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DAMAGE PREDICTION ON BURIED PIPELINE UNDER SEISMIC RISK

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SUMMARY

In order to realistically assess the seismic risk for a pipeline network system, the accurate estimate of pipe damage is critical. This study presents a method of estimating the system's performance for a seismically damaged large-scale network system in which a typical failure mode which is most appropriate for the pipeline is introduced to evaluate the damage of a pipe element. The final goal of this study is to show by using a simulated model network how the system's performance is related to structural damage caused by a severe earthquake.

INTRODUCTION

A seismic risk analysis procedure to evaluate the loss of system connectivity for a large-scale lifeline network system which is defined as a measure of the system's performance, for example, such as the capability of the network system to transmit water from at least one of the supply stations to the demand node, is presented.

In the previous study (Refs. 1,2), Shinozuka and Koike developed a method to assess the serviceability for a water transmission network system. In order to extend this approach to a more realistic network system, the following two factors must be considered:(1) developing a method to efficiently analyze the reliability of performance for a large-scale network system, and (2) refining the pipe failure model appropriate to the network composed of various types of pipe each with its own joint mechanism.

The approach for reliability of performance used herein is based on the method recently developed by Shinozuka et al (Ref. 3) who demonstrated the expediency as well as numerical efficiency for large-scale network systems. A failure model must be established based on a potential defect or imperfection from which leakage or breakage may be initiated during seismic loading for the refinement of the failure model.

Pipeline Network System   A large-scale pipeline network system is composed of several sub-systems which can be classified into high-pressure transmission, medium-pressure distribution, and low-pressure supply. Fig.1 is a schematic example of such a network system in which simple but long transmission pipelines branch out at several nodes to the distribution network. A distribution network also consists of several (distribution) main lines from which the (distribution) local network extends to the perimeter of each residential area block.

Current studies have presented many analytical methods to estimate the physical and functional damage of transmission and distribution main systems under seismic risk, but they have not concentrated their discussion on the functional damage of the local distribution and supply system, the availability of which is of primary concern to the local inhabitants, because the large-scale network system requires numerical dificulties in the reliability analysis of system's performance. A graphical method proposed by Sato et al (Ref. 4) presents a possible solution to this difficulty, although their method still consumes much CPU time.

The method presented herein is based on the concept originally developed by Shinozuka who divides a large-scale network into two systems: one is the network of transmission and distribution main lines and the other the network of a distribution local system. Both systems are interconnected through the nodes denoted by X_A and X_B in Fig.1.

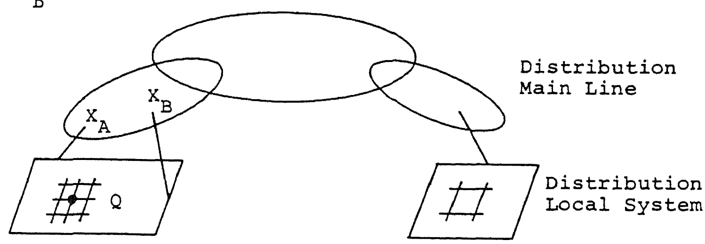

Fig.1 Illustration of a Typical Network System

The conditional probability of the system serviceability under seismic risk can be formulated:

$$R = P[\text{Serviceable at demand node } Q \mid EQ]$$

$$= \bigcup_{\substack{\text{all damaged}\\ \text{states}}} P\left[\begin{matrix}\text{Serviceable at}\\ \text{demand node } Q\end{matrix} \,\middle|\, \begin{matrix}\text{damaged}\\ \text{system}\end{matrix}\right] \cdot P\left[\begin{matrix}\text{Occurrence of}\\ \text{damaged system}\end{matrix} \,\middle|\, EQ\right]$$

$$= \bigcup_{\substack{\text{all damaged}\\ \text{states}}} \Bigg\{ \bigcup_{\substack{\text{all combinations of}\\ \text{interconnected nodes}}} P\left[\begin{matrix}\text{Serviceable at}\\ \text{demand node } Q\end{matrix} \,\middle|\, \begin{matrix}\text{serviceable at}\\ \text{interconnected}\\ \text{nodes}\end{matrix}\right]$$

$$\cdot P\left[\begin{matrix}\text{Serviceable at inter-}\\ \text{connected nodes}\end{matrix} \,\middle|\, \begin{matrix}\text{damaged}\\ \text{system}\end{matrix}\right] \cdot P\left[\begin{matrix}\text{Occurrence of}\\ \text{damaged system}\end{matrix} \,\middle|\, EQ\right]\Bigg\} \qquad (1)$$

where EQ denotes the condition of seismic risk.

Equation (1) is directly applicable when the system serviceability is defined in terms of system connectivity, while if the system serviceability is given as flow rate and pressure at demand node, the flow condition of the interconnected nodes must be prepared as the boundary condition for the distribution local network system.

In the following discussion, the geological conditions are defined for each square grid area which overlies the network system. Soil conditions in each square area are classified into three categories, A(poorly unconsolidated), B (moderate) and C(well). Another category L is given for the square area in which large ground motion induced by liquefaction, landslide or uneven settlement may exist.

Pipe Strains When the local soil and geological conditions are classified as A, B or C so that neither liquefaction nor relative ground displacement due to fault action or landslide is likely to occur ground motion is induced primarily by the propagating seismic wave originating from the earthquake source. The free field strains ε_G associated with these wave-induced ground motions are obtained by using an approximate formula (Ref. 5) as

$$\varepsilon_G = \frac{2\pi}{L} u_G \qquad , \qquad u_G = \frac{2}{\pi^2} S_V\ T\ k \cos\{\frac{\pi z}{2H}\} \tag{2}$$

where L = apparent wave length, S_V = design response spectrum, T = typical period of surface ground, k = seismic intensity at the base rock in g, z = pipe depth and H = depth of surface ground to the base rock.

The free field strain is intrinsically random due to the uncertainty involved in the propagation path from the seismic source and the ground response. The free field strain is therefore assumed herein to be a Gaussian random variable.

The pipe strains ε_S are then estimated on the basis of the free field strains. A conversion factor β is introduced for this purpose in such a way that the pipe strains ε_S are obtained as $\beta\varepsilon_G$ (Ref. 5). For instance, the value of β is obtained as

$$\beta = 1/\{1 + (\frac{2\pi}{L})^2(\frac{AE}{K_G})\} \tag{3}$$

for straight parts of the pipe, where A = pipe cross-sectional area, E = Young's modulus, and K_G = equivalent soil spring constant per unit area.

The maximum structural strains for bend and tee-junctions are also evaluated with the conversion factors β_B and β_T as

$$\varepsilon_B = \beta_B\varepsilon_G \qquad , \qquad \varepsilon_T = \beta_T\varepsilon_G \tag{4}$$

in which the simple formula of β_B and β_T are given in (Ref. 5), while more elaborate analysis to estimate the structural strain at the bent corner is proposed by the author (Ref. 6) in which the flexibility analysis is developed in order to take into consideration the stress intensification and flexibility factors of the bent pipe.

Relative ground displacement at sleeve type joint can be estimated under the assumption of the local inhomogeneity in the microzoned area classified by soil conditions as

$$\Delta u = \max_x |u_G(x) - u_G(x+L_p)| = u_G\sqrt{2\{1 - \rho(L_p)\}} \tag{5}$$

where L_p = pipe unit length and ρ = coefficient of correlation between two different points.

Large ground motion induced by liquefaction and landslide often causes severe pipe damages to the pipeline. In this study, pipe failure associated with the occurrence of such geological instabilities can be estimated only for the microzoned area designated L in which, for simplicity, when an acceleration exceeds the critical value to initiate the geological instability, the pipeline is assumed to be in the state of major damage.

Pipe Failure Model Three states of damage are considered when evaluating the probability of failure of structural (pipe) segments, the state of minor damage represents no loss (including minor leakage), the state of moderate damage some loss (considerable leakage) and the state of major damage total loss (pipe breakage). Leakage or breakage of a pipeline are assumed to result from a defect at a poorly controlled welded joint of steel pipe or from an imperfection at a sleeve type joint of a segmented pipe.

In general, non-destructive inspection is thoroughly executed for transmission and distribution main lines, although a potential defect or imperfection can not be necessarily eliminated, so that such a potential defect (or imperfection) is, for simplicity, assumed to be randomly distributed in a Poisson pattern.

The distribution local network is usually sustained by traffic load alongside the paved street or by lateral pressure resulting from excavation or other construction work, so that the pipe damage is very much dependent upon the environmental condition surrounding the pipeline along the street. Ishikawa (Ref. 7) proposes one method to evaluate an occurrence rate of potential defect in such a way that the occurrence rate ν_j along the j-th sublink of the i-th link is given, based on the theory of quantification I, as a linear combination of several control variables Q_i:

$$\nu_j = \nu(Q_1, Q_2, Q_3, \cdots\cdots, Q_6; x_j) \tag{6}$$

where Q_1, Q_2, Q_3, Q_4, Q_5 and Q_6 = variables for the items of pipe diameter, joint type, internal pressure, traffic load condition, earth cover to the pipe head and annual period since installation, respectively, which are evaluated at the representative point x_j along the j-th sublink.

Based on the occurrence rate of a potential defect, the mean damage rate $\lambda_i(x)$ and $\lambda_i^*(x)$ for transmission and distribution main lines and $\kappa_i(x_j)$ and $\kappa_i^*(x_j)$ for distribution local line are formulated, respectively, in the following way:

$$\begin{aligned} \lambda_i(x) &= P[\varepsilon_S(x) > \varepsilon_{cr}]\cdot\nu_W \quad , \quad \lambda_i^*(x) = P[\varepsilon_{cr}^* < \varepsilon_S(x) \leqq \varepsilon_{cr}]\cdot\nu_W \\ \kappa_i(x_j) &= P[\varepsilon_S(x_j) > \varepsilon_{cr}]\cdot\nu_j \quad , \quad \kappa_i^*(x_j) = P[\varepsilon_{cr}^* < \varepsilon_S(x_j) \leqq \varepsilon_{cr}]\cdot\nu_j \end{aligned} \tag{7}$$

where ν_W = mean occurrence rate of potential defect along a transmission and distribution main line, and ε_{cr} and ε_{cr}^* are the critical strain initiating the major or moderate damage to the continuous pipeline, respectively, while $\Delta u(x)$, u_{cr} and u_{cr}^* instead of $\varepsilon_S(x)$, ε_{cr} and ε_{cr}^* are used for a segmented pipeline. The probability of structural failure is calculated on the assumption that ε_{cr}, ε_{cr}^*, u_{cr} and u_{cr}^* are also Gaussian random variables because of the uncertainty of workmanship and randomness of structural defect and imperfection.

<u>System Reliability</u> Since a link constitutes a series of unit elements which consist of the pipe unit element of length L_p possibly including bent corners and ends of tee-junctions, the conditional probability that the link will be in the state of major, minor or moderate damage immediately after an earthquake are given in the following way: for a transmission and distribution main line where a potential defect can be assumed to be randomly distributed in a Poisson pattern,

$$\begin{aligned} &P[L_i(F)|EQ] = 1 - \exp[-\int\lambda_i(x)dx] \quad , \quad P[L_i(S)|EQ] = \exp[-\int\lambda_i^*(x)dx] \\ &P[L_i(M)|EQ] = 1 - P[L_i(F)|EQ] - P[L_i(S)|EQ] \end{aligned} \tag{8}$$

and for a distribution local system in which an existing rate of potential defect may be assumed to be mutually independent along each sublink,

$$\begin{aligned} &P[L_i(F)|EQ] = 1 - \prod_{j=1}^{NL_i}\{1 - \kappa_i(x_j)\cdot\ell_j\}, \quad P[L_i(S)|EQ] = \prod_{j=1}^{NL_i}\{1 - \kappa_i^*(x_j)\cdot\ell_j\} \\ &P[L_i(M)|EQ] = 1 - P[L_i(F)|EQ] - P[L_i(S)|EQ] \end{aligned} \tag{9}$$

where event $L_i(F)$ = the i-th link state under major damage, or equivalently, link failure implying that at least one of the pipe element with a potential defect sustaining major damage, $L_i(S)$ = the i-th link state under minor damage, or link survive indicating all the pipe elements are subjected to only minor damage, $L_i(M)$ = the i-th link state under moderate damage, NL_i = number of sublinks included in the i-th link, and ℓ_j = length of the j-th sublink.

The network system has several key facilities such as storage tank, pumping station or system control facility. The conditional probability of failure of such a node can be evaluated with the fragility curve which provides the probability of failure for the maximum acceleration acting to the node with

$$\begin{aligned} &P[N_i(F)|EQ] = f_{N_i}(F|EQ), \quad P[N_i(M)|EQ] = f_{N_i}(M|EQ) - f_{N_i}(F|EQ) \\ &P[N_i(S)|EQ] = 1 - P[N_i(F)|EQ] - P[N_i(M)|EQ] \end{aligned} \tag{10}$$

where events $N_i(F)$, $N_i(M)$ or $N_i(S)$ = the i-th node state under major, moderate or minor damage, respectively, and $f_N(\cdot|EQ)$ = the value of probability given from the fragility curve to the corresponding acceleration for the i-th node.

To perform the analysis of the system failure, the physical network system is transformed into its corresponding Series System in Parallel (SSP), where each tie-set consists of not only links connected in a series but also nodes at both ends of their links. The conditional probability of the tie-set failure for different damage states is also expressed in terms of that of the link and node failure as

$$\begin{aligned} &P[T_k(F)|EQ] = 1 - \prod_{i=1}^{TL_k}\{1 - P[L_i(F)|EQ]\} \prod_{i=1}^{TN_k}\{1 - P[N_i(F)|EQ]\} \\ &P[T_k(S)|EQ] = \prod_{i=1}^{TL_k} P[L_i(S)|EQ] \prod_{i=1}^{TN_k} P[N_i(S)|EQ] \\ &P[T_k(M)|EQ] = 1 - P[T_k(F)|EQ] - P[T_k(S)|EQ] \end{aligned} \tag{11}$$

where TL_k and TN_k are the numbers of the links and nodes belonging to the k-th tie-set.

Finally, the conditional probability of the connectivity failure in different states of damage is estimated as

$$\begin{aligned} &P[C(F)|EQ] = P[\prod_{k=1}^{NT} T_k(F)|EQ] \quad , \quad P[C(S)|EQ] = P[\bigcup_{k=1}^{NT} T_k(S)|EQ] \\ &P[C(M)|EQ] = 1 - P[C(F)|EQ] - P[C(S)|EQ] \end{aligned} \tag{12}$$

where NT = number of the tie-sets.

Numerical Example and Summary Using the simulated model network shown in Fig.2, the probability of failure of system connectivity is calculated to demonstrate that (1), in Fig.3, the link failure caused by liquefaction is one of the key factors injuring the system's performance, while (2), in Fig.4, the seismic reliability of the rehabilitated local system, the old pipes of which were replaced by new ones, can be improved in a future service period.

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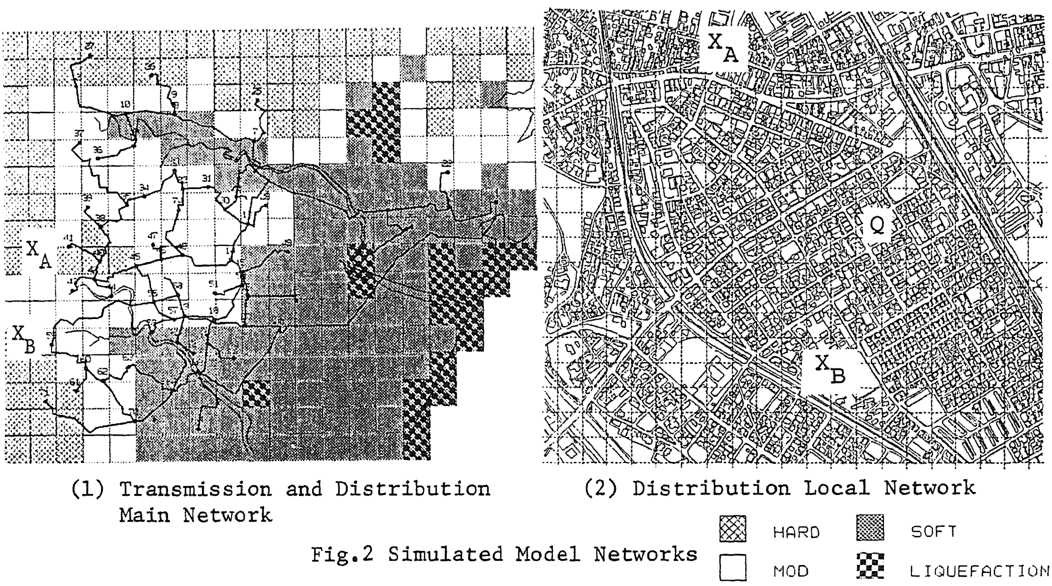

(1) Transmission and Distribution Main Network

(2) Distribution Local Network

Fig.2 Simulated Model Networks

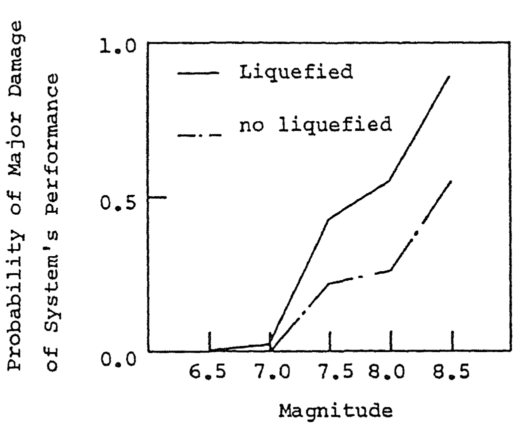

Fig.3 Probability of major damage of system performance under the liquefaction risk

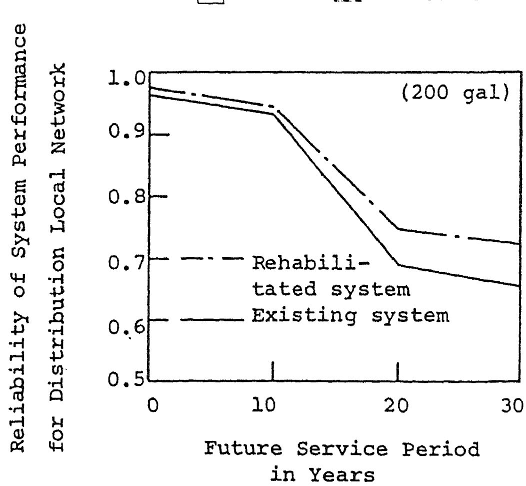

Fig.4 Reliability of system performance for future service period