Synthesis of Design Input Motion Reflecting Information of Possible Ground Motions

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SUMMARY:
Quality of input motions is essential for dynamics analysis for the design. Selection of ground motion based on intensity measure (IM) such as GPA is widely accepted. IM-based selection of ground motion, however, may not be highly reliable, because of insufficient accuracy of IMs. We propose to consider a set of possible ground motions in design. The quality of the set is quantitatively evaluated using the information entropy. The design ground motion is synthesized so that the GM can represent the set of possible ground motions. A practical method to synthesize an input motion reflecting various characteristics of ground motions is also presented. Efficiency of the proposed method is verified through numerical simulations. Results are compared with those of conventional approaches and advantages of the proposed scheme are discussed.

Keywords: performance-based seismic design, design input motion, information entropy, information geometry space, Kullback-Leibler divergence

1. INTRODUCTION

In seismic design of infrastructures, performance-based seismic design has become general concept and earthquake-resistant performance of structures is verified through dynamic analysis. In order to ensure validity of this procedure, it is an important issue to establish an appropriate design input motion as a design load.

Conventionally, a design input motion is established based on some presumed conditions. In this scheme the conditions are determined in the form of specific fault source like San Andreas Fault or hazard levels like return periods, which are satisfied by a number of candidates of input motions. Therefore, design input motions are selected among them based on intensity measures (Kastanos et al. 2010) such as PGA and response spectra. In these schemes performance of each ground motion is quantified as the values of intensity measures. For the purpose of improving accuracy of the intensity measures, a number of researches have been conducted. For example, Lamprey et al. (2006) and Baker (2007) indicated that the accuracy is improved by using plural indices as vector-valued intensity measure. Zhai et al. (2007), Luco et al. (2007) and Tothong et al. (2007) proposed to use indices considering specific nonlinearity of target structures' behaviour such as material nonlinearity and dissipated energy.

These approaches set their objective as the improvement of accuracy of intensity measures. Behavior of structures, however, is complicated and almost unpredictable. Damage of structures due to ground motions consists of a number of nonlinear mechanisms, and it is difficult to establish intensity measures which can evaluate the influence of all of such mechanisms accurately. Even if some intensity measures can evaluate some of such influence appropriately, damage can be caused by other mechanisms. As a result, no intensity measure can evaluate effects of ground motions on structures perfectly, and selected design input motions based on intensity measures cannot realize target safety with high confidence. Inherent difficulty of the predictability of intensity measure requires different approach.

Since reliability of intensity measures is limited, it is very difficult to select some ground motions for seismic design based on intensity measures. Therefore, we propose, not to select specific ground motions, but to utilize the whole "set" of ground motions. Making use of sufficiently large set enables us to consider all the possibility of structural behavior and to overcome the difficulty to select specific input motion. However, such set yet includes a number of ground motions and therefore it is difficult to consider all elements belonging to the set. Then we also present a practical method to synthesize the input motion that can rationally represent the set of ground motions. Since it is discussed that intensity measures are not reliable for such purposes, we will present another scheme that can solve the problem of insufficient reliability of intensity measures.

2. DESIGN INPUT MOTIONS BASED ON INFORMATION OF POSSIBLE GROUND MOTIONS

Because of complexity of nonlinear behaviour of structures, it is very difficult to evaluate the influence of ground motions on them by some indices such as conventional intensity measures. For example, if the ground motion is determined based on the response spectra, there are millions of possible ground motions and they all trigger different response in the nonlinear behavior of structures. Such difference should be considered as the uncertain factor remaining. In order to overcome this problem, we propose to consider the set of all possible ground motions in the design, instead of selecting specific ground motions.

Based on this proposal, we present a practical scheme for setting design input motions. This scheme consists of two stages and detail of each stage is explained below.

In the first stage, a "set" of ground motions is selected. The more ground motions are belonging to the set, the more reliable the set should be, because it allows us to consider wide range of situations. If all the ground motions have similar properties, however, we just consider almost one ground motion in the design and it does not reduce the remaining uncertainty. It means that the number of ground motions belonging to the set is not an appropriate index to evaluate the set of ground motions. If the set consists of ground motions possessing various characteristics, it can reduce remaining uncertainty, because it forces us to consider various mechanisms of nonlinear behaviour of structures. Therefore, we propose to use the variety of characteristics of ground motions as the index to evaluate the quality of the set. The evaluation is quantified using information entropy.

It is impossible, however, to consider all the ground motions belonging to the determined set. In the second stage, a method for synthesizing a wave which represents the ground motions belonging to the determined set is constructed. The toughest ground motion in terms of intensity measures may not be the critical wave, because intensity measures cannot consider the influence of the complexity of nonlinear structural behavior. Therefore a procedure to synthesize a wave reflecting various characteristics is presented. It is expected that the synthesized wave should be tough to various mechanisms of the target structure. In order to evaluate characteristics of a ground motion from the view point of its effect on the target structure, response values of structural system, such as response displacement, are utilized as feature indices. Fluctuation is given to structural parameters and feature indices are obtained in the form of a probability density function, which enables us to evaluate characteristics of a ground motion including its sensitivity against parametric fluctuations. Ground motions are mapped into an information geometry space, which is a space of probability density function. The procedure of input motion synthesis is formulated as the learning problem in that space.

2.1. A set of design input motions and quantification of its performance

2.1.1. Seismic evaluation of structures against a set of ground motions

For the selection of an appropriate set corresponding to the targeted safety level, quality of the sets, or the size of the sets, should be evaluated quantitatively. For example, it is natural to regard the number of considered ground motions as such an index because the performance of a set is expected to be enhanced with the increase of number of the elements. However, even if a number of waves are considered, performance of the set is not necessarily high when it consists of only waves of similar characteristics. Simultaneously, it is not sufficient to consider how strong waves are contained in maximum based on some indices because of the limit of accuracy of intensity measure.

Based on the consideration above, we quantify the performance of wave sets in terms of divergence of characteristics of the waves belonging to the sets. A set of ground motions possessing various characteristics affects real structures in various manners. Even when there exist some unexpected damage mechanisms that are not considered explicitly in the design, a set with high diversity is more likely to include waves that require consideration of such mechanisms than the set which consists of similar waves only.

Note that a set of similar waves includes the case where only intense ground motions are selected based on intensity measures. Generally such a set is thought to realize high level of safety. Meanwhile, from the viewpoint of diversity the set comprises input motions of similar characteristics and then its performance is regarded as not high when we premise the unpredictability of nonlinear behaviour of real structures. The purpose of the proposed method is to ensure robustness of design input motion selection under that unpredictability.

2.1.2. Description of ground motions characteristics based on probability density functions of structural response values

In the proposed method, ground motions characteristics are expressed based on response values of nonlinear structural models in order to consider their relationship to behavior of a target structure. For example, response of a simple bilinear single-degree-of-freedom system which has the identical natural period as the target structure is utilized. For the purpose of considering various features, plural response values such as maximum displacement and dissipated energy are utilized.

Fluctuation is given to the structural model parameter, because consideration of only a few values does not necessarily characterize ground motions sufficiently. By introducing fluctuation of parameters, a number of structural values are obtained against one ground motion. In our method, a distribution of these plenty of values is regarded as a probability density function (pdf), and characteristics of each ground motion is expressed as a pdf. By considering not only certain moment values such as mean values and standard deviations but also whole forms of pdfs, properties of ground motions are evaluated including their sensitivity to the fluctuation. It enhances robustness of the evaluation. Even when two ground motions are identical in terms of deterministic response values, the proposed approach can detect the difference of these waves by comparing the whole forms of pdfs.

As a result, characteristics of one ground motion or a wave set is described in the form of a joint probability density function of several response values. Therefore, diversity of ground motions characteristics is evaluated based on this pdf. Because structural models used for derivation of the pdfs are prepared according to the target structure, diversity of the pdfs is expected to relevant to that of input motions' effect for its damage mechanisms.

2.1.3. Quantification of diversity of a wave set

As an index for diversity of pdfs of response values, we utilize information entropy $H[p(\boldsymbol{x})]$:

$$H[p(\boldsymbol{x})] = \sum_{i=1}^{n} - p(\boldsymbol{x}_i) \log p(\boldsymbol{x}_i) \tag{2.1}$$

where $\boldsymbol{x}$ denotes a vector-valued structural response value and $p(\boldsymbol{x})$ its probability density function. In our approach $\boldsymbol{x}$ is discretized into $\boldsymbol{x}_i$ and pdf $p(\boldsymbol{x})$ is also discretized so that it stands for the value corresponding to $\boldsymbol{x}_i$ (i=1,…,n). The entropy is evaluated by the summation with respect to $\boldsymbol{x}_i$'s. Information entropy can quantify essential size of phenomena generated from the pdf. It is suitable to evaluate the diversity of a set of ground motions based on response values.

Making use of information entropy enables us to quantify diversity of wave sets. It is assumed that a set of diverse input motions shows high performance as design loads, so based on information entropy we can select an appropriate set of ground motions according to the target level of safety. The idea of quantification of ground motions performance utilizing information entropy is verified through numerical simulations in section 3.

2.2. Synthesis of a design input motion reflecting information of selected waves

2.2.1. A wave reflecting various characteristics

After a set of ground motions corresponding to the target safety level is selected based on information entropy, an artificial wave which represents the selected ground motions is synthesized in the next stage. Synthesis of representative wave is often regarded as setting up the most intense input motions as the critical excitation method (e.g. Takewaki 2002). However, as is discussed above, the wave which is the largest in the meaning of some indices does not always give the most severe effect on real structures.

Considering the limit of the accuracy of intensity measures, we propose to consider a wave reflecting various characteristics, instead of a wave possessing the largest intensity measure. It is expected that ensuring diversity of characteristics of the input motion enables us to take into account information which cannot be considered by maximizing intensity measures. As a result, the synthesized wave possesses severity for various damage mechanisms of the target structure.

2.2.2. Information geometry space

As it is proposed in the section *2.1.2.*, characteristics of ground motions are expressed in the form of probability density functions of structural responses. Based on this method, we map ground motions into a space of probability density functions called information geometry space, which introduces a scheme of differential geometry to sets of pdfs (Amari et al. 2007). Utilizing information geometry space, we can consider the geometry of ground motions. For example, difference between two ground motions is evaluated quantitatively based on a distance function of the space.

Structure of information geometry space is defined by Fisher information. In the theory of information geometry, Fisher information has a meaning of metric tensor. Since Fisher information is difficult to evaluate, Kullback-Leibler divergence $D[p,q]$ is often utilized as an alternative distance function in practice.

$$D[p,q] = \sum_i p(\boldsymbol{x}_i) \log \frac{p(\boldsymbol{x}_i)}{q(\boldsymbol{x}_i)} \tag{2.2}$$

where $p(\boldsymbol{x})$ and $q(\boldsymbol{x})$ stand for probability density functions of vector-valued structural response $\boldsymbol{x}$ possessed by two ground motions. Kullback-Leibler divergence does not hold symmetry $D[p,q] = D[q,p]$ and not satisfy conditions as a distance function in a rigorous manner. However, because it is easily calculated and corresponds to Fisher information in infinitesimal distance, it is widely used as quantitative measure of difference between two pdfs.

In summary, we express characteristics of each ground motion in the form of probability density function of structural response, and then map it into a space of pdfs.

2.2.3. Procedure of wave synthesis

Utilizing the scheme of information geometry space, a procedure for synthesis of a representative wave is constructed. The purpose of the procedure is to synthesize an artificial wave which reflects diversity of selected ground motions and has severity for various damage mechanisms of a target structure.

In order to achieve the purpose, two objectives are introduced:

- To learn characteristics of ground motions which are selected as design loads in the first stage
- To reflect characteristics corresponding to various positions of information geometry space

The objective of the former concept is to collect various characteristics of a set of selected ground motions into the synthesized wave. In the first stage of the proposed method, a set comprising ground motions of various characteristics is established. By learning these characteristics, the synthesized wave is expected to reflect important information relevant to damage mechanisms of a target structure.

The aim of the latter concept is to improve robustness of the procedure. Characteristics of ground motions are described based on response values of nonlinear structural models. However, it is difficult to set up a specific model which sufficiently corresponds to the target structure. Therefore, even if it is judged that all the characteristics are learned adequately by the synthesized wave based on the proposed description method, sometimes other important information can be overlooked. In order to overcome this problem, we try to reflect more characteristics than those possessed by the selected input motions into the synthesize wave. We modify property of the synthesized wave so that it moves a large distance, which indicates large difference in property, in the information geometry space. The wave is expected to obtain diverse features according to its temporary position in the space, and as a result it reflects various characteristics including those critical for the target structure.

Based on these concepts, a procedure for synthesis of the representative wave is formulated. First, a set of n ground motions are selected as design ground motions. Let $f^k(t)$ stand for the synthesized wave in the k-th step of the iterative phase. Next, a slight change $\mathrm{d}f(t)$ is given to the $f^k(t)$ and a candidate of the next wave $f^{k+1,\mathrm{candidate}}(t)$ is generated.

$$f^{k+1,candidate}(t) = f^k(t) + \mathrm{d}f(t) \tag{2.3}$$

where $\mathrm{d}f(t)$ is added so that power of $f^k(t)$ is increased. The increment $\mathrm{d}f(t)$ is given as, a wavelet function $\varphi(t)$, because we can modify time-frequency characteristics of the wave efficiently. By considering the time-frequency characteristics of input motions, we can handle information relevant to nonlinear behavior of structures more efficiently (Honda, et al. 2011), in comparison to considering frequency characteristics based on Fourier transform.

Let us describe the updating process of the input motion. In order to determine an appropriate function $\varphi(t)$, first the closest ground motion to $f^k(t)$ is selected as a learning target. The distance to the ground motions is evaluated by Kullback-Leibler divergence. Next, based on a dynamic response analysis with the learning target and a structural model, the most dominant time-frequency characteristics of the response is extracted. The structural model is established based on the target structure, so the extracted characteristics include information relevant to the behavior of the target structure. Then, a $\varphi(t)$ whose dominant time-frequency is identical to the extracted characteristics is established and added.

Considering that the determined $\varphi(t)$ is not always optimal, we generate plural wave candidates $f^{k+1,\mathrm{candidate}}(t)$ giving fluctuations to $\varphi(t)$. Then based on the idea of reflection of diverse features according to positions in information geometry space, the best candidate is selected as the one which maximize the moving distance.

The updating procedure is repeated until some prescribed condition is satisfied. It is important to avoid generating too strong input motion. In the following example, the power of the wave is used as the criteria. The procedure is iterated until its power reaches the largest value of the power of all ground motions in the assumed set.

3. SELECTION OF A SET OF DESIGN INPUT MOTIONS BASED ON INORMAITON ENTROPY

The purposes of this and the next section are to verify both two stages of the proposed scheme through numerical simulations. The simulations for each stage are conducted respectively. Analysis conditions and numerical results are explained in each section.

3.1. Analysis conditions

3.1.1. Target structure

A 10-story RC building was assumed as a target structure of seismic design. The building was modelled with a 10 degree-of-freedom system in which behavior of springs is expressed by tri-linear Clough model, following an example conducted by Architectural Institute of Japan (2006) as is shown Fig. 1. Damage of the structure caused by ground motions was evaluated by Park-Ang damage index of each spring (Park et al. 1985). Preliminary analysis shows that plural vibration modes appear against ground motions and the most damaged spring among the model varies according to properties of input motions.

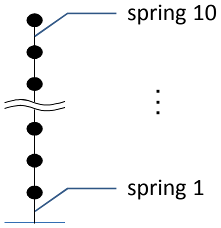


Figure 1. Analysis model of the target structure

3.1.2. Candidates of design input motions

1,000 ground motions were prepared as the ground motions to be considered. These waves were obtained from online database of K-NET, and their frequency characteristics were modified so as to fit a target acceleration response spectrum. We used the target spectrum of the design codes for highway bridge piers in Japan (Japan Road Association 2002).

3.1.3. Selection of sets of design input motions

In order to verify the efficiency of our methods, many sets of design input motions were generated by randomly selecting waves from the 1,000 ground motions. The number of selected waves belonging to sets was also randomly determined.

Let ***G*** denote the set of selected ground motion records. In order to discuss the performance of ***G*** as the design loads, we consider the exceedance probability $P^{ex}(I^j{}_{PA})$:

$$P^{ex}(I^j{}_{PA}) = \frac{\sum_{k=1}^{1000} \mathrm{Ind}\left\{ I^j{}_{PA}[f^k(t)] > I^j{}_{PA}[\boldsymbol{G}] \right\}}{1000} \tag{3.1}$$

where $I^j{}_{PA}[f^k(t)]$ is Park-Ang index of *j*-th spring caused by the *k*-th ground motion. $I^j{}_{PA}[\boldsymbol{G}]$ is the maximum value of Park-Ang index of *j*-th spring among those caused by ground motions belonging to the set ***G***. $P^{ex}(I^j{}_{PA})$ is defined for each spring. If $P^{ex}(I^j{}_{PA})$ is large, it means that the ground motion that affects the *j*-th spring is included in ***G***, therefore the set ***G*** is tough for the *j*-th spring.

3.1.4. Evaluation of information entropy

In evaluating information entropy possessed by ***G***, response values of single degree-of-freedom (SDOF) system were utilized for describing characteristics of ground motions. In order to take the property of the target structure into account, the natural period of the SDOF is adjusted to the first mode period of the 10DOF. Behavior of the spring of SDOF was expressed by perfect elasto-plasticity in order to consider nonlinear behavior of the target structure.

By giving 5 % fluctuations to parameters of both initial stiffness and initial yielding stress, we obtained a joint probability density function of maximum displacement and dissipated energy. Information entropy H was delivered from this pdf and was regarded to express diversity of $\boldsymbol{G}$. The relationship between the obtained value of H and each $P^{ex}(I^{j}_{PA})$ (j=1,…,10) is discussed.

In order to see the performance of conventional approach, we computed the maximum value of an intensity measure $I_{\max}$ among $\boldsymbol{G}$, and computed quantile value q^I:

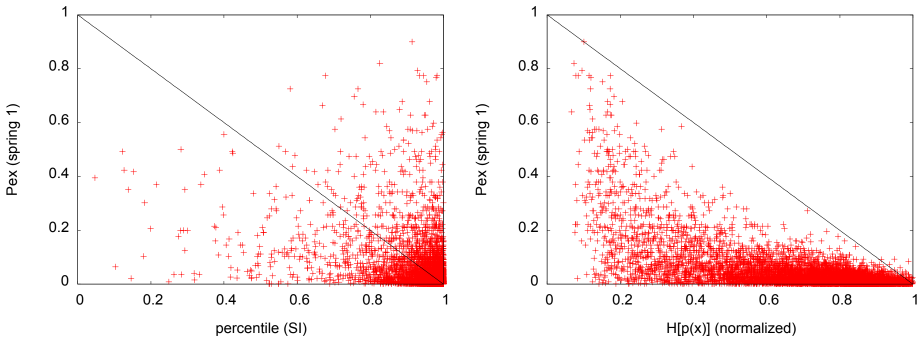
$$q^{I} = \frac{\sum_{k=1}^{1000} \mathrm{Ind}\left\{I_{\max} > I[f^{k}(t)]\right\}}{1000} \tag{3.2}$$

where $I\,[\,f^k(t)\,]$ is the value of the intensity measure of the k-th ground motion. q^I corresponds to the rank of $I_{\max}$ in the whole 1,000 values of that intensity measure. In conventional schemes, q^I is regarded as an index of performance of $\boldsymbol{G}$ and compared its efficiency with information entropy H. As the intensity measure, we utilized Spectral Intensity (SI) value and the quantile value is denoted by q^{SI}.

The procedure was conducted for different 10,000 sets of $\boldsymbol{G}$ to see the relationship between $P^{ex}(I^{j}_{PA})$ and H or q^{SI}.

3.2. Results and discussion

Fig. 2. shows the relationship between $P^{ex}(I^{j}_{PA})$ of spring 1 and H or q^{SI} evaluated for 10,000 sets of ground motions. The black lines in the figures indicate the relationship between the vertical value and horizontal values for ideal situation where the horizontal values can give vertical values perfectly.



(a) Conventional method (b) Proposed method

Figure 2. Relationship between the $\mathrm{P_{ex}}$ and index for evaluating performance of sets (at spring 1); (a) quantile value of Spectrum Intensity (b) information entropy

It is observed in Fig. 2.(b) that exceedance probability decreases appropriately with increase in information entropy, while the trend is not clear with the results by conventional method in Fig. 2.(a).

In the results of conventional approach, some red points locate above the black line, which means the true response value of the target structure is lower than value evaluated by indices. On the other hand, Fig. 2.(b) shows that the proposed method predicted most of the value lower than the black line, indicating that aimed performance is realized in most case. These results indicate that the proposed method enables us to select ground motions which can realize expected performance with higher reliability.

Fig. 3. shows the relationship between $P^{ex}(I^{j}_{PA})$ of spring 10 and H. In spite that information entropy is delivered based on response values of simple models considering only the first mode, it appropriately works against springs whose damage are mainly due to higher mode vibrations as is

shown in Fig. 3. This result implies that information entropy can evaluate performance of input motions against unexpected damage mechanisms, which is an advantage of the proposed method.

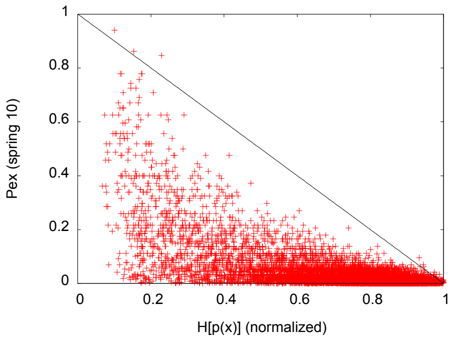


Figure 3. Relationship between the P_{ex} and information entropy (at spring 10)

4. SYNTHESIS OF AN ARTIFICIAL WAVE REPRESENTING INFORMATION OF SELECTED SET

The purpose of this section is to verify the second stage of the proposed scheme through numerical simulations. A target structure and a set of input motions are assumed, and then an artificial wave which represents important information relevant to nonlinear behavior of the target structure is synthesized.

4.1. Analysis conditions

4.1.1. Target structure and a set of input motions

The same structure as *3.1.1.*was assumed as the target structure for the seismic design. We made a set consisting from 98 ground motions. The information entropy of the set is calculated and it is confirmed that the set is of sufficient diverse. Note that the toughest wave among the 98 waves is different for a different spring, and that no single wave is the toughest for all the springs.

4.1.2. Parameters for the wave synthesis

Following the conditions explained in the previous part, we conducted a wave synthesis. First, one of ground motions among the set was selected as an initial wave f^0(t). If this wave is used as the initial wave as it is, its power will exceed the criteria within a small number of iteration and sufficient modification will not be conducted. Therefore the initial wave was set by multiplying 0.5 to this time series.

Probability density functions which express characteristics of input motions were obtained as response values of perfect elasto-plastic SDOF systems with parametric fluctuations. Parameters of the SDOF were established as the same as used in section *3.1.4.*, and joint pdfs of peak displacements and dissipated energy were utilized. Structure of information geometry space was determined by Kullback-Leibler divergence as distance function.

Let us describe the updating procedure, taking the k-th step as an example. First, the target wave to learn is chosen based on distance from $f^k(t)$. The distance is measured by Kullback-Leibler divergence. The closest wave among 98 waves is to be selected. Then a wavelet function $\varphi(t)$, which is utilized as $df(t)$ in Eqn 2.3, was determined so as to correspond to dominant time-frequency characteristics of dynamic response of SDOF system. Parameters of SDOF system was set as the same as section *3.1.4.* After $\varphi(t)$ was determined, 30 candidates were generated giving fluctuations to $\varphi(t)$. Finally, the best wave which maximized moving distance among all candidates was selected as the synthesized wave of next step, $f^{k+1}(t)$.

These procedures were repetitively conducted until the power of the synthesized wave exceeds the
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largest value among learning targets.

4.2. Results and discussion

The time series of the synthesized wave is shown in Fig. 4., compared with that of the initial wave and waves belonging to the targeted set. It is found that properties of the synthesized wave such as PGA, as well as dominant frequency, are similar to those of target waves. Since the power of the synthesized wave is restricted in the algorithm, the amplitude of the synthesized wave is equivalent with those of the target waves.

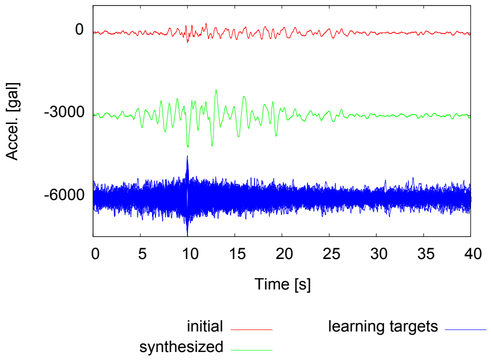
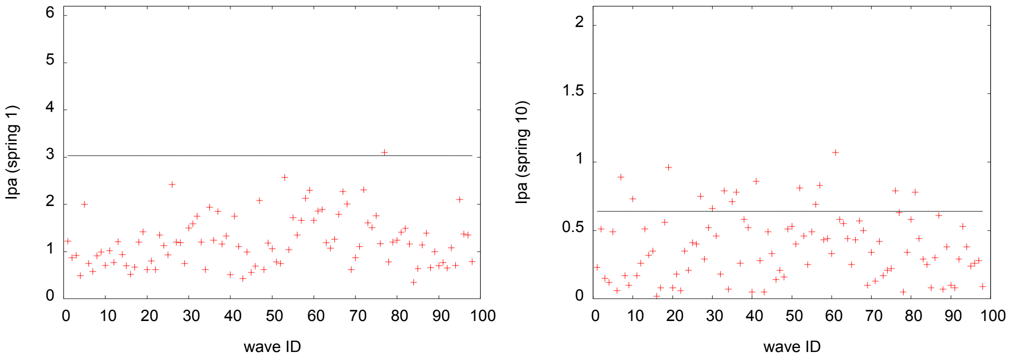


Figure 4. A sample of the synthesized wave comparing with the initial input motion and learning targets

In Fig. 5. response values of the structure against the learning targets and the synthesized wave are compared. Red dots denote the response values against the target waves and the black horizontal line shows the value against the synthesized wave. Fig. 5.(a) shows that, as for the spring 1, damage due to the synthesized wave is greater than most of that due to target waves. This is because dominant mechanism for the behavior of spring 1 is the first mode vibration, which is considered in the wave synthesis procedure. The results indicate that the presented procedure generated a sufficiently tough input motion for the design.



(a) spring 1 (b) spring 10

Figure 5. Comparison of response values of the target structure: red points stand for those of learning targets and black lines stand for those of the synthesized wave.

Fig. 5.(b) shows that the results about spring 10. Behavior of spring 10 is mainly affected by higher modes, which are not considered in the synthesis procedure, but synthesized wave exceeds most of the values of target waves. The results indicate that through the synthesis procedure of learning the target waves and expanding the diversity, the synthesized wave gained associated property relevant to such unconsidered mechanisms. It shows the efficiency of the concept of synthesis of a wave reflecting various characteristics.

5. CONCLUSION

Considering the limit of reliability of intensity measures, we proposed a scheme for establishing a design input motion for performance-based seismic design. In this scheme we present to consider a "set" of input motions as external loads, and then quantify its performance as divergence evaluated by information entropy. Furthermore, we present a practical method to synthesize the input motion that can rationally represent the set of ground motions. In the method we introduce a concept of *a wave reflecting various characteristics* in order to solve the problem of insufficient reliability of intensity measures. Note that the purpose of the proposed method is to ensure robustness of design input motion selection under unpredictability of real structures' behavior, and this concept is a new idea in the point that this unpredictability is regarded a presupposition.

Based on numerical simulations, efficiency of these two stages is discussed. It is shown that information entropy can quantify performance of sets of ground motions with higher reliability than conventional intensity measures. It is also indicated that selection of ground motions based on information entropy can work even against unexpected damage mechanisms, which is an advantage of considering diversity of the waves. Next, efficiency of the procedure for wave synthesis is verified. Though behavior of the target structure is dominated by several vibration modes, the synthesized wave obtains important information and affects those mechanisms.

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