Quantification of Reliability of Ground Motion Selection by Using Nonlinear Response of Structure as Feature Indices

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SUMMARY:
Selection of design ground motions is an important aspect of seismic design. Owing to computational constraints, it is required to have a limited number of representative ground motions. On the other side, consideration of ground motion from various sources is necessary to enhance the reliability of seismic performance of structure. Indices are commonly deployed for the selection of design ground motions, but intensity measure cannot circumscribe the complexity and unpredictability of nonlinear response. This paper proposes to consider a fluctuation to the parameters of indices to cope with modifying dynamic characteristics of structure in progressive damage of structure. The results indicate that the reliability of design ground motion selection is enhanced by considering the indices which reflect the effect of nonlinear response.

Keywords: Feature index, index parameters, nonlinear dynamic response, seismic design, input motion

1. INTRODUCTION

Nonlinear dynamic analysis of structure is one of the most effective ways to look into the performance of structure in nonlinear range. Meanwhile, selection of design ground motions out of a large number of possible ground motions is complicated due to complexity and unpredictability of nonlinear response. Such complexity of design ground motions selection out of possible ground motions may increase, if affect of stochastic nature of structural characteristics in nonlinear analysis is considered.

Consideration of set of possible ground motions for dynamic nonlinear analysis of the structure (structure under consideration) is important to enhance the reliability of seismic performance of structures. But it is not possible to perform nonlinear analysis for a large number of ground motions. Thus, a limited number of ground motions is required which can represent the set of possible ground motions so that designing the structure against the representative ground motions is equivalent to design the structure considering the set of possible ground motions.

In literature, a good number of procedures are proposed for selection of design ground motions by using indices (K. Matsumura, 1992). In these procedures, indices (intensity measures) are used to quantify the effectiveness of ground motions. It is assumed that a ground motion which is large in terms of indices is expected to be ‘tough’ for the structure. In such situation, index that can consider the complexity of nonlinear response of structures is required for selection/synthesis of design ground motions.

1.1 Index Based Ground Motion Selection and Associated Challenges

Index-based design ground motion selection approach has been widely accepted (Zhai and Xie, 2007) and a number of simple to complex indices are proposed (Akkar and Ozen, 2005). Most of indices are based on the information of ground motion signal such as peak acceleration and duration of ground motion. Some other indices consider the effect of structural characteristics (Park and Ang, 1985). Authors have proposed a scheme for synthesis of design ground motion, considering the uncertainty of structural and seismic uncertainty (Honda and Ahmed, 2011, Ahmed and Honda, 2010). In the proposed approach, feature indices are used to represent the set of possible ground motions. In these situations indices are objected to quantify the damaging capabilities of ground motions.

In evaluation of the performance of ground motion based on indices, following should be taken into consideration.

- Different ground motion could be regarded as effective when structural properties are changed due to fluctuation in structural characteristics.
- Indices are simple and cannot circumscribe the complexity and unpredictability of nonlinear response.

It is required that indices must be equipped with characteristics that can reflect the complexity of nonlinear response in selection/synthesis of design ground motions.

2. OBJECTIVES

The objective of this work is performance enhancement of index-based design ground motion selection approach. For that objective, effectiveness of indices for selection of design ground motion is enhanced by considering the effect of nonlinear response of structure. To enhance the performance of indices in context of nonlinear response of structure, it is proposed that indices should be sensitive to the stochastic nature of structural characteristics and modification of influencing parameters of nonlinear response of structure in progressive damage of structure.

Due to variety of uncertain factors, it is difficult to quantitatively consider complexity and unpredictability of nonlinear response of structure in selection of design ground motions. Thus, we propose to consider the fluctuation to the parameters of indices. This will be helpful to evaluate a variety of aspects of a ground motion in context of nonlinear response of structure. This will contribute to enhance the reliability of indices based design ground motion selection approaches.

The results from this study indicate that the reliability of design ground motion selection is considerably enhanced by considering the indices which are equipped with such characteristics, which are efficient to reflect the effect of nonlinear response.

3. SELECTION OF DESIGN GROUND MOTION AND RELIABILITY OF DESIGN GROUND MOTION SELECTION

Indices are used as condition to select the design ground motions (Ahmed and Honda, 2010). It is required that design ground motion should be selected so that probability (P) of occurrence of damage (D) under the condition that the structure is designed against that ground motion (GM) is smaller than a certain value $(\overline{\mathrm{P}})$.

$$\mathrm{P} = \mathrm{prob}(\mathrm{D}|\mathrm{GM}) < \overline{\mathrm{P}} \tag{3.1}$$

The value of probability (P) depends on the selected design ground motion. Since we cannot know the influence of a ground motion on the structure in advance, we need to select a ground motion which satisfies the specified condition(C). Therefore we should consider the probability that Eqn. 3.1 is satisfied when ground motion is randomly selected based on the condition (C). This probability can be regarded as reliability(R), which can be written as

$$\mathrm{R} = \mathrm{prob}[\{\mathrm{prob}(\mathrm{D}|\mathrm{GM}) < \overline{\mathrm{P}}\}|\mathrm{C}] \tag{3.2}$$

In this procedure, feature indices are used in the condition(C). If indices are efficient to represent the damage capabilities of ground motions, then reliability of having the required design ground motion is higher. Thus, the reliability (*R*, defined in Eqn. 3.2) has a direct correlation with the efficiency of an index. In this study, we will use the reliability (R) of selection of required design ground motion as criteria to evaluate the goodness of an index.

4. SELECTION OF PROPERTIES OF INDICES CONSIDERING NONLINEAR RESPONSE OF STRUCTURES

Indices for the selection of design ground motions can be categorized into two types. First types of indices are based on the properties (statistics) of ground motion signal (Zhai and Xie, 2007) such as peak acceleration, duration of ground motion signal, spectral values, etc. They do not consider the effect of structural characteristics. Second types of indices consider the affect of ground motions on structures such as response of single degree of freedom (SDOF) system which includes dynamic characteristics similar to the structure under consideration. We use the latter types because ground motions for design should be selected based on their influence on structures.

In general, for indices which consider the effect of structural characteristics (Park and Ang, 1985), the indices parameters such as yield force and natural time period of bilinear SDOF system, are decided by considering the characteristics of the structure under consideration. In such situation two points are important to mention here, first, dynamic characteristics of structure are modified in progressive damage of structure, thus the deterministic parameters of indices based on linear response of structure is not justifiable. Second, indices are simple and cannot represent the complex nonlinear response of structure.

4.1 Fluctuation in the Parameters of Indices to Consider Nonlinear Response

Considering the background presented in above, we propose to consider a fluctuation to the parameters of indices to cope with complexity and unpredictability of nonlinear response. Let us emphasize that we add fluctuation not to reproduce the complicated nonlinear response of the structure. Rather than that, it is assumed that consideration of fluctuation to the parameters of indices will be helpful to enhance the efficiency of indices to represent the damaging capabilities of design ground motions.

The amplitude of fluctuation added to the index parameters is not easy to specify. Comparing the simplicity of indices and complexity of nonlinear response, it is not a good option to fix the value of fluctuation. We need to specify the range of fluctuation suitable to cope with complexity of nonlinear response and we try to evaluate an optimum range of fluctuation to the parameters in the following.

5. NUMERICAL SIMULATION

This section discusses the optimal amplitude of fluctuation in index parameters, taking a two dimensional RC frame structure as an example. The indices are used to select the design ground motions out of sets of possible ground motions. The ranges of fluctuation added to the index are changed gradually. The reliability of obtaining appropriate design ground motions is checked to find the optimal range of fluctuation to the index parameters.

5.1 Structural Model

Design ground motions are synthesized for a two dimensional five-story moment resisting concrete frame, elevation of the frame is shown in Fig. 5.1 and sectional details are shown in Table 5.1. This structure is referred to as a target structure hereafter. The dead load for the nonlinear analysis is contributed by the self weight of members such as beam, columns, concrete slab and weight of floor finishes. Nonlinear dynamic analysis is conducted by using OpenSees (OpenSees, 2006).

Table 5.1 Detail of beam and column sections

	Width [cm]	Depth [cm]	Reinforcement
Column	38	38	19mm dia. 22 bars uniformly distributed on all faces
Beam	30	38	Top. 19 mm dia. 7 bars Bot. 19 mm dia. 7 bars

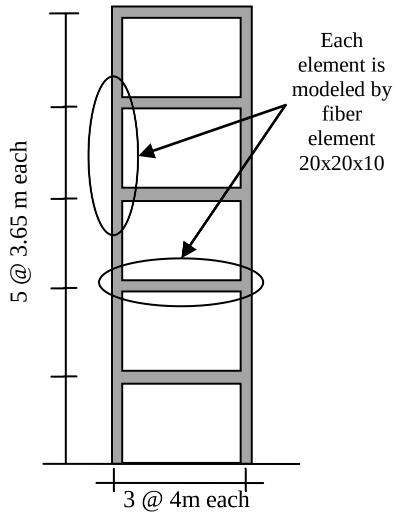

Figure 5.1 Elevation of concrete frame

Beams and columns of the frame are modeled by using unidirectional steel and concrete fibers, which are characterized by stress strain relationships. To characterize stress strain curve for the fibers of concrete and steel different models are available as recipes in OpenSees. Among material models available on OpenSees, `Concrete02` (OpenSees, 2006) model is used to model confined and unconfined concrete and material model `Steel02` (Filippou et al, 1983) is used to characterize the stress strain behavior of steel fibers. Beams and columns of concrete frame under consideration are modeled by using 20 x 20 x 10 fiber elements. In total 60,000 elements are used to model the frame and finite element analysis is conducted by using OpenSees. As example, the stress strain distribution of longitudinal steel bar at the maximum stressed section of first-story column is plotted in Fig. 5.2.

In order to consider the effect of uncertain material properties on structure response, we consider material properties of elements as independent stochastic variables. We consider a uniform distribution of material properties to give an equal importance to possible values of material properties. Yield strength of steel, modulus of elasticity of steel and compressive strength of concrete are considered as stochastic variables.

5.2. Possible Ground Motions

Set of possible ground motions is considered for the design of structures to enhance the reliability of structural performance. To check the stability of the proposed method, we consider two sets of possible ground motions: Set A and Set B. Different ground motions records are used to formulate the sets of possible ground motions. Two sets of possible ground motions are used to verify the stability of the proposed approach. Each set is comprises of 500 ground motions. The ground motions records of past earthquake events are obtained from K-NET (K-NET, 2008). It would be possible to generate such ground motions using numerical techniques, but actual ground motion records are used in order to discuss the applicability of the presented scheme for real ground motions. The ground motion records are factored so that their peak ground acceleration values are ranging between 600cm/sec^2 to 800cm/sec^2.

Selection of set of possible ground motions is important. Magnitude of event, source to site distance, site characteristics, etc are considered as criteria to formulate the possible ground motions which are required to be consider for the design of important structures. In the presented work, intentionally, we randomly selected the design ground motion to incorporate a variety of ground motions in set of possible ground motions.

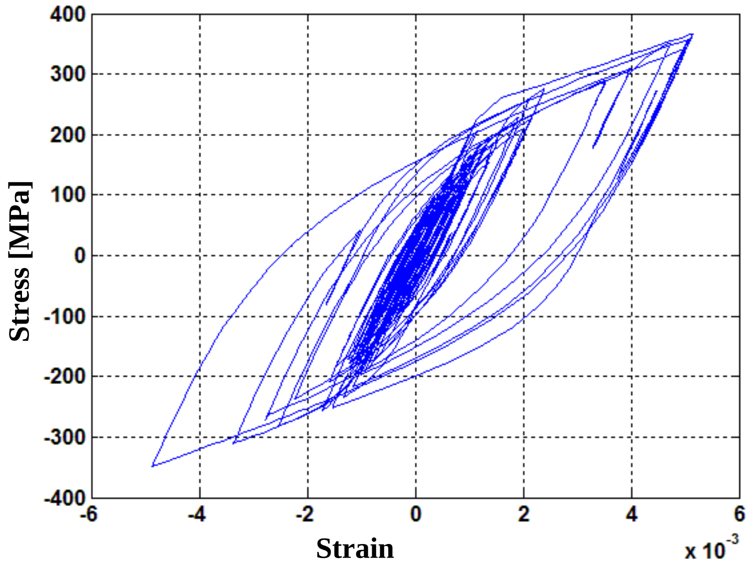

Figure 5.2 Stress strain distribution of longitudinal steel bar of maximum stressed section of first-story column.

5.3. Feature Indices Based Design Ground Motion Selection Considering Complexity of Nonlinear Response

Authors have presented the concept of damage mechanism based indices to select appropriate indices (Ahmed and Honda 2011, b). According to that concept, influential damaging mechanisms are accessed and accordingly indices are selected.

In our simulation, same strength columns are used for all the floors, because columns have the same size and reinforcement. The damage will be contributed at lower part of structure due to peak bending moments. Utilizing the concept of damage mechanism based indices, response of a bilinear SDOF is adopted as an appropriate index for the concrete moment resisting frame under consideration.

This index is a response of a spring mass system, and it cannot circumscribe the complexity of nonlinear response of concert structure. Meanwhile, we cannot quantitatively consider the aforementioned uncertainties and complexities of nonlinear response in selection/synthesis of design ground motion. Thus, we consider fluctuation to the parameters of indices to consider various aspects of influence of ground motion on the structure under consideration, which we cannot know if we use a single spring mass system.

5.4 Quantification of Structural Damage

OpenSees calculated the strain of each fiber against the deformation of member. This is used to quantify the effect of ground motion on the structure.

The structural damage is judged by comparing the strain of steel bars of all columns and beams. Damage level caused by ground motions is assessed by comparing maximum strain experienced by steel rebar of beams and columns of the structure. Let ε_m^i denote the strain of the rebar of the m-th structural member when the structure is exposed to the i-th ground motion. Suppose that the d-th ground motion is the design ground motion, then ε_m^d is regarded as reference value of strain of the m-th structural member. Here we define the structure is damaged, if strain of half of the members exceeds the corresponding values given by the design ground motion.

Strength of the design ground motion can be quantified by considering the probability that the structure designed by the d-th ground motion is damaged when it is exposed to all possible ground motions. It can be written as

$$P_d = \text{prob}\left[\frac{\sum_{m=1}^{M} \text{Ind}\{\varepsilon_m^n > \varepsilon_m^d\}}{M} > \frac{1}{2}\right] \tag{5.1}$$

where M is the number of beams and columns; n is the script to denote ground motion; ε_m^i denotes the strain of steel bar of the m-th structural member caused by the i-th ground motion; and $\text{Ind}\{C\}$ denotes an indicator function that is given as

$$\text{Ind}\{X\} = \begin{cases} 1, & \text{if condtion X is true} \\ 0, & \text{otherwise} \end{cases}$$

5.5 Conditions to be Design Ground Motion

Displacement response of bilinear SDOF system (D1) is used as index to select the ground motion representing the set of possible ground motions. We compare two conditions as examples:

Case-I: *Critically damaging ground motions out of set of possible ground motions*: A ground motion with 10% exceedance probability is selected as the condition to be design ground motions. It is important to note that any ground motion which would satisfy the condition, will be the design ground motion. As mentioned earlier, indices are used in conditions, thus a ground motion which shows 10 % exceedance probability in terms of feature indices would be design ground motion. 10% of exceedance probability means that at most 10% of ground motions out of set of possible ground motions may exceed beyond the design ground motion. In general, in this case we are looking for tough ground motions out of set of possible ground motions. And accordingly it is required that indices must quip with properties which reflect the complexity and unpredictability of nonlinear response.

Case-II: Least damaging ground motions out of set of possible ground motions: In this case, we are interested to have least damaging ground motions out of set of possible ground motions. A ground motion for which exceedance probability is 90% to 100% are required ground motions in this case. 90% of exceedance probability means that 90% of ground motions out of set of possible ground motions may exceed beyond the required ground motion. Thus, the required ground motions in this case are expected to be least damaging for the structure under consideration, hence it is expected that we need to consider less fluctuation to the parameters of indices.

6. SIMULATION RESULTS AND DISCUSSION

Based on the natural time period and yield force of concrete moment resisting frame, the properties of the bilinear SDOF system are formulated. Displacement response of the bilinear SDOF system is used an index. We consider fluctuation in parameters of bilinear SDOF system.

First, let us explain how we consider the fluctuation (say *x* % of original value) to the parameters of indices. We consider *x* % fluctuation to the parameters of indices and 50 realizations of bilinear SDOF systems are formulated. The average of displacement responses of aforementioned 50 bilinear SDOF realizations is used as index to show the effectiveness of a ground motion. This is used to formulate exceedance probability in terms of feature indices for the set of possible ground motions. Thus the ground motions which show the required exceedance probabilities are selected as required design ground motions.

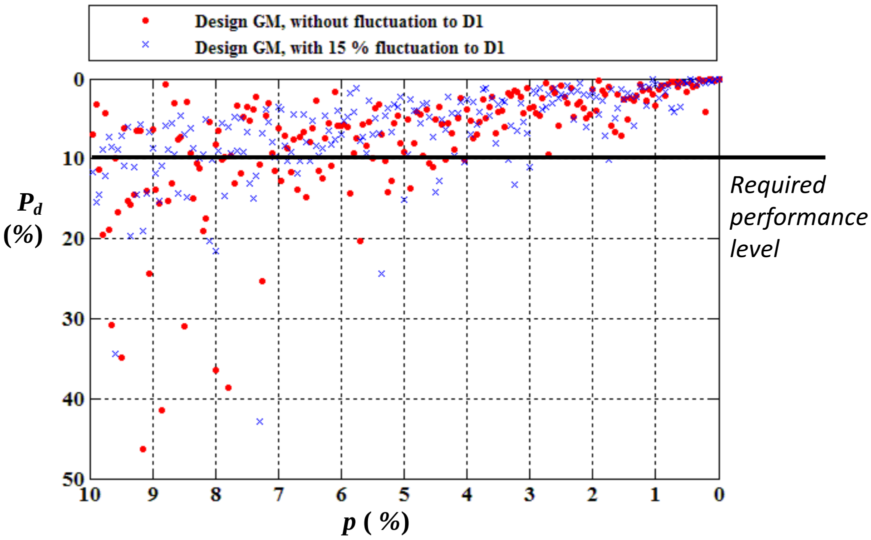

Figure 6.1 Distribution of exceedance probability of structural damage (P_d) against exceedance probability in terms of indices (p) for design ground motions for two different values of fluctuation to the parameters of indices.

Secondly, the responses of all ground motions, which conform the condition to be design ground motions are plotted in Fig. 6.1. Exceedance probability in terms of feature indices (*p*) is plotted in the horizontal axis and exceedance probability of structural damage (P_d , formulated by Eqn. 5.1) is plotted on vertical axis. According to Eqn. 3.1, the probability of structural damage should be less than a certain value($\overline{P}$). This required performance level is marked by horizontal solid line in Fig. 6.1. Selected design ground motions are expected to be above the required performance level. But some ground motions lie below the target level.

To show the goodness of indices, the percentage of ground motions showing the required performance for full scale structures to the ground motions conforming the condition to be design ground motion are calculated. This corresponds to the reliability defined in Eqn. 3.2.

For the specific results presented in Fig. 6.1, the fluctuations to the parameters of indices are 0% and 15%. For the 0% case, the aforementioned reliability is 76.1%. It means if we randomly select a ground motion which conform the required condition, there is 25% chance that the selected design ground motion do not cause the expected response in context of the full scale structure. For 15% case, the reliability of having required design ground motion is 81.0%. This shows that reliability of having the required design ground motions is increased as compared to 0% case, for which reliability was 76.1%.

It is important to know the optimal range of fluctuation to the parameters of indices for having maximum reliability. This aspect is discussed in the followings.

6.1 Case-I: Critically Damaging Ground Motions

The ground motions with 10% exceedance probability are expected to be most damaging for the structure under consideration. We use D1 as index to select the design ground motions and we consider the fluctuation to the parameters of bilinear SDOF.

We considered a fluctuation up to 50 % in the parameters of indices. Similar to the 0 % and 15 % fluctuation cases discussed in the previous section, we fluctuated the parameters by a step of 1%, and check the variation of reliability of having required design ground motion for both Set A and Set B of

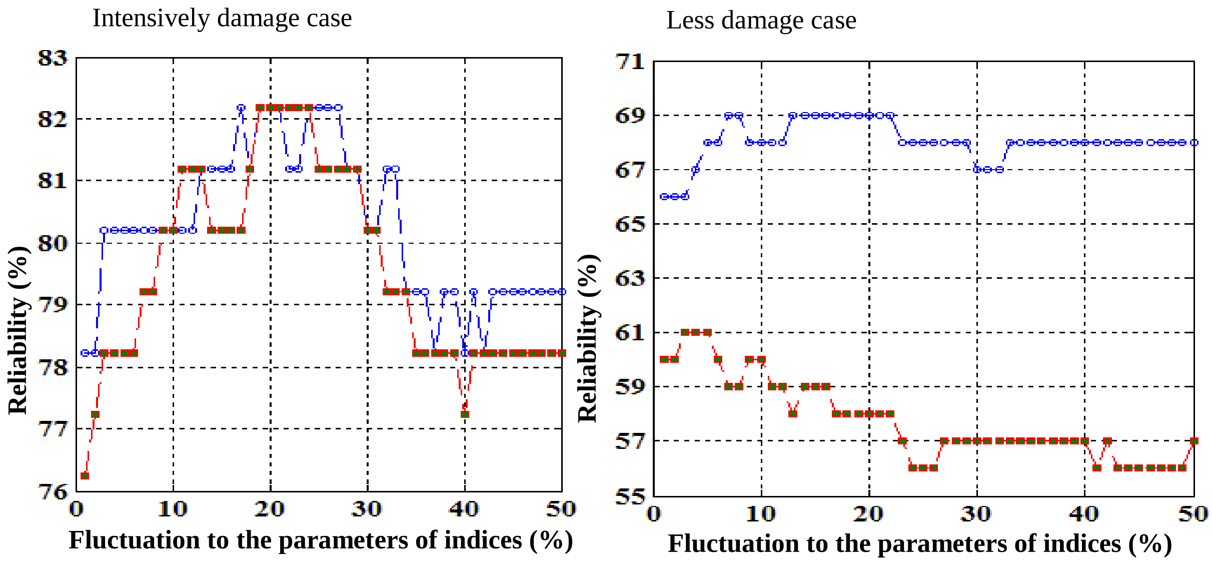

Figure 6.2 Effect of fluctuation to the parameters of indices on reliability of having required design ground motion for two sets of possible ground motions for (a) Intensively damage case (b) Less damage case.

possible ground motions. The results are presented in Fig. 6.2 (a), in which the fluctuations to the parameters of indices are shown along horizontal axis, and the reliability (based on Eqn. 3.2) of the case having the required ground motion is on vertical axis.

Fig. 6.2 (a) clearly shows that if we do not consider the fluctuation to the parameters of indices (which is a common practice) then the reliability of having the required design ground motion is lower. Also, the reliability of having required design ground motion is keep on increasing with increase in fluctuation to the parameters of indices and attain a maximum value between 20 and 30 % fluctuation to the indices parameters, and then decreases. This bell shape trend is common for both sets of possible ground motions, which indicates the stability of the proposed approach

The reason to increase the reliability of having the required design ground motion with increase in fluctuation to the parameters of indices is that, due to consideration of fluctuation to the parameters of indices, we can evaluate diverse aspects of ground motions which are influential in nonlinear analysis. While if we consider deterministic parameters of bilinear SDOF (0% fluctuation) then we may not effectively evaluate the ground motions in the aforementioned context. This approach fairly works for the structure under consideration. For the structure under consideration the optimum range of fluctuation to the parameters of indices is 20% to 30%

6.2 Case-II: Less Damaging Ground Motions

In case-II, we look for the ground motions which are least damaging to the structure. The ground motions with exceedance probability 90% to 100% are required ground motions in this case. As with the case I, we investigated the fluctuation up to 50% in the parameters of indices with a step size of 1%. The reliability (from Eqn. 3.2) of having required design ground motion is formulated for 50 cases. The results are presented in Fig. 6.2(b).

The results presented in Fig. 6.2(b) shows that initially the reliability of having required design ground motion increases with increase in fluctuation to the parameters of indices. Reliability attains a maximum value corresponding to a fluctuation of 4% to 8%.

The reason is that the required ground motions are not damaging to the structure, thus the structure remains in linear range, and we do not need to consider a wider fluctuation to the parameters of indices. While in case-I, the required ground motions were expected be damaging for the structure, thus it was required to select a wider range of fluctuation to the parameters of indices for having the required design ground motions.

For the structure under consideration, the proposed approach shows that the reliability of ground motion selection is considerable enhanced if the indices are equipped with the characteristics, which are required to reflect the uncertainty and complexity of nonlinear response.

7. CONCLUSION

Simulation techniques to generate the ground motions from fault parameters and facilities to record the seismic events are considerable enhanced in past two decades. This resulted into large number of ground motions. Consideration of such ground motions is essential to enhance the seismic performance of the structure. But, due to time and computational constraints, a limited number of ground motions representing the possible ground motions are required for the design.

Available methods of ground motion selection incorporate the intensity measures (indices) to evaluate the relative performance of ground motions. In comparison with complexity and unpredictability of nonlinear response, the indices are simple. Indices may not represent the possible ground motions in context of nonlinear response of structure. To improve the performance of index based design ground motion selection approaches, the effect of nonlinear response must be reflected in the ground motion selection.

We propose to consider a fluctuation to the parameters of indices to improve the performance of indices to represent the possible ground motion. Because, it is not possible to quantitatively consider the effect of complicated nonlinear response of structure in selection of design ground motions. It is assumed that consideration of fluctuation to the parameters of indices will be helpful to evaluate a variety of aspects of ground motions, hence, it will increase the reliability of selection of required design ground motions.

Results of numerical simulations show that selecting the parameters of indices by considering the influence of nonlinear response of structure, the reliability of having the required design ground motion is considerably enhanced.

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