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EVALUATION OF JOINT PROBABILISTIC SEISMIC HAZARD SURFACE

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ABSTRACT

In case of conducting seismic PRA or nuclear power plant facilities, it is important to evaluate the risk of network as well as the risk of individual facilities since the damage to the power plants is affected by those to facilities constructing the network such as off-site power. It is apparent that it is inadequate neither to apply individual seismic hazard curve to each facility nor to apply identical seismic hazard curve to all the facilities. Recently, so-called "multi event model" in which a huge number of scenario earthquakes are modeled, has come to be employed in the field of finance technologies in order to evaluate loss of portfolio of building located in multiple sites. However, the method may not be applicable to the seismic PRA where very low probability of occurrence is of concern.

This research proposed a joint seismic hazard analysis for two sites, considering the following correlations on ground motion intensity; one is the spatial correlation of each scenario earthquake employed in hazard analysis, and the other is the correlation introduced by the geometry of sites and scenario earthquake. The method was applied to some sites in Kanto region of Japan, followed by the remark outcomes shown below;
[1] Joint seismic hazard is affected by the distance between to sites as well as by the locations to the dominant earthquakes, and,
[2] The correlation given by the geometry of site and scenario earthquake is affected by spatial correlation of each scenario earthquakes.

INTRODUCTION

In case of conducting seismic PSA or nuclear power plant facilities, it is important to evaluate the risk of network as well as the risk of individual facilities since the damage to the power plants is affected by those to facilities constructing the network such as off-site power. Authors have proposed the seismic risk analysis method for business supply-chain followed by the conclusion that the risk for functional damage of network depends not only on the seismic capacity of each building in the supply-chain but also on the connectivity of network (Fukushima et al. (2010)). For example, series system requires all the buildings be sound. On the other hand, parallel system requires one building be sound. Of course, the soundness of or damage to buildings depend on the ground motion intensity, and therefore it can be concluded that the correlation of ground motion intensities at building sites have great effect on the risk of network.

Recently so-called "multi event model" has been introduced to analyze the seismic risk of portfolio of buildings in the field of financial market. Though this model can solve the issues on damage correlation numerically, it is time consuming to evaluate the risk at very low probability of occurrence, since it is based on the Monte-Carlo simulation. Therefore, the method cannot be applied to seismic PRA for network where the occurrence probability of 10^{-6} or less is of concern.

For the issue mentioned above, this paper proposes a joint seismic hazard analysis for two sites, considering the following correlations on ground motion intensity; one is the spatial correlation of each scenario earthquake employed in hazard analysis, and the other is the correlation introduced by the geometry of sites and scenario earthquake.

DEFINITION OF CORRELATIONS

This paper employs two (2) correlations; one is the spatial correlation of each scenario earthquake employed in hazard analysis, and the other is the correlation introduced by the geometry of sites and scenario earthquake. For convenience, let the former be called intra-correlation and the latter be called inter-correlation, respectively.

Intra-correlation

When establishing attenuation formula for ground motion intensity prediction, two (2) uncertainties are estimated; the one is inter-event uncertainty and the other in intra-event uncertainty. It is said the inter-event uncertainty is given by the insufficient knowledge on source mechanism and the correlation factor is unity since the uncertainty is common for all the sites of concern. On the other hand intra-event uncertainty is introduced by the ground motion path from the source to site. Therefore, if sites of concern are located close to one another correlation factor gets higher, and vice versa. Some researches proposed the formula to estimate the intra-event uncertainty using site-to-site distance as parameter.

Inter-correlation

To understand the inter-correlation, let us consider the simple case as illustrates in Fig.1. In the figure, parameter x_{ij} denotes the distance from site i to source j. In case of arrangement 1, since source 1 is dominant for site 1 and source 2 is dominant for site 2, simultaneous damage to sites 1 and 2 may be negligible. On the contrary in case of arrangement 2, since source 1 is dominant for both sites 1 and 2, the simultaneous damage cannot be avoided.

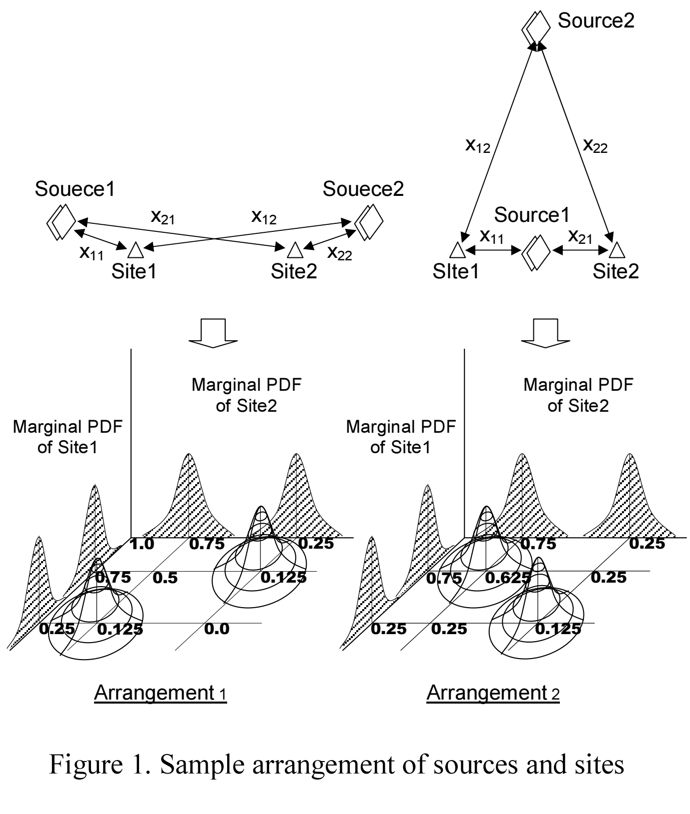

Figure 1. Sample arrangement of sources and sites

Figures in bold letters denote the joint exceedance probability. It is apparent that the marginal probability density functions in arrangement 1 and 2 are identical, and that the intra-correlation has large effect on estimating inter-correlation. As illustrated by Fig.1 inter correlation may be affected various factors such as site-to-site distance, site-to-source distance, intra-correlation, and magnitude and occurrence frequency of each scenario earthquake, so that it is impossible to determine the inter-correlation in the explicit form. In this paper, therefore, a joint probabilistic seismic hazard (J-PSH) is employed to quantify the inter-correlation though it is not a direct procedure.

JOINT PROBABILISTIC SEISMIC HAZARD

J-PSH is defied the probability that the ground motion intensity at site 1 exceeds the given threshold and that at site 2 does the given threshold, simultaneously. This chapter shows the method to evaluate inter-correlation using J-PSH.

Evaluation of Joint Probabilistic Seismic Hazard

Let $p(a_1, a_2)$ be the joint probability that the ground motion intensity at site 1 exceeds a_1 and that at site 2 exceeds a_2, simultaneously. $p(a_1, a_2)$ is obtained by the following equation,

$$p(a_1, a_2) = 1 - \exp[-\nu(a_1, a_2)], \tag{1}$$

where, $\nu(a_1, a_2)$ is the joint frequency and obtained by the following equation,

$$\nu(a_1, a_2) = \sum_{k=1}^{n} \nu_k^* \sum_{i=1}^{n_{mk}} p_k(m_i) \frac{1}{n_{ek}(m_i)} \sum_{j=1}^{n_{ek}(m_i)} \hat{p}(a_1, a_2 \mid m_i, x_{1j}, x_{2j}, h_j)\,. \tag{2}$$

Each parameter is explained below;

ν_k^* : Annual earthquake occurrence rate of source zone k,
$p_k(m_i)$: Relative occurrence rate of earthquake with magnitude m_i in source zone k,
$\hat{p}(a_1, a_2 \mid m_i, x_{1j}, x_{2j}, h_j)$: Joint exceedance probability on the condition of magnitude m_i, distances x_{1j} and x_{2j} earthquake, and, depth h_i,
n : Number of source zone,
n_{mk} : Number of magnitude interval in source zone k, and,
$n_{ek}(m_i)$: Number of rupture planes corresponding to magnitude m_i in source zone k.

Joint exceedance probability $\hat{p}(a_1, a_2 \mid m_i, x_{1j}, x_{2j}, h_j)$ can be obtained by integrating the joint probability density function for the region of $a_1 < A_1 \leq \infty, a_2 < A_2 \leq \infty$. A_1 is a random variable of ground motion intensity at site 1, and A_2 is the one at site 2. Eliminating the conditional symbol "$\cdot \mid m_i, x_{1j}, x_{2j}, h_j$" for simplicity, the joint exceedance probability is evaluated by the following equation,

$$\hat{p}(a_1, a_2) = \int_{a_1}^{\infty} \int_{a_2}^{\infty} f_{A_1, A_2}(a_1, a_2) da_1 da_2\,, \tag{3}$$

where, $f_{A_1, A_2}(a_1, a_2)$ is a joint probability density function of ground motion intensity. Assuming the logarithmic normal distribution for the ground motion intensity, the joint probability density function $f_{A_1, A_2}(a_1, a_2)$ is given by the following equation,

$$f_{A_1,A_2}(a_1,a_2)=\frac{1}{2\pi\zeta_1\zeta_2\sqrt{1-\rho^2}}\exp\left[\frac{-1}{2(1-\rho^2)}\left\{\left(\frac{\ln a_1-\lambda_1}{\zeta_1}\right)^2\right.\right.$$
$$\left.\left.-2\rho\left(\frac{\ln a_1-\lambda_1}{\zeta_1}\right)\left(\frac{\ln a_2-\lambda_2}{\zeta_2}\right)+\left(\frac{\ln a_2-\lambda_2}{\zeta_2}\right)^2\right\}\right], \tag{4}$$

where, λ and ζ are logarithmic mean and logarithmic standard deviation of ground motion intensity whose subscripts correspond to sites 1 and 2. ρ is the correlation factor of intra-correlation.

Eqn. (4) can be rewritten as follows,

$$f_{A_1,A_2}(a_1,a_2)=\frac{1}{\sqrt{2\pi}\zeta_1}\exp\left[-\frac{1}{2}\left(\frac{\ln a_1-\lambda_1}{\zeta_1}\right)^2\right]\times\frac{1}{\sqrt{2\pi}\zeta_2\sqrt{1-\rho^2}}$$
$$\times\exp\left[-\frac{1}{2}\left\{\frac{\ln a_2-\lambda_2-\rho(\zeta_2/\zeta_1)(\ln a_1-\lambda_1)}{\zeta_2\sqrt{1-\rho^2}}\right\}^2\right]. \tag{5}$$

It is noted that eqn.(5) shows the joint probability density function of ground motion intensity can be evaluated as the product of the probability density function of ground motion intensity at site 1 and the conditional probability density function of ground motion intensity at site 2. Namely,

$$f_{A_1,A_2}(a_1,a_2)=f_{A_2|A_1}(a_2\mid a_1)\times f_{A_1}(a_1), \tag{6a}$$

$$f_{A_1}(a_1)=\frac{1}{\sqrt{2\pi}\zeta_1}\exp\left[-\frac{1}{2}\left(\frac{\ln a_1-\lambda_1}{\zeta_1}\right)^2\right], \text{ and,} \tag{6b}$$

$$f_{A_2|A_1}(a_2\mid a_1)=\frac{1}{\sqrt{2\pi}\zeta_2\sqrt{1-\rho^2}}$$
$$\times\exp\left[-\frac{1}{2}\left\{\frac{\ln a_2-\lambda_2-\rho(\zeta_2/\zeta_1)(\ln a_1-\lambda_1)}{\zeta_2\sqrt{1-\rho^2}}\right\}^2\right]. \tag{6c}$$

Therefore, joint exceedance probability $\hat{p}(a_1,a_2)$ can be rewritten as follows,

$$\hat{p}(a_1,a_2)=\int_{a_1}^{\infty}\int_{a_2}^{\infty}f_{A_2|A_1=a_1}(a_2)\cdot f_{A_1}(a_1)da_1da_2$$
$$=\int_{a_1}^{\infty}[1-F_{A_2|A_1=a_1}(a_2)]f_{A_1}(a_1)da_1 \tag{7}$$

where, $F_{A_2|A_1=a_1}(a_2)$ is the probability density function of A_2, ground motion at site 2, on the condition that $A_1=a_1$. The concept of eqn.(7) is illustrated in Fig.2.

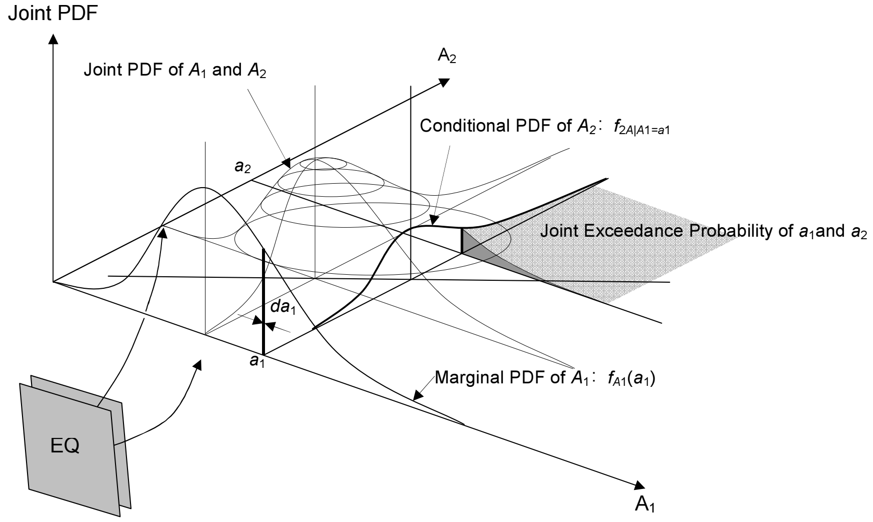

Figure 2. Concept of joint exceedance probability

Evaluation of Correlation Factor of Inter-correlation

As mentioned before, correlation factor for the inter-correlation cannot be given in the explicit form. So, in order to quantify the inter-correlation, this paper introduces the probability p_C (herein after called conditional joint probability) as a measure of correlation, which is given by the following equation,

$$p_C(a_1, a_2) = \frac{p(a_1, a_2)}{p(a_1, 0) + p(0, a_2) - p(a_1, a_2)} \tag{8}$$

Since $p(a_1, 0)$ and $p(0, a_2)$ are marginal seismic hazard of sites 1 and 2, eqn.(8) means that p_C is the probability that ground motion intensity exceeds a_1 at site 1 and exceed a_2 at site 2 simultaneously on the condition that ground motion intensity exceeds a_1 at site 1 or ground motion intensity exceeds a_2 at site 2. If two sites are located very close to each other, p_C is evaluated as unity since $p(a,0) = p(0,a) = p(a,a)$ when $a_1 = a_2 = a$. On the contrary, if the distance between two sites is large enough, p_C will be evaluated null since $p(a_1, a_2) = 0.0$. Conditional joint probability p_C is not a correlation coefficient but can be an alternative measure to quantify the magnitude of correlation indirectly, so that this paper employs p_C to examine the correlation between two sites.

APPLICATION

Nine sites are selected to examine the inter-correlation. Since a lot of previous studies on intra-correlation exist, this paper does not mention the intra-correlation itself but its effect on the inter-correlation.

Condition Setting

Figure 3 shows the location of nine (9) model sites; site-0 is the reference one located at Tokyo metropolitan government office, site-11 to site-14 are arranged in the north direction from site-0, and, site-21 to site-24 are arranged in the southeast direction from site-0.

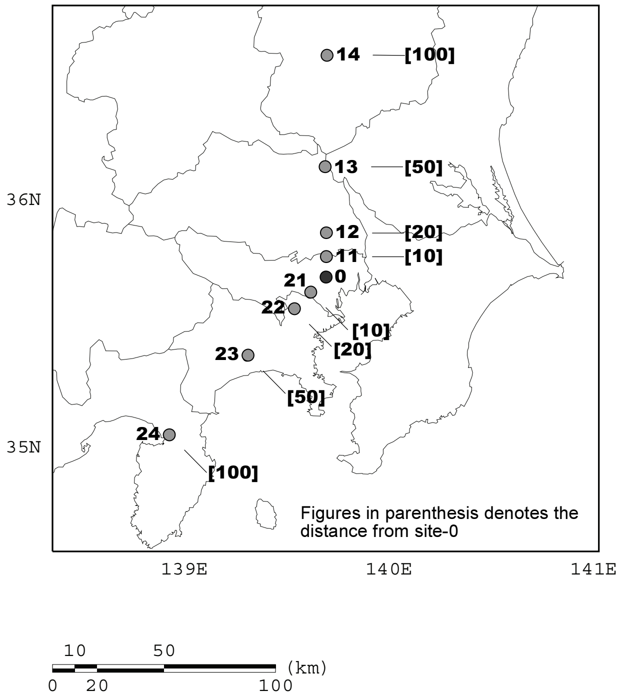

Figure 3. Arrangement of the model sites

Seismic source zone model is based on AIJ (2004), where two (2) types of source models are established; one corresponds to the characteristic earthquakes and the other to the background earthquakes. Ground motion prediction is done using attenuation formula by Annaka et al. (1998). Peak ground acceleration at engineering bed rock is selected as a ground motion measure, which is given by the following formula,

$$\begin{aligned} \log a &= 0.606M + 0.00459h - 2.316\log(d) + 1.730 \\ d &= \Delta + 0.334\exp(0.653M) \end{aligned}, \tag{9}$$

where, a is a peak ground acceleration, Δ is the shortest distance from the source, h is a focal depth, and M is a magnitude in JMA scale, respectively.

Standard deviation of ground motion prediction is given by Hayashi (2006), by which inter-event standard deviation is 0.239 (in common logarithms) and intra-event one is 0.198 (in common logarithms), respectively. Intra-event correlation ρ is given by the following equation,

$$\rho = \exp(-0.042 \cdot z^{1.033}), \tag{10}$$

where, z is a distance between sites.

Joint Probabilistic Seismic Hazard

Figure 4 shows the joint probabilistic seismic hazard planes, where the figures denote the power of ten (10). Since seismic hazard of site-11 to site-14 is dominated by in-crust earthquakes, correlation gets smaller with the increment of site-to-site distance. Especially correlation is quite small for site-13 and site-14 which are located very far from site-0. On the contrary, large inter-plate earthquake is dominant to site-21 to site-24, effect of site-to-site distance is not large. Also it is noted that the effect of the site-to-site distance cannot be judged for site-23 since the seismic hazard of site-23 itself is larger than other sites due to the location of dominant earthquake.

Therefore it can be concluded that the joint probabilistic seismic hazard is applicable to the risk assessment of the portfolio of buildings, however it is not adequate to examine the correlation of damage to the portfolio.

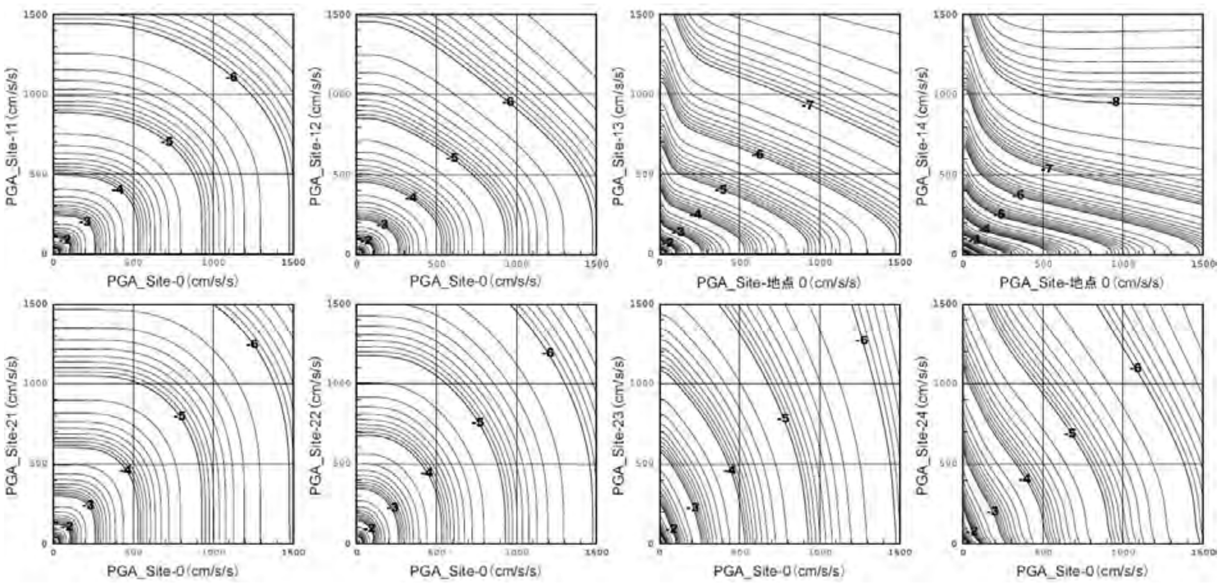

Figure 4. Joint probabilistic seismic hazard

Conditional Joint Probability

Figure 5 shows the conditional joint probability. From the figure it can be seen that the effect of site-to-site distance appears more clearly, since the magnitude of seismic hazard of individual site is cancelled as expressed by eqn. (8). It is apparent that there is a monotonic relationship between the site-to-site distance and inter-correlation. Comparing the conditional joint probabilities for sites-11 to -14 and those for sites-21 to -24, it can be seen that the former decreases more rapidly with the increment of the site-to-site distance. This tendency comes from the deference in dominant earthquake as mentioned before.

From the features above, it is concluded that the conditional joint probability can be a good estimator of inter-correlation.

Effect of Intra-correlation on Inter-correlation

As illustrated in Fig.1, it is apparent that intra-correlation affects the inter-correlation. However some studies on risk management of portfolio of buildings assume that intra-correlation is unity or null for the convenience in calculation.

In order to examine the adequacy of the assumption, two intra-event correlations; one is unity and the other is null, are employed instead of the intra-event correlation by eqn. (10). Please be noted that inter-event correlation remains unity for all the cases.

Figure 6 shows the conditional joint probability in case that intra-event correlation is unity, and Fig.7 shows the one in case that intra-event correlation is null, respectively. From the Figs 6 and 7 it is apparent that the effect of intra-event correlation on inter correlation is large so that the assumptions mentioned may overestimate or underestimate the possibility of simultaneous damage to the buildings constructing the portfolio.

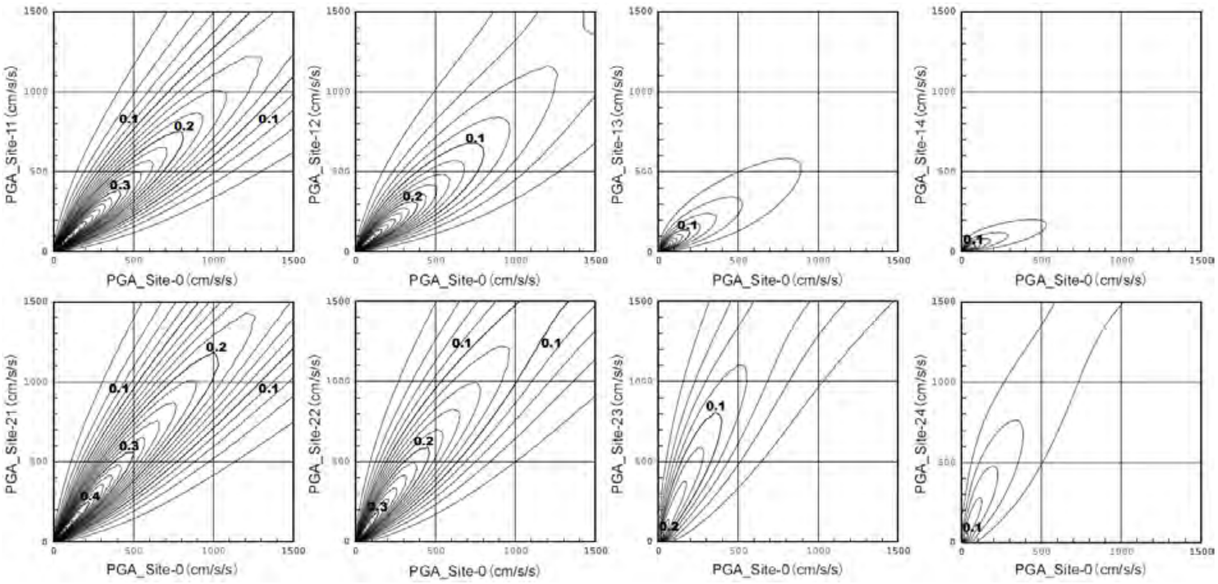

Figure 5. Conditional joint probability

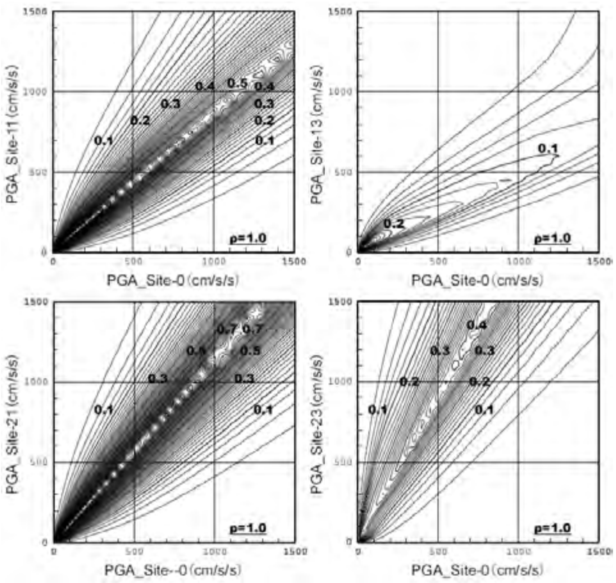

Figure 6. Conditional joint probability incase intra-correlation is unity

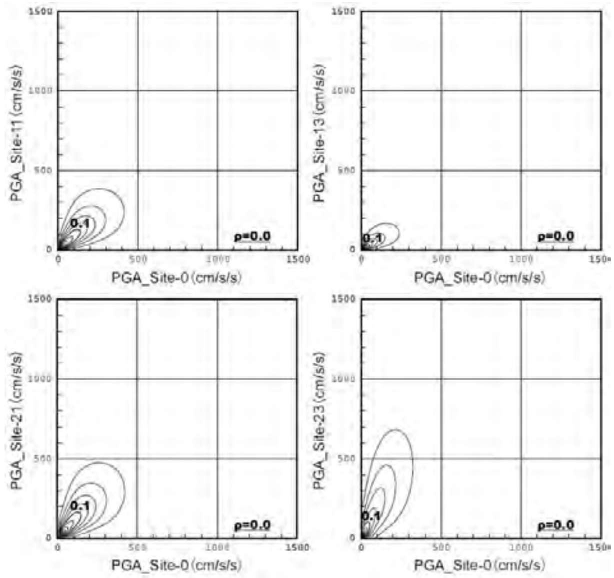

Figure 7. Conditional joint probability incase intra-correlation is null

CONCLUSION

This research proposed a joint seismic hazard analysis for two sites, considering the following correlations on ground motion intensity; one is the spatial correlation of each scenario earthquake employed in hazard analysis, and the other is the correlation introduced by the geometry of sites and scenario earthquake. Also, the measure to quantify the latter correlation was proposed. The method was applied to some sites in Kanto region of Japan, followed by the remark outcomes shown below;
[1] Joint seismic hazard is affected by the distance between to sites as well as by the locations to the dominant earthquakes, and,
[2] The correlation given by the geometry of site and scenario earthquake is affected by spatial correlation of each scenario earthquakes.

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