SETTING DESIGN GROUND MOTION REFLECTING INFOREMATION OFA SET OF OBSERVED AND SIMULATED GROUND MOTIONS BASED ON DATA-DRIVEN APPROACH

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Abstract

Number of ground motions available for the design purposes is increasing, because strong motion observation stations are increasing and strong motion simulation techniques have been improved. In order to utilize information possessed by a suite of those ground motions, we proposed a concept to use a set of design ground motions for seismic design. It is impossible, however, to utilize huge number of such ground motion data for the evaluation of seismic performance. Selection or synthesis of a design input motion among the available ground motion records is required. Conventionally, design ground motions are selected based on the response spectra or intensity measures (IMs) such as PGA. But they cannot fully consider complicated nonlinear behavior of real structures under strong motions.

This paper proposes to utilize a data-driven approach, a general scheme for information extraction from big amount of data as a tool to generate the design input motions which represent ground motions included in a design set of ground motions.

First, for the purpose of evaluation of ground motion characteristics in terms of their influence on the structures, we set up indices that are associated with expected damage mechanism of nonlinear structures.

When a ground motion set consists of wide variety of ground motion records, it is not efficient to integrate all the information into a single input motion. Therefore, we first divide the original set of ground motions into several subgroups according to their characteristics. Response values of simplified structural models can be used as indices. For the purpose of robust evaluation, fluctuations are given to the models, and response values are obtained as stochastic variables. It allows us to evaluate the characteristics of ground motions including their sensitivity to fluctuation of structural parameters. Based on the evaluated characteristics, we perform cluster analysis of ground motions set. Jensen-Shannon divergence is used as the distance between stochastic variables, considering its advantage over the conventional Kullback-Leibler divergence.

In the stage of representative ground motion synthesis, information of ground motions are extracted and representative waves are synthesized in one subgroup. Applying wavelet transform, we construct a scheme to extract information from ground motions. Important characteristics relevant to target structure's response, which is difficult to be expressed by forms of indices, are extracted as wavelet functions. Extracted information is superposed to one artificial wave, and its performance as a representative of one subgroup is evaluated by numerical experiments.

Keywords: design ground motion, clustering, machine learning, wavelet transform

1. Introduction

Owing to the development of the simulation technique of strong ground motion and the improvement of observation networks for strong ground motion, it is becoming possible to evaluate the time history waveform of scenario ground motion in accordance with earthquake environment conditions by region. Setting input earthquake motions for seismic performance examination based upon evaluated scenario ground motions leads to streamlining seismic-resistant design processes. However, because a myriad of scenario ground motions exist which satisfy the same condition, a method to objectively select a specific waveform from candidate waveforms is required for seismic performance evaluation. In the existing earthquake resistant design codes[1)], it is described that attention should be paid to how to set waveforms, but no concrete method is stated. Therefore, in practice, it is often the case that a few arbitrary waveforms are used, which lacks basis for selection.

In order to effectively utilize the information from the scenario ground motion, it is required to select ground motion waveforms representing the aggregated scenario ground motion. The representativeness of ground motion waveforms here means an input wave so that the safety against the failure modes that are excited from the initial scenario ground motions can be confirmed by performance examinations for the waveform being implemented, without direct examination for all ground motions. More specifically, the waveform that gives a large enough response value to each structural member compared with any other scenario ground motion waveforms can be the representative wave. The wave fitted to the envelope of design response spectrum that is used in many design codes may have the above representativeness; however, it cannot represent nonlinear systems enough.

From the perspective of earthquake engineering, this problem can be understood as the maximization of the influence of ground motion on nonlinear systems. The method to synthesize such representative waves has been broadly researched by using Intensity Measure[2)] (IM), expressing the strength of each ground motion. As a typical example, there is methods of ranking each element of an aggregated ground motion based on IM and selecting the waveform responding to the credibility required in designing as an external design force[3)]. There is also a method of obtaining an artificial simulated waveform maximizing IM as a certain condition from a formularization as an optimization problem[4)]. However, these methods has the problem that, in the case where the behavior of structure has a strong nonlinear nature, the value of IM and the strength of the influence that ground motion actually gives to structure do not correspond with each other adequately. Although a development of a new IM to enhance the correlation between both indices and real response has been attempted[5-7)], it has not been resolved. The core of this problem is considered to be that although the influences that ground motion characteristics exert to actual structure covers a variety such as degree of amplitude, duration, frequency components and their change over time, etc., a small number of IM cannot adequately express the complex nature of ground motion characteristics.

This problem is considered to be solved by extracting important characteristics involved in the response to the target structure from the complex ones that ground motion has and directly reflect them on the representative wave. This is because the representative wave which is synthesized simultaneously excites various failure modes, which are excited by scenario ground motions, with waveform 1. As a result, it is expected that the response to the structure becomes larger. Therefore, in this paper, we proposed a synthesis method of representative waves of ground motions, consisting of two approaches which are under mentioned and effectiveness is verified.

2. Proposed method

2.1 Overview of the method

In the design guide of each structure in Japan, it is often the case that the condition to be satisfied by design ground motion is given as a response spectrum[1)]. Recently, owing to the improvement of the strong ground motion observation network and the development of strong ground motion simulations, it is becoming possible to set up ground motion waveforms according to earthquake environment conditions of the region as the waveforms obtained from the observed waveforms under similar physical conditions in other sites, or from a strong ground motion simulation[8)]. The waveforms satisfying the given conditions such as response spectrum and earthquake environment condition are called "reference ground motions" in this research. The reference ground motions are consistent with the earthquake hazards assumed in a specific region reflected by the engineering knowledge of response spectrum and the physical knowledge of the technology of strong ground motions. They are also established site-specifically and independently from the structure of the design.

Meanwhile, because of the uncertainty of earthquake phenomena and phase arbitrariness, a number of the reference ground motions can be assumed. It is widely recognized that these reference ground motions greatly differ from each other in their influence on the behavior of nonlinear systems of structural systems. Furthermore, the extent of the difference depends on characteristics of the structural systems. Therefore, in practice of earthquake-resisting design, it is required to set a specific waveform obtained by a method assured of its objectivity as design ground motion instead of a number of design ground motions that can be assumed. The waveform should be set as a representative waveform containing nonlinear behavior of target structure of design. The amount of nonlinear behavior caused by ground motion differs in accordance with the dynamic characteristics of the target structure. Therefore, it is required to set the design ground motions in a structure-specific way with the characteristics of structure into consideration.

In this research, it was aimed to set structure-specific design ground motions, taking the influence of structure into consideration, based upon site-specific reference ground motions, not depending upon the structure reflected by the earthquake environment conditions of the region.

First, the reference ground motions that can be assumed from the given earthquake environment conditions are classified into several groups in accordance with their characteristics, because it is presumed that there are several types in the characteristics of waveforms among the scenario ground motions, such as ones with pulse-like characteristics and ones with a relatively long duration time. It is considered that the structure also shows different behaviors depending upon such types of waveforms so that the ground motions are classified beforehand in order to effectively extract the characteristics.

Then, a method to synthesize the representative waveform is developed, in which the characteristics of individual waveforms form can be reflected, for a certain group of ground motions. An artificial waveform can be synthesized by a machine, learning by repeating the learning of the characteristics related to the target structural system having individual waveforms. If the waveform thus synthesized excites several failure mechanisms and gives a large response value to each constructional element of the structure, it is confirmed that it is appropriate as a representative wave of the group of design ground motions.

2.2 Clustering of reference ground motions

2.2.1 Evaluation of dissimilarity of ground motions

It is presumed that among the reference ground motions that are site-specifically generated, there are several types in characteristics of waveforms, such as ones with pulse-like characteristics and ones with a long duration time. There are also differences in failure modes that excite structure systems in accordance with their characteristics. Therefore, it is considered to be possible to set rational reference ground motions by grouping the reference ground motions in accordance with type and by setting a representative waveform in each group. Therefore, in this research, the method for clustering the reference ground motions from the viewpoint of their influence to structure system was established.

In order to apply the clustering method to certain set, it is necessary to quantitatively evaluate the dissimilarity between the elements of the set. It is the purpose to group the aggregated ground motion waveforms, based on the difference in characteristics, as design ground motion. Because the ground motion waveforms' characteristics should be expressed and their dissimilarity should be evaluated from the viewpoint of the influence that the ground motion waveforms exert to structure and to nonlinear response, in particular, the dissimilarity of ground motion is defined as follows.

In order to express a certain ground motion $f(t)$ from the viewpoint of the influence to the structure, it is considered to use the n response values ($\boldsymbol{x} = \{x_1, \ldots, x_n\}$) of a nonlinear model simulating target structure. However, in consideration of calculation load of evaluating the responses for all assumed waveforms, the response values of simple models at the level that can reflect important dynamic characteristics of the target structure are used. The examples of such response values include the maximum displacement and cumulative energy of nonlinear single degrees of freedom where a structure's own natural period and its important mode cycle are matched. In order to make the expression of characteristics of ground motion robust, variation is given to the parameter of nonlinear models used for the evaluation of $\boldsymbol{x}$, and obtain probability distribution, $p(\boldsymbol{x})$, of response value $\boldsymbol{x}$ for ground motion $f(t)$. The sensitivity of response for the variation of structure parameter differs in accordance with the characteristics of ground motions. Therefore, accordingly, because the shape of $p(\boldsymbol{x})$ changes, it is considered to be able to emphatically express the difference in ground motion characteristics compared with the case when single response values are used.

The probability distributions of the responses of structural models, $p(\boldsymbol{x})$ and $q(\boldsymbol{x})$, are presumed to be made to correspond to ground emotions, $f(t)$ and $g(t)$, now. In order to quantify the dissimilarity of $f(t)$ and $g(t)$, JS divergence[9)] $D_{JS}(p, q)$ is used as shown in the following equation:.

$$D_{JS}(p,q) = \frac{1}{2} D_{KL}(p,M) + \frac{1}{2} D_{KL}(q,M) \tag{1}$$

where M of (1) is defined as

$$M(\boldsymbol{x}) = \frac{1}{2} p(\boldsymbol{x}) + \frac{1}{2} q(\boldsymbol{x}) \tag{2}$$

and $D_{KL}(p, q)$ is KL divergence defined as

$$D_{KL}(p,q) = \sum_i p(\boldsymbol{x}_i) \log \frac{p(\boldsymbol{x}_i)}{q(\boldsymbol{x}_i)} \tag{3}$$

Divergence function is a function that corresponds to strict Riemannian distance on a manifold by a small distance and $D_{JS}(p, q)$ and $D_{KL}(p, q)$ are divergence functions on a manifold of probability distribution. $D_{JS}(p, q)$ resolves asymmetry of $D_{KL}(p, q)$ and overcomes the drawback of it whose value diffuses in the cases where there are the areas become $q(\boldsymbol{x})=0$, $p(\boldsymbol{x})\neq 0$.

2.2.2 Clustering method

The methods of clustering a set which dissimilarity between elements has been defined are roughly divided into hierarchical methods repeating the process of consolidating the clusters with the least dissimilarity and non-hierarchical methods constructing n clusters at once based on the distance from the n central points on the spaces. For the method of this research in which no coordinate value is given to each ground motion, a hierarchical method is employed, which consists of the following procedures with which an algorithm can be constructed using dissimilarities between elements only.

i) First, each element is regarded as one cluster

ii) Evaluate the dissimilarity between clusters and consolidate a pair of clusters with the least dissimilarity.

iii) If the number of clusters reached the predetermined number, the algorithm is completed. If not, return to the step ii) and run the next loop.

In this research, the dissimilarities between ground motions were evaluated using JS divergence and the dissimilarities between the clusters consisting of more than one element are evaluated with the group average method that is said to be standard.

2.3 Synthesis of representative waveform as a design ground motion

It is considered to artificially synthesize a waveform representing the reference ground motions in the sense of their influence on the structures in each cluster, after the clusters of the reference ground motions are established by the above process. The representative waveform described here is an input wave that can confirm the safety against the failure modes which can be excited from reference ground motions initially assumed, without directly examining all reference motions. More specifically, the waveform that can give a large enough response value to each structural member compared with any other scenario ground motion can be the representative waveform.

In order to excite several failure modes caused by reference ground motions, it can be considered to integrate the information that waveforms have into an artificial wave by repeated learning of the characteristics of those waveforms. The characteristics that the representative wave should learn are related to the influence on the structure system. For this purpose, conventionally frequency characteristics of ground motions has been considered in seismic design. However, in this paper we focus on and time-frequency characteristics and manipulate it in order to update the wave's characteristics more efficiently.

Therefore, the following learning algorithm is established:

i Select a reference ground motion, $g^{target}(t)$, having the characteristics closest to the synthesized waveform in the k-step, $f^k(t)$, as a learning target

ii Expand $g^{target}(t)$ in the wavelet series and extract several main component waves.

iii Let $\phi_i(t)$ stands for wavelet function and A_i corresponding wavelet coefficient, and several dominant components are extracted. Add each extracted element to the synthesized wave and obtain several candidates of the synthesized waves of the next step, $f^{k+1}_{candidate}(t)$.

$$f^{k+1}_{candidate}(t) = f^k(t) + c \cdot A_k \cdot \phi_k(t) \tag{4}$$

where c is a coefficient to adjust learning rate and $A_k \cdot \phi_k(t)$ is dominant components extracted from $g^{target}(t)$.

iv Among several candidates of synthesized waveforms, select the one which characteristic was changed the most compared with the synthesized waveform in the k-step for the synthesized waveform of the next step.

Through these processes, the main characteristics of each waveform extracted as wavelet component will be reflected on the synthesized waveform. When the component extracted from the waveform of the learning target is added to synthesized wave, various characteristics can be obtained in the learning process and their influences exerted on structural systems become large by coefficient c being established so that the total energy of the waveform increases.

The waveform synthesized by this method is expected to become one that can excite several failure modes that are excited by reference ground motions, at one time, with only one waveform. Therefore, this will be confirmed by a numerical experiment in the following section.

3. Clustering a set of observed earthquake ground motions

As a setting method of design earthquake ground motion, in addition to the existing methods to correct observed waveforms using an attenuation model, it has been recently proposed to use a large number of observed earthquake ground motions having similar earthquake source characteristics and earthquake propagation path characteristics to those presumed. Setting up the design ground motion by referring to the observed waveforms is important from the standpoint of reflecting the information of actual phenomena. However, as described in the beginning of this paper, it is difficult to use a large number of the waveforms directly for seismic performance evaluation, the grouping of waveforms by applying the proposed clustering method is considered to be effective.

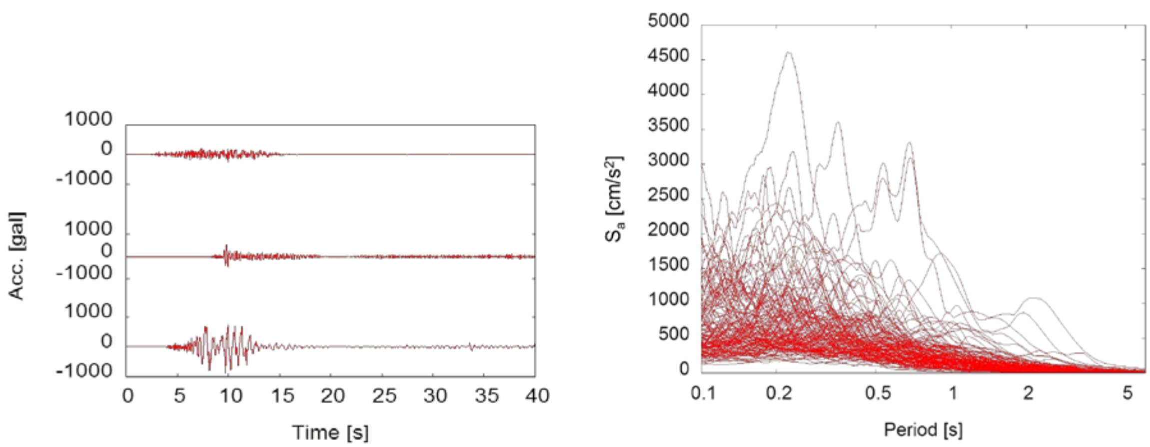
In this section, the proposed method was applied to records of observed earthquake ground motions. It was confirmed, from numerical analysis, that the structured clusters were appropriate because they were classified from the viewpoint of non-linear behavior given to the presumed target structural system and the applicability of the proposed method was verified.

3.1 Target ground motions

When the records of observed earthquake ground motions is used as the design earthquake ground motion, the waveform close to the target value of physical characteristics, such as earthquake source characteristics and earthquake propagation path characteristics, is used. Taking into consideration of that, ground motions records meeting these conditions added by following certain constraints were extracted as target ground motions from all data published on K-net[10] from January 1996 to August 2015.

- Earthquake source characteristics: Magnitude Mj>6.0
- Earthquake propagation path characteristics: Hypocentral distance R<40.0 km
- ground motion intensity: Instrumental seismic intensity I>5.0

We chose 71 records satisfying these constraints and used both EW component and NS component in horizontal acceleration respectively. As a result, 142 waveforms were prepared as the target waveform group of clustering. Figure 1 shows the target record group of earthquake ground motions. As shown above, the record group, on each physical property for which a certain condition is imposed, is found to be constituted of various waveforms having different characteristics and shapes of response spectrum.



(a) Examples of time series waveform (b) Response spectra of all ground motions

Fig. 1 – Target ground motions of cluster analysis

3.2 Target structure

As the structure system subjected to earthquake performance verification, a nonlinear 10 degree-of-freedom system simulating a ten-story RC building was set up. The characteristics of the springs connecting each mass are expressed by tri-linear Clough model and the parameters of mass and rigidity were set to the same values of the existing cases[11].

The purpose of this analysis was to verify that the record group of the ground motions can be classified by the proposed method from the viewpoint of response value given to the target structure system. Then as a pre-analysis, a time history response analysis of the target structure system for each waveform was conducted, and the trend of the response values that the record group of the earthquake ground motions gives to the structure system was confirmed. OpenSees[12] was used for the time history response analysis. For the purpose of evaluating the damage ratio of each spring against the record group of the observed earthquake ground motions, Park-Ang index [13] I_{PA} below.

$$I_{PA} = \frac{\delta_{\max}}{\delta_u} + \frac{0.15}{Q_y \delta_u} \int \mathrm{d}E \tag{5}$$

where $\delta_{\max}$ and $\int dE$ denote the maximum displacement of spring and hysteretic energy of springs caused by ground motion, respectively. δ_u and Q_y denote ultimate displacement and yield strength by each spring. The ultimate displacement was set as the displacement when the inter-story drift angle between each story of a 10-story building became 1.00%.

3.3 Results and discussion

The record group of the observed earthquake ground motions, which is subject to clustering, consists of the waveforms that variously influence the target structure system. It was verified, as stated below, whether or not a waveform group like this can be appropriately classified from the viewpoint of influence on the structure system.

First, the validity of dissimilarity evaluation between earthquake ground motions using a JS divergence was confirmed. The difference between the influences on the target structure system by a pair of ground motions $f(t)$ and $g(t)$ are evaluated by $D_2[f, g]$ of the following formula.

$$D_2[f,g] = \left\{ \sum_{i=1}^{10} (\bar{x}_i - \bar{y}_i)^2 + \sum_{i=1}^{10} (\bar{E}_i - \bar{F}_i)^2 \right\}^{0.5} \tag{6}$$

x_i and y_i show the maximum displacements that f and g give to 10 degree freedom system spring i, respectively, and Ei and Fi show the hysteretic energy absorption that f and g give to spring i, respectively. The bar above each variable means that it is normalized, so that the average of all 142 waveforms becomes 0 and the variance becomes 1. $D_2[f, g]$ is the difference between the influences on the target structure system by two earthquake ground motions evaluated by Euclidean distance in 20-dimentional vector space (x_1, …, x_{10}, E_1, …, E_{10}), using 20 response values as coordinates.

Fig. 2 shows the relationship between $D_2[f, g]$ and $D_{KL}[f, g]$ for every pairs of ground motions selected from 142 waves. The determination coefficient between the variables of two axes is 0.40, and it basically tends to have a positive slope. Therefore, it can be said that there is a weak relationship between the degree of dissimilarity between earthquake ground motions evaluated by JS divergence and the difference of the influence actually exerted on the target structure system by these ground motions. Additionally, it can be indicated that JS divergence always takes small value when $D_2[f, g]$ is also relatively small. Therefore, when we make clusters of ground motions based on JS divergence, a hierarchical algorithm explained before works well especially in early steps, where pairs of ground motions with least dissimilarity is consolidated.

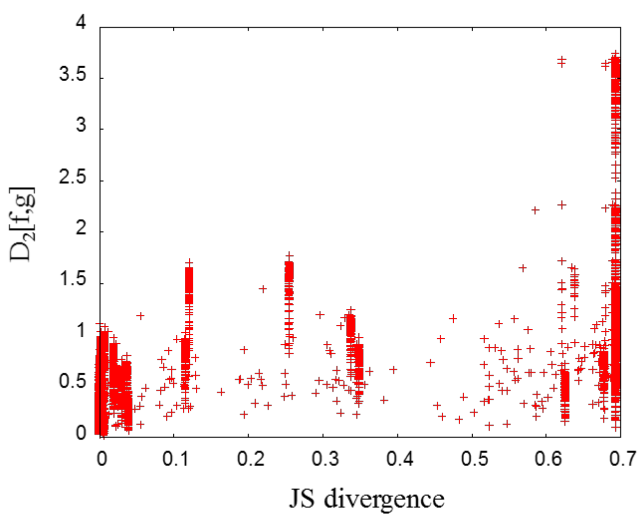
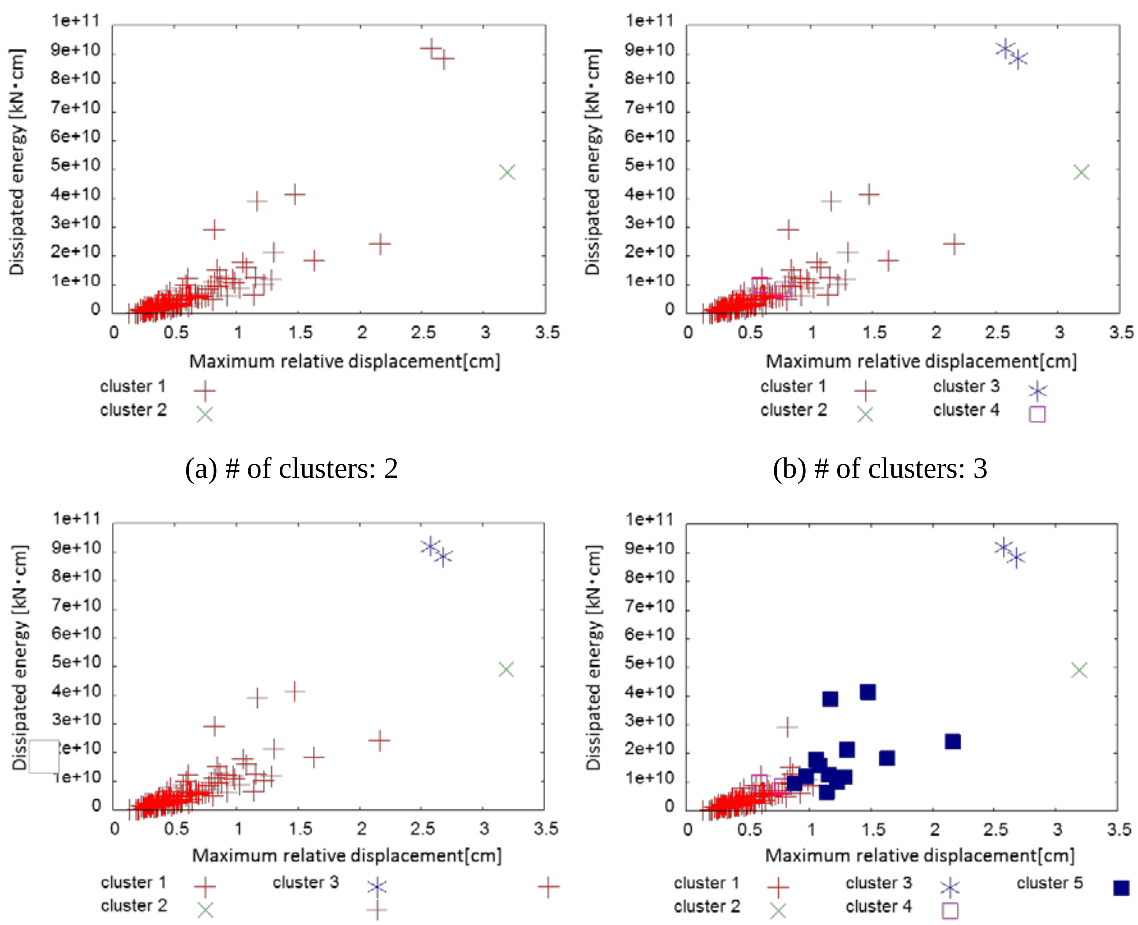


Fig. 2 – Relationship between $D_2[f, g]$ and JS divergence

Next, the result of implementation of clustering was analyzed. In order to visualize the cluster, the cluster was confirmed on a 2-dimentional vector space with the coordinates of two values of the maximum relative displacement x_i that each ground motion gives to a particular spring *i* of the target structure system and hysteretic energy absorption E_i.

As an example, we compare the clustering result with ground motions' effect on spring 7. Fig. 3 shows the clustering result on the space of response value of spring 7 when the number of clusters was increased from two to five. First, when the number of clusters is set as two, it is found that the ground motions are classified into 1 wave, which gives the largest maximum relative displacement, and all other waveforms. The waveform that forms an independent cluster that gives a particularly large response value to only spring 7 and therefore it can be regarded unique in that meaning.



(a) # of clusters: 2

(b) # of clusters: 3

(c) # of clusters: 4

(d) # of clusters: 5

Fig. 3 – Visualization of clustering result in the space of response value given to spring 7

Next, when the number of clusters is increased to three, the cluster consisting from 2 waves that gives particularly large hysteretic energy absorption energy (Fig. 3 (b), Cluster 3) is newly formed. This cluster is comprised of waveforms giving a large response value to many springs. When compared with the wave in Cluster 2, although the maximum relative displacement is small, its value of hysteretic energy absorption is large. In other words, the wave in Cluster 2 and those in Cluster 3 give large response values to Spring 7; however, their mechanisms are different. Therefore, it is reasonable that they are identified as different clusters.

Then, when the number of clusters is 4, the newly created cluster 4 is not in a positional relation clearly separated from Cluster 1 on the space. However, if the number of clusters is further increased to 5, it is found that the group of the waveforms with large maximum relative displacement is separated as Cluster 5 out of the waveforms belonging to Cluster 1 in (a)-(c) in the figure and the cluster of waveforms grouped by similar response characteristics is formed.

As is shown in Fig. 3, clusters of ground motions formed by the proposed method cause different response to the target structures respectively. In this meaning formed clusters are valid and effectiveness of the method is indicated.

4. Synthesis of an artificial wave representing reference ground motions

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 behaviour of the target structure is synthesized.

4.1 Target ground motions and structure

A set consisting from 98 ground motions are prepared as reference ground motions. (The efficiency of the two schemes of clustering and wave synthesis is verified respectively. So ground motions utilized in this section 4 are different from those in section 3.) Those waves are amplified to fit design response spectrum of Specification for Highway Bridge in Japan. Meanwhile, the same structure as section 3 was assumed as the target structure for the seismic design.

4.2 Parameters setting for 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 learning will not be conducted. Therefore the initial wave was set by multiplying 0.5 to this time series. Learning rate coefficient c in equation (4) is determined in order that the power of the initial wave increases by 10 % of initial value in each step.

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, 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.

Under these conditions, the learning procedures described in section 2.3 were repetitively conducted until the power of the synthesized wave exceeds the largest value among learning targets.

4.3 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.

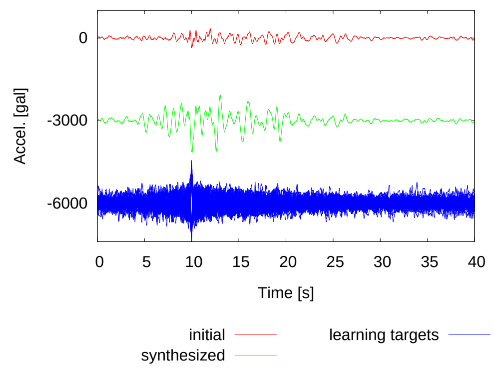
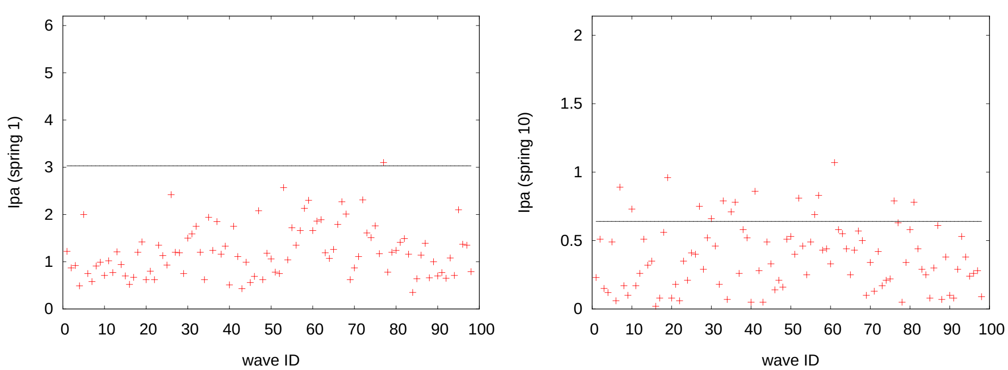


Fig. 4 – The synthesized wave comparing with the initial input motion and learning targets

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. x.(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.

Fig. 5 (b) shows that the results about spring 10. Behaviour of spring 10 is mainly affected by higher modes. 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 damage of various structural members. It shows the efficiency of the concept of synthesis of a wave reflecting various characteristics.



(a) spring 1 (b) spring 10

Fig. 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.

5. Conclusion

In order to resolve the problem of setting design ground motion among myriad candidates, we proposed a concept of site-specific reference ground motions, a suite of waveforms which are consistent with the earthquake hazards assumed in a specific region, and structure-specific design ground motions, which are set based on reference ground motions and property of target structure. Furthermore, we proposed a method to synthesize representative waves of reference ground motions as a design ground motion, consisting of following two approaches.

First, a scheme to make clusters of reference ground motions according to their influence on target structure is constructed. Dissimilarity of ground motions is evaluated based on a simple structural model with variety of parameters. A hierarchical approach is used for the clustering method. Numerical simulations show that ground motions are appropriately classified according to their influence on nonlinear response of the target structure.

We also proposed a scheme to synthesize a representative wave as a design ground motion within one cluster of waveforms. The representative waveform is an input wave which can confirm the safety against the failure modes which can be excited from reference ground motions initially assumed, without directly examining all reference motions. A learning algorithm to integrate important characteristics of reference ground motions into the synthesized waveform is constructed, and its effectiveness is verified through numerical simulations.

6. Acknowledgement

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7. References

[1] Japan Road Association (2012): *Specifications for Highway Bridges Part V Seismic Design*, Maruzen Co. (in Japanese).

[2] Katsanos E.I., Sextos A.G., Manolis G.D. (2010): Selection of earthquake ground motion records: A state-of-art review from a structural engineering perspective. *Soil Dynamics and Earthquake Engineering*, **30**(4), 157-169.

[3] Zhai C.-H., Xie L.-L. (2007): A new approach of selecting real input ground motions for seismic design: The most unfavourable real seismic design ground motions, *Earthquake Engineering and Structural Dynamics*, **36**(8), 1009-1027.

[4] Takewaki I. (2002): Seismic critical excitation method for robust design: a review, *Journal of Structural Engineering*, **128**(5), 665-672.

[5] Lamprey J. W., Abrahamson N. (2006): Selection of ground motion time series and limit on scaling, *Soil Dynamics and Earthquake Engineering*, **26**(5), 477-482.

[6] Luco N., Cornell C.A. (2007): Structure-specefic scalar intensity measures for near-source and ordinary earthquake ground motions, *Earthquake Spectra*, **23**(2), 357-392.

[7] Tothong P., Luco N. (2007): Probabilistic seismic demand analysis using advanced ground motion intensity measures, *Earthquake Engineering and Structural Dynamics*, **36**(13), 1837-1860.

[8] Railway Technical Research Institute(2012): Design Standards for Railway Structures and Commentary (Seismic Design), Maruzen Co. (in Japanese)

[9] Fuglede B., Topsoe F. (2004): Jensen-Shannon divergence and Hilbert space embedding, *Proc. IEEE Int. Symp. Inform. Theory*, 31-36.

[10] Strong-motion Seismograph Netwoks(K-net, KiK-net)

http://www.kyoshin.bosai.go.jp/

[11] Architectural Institute of Japan (2006): Seismic response analysis and design of buildings considering dynamic soil-structure interaction, Architectural Institute of Japan [in Japanese].

[12] Open System for Earthquake Engineering Simulation

http://opensees.berkeley.edu/

[13] Park Y.J., Ang A. H.-S. (1985): Mechanistic seismic damage model for reinforced concrete, *Journal of Structural Engineering* **111**(4), 722-739.