Risk Assessment of Lifelines
Subjected to Spatial Correlated Seismic Intensities

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SUMMARY:
Critical infrastructures spatially lifelines, such as pipelines, power transmission, communication, and transportation systems, are networks that extend into the wide geographic areas. Lifeline risk assessment requires knowledge of ground-motion intensities at several sites, but limited information on seismic wave propagation and local site conditions makes these predictions difficult. In fact, when a spatially distributed infrastructure is of concern, tools use for determining site-specific hazard may be not adequate to assess accurately the seismic risk and the joint distribution of ground motion parameters at different sites may be needed. In addition, the effects of spatially correlated seismic intensities on lifelines system performance, is generally not available in closed form. In this paper, the risk assessment of a lifeline system was evaluated with the model taking into account the spatial correlation in seismic intensity. This is introduced as the conditional seismic hazard for the link.

Keywords: lifeline, risk assessment, spatial correlation, seismic intensity, joint probability

1. INTRODUCTION

Seismic risk analysis of distributed systems and infrastructures requires a different approach than that commonly used for site-specific structures. One of the key issues, at least on the hazard side, is to account for the existence of a statistical correlation between ground motion intensity measures at the different sites where the segments, spatially extend over long distances.

Prediction of strong ground motion in a wide area has played a very important role in earthquake disaster prevention and damage mitigation, as well as in seismic design and assessment of infrastructures spatially spread. Mean attenuation characteristics of the ground motion induced from a seismic source can be conveniently predicted by using the mean attenuation relation. The spatial correlation structure of the uncertainty of the empirical ground motion attenuation relationships also has to be adequately modeled. For example, Boore et al. (2003) report a spatial correlation model for peak ground acceleration (PGA) from data of the 1994 Northridge earthquake. Wang and Takada (2005) calculated different correlation models using peak ground velocity (PGV) observations of Japanese earthquakes occurred from 2000 to 2003 as well as the 1999 Chi-Chi earthquake. Goda and Hong (2008) computed correlation for PGA, PGV and pseudo spectral acceleration (PSA) residuals based on the California dataset and the Chi-Chi earthquake. Moreover Jayaram and Baker (2009) referred to PGA and PSA from Northridge earthquake records, Chi-Chi, and Japanese earthquakes (Esposito et al. 2010).

Previous research of models for the spatial correlation of seismic intensity from large earthquakes is limited. Among the particular challenges are: modeling the effect of spatial correlation in ground motion intensity in the absence of information on seismic wave propagation and local site conditions as well as evaluating the impact of this spatial correlation on response of distribution elements that are found in distributed lifeline systems. Takada and Shimomura (2003, 2004), Shimomura and Takada (2004), and Wang and Takada (2005) analyzed the spatial correlation of PGA and PGV using ground motion records obtained from dense arrays in Japan and Taiwan. In those studies, it was assumed that the residuals of seismic intensity with respect to the median intensity computed from the attenuation equations were correlated with random variables, leading to an auto-covariance in intensity describing the spatial correlation as an exponential function of the distance between two sites (Adachi et al 2009).

Although these previous analyses considered the spatial distribution in seismic demand in a first-order sense, as measured through the dependence of the mean or median attenuation relationships on epicentral distance, seldom has addressed the effect of statistical correlation in seismic intensities on network performance.

In this study a probabilistic model is developed for the assessment of the vulnerability of lifelines links under earthquake loads. The functionality of segments within the system that are damaged as a result of stochastically correlated seismic intensities is evaluated.

2. SPATIAL CORRELATION

Earthquake ground motion intensity y and mean value $\overline{Y}$ of earthquake ground motion intensity at point p due to earthquake i is related as below.

$$\log y_{pi} = \overline{\log Y_{pi}} + \eta_i + \varepsilon_{pi} \tag{2.1}$$

where y_{pi} denotes the observed intensity of interest $\overline{Y_{pi}}$ is the mean of the logs η_i variation of source denotes the inter-event residual, which is due to the destruction process of fault and is unique in a given earthquake; and ε_{pi} is the variation of earthquake motion propagation represents the intra-event heterogeneity of ground motion, which is due to the path or site amplification. ε_{pi} and η_i are usually assumed to be independent, normally distributed with zero mean and standard deviation σ_{intra} and σ_{inter}, respectively. Generally, $\log y_{pi}$ is modelled as a Normal random variable with total standard deviation σ (Esposito et al. 2010).

The data observed from recent earthquakes are used to build up the spatial correlation model whereby the auto-covariance function $C(h)$ is estimated through statistical analysis. The observed data were firstly grouped into several bins with the same separation distance h between two sites (p, q) so that the separation distance in the same bin is within $h \pm \Delta h/2$. Therefore the auto-covariance function can be written by discrete expression (Wang et al. 2005). The classical estimator of the auto-covariance is the method-of-moments estimator, which is unbiased; however it is badly affected by atypical observations. Therefore Cressie and Hawkins (1980) propose a more robust estimator, Eqn. 2.2.

$$C(h) = \left[\frac{1}{N(h)} \sum_{i=1}^{N(h)} \left(L(x_{p_i}) - \mu_L \right)\left(L(x_{q_i}) - \mu_L \right) \right]^4 \Big/ \left(0.457 + \frac{0.494}{N(h)} \right) \tag{2.2}$$

$$\mu_L = \frac{1}{N_{all}} \sum_{i=1}^{N(h)} L(x_i) \tag{2.3}$$

$$L(x_{pi}) = \ln\left(\frac{y_{pi}}{\overline{\overline{Y_{pi}}}} \right) \tag{2.4}$$

where N_{all} is the total number of observation sites, $N(h)$ is the number of pairs of sites (x_p, x_q) that meet the condition $h - \Delta h/2 < \left| x_p - x_q \right| < h + \Delta h/2$; h is the discrete distance whose interval is Δh.

Assuming that $L(x)$ constitutes a homogeneous two-dimensional stochastic field, then auto-covariance function of $L(x)$ between different two sites depends only on the relative distance. Normalized auto-covariance function $R(h)$, auto-covariance function normalized by the variation of $L(x)$, σ_L^2, is obtained from $C(h)$ as following.

$$R(h) = C(h) / \sigma_L^2 \tag{2.5}$$

Now the macro-spatial correlation model can be built up by modeling the discrete values of the normalized auto-covariance function $R(h)$ with an exponential decaying function as in Eqn. 2.6.

$$R(h) = \exp\left(-h/b\right) \tag{2.6}$$

where h is a separation distance between two observations and b is called a correlation length, which can characterize the degree of correlation of ground motions between two locations. It can be seen from Eqn. 2.6, that this exponential function satisfies two essential conditions, $R(0)=1$ and $R(\infty)=0$. Therefore the co-variances between sites p and q meet the Eqn. 2.7.

$$Cov(h)_{pq} = \sigma_{\mathrm{int}\,er}^2 + R(h)\sigma_{\mathrm{int}\,ra}^2 \tag{2.7}$$

where σ_{intra} and σ_{inter} are standard deviation of inter and intra-event residuals, respectively.

3. PROBABILISTIC HAZARD ANALYSIS

Using spatial correlation model, the seismic intensity of a site can be estimated stochastically from seismic intensities of other n sites nearby. This implies that the accuracy of the prediction becomes better increasingly with conditional probabilistic using the spatial correlation model.

In estimating the conditional probabilistic hazard, at first, it should be select the main site where have most important facilities of the estimated area. Another point other than main site are called sub-main site in this estimation. Seismic hazard at main site are evaluated by normal Probabilistic Seismic Hazard Analysis PSHA procedure. One at sub-main site are evaluated the conditional seismic hazard of main site seismic hazard. The seismic hazard of a main site is obtained as a sum total of the earthquake hazard due to enormous earthquake events generated by seismic source zone model. Seismic hazard is expressed as annual exceedance probability $P_\lambda(y)$, and when Poisson process is assumed as a process of the earthquake occurrence, $P_\lambda(y)$ is given by:

$$P_\lambda(y) = 1 - \exp\left\{-\sum_{i=1}^{N} \nu_i \Phi\left[\frac{\ln y - \ln \overline{Y}_i}{\sigma}\right]\right\} \tag{3.1}$$

Where, ν_i is annual frequency of event i, $\overline{Y}_i$ mean of ground motion intensity due to earthquake event i, σ logarithmic standard deviation of estimated residuals of empirical attenuation equation, Φ standard normal distribution and N total number of events.

The seismic hazard of sub-main site is defined as expect value of earthquake motion caused by the same incidence when ground motion intensity hit the primary site. Seismic motion intensity in sub-main site which is not observed can be estimated stochastically using seismic motion intensities observed nearby (Hayashi et al. 2006). Event frequency $\lambda_i(y)$ which given ground motion intensity y due to event i occurs at sub-main site is given by:

$$P_\lambda(y)=1-\exp\left\{-\sum_{i=1}^{N}\nu_i\left(\Phi\left[\frac{\ln(y-\Delta y)-\ln\bar{Y}_i}{\sigma}\right]-\Phi\left[\frac{\ln(y+\Delta y)-\ln\bar{Y}_i}{\sigma}\right]\right)\right\} \tag{3.2}$$

where, $\lambda_i(y)$ annual exceedance probability which the earthquake ground motion intensity exceeds y, Δy is disaggregation range of ground motion intensity and is appropriately set. Therefore, ground motion intensity at sub-main site $y_i(y)$ when ground motion intensity y accord in main site by event i is defined below:

$$y_i(y)=\frac{\sum_{i=1}^{N}\lambda_i(y).\bar{Y}_{qi}\exp[\alpha_1+\alpha_2]}{\lambda(x)} \tag{3.3}$$

where, $\bar{Y}_{q|i}$ is mean value of the ground motion intensity at sub-main site q due to earthquake event i and α_1,α_2 are given by:

$$\alpha_j=\frac{\sigma_j^2}{\sigma^2}\ln\left(\frac{y}{\bar{Y}_i}\right)R_j(h) \quad , \qquad j=1,2 \tag{3.4}$$

where, h is distance between main site and sub-main site, σ_j logarithmic standard deviation of the empirical attenuation equation, $j=1$ consider intra-event condition with $h=0$ and $j=2$ consider inter-event condition with $h=d_{pq}$. For a single earthquake the joint distribution of $\log y_{pi}$ for all sites of interest can be considered a multivariate normal distribution characterized by the following covariance matrix Γ according to Eqn. 3.5.

$$\Gamma=\begin{bmatrix}\sigma^2_{inter} & . & . & . & \sigma^2_{inter}\\ . & . & & & .\\ . & & . & & .\\ . & & & . & .\\ \sigma^2_{inter} & . & . & . & \sigma^2_{inter}\end{bmatrix}+\sigma^2_{intra}\begin{bmatrix}1 & . & . & . & R(h)\\ . & . & & & .\\ . & & . & & .\\ . & & & . & .\\ R(h) & . & . & . & 1\end{bmatrix} \tag{3.5}$$

Where the inter-event variability produces fully correlated residuals and the intra-event variability produces correlated residuals (Esposito et al. 2010). In this model it is assumed that, under specific hypotheses, spatial variability of intra-event residuals are a function only of the inter-site separation distance, and as the separation distance increases, the correlation asymptotically tends to disappear.

4. SEISMIC RISK ASSESSMENT OF THE LIFELINE

The lifelines are infrastructures which extend spatially over large geographical regions. They consist of two types of segments, node and link (Adachi et al. 2009). For the assessment of the links failure which are linearly extending elements, each member is divided into segments and seismic demand is identified at the midpoints of each segment. It is represented as a series system and generally the damage probability of link is calculated by Eqn. 4.1 in which P_{fi} is damage probability of segment i.

$$P_{\lambda_{link}}(y)=1-\prod_{i=1}^{m}(1-P_{fi}) \tag{4.1}$$

But in fact, the failure events of the segments on the same member are expected to be highly correlated because of the fact that they are subjected to the same earthquake excitation and the same material properties are expected to exist along the total length of the element. The joint probability distribution of m segments of the link can be considered a multivariate normal distribution characterized by the covariance matrix Γ, where the inter-event variability produces fully correlated residuals and the intra-event variability produces correlated residuals. In this case, one of the most important applications of the model is in the link hazard curve assessment. Therefore, annual exceedance probability of the link $P_{\lambda_{link}}(y)$ which the earthquake ground motion intensity exceeds y, can estimate by Eqn. 4.2.

$$P_{\lambda_{link}}(y)=1-\exp\left\{-\sum_{i=1}^{N}\nu_i\left(1-\frac{1}{\sqrt{|\Gamma|(2\pi)^m}}\int_{-\infty}^{l_1}\ldots\int_{-\infty}^{l_m}\exp\left[-\frac{1}{2}Y^T\Gamma^{-1}Y\right]d\mathrm{X}\right)\right\} \tag{4.2}$$

Where, N is the number of is observed points and m the number of link segments. In this model it is assumed that, under specific hypotheses, the spatial variability of intra-event residuals can be assumed as a function only of the inter-site separation distance, b, and as the separation distance increases, the correlation asymptotically tends to disappear.

Most typical approach of seismic response analysis of continues buried pipelines for wave effect is to adopt the response spectrum method in Japan, The probability of damage states for buried pipelines under wave effect can be given by Eqn. 4.3.

$$P_{damage}=P\lfloor\varepsilon_{pipe}>\varepsilon_{cr}\rfloor \tag{4.3}$$

where ε_{cr} are the critical strain for the damage state which consider 0.03 and ε_{pipe} is pipe strain which is formulated as;

$$\varepsilon_{pipe}=\alpha.\varepsilon_G \tag{4.4}$$

$$\varepsilon_G=\frac{4H}{L.V_S}\eta(T)S_V(T)\cos\left(\frac{\pi z}{2H}\right) \tag{4.5}$$

$$\alpha=\left[1-\cos\xi+\left(\frac{\pi}{2}-\xi\right)\sin\xi\right]\Big/\left[1+\left(\frac{4\pi^2EA}{K_AL^2}\right)\right] \tag{4.6}$$

$$\xi=\arcsin\left\{\left[\frac{LD\tau_{cr}}{2EA\varepsilon_G}\right]\Big/\left[1+\left(\frac{4\pi^2EA}{K_AL^2}\right)\right]\right\} \tag{4.7}$$

where ε_G is free field strain, $\eta(T)$ surface response ratio, $S_V(T)$ velocity response spectrum (T=1.0sec), L wave length, T typical period of the surface ground, K_A soil spring modulus, τ_{cr} slippage initiating shear stress of the soil surrounding a pipe, E Young's modulus, A cross section area and D is pipe diameter.

5. APPLICATION OF SPATIAL CORRELATION

The 2011 great east Japan earthquake in Tohuku caused significant damage to coastal structures, not only due to tsunamis but also due to strong ground motions. It is reported that ground acceleration over 2.5g was recorded in Miyagi Prefecture. The trend segment in the stochastic model of ground motion is usually characterized by the mean attenuation relationships. In this study, it is considered to use a model that proposed for north-east of Japan, Kanno et al. (2006) proposed predictive model especially for Japan seismic zones, Eqn. 5.1.

$$\log Y = a_1 M_W + b_1 X - \log\left(X + d_1.10^{e_1 + M_w}\right) + c_1 + \varepsilon_1 \quad , \qquad (D \le 30km) \tag{5.1}$$

where Y is the predicted peak ground velocity PGV in units of cm/s in different periods, M_W the moment magnitude, D the focal depth (km), X the source distance and regression coefficients a_1, b_1, c_1 and d_1 are 0.7, -0.0009, -1.93, 0.0022 respectively. The standard deviation ε_1 is 0.32.

Therefore, the logarithmic deviation can be obtained from the data observed in the earthquake and the value predicted by the attenuation relationship. Through statistical analyses, the discrete value of auto covariance function is calculated of peak ground velocity and an exponential decay function is fitted to the correlation model, Fig. 5.1. The value of correlation length (b) is about 79.

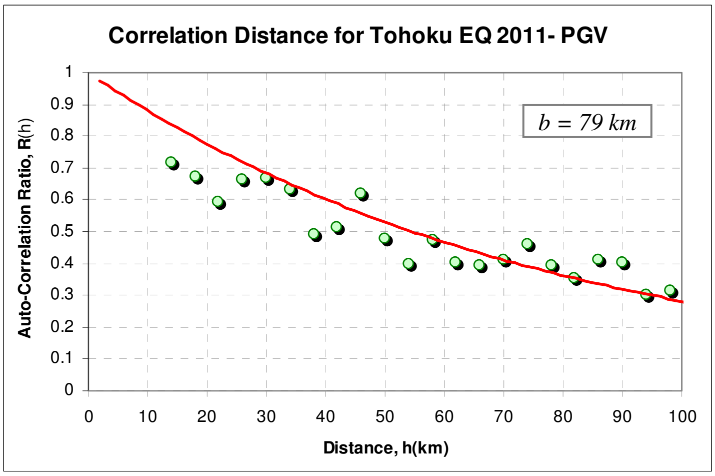

Figure 5.1. Normalized auto-covariance function of peak ground velocity

There are many factors affecting the correlation model. The source characteristic, wave propagation, and site effect are dominant. In the probabilistic seismic hazard analysis, the uncertainty of the prediction with the attenuation relationship is still great. Incorporating this correlation model associated with those physical phenomena inherent to earthquakes not described in the attenuation relationship, the prediction will be greatly improved.

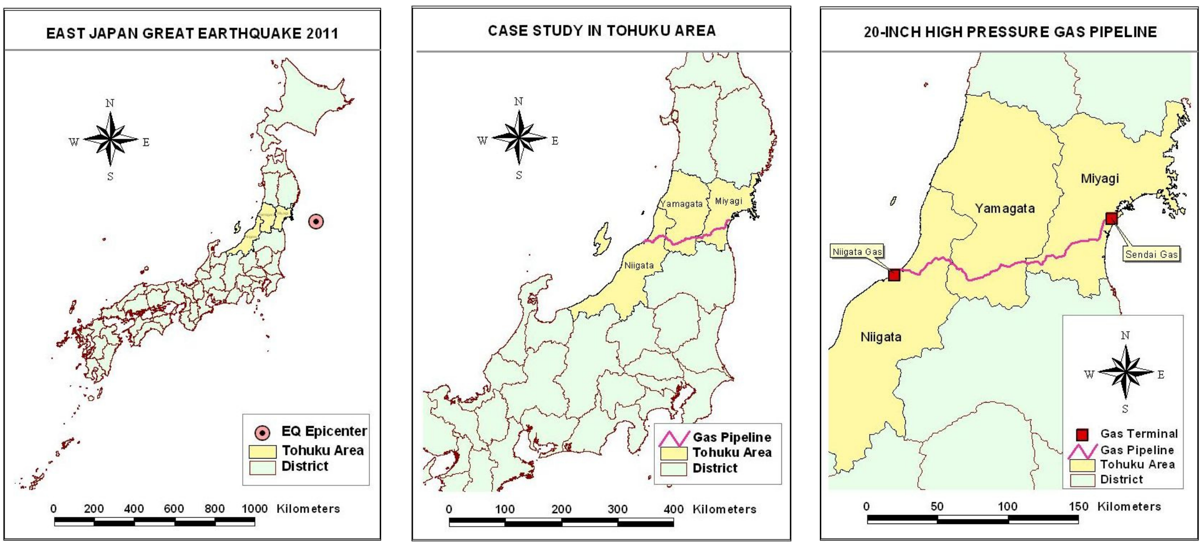

Figure 5.2. Schematic map of the case study, 20-inch high pressure gas pipeline in Tohuku -Japan

As application, the 20 inch high pressure gas pipeline near Tohuku area is selected. As it is shown schematic in Fig. 5.2, this link has been located in Miyagi, Yamagata and Niigata prefectures and connected two high pressure gas substations. The length of the line is about 200 km which connected the Nigatta gas terminal in west to the Sendai area in the east part of Japan.

In order to optimize the computing process as described by Faraji et.al (2012), the case study link is divided to five sub-link with length about 40 km which include one main point. Seismic hazard is defined as the probable level of ground shaking associated with the recurrence of earthquakes. In this study it is considered an earthquake catalogue comes from Japan Seismic Hazard Information Station (J-SHIS). The hazard curve of the main point is defined by Eqn. 3.1 based on the catalogue. Fig. 5.3 shows the hazard curves of the main points of the link which are used to calculate the hazard curves of sub-main points based on the spatial correlation concept.

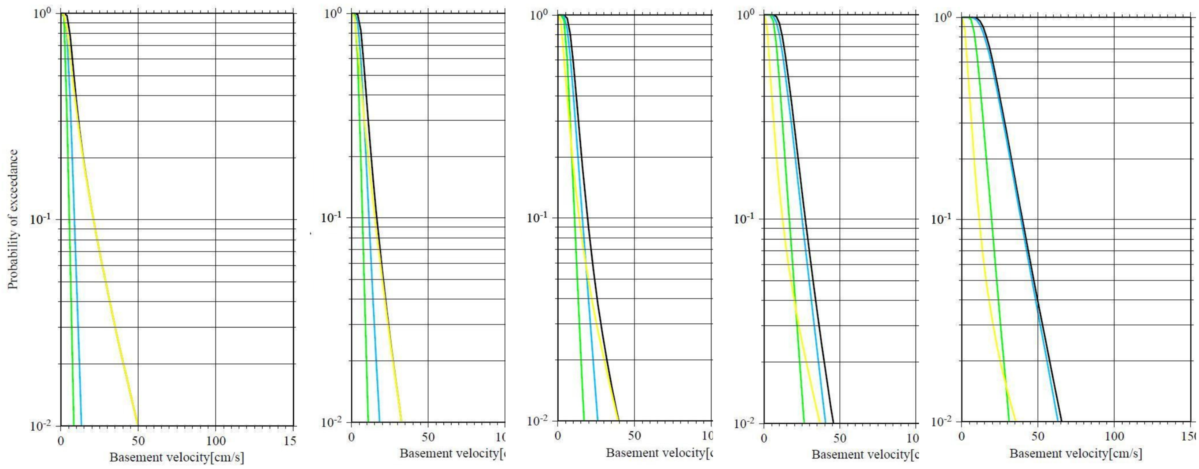

Figure 5.3. Hazard curve of five main points of the case study link (J-SHIS)

The number of sub-link segments required to achieve an accurate estimate of P_λ (optimum number of the sub-link segments) depends on the correlation length, b. If $b=0$ *km*, the seismic intensities at the two sites are statistically independent. It seems that failure probability increases when the number of segments goes up, and this trend holds for different correlation lengths. To avoid additional calculations, 20 segments (sub-main points) for each sub-link is considered. Therefore the hazard curves of sub-main points are calculated by Eqn. 3.2, using hazard curve of main points. Finally, the hazard curve of the sub-link is obtained by using Eqn. 4.2.

Now, the obtained hazard curve can be used for seismic vulnerability analysis of the link. In this case, for 475-years return period that means 50 years of exposure time corresponds to 10% probability of exceedence, the peak ground velocity is defined for each sub-link and subsequently, the probability of damage can be calculated. As it is illustrated in table 5.1; the results of proposed model is more reliable than the general approach.

Table 5.1. The probability of sub-links damage

Sub-link	**General method**		**Proposed method**	
	PGV (cm/s)	**Prob. of damage**	**PGV (cm/s)**	**Prob. of damage**
Niigata	42	0.112267	36	0.095236
Sekikawa	37	0.09141	34	0.083743
Higashiokitama	41	0.114342	38	0.107556
Shiroishi	48	0.151612	43	0.142045
Sendai	67	0.321076	57	0.267818

6. CONCLUSION

The seismic assessment of a link of Lifeline system following an earthquake in this article takes into account spatial correlations in seismic intensity and demand on segments within the distributed system. Seismic intensity over the affected area of the system was modeled as a stochastic field, both at sites of discrete segments within the network system.

The spatial distribution of ground motion intensity for a particular earthquake source can be easily evaluated with the emphasis on simultaneity of ground motion intensities at two different sites. It is shown that the accuracy of the prediction is improved considering the correlation of sites rather than the traditional prediction only with the attenuation relation. With the macro-spatial correlation model, the joint exceedance probability of sites can be easily calculated. It is very useful when the spatial-spread system should be treated as a whole, such as a group of buildings, lifeline, communication network etc. The macro-spatial correlation model can easily be incorporated into the probabilistic seismic hazard assessment for multiple sites. Based on this concept, the link hazard curve is evaluated based on the joint exceedance probability considering the correlation between different sites and segments.

In this study macro-spatial correlation is modeled for the great east Japan earthquake and correlation length is obtained about 79 for peak ground velocity. Then as a case study, hazard curve of the 20-inch high pressure gas pipeline is calculated based on the correlation length. The result indicate that proposed model is more reliable than the general approach which over estimates the link damage probability of damage.

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