NEW RELIABILITY-BASED DETERMINATION OF DESIGN GROUND MOTIONS BASED ON SIMULATION OF SCENARIO EARTHQUAKE

M. Ohbuchi
Takenaka Corporation, Japan

T. Itoi, T. Takada
University of Tokyo, Japan

SUMMARY:
Performance-based seismic design of structures has been widely recognized as useful design concept, in which required performance such as safety, serviceability and others are explicitly described, and the required level of the performance are quantitatively specified. The required level has often been expressed in terms of return periods of earthquake ground motion intensities such as PGA or spectral acceleration, all of which do not fully represent ground motion time histories. Recent advancements on ground motion simulation based on fault models in engineering seismology should be incorporated into performance-based design of structures. Therefore, this paper proposes a new reliability- based methodology for determination of source parameters of the fault model which correspond to the return period specified by design requirement.

Keywords: Design Ground motion, Strong Ground Motion Prediction, Uncertainty, Reliability, Advanced First-Order Second Moment Method (AFOSM), Response Surface Method

1. INTRODUCTION

First of all, the most important thing on designing a structure is setting and verifying the performance level. So, performance-based seismic design of structures has been widely recognized as a useful design concept, in which required performance such as safety, serviceability and others are explicitly described, and the required level of the performance are quantitatively specified. For example, International Organization for Standardization (ISO) establishes ISO2394 which is the basis of performance based design. And it mentions that the performance level of the structure should be based on the reliability concept. Since there is much uncertainty in earthquake phenomenon deterministic description of seismic ground motions that will hit structures is not sufficient. The required level should be a probabilistic expression that can quantify the earthquake phenomenon uncertainty.

So far, required levels have often been expressed in terms of return periods of earthquake ground motion intensities such as PGA or spectral acceleration and a simulation method of seismic ground motion fitting response spectrum to target Uniform Hazard Spectrum (UHS) which is defined in terms of probability or return period. However, all of these indices do not fully represent seismic ground motion. On the other hand, since the 1995 Kobe Earthquake which occurred in the southern part of Hyogo Prefecture on January 17, 1995, seismic theory has made innovative advance and various simulation methods of seismic ground motion have been proposed from a seismological standpoint. One of the most well-known methods among them is strong ground motion prediction proposed by Irikura. The method can make clear a theory of relationship between seismic ground motion and scenario earthquake, which is assumed as a fault model consisting of parameters such as magnitude, length and width of fault, stress drop, dip angle, and so on.

In engineering seismology, however, recent advancements on theoretical aspect have been leveraged in a deterministic way such as semi-empirical fault models in which fault parameters are given not by engineering judgment based on desired design margins but by seismology and geology. With this way, the relation between structure performance level and design ground motion is unclear. The recent advancements on theoretical fault modeling should be mentioned probabilistically and incorporated to meet the required performance levels of structures, for example, assuming the ground motion corresponded to a return period of 500 years as level 1 and 2500 years as level 2.

Therefore, this paper proposes a new reliability-based methodology for determining design margins of fault parameters which correspond to the return period specified by design requirements. In the proposed method, design ground motion is evaluated based on a scenario earthquake where fault parameters are defined by return period, probabilistic seismic hazard analysis and its deaggregation. First, a fault is chosen as a scenario earthquake by return period, probabilistic seismic hazard analysis and its deaggregation. Then, a reliability index, which represents desired design margins of the fault parameters, is evaluated by the deaggregation. Lastly, parameters of the fault are determined with the Advanced First Ordered Second Moment Method (AFOSM) and the desired design margin.

2. OUTLINE OF THE PROPOSED METHOD

The proposed method has the seven steps which are shown Fig.1.

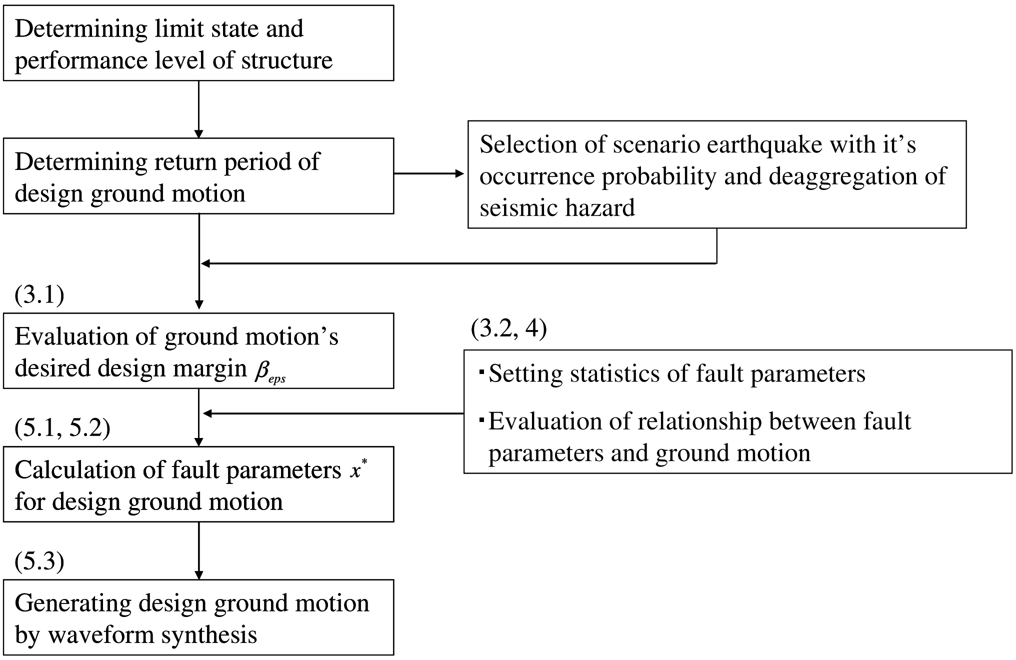

Figure 1. Flow diagram of the proposal method

Step 1. Determine required level of structure performance
Step 2. Set the return period and exceedance probability of design ground motion correspond to the required level of structure performance.
Step 3. Choose scenario earthquake by return period, probabilistic seismic hazard analysis and its deaggregation.
Step 4. Design values of the fault parameters is evaluated
Step 5. Evaluate statistical properties of fault parameters and relationship between it and seismic ground motion.
Step 6. Determine fault parameters by Advanced First Ordered Second Moment Method (AFOSM) and the desired design margin.
Step 7. Simulate design ground motion based on the fault model which parameters are determined in the above 6 steps.

In the following application, choosing scenario earthquake is abbreviated as assuming that the procedure 1st to 3rd is done by same method as previous study. Evaluation of the fault parameters' desired design margin and design ground motion simulation are shown in this paper.

3. ANALYSIS CONDITION AND CALCULATION OF RELIABILITY INDEX

In chapter 3.1, analysis conditions such as return period *T*, exceedance probability *P*, probability of earthquake, and the desired design margin of design ground motion which is evaluated by deaggregation, are shown. In chapter 3.2, site condition of scenario earthquake and a spatial distribution of fault parameters are shown.

3.1 Determination of Reliability According Performance Level of Structure

Herein, two required performance levels are assumed as return period 970 years and 2500 years. Two types of earthquake; one is inter-plate earthquake and the other is intra-plate earthquake, are assumed. Probability of inter-plate earthquake is 1.4×10^{-2} and probability of intra-plate earthquake is 2.1×10^{-3}. The exceedance probability of design ground motion $P[IM > \alpha|E]$ is calculated according to Eqn. 3.1.

$$P_{IM}(\alpha) = P[IM > \alpha|E] \times P_E \tag{3.1}$$

Where, IM indicates the intensity measure of ground motion, $P_{IM}(\alpha)$ indicates the probability of the ground motion intensity exceeding a specified value α, $P[IM > \alpha|E]$ indicates the exceedance probability of ground motion on the premise of earthquake occurrence, and P_E indicates an earthquake occurrence probability,

$$\beta_{eps} = \Phi^{-1}(1 - P[IM > \alpha|E]) \tag{3.2}$$

Where, β_{eps} is the reliability index, which implies the degree of the fault model's desired design margin, Φ is cumulative of standard normal distribution and Φ^{-1} is its inverse function.

β_{eps} evaluated based on return period which is corresponding to structure performance is listed in Table 3.1. From the table, β_{eps} varies depending on not only return period but also occurrence probability of earthquake.

Table 3.1. Degree of fault model's the desired design margin β_{eps} correspond to specified return period

Assumed Return Period (year)	Degree of fault model's the desired design margin β_{eps}	
	High Occurrence Probability of Earthquake (P_E=1.4×10^{-2})	Low Occurrence Probability of Earthquake (P_E=2.1×10^{-3})
970	1.4	0.0
2500	1.9	0.8

3.2 Condition of Site and Fault

A hypothetical fault which is strike-slip and seismic magnitude 7.0 is assumed. Fig. 2 illustrates positional relationship between a site and fault and it also shows and asperity and rupture point. Six fault parameters (i.e. fault length, rate of asperity area, stress drop, slip, asperity location, rupture velocity) are treated as stochastic variables. Statistical properties of these parameters are determined as written in Table 3.2.

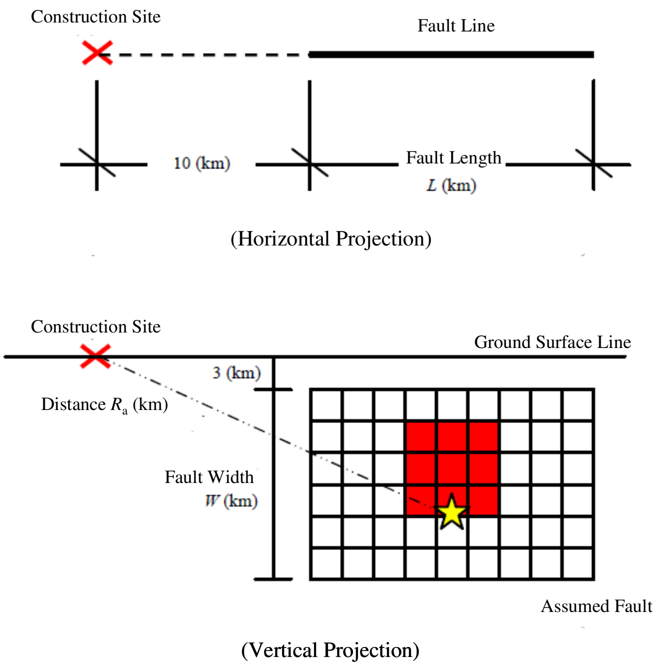

Figure 2. Model of site and assumed fault

Table 3.2. Statistical properties of fault parameters

Fault Parameter	Distribution Form	Mean Value	Standard Deviation
Fault Length L	Normal Distribution	27	5
Ratio of asperity slip D_a/D	Lognormal Distribution	2.0	0.37
Ratio of asperity area S_a/S	Normal Distribution	0.23	0.04
Ratio of asperity stress drop $\sigma_a/\overline{\sigma}_a$	Lognormal Distribution	1.0	0.39
Rupture Velocity V_r	Normal Distribution	2.52	0.2
Distance between site and asperity R_a (km)	Normal Distribution	27.4	7.4

4 POLYNOMIAL APPROXIMATION OF STRONG GROUND MOTION PREDICTION BASED ON RESPONSE SURFACE METHOD

4.1 Outline of Response Surface Method (RSM)

Response Surface Method (RSM) is a method approximating response surface associated with input-output relationship of complicated systems as polynomial expression by regression analysis. The polynomial function could be applied for evaluating structure reliability on determining design ground motion. This paper refers only to outline of RSM and detail of RSM are found in past study. In RSM, first, sampling method, number of samples and level of response surface which means maximum polynomial order of the function are determined. The result of approximating ground motion simulation by statistical Green's function is shown below.

4.2 Response Surface Expression and Sampling

In RSM, it would be a first matter to decide a level of response surface, sampling method and number of samples. For example, quadratic model consists first order term, second order term, interaction terms and error term as shown in Eqn. 4.1.

$$Y = \sum_i C_i X_i^{\ 2} + \sum_i \sum_{j \neq i} C_{ij} X_i X_j + \sum_i C_i' X_i + C_0 + \varepsilon(0, \sigma) \qquad (4.1)$$

Higher the level of response surface, less the approximation error, but it carries the disadvantage that a higher level response surface needs more samples and the solution of it becomes less stable. Therefore, in terms of efficiency and practical use, the quadratic approximation model is adopted in this study.

In addition to this, sampling method for the approximation should be carefully examined. Several sampling methods are known such as Latin Hypercube Sampling (LHS), Central Composite Design (CCD) and Box-Behnken Design (BBD). CCD and BBD were proposed for the purpose of evaluating quadratic response surface expression. They both set three values for each design variables and arrange the standards by grid pattern as shown in Fig. 3.

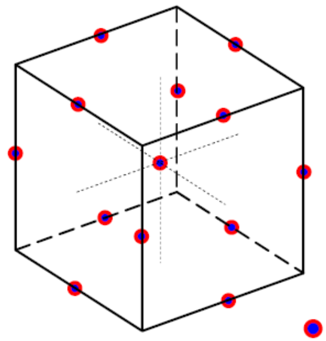

Figure 3. Pattern diagram of 3rd order BBD sampling

They are different from LHS in the respect that the number of samples and combination of samples are theoretically derived, although they all choose the sample point on a grid pattern. In CCD, the number of samples is determined as (n + 2) (n + 1) /2, with n as the number of design parameters. On the other hand, the number of samples for BBD is as shown in Table 4.1. The number of fault parameters considered as design variables in this simulation is 6. In this case, the number of samples of CCD is seventy seven and that of BBD is fifty four. Consequently, BBD is adopted because the number of samples of BBD is smaller than that of CCD.

Table 4.1. Samples of BBD

Number of Design Parameters	3	4	5	6	7
Number of Samples	15	27	46	54	62

4.3 Regression Analysis and Accuracy Validation of Response Surface

Even though this method can evaluate various indices of seismic ground motion such as PGA, PGV and response spectrum, this study discusses about PGA because PGA relates not only to structure performance levels but also to fault parameters such as asperity. Fig. 5 shows several example of ground motion simulated with BBD. In this research, polynomial approximation is conducted based on the fifty four samples of BBD. Six fault parameters are used as the design value so regressions is expressed using Eqn. 4.2 with twenty eight terms; one constant term, six first-order terms, six second-order terms and fifteen interaction terms. The results of multiple regression analysis are shown in Table.4.2 and Table.4.3.

$$\log PGA = \sum_{i=1}^{6} C_i X_i^{\ 2} + \sum_{i=1}^{6} \sum_{j=1 \neq i}^{6} C_{ij} X_i X_j + \sum_{i=1}^{6} C_i' X_i + C_0 \qquad (4.2)$$

Then, the accuracy of the acquired regression equation is verified. Fig.6 compares the regression equation derived from the samples of BBD with the one thousand samples by Monte Carlo simulation of strong ground motion prediction. The line in Fig.6 is the area where the regression equation corresponds with strong ground motion prediction. Both the regression equation and strong ground motion prediction share this line at the center. Therefore regression equation derived from the samples describes the property of the Monte Carlo simulation result properly.

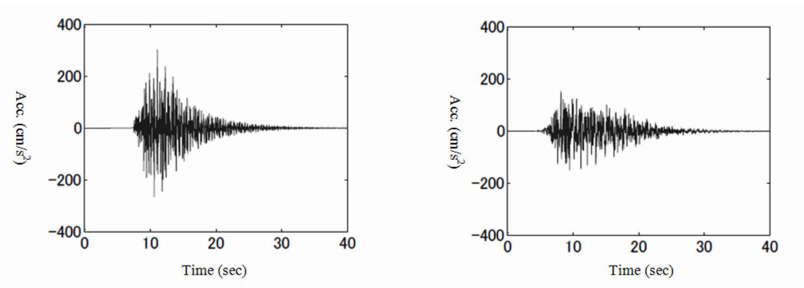

Figure 5. Samples of ground motion simulation using BBD

Table 4.2. Regression Coefficient of 1st-order, 2nd-order and Constant Term

Fault Parameters	1st-oder term	2nd-order term
L	-1.925	0.689
S_a/S	-1.419	0.030
D_a/D	-0.019	-0.116
$\bar{\sigma}_a/\sigma_a$	1.414	0.076
V_r	4.282	1.354
R_a	11.29	-0.727
Constant Term	-12.68	

Table 4.3. Regression Coefficient of Interaction Terms

	S_a/S	D_a/D	$\bar{\sigma}_a/\sigma_a$	V_r	R_a
L	-0.694	0.0549	0.0127	-0.00232	-1.119
S_a/S		0.0187	-0.177	0.616	0.837
D_a/D	-		0.0325	0.194	-0.0443
$\bar{\sigma}_a/\sigma_a$	-	-		-0.172	-0.284
V_r	-	-	-		-2.081
R_a	-	-	-	-	

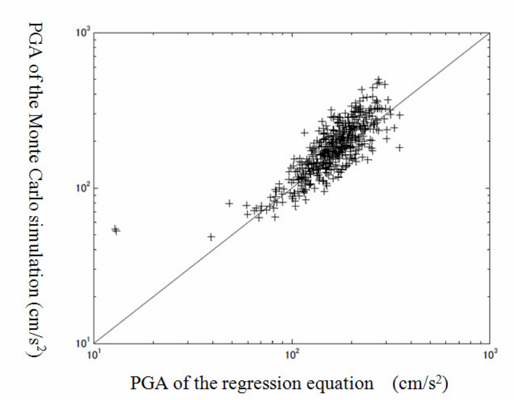

Figure 6. Comparing the regression equation derived from BBD and result of Monte Carlo simulation

5. METHOD OF DETERMINING GROUND MOTION FOR DESIGN BASED ON PERFORMANCE STANDARD

This chapter explains the method for determining a fault model based on maintainability β_{eps} of ground motion. Section 5.1 describes the theory of advanced first-order second-moment method. Section 5.2 examines relationship between β_{eps} and fault model parameters. Lastly, in section 5.3, the fault model and ground motion for design are determined using of β_{eps} which is evaluated through the level of structure performance.

5.1. Advanced First-Order Second Moment Method (AFOSM)

As an example, the limit state function of 2 variables is shown in Fig. 7. Joint probability density has its maximum at the origin which is the point where the variables is mean value. β_{eps} coincides with the shortest distance between the limit state function (G_1,G_2) and the origin. In this research, limit state function G is expressed by difference between ground motion S and design value of ground motion R. R is determined by return period T and S is evaluated by response surface of chapter 4. When T varies to T_1 and T_2, G varies to G_1 and G_2 as shown as Fig.7. By assigning response surface Eqn. 4.2 into S, Eqn. 5.1 which expresses the limit state function G can be acquired.

$$G = R - S = R - \left\{ \sum_{i=1}^{6} C_i X_i^{\,2} + \sum_{i=1}^{6} \sum_{j=1 \neq i}^{6} C_{ij} X_i X_j + \sum_{i=1}^{6} C_i' X_i + C_0 \right\} \tag{5.1}$$

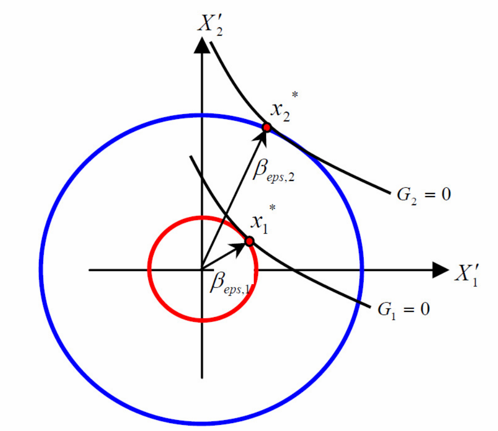

Figure 7. Pattern diagram of relationship between limit state G and β_{esp}

To determine the fault model that corresponds with the design value, it seeks a combination of X. However, the combination of design variables X cannot be determined uniquely because the combination of X satisfying G=0 exists infinitely. Past methods of strong ground motion prediction have arbitrary in combination of fault parameters. As this study would like to exclude this arbitrariness, this study calls the combination of the most probable in X_i options which satisfy G =0 as "Most Likelihood Point". This point is chosen as design point. The design point is determined with a convergent calculation based on AFOSM.

5.2. Relationship of Fault Parameters and Structure Performance Level

The design point of fault parameters corresponding with β_{esp} will be assessed in this section. Table.5.1 shows the relationship between β_{esp} and PGA. This table shows that ground motion where PGA is 150 (cm/s^2) corresponds to the average performance level (β_{esp}=-0.04) and that a bigger ground motion, where PGA is 400 (cm/s^2) corresponds to a more conservative performance level (β_{esp}=1.9).

Table 5.1. Relationship between β_{esp} and PGA

PGA	150	200	300	400
β_{eps}	-0.04	0.61	1.51	2.07

Next is the relationship between respective fault parameters and β_{eps} which is shown in Fig. 8. Ratio of asperity stress drop ($\sigma_a/\bar{\sigma}_a$) and ratio of asperity area (S_a/S) out of six fault parameters vary largely as β_{eps} changes. This means that asperity has the biggest effect on evaluation of ground motion for design. When β_{eps} becomes larger, the ratio of asperity stress drop $\sigma_a/\bar{\sigma}_a$ increases and the ratio of asperity area (S_a/S) decreases. Thus, when assuming a strong ground motion, area of asperity should be smaller and asperity stress drop should be larger. And this corresponds with past studies. However there is a big difference between this study and past studies. In this study, fault parameters such as asperity area ration and so on are determined by quantitative engineering judgment based on reliability index and structure performance level. In contrast; those variables are determined by structure designer's non-quantitative engineering judgment in the past studies. This is the biggest difference between this study and past studies.

5.3. Determination of Fault Parameters and Design Ground Motion

In this section, fault model and ground motion for design are determined by assigning β_{esp} into AFOSM. In the method, probability distribution and design value are input and β_{esp} is an output. This study uses inverse analysis in which design value is derived from probability distribution and β_{esp}. So convergent calculation is carried out until the result of AFOSM is the same as β_{esp} by changing design value.

The value of fault parameters which are corresponding to the cases β_{esp} is 0.0, 0.8, 1.4 and 1.9 is shown in Table 5.2. When level 1 ground motions (return period = 970 years) are assumed for an earthquake of low probability of occurrence, fault parameters are almost the same as the mean values derived from strong ground motion prediction recipe. However, when level 2 ground motions are assumed, PGA becomes larger as stress drop and ratio of asperity area changes while fault length L, ratio of fault slip D_a/D and velocity of rupture velocity V_r stay the same.

The fault model determined by the proposed method is shown in Fig. 8. It shows that the asperity area becomes smaller and the location of asperity becomes closer to the site as β_{esp} becomes bigger. PGA of design ground motion does not completely correspond to the target PGA as shown in Table.5.3.

Table 5.2. Fault parameters set by the proposal method

Fault Parameters	High Occurrence Probability of Earthquake		Low Occurrence Probability of Earthquake	
	Return Period 970 years	Return Period 2500 years	Return Period 970 years	Return Period 2500 years
β_{esp}	0.0	0.8	1.4	1.8
L	27.00	27.16	27.70	28.46
S_a/S	0.230	0.209	0.185	0.157
D_a/D	1.97	1.97	1.97	1.97
$\bar{\sigma}_a/\sigma_a$	0.932	1.088	1.179	1.236
V_r	2.52	2.50	2.48	2.47
X	27.4	25.9	24.6	23.2
PGA	152.9	217.3	284.5	364.5

Table 5.3. Comparison of Target PGA and PGA of generated ground motion

β_{eps}	0.0	0.8	1.4	1.9
Target PGA	152	217	284	364
PGA of generated ground motion	145	217	298	338

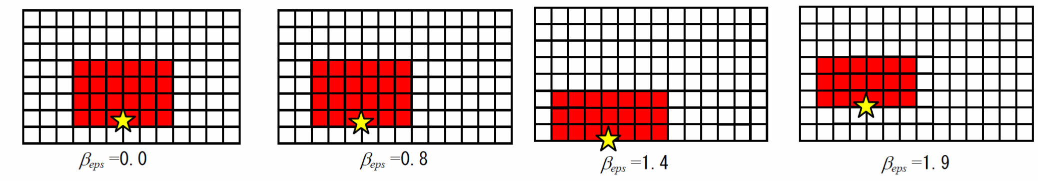

Figure 8. Fault Models evaluated by β_{esp}

As described before, this study defines the location of asperity by distance X between a site and asperity. Therefore, the location of asperity which corresponds to certain design value of X cannot be determined uniquely. To be exact, if two asperities are defined by two parameters (fault length and fault width), the asperity location can be determined uniquely. However, this study uses a simplified method that adopts the location of asperity as the closest to target value of distance X. Although the ratio of asperity area S_a/S is a continuous variable in the AFOSM, model of asperity area must be discrete quantity because its model is aggregation of minor fault.

Lastly, the design ground motion is shown in Fig. 9. It can be said that PGA of design ground motion which arises from the same fault ranges of 145 (cm/s^2) to 338 (cm/s^2) corresponds to the structure performance level by applying the suggested method. Therefore the purpose of this study can be achieved, which is inventing the evaluation method of design ground motion and fault model corresponding to structure performance level.

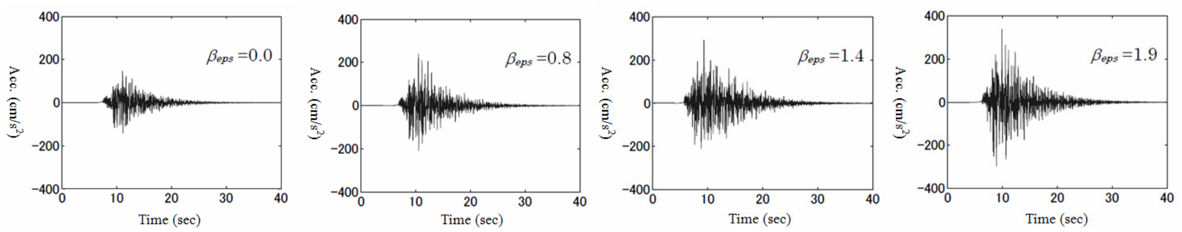

Figure 9. Evaluated design ground motions

6. CONCLUSIONS

This paper proposes a new reliability-based methodology for determining source parameters of the fault model that corresponds to the return period specified by design requirements. In the proposed method, first, a fault is chosen as a scenario earthquake and fault parameters' design margin β_{eps} is evaluated by return period, probabilistic seismic hazard analysis and its deaggregation. While choosing a fault by deaggregation of seismic hazard is usual in probabilistic evaluation, the fault parameters' design margin β_{eps} had not been evaluated probabilistically so far. Therefore, originality of the proposed method is a probabilistic evaluation of the fault parameters. As the second step, parameters of the fault are determined by the Advanced First Ordered Second Moment Method (AFOSM) and the desired design margin β_{eps}. Lastly, the design ground motion is simulated with the fault parameters. The proposed method makes it possible to evaluate fault model probabilistically and to simulate design ground motion by reflecting required structure performance level and possibility of an earthquake. It may be said that the proposed method makes the connection between seismic fault and structure performance, and so, what remains to be done is a more general discussion of what characters of seismic faults effect structure performance such as safety, serviceability and others.

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