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SEISMIC RISK DENSITY CURVES FOR GRAVITY-TYPE QUAY WALLS

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In order to discuss the determination of the design ground motion level in seismic design for gravity type quay walls, characteristics of seismic risk density curves are analyzed. First, seismic loss functions for many situations are proposed based on fragility curves, which were calibrated by the results of effective stress-based FEM analysis considering many parameters including liquefaction resistance of foundation. Then, seismic risk density curves for these situations are calculated using proposed seismic loss function with the results of seismic hazard analysis at Kobe Port and Sakai Port. These seismic risk density curves can be classified into three types. Finally, a concept of design ground motion level definition was discussed based on the evaluated seismic risk density curves.

***Key words**: seismic design, ground motion level, seismic risk density curve, gravity-type quay wall*

1. INTRODUCTION

Since shortly after the Kobe disaster in 1995, the two-level approach has been commonly used in the definition of the design ground motion level in Japan. For example, the concept of performance-based design has been introduced in the new technical standard for port facilities, which was revised in 1999, and it stated that high seismic resistant facilities should maintain the required performance against the level-2 earthquake motions whose return periods are over some hundred years1). However, there is no supporting explanation of the basis for defining the design ground motion level. The level-1 ground motion is defined as the ground motion with a return period of 75 years, and the level-2 is defined as either the ground motion due to an intra-plate earthquake with a return period of more than several hundred years or the ground motion due to a subduction zone earthquake. However, the meaning of these definitions is still quite vague. In other words, ‘ Why is it 75 years for level-1? ’, and ‘What does the return period of several hundred years mean? ’.

For the first question, the author conducted a research study and clarified the background of the level-1 ground motion level definition for a limited number of cases, those in which the pseudo-static approach can work well2). However, the background is not verified for the general case. In a new proposal of seismic design guidelines for port structures by the International Navigation Congress (PIANC), level-1 and level-2 earthquake motions are defined as the motions with a 50 % and 10 % chance of being exceeded during the life span of a structure (probability of exceedance of 50 % and 10 %), respectively3). In this case, the second question can be answered. However, similar questions such as ‘why 50 % and 10 %? ’ still remain.

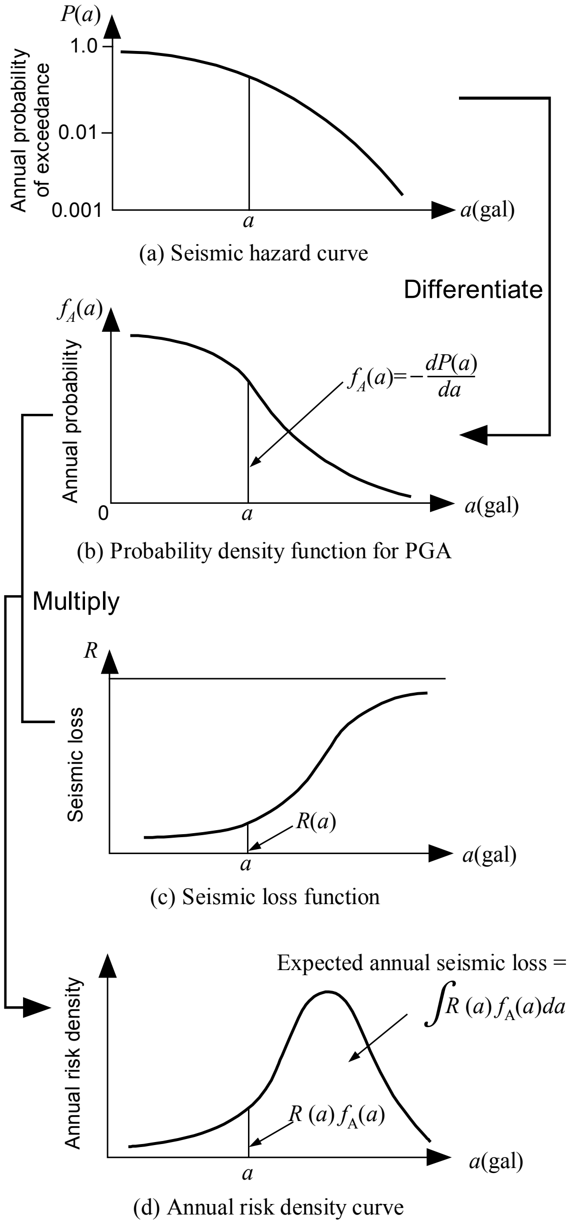
The author believes the design ground motion level should be determined with the consideration of seismic hazard characteristics at the site and seismic loss characteristics for the structures. Since the seismic risk density curve concept is useful to consider these characteristics simultaneously, a procedure to calibrate these curves for gravity-type quay walls is proposed. Furthermore, the characteristics of these curves are discussed and classified into three categories.

2. CONCEPT OF RISK DENSITY CURVE

Risk density curve is the curve showing the distribution of annual seismic risk densities, which can be calculated by a seismic hazard curve and seismic loss function.[4] The procedure for making the risk density curve is shown in **Figure 1**, schematically. First, the seismic hazard curve at the site should be given based on historical earthquake record and/or active fault information around the site. Since the seismic hazard curve shows the annual probability of the occurrence of ground motion beyond a certain level (probability of exceedance), annual probability of the occurrence of the ground motion at a certain level can be computed by differentiation of the seismic hazard curve. This curve is the probability density function of the annual peak value of PGA at the site. Seismic loss function shows how much of loss would occur if a certain level of ground motion attacks. Therefore, multiplication of annual probability density function of PGA and seismic loss function gives the seismic risk density distribution.

The total area below the seismic risk density curve is identical with expected annual seismic loss. Therefore, a structure with high seismic resistance shows a shallow curve with low peak. On the other hand, the risk density curve for a structure with low seismic resistance is wide and having a high peak.

Risk density curve for the whole life span of a structure can be defined in the same way, just by the multiplication of annual risk density and the year of life span. Another type of risk density curves can be defined as the risk density for the ground motion level expressed by the probability of the exceedance during the life span of a structure, since it is uniquely related with each PGA level at a specific site. Although these two types of risk density curve could give different impressions, the concept is same. In order to discuss the design ground motion level definition, the risk density curve expressed by the probability of exceedance is used in the following section.



(a) Seismic hazard curve

(b) Probability density function for PGA

(c) Seismic loss function

(d) Annual risk density curve

Fig.1 Concept of risk density curve [4] with modification

3. SEISMIC LOSS FUNCTIONS FOR GRAVITY TYPE QUAY WALLS

Gravity type quay walls are made of concrete caissons or other retaining structures placed on a foundation, sustaining earth pressures from backfill soil behind the wall. The factors governing seismic performance of a gravity type quay wall include wall dimensions, the thickness of soil deposit below the wall, and the liquefaction resistance of subsoil below and behind the wall, as well as the levels of seismic shaking at the basement. A comprehensive parametric study was carried out to clarify the importance of these factors[5]. The results of the parametric study were summarized as simplified seismic performance evaluation charts, and a seismic risk assessment procedure with these charts was also proposed by the author[6].

In the risk assessment procedure, the fragility curves are generated for various situations based on the seismic performance evaluation charts. The fragility curve is a widely practiced approach to evaluate the seismic vulnerability of structures in terms of probability[7]. In the fragility curve approach, it is assumed that the curve is expressed in the form of two parameter lognormal distribution functions.

$$F(a) = \Phi[\ln(a/c)/\varsigma] \qquad (1)$$

Where $F(a)$ represents the conditional probability of occurrence for the specific states of damage; a is the peak input acceleration, commonly referred to as PGA; c and ζ are parameters. These parame-

Table 1 Parameters of fragility curves [6)]

Equivalent SPT N values	Aspect ratio (*W/H*)	Normalized thickness of sand deposit (*D1/H*)	Degree I		Degree II		Degree III		Degree IV	
			c	ζ	c	ζ	c	ζ	c	ζ
5	0.90	0.00	160.1	1.12	414.8	0.50	615.6	0.38	689.7	0.25
8	0.90	0.00	246.3	0.65	438.5	0.40	611.9	0.33	663.7	0.19
10	0.90	0.00	291.6	0.50	453.7	0.36	607.9	0.28	649.2	0.17
15	0.90	0.00	337.5	0.45	505.2	0.25	608.0	0.16	635.3	0.09
20	0.90	0.00	388.2	0.37	545.7	0.18	619.7	0.12	678.6	0.11
25	0.90	0.00	412.7	0.34	574.4	0.15	631.9	0.09	2650.1	0.29
5	0.90	1.00	0.1	7.05	0.1	8.27	0.1	9.39	0.2	11.68
8	0.90	1.00	11.3	3.27	146.3	1.17	276.9	0.79	366.7	0.65
10	0.90	1.00	93.6	1.40	268.1	0.65	390.1	0.46	462.6	0.39
15	0.90	1.00	209.6	0.75	392.5	0.42	511.0	0.29	589.9	0.22
20	0.90	1.00	353.1	0.41	506.6	0.23	600.5	0.16	617.7	0.08
25	0.90	1.00	404.9	0.33	560.5	0.19	617.1	0.10	1751.9	0.49
15	0.65	0.00	262.7	0.55	429.2	0.35	555.1	0.28	625.8	0.21
15	0.90	0.00	337.5	0.45	505.2	0.25	608.0	0.16	625.3	0.09
15	1.05	0.00	375.4	0.38	547.2	0.22	629.6	0.14	713.9	0.12
15	0.65	1.00	208.1	0.74	378.8	0.41	484.4	0.31	568.8	0.26
15	0.90	1.00	209.6	0.75	392.5	0.42	511.0	0.29	589.9	0.22
15	1.05	1.00	215.5	0.73	400.0	0.41	512.5	0.29	587.5	0.20
10	0.90	0.50	145.8	1.01	307.9	0.53	414.8	0.45	499.8	0.41
20	0.90	0.50	375.2	0.37	523.2	0.19	609.8	0.14	638.7	0.09

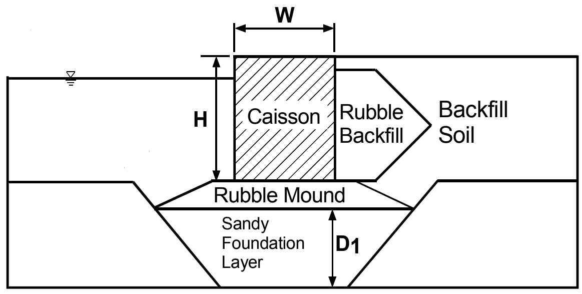


Fig. 2 Cross section and parameters of a gravity type quay wall

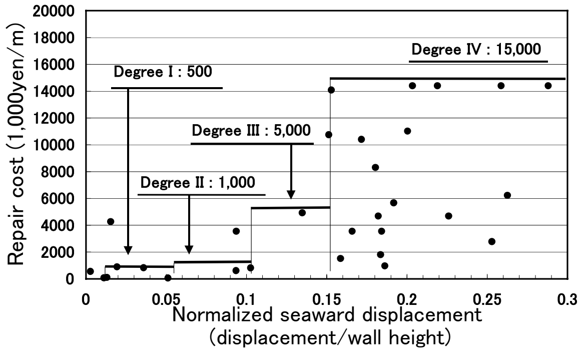


Fig. 3 Damage level criteria and seismic loss [6)]

ters were calibrated as shown in **Table 1**.[6)] The situations shown in **Table 1** is based on the difference of liquefaction resistance of foundation and backfill soil (Equivalent SPT N values), depth of sandy foundation layer (*D1/H*), and aspect ratio of caisson (*W/H*) which is related with the design seismic coefficient. The meaning of these parameters is schematically shown in **Figure 2**.

The damage level for these fragility curves are defined based on restoration cost as shown in **Figure 3**.[6)] Thus, seismic loss can be evaluated for each ground motion level by the fragility curves and the restoration cost (loss) for each damage level. It should be noted here that the seismic loss assessment procedure described here is fairly dependent on the seismic damage cost assumption shown in **Figure 3**, and for simplicity, only the restoration cost was taken into account as the seismic loss in this process.

Once the fragility curves for various situations and estimated seismic loss for each damage level were obtained, seismic loss function can be calculated. **Figure 4** shows the seismic loss functions for 20 situations, where the fragility curves for corresponding situations were proposed in **Table 1**. Since the extreme case with deep loose sandy deposit (*N*=5, *W/H*=0.9, *D1/H*=1.0) shows a different tendency (* in **Figure 4**), the remaining 19 situations are discussed in the following chapter.

4. SEISMIC RISK DENSITY CURVES

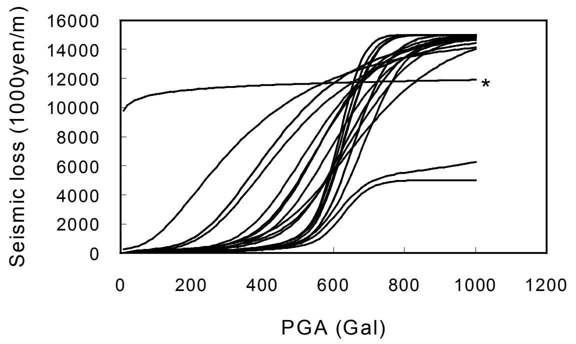


Fig. 4 Seismic loss evaluation for 20 situations

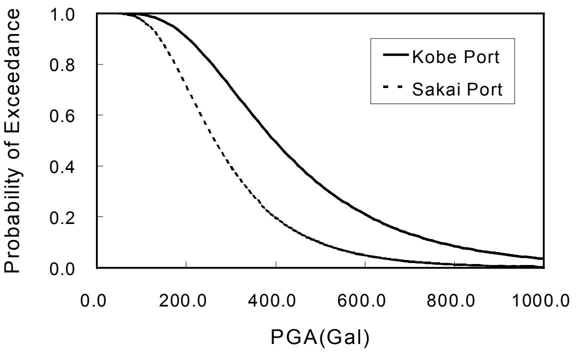
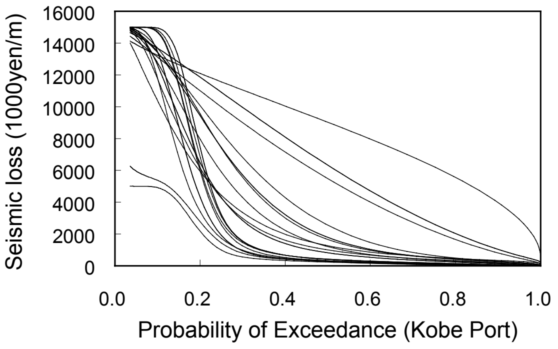


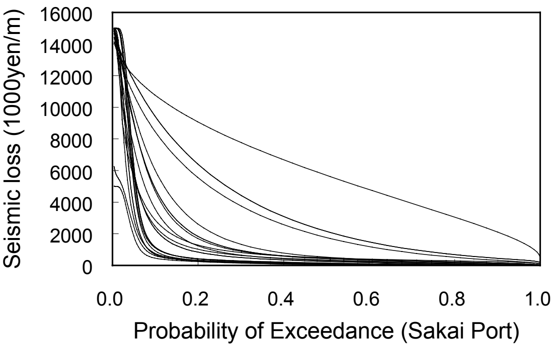
Fig. 5 Results of seismic hazard analysis

For samples of seismic hazards, Kobe Port and Sakai Port are selected. The seismic hazard for these ports is evaluated based on the historical earthquakes from 1885 to 1995[7)], as shown in **Figure 5**. Here, seismic hazard is expressed as the probability of exceedance for the specific level of ground motion in a 50-year life span, and not in terms of the probability of occurrence discussed above, since the background of design ground motion level definition, which is usually defined in terms of the probability of exceedance, is the focus.

The estimated seismic loss for these ports can be evaluated as shown in **Figure 6**. Though the seismic hazard is different for these ports, the seismic loss differs mainly by the specifics of structures, such as liquefaction resistance of foundations and aspect ratios of caisson walls. The spiky peaks at the low probability of exceedance occur because the calculation of seismic loss was conducted only up to 1000 Gals and the loss for the ground motion beyond that level accumulates at that point. It should be noted here that the calculation of the seismic loss were conducted for each 10 Gal and not equally spaced in the scale of the probability of exceedance. The risk density curves in **Figure 7** indicate the seismic risk (seismic loss multiplied by its occurrence probability) for the ground motion level in 10

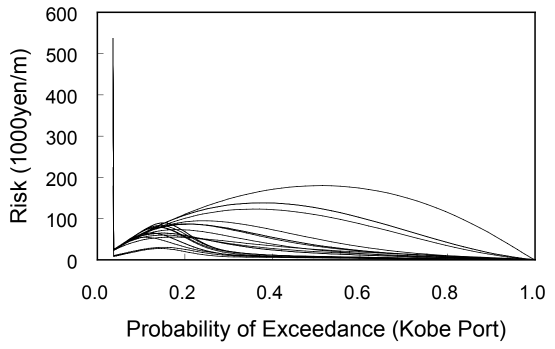


(a) Kobe Port

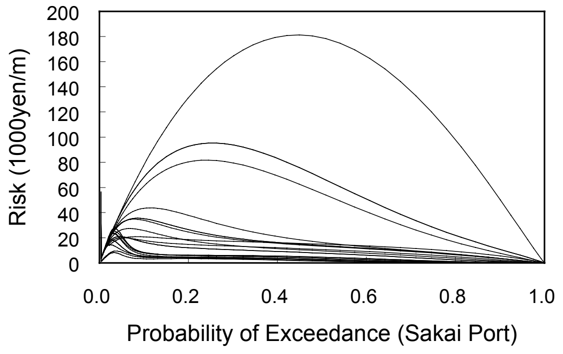


(b) Sakai Port

Fig. 6 Seismic loss evaluation considering seismic hazard



(a) Kobe Port



(b) Sakai Port

Fig. 7 Evaluated seismic risk density curves

Gal increments (400 Gal to 410 gal, for example). However, the magnitude of the ground motion level is indicated by the probability of exceedance to discuss the design ground motion level from the viewpoint of seismic hazard.

Based on the shape of the risk density curves, the curves can be classified into three types as follows.

The elliptical risk density curves

For the poor seismic performance situation, the risk density curves show elliptical shapes and their peaks are in between 0.3 to 0.6 in terms of probability of exceedance, as shown in **Figure 8**. In this case, frequent levels of earthquake easily damage the structure. Thus, seismic retrofits are necessary for the situation with an elliptical shape risk density curve. The ground motion level of level-1 earthquake in the PIANC guideline (probability of exceedance is 50 %) can yield an elliptical shaped risk density curve, since the seismic risk at the level is very high.

The hump shaped risk density curves

For the medium seismic performance situation, the risk density curves show peaks in between 0.1 to 0.3 in terms of probability of exceedance, as shown in **Figure 9**. In this case, the ground motion levels of level-1 and level-2 earthquake in the guideline (probabilities of exceedance are 50 % and 10 %, respectively) can yield the shape and magnitude of risk density curve.

The sharply peaked risk density curves

For the high seismic performance situation, the risk density curves show sharp peaks in between 0.05 to 0.15 in terms of occurrence probability, as shown in **Figure 10**. In this case, the seismic risk evaluation at the ground motion level of level-1 earthquake (probability of exceedance is 50 %) gives no useful information, but the evaluation at the ground motion level of level-2 earthquake (probability of exceedance is 10 %) could give useful information to estimate the total risk, since the seismic risk at the point is close to the peak of risk density curves. However, the peak of risk density is so sharp that only one-point evaluation at level-2 could be insufficient.

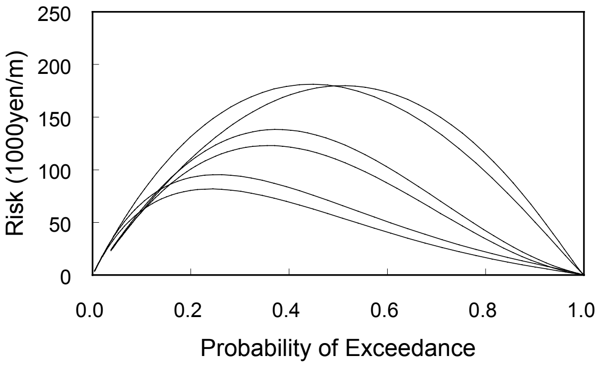


Fig. 8 Elliptical risk density curves

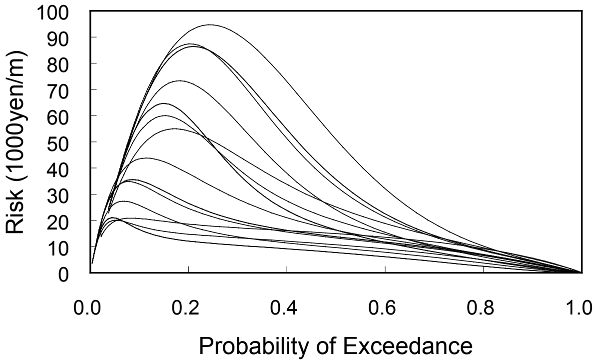


Fig. 9 Hump shaped risk density curves

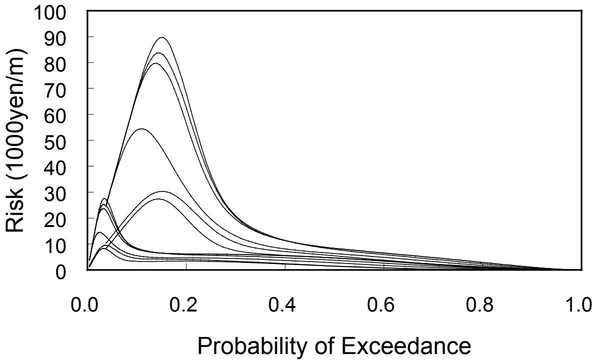


Fig. 10 Sharply peaked risk density curves

Thus, the seismic risk density curves are classified into three types. The seismic performance evaluation at the level-1 earthquake is meaningful if the risk density curves are of the elliptical or hump shaped type, and the seismic performance evaluation for the level-2 earthquake is meaningful if the risk density curves are of the hump shaped or sharply peaked type. Therefore, the current two-level approach works well for the seismic performance evaluation of gravity type quay walls. In other words, the answer for the question in the beginning, ‘why 50 % and 10 %? ’, is that the seismic performance evaluation for the 50 % exceedance level is meaningful if the seismic performance is low or medium (the elliptical or hump shaped curve cases) and the evaluation for the 10 % exceedance level is meaningful if the seismic performance is medium or high (the hump shaped or the sharply peaked curve case).

However, since the location of the peak of the risk density curves varies continuously in wide range, the evaluation for the 10 % exceedance level could not be sufficient to estimate the peak of risk density curve for the some case with high seismic performance, as shown in **Figure 10**. Therefore, if possible, input motion level should be defined from low level to high level continuously.

5. CONCLUSIONS

The characteristics of risk density curves for various situations of gravity type quay walls were discussed. Major conclusions obtained in this paper are as follows.

1) The seismic risk density curves for many situations are evaluated by the seismic loss function based on fragility curve approach. The curves can be classified into three types. These three types of seismic risk density curves are dependent upon the seismic performance of the structure.
2) Based on the three types of seismic risk density curves, the meaning of seismic performance evaluation for the level-1 and level-2 earthquakes is discussed. The evaluation for the level-1 works well if the risk density curves are of the elliptic or hump shaped type, and the evaluation for the level-2 is useful if the risk density curves are of the hump shaped or sharply peaked type. Thus, the proposed definition of level-1 and level-2 earthquake by PIANC seems to be reasonable.
3) Although selecting two-level design ground motions in terms of probability of exceedance is reasonable, the evaluation for the 10 % exceedance level could not be sufficient to evaluate the peak of risk density curve for some cases with high seismic performance. Therefore, if possible, input motion level should be defined from low level to high level continuously.

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