕ75	1.6
ϕ100-150	1.0
ϕ200-250	0.9
ϕ300-450	0.7
ϕ500-600	0.5*
ϕ700-1000	0.4#
ϕ1100-	0.2#

Pipe material/joint type	Factor C_p
CIP : Cast Iron Pipe	1.0
DIP : Ductile Cast Iron Pipe (Standard joint : Type A, K, and T)	0.3
DIP : Ductile Cast Iron Pipe (Aseismic joint: Type S and S-II)	0.0
SP : Welded-joint Steel Pipe	0.3*
SGP : Screw-joint Steel Pipe	4.0*
VP : Polyvinyl Chloride Pipe	1.0
ACP : Asbestos Cement Pipe	2.5*

* Takada et al. (2001) points out that marked results may be unreliable due to statistical insufficiency.

The original table does not give factors for ϕ700mm or larger. Therefore, correction factors were assigned with reference to Non-Life Insurance Rating Organization of Japan (1998).

3. EVALUATION METHOD OF VULNERABILITY FACTOR (V-FACTOR) OF PIPELINES

3.1 Detailed method

The total number of pipe breaks and joint failure estimated using Eqn. 2.1 contains three major contributors: amount of facility (= length of pipeline L), vulnerability (= pipe diameter and material/joint type C_d and C_p), and hazard (= severity of ground motion x and ground condition C_g). Paying particular attention to the vulnerability term, Suzuki et al. (2003) proposed a simple index termed "vulnerability factor (**V-factor**)" to quantify relative vulnerability of buried pipeline of lifeline networks. As Eqn. 3.1 shows, the V-factor is evaluated by averaging the correction factor for pipe material and joint type C_p and the correction factor for pipe diameter C_d over the entire network with the weighting factor of corresponding length of pipeline.

$$V = \frac{\sum_i \sum_j C_{d_i} C_{p_j} L_{ij}}{\sum_i \sum_j L_{ij}} \tag{3.1}$$

where C_{d_i} : correction factor for pipe diameter i, C_{p_j} : correction factor for pipe material/joint type j, L_{ij} : extended length of pipeline with pipe diameter i and pipe material/joint type j.

When correction factors in Table 2.1 are applied, the theoretical range of the V-factor is from 0 to 6.4. Obviously larger value of the V-factor indicates higher vulnerability. The V-factor can also be interpreted as a relative failure rate under the hypothetical condition where the entire pipelines are exposed to a uniform seismic loading. The original aim of the vulnerability factor by Suzuki et al. (2003) was to modify the evaluation model for post-earthquake serviceability of utility lifelines solely on the basis of seismic intensity distribution (Nojima et al., 2003) in the light of relative difference in vulnerability of network systems.

3.2 Simplified method

Evaluation of Eqn. 3.1 requires extended length of pipeline L_{ij} with respect to all the combination of pipe diameter i and pipe material/joint type j. Even though such detailed data can be obtained through in-depth investigation to a particular network system, exhaustive collection from many systems is still difficult. On the other hand, extended length of pipeline independently categorized into pipe diameter and pipe material/joint type tends to be available from official statistics of inventory data. In this study, simplified vulnerability factor V_{pd} evaluated on the basis of two independent vulnerability factors for pipe diameter and pipe material/joint type is proposed (Nojima, 2008).

$$V_{pd} = V_d \cdot V_p \approx V \tag{3.2}$$

$$V_d = \frac{\sum_i \left(C_{d_i} \sum_j L_{ij} \right)}{\sum_i \sum_j L_{ij}}, \quad V_p = \frac{\sum_j \left(C_{p_j} \sum_i L_{ij} \right)}{\sum_i \sum_j L_{ij}} \tag{3.3), (3.4}$$

where V_d : vulnerability factor for pipe diameter, V_p : vulnerability factor for pipe material/joint type, $\sum_j L_{ij}$: extended length of pipeline with pipe diameter i, $\sum_i L_{ij}$: extended length of pipeline with pipe material/joint type j.

The simplified method remarkably enhances the applicability of the concept of the V-factor because of high availability of required data, and allows one to perform various comparisons from the viewpoints of both spatial distribution and temporal change. In the following two sections, the simplified V-factors for water delivery systems in Japan are evaluated over the country.

4. EVALUATION OF V-FACTOR OF WATER DELIVERY SYSTEMS IN JAPAN (FY 2005)

4.1. Water Supply Statistics, fiscal year of 2005

The proposed method of evaluating the simplified V-factor was applied to 1,062 water suppliers compiled in the "Water Supply Statistics, fiscal year of 2005" (Japan Waterworks Association, 2007). In the statistics, pipe material/joint types are 13-fold: cast iron pipe (CIP), ductile cast iron pipe (DIP) with standard/aseismic joint, steel pipe with welded-joint (SP) and screw-joint (SGP), asbestos cement pipe (ACP), polyvinyl chloride pipe (VP), concrete pipe (CP), lead pipe (LP), polyethylene pipe (PP) with standard/aseismic joint, stainless steel pipe (SSP), other pipes. As for pipe material/joint types that correction factors are not assigned to in Table 2.1 (CP, PP, SSP, and others), extended lengths are short enough to be omitted in evaluating the V-factor.

Pipe diameters are six-fold (ϕ300mm or smaller to ϕ2000mm or larger) for aqueduct and water transmission line and 25-fold (ϕ50mm or smaller to ϕ2000mm or larger) for water distribution line (water main and branch line). In this study, extended lengths for each pipe diameter are recompiled to be consistent with Table 2.1 in order to apply the corresponding correction factors.

4.2. V-factors for water distribution lines

The simplified V-factors were evaluated for aqueducts, water transmission lines and water distribution lines (including both water mains and branch lines) of 1,602 water suppliers (Nojima, 2008). In this paper, only a part of the results for water distribution pipe are shown below. First, the histogram of the extended lengths of water distribution lines, which reflects the size of the water suppliers, and the spatial distribution of those are shown in Figure 4.1 and 4.2, respectively. Obviously, the water suppliers in Japan show diversity in their size ranging from several kilometers to over 25,000 km.

Next, V_d, V_p, and $V_{pd}\,(=V_p \cdot V_d)$ in Eqns. 3.3, 3.4, and 3.2, respectively, were evaluated for all the suppliers. Histogram of the simplified vulnerability factors V_{pd} of water distribution lines and the spatial distribution of those are shown in Figure 4.3 and 4.4, respectively. Major findings are as follows:

1) The nation-wide average value of the V-factor for pipe diameter V_d is 1.173. Its main range is 0.6 (from 0.9 to 1.5) except for some outliers.
2) The average of the V-factor for pipe material/joint type V_p is 0.677. Its main range is 1.3 (from 0.3 to 1.6) except for some outliers.
3) The wider range of V_p than that of V_d suggests that the difference in pipe material/joint type has more significant effect on vulnerability factor of water delivery systems than that in pipe diameter.
4) The average of the simplified V-factor V_{pd} is 0.795. Its main range is 1.6 (from 0.3 to 1.9) except for some outliers. Such a wide range of V_{pd} indicates significant gap among water suppliers in terms of aseismic performance.
5) Water suppliers of large size tend to have small value of V_{pd}, which indicates less vulnerability.

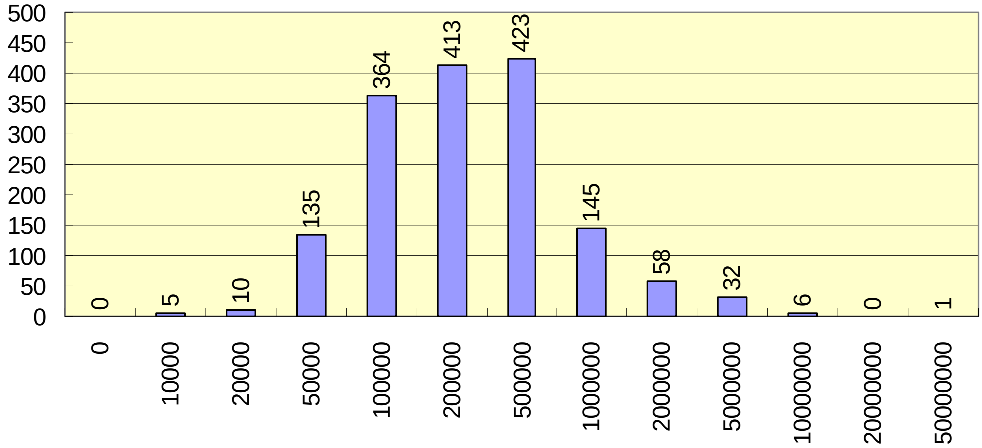

Figure 4.1 Histogram of extended length of water distribution lines (m)
(horizontal axis reads "up to the value")

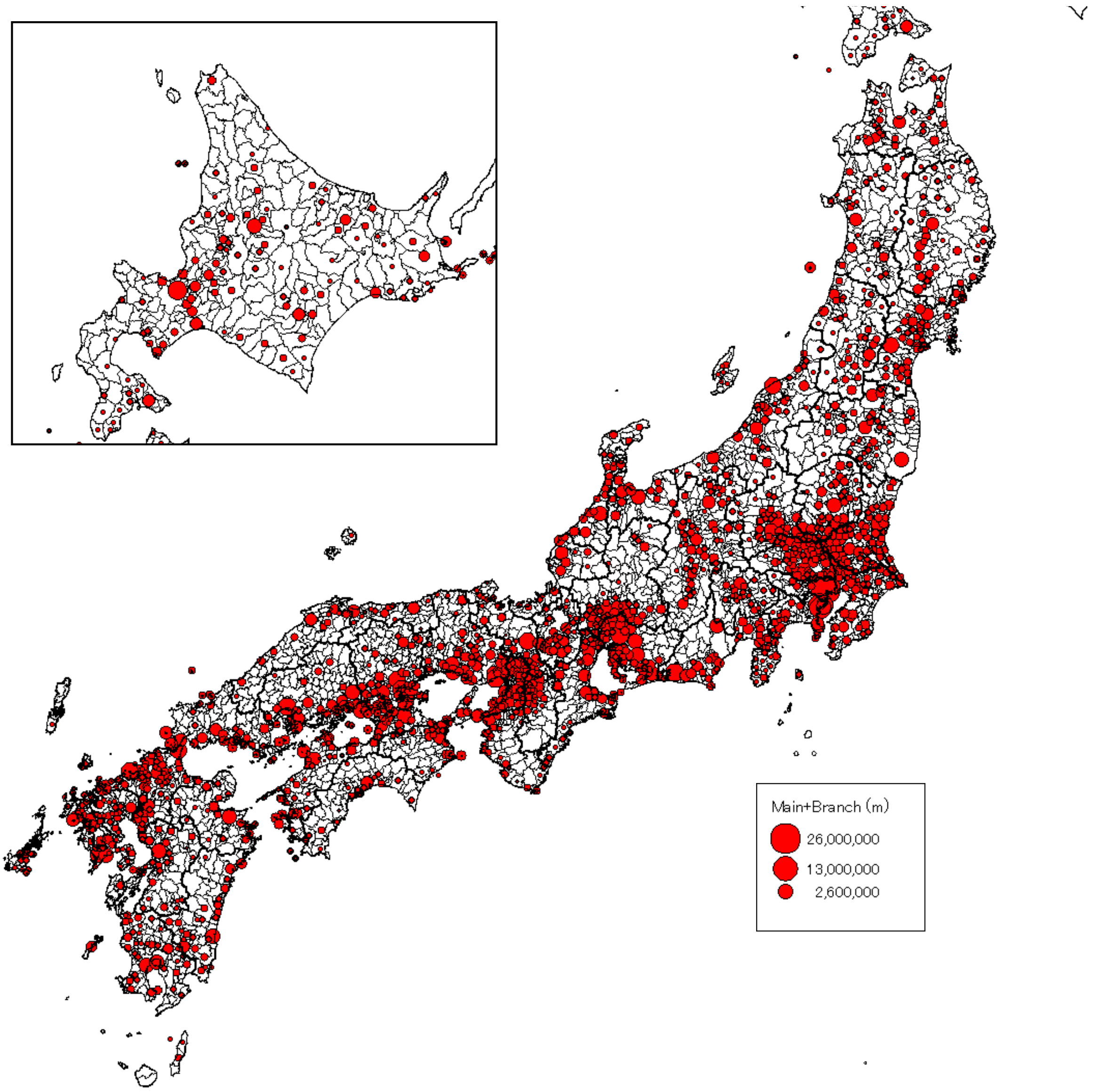

Figure 4.2 Spatial distribution of extended lengths of water distribution lines in Japan

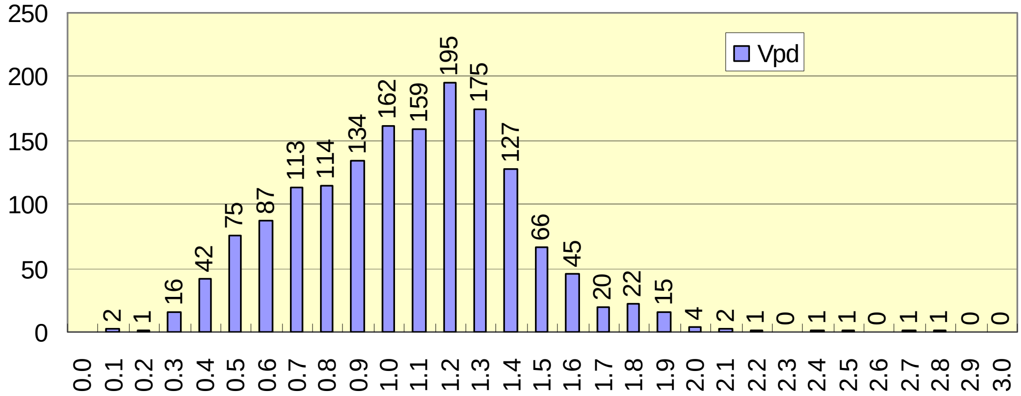

Figure 4.3 Histogram of $V_{pd}\,(=V_p \cdot V_d)$ (horizontal axis reads "up to the value")

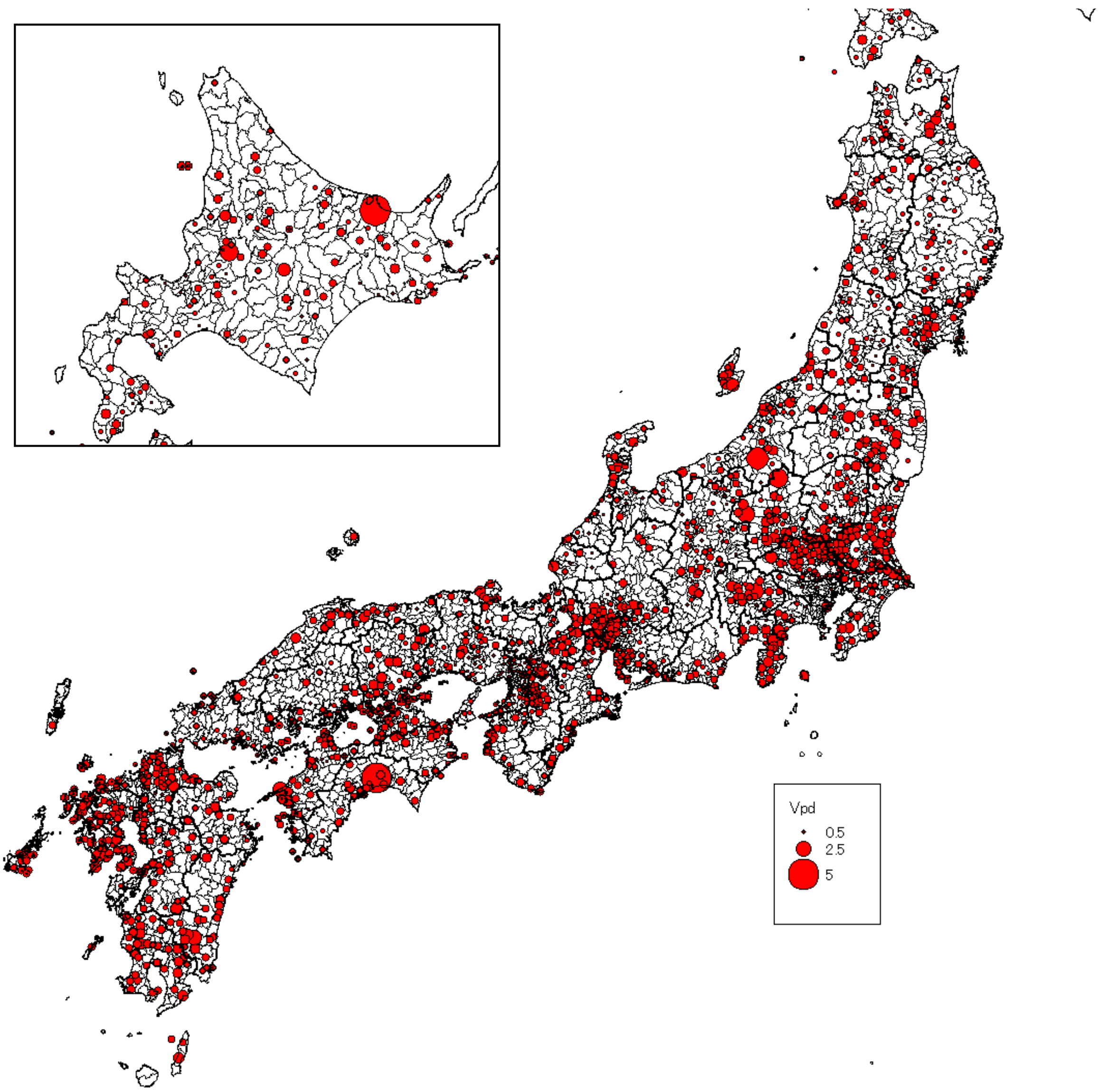

Figure 4.4 Spatial distribution of the simplified V-factor $V_{pd}\,(=V_p \cdot V_d)$ in Japan

5. ANNUAL CHANGE OF V-FACTOR OF WATER SUPPLY SYSTEMS (FY 1994-2005)

One of those frequently asked questions is such as "Have lifeline systems in Japan become earthquake resistant after the South Hyogo prefecture (Kobe) Earthquake in 1995?" To answer this question, "Water Supply Statistics" for FY 1994-2005 published in the past twelve years (Japan Waterworks Association, 1996-2007), were surveyed (Nojima, 2008). During this period, changes of extended lengths of major pipe material/joint types of water distribution branch lines are as follows:

1) Ductile iron pipe (DIP) with standard joint increased from 199,000 km to 275,000 km.
2) Ductile iron pipe (DIP) with aseismic joint increased from 9,300 km to 26,600 km.
3) Asbestos cement pipe (ACP) decreased from 49,000 km to 13,000 km.
4) Polyvinyl chloride pipe (VP) increased from 149,000 km to 186,000 km.

The statistics indicates that pipe material/joint types have been gradually improved. In order to quantify the recent progress of decreasing vulnerability, the annual change of the simplified V-factor V_{pd} was examined. Here, aseismic joint had not been distinguished from standard joint for steel type and polyethylene pipe on the statistics up until 2004. Since polyethylene pipe is omitted in this study, the following two cases were compared in this study.

Case A: Consider the ratio of aseismic joint of steel pipe as in the same level as 2005.
Case B: Consider the ratio of aseismic joint of steel pipe as zero.

Figure 4.5 shows the annual change of the simplified V-factor V_{pd} of water distribution pipe in all the water suppliers during the period of the fiscal year 1994-2005. It is obvious that the V-factor has been constantly decreasing. The changes during the full period (11 years of FY 1994-2005) and port-Kobe event period (10 years of FY 1995-2005) are summarized as follows:

Case A :	FY 1994-2005 (11 years)	1.041 to 0.795 (76.3%)
	FY 1995-2005 (10 years)	1.004 to 0.795 (79.1%)
Case B :	FY 1994-2005 (11 years)	1.084 to 0.795 (73.3%)
	FY 1995-2005 (10 years)	1.045 to 0.795 (76.0%)

Some of such achievement may attribute to planned efforts of seismic improvement. However, replacement of deteriorated pipeline, which is not necessarily intended for seismic improvement, also contributes to reducing the V-factor. For effective reduction of network vulnerability, it is an important consideration to associate renovation of existing facilities with seismic improvement.

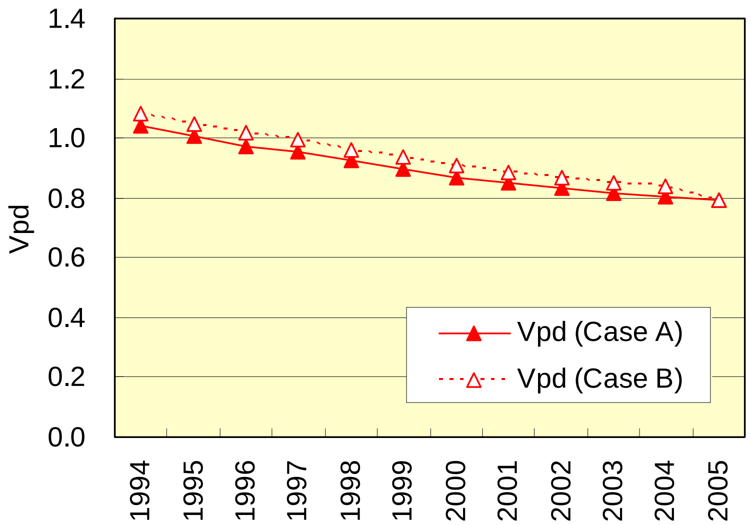

Figure 4.5 Annual change of the simplified V-factor V_{pd} during FY 1994-2005

CONCLUDING REMARKS

Major results derived from this study are summarized as follows:

1) A simplified vulnerability factor "V-factor," was proposed for evaluation of relative vulnerability of lifeline networks. The model employs correction factors defined in statistical models for estimation of number of pipe breaks and joint failure. The correction factors with respect to various pipe diameters, pipe materials, and joint types are averaged over the entire networks.
2) Practical examples were shown for water delivery systems in Japan. By employing correction factors proposed by Takada et al. (2001), the V-factors of water distribution lines were compared across the country. The nation-wide spatial distribution of the V-factor demonstrates a significant gap of seismic vulnerability among water delivery systems.
3) Reduction of the simplified V-factor in the past twelve years was quantified. The V-factor is a parameter proportional to damage rate and total number of pipeline damage for the same hazard level. Therefore, if we are asked "After the Kobe event of 1995, how resistant have water delivery pipeline networks become?" we may answer in this way: "On the average, compared to the pre-Kobe event level, we have come to the position that we can decrease pipeline damage by 20 to 25%."

Obviously the status quo is not satisfactory. However, the achievement in the past twelve years is indispensable for the way to go beyond. There may not be an apparent goal for seismic improvement of facilities. However, the V-factor is considered as a useful index for tracking past efforts and also setting a practicable and numerical target for seismic improvement of lifeline network facilities.

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