# SEISMIC DAMAGE PREDICTION OF WATER SUPPLY SYSTEM WITH PML INDEX

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## ABSTRACT

The numerous major earthquakes such as the Great Hanshin-Awaji earthquake, Nigata-Chuetsu earthquake caused substantial casualties and property damages. Private companies/public utility enterprises should provide disaster reduction investment as part of risk management and prepare a strategic Business Continuity Plan. The significance of the Business Continuity Plan has been increasingly important in the connection of corporate social responsibility. This study focuses on the seismic risk analysis of the existing water supply system. The probable maximum loss index is employed to evaluate the seismic risk. An alternative method is proposed to evaluate Probable Maximum Loss index of the high order water supply network system.

**Keywords:** water supply system, seismic risk analysis, probable maximum loss

## 1. INTRODUCTION

The numerous major earthquakes such as the Great Hanshin-Awaji earthquake, Nigata-Chuetsu earthquake caused substantial casualties and property damages. Private companies/public utility enterprises should provide disaster reduction investment as part of risk management and prepare a strategic Business Continuity Plan. The significance of the Business Continuity Plan has been increasingly important in the connection of corporate social responsibility (Hoshiya & Yamamoto 2005).

This study focuses on the seismic risk analysis of the existing water supply system. Water supply system may be modeled as a network that consists of supply nodes (purification plants), demand nodes (pumping stations and service reservoirs) and links (buried pipes). It may be postulated that water can be supplied to a demand node as long as this node is connected at least to either one of supply nodes, and each demand node is connected to and is in charge of the corresponding supply area of a lower network. It is also postulated that links are subject to seismic risk and they have probability of two events, failure or success, whereas nodes are modeled as a system of components

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such as motors, water pipes, electric systems and so forth. Each component has probability of failure or success, and because of the combination of plural component probabilities, failure of a node system has different failure modes, and their probabilities must be evaluated, for example, by the event tree analysis.

In this research, probable maximum loss index is employed to evaluate the seismic risk of a lower network. An alternative method is proposed to avoid the complicated event tree analysis and evaluate probable Maximum Loss index of the high order water supply network system. Then a numerical analysis is carried out to demonstrate the efficiency of the proposed method.

## 2. STOCHASTIC MODEL OF PIPELINE FAILURE

In this research, we will use the Map Info as a data management tool, all information treated as mesh data with (500m x 500m). A water supply system in a blank City in the vicinity of Tokyo is employed as a numerical example in Figure 1. The stochastic earthquakes $E_q$ in fifty years that influence the water supply network and the data are downloaded from the data base of J-SHIS (National Research Institute for Earth Science and Disaster Prevention, Japan 2005. Figure 1 shows a water supply area with 500m square meshes. Figure 2 shows a peak ground velocity (stochastic earthquake: probability of an earthquake excess in fifty years=0.1).

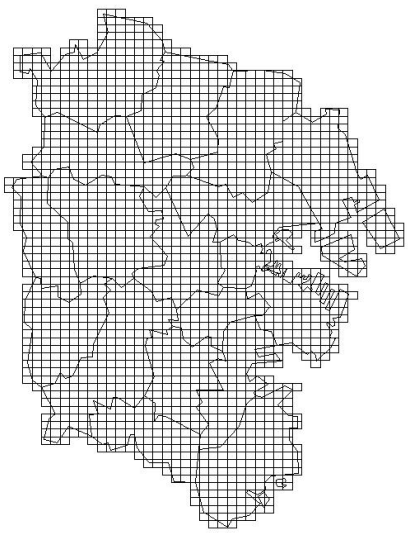

Figure 1. Water Supply Area

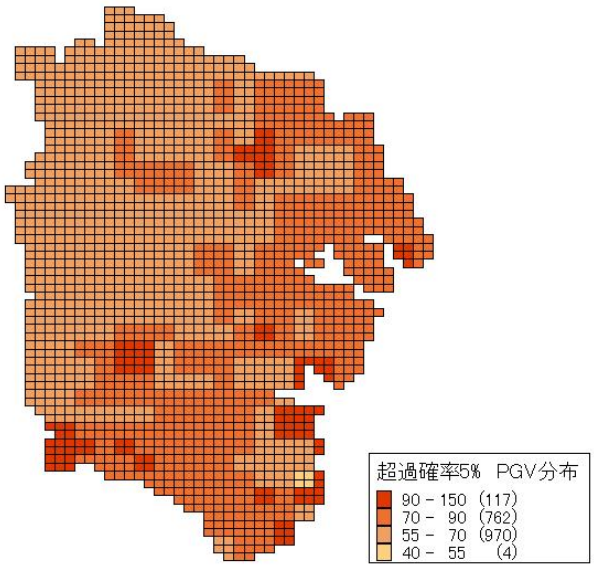


Figure 2. Peak Surface Ground Velocity

Probability of failure $PF_{j,i}$ of j th pipe characteristics, categorized as pipe material, pipe diameter in i th mesh conditioned on the stochastic earthquake is evaluated based on the average damage rate $n_{j,i}$ (total number of damage spots / km) which empirical formula is given by

$$n_{j,i} = C_p \times C_d \times C_g \times C_l \times R(V) \tag{1}$$

$$R(V) = 3.11 \times 10^{-3} \times (V - 15)^{1.30} \tag{2}$$

where coefficients $C_p, C_d$ , $C_g$ and $C_l$ are associated respectively with pipe material, pipe diameter, surface ground condition and liquefaction(Table.1(a),(b)). $V$ is the maximum ground velocity. Then, damage is assumed to occur along each link being distributed in a Poisson distribution.

Table 1 (a) Pipe material correction coefficients

| Pipe material | Symbol | Correction coefficient $C_p$ |
|---|---|---|
| Asbestos cement | ACP | 3.0 |
| Cast iron | CIP | 1.1 |
| Ductile cast iron | DCIP | 0.3 |
| Steel | SP | 0.5 |

Table 1 (b) Pipe diameter correction coefficients

| Pipe diameter (mm) | Correction coefficient $C_d$ |
|---|---|
| – Φ75 | 1.6 |
| Φ100 – 150 | 1.0 |
| Φ200 – 450 | 0.8 |
| Φ600 – | 0.5 |

Table 1 (c) Ground correction coefficients

| Surface ground | Correction coefficient $C_g$ |
|---|---|
| Modified mountainous region | 1.1 |
| Modified hilly areas | 1.5 |
| Valley, old water routes | 3.2 |
| Alluvial plain | 1.0 |
| Good ground | 0.4 |

Table 1(d) Liquefaction effect correction coefficients

| Hazard level | Correction coefficient $C_l$ |
|---|---|
| No liquefaction | 1.0 |
| Medium liquefaction | 2.0 |
| Significant liquefaction | 2.4 |

$$P_{j,i}(X_{j,i} = x_{j,i}) = \frac{(r_{j,i})^x}{x_{j,i}!} \exp[-r_{j,i}] \tag{3}$$

in which $r_{j,i} = n_{j,i} \times L_{j,i}$ and $L_{j,i}$ is a pipe length of j th pipe in i th mesh. $X_{j,i}$ are damage spots with means $\overline{X}_{j,i} = r_{j,i}$ and variances $\sigma^2{}_{X\,j,i} = r_{j,i}$ .

Let $P(X_{j,i} = x_{j,i}, X_{k,m} = x_{k,m})$ be the joint Poisson probability mass function, having the marginals $P_{j,i}(X_{j,i} = x_{j,i})$ and $P_{k,m}(X_{k,m} = x_{k,m})$ respectively. $P_{j,i}(X_{j,i} = x_{j,i})$ and $P_{k,m}(X_{k,m} = x_{k,m})$ be two Poisson probability mass functions with paremeters $r_{j,i}$ and $r_{k,m}$ respectively.

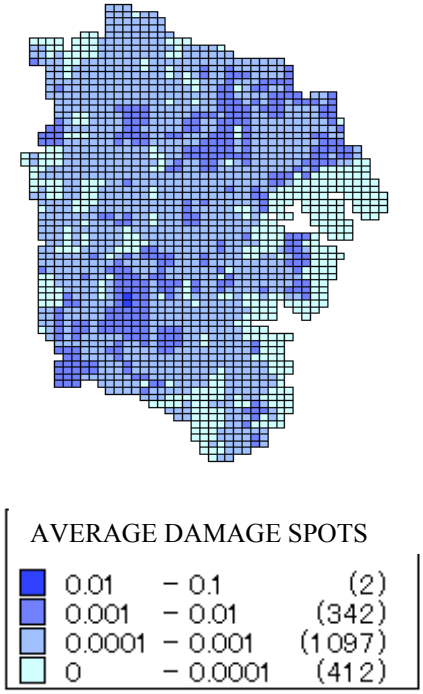


Figure 3. Estimated Average Damage Spots (DIAMETER : BelowΦ75)

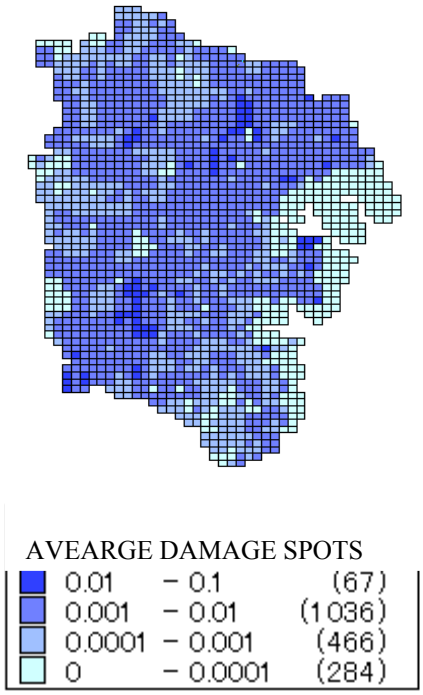


Figure 4. Estimated Average Damage Spots (DIAMETER:Φ100～Φ150)

Lakshminarayana et al. (1999) defined a bivariate Poisson distribution as a product of Poisson marginal with a multiplicative factor. The probability function is given as

$$P^*(X_{j,i}=x_{j,i},\, X_{k,m}=x_{k,m}) = \frac{(r_{j,i})^{x_{j,i}}(r_{k,m})^{x_{k,m}}}{x_{j,i}!\,x_{j,i}!} e^{-(r_{j,i}+r_{k,m})}[1+\alpha(e^{-x_{j,i}}-e^{-r_{j,i}\cdot c})(e^{-x_{k,m}}-e^{-r_{k,m}\cdot c})] \quad (4)$$

Where $c = 1 - e^{-1}$, $\alpha$ is a range factor .

The mean vector is given as

$$E\begin{bmatrix} X_{j,i} \\ X_{k,m} \end{bmatrix} = \begin{bmatrix} r_{j,i} \\ r_{k,m} \end{bmatrix} \quad (5)$$

The covariance matrix is given as follows.

$$COV(X_{j,i},\, X_{k,m}) = \begin{bmatrix} r_{j,i} & \alpha r_{j,i} r_{k,m} c^2 e^{-r_{j,i}c} e^{-r_{k,m}c} \\ \alpha r_{j,i} r_{k,m} c^2 e^{-r_{j,i}c} e^{-r_{k,m}c} & r_{k,m} \end{bmatrix} \quad (6)$$

Hence the correlation coefficient turns out to be

$$\rho = \alpha\sqrt{r_{j,i} r_{k,m}}\, c^2 e^{-(r_{j,i}+r_{k,m})c} \quad (7)$$

Rang of $\alpha$, it can be shown that $\alpha$ should lie on the range

$$|\alpha| \le \frac{1}{(1-e^{-r_{j,i}c})(1-e^{-r_{k,m}c})} \tag{8}$$

The correlation coefficient is having the range

$$|\alpha| \le \frac{\sqrt{r_{i,j} \cdot r_{k,m}}\, e^{-r_{j,i}c} e^{-r_{k,m}c} c^2}{(1-e^{-r_{j,i}c})(1-e^{-r_{k,m}c})} \tag{10}$$

## 3. PHYSICAL LOSS OF WATER SUPPLY NETWORK

We consider the physical loss of network system. There are numerous ways to evaluate the physical loss, among that most popular approaches is direct network analysis with considering the connectivity. However, if there is m links in the network system, we must evaluate failure or safety in each link. This means, we must evaluate total number of $2^m$ combinations. In this paper propose, alternative ways to evaluate the physical loss of a realistic existing network system.

The failure events in a mesh area (500m x 500m), stochastic nature of failure spots $X_{j,i}$ are given by Poisson distribution. However, if we consider the total number of failure spots of whole area $Z$ in Eq.(11) becomes $\infty$. Even though failure spots in each mesh is spatially correlated, we assume that stochastic characteristics of $Z$ is converge to Gaussian distribution by central limit theorem. Indeed, the mean failure spots in one mesh is a very small number, but the mean failure spots in whole area becomes a large number such as over 1000 spots.

$$Z = \sum_{j=1}^{\ell} \sum_{i=1}^{n} X_{j,i} \tag{11}$$

By using this, physical loss of in whole area is evaluated as.

$$W = a_1 \cdot Z_1 + a_2 \cdot Z_2 + \cdots + a_\ell \cdot Z_\ell = \sum_{j=1}^{\ell} \sum_{i=1}^{n} a_j \cdot X_{ji} \tag{12}$$

in which $a_j$ is a re-construction price in one damaged spot and total number of damage spot in each pipe category is Gaussian stochastic variable.

Therefore $W$ is a Gaussian stochastic variable, its mean $\overline{W}$ and variance $E[(W-\overline{W})^2]$ is given by,

$$\overline{W} = \sum_{j=1}^{\ell} \sum_{i=1}^{n} a_j \cdot r_{j,i} \tag{13}$$

$$\sigma^2{}_W = \sum_{j=1}^{\ell} a^2{}_j \cdot \sigma^2{}_{zj} + \sum_{j}^{\ell} \sum_{\neq k}^{\ell} a_j a_k \cdot \mathrm{cov}(z_j, z_k) \tag{14}$$

In Eq.(14),

$$\sigma^2{}_{zj} = \sum_{i=1}^{n} r_{ji} + \sum_{i}^{n} \sum_{\neq m}^{n} r_{im}^{jj} \tag{15}$$

$$\mathrm{cov}(z_j, z_k) = \sum_{i=1}^{n} \sum_{m=1}^{n} r_{im}^{jk} \tag{16}$$

If stochastic variable $Z$ is a Gaussian in nature, the Probable Maximum Loss may be obtained directly by the following way.

Normalizing $W$ into $Y = (W - \overline{W})/\sigma_W$ , we can obtain analytical solution of probability of excess as follows.

$$P = 1 - \int_{-\infty}^{\alpha} \frac{1}{\sqrt{2\pi}} \exp(-\frac{Y^2}{2}) dY \tag{17}$$

The value of loss correspond to probability of excess 0.1 is defined as Probable Most Loss Index. Therefore we seek the $\alpha$ value and then we can evaluate physical loss of PML as follows.

$$W = \alpha\sigma_W + \overline{W} \tag{18}$$

## 4. CONCLUDING REMARKS

This study focuses on the seismic risk analysis of the existing water supply system. The Probable maximum Loss index is employed to evaluate the seismic risk. An alternative method is proposed to evaluate Probable Maximum Loss index of the high order water supply network system. Numerical example will be presented to demonstrate the efficiency of the proposed method.

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