GROUND MOTION RECORD SELECTION FOR THE SEISMIC DESIGN OF STRUCTURES

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ABSTRACT :

The selection of a ground motion record is not a trivial problem since quite a different seismic response can be observed if a structure is subjected to different sets of ground motion records, especially if the number of ground motion records within the set of records is low as is usually prescribed in the design codes. In this case it is difficult to take into account all those parameters which are important for the selection of ground motion records for non-linear time history analysis. For example, the magnitude, the distance from the fault, and the scaling to a certain design level, are the three basic parameters which have to be carefully selected for an earthquake scenario. Additionally, the problem also arises how to select a few number of ground motion records and not to introduce bias in the seismic response, which can appears, if the analysis is performed for only a few ground motion records. In this paper the progressive IDA analysis, which involves precedence list of ground motion records, and can also be used to minimize the bias in the seismic response by selecting only a limited number of ground motion records, is briefly summarized. Its applicability is then demonstrated for a reinforced concrete building and the design set of ground motion records, consisting of ninety-eight ground motion records. It is shown that the nonlinear seismic response can be predicted with acceptable accuracy by employing only a few ground motion records instead of all ninety-eight ground motion records.

KEYWORDS: Record selection, progressive IDA analysis, optimization, design of structures, reinforced concrete frames, seismic response

1. INTRODUCTION

The current design codes recommend selecting of at least three ground motion records for determination of the structural response by using the nonlinear time-history analysis. In this case it is prescribed that the maximum response has to be used for the performance assessment of a structure. If the mean response of a structure for the performance assessment is of interest, then at least seven ground motion records shall be used in the analysis. Although it is further prescribed in the codes that the spectral shape of the selected ground motion records shall be in a good agreement with the elastic (design) spectrum, the number of selected ground motion records may not be enough for the prediction of the stable and unbiased structural response, since there are many aspects how to select the ground motion records for nonlinear time history analysis. In addition there are many different possibilities how to select a few number of ground motion records from a large set of records, which are consistent with an earthquake scenario of a site. Recently, the progressive incremental dynamic analysis was proposed (Azarbakht and Dolšek 2008), which involves a precedence list of ground motion records. It provides the advantage of a simple mathematical model, which is not computationally demanding, and it is defined as an optimization problem, which can be solved by means of a genetic algorithm or a proposed simple procedure. Once the precedence list of ground motion records is known, the response of the structure is computed progressively, starting from the first ground motion record in the precedence list. When the required tolerance in the prediction of the seismic response is achieved, the analysis can be terminated, although the single-record IDA curves are computed only for a certain number of ground motion records from a set. The proposed method is demonstrated using an example of a four-storey reinforced concrete frame structure subjected to a set of ground motion records, which consists of ninety-eight ground motion records.

2. SUMMARY OF PROGRESSIVE IDA ANALYSIS

The progressive incremental dynamic analysis (Azarbakht and Dolšek 2008) involves a precedence list of ground motion records, which is a new element in the analysis, when compared to the elements of the IDA analysis (Vamvatsikos and Cornell 2002). The precedence list of ground motion records is determined using a simple mathematical model, which is not computationally demanding. This difference between the IDA analysis and progressive IDA analysis is shown schematically in Figure 1. In IDA analysis, the single-record IDA curves are calculated for all the ground motion records in a set of such records (Figure 1a), while in the progressive IDA analysis (Figure 1b), the single-record IDA curve is first calculated for the first ground motion record from the precedence list, and then progressively for other ground motion records from the precedence list of these records. After calculation of some single-record IDA curves, the analysis can be terminated, since the acceptable tolerance is achieved. It is convenient to check the tolerance only after every three single-record IDA curves are computed, since the precedence list of ground motion records is optimized for subsets of ground motion records, where each subset contains three ground motion records. However, the tolerance can be evaluated only after the single-record IDA curves are calculated for the second subset of three ground motion records. Optimization based on the defined subsets of ground motion records is effective because the aim of progressive IDA analysis is to predict three summarized IDA curves with a limited number of ground motion records from a set of ground motion records. The total number of subsets of ground motion records (m) is determined as the downward rounded integer of $n/3$, where n is the total number of ground motion records in a set of ground motion records.

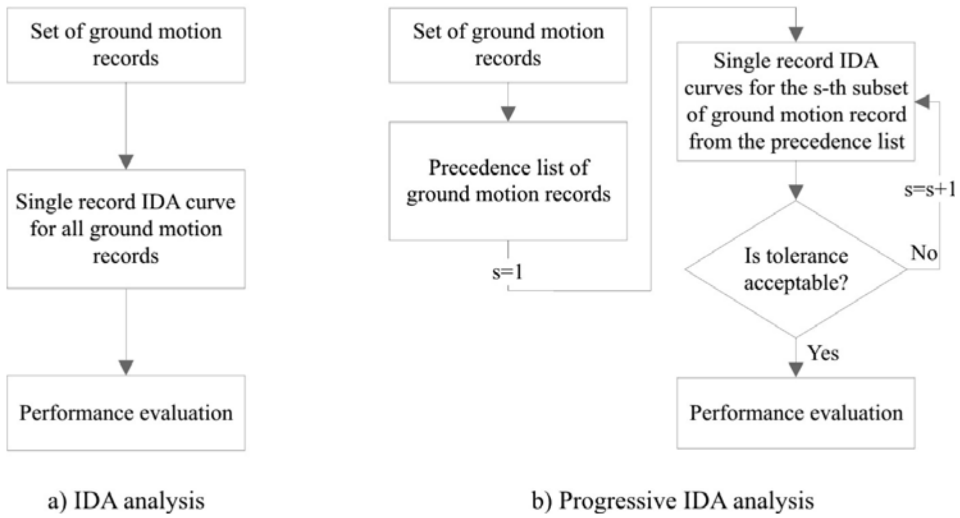

Figure 1. Comparison between IDA analysis for a set of ground motion records and progressive IDA analysis.

The benefit of the progressive IDA analysis, in comparison to the IDA analysis, is the reduction of the computational effort. However, determination of the precedence list of ground motion records also requires some computational time, firstly for the additional IDA analysis, which has to be performed for a simple model, and secondly for the optimization of the precedence list of ground motion records. The simple model is usually defined based on the results of the pushover analysis, which is performed for the complex, multi-degree-of-freedom (MDOF) model. It is important that the simple model being a good representative of the linear and nonlinear characteristics of the MDOF structural model, yet simple enough for it to be possible to perform a large number of non-linear time history analyses, without the need of going through time-consuming calculations. The appropriate simple models can therefore be a single-degree-of-freedom (SDOF) model, or a model which has one degree of freedom per each storey. However, the computational time for the determination of the precedence list of ground motion records, which is appropriate for different levels of intensity measure, is usually less than the computational time for the determination of a few seismic responses of structure for different ground motion records, especially if the structure is complicated.

Ground motion records from a precedence list of ground motion records can be used for prediction of the median IDA curve (Azarbakht and Dolšek 2007) or the summarized IDA curves, i.e. the 16%, 50% and 84% fractiles (Azarbakht and Dolšek 2008). Since the precedence list of ground motion records is optimized for an IDA curve, it can be used also for predicting the seismic response parameters of a given seismic intensity, which is usual approach in the design process. The determination of the precedence list of ground motion records is, in fact, an optimization problem. The objective of the optimization is to minimize the differences between the “original” and the “selected” summarized IDA curves calculated based on the simple model, usually a single-degree-of-freedom system, which is not computationally demanding. The “original” summarized IDA curves are obtained from all the single-record IDA curves, whereas the “selected” summarized IDA curves are obtained only for the first s subsets of the ground motion records from the precedence list, where s is the number of “selected” subsets of ground motion records from m, which is the number of all subsets of ground motion records. The optimization problem can be solved by the GA optimization technique or by the simple procedure. The later procedure is based on the assumption that the best precedence list can be obtained by gradual minimization of the error function at each step corresponding to the selected number of subset of ground motion records and for each selected summarized IDA curve. Note that the error function is a measure for an error between the “selected and “original” fractile IDA curves. Therefore it depends on the selected f fractile IDA curve (16%, 50% and 84% fractile) and also depends on the number of the selected subsets of ground motion records s. The error function is defined as the ratio between the area, which is surrounded by the “original” and “selected” fractile IDA curves, and the area under the “original” fractile IDA curve (Azarbakht and Dolšek 2008). Following steps have to be performed in order to determine the precedence list of ground motion records by employing the simple procedure::

1) Calculate the single-record IDA curves for all ground motion records and determine the “original” summarized IDA curves (16%, 50% and 84% fractiles) for the simple model (e.g. a SDOF model).
2) Calculate the error function for s=1 and for each ground motion record from the given set of ground motion records, firstly for f=1, i.e. only for the “original” 16% fractile IDA curve. Clearly there are n results for the error function, where n is the total number of ground motion records in the given set. It is clear that the best ground motion record (ID number) for the prediction of the “original” 16% fractile curve is that with the corresponding minimum value of the error function. This defines the ground motion record, which is the first in the precedence list.
3) Increase f by one (f=2) in order to find the best ground motion records which have the minimum deviation from the “original” 50% IDA curve. Obviously there are n-1 records left to be placed in the precedence list of ground motion records. The error function is therefore calculated only for these ground motions records, which are not yet placed in the precedence list of ground motion records. Again, the minimum value of the determined values of error functions defines the second ground motion in the precedence list.
4) Increase f by one (f=3) in order to select the best ground motion record for the prediction of the “original” 84% fractile curve. At the end of this step the first subset of ground motion records has been determined, and n-3 ground motion records are left to be placed in the precedence list of ground motion records.
5) Increase s by 1 and evaluate the error function for the “original” f-th summarized IDA curve, i.e., begin with the setting f=1. There are $n-3(s-1)-(f-1)$ different values for the error function, which is the same number as the number of ground motion records still waiting to be placed in the precedence list. In order to evaluate the error function, the “selected” f-th summarized IDA curve is determined as the median value of the single-record IDA curves, which are specifically selected from the ground motion records already placed in the precedence list and the additional ground motion record, which is still a candidate for the next place in the precedence list. For example, if s=4, the “selected” 16% fractile curve (f=1) is determined as the median of the single-record IDA curves, which corresponds to the ground motion records placed in the 1st, 4th, and 7th places of the precedence list and the additional ground motion record which is arbitrarily selected from the other ground motion records, which are candidates for the precedence list of ground motion records. Again the minimum value of the error function defines the new ground motion record in the precedence list of ground motion records.
6) Continue with step 5 until all the ground motion records are placed in the precedence list of ground motion records.

3. EXAMPLE

The four-storey RC frame building was selected for a case study structure. The structure was designed according to previous versions of Eurocodes 2 and 8 for high seismic region by adopting peak ground acceleration of 0.3 g, the B soil type and the high ductility class. For this ductility class and for RC frame structures the prescribed behavior factor (q) according to the previous version of Eurocode 8 was 5, as also assumed in the design of the four-storey building, since the structure is regular in the plan and elevation. The elevation and the plan of the building, as well as the typical reinforcement in the columns and beams are shown in Figure 3. For this structure different pseudo-dynamic tests were performed at the European Laboratory for Structural Assessment (ELSA, Ispra) (Fardis (Eds.) 1996, Negro and Verzeletti 1996).

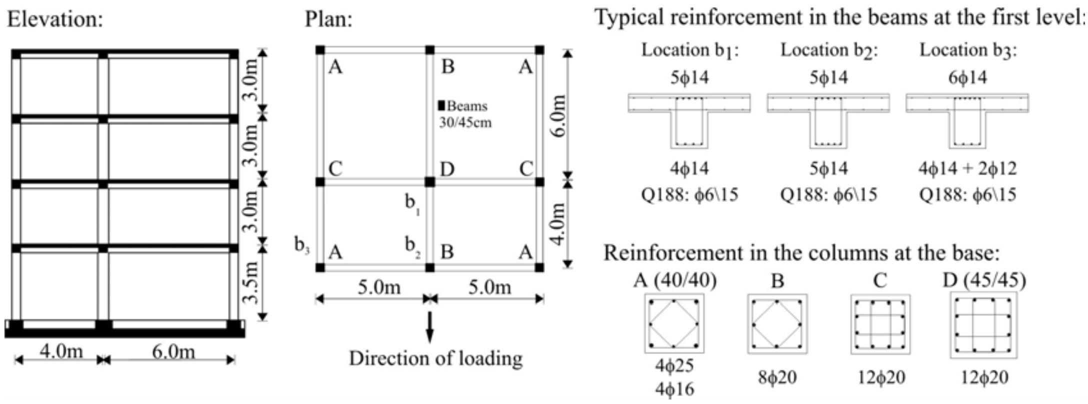

Figure 2. The elevation, the plan view and the typical reinforcement in the beams and in the columns at the base.

The mathematical model of the test structure is basically developed in compliance with the Eurocode 8 (CEN 2004) requirements. The model of the case study structure consists of one-component lumped plasticity elements, which were used for modelling of beams and columns. The zero moment point was assumed to be at the mid-span of the columns and beams. The moment-rotation relationships of plastic hinges were determined according to the procedure described by (Fajfar et al. 2006). A trilinear moment–rotation relationship for plastic hinges (Figure 3a) in columns and beams, with an initial elastic part corresponding to a cracked cross section, a second part representing yielding, and a strength degrading part after the NC limit state, was assumed for both case study structures. The ultimate rotation Θ_u in the columns at the near collapse (NC) limit state, which corresponds to a 20% reduction in the maximum moment, was estimated by means of the CAE method (Peruš et al. 2006) and according to the EC8-3 (CEN 2005) formulas for the columns and beams, respectively. All analyses were performed by the OpenSees (McKenna et al. 2000) in combination with the OS Modeler (Dolšek 2008a), which enables creating the input files for the OpenSees and post-processing of the analysis results. The structural models, which were developed by assuming the best estimates for the input parameters, were validated with the experimental results (Dolšek 2008b), as presented for the top displacement time history (Figure 3b).

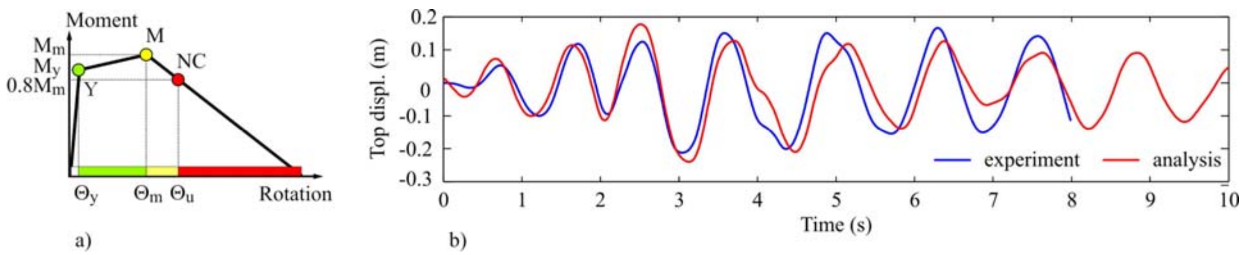

Figure 3. a) the moment-rotation relationship of plastic hinge and b) the calculated and experimental results for top displacement time history.

In order to determine the precedence list of ground motion rerecords, the set of ninety-eight ground motion records were selected from the PEER Strong Ground Motion Database (PEER 2005). These records were used also by the PEER Ground Motion Selection and Modification Group. The records are consistent with a magnitude 7.0 earthquake occurring on a strike-slip fault, the site being at a distance of 10 km and having a 30 m shear-wave velocity of 400 m/s. The elastic response spectra, together with the 16%, 50% and 84% fractile curves, are presented in Figure 4.

Two SDOF models were defined for the determination of the precedence list of ground motion records. The first SDOF model, called SDOF-design model, was defined only from the design assumptions, whereas the second SDOF model (SDOF-pushover) was determined from the pushover analysis. The first period T=0.67 s and the corresponding mode shape, resulting from the eigenvalue analysis, was assumed for the SDOF-design model. In this case the yield force of the structure F_y was determined by multiplying the design base shear F_d with the over-strength factors $F_y=\gamma_s\,\gamma_m\,\gamma_j\,\gamma_{Rc}\,F_d$, where γ_s=1.15 is the partial factor for steel, γ_m=1.10 is the ratio between the mean and the characteristic strength of steel, γ_j is the required over-strength of the columns in comparison to the strength of the beams, which is calculated as 1.3 γ_{Rb}=1.3·1.1=1.43, where γ_{Rb} is the assumed ratio between the selected and designed longitudinal reinforcement in beams (1.1), and γ_{Rc} is the assumed ratio between the selected and designed longitudinal reinforcement in columns (1.1). Since the design base shear is 16% of the weight of the structure, i.e. 537 kN, the predicted yield force of the structure is 1070 kN. Further it was assumed that the strength of the structure begins to deteriorate for ductility equal to the behavior factor q=5, which was assumed in the design of the structure. In the case of the SDOF-pushover model, used for determination of the precedence list of ground motion records, the force-deformation relationship was determined from the result of the pushover analysis. The load pattern corresponded to the product between the components of the storey mass vector M=[87, 86, 86, 83] t and the first mode shape vector φ=[0.296, 0.603, 0.858, 1]. The pushover curves were idealized with a tri-linear force-displacement relationship, as presented in Figure 5. The symmetric positive and negative backbone curves were assumed. This idealized force-displacement relationship was also used for the determination of the period of the SDOF-pushover model, which is equal to 0.71 s. The idealized force-displacement relationship, which was used for the determination of the SDOF-design model, is also presented in Figure 5. Some differences can be observed between the two idealized curves. However, as discussed later, both models are accurate enough for the prediction of the precedence list of ground motion records. The force-displacement relationship of the SDOF models were then determined by employing the transformation factor Γ=1.266, which was calculated according to Fajfar (2000).

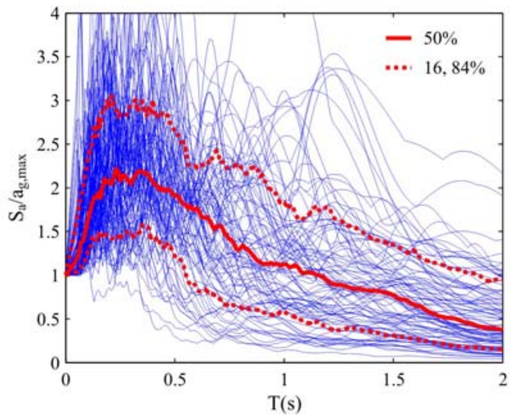

Figure 4. The elastic response spectrum (5% damping) for the ninety-eight ground motion records, and the 16, 50 and 84% fractile values.

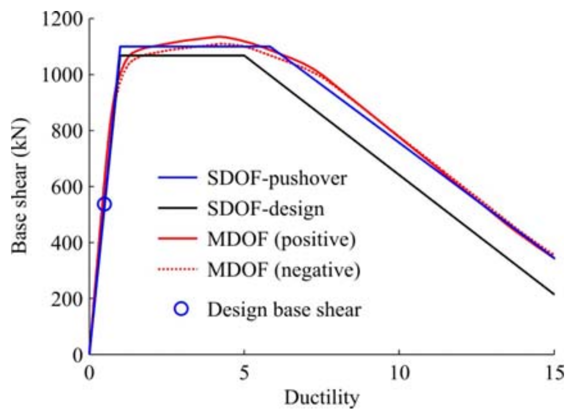

Figure 5. The pushover curves for the positive and negative directions of loading (Figure 2) for the MDOF model, and the idealized force-displacement relationship used for determination of the SDOF model, which was defined using the assumption of the design parameters and using the results of pushover analysis.

The incremental dynamic analysis (Vamvatsikos and Cornell 2002) have been performed for the defined SDOF models by employing the hunt and fill tracing algorithm. The peak ground acceleration was selected as the intensity measure. The global dynamic instability was determined with the tolerance of 0.02 g. Once the results of the IDA analysis for the SDOF system were available, the precedence list of ground motion records was calculated with the described simple procedure. The IDA curves, together with the summarized IDA curves (counted 16%, 50% and 84% fractiles), are presented in Figure 6. Very good agreement can be observed between the "original" summarized IDA curves, which are determined from the results of all ground motion records, and the "selected" summarized IDA curve, presented in Figure 6 only for the first four subsets of ground motion records, i.e., first twelve ground motion records from the precedence list of ground motion records.

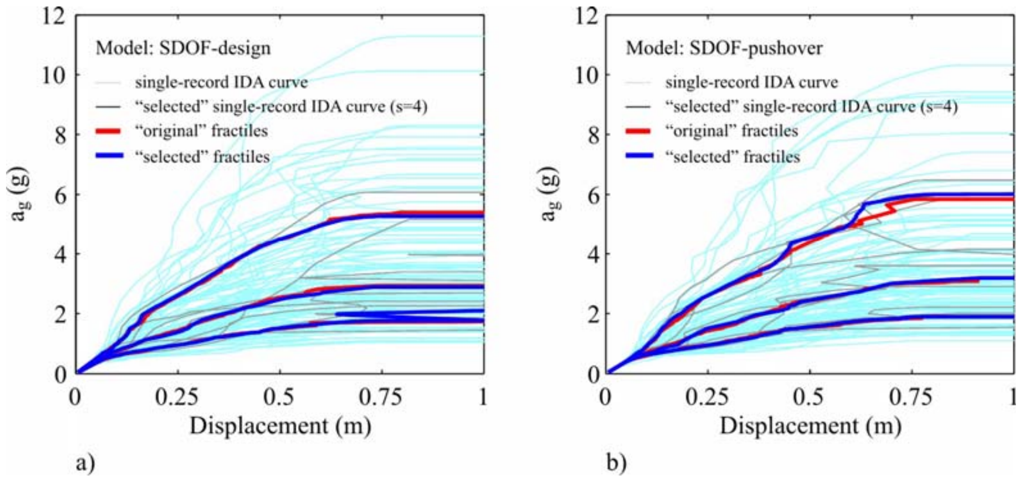

Figure 6. The "selected" summarized IDA curves based on the first four subsets of ground motion records from the precedence list, the "original" summarized IDA curves, and the single-record IDA curves for all the ground motion records, presented for a) the SDOF-design model and b) the SDOF-pushover model.

The applicability of the precedence list of ground motion records, for prediction of the seismic response parameters of the MDOF structural model, is presented for a one level of peak ground acceleration of 0.9 g, which is three times of the design peak ground acceleration. The results, in terms of the maximum drift and the top displacement, for both precedence lists of ground motion records, are presented in Figure 7 and 8. If the number of selected subsets of ground motion records from the precedence list of records is equal or more than 2, then, the maximum drift and the top displacement are predicted with a reasonable accuracy, especially, for the median value and 84% fractile. It can also be observed, that the precedence list of ground motion records, which was determined from the results of the SDOF-design model, is better for the prediction of the median value of the maximum drift, although the SDOF-design model is less accurate in comparison to the SDOF-pushover model. For the precedence list based on the SDOF-design model the median maximum drift and the top displacement are predicted with less than 2% error provided that the response is computed for the first 12 (four subsets, s=4) or more ground motion records from the set of records. The same quantity is predicted with less than 8% of error, if the seismic response parameters are predicted from the precedence list of ground motion records, which was determined based on the SDOF-pushover model. The maximum error for both predicted seismic response parameters, if both precedence lists and all three fractiles are considered in the comparison, never exceeds 14% for s equals or more than 4 (12 ground motion records). In this case the average error is very low (± 6%), especially, because the response is predicted only from 12% of all ground motion records. Comparison between the target spectrum (16%, 50% and 84% acceleration spectrum of all ground motion records) and the spectrum based on the selected ground motion records was made in order to see if the target spectrum is a good measure for selection of the motion records. In Figure 9 it can be observed that the differences between the 16% and 50% fractile acceleration spectrum is very small, but quite large in the case of the 16% fractile acceleration spectrum.

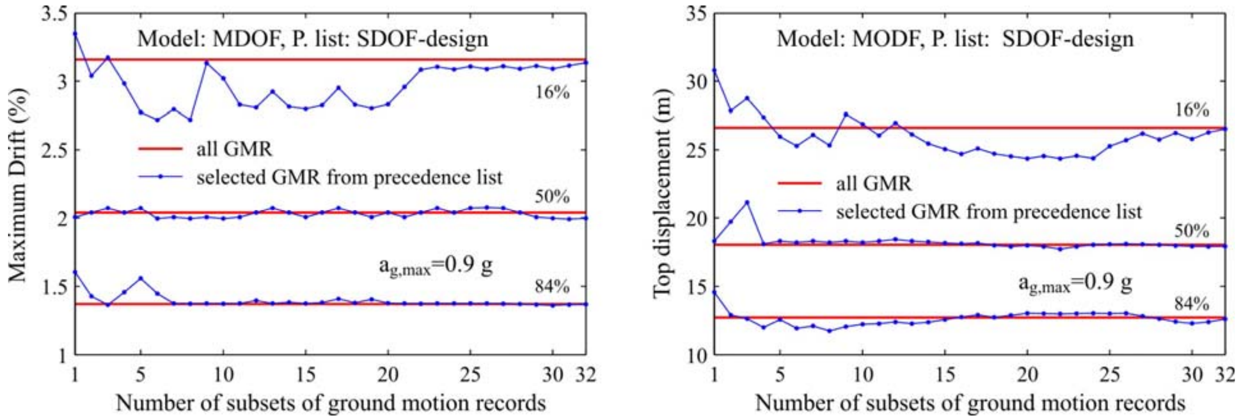

Figure 7. The 16%, 50% and 84% fractile of the maximum drift and top displacement as a function of the selected subsets of ground motion records for an $a_{g,max}$=0.9 g and the precedence list of ground motion records defined from the results of the SDOF-design model.

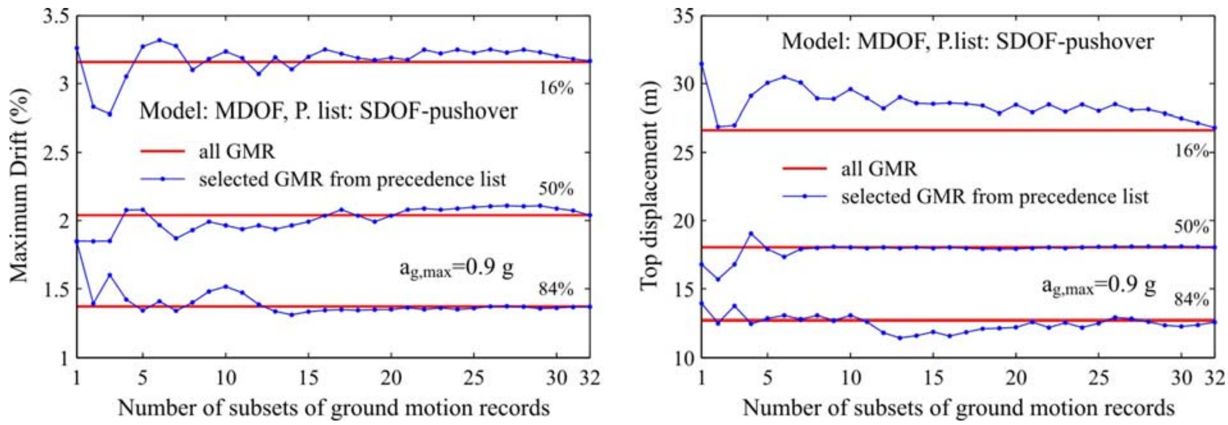

Figure 8. The 16%, 50% and 84% fractile of the maximum drift and top displacement presented as a function of the selected subsets of ground motion records for an $a_{g,max}$=0.9 g and the precedence list of ground motion records defined from the results of the SDOF-pushover model.

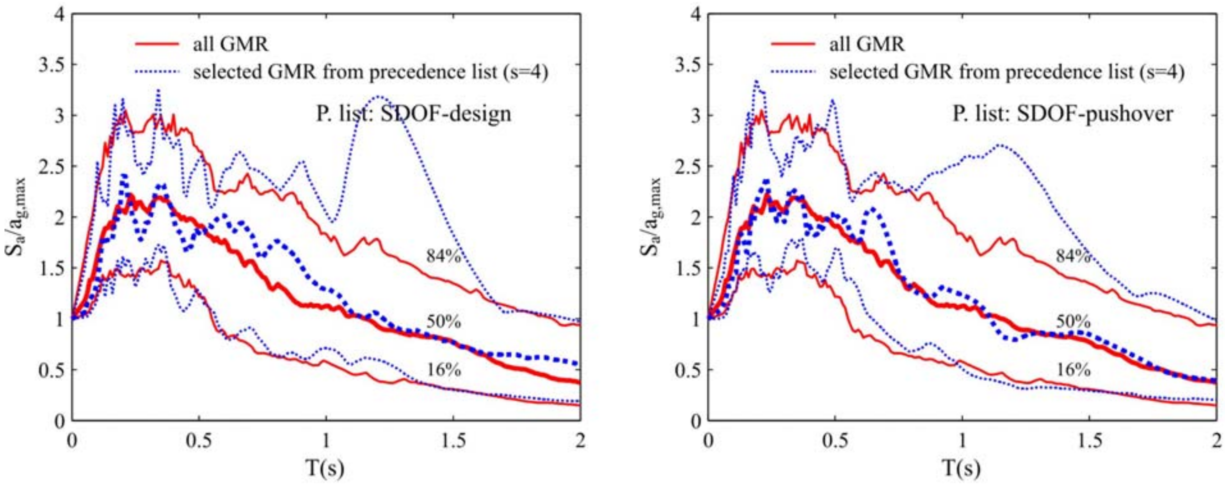

Figure 9. The 16%, 50% and 84% elastic response spectra calculated for all ninety-eight ground motion records and for a first four subsets (twelve ground motion records) selected from the precedence list of ground motion records, which was determined from the results of the SDOF-design and SDOF-pushover model.

4. CONCLUSIONS

A precedence list of ground motion records, which is a part of progressive IDA analysis, was used to select ground motion records from a large set of ground motion records. The precedence list of ground motions is determined by rearranging the ID numbers of the ground motion records in order to minimize the difference between the "selected" summarized IDA curves and the "original" summarized IDA curves, which are computed employing a simple, usually SDOF model. Since the simple model is not computational demanding, and the precedence list of ground motion records is appropriate for different levels of seismic intensity, the computational effort can be substantially reduced. The case study presented in this paper has proved that the seismic response parameters can be predicted with a high level of confidence when using only the first 12% of ground motion records from the precedence list of records. A fairly accurate prediction can be obtained when only six ground motion records out of ninety-eight ground motion records are used in the analysis. In this case the error in the prediction of the seismic response parameters did not exceed 14%. However, the reduction in the computational time for the fairly accurate prediction of seismic response requires some additional work, which is needed in order to determine the precedence list of ground motion records. If, as is presently foreseen, the procedure for the selection of ground motion records is automated and becomes available online, the amount of additional work will become negligible.

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