Evaluation of Seismic Risk of Plant Site Consisting of Various Types of Structures Using Multi-Event Model

A. Satoda[(1)], M. Oshima[(2)], S. Fukushima[(3)]

[(1)] *Senior Engineer, Chiyoda Corporation, satoda.akira@chiyodacorp.com*
[(2)] *Technical Expert, Chiyoda Corporation, oshima.masami@chiyodacorp.com*
[(3)] *CEO, RKK Consulting Co., Ltd., fukushima@rkk-c.co.jp*

Abstract

Authors have conducted probabilistic seismic risk evaluation of petrochemical plant facilities using peak ground acceleration (hereinafter called PGA) as ground motion parameters by the reason that PGA is the parameter used in the seismic design so that it was convenient for authors to estimate median capacity of structures referring to the current design standards. Another advantage in using PGA is that many ground motion prediction equations have been proposed by many researchers.

It is however pointed out that PGA is not always a good estimator to express real damage to structures, especially one to mid and long period structures. Therefore, selecting the ground motion parameter has been a problem not only for single structure but also for portfolio consisting of various types of structures such as petrochemical plant. It is noted that seismic hazard curves with different ground motion parameters cannot be used simultaneously since dominant earthquake may differ for given exceedance probability.

So this paper proposes the risk evaluation using multi-event technique so that deferent ground motion parameters suitable for each structure, such as PGA, peak ground velocity (hereinafter called PGV) and spectral accelerations corresponding to the natural period of concern, can be applied simultaneously.

Each structure in the plant facilities is modelled by fragility curve using the best ground motion parameter that may be the one with the smallest aleatory uncertainty. PGA, PGV and some spectral acceleration are the candidates of ground motion parameters.

Numerous individual earthquakes generated from seismic sources model are called events. Each event has its location, shape, magnitude and annual frequency of occurrence so that ground motion parameter at given site can be evaluated. The seismic source model employed in the analysis is downloaded from the web-site of J-SHIS data based and modified.

For each event, not only conditional damage to individual structure but also one to plant is estimated using fault tree analysis. Variability in ground motion parameter is reflected by Monte Carlo simulation so that the correlations among ground motion parameters with different ground motion parameters can duly be introduced.

As model plant site, selected is the Yokkaichi industrial complex in Mie prefecture prone to the large Nankai Trough earthquakes with high probability of occurrence. The model plant consists of several tanks with different diameter, several towers with different height and pipe racks.

Response accelerations for some natural period corresponding to each model structures are used as ground motion parameters. For this, ground motion prediction equation by NIED (2009) based on Kanno et al. (2006) is employed.

Keywords: Petrochemical plant, Seismic risk, Ground motion parameter, Risk curve, Multi-event model

1. Introduction

Authors have conducted probabilistic seismic risk evaluation of the plant facilities such as refinery or petrochemical plant using peak ground acceleration (hereinafter called PGA) as ground motion parameters by the reason that PGA is the parameter used in the seismic design so that it was convenient for authors to estimate median capacity of structures referring to the current design standards. Another advantage in using PGA is that many ground motion prediction equations have been proposed by many researchers.

It is however pointed out that PGA is not always a good estimator to express real damage to structures, especially one to mid and long period structures. Therefore, selecting the ground motion parameter has been a problem not only for single structure but also for portfolio consisting of various types of structures such as petrochemical plant. It is noted that seismic hazard curves with different ground motion parameters cannot be used simultaneously since dominant earthquake may differ for given exceedance probability.

So this paper proposes the risk evaluation using multi-event technique so that deferent ground motion parameters suitable for each structure, such as PGA, peak ground velocity (hereinafter called PGV) and spectral accelerations corresponding to the natural period of concern, can be applied simultaneously.

2. Methodology of seismic risk evaluation

2.1 Concept of Multi-Event Model

Figure 1 shows the concept of multi-event model employed in this paper, where events can be characteristic earthquake such as active faults or inter-plate earthquake, and discretized background earthquakes as used in the seismic hazard analysis. So far as illustrated in Fukushima (2015), a single ground motion parameter was used to evaluate the damage of the structures, so that selection of ground motion parameter was the issue in order to conduct the accurate risk evaluation since the uncertainty of structure's capacity is affected by the ground motion parameter. For example, it is known that PGA or spectral acceleration (hereinafter called SA) for short period is adequate for structures with short natural period, and the peak ground velocity (hereinafter called PGV) or SA for middle period is adequate for structures with middle or long natural period.

Therefore, it may be difficult to select the proper ground motion parameter if the plant site consists of structures with various natural periods. The feature of multi-event model employed is that plural ground motion parameter adequate to each structure are used simultaneously. Another advantage of using multi-event model is that it is applicable not only to structures in a single site but to ones in multi sites.

2.2 Generation of events and estimation of ground motion parameter

Events are generalized from the seismic zone models around the sites. Each event has following information; location such as longitude, latitude and depth of reference point, shape such as strike, dip angle, fault length and focal width, magnitude and annual occurrence frequency. These parameters are usually used in calculating probabilistic seismic hazard curve.

For given each event, ground motion parameter are estimated using ground motion prediction equation, followed by being amplified due to surface soil. In Fig. 1, ground motion parameter is denoted by $x_{j|i}$, where, i is an index for i^{th} event, j is an index for j^{th} structure whose natural period is T_j. It is noted that the ground motion parameters scatter about mean value and correlate with one another.

2.3 Calculation of failure probability

Capacity of each structure is characterized by seismic fragility curve, whose x-axis is the ground motion parameter $x_{j|i}$, and y-axis is the conditional failure probability $p_{j|i}$. Since ground motion parameters scatter, the conditional failure probabilities also scatter.

The conditional failure probability of the plant $p_{0|i}$ site is evaluated from those of structures in the plant considering the connectivity of them if the failure of the plant performance is of concern. Eq. (1) gives $p_{0|i}$ in case structure is connected in parallel, and Eq. (2) gives $p_{0|i}$ in case of series connection, where, n is the number of structures in the plant.

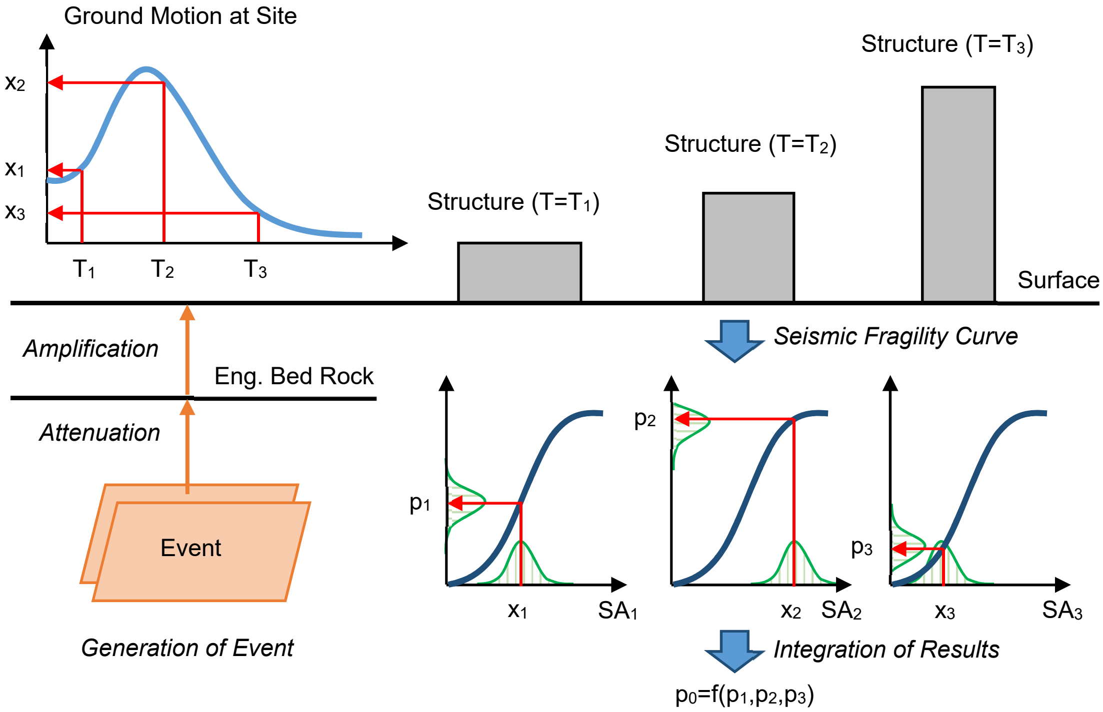

Fig. 1 – Concept of multi-event curve.

$$p_{0|i} = \min[p_{j|i}], j = 1, \cdots, n \tag{1a}$$

$$p_{0|i} = \prod_{j=1}^{n} p_{j|i}, j = 1, \cdots, n \tag{1b}$$

$$p_{0|i} = \max[p_{j|i}], j = 1, \cdots, n \tag{2a}$$

$$p_{0|i} = 1 - \prod_{j=1}^{n} (1 - p_{j|i}), j = 1, \cdots, n \tag{2b}$$

2.4 Evaluation of risk curve

Let p_{th} the threshold of failure probability. Then the annual frequency $\nu_j(p_{th})$ that failure probability exceeds the threshold is given by Eq. (3).

$$\nu_j(p_{th}) = \sum_{i=1}^{m} [\lambda_i \cdot \tilde{p}(p_{j|i} > p_{th})], j = 0, \cdots, n \tag{3}$$

where, λ_i is annual occurrence frequency of i^{th} event, $\tilde{p}(p_{j|i} > p_{th})$ is the probability that failure probability of j^{th} structure by i^{th} event exceeds the threshold.

By repeating the above calculation for some threshold, the risk curve for plant and for each structure can be obtained as the relationship between p_{th} and $\nu_j(p_{th})$. If the annual probability $pex_j(p_{th})$ that failure probability exceeds the threshold is requested, Eq. (4) is available to convert from frequency to probability.

$$pex_j(p_{th}) = 1 - e^{-\nu_j(p_{th})}, j = 0, \cdots, n \quad (4)$$

3. Application Example

3.1 Model site and model structures

Yokkaichi Industrial Complex in Mie prefecture is selected as model plant site as shown in Fig. 2. Because the Yokkaichi city in Mie prefecture is located in the vicinity of many active faults and the Nankai Trough earthquake occurrence area. In particular, in the area along the Nankai Trough, trench type mega earthquakes have occurred on a 100 to 150 year recurrence period, causing great damage to the area. And a tower supported on skirt is selected as model structure. Specification of towers are summarized in Table 1.

Fig. 2 – Location of model site. (Source: J-SHIS Map)

Table 1 – Specification of towers

Item	unit	Tower-1		Tower-2	
		Body	Skirt	Body	Skirt
Height (Above the ground)	[mm]	10,000	1,220	30,000	3,660
Mean Diameter	[mm]	2,000	1,000	3,500	3,500
Thickness	[mm]	9	12	17	19
Operational Weight	[N/mm]	137.5	137.5	125.8	125.8

3.2 Fragility analysis of towers

Seismic fragility curves of towers are estimated by numerical simulation. Input ground motions are generated from the uniform hazard spectrum (hereinafter called UHS) derived by seismic hazard analysis, in which 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) is employed.

UHSs and UHSs normalized by PGAs for some annual exceedance probabilities is shown in Fig. 3, from which it can be seen that normalized UHSs, namely spectral shapes, are almost identical except for the one corresponding to annual exceedance probability of 0.1.

For normalized UHS corresponding to annual exceedance probability of 0.001, 200 response spectra are generated assuming that the standard deviation about the median UHS is 0.2 in common logarithm. Also assumed is the inter-period correlation by Tanaka et al. (2008), in which the correlation is given by Eq. (5),

$$\rho(t_1, t_2) = 1 - 0.308 \cdot abs\left[\ln\left(\frac{t_1}{t_2}\right)\right] \quad for\ t_1, t_2 \geq 0.1 \tag{5}$$

where, t_1 and t_2 are the periods of concern. In case t is smaller than 0.1, the correlation is assumed unity.

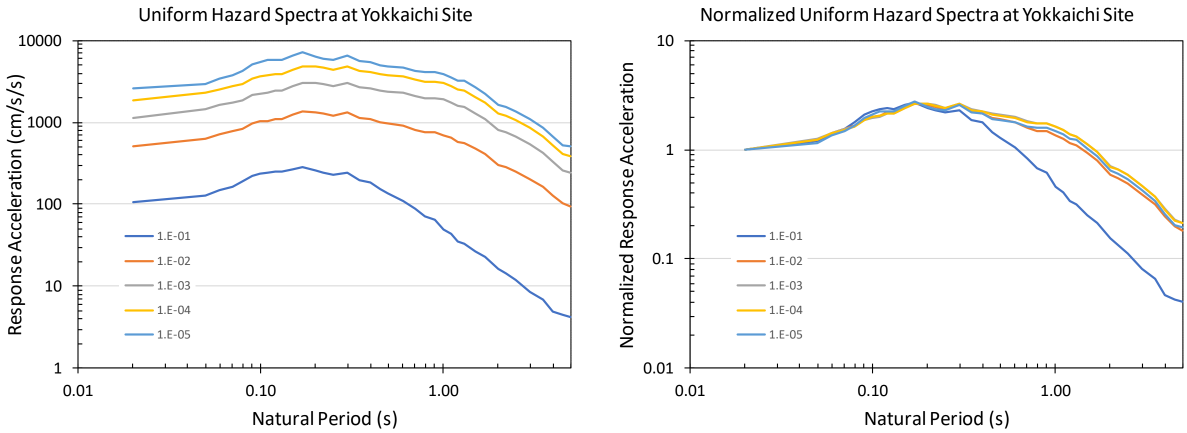

Fig. 3 – UHS and normalized UHS at Yokkaichi site.

Figure 4 shows the samples and fractiles of response spectra, from which input ground motions are generated. Generated ground motions are normalised by PGA of 100 [cm/s/s], SA(0.3) of 300 [cm/s/s] and SA(0.8) of 200 [cm/s/s], respectively. It is noted that SA(0.3) is chosen for Tower-1 with natural period of 0.3, and SA(0.8) is for Tower-2 with that of 0.8. PGA is for reference.

Towers are modelled as lumped mas model with fixed base, in which nodes are connected by linear beam elements. Specifications of models, such as mass, inertia, shear area and moment inertia are calculated using the data given in Table 1. Also given are Elastic modulus of material of 200,800 [N/mm2], Poisson's ratio of 0.3 and damping factor of 0.03.

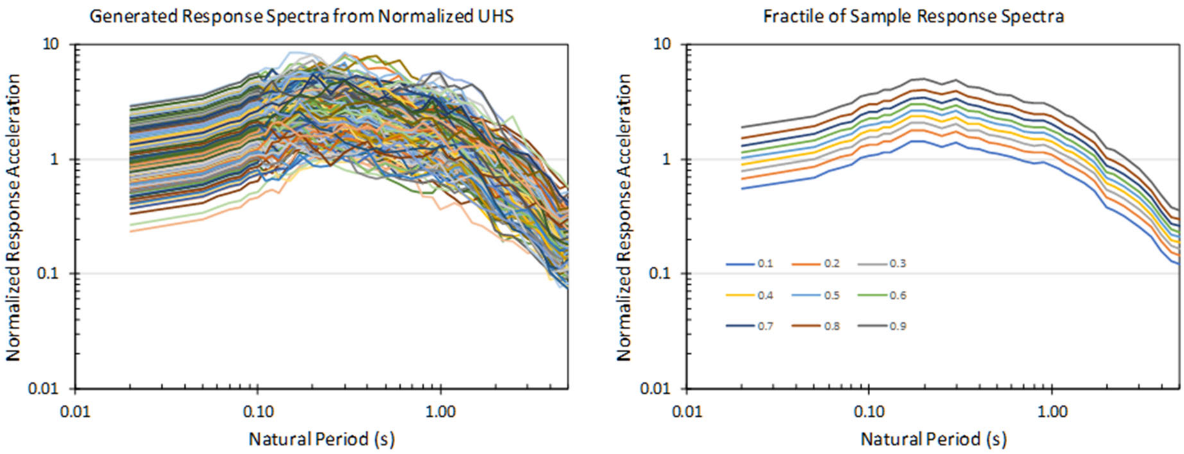

Fig. 4 – Samples of response spectra for fragility analysis.

The results of simulation is summarized in Fig. 5, in which median and common logarithm standard deviation of bending moment are shown since flexure is dominant as mentioned in Satoda et al. (2017). The ground motion parameter is set to 100 [cm/s/s] for PGA, 300 [cm/s/s] for SA(0.3) and 200 [cm/s/s] for SA(0.8), respectively. Though the median value of response cannot be compared with one another since ground motion parameter is not same, the standard deviations can be compared. From the viewpoint of variability, SA(0.3) is a proper parameter for Tower-1, and SA(0.8) is for Tower-2, respectively. This tendency is consistent with general knowledge.

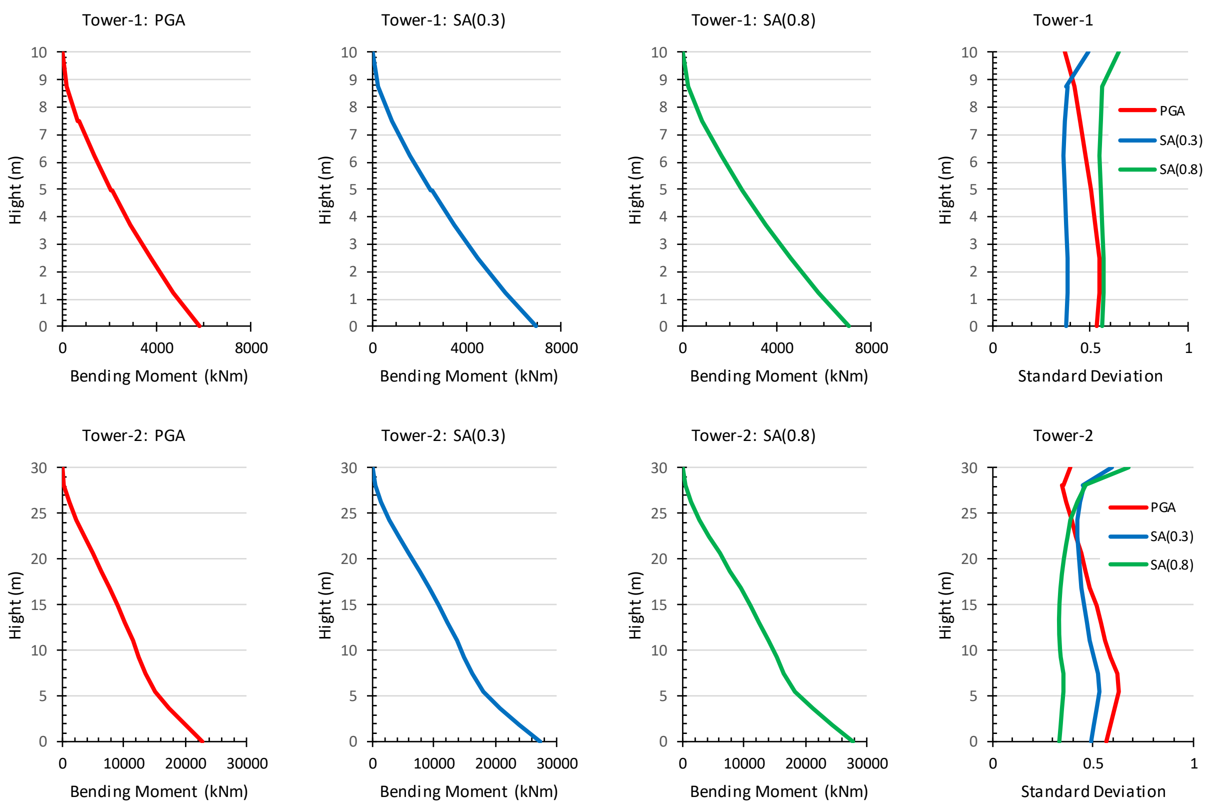

Fig. 5 – Results of response analysis

It is noted that PGA is not a good parameter to predict the responses for the structures used in the analysis, though PGA may be a good parameter for structures with shorter period. On the contrary, PGV may not be appropriate for structures with shorter period, but for ones with longer period. So it can be concluded that using single parameter may bring larger uncertainty into risk evaluation for plant site consisting of various structures.

Seismic fragility of towers are assumed log-normally distributed, so that two parameters, median and log-normal standard deviation, are necessary to obtain seismic fragility curve. Seismic fragility curve $F(x)$ is given by Eq. (6),

$$F(x) = \Phi\left[\frac{\ln(x) - \ln(\bar{x})}{\zeta}\right] \tag{6}$$

where, $\Phi[\cdot]$ is normal distribution function, x is a ground motion parameter, $\bar{x}$ is a median capacity parameter, ζ is logarithmic standard deviation. It is noted that ζ is given in natural logarithm.

Authors assume that the failure of towers is dominated by flexural buckling, the median capacity parameter $\bar{x}$ is given by Eq. (7),

$$\bar{x} = \frac{\bar{M}}{m(x_R)} x_R = \frac{(\sigma_c - \sigma_0)Z}{m(x_R)} x_R \tag{7}$$

where, $\bar{M}$ is the median of buckling moment that is given by allowable buckling stress σ_c, permanent stress σ_0 and section modulus Z. $m(x_R)$ is the median of resulting flexural moment for the input ground motion parameter x_R. Evaluation of σ_0 is based on the KHK(2012). Table 2 summarizes the parameters employed in Eq. (7).

Table 2 – Summary of parameters used in Eq. (7).

Item	unit	Tower-1		Tower-2	
		Body	Skirt	Body	Skirt
Allowable buckling stress σ_c	[N/mm^2]	165.00	199.0	165.00	199.0
Permanent stress σ_0	[N/mm^2]	25.11	17.02	21.80	17.40
Section modulus Z	[m^3]	0.028	0.037	0.162	0.181
Median of buckling moment $\bar{M}$	[kN*m]	3,920	6,779	23,197	32,841

Authors also assume that the buckling occurs in the tower at the top of skirt or in the skirt at the base. Using the Eq. (7), the median capacity parameter $\bar{x}$ is calculated for each ground motion parameter. The natural log-normal deviation is given by response analysis as shown in Fig. 5. Other variability factors for capacity parameter, such as the variabilities in material strength and damping, are ignored, since they are negligible. Table 3 summarizes the capacity parameters and Fig. 6 shows the seismic fragility curves, followed by the conclusion that the fragility of tower is dominated by that of body in case of both Tower-1 and Tower-2.

Table 3 - Summary of capacity parameters.

Capacity Parameter	Parameters in Eq. (6)	unit	Tower-1		Tower-2	
			Body	Skirt	Body	Skirt
PGA	x_R	[cm/s/s]	100	100	100	100
	$m(x_R)$	[kN*m]	4,729	5,818	17,427	22,801
	$\bar{x}$	[cm/s/s]	82.9	116.5	133.1	144.0
	ζ	-	0.548	0.531	0.610	0.568
SA(0.3)	x_R	[cm/s/s]	300	300	300	300
	$m(x_R)$	[kN*m]	5,650	6,951	20,821	27,241
	$\bar{x}$	[cm/s/s]	208.1	292.6	334.2	361.7
	ζ	-	0.383	0.375	0.517	0.489
SA(0.8)	x_R	[cm/s/s]	200	200	200	200
	$m(x_R)$	[kN*m]	5,756	7,081	21,210	27,750
	$\bar{x}$	[cm/s/s]	136.2	191.5	218.7	236.7
	ζ	-	0.568	0.561	0.347	0.332

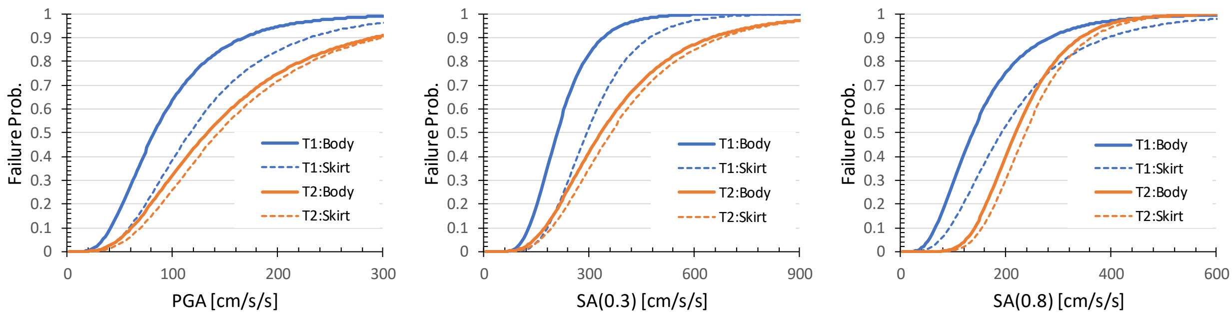

Fig. 6 – Fragility curve of tower.

3.1 Risk Analysis

As same as fragility analysis, seismic source zone model and ground motion prediction equation are based on NIED (2009). Figure 7 shows the risk curves for each tower. The blue curve shows the risk curve whose ground motion parameter is PGA. Orange and grey curves corresponds to risk curves using SA(0.3) and SA(0.8) as ground motion parameters, respectively. Though the level of annual exceedance probability may differ according to the ground motion parameter, the inclination of risk curve of Tower-1 is steepest when using SA(0.3), and that of Tower-2 is steepest when using SA(0.8). It is noted the inclination is defined by the ratio of deference in annual exceedance probability to deference in failure probability. Therefore ground motion parameter giving steeper inclination is better risk estimator.

From the figure it can be seen that PGA is not a good estimator of risk for Tower-1 or Tower-2. And it can also be seen that employing single ground motion parameter may bring the unavoidable uncertainty in risk evaluation in case that the plant of concern consists of equipment with different natural periods.

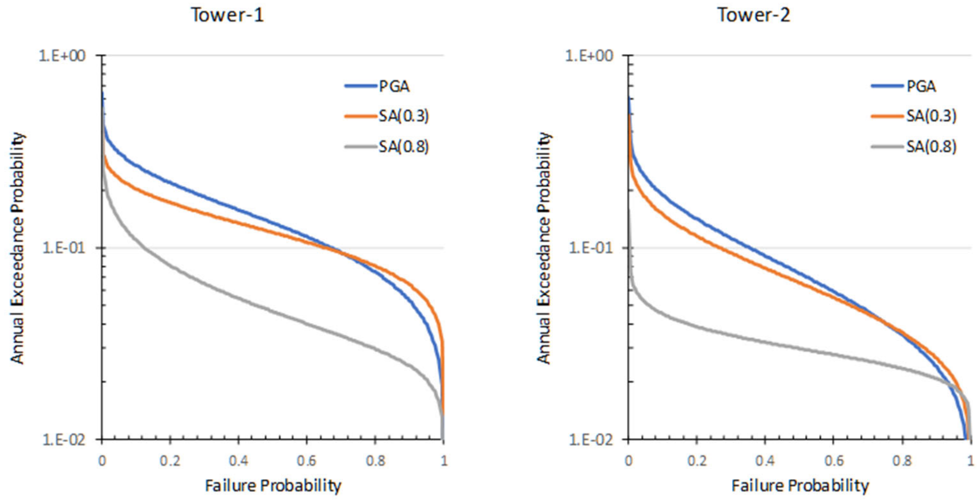

Fig. 7 – Risk curve of tower

Figure 8 shows the risk curves for parallel and series system, in which blue, orange and grey curves correspond the ground motion parameters above, respectively. The yellow dashed line, referred as "composite", corresponds the case that two ground motion, SA(0.3) and SA(0.8), are employed simultaneously. It can be seen that the "composite" is good risk estimator for both parallel and series system; the former is dominated by Tower-2 and the latter is dominated by Tower-1.

In Figs. 7 & 8, the x-axis of risk curves is failure probability. However, it is often necessary to employ loss or damage ratio instead of failure probability, where the damage ratio is defined as ratio of loss to construction cost. For illustration, Eq. (8) is introduced to evaluate damage ratio for i^{th} event assuming that the costs of Tower-1 and Tower-2 are identical.

$$dr_i = \frac{\sum_{j=1}^{n} p_{j|i}}{n} \tag{8}$$

Figure 9 shows the risk curve employing damage ratio as risk index. By taking the mean of failure probabilities as risk index, inclination of each risk curve is similar to one another, though "composite" is a good estimator and PGA is a bad estimator. It must be noted that this tendency depends on the construction cost of each equipment.

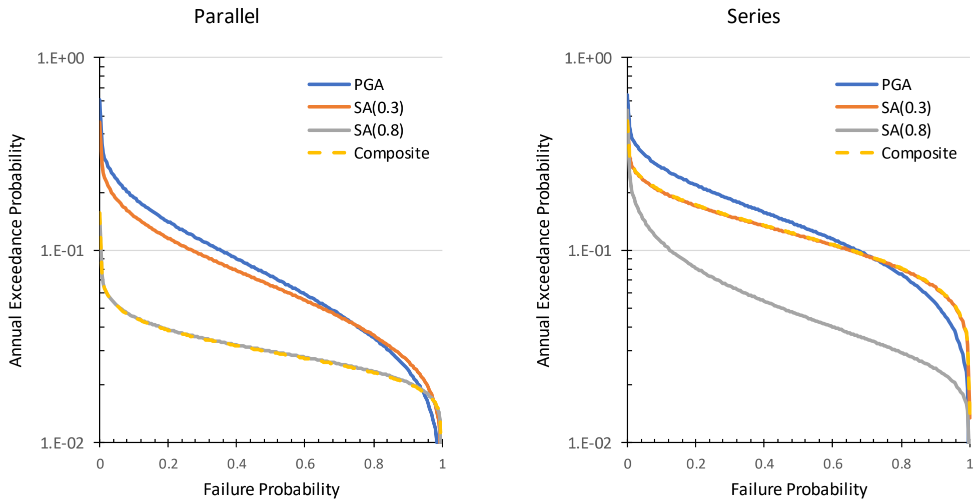

Fig. 8 – Risk curve of system

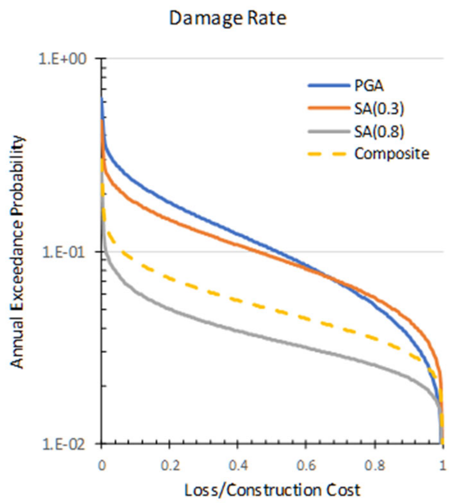

Fig. 9 – Risk curve of Damage Ratio.

4. Conclusion

Authors have conducted probabilistic risk evaluation of petrochemical plant structures using PGA as ground motion parameter. However plant sites consist of various structures and equipment with various natural period, for which PGA is not a good risk estimator from the viewpoint of variability. On the contrary, PGV or SAs are not also good estimator since their advantage is natural period dependent. So instead of using single ground motion index, authors proposed the multi-event model using plural indices aiming to reduce the uncertainty the risk evaluation.

The effectiveness of the method was examined by model plant site consisting of two towers whose natural periods are 0.3s and 0.8s, respectively. At first, some sets of ground motions were developed based on the UHS at Yokkaichi site, followed by normalization by natural period of concern. Then seismic fragility curves of towers were developed by Monte-Carlo simulation using each set of ground motion. The fragility curves identified critical failure mode of towers, which was the buckling of the body by flexure.

Finally, risk curve of each tower and that of system were calculated using multi-event model proposed. In the analysis four types of ground motion parameter, PGA, SA(0.3), SA(0.8) and combination of SA(0.3) and SA(0.8), were employed for comparison. By the comparison, it was pointed out that the combination of SA(0.3) and SA(0.8) is the best estimator of risk. On the other hand, PGA was not a good estimator regardless of objects.

In future, more realistic and complex system will be examined to examine the effectiveness of the method by introducing fault-tree into risk analysis.

6. References

[1] Fukushima, S. (2015). "Risk analysis of portfolio of facilities using multi-event model," Transaction of 23rd SMiRT, Paper No. 562, IASMiRT.

[2] J-SHIS Map, "Japan Seismic Hazard Information Station," http://www.j-shis.bosai.go.jp/en/, National Research Institute for Earth Science and Disaster Prevention.

[3] KHK (2012), "Seismic Design Code of High Pressure Gas Facilities", The High Pressure Gas Safety Institute of Japan.Park R, Gamble WL (2000): *Reinforced Concrete Slabs*. Wiley, 2nd edition.

[4] NIED (National Research Institute for Earth Science and Disaster Prevention) (2009). "A Study on National Seismic Hazard Maps for Japan," Technical Note of NIED No.336. (in Japanese)

[5] Satoda, A., Oshima, M. (2017) "Method for the evaluation of seismic risk and cost-effective strengthening of plant facilities," Transaction of 24th SMiRT, Paper-07-11-04, IASMiRT.

[6] Tanaka, K., Wang, M., Takada, T. (2008). "Covariance structure between spectral accelerations with different periods and its application," J. Struct. Const. Eng., AIJ, Vol.73, No.632, 1727-1733. (in Japanese)

