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A FRAMEWORK FOR CONDUCTING INCREMENTAL DYNAMIC ANALYSIS CONSIDERING THE PHYSICAL BOUND OF GROUND MOTION

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Abstract

Incremental dynamic analysis (IDA) has been widely used in probabilistic seismic response analysis (PSRA), where the performance of the structure at each intensity level could be achieved probabilistically. It is conducted by progressively increasing the ground motion intensity and performing nonlinear response history analysis (NLRHAs) at each intensity level, considering a set of ground motion records. By selecting a seed ground motion set and scaling, the IDA method would introduce a log-normally distributed ground motion values at each intensity level. However, this imposes a concern that the ground motion at a high-intensity level and high percentile might not be realistic, although the probability of happening is small. The ground motion intensity could have a physical upper bound due to the geological nature of the site. The physical bound tends to result in a truncated distribution of ground motion values when the intensity level considered is approaching the physical limit. By scaling the log-normally distributed motion set and performing incremental dynamic analysis without considering the physical feasibility of ground motion might lead to biased' results and over conservatism in practical design.

This study proposed a methodology for re-scaling the ground motion records selected in incremental dynamic analysis to incorporate the existence of the physical bound. The framework of redistributing the ground motion values at each intensity level is developed using an optimization scheme to fit a truncated distribution capped by the physical limit. The target truncated distribution is determined based on the physical bound and the characteristics of the original log-normally distributed ground motion values at each intensity level. Considering the proposed framework, a case study was conducted to redistribute the ground motions for NRHAs. An SDOF nonlinear oscillator was used in the analysis to compare the effect of incorporating ground motion bound on the responses. The results indicate a significant reduction in the failure probability at a high ground motion intensity level would be achieved using the capped motion set. The responses at the high percentile at each intensity level were significantly reduced, especially for the nonlinear displacement responses.

Keywords: Incremental dynamic analysis, Physical bound of ground motion, Optimization scheme, Truncated probabilistic distribution

1. Introduction

1.1 Incremental dynamic analysis (IDA)

With the development of the performance-based seismic design concept and procedure, quantitative structural performance assessment is frequently needed. A critical step is to estimate responses of a structure during seismic events, through numerical simulations. Due to different sources of uncertainties through the process, probabilistic methods have been extensively used. The incremental dynamic analysis (IDA) [1] is one of the most widely used frameworks to assess the cumulative risk, derive the seismic fragility curve, investigate the probability of collapse, understand the behavior of structure at various ground motion shaking intensities. By running nonlinear time history analysis (NLTHAs) at different intensity levels, response distributions could be obtained to address the inherent variability within the ground motion records. One of the critical steps within the IDA procedure is to derive the ground motion records set to represent the seismic intensity at each level. The standard method is to select a generic ground motion set and amplitude scaling the entire set up and down to match the specific ground motion spectrum acceleration value (Sa) at each target intensity level. It is known as the “generic method”. Within the ground motion set, the individual ground motion Sa tends to have a log-normal distribution.

1.2 Ground motion selection methods for IDA

The generic method for selecting and scaling the ground motions for IDA is the most widely used option. There are several commonly used ground motion sets for this purpose, such as the "SAC ground motion sets. However, the ground motion record characteristics (such as magnitude, distance, and epsilon) are not the same at different intensity levels. Using the same ground motion record sets might result in ground motion records which are not realistic at different intensity values and biased estimation of responses. Alternatively, the "Multi-strip analysis (MSA)" method [2] could be used to establish the target spectrum at each intensity level considering the hazard disaggregation as well as the possible spectra shape. A different set of ground motion would be selected at each intensity level to match the target multi-variate distribution of the ground motion. The resulted ground motion records using this refined method would be more realistic as it accounts for the different characteristics of ground motion records at various intensity level. In addition, the "Adaptive incremental dynamic analysis" has been developed [3] to only use the ground motion records in a specific range of IM considering the expected characteristics. These advanced ground motion selection methods address the change of ground motion record characteristics well, and it would potentially result in the realistic ground motion record shape.

1.3 Potential issues

The purpose of IDA is not only to capture the average responses at each intensity level but also to get the dispersion of the responses so that statistical evaluation of the analysis data could be conducted to obtain the fragility curve or other information. Therefore, the dispersion of the ground motion records at each intensity level is essential. The standard deviation of the distribution might be derived considering the correlation between different periods, and it changes at each intensity level. However, due to the nature of log-normal distribution, there would be ground motion records that have enormous intensity within the set. This is reasonable when considering the nature of uncertainty of the ground motion generated from a given seismic source. It represents a very high percentile value.

However, there may exist an upper bound for the ground motion values, rather than the assumption that the ground motion value could be infinitely large given it has a very low probability of happening. The log-normal distribution for the ground motion is hard to be verified, considering the high percentile range. If an upper bound exists, the distribution of the ground motions at a high-intensity level will follow a truncated log-normal distribution. In this case, it would potentially affect the dispersion of structural responses at high-intensity levels. Therefore, it is meaningful to investigate this issue, particularly when conducting IDA where large intensity motions are needed.,

1.4 Motivation and scope of this study

In this study, the effect of considering an upper physical bound of the ground motion when conducting IDA is investigated. Firstly, the concept of incorporating ground motion upper bound is discussed. The target distribution considering the effect of bound would be truncated, which needs to be considered when selecting and scaling the ground motion record. To meet the truncated distribution, an algorithm was proposed in the study to re-distribute the ground motion records within a set to fit a truncated distribution. The proposed method is aimed to calculate a set of adjustment factors acting on the ground motion record to re-adjust them for the target truncate distribution. Then using the proposed method, several cases are considered, and the responses of a simplified SDOF oscillator have been checked to evaluate the effect of incorporating the ground motion limit bound. The focus of this paper is to introduce and evaluate the concept when incorporating the ground motion physical limit bound in structural analysis, especially IDAs.

2. Ground motion bound and distribution

2.1 Distribution of ground motions and physical limit bound

Given a target mean, the (Sa(T)) values within the ground motion set is frequently considered as log-normally distributed with a certain dispersion. The log-normal distribution represents the nature of the uncertainty and dispersion of ground motions, which lies in with the concept considered in the ground motion prediction equation (GMPE), where the ground motion value is log-normally distributed given specific characteristics of the seismic event. Various ground motion selection methods are available to determine the target mean and dispersion. Fig.1[4] shows an example of the selected ground motions using the conditional mean spectrum method. The dispersion of the ground motions at a given period tends to follow a log-normal distribution.

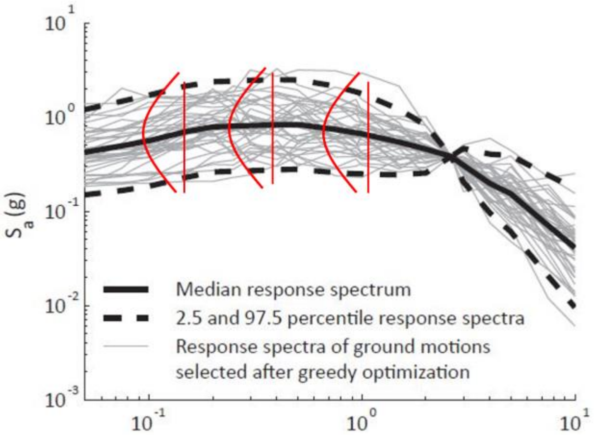


Fig. 1- Example of selected ground motion records and the dispersion (Adapted from [4])

For the ground motions which lie in the upper tile of the distribution, they are considered to have a high ε value, which represents the number of a standard deviation above the median GMPE estimation. However, the realism of these high amplitude ground motion records is questioned. For example, ground motion records with 3 or 4 times the MCE_R level are very likely to be included. Without the actual data, the randomness of ground motion is hard to be justified at the high percentile. The ground motion records would potentially have an upper bound due to seismic source characteristics [5]. If this is the case, assuming the log-normal distribution and including the extremely large event in the analysis might result in unrealistic results when the interested return period is very high. Whether the ground motion upper bound exists and at which percentile are complicated seismology problems, which are not the main scope of this discussion. However, if we assume there exists a physical limit bound for the actual ground motion, the distribution of the ground motion would be truncated. The selection and scaling of the ground motion records at a high-intensity level would need to incorporate this.

2.2 The effect on IDA

The effect of the truncated distribution would become significant when the ground motion intensity is large. For example, in the application of IDA, when the intensity level is increasing, the distribution of the ground motion would be more skewed as the bound does not change with increasing intensity. This would significantly reduce the dispersion on the structural responses, especially considering the nonlinear case. The results of IDA could potentially change significantly.

2.3 Focus of this study

If we assume the physical limit bound of the ground motion exists, the truncated distribution needs to be applied when selecting the ground motion records. However, this requires the existing ground motion selection methods to be modified to accommodate this. The idea of this study is to treat this as an additional step, which could be used together with the existing ground motion selection and scaling methods. One straight forward method is to simply drop all the records which exceed the physical limiting bounds. However, this would reduce the number of records in the set, especially at high-intensity levels. Another method is to redistribute the existing records so that the new distribution would follow the target truncated distribution. This requires the calculation of the new scale factors.

The focus of this study is to propose a method for determining a set of adjustment factors so that after applying to the original selected ground motion records, the target truncated distribution could be achieved considering the physical limit bound. This could be used together with any existing ground motion selection methods as it only modifies the original ground motion record scale factors.

3. The proposed method for redistributing ground motion records

The proposed methodology is aimed to redistribute the selected set of ground motion records to best match the targeted truncated lognormal distribution at each interested period. A set of additional adjustment factor α_j (j represents each record) would be determined for each ground motion record to act upon the original scaled ground motion record. α_j values are determined so that the error between the distribution of the adjusted ground motion spectral values and the target could be minimized. An optimization algorithm is considered for this purpose. One set of α_j would be determined for each intensity level. In the following discussion, we use the "original ground motion set" to represent the ground motion records set selected and scaled without considering any effect of limit bound.

3.1 Targeted distribution

The targeted distribution considering a ground motion upper limit could be expressed as a truncated distribution. Considering the ground motion spectral acceleration (Sa) in logarithm scale, the target distribution at T_i at one intensity level could be expressed as:

$$\mathrm{Trun\_Normal}_{\mathrm{T_i}} = \mathrm{Trun}_{\mathrm{Normal}}(\mu_{\ln(\mathrm{Sa(T_i)})}, \sigma_{\ln,\mathrm{Sa(T_i)}}, \ln(\mathrm{C_{T_i}}))$$

C_{T_i} is the ground motion physical limit at period T_i. $\mu_{\ln(Sa(T_i))}$ is the mean of the original ground motion sets at period T_i. $\sigma_{ln,Sa(T_i)}$ is the standard deviation of the original normal distribution ground motion sets. Although the original mean and standard deviation are used as the parameters to define the distribution, the resulted mean and standard deviation for the truncated distribution would be shifted due to the redistribution of the probability density function.

3.2 Proposed optimization algorithm

Considering a period T_i, the original ground motion Sa at T_i is represented as $Sa_j(T_i)$. After applying the adjustment factor α_j, the new ground motion values could be sorted and expressed as:

$$[\alpha_1 \mathrm{Sa}_1(\mathrm{T_i}), \alpha_2 \mathrm{Sa}_2(\mathrm{T_i}), \alpha_3 \mathrm{Sa}_3(\mathrm{T_i}) \ldots \alpha_j \mathrm{Sa}_j(\mathrm{T_i}) \ldots], j = 1{:}\,n$$

Where n represents the total number of ground motions within the set. Considering the distribution of these adjusted ground motion values, the cumulative percentile associated with each ground motion record in the above series could be expressed as:

$$p_j = \frac{j}{n} \quad j = 1,2,3 \dots n$$

If we use $F_{i_{empirical}}(Sa(T_i))$ to represent the empirical cumulative distribution of the series of ground motion values, the ground motion values correspond to the percentile p_j could be expressed as:

$$F^{-1}_{i_{empirical}}(p_j) = \alpha_j Sa_j(T_i)$$

Considering a general case when ground motion limit bound exists, the target truncated distributions introduced above could be represented by the cumulative distribution function $F_{i_{target}}(Sa(T_i))$ at period T_i. The Sa corresponding to p_j for the target distribution could be expressed as:

$$F^{-1}_{i_{target}}(p_j)$$

Then the error between the fitted and the target truncated distribution for percentile p_j could be expressed as:

$$F^{-1}_{i_{target}}(p_j) - F^{-1}_{i_{empirical}}(p_j)$$

The objective function f_i representing the normalized error term for the entire distribution could be expressed as:

$$f_i(\alpha_1, \alpha_2, \dots, \alpha_n) = \sum_{j=1}^{n} w_j\left(\frac{F^{-1}_{i_{target}}(p_j) - F^{-1}_{i_{empirical}}(p_j)}{F^{-1}_{i_{target}}(p_j)}\right)^2$$

Where w_i represents the weight for the error term for the jth percentile value in the distribution. As the optimization is operated at multiple periods simultaneously, the fit would not be exact for all periods. Therefore, the weight term is introduced to prioritize the percentile level in the ground motion distribution, which are more interested. For example, $p_j = 1$ represents the error term of the ground motion bound, $p_j = 0.5$ represents the error term at the median value. A zero value could be used if a certain percentile is not considered.

Then the overall objective function F could be expressed as the weighted sum of $f(T_i)$

$$F(\alpha_1, \alpha_2, \dots, \alpha_n) = \sum_{i=1}^{m} W_i f_i(\alpha_1, \alpha_2, \dots, \alpha_n) = \sum_{i=1}^{m} W_i \sum_{j=1}^{n} w_j\left(\frac{F^{-1}_{i_{target}}(p_j) - F^{-1}_{i_{empirical}}(p_j)}{F^{-1}_{i_{target}}(p_j)}\right)^2$$

W_i indicates the weight on the ith target period considered. The optimization algorithm would aim to find the best set of α_i so that the overall objective function introduced above could be minimized. The results of this optimization significantly depend on the physical limit bound set. More error is expected if the differences between the physical limit bound and the original distribution are significantly different as the same α_i factor would be used for different periods. Theoretically, if the ratio of the physical limit bound and the largest ground motion value at each period is similar, the best optimization results would be derived. This proposed optimization scheme would result in the best fitted re-adjusted ground motion records considering the truncated target ground motion distribution at different periods. A Matlab procedure was created to automate this optimization process as an example, which would be discussed later. This optimization process would be conducted separately at each intensity level. Note that one can select different periods and different weights associated with each period for different intensity levels using the proposed approach.

3.3 Single period case

For the general case discussed above, the fit could not be conducted precisely simultaneously. Some mismatch needs to be accepted as the same α_j factor is applied to the ground motion considering multiple periods, and different scales of re-distribution is needed for each period as the truncation is not the same. However, for the single-period case, this optimization would result in the exact fit. Without performing the optimization, this could also be easily done by horizontally shift the data point to fit the target curve. The scale factor, which represents the distance to move the ground motion data point, could be mathematically calculated as:

$$\alpha_j = \frac{F^{-1}_{i_{target}}(p_j)}{Sa_j(T_i)}$$

3.4 Discussion on the proposed method

Note the truncated distribution will shift the mean value of the ground motion set as redistribution is needed to maintain the general distribution level. This is always true unless the lower intensity ground motion records would have scaled up to maintain the original mean. This assumes that if the ground motion energy has a bound, it also affects the likelihood of the ground motion it can produce at a lower level. For example, at the extreme case, if the ground motion values within a set have a mean of 1g, the physical limit bound is also 1g, the ground motion would tend to generate smaller events. However, this is an interpolation of statistical behavior. More seismology studies on this are needed, which is not the scope of this paper.

The effectiveness of the optimization procedure considering the targeted truncated distribution at multiple periods significantly depends on the setting of physical limit bounds. As the determination of ground motion physical limit bound is not within the scope of this paper, we assume a fixed ratio against MCE_R event in the following discussion when assigning the physical limit bound value at each period.

4. Case study discussions

Using the proposed algorithm, a suite of ground motion records is considered for a case study. An SDOF nonlinear system is used to investigate the effects of re-scaled ground motion on the structural responses

4.1 Ground motion set considered

The FEMA P695 far-field ground motion set is considered for the case study, 44 individual ground motion records are considered, detailed info for each ground motion set could be found in FEMA P695 report [6]. This ground motion set has been used in various probabilistic studies to represent different levels of shakings. The target spectrum is considered as a generic MCE_R spectrum with S_{MS} and S_{M1} of 1.5g and 0.9g, respectively. The original ground motion records are scaled so that the mean of the 44 motions matches the target spectrum from 0.5-5s. The physical limit bound is defined as two times the MCE_R spectrum value. As discussed, the determination of physical limit bound is a complex seismology problem, which is not the scope of this study.

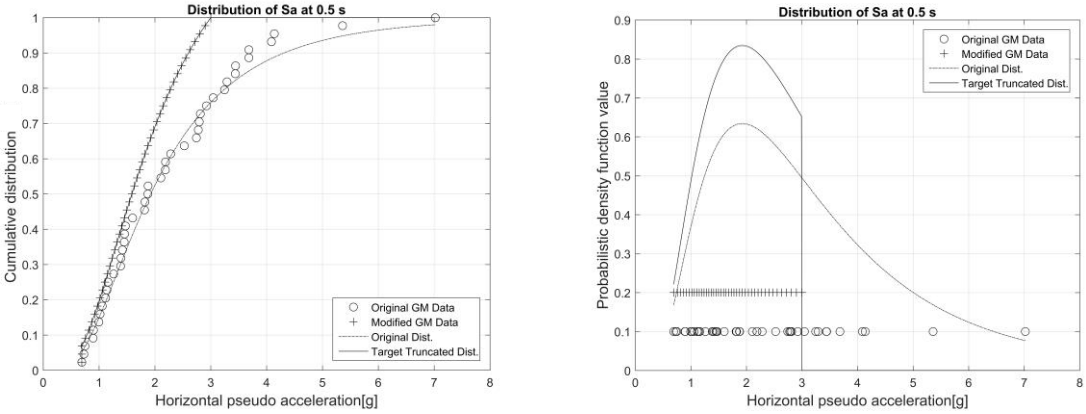
4.2 Description of structural systems

The simplest SDOF system has been considered to evaluate the effect on the structural responses. Nonlinear response history analysis (NRHAs) is conducted using OpenSees[7]. The SDOF model considered has a fundamental period of 0.5 secs. A bilinear backbone curve with post-yield stiffness around 10% of the elastic stiffness was assigned. A strength reduction factor R characterizes the strength of the SDOF model. This represents the ratio between the elastic demand at 0.5s from the MCE_R target spectrum considered. Note this is not the same as the R factor used in seismic design code. Different strength cases are considered including elastic, R=1, R=2. The maximum shear and the displacement responses of the SDOF oscillators are recorded and reported.

4.3 Effects on single intensity level responses

4.3.1 Single period adjustment

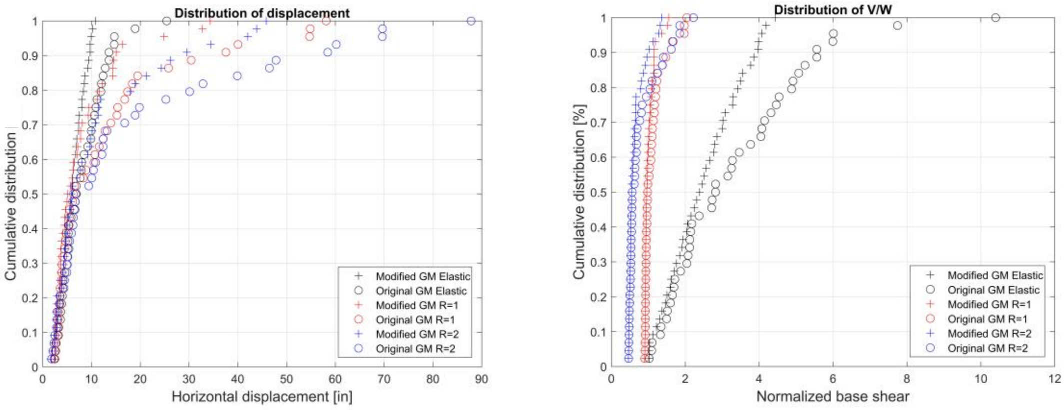
The adjustment of the ground motions considering the physical limit bound at a single dominant period (T=0.5s) is conducted. Using the proposed algorithm, the original records were rescaled to match the target truncated distribution. The comparison of the target distribution and the resulted ground motion values are shown in the Fig. 2 below. It could be observed that the rescaled motion matches the target precisely in the single-period case. In this case, the same ground motion record represents the same percentile value in the set before and after re-scaling.



(a) (b)

Fig. 2 –Distribution of the ground motion value. (a) Cumulative distribution (b) Density function value

Responses of the SDOF elastic and inelastic systems with different response reduction factor (R) are shown in the Fig. 3. For the maximum shear responses, Since the structural yields, the normalized base shear for the nonlinear case is almost the same. Slight differences were expected at the higher percentile, where the original ground motions result in slightly larger responses. This is because of the post-yield stiffness assigned. The elastic response represents the Sa values, which is the same as Fig. 2 (a). A significant reduction of responses is observed using the bounded motion sets. However, the median does not shift much. For the displacement responses, significant differences were observed at the high percentile. Although the weaker system has significantly larger displacement demand, the relative reduction on high percentile responses is similar. The absolute reduction achieved is much higher for the weaker system. For example, if the design follows a 10% probability of failure, using the bounded motions, the demand needs to be considered would be significantly reduced. This indicates a significant effect of the ground motion bound on the nonlinear displacement demand.

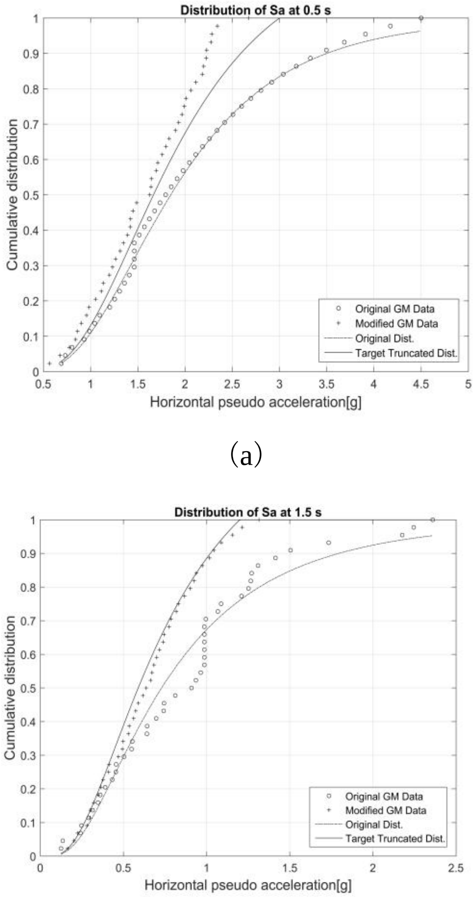


(a) (b)

Fig. 3 – Cumulative distribution of maximum responses (a) Horizontal displacement (b) Normalized shear

5.3.2 Multiple periods adjustment

The optimization algorithm is applied to the case when the physical limit bounds of ground motion are considered at multiple periods (0.5s, 1.5s, 2.0s, and 2.5s). The physical limit bound of 2 times MCE_R motion intensity is used across all periods. When assigning the relative weight for each percentile, the largest weights (0.5) are assigned to the median and bound values when matching the targeted truncate distribution while a weight of 0.2 is set for the other percentile locations. Using the proposed algorithm, the spectra acceleration values of the re-adjusted ground motion are shown in Fig. 4 at each period considered. It could be observed that the exact fit could not be obtained simultaneously for all interested periods. However, the general mean and bounds of the ground motion values are captured relatively well.



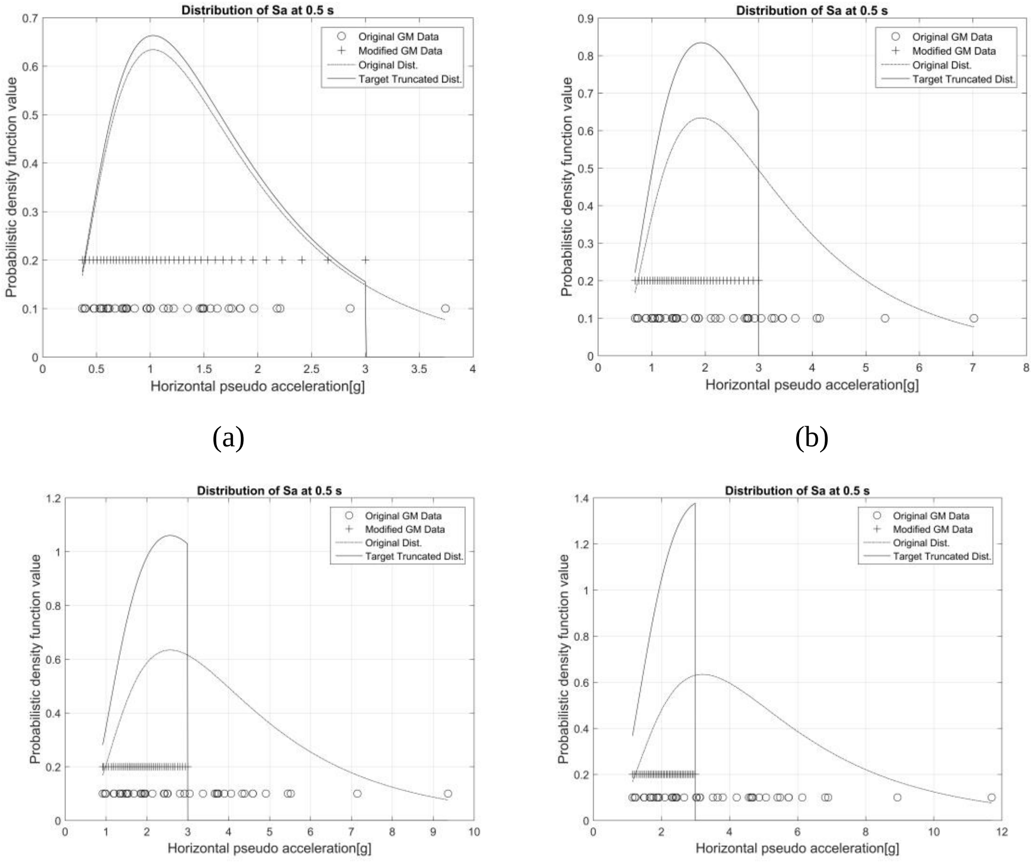
(a) (b)

(c) (d)

Fig. 4 – Cumulative distribution of ground motion values at various period (a) T=0.5s (b) T=1.0s (c) T=1.5s (d) T=2.0s

5.4 Effects on multiple intensity levels responses (IDA)

The implementation of the proposed algorithm considering the analysis at multiple intensity levels considered. IM levels with a relative scale factor of 0.6 to 2.5 to the MCE_R level event are considered with a step of 0.1. The proposed algorithm was performed independently at each IM level to derive a unique set of adjustment factors. The original ground motion sets at each intensity level were obtained by scaling the ground motion sets selected for the MCE_R level event. The physical limit bound is set as 2.0 MCE_R, which is constant throughout different intensity levels. Considering a single-period case, the original and truncated ground motion distribution data were obtained and shown in Fig. 5 for four representative intensities. It could be observed that for high intensity, the truncation effect is significant that more than half of the original ground motion records are shifted within the physical limit. A significant reduction in the spectra demand would be expected, especially at high-intensity levels.



(a) (b)

(c) (d)

Fig. 5 – Density function for ground motion distribution at T=0.5s (a) Scale factor of 0.8 (b) Scale factor of 1.5 (c) Scale factor of 2.0 (d) Scale factor of 2.5

Considering the SDOF oscillators, the incremental dynamic analysis was conducted using the original ground motion set and the readjusted truncated motion sets. The displacement response is shown in Fig .6 below for different strengths of structure. It could be observed that a significant reduction in response would be achieved using the truncated distribution. The reduction in the higher percentile response could be a factor 3 or more. The larger the intensity, the more significant effect was expected. Considering a predefined displacement limit, the fragility curve could be obtained, which is shown in Fig. 7. The reduction in the probability of failure depends on the threshold selected to define the failure. However, for all systems considered, a significant reduction on the probability of failure would be expected using the truncated ground motion sets.

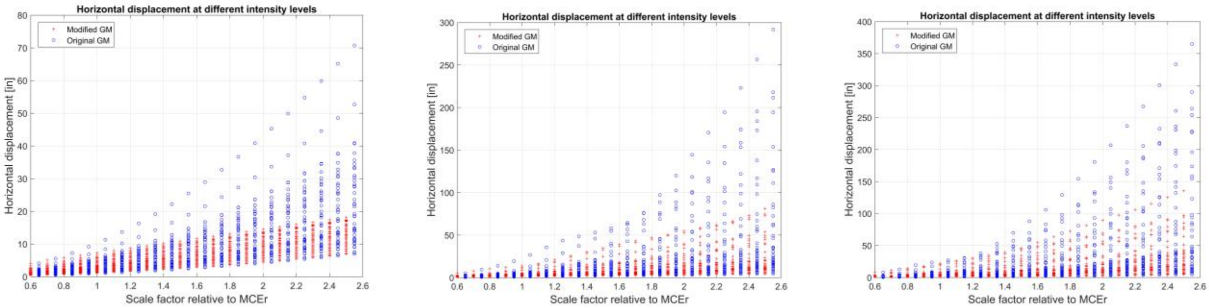


Fig. 6 – Distribution of maximum displacement demands for each intensity levels. (a) Elastic system (b) R=1 (c) R=2

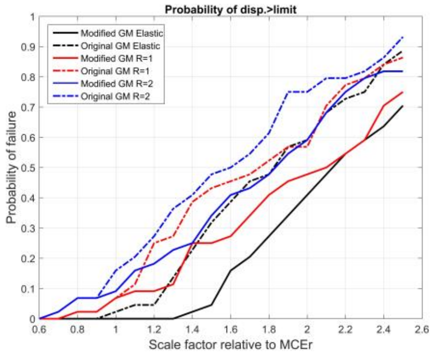


Fig. 7 – Probability of failure at each intensity level

5. Discussions

5.1 Define the ground motion physical limit bound

The existence of the physical limit on the ground motion values and how to define this limit bound is a complicated question in seismology, not within the scope of this study. Assuming this exists, the study proposes a simplified way to address this when conducting structural analysis and investigates how this would affect the statistical nature of the structural responses for different simplified systems. Eventually, the incorporation of ground motion physical liming bound could happen within the ground motion prediction equation (GMPE) if the concept is well established with enough studies. In this case, the hazard curve and the target spectrum would be capped. However, if a set of ground motion records with dispersion is needed, the physical limit bound needs to be incorporated in the target distribution, the proposed concept and methodology would still be valuable.

5.2 Use of the proposed method with other ground motion selection methods

The idea of this study is to propose a way to adjust the ground motion records assuming the ground motion selection is conducted based on the existing methods without considering the physical bound. This proposed algorithm could be an additional step for the case when the effect of ground motion bound needs to be incorporated. It does not depend on which ground motion selection method is used in the first place. It just adds another layer on top of the existing methods.

5.3 Alternative option to account for the physical limit bound

The proposed method is aimed to work with the current selection of ground motion records and re-distribute them based on the information of the physical bound. Alternatively, one can account for this effect when initially select the ground motion. For example, when using the ground motion selection methods discussed in [4], a multinormal target distribution is considered for various periods. The individual target spectrum is generated from the target distribution. And this could be modified so that the target distribution used to generate the target spectrum is the truncated normal.

5.4 Limitations on the proposed method

If ground motion records are selected such that the scaled motions all come through the same point on the target spectrum at a certain period, re-adjusting the distribution of the ground motions would lead to un-match at the original period. However, the mean could be kept the same at the originally considered period. The effect and usage of the proposed method on these cases need to be further studied.

5.5 Future work on this subject

In this study, the MATLAB built-in optimization algorithm is used. For the multi-period case, the results are acceptable but might have room to be improved. Some special technics considering the nature of the ground motion distribution might need to be used instead of conducting the task purely mathematically.

The definition of ground motion bounds and the correlation of the bounds at different periods need to be investigated. As the change of the bounds defined in the method would significantly affect the target truncated distribution, and it would also affect the results

The usage of the proposed method on top of the currently used ground motion selection methods need to be investigated. Modification of the proposed method might be needed, and the effect of the method on different ground motion selection methods could be investigated separately.

The effect of incorporating the concept of physical limit bound and the proposed method should be investigated considering various types of structures. And the effect on the consequence calculation in performance assessment could be investigated

6. Conclusions

This study proposes a methodology to redistribute the selected ground motion records set to account for the physical limiting bound of the ground motion. The proposed methodology uses the optimization algorithm to fit the target truncated ground motion distributions. The main findings and remarks are summarized as follows:

The physical upper bound of ground motion would result in a truncated log-normal distribution for the ground motion values. The existing ground motion selection methods do not account for this truncation.

The proposed algorithm could be used to derive the adjustment factor for the original selected ground motion records. It works considering the target truncate distribution at a single period or multiple periods simultaneously. For the single-period case, the adjusted motions would fit the target truncated distribution precisely.

Incorporating the physical limit bound of the ground motion would significantly reduce the structural responses at the high percentile. The median would not be affected much. The nonlinear displacement demand would be reduced most. The probability of failure obtained from IDA would be significantly reduced due to the reduction of response dispersion when the ground motion bound is considered.

6. Acknowledgments

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7. Copyrights

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