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EVALUATION OF JOINT PROBABILISTIC HAZARD OF GROUND SHAKING AND DEFORMATION USING MULTI-EVENT MODEL

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Abstract

Authors have implemented probabilistic seismic risk analysis for plant facilities, such as refineries and petrochemical plants subjected to ground shaking. Ground shaking is undoubtedly the biggest cause damaging structures. However as shown in 2011 Great East Japan earthquake, the ground deformation such as settlement and lateral displacement due to liquefaction as well as ground shaking has become of concern for long connected structures such as piping and its support structures. The excessive ground deformation may destroy the structures, if the structures are not designed in consideration of the relative displacement due to ground deformation.

In probabilistic risk analysis, it is needed to prepare seismic hazard curve which shows the relationship between hazard values and their exceedance probabilities. So far, a lot of researches on probabilistic ground motion hazard curve have been carried out, on the other hand, the number of research paper on probabilistic hazard curve of liquefaction of ground is limited. These two probabilistic hazards are assessed separately, even though they are not actually independent to each other. In addition, it is also noted that it is not adequate to determine ground motion intensity and amount of settlement for a given annual exceedance probability from the two seismic hazard curves and combine them, since the dominant earthquakes that greatly contribute to each hazard curves may differ.

This paper proposes the joint probabilistic hazard of ground shaking and deformation to assess the risk of plant facilities whose damage is given by both ground shaking and deformation.

As the solution, authors employ the multi-event model, in which numerous scenario earthquakes are generated with their attributes such as location, shape, magnitude and annual occurrence probability so that ground shaking and deformation by each scenario earthquake can be obtained. Finally the hazard is evaluated by combining each hazard with its annual occurrence probability. It is noted that the correlation between ground motion intensity and amount of ground deformation is automatically incorporated in the estimation.

Seismic source zones downloaded from J-SHIS web site are used to generate numerous scenario earthquakes from the viewpoint of accountability. Response accelerations for some natural period corresponding to each model structures are used as ground motion parameters. For this, ground motion prediction equation of NIED is used.

For the evaluation of ground deformation, the procedure described in “Recommendations for Design of Building Foundations” is applied. Some sites where large ground motions have been expected are selected as model sites.

The result of seismic hazard analysis is shown by seismic hazard surface or by conditional hazard curve; the former gives the annual probability when two hazard parameter, ground motion intensity and deformation, exceed their thresholds simultaneously, and the latter is given as the cross section of the former given the condition. The results will be compared with past records for validation.

Keywords: Petrochemical plant, Seismic hazard, Ground shaking, Ground deformation, Multi-event model

1. Introduction

Authors have implemented probabilistic seismic risk analysis for plant facilities subjected to ground shaking. Ground shaking is undoubtedly the biggest cause damaging structures. However as shown in 2011 Great East Japan earthquake, the ground deformation such as settlement and lateral displacement due to liquefaction of ground as well as ground shaking has become of concern for long connected structures such as piping and its support structures. The excessive ground deformation may destroy the structures, if the structures are not designed in consideration of the relative displacement due to the ground deformation.

Though some liquefaction analysis methods has proposed by researches to analyze the phenomenon of liquefaction of ground and to evaluate liquefaction potential, settlement, and so on for design purpose, probabilistic hazard analysis of liquefaction of ground in the field of risk assessment have not been conducted so many. This is because some of liquefaction analysis methods are too time consuming to be employed in risk analysis. Kurita and Fukushima [1] proposed a liquefaction hazard analysis method by combining multi-event model and simple liquefaction estimation procedure focusing on the settlement of ground. However evaluation of lateral displacement of liquefied ground as well as settlement is necessary to assess the safety of plant facilities located in coastal area.

So, authors developed the probabilistic liquefaction analysis method that can evaluate liquefaction potential (P_L-value), settlement and lateral displacement. This method can also provide the joint probability of the values and ground motion intensities, so that the safety of plant facilities can be examined from viewpoint of ground shaking and of ground deformation, simultaneously.

2. Methodology

Authors employ the multi-event model which evaluates the probability of hazard value for each event with annual occurrence probability and integrates them to produce hazard curve. The detailed explanation of multi-event model is, for example, given by Fukushima and Yashiro [2]. Figure 1 shows the flowchart of liquefaction analysis.

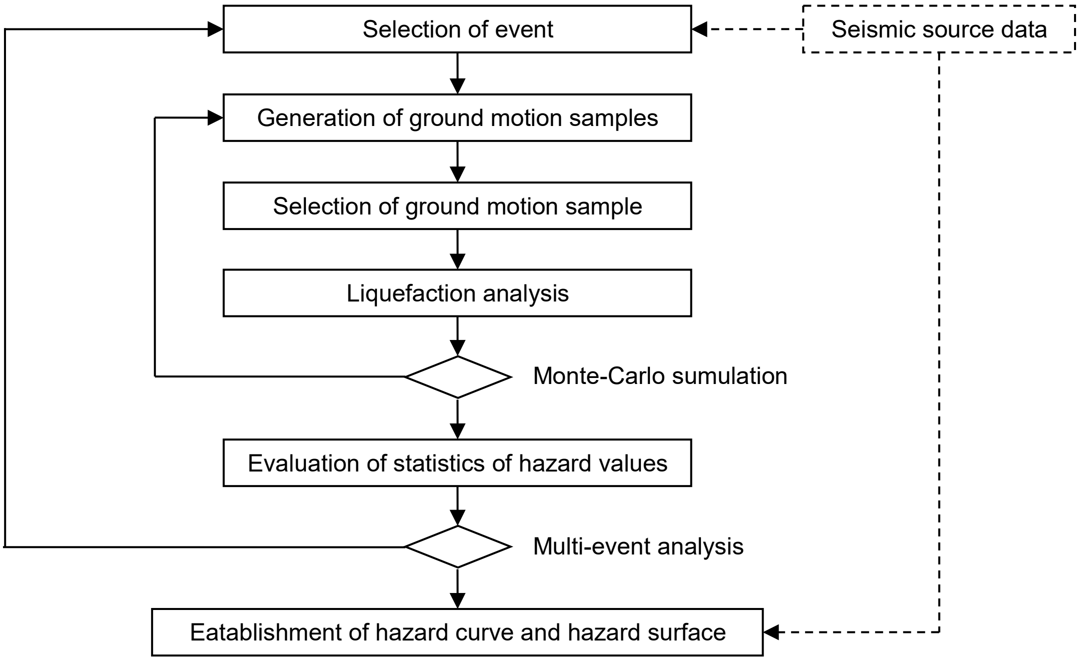

Fig. 1 Flowchart of probabilistic liquefaction analysis

2.1 Selection of event

From the seismic source model, events that are discretized seismic source model having magnitude, location, shape and annual occurrence frequency are generated and selected. Selection is done considering magnitude and distance which are the dominant factors to give damaging ground motion to plant facilities.

2.2 Generation of ground motion samples

The variability of ground motion intensity is considered as one of biggest factors giving uncertainty in hazard values. Since the uncertainty of hazard values cannot be obtained theoretically, this procedure employs Monte-Carlo simulation, for which a set of ground motion intensity are provided. It is noted that the peak ground acceleration (hereinafter called PGA) is used as ground motion parameter.

One of the advantage to prepare the set of PGAs in advance, it can easily be possible to reflect the correlation of PGAs among the site in case that plant sites in different locations are of concern.

2.3 Selection of ground motion sample

This is a simple procedure just to select PGA for the analysis from the generated set of PGAs. As well as PGA, the magnitude of event is also selected to conduct liquefaction analysis.

2.4 Liquefaction analysis

In the multi-event model, numerous liquefaction analysis need to be conducted. For this purpose, the simple method described in “Recommendations for Design of Building Foundation”[3] is employed, by which three hazard values, the P_L-value, settlement and lateral displacement can be evaluated.

2.4.1 Evaluation of P_L-value

P_L-value can be evaluated as the weighted sum of F_L-values which are safety factors of layers up to the depth of 20m as shown below,

$$P_L = \int_0^{20} F \cdot W(Z)dx \tag{1a}$$

$$F = \begin{cases} 1 - F_L & (F_L < 1.0) \\ 0 & (F_L \geq 1.0) \end{cases} \tag{1b}$$

$$W(Z) = 10 - 0.5Z \tag{1c}$$

where, Z is depth.

F_L-value is obtained as shown below,

$$F_L = R/L \tag{2}$$

where, R is dynamic shear strength ratio of layer and L is shear stress ratio during earthquake, respectively.

2.4.2 Evaluation of Settlement

Amount of settlement D_S is obtained by following equation,

$$D_S = \sum_{i=1}^{n} h_i \cdot \varepsilon_v \tag{3}$$

where, h_i is thickness and ε_v is volumetric strain of liquefied layer up to the depth of 20m. ε_v is evaluated by adjusted N-value N_a and stress ratio τ_d/σ'_Z using diagram shown in Fig. 2

2.4.3 Evaluation of lateral displacement

Amount of lateral displacement D_{LF} is obtained by following equation,

$$D_{LF} = \sum_{i=1}^{n} h_i \cdot \gamma_{max} \tag{4}$$

where, h_i is thickness and γ_{max} is the maximum residual strain of liquefied layer up to the depth of 20m. γ_{max} is evaluated by adjusted N-value N_a and stress ratio τ_d/σ'_z using diagram shown in Fig. 3

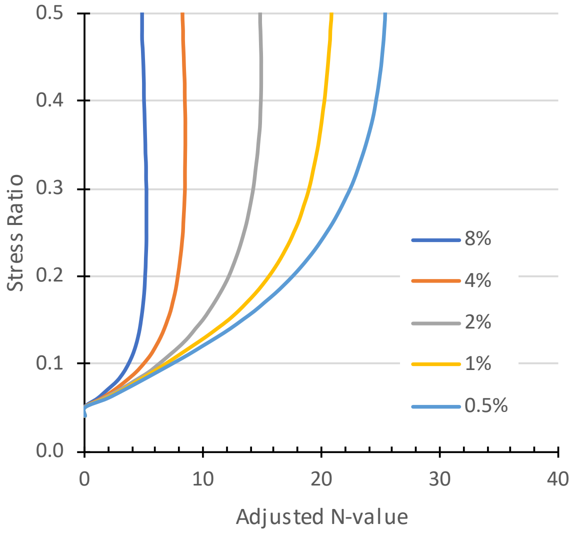

Fig. 2 Relationship between adjusted N-value and volumetric strain

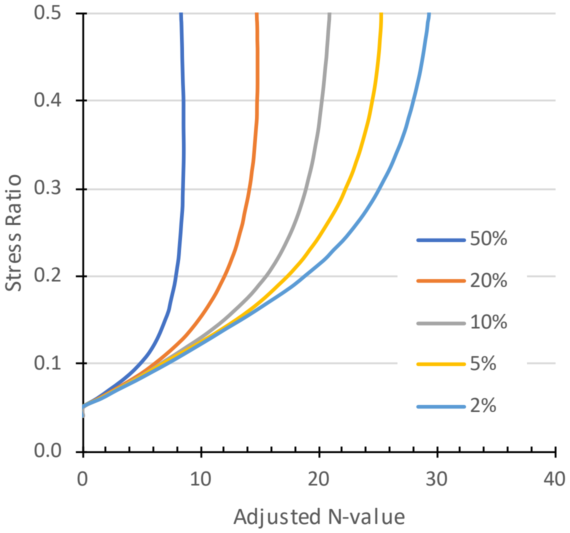

Fig. 3 Relationship between adjusted N-value and maximum residual strain

2.5 Evaluation of statistics of hazard values

Statistics of hazard values are modelled from the result of Monte-Carlo simulation. Since these hazard values take null when the ground of concern is not liquefied due to small ground motion, ordinary probability density function such as normal distribution or log-normal distribution cannot be applied. In order to solve this situation, authors introduce the probability density function shown in Fig. 4.

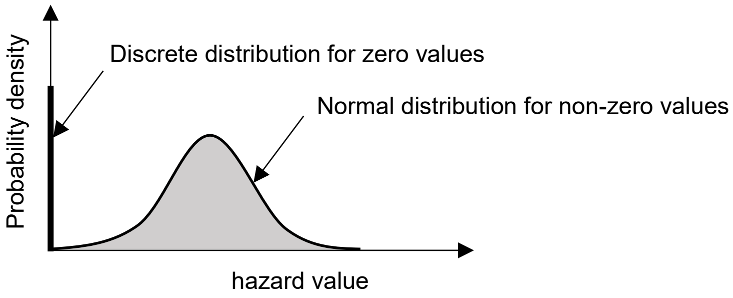

Fig. 4 Probability density function of liquefaction hazard values

Probability density of hazard value is divided into two parts; normal distribution for non-zero values and discrete distribution for zero values. The ratio of these distribution is determined by the number of Monte-Carlo simulation.

2.6 Establishment of hazard curve and hazard surface

Let R_i be the hazard value for event i. So annual exceedance probability of the hazard value $y_{j,i}$ for event i is given by the following equation,

$$y_{j,i} = \nu_i \cdot P(R_i > x_j) \tag{5}$$

where, ν_i is annual occurrence frequency of event i, x_j is j th threshold.

Since events are independent to one another, annual exceedance probability of the hazard value Y_j is given as follows,

$$Y_j = \sum_{i=1}^{n} y_{j,i} \tag{6}$$

where, n is the number of events. By repeating this step for every thresholds, hazard curve that is the relationship between threshold and annual exceedance probability of hazard value is obtained.

Above approach is extended to generate 2-dimensional hazard surface that shows the joint annual exceedance probability. Let R_{1i} and R_{2i} be the hazard values for event i, and x_{1j} and x_{2k} be the j th and k th thresholds. Then annual exceedance probability of the hazard value $y_{j,k,i}$ is given by the following equation.

$$y_{j,k,i} = \nu_i \cdot \bigcap \left[P(R_{1i} > x_{1j}), P(R_{2i} > x_{2k}) \right] \tag{7}$$

Since two hazard values may be correlated to each other, correlation function needs to be evaluated to obtain intersection of two probabilities. However it is difficult to obtain such correlation function, this paper employs two cases in which two probabilities are independent or perfectly correlated. So intersection of probability is given as follows.

$$\bigcap \left[P(R_{1i} > x_{1j}), P(R_{2i} > x_{2k}) \right] = P(R_{1i} > x_{1j}) \cdot P(R_{2i} > x_{2k}) \tag{8a}$$

$$\bigcap \left[P(R_{1i} > x_{1j}), P(R_{2i} > x_{2k}) \right] = \min \left[P(R_{1i} > x_{1j}), P(R_{2i} > x_{2k}) \right] \tag{8a}$$

Annual exceedance probability of the hazard value $Y_{j,k}$ is given as follows,

$$Y_{j,k} = \sum_{i=1}^{n} y_{j,k,i} \tag{9}$$

3. Application

3.1 Model site and layer sequence

Yokkaichi Industrial Complex in Mie prefecture is selected as model plant site as shown by J-SHIS Map [4] in Fig. 5, since the Yokkaichi city in Mie prefecture is located in the vicinity of many active faults and the Nankai Trough. It is noted that mega earthquakes have occurred on a 100 to 150 year recurrence period in the area along the Nankai Trough. Table 1 shows the layer sequence of model site. The under water level was set as 1.0m below surface.

Source: J-SHIS Map

Fig. 5 Location of model site

Table 1 Layer sequence of model site

Depth (m)	Soil	N-value	Fine grain fractions (%)	Unit weight (kN/m^3)
2	Fill	14	80	17.6
3	Fill	8	80	17.6
4	Stone mingling silt	32	65	18.6
5	Silt	6	75	17.2
6	Gravel	22	0	20.6
7	Stone mingling sand	60	0	19.6
8	Stone mingling clay	43	65	16.7
9	Gravel	60	0	20.6
10	Sand mingling clay	14	65	16.2
11	Stone mingling sand	40	0	19.6
12	Stone mingling sand	45	0	19.6
13	Gravel	60	0	20.6
14	Gravel	51	0	20.6
15	Stone mingling silt	15	65	18.6
16	Gravel	46	0	20.6
17	Gravel	60	0	20.6
18	Sand	60	0	18.2
19	Sand	60	0	18.2
20	Sand	40	0	18.2

3.2 Seismic source model and ground motion prediction equation

Seismic source model is constructed based on the database prepared by National Research Institute for Earth Science and Disaster Resilience (NIED) to assure the accountability. And ground motion prediction equation in NIED (2009) [5] is employed.

3.3 Seismic hazard curve

Seismic hazard curves of PGA and liquefaction related values are shown in Fig. 6. The effect of discrete distribution of zero-value on hazard curves can be seen regarding to P_L-value, settlement and lateral displacement, respectively. Though the hazard values are different, trend of hazard curves regarding to settlement and lateral displacement are quite similar to each other since the relationships between strain and adjusted N-value indicated in Figs 2 and 3 are similar.

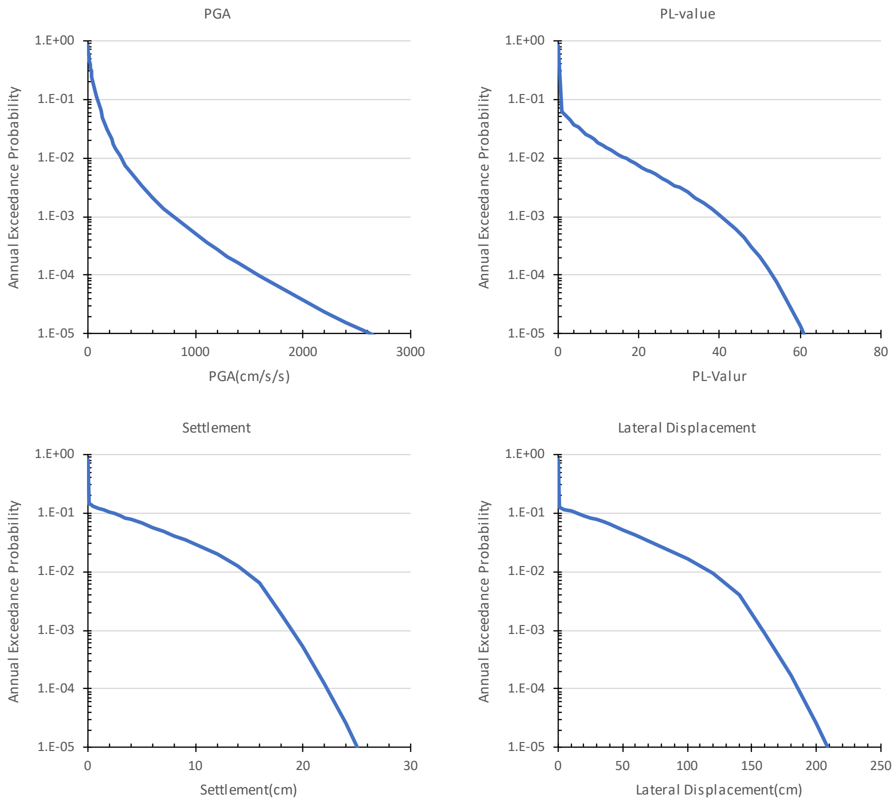

Fig. 6 Hazard curves of PGA and liquefaction related values

3.4 Seismic hazard surface

Figure 7 shows the seismic hazard surface as the cross section regarding to the given threshold. It is noted that parameters of seismic hazard are assumed independent to each other. From the figure it can be seen that hazard of PGA is not affected so much by given liquefaction values except for the case of small PGA. On the contrary hazards of liquefaction values are affected by PGA. These tendencies are given by the shape of seismic hazard surfaces, whose marginal shapes are shown in Fig. 6.

Figure 8 shows the seismic hazard surface in case that two parameters are perfectly correlated to each other. The tendency described above is also observed though the shape of seismic hazard shape is different.

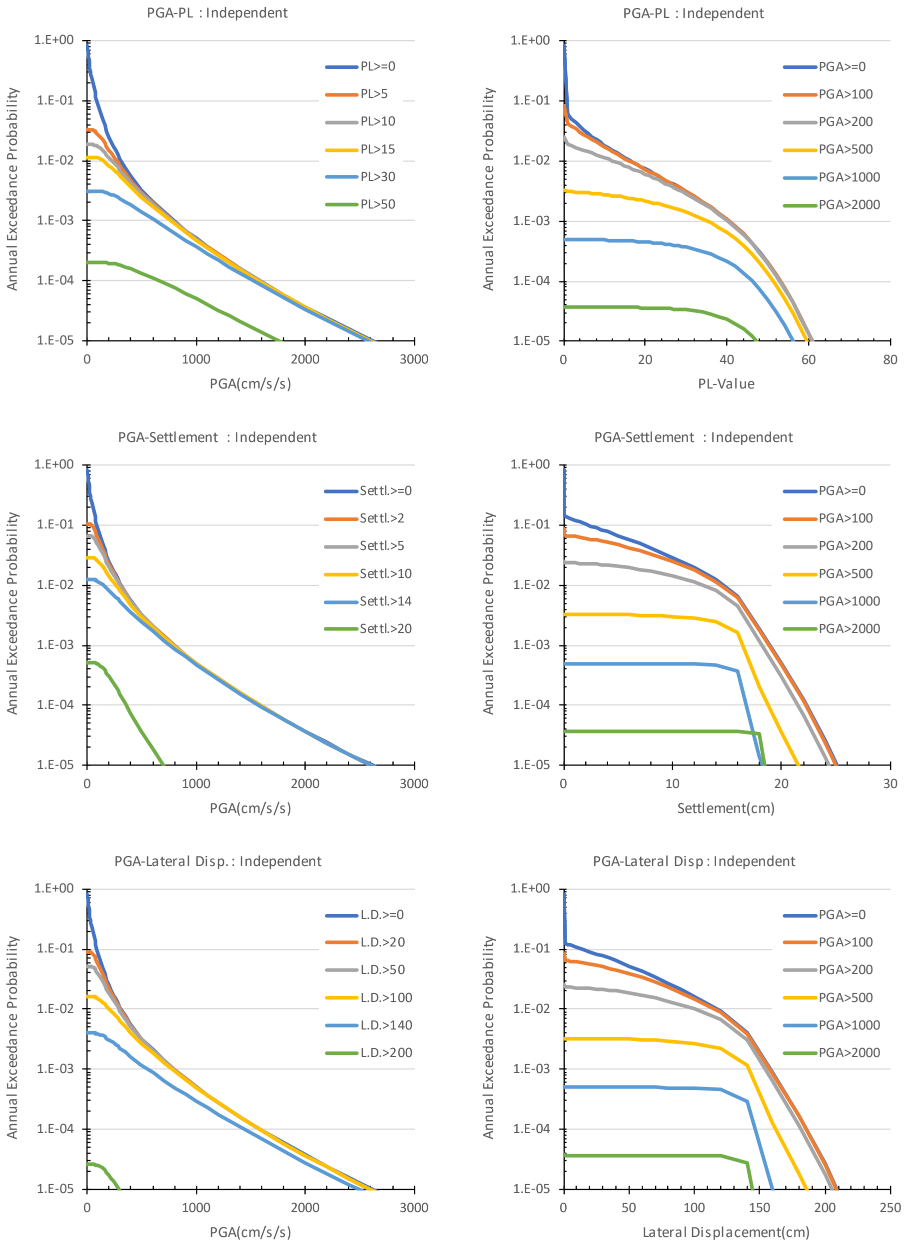

Fig. 7 Hazard surface of PGA and liquefaction related values (Independent case)

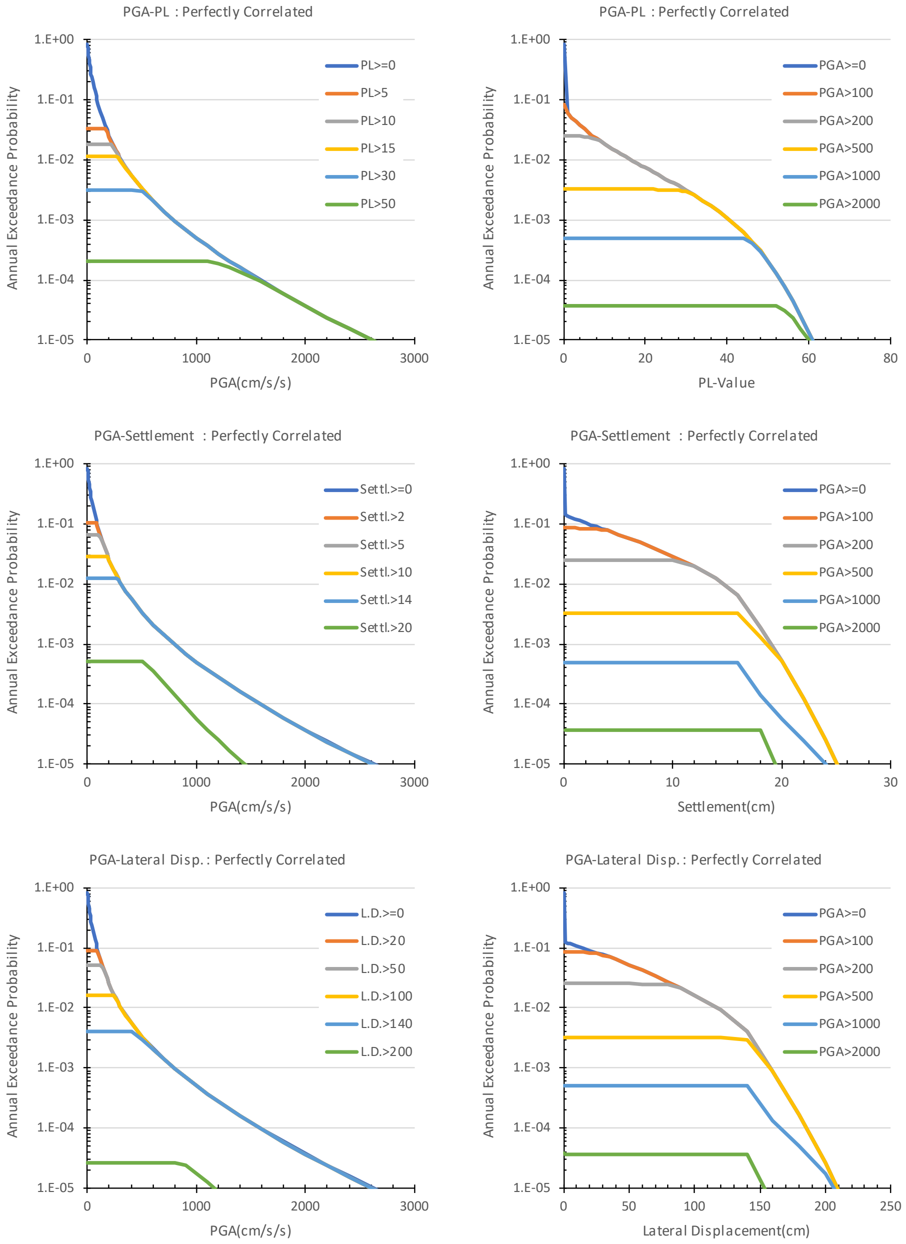

Fig. 8 Hazard surface of PGA and liquefaction related values (Perfect correlation case)

3.5 Conditional liquefaction probability

From the viewpoint of estimating safety of plant facilities, it becomes important to know the liquefaction probability after earthquake of given intensity. So conditional liquefaction probability that is the joint probability normalized by annual exceedance probability of PGA, is established as shown in Fig. 9.

For example, the probability that P_L-value exceeds 10 will be 0.5 if PGA is 300 (cm/s/s) and these two parameters are independent to each other. Namely, if plant facility is subjected to a certain amount of ground motion intensity, ground deformation due to liquefaction, such as settlement and lateral displacement will effect on the facilities.

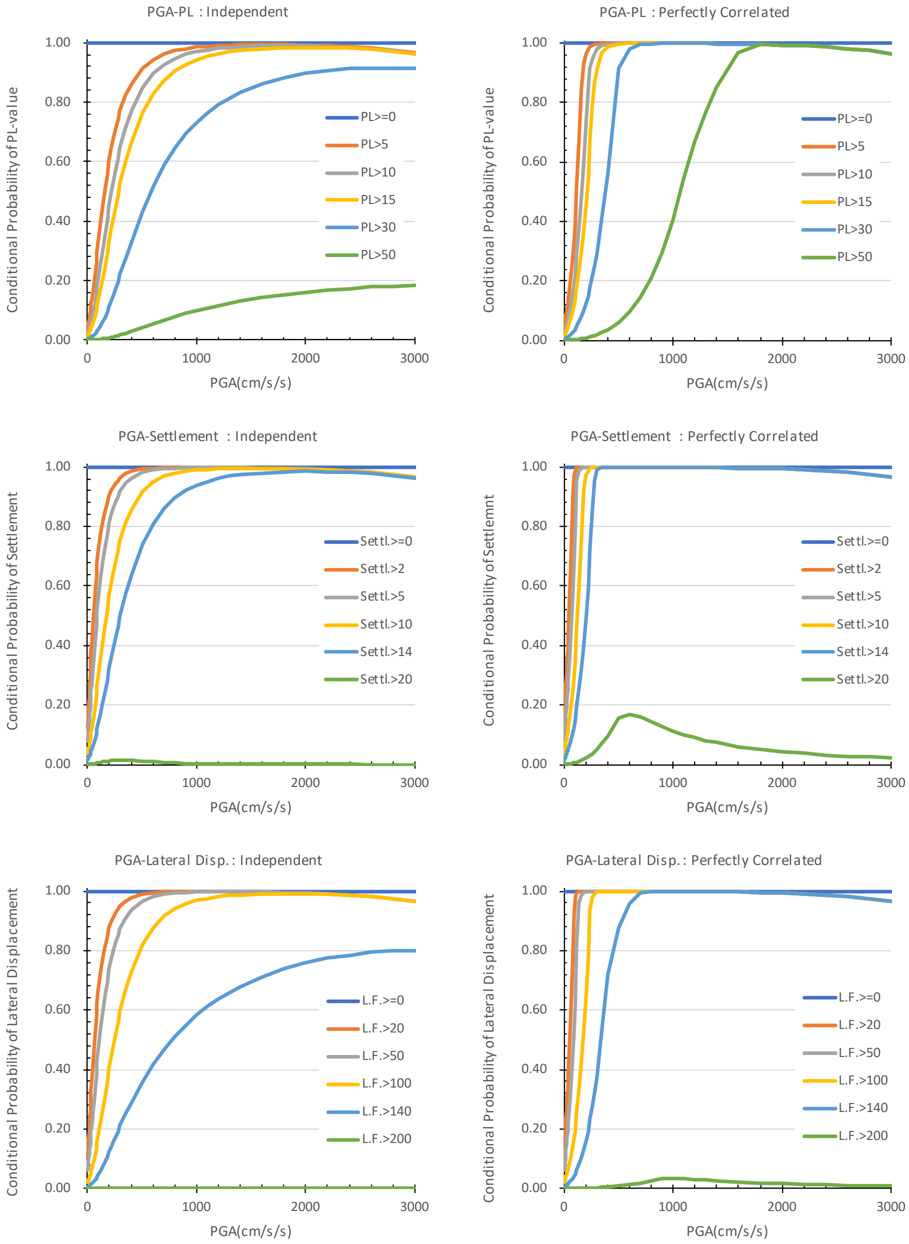

Fig. 9 Conditional hazard of liquefaction values on PGA

4. Conclusion

Authors have implemented probabilistic seismic risk analysis for plant facilities subjected to ground shaking. Ground shaking is undoubtedly the biggest cause damaging structures. However as shown in 2011 Great East Japan earthquake, the ground deformation such as settlement and lateral displacement due to liquefaction as well as ground shaking has become of concern for long connected structures such as piping and its support racks. The excessive ground deformation may destroy the structures, if the structures are not designed in consideration of the relative displacement due to ground deformation. Therefore, authors focused on the risk analysis of long connected structures subjected to ground deformation as well as ground shaking.

There are two ways to anticipate risk, one is deterministic approach so-called scenario-base damage estimation and the other is probabilistic approach. From the risk management point of view, it is very important to grasp the risk both by the intensity of damage and by the occurrence probability, so that the latter, the probabilistic approach was employed in this study.

At first, the risk evaluation method for ground shaking was established by introducing multi-event model, which evaluate risk for numerous discretized earthquake and integrate the results to obtain risk curve. In establishment of the method, utilized was the simple method to evaluate the potential of liquefaction, settlement and lateral displacement.

Then, the method was applied to model plant site at Yokkaichi, where large earthquake has been expected to occur with high probability. In the application, seismic hazard curves of ground shaking, liquefaction potential (P_L-value), settlement and lateral displacement were evaluated. It is noted that joint hazards showing simultaneous exceedance probability were developed for the combination of ground shaking and ground deformation. Moreover, it is demonstrated that normalizing joint hazard by the occurrence probability of ground shaking gives the useful information as conditional hazard of liquefaction values.

The future work will be the combination of the hazard and fragility of ground shaking, considering realistic plant facilities. The joint fragility showing the failure probability for given combination of ground shaking and deformation will be developed, in order to establish risk by combining hazard surface proposed in this paper.

5. References

References must be cited in the text in square brackets [1, 2], numbered according to the order in which they appear in the text, and listed at the end of the manuscript in a section called References, in the following format:

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