COMPARISON OF ASCE/SEI STANDARD (2010) AND MODAL PUSHOVER BASED GROUND MOTION SCALING PROCEDURES FOR PRE-TENSIONED CONCRETE BRIDGES

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ABSTRACT:
Complex analysis methods such as non-linear time history analyses (NTHA) are often required for the design of non-standard bridges. The selection of the ground motions for the NTHA is a crucial task as the results of the analyses show a wide variability according to the selected records. In order to predict the demand in accordance with the seismic hazard conditions of the site, the selected motions are usually modified by scaling procedures. Within this context, the performance of two scaling methods, namely the Modal Pushover Based Scaling (MPS) and ASCE/SEI (2010) procedures, are compared for the NTHA of a large bridge, the Demirtas Viaduct (longitude 29.10°, latitude 40.28°), in this study. The system comprised of 28 spans was idealized with two different analytical models in order to assess the effect of the modelling on the scaling procedures’ results. The effects of the hazard level on the scaling results were evaluated. The required number of motions for conducting effective analyses, i.e. the minimum number of motions for estimating the target goals, was investigated at different hazard levels. MPS reduced the dispersion considerably more than the ASCE scaling, indicating sets can be formed with fewer motions to predict the target levels.

KEYWORDS : Seismic analysis of bridges, non-linear time history analysis, ground motion scaling, ASCE/SEI scaling, modal pushover scaling

1. INTRODUCTION

The use of time history analysis poses an additional difficulty in contrast to the traditional analysis approaches based on the ground-motion response spectrum, since varying results can easily be obtained using different ground motions. Therefore, with the common use of time history analysis, the selection and scaling methods are used with the goal of reducing the dispersion of the results as well as reducing the workload in the assessment, i.e. increasing both the accuracy and efficiency in the analysis stages.

The ground motion scaling procedures can be loosely classified as the spectral matching methods and the amplitude scaling methods. In amplitude scaling procedures, the record is factored by a single multiplier, while in the spectral matching procedures both the amplitude of the record and the frequency content are modified to match the target spectrum.

Scaling ground motions based on the intensity measure parameters such as the peak ground acceleration (PGA), Arias Intensity, effective peak acceleration and effective peak velocity were the early approaches to the amplitude scaling methods. These procedures generally yield inaccurate results with large variation for long period structures (Kurama and Farrow, 2003). Scaling ground motions to the median spectral acceleration at the fundamental period of the structure, provides better accuracy with low dispersion (Shome et al. 1998). However, this method was determined to be not accurate and efficient enough for the structures undergoing large nonlinear displacements.
(Kurama and Farrow, 2003). The ASCE approach to scaling, probably the most popular scaling approach, recommends amplitude based scaling within a range of the fundamental period of the structure.

Modal pushover based scaling (MPS) method, recently proposed by Kalkan and Chopra (2010), uses the deformation of the first mode inelastic single degree of freedom (SDOF) system as a target for scaling. Low-, mid- and high-rise building structures analysed with the motions scaled by MPS technique was observed to yield results with better consistency and variability compared to the ASCE/SEI (2005) counterparts. A similar study conducted for "Ordinary Standard Bridges" by Kalkan and Kwong (2012) verified that MPS yields demand parameters close enough to the considered benchmark with low dispersion for single bent over-pass and multi-span bridges. O'Donnell et al. (2013) investigated four scaling methods including the ASCE (2010) scaling procedure and MPS method for multi-story building frame structures. In this study, MPS scaling was observed to yield median values at the conservative side.

The primary objective of this study is to evaluate the efficiency and consistency of two commonly applied scaling techniques, the ASCE/SEI (2010) Standard and the Modal Pushover based Scaling (MPS) in the determination of the seismic demand levels for a long, pre-tensioned bridge system. Three different levels of seismic demands were considered in order to assess the effect of the seismic demand level on the time history scaling approach. The effect of the ground motion scaling was evaluated using two different analytical models. The required number of motions for estimating the target goals with a certainty was investigated at different hazard levels.

2. THE CASE STUDY

2.1 Ground motion ensemble

The ground motions were chosen from the former events with the magnitudes, soil conditions and fault distances in accordance with the hazard expected at the Demirtas site. The 35 ground motions were selected from the PEER Strong Motion Database with the criteria: moment magnitude range was from 6.5 to 7.9; $V_{s30}$ was changing between 300 and 400 m/s; and the maximum fault distance was 12 km. The list of selected motions can be found in the study of Ozgenoglu and Arıcı (2017).

2.2 Target earthquake spectra

In order to evaluate the performance of the scaling procedures at different demand levels, three different hazard levels corresponding to demand reduction (R) values of 1, 2 and 3, were determined, in this study. The geometric mean spectrum of the selected 35 motions at 5% damping ratio were chosen to represent the lower seismic hazard condition, i.e. an Operation Based Event (OBE) The 1000-year return period event from AASHTO (2010) was utilized as the Maximum Design Earthquake. Finally, a higher design level – an extreme event level was set with a Maximum Credible Earthquake designation for the site. The MCE event, was formed by increasing the MDE spectrum by 1.5x in order to obtain the demand level at three times the elastic capacity at the fundamental period of the structure. The spectra of the selected ground motions and the three different target spectra signifying different hazard levels for the Viaduct are presented in Figure 1.
Figure 1 The response spectra for the (a) selected motions and the (b) target spectra

2.3 Analytical models for the simulation of the bridge

The Demirtas Viaduct, a multi-segment pre-tensioned concrete highway bridge located in Bursa, was chosen as the case study in this work. The Viaduct is composed of two 1080 m long parallel systems. For the purposes of this study, the Westbound segment was chosen and modelled. The span length of the selected bridge is 39 m at the interior spans and 37 m at the first and last spans. The 28 span bridge is comprised of a number of sub-systems connected by expansion joints over the cap-beams. The roadway is continuous over the expansion joints in effect providing a connection between the independent spans separated by expansion joints. The bridge has been modelled with two analytical models following the CALTRANS (2013) suggestions. The first model of the bridge, Model A, the three segment system, consists of 15 spans (Pier 5 to Pier 18) and two expansion joints at the top of the Pier 9 and Pier 14. The second model used, i.e. Model B, the one segment system, consists of 5 spans corresponding to the smallest system in which the segment behaviour can be simulated (Pier 10 to Pier 13). More details related to the analytical models can be found in the study of Ozgenoglu and Arıcı (2017).

The analytical models for the bridge were built in OpenSees - an open-source software framework. Eigen value analyses were conducted in order to determine the effective mode shapes of the system. The first transverse mode, obtained at 1.2 seconds for the Model A, and 1.1 seconds for Model B, was considered as the critical structural mode in this study. The non-linearity was modelled on the column elements by defining possible plastic hinge regions at the top and bottom parts of the columns.

3. GROUND MOTION SCALING

ASCE scaling procedure recommends the scaling of the selected records such that the mean spectrum of the scaled records are greater than the target spectrum in the range between 0.2 \( T_n \) and 1.5 \( T_n \) where \( T_n \) is the natural period of the structure. In this study, the ASCE scaling factors were calculated using the algorithm provided by Reyes and Kalkan (2012), developed to obtain the scale factors close to unity.

In the modal pushover based scaling (MPS) method, the scale factors for the time history analysis of the structure are obtained from the analysis of the first mode inelastic SDOF system of the structure with scaled earthquake records. The inelastic SDOF system is analysed multiple times with increasing scaling factors to determine the scale factor for a motion yielding a displacement close enough to the target inelastic displacement which can be calculated by multiplying the elastic deformation obtained from the target response spectrum with the inelastic deformation ratio (\( C_R \)) based on an empirical equation (Chopra and Chintapakdee, 2004).

4 RESULTS FROM TIME HISTORY ANALYSES

4.1 Non-linear time history analysis

Nonlinear transient analyses were performed for the two models, Model A and B, with the scaled and the unscaled motions in the transverse direction. A total of 490 analyses were conducted using the unscaled and scaled motions at three different demand levels for the two different analytical models.

4.2 Benchmark values

The expected demand at the three different levels, the OBE, MDE and MCE hazards, is referred to as the “benchmark” demand in this study. This value was obtained as the geometric mean of the maximum drift values obtained from the 35 unscaled motions for the OBE level. For the MDE and MCE target levels, the benchmark values were computed by multiplying the elastic spectral displacements with the inelastic deformation ratio (\( C_R \)). The benchmark drifts are obtained as 0.55 and 0.54 for the OBE level; 1.24 and 1.17 for the MDE level; 2.01 and 1.92 for MCE level, for Model A and Model B, respectively.
In order to show the effect of the scaling measures on the dispersion of the results, the maximum drift values for the scaled and unscaled ground motions were obtained using the full suite of 35 motions (Figure 2). For OBE level, the dispersion of the drift values were obtained as 0.65 and 0.66 for Model A and Model B, respectively, without scaling. When scaling was applied to the motions, these numbers decreased to 0.25 and 0.08. The mean and dispersion values of the maximum drift ratio are presented for both models in Figure 3.

Figure 2 The maximum drifts for models A & B, OBE, MDE and MCE hazard levels, 35 motions

Figure 3 The mean maximum drift ratio from 35 ground motions for the different models at different hazard levels for the MPS and ASCE scaling techniques
4.3 Results from the selected ground motion sets

The results obtained from the analyses with scaled motions are evaluated in the context of the performance of the scaling procedures from the point of view of accuracy, efficiency and consistency for a number of motion sets. The accuracy of the analysis results are implied by the proximity of the mean of the engineering demand parameter (EDP) values to the expected response. The efficiency of the results was computed as the dispersion within a ground motion set measured as the coefficient of variation (COV) of the motion set while consistency of the results was computed as the inter set variability estimated by COV among the mean EDP values of the motion sets for the relevant scale method and the hazard level.

Five motion sets comprised of 7 ground motions were arbitrarily selected from the ground motion suite. In order to see the results clearly, the ratio of the mean values of each set to the target drift demands and the COV values of each set are presented in Figure 4. An additional set was added to the comparison for the MCE hazard level.

The results showed the mean drift ratio was underestimated by using the MPS scaling for almost all cases. The opposite was true for the ASCE scaling procedure. On the other hand, the discrepancy compared to the benchmark levels were considerably low for the sets scaled with the MPS technique. The largest discrepancy of the mean with respect to the benchmark results was obtained as 20% for the MPS technique. Maximum 55% discrepancy from the benchmark mean was obtained for the sets scaled with the ASCE procedure. For the increase in the target demand level, the accuracy of the MPS estimates did not change. However, the estimates from ASCE level got markedly closer to the benchmark levels for both models for the increased hazard levels.

According to the COV values computed for the sets, the dispersion of the drift values due to the scaled motions was greater for the larger model, both scaling techniques. For both analytical models, the dispersion in the results was considerably smaller for the MPS technique compared to the ASCE scaling. In terms of the hazard level comparison, there appeared to be no correlation between the target level and the dispersion within the data set.

Finally, the consistency among the sets was evaluated using the coefficient of variation among the mean estimates of each set (Figure 5). Except for the MDE target for the Model A, the variation between the mean of the sets was obtained smaller for the MPS technique compared to the ASCE procedure indicating that the MPS approach
provided more consistent results. Consistency between the mean values of the MPS scaled sets decreased in small quantities with the increase of target spectrum for the smaller Model B. Such a trend was not observed in the results for the Model A due to the relatively large deviation of the mean values from the benchmark demands for the sets 2 and 3 for the MDE level. For the ASCE scaling, the consistency among the sets increased for the increased demand level for both models.

![Figure 5](image)

**Figure 5 Evaluation of the consistency of the estimates, the COV of the inter-set estimates**

### 4.4 Investigation of the required number of records

The number of motions that can be used to predict the mean response reasonably well is often a very important question in a design process. In this context, the effectiveness of the scaling methods was investigated in this section for the two models at different hazard levels.

For the purpose of determining the appropriate number of ground motions, motion sets comprised of 1 to 8 ground motions out of the 35 records were formed for each scaling method. In this fashion, the sample set for a selected number of ground motions was comprised of the mean for each set: this mean was treated as the random variable and the statistics were compiled for this set of mean values. Prediction of the (mean) EDP lower than 90% of the target mean quantity corresponding to the benchmark target drift ratios was assumed as unacceptable. The results are presented in Figure 6, in which the mean and the maximum of the drift ratio values from each possible set was used as the EDP predictor.

For the more complex model A, ASCE scaling requires sets to be formed of at least 9 motions in order to get a sample mean within 10% of the benchmark goal with 90% probability. For the MPS scaling, the corresponding numbers were 5-7 motions. For the simpler model B, the use of 2-4 motions was adequate for the MPS scaling while 7-9 motions were required with the ASCE scaling technique. The reduction in the number of motions when the maximum instead of the mean from the set was used as the EDP was drastic as shown in the Figure 6.

For the ASCE scaling, there did not appear to be a significant correlation with the hazard level and the required number of motions. For the MPS scaling, contradicting trends were observed for the different models: for the larger model A, the required number of motions decreased with increasing hazard level, while for the simpler model B, the required number of motions increased with an increase in the hazard level. On the other hand, using the maximum EDP from the set as the predictor, the number of motions for an effective prediction reduced with the decreasing hazard level for the MPS scaling technique.
In this study the use of two scaling procedures namely the modal pushover based scaling (MPS) and ASCE/SEI Standard (2010) procedure was compared using two different analytical models of a pre-tensioned bridge at different seismic demand levels. 35 ground motion records were selected to this end, based on the magnitude of the event, distance to the fault and the $V_{s,30}$ value at the bridge site. Target parameters necessary for the scaling were determined from three different target spectra corresponding to different hazard levels. The critical EDP for the bridge system, i.e. the drift ratio at the critical bents, was compared for the two scaling procedures and the different bridge models at the target earthquake levels. The main findings of the study can be summarized as follows:

- The benchmark drift ratios for both models were obtained similarly for all hazard levels. The difference between the results of the models slightly increased for increasing hazard levels. The complexity of the analytical model increased the dispersion on the obtained EDPs.
- The mean predictions for both scaling procedures were close to the benchmark drift ratios. The mean predictions from the ASCE scaling was mostly on the higher side. For the MPS scaling, the predictions were generally on the lower side of the benchmark.
- Both scaling procedures decreased the dispersion of the drift values. Regardless of the hazard level and the model choice, the dispersion obtained from the MPS scaled motions was lower than the ASCE scaling.
- When the constituted motion sets are considered, the inter-set dispersion for the ASCE scaling reduced with increasing hazard level. An opposite trend was observed for the MPS scaling for the simple one segment model.

Figure 6: The ratio of the samples with unacceptable prediction for the models A and B at three hazard levels

5. CONCLUSION

In this study the use of two scaling procedures namely the modal pushover based scaling (MPS) and ASCE/SEI Standard (2010) procedure was compared using two different analytical models of a pre-tensioned bridge at different seismic demand levels. 35 ground motion records were selected to this end, based on the magnitude of the event, distance to the fault and the $V_{s,30}$ value at the bridge site. Target parameters necessary for the scaling were determined from three different target spectra corresponding to different hazard levels. The critical EDP for the bridge system, i.e. the drift ratio at the critical bents, was compared for the two scaling procedures and the different bridge models at the target earthquake levels. The main findings of the study can be summarized as follows:

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- When the constituted motion sets are considered, the inter-set dispersion for the ASCE scaling reduced with increasing hazard level. An opposite trend was observed for the MPS scaling for the simple one segment model.
The number of motions to be included in an analysis set for predicting the target displacement of a bridge system appears to be somewhat larger than the guidelines proposed by ASCE (2010) when using the mean EDP from the set. The guideline for using the maximum EDP from the sets comprised of 3 motions was determined to be appropriate.

With the reduced dispersion in the results, the MPS technique warranted the use of a lesser number of motions in a given set for the prediction of the EDPs.

The number of motions was equally low for both scaling procedures when the maximum out of a given set was used to predict the target displacement. However, it should be mentioned that given the same number of motions, the probability of mis-prediction of the target displacement was much lower using the MPS scaling.

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