Effects of Near-Field Earthquakes on Seismically Isolated Bridges under Bi-Directional Loading

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SUMMARY:
Major effort in the design or assessment process of structures is based on conducting nonlinear time history analysis. In general framework, seismic hazard assessment and structural analysis have to be performed, respectively. The performance-based earthquake engineering requires reliable assessment of long-period ground motion particularly for seismically isolated structures, liquid storage tanks, long bridges such as cable-stayed, suspension bridges and structures that are designed to deform beyond the elastic range. Seismic isolation is one of the innovative techniques which can be used in the design of new bridges or retrofitting of existing bridges. This study aims to review and discuss issues related with the selection and scaling procedures for seismically isolated structures which have fundamental period in the long period range. Selection and scaling of real earthquake records of long period structures have to be based on the seismicity of the region, seismic hazard assessment as well as characteristic of the structure. Moreover, bi-directional loading is utilized for the analytical models rather than using unidirectional analysis which leads to crude estimation. The selected bridge for the dynamic analysis is a continuous, three-span, cast-in-place concrete box girder structure with a 30-degree skew. The two intermediate bents consist of two circular columns with a cap beam on top. The geometry of the bridge, section properties and foundation properties are assumed to be same as in the original bridge in the FHWA example. Sliding type of seismic isolation devices are implemented into analytical bridge model.

Keywords: Seismic Isolation, Selection and Scaling of records, Near-Field Effects

1. INTRODUCTION

Earthquakes have significant effects on structures in seismically prone regions and it is mandatory to design conventional earthquake-resistant bridges based on concentration of significant inelastic action (energy dissipation) in the selected structural components during the design process. Bridges are categorized as simple structures however they constitute the critical part of the transportation systems and their desired performance during earthquake is essential. Thus, designers have to minimize risks, and maintain the functionality of bridges after an expected earthquake. Major seismic events demonstrated that even newly constructed bridges by contemporary seismic provisions were damaged in California, Japan, Turkey, New Zealand, Central and South America. Poor performance of bridges were attributed to several reasons such as design philosophy adopted, lack of good detailing, and erroneous definition of probable expected ground motion in seismic hazard studies. The 1971 San Fernando earthquake revealed the inadequacy of both 1965 AASHTO Design guideline and previous seismic provisions in that era. The 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes lead to the development of AASHTO Guide Specifications for Seismic Isolation Design 1991, 1999 and AASHTO LRFD Bridge Design Specifications 2007, 2010 respectively.

Due to emphasized importance of bridges, new innovative rehabilitation methods have to be applied to structural members to protect them from major seismic events. Among those proposed innovative systems, seismic isolation has been implemented for buildings, bridges, liquid storage tanks (LNG tanks), nuclear power plants, offshore platforms and electrical substations. The deck of the bridge has the largest portion of the mass and piers should transfer the lateral load which is induced by ground shaking to the foundation level. Installation of isolation bearing aims to elongate the fundamental period and decouple the superstructure from the substructure since the substructure part of a bridge is more vulnerable under seismic events. Therefore, seismic isolation and/or supplemental damping devices can be used effectively to prevent casualties, economic losses in critical lifeline structures. In a conceptual framework, firstly seismic hazard analysis has to be conducted to identify the characteristics of the expected earthquake and then the structural analysis has to be performed for the considered bridge.

In particular, near-fault earthquakes have significant impact on bridges. Near-fault ground motions often contain long period pulses, and permanent ground displacements are observed as a result of rupture directivity effects. For large magnitude earthquakes, the directivity effects are generally associated with long-period (about 2-3s) ground motions consisting predominantly of horizontally polarized SH-waves with a PGV in the vicinity of 1m/s which corresponds to fundamental periods of seismically isolated bridges. Another important topic is the analysis of structures under bi-directional loading. The analysis of structures with uni-directional seismic input often requires crude assumptions regarding to the interaction of the structural system in the two horizontal directions or the application of simplifying combination rules, such as the "30%-rule (Beyer and Bommer, 2007). In a similar manner, single mode method is carried out for preliminary analysis of seismically isolated bridges and simplifying combination rules are accounted for bi-directional loading. However, theoretical studies have confirmed that there exists significant coupling between the orthogonal components of the response in structures that extend into the nonlinear range and it is a necessity to perform nonlinear dynamic analysis under bi-directional loading for seismically isolated bridges.

In this study, seismically isolated bridge model is exposed to 7 pairs of earthquake sets and its performance is investigated under different selection and scaling procedures. Regarding to selection scaling methods, dynamic nonlinear time history analyses are also compared with the result of simplified methods of seismically isolated bridges. First earthquake data set consists of near-field motions, which are identical to those used in the study of Constantinou et al. (2011). Other sets of ground motions are selected and scaled with respect to proposed conditional mean spectrum (Baker et. al.) and weighted scaling procedure. Seismic demand was estimated through NGA ground motion prediction equations, and PSHA.

2. DESCRIPTION OF THE BRIDGE

The bridge was used as an example of bridge design without an isolation system in the Federal Highway Administration Seismic Design Course, Design Example No.4, prepared by Berger/Abam Engineers, Sep. 1996 (document available through NTIS, document no. PB97-142111). The bridge is a continuous, three-span, cast-in-place concrete box girder structure with a 30-degree skew. Design example is modified for seismic isolation application. It has three traffic lanes and isolated with two isolators at each abutment and pier location. Loadings were determined based on AASHTO LRFD Specifications (AASHTO, 2007, 2010) with live load consisting of truck, lane and tandem and wind load being representative of typical sites in the Western United States (Constantinou, et al. 2011). The isolated bridge structure was modeled in the program SAP2000.

3. REPRESENTATION OF THE SEISMIC DEMAND

Ground motion selection is often associated with a target response spectrum which depends on the proper identification of seismic hazard. There are generally two well-known approaches for the quantification of earthquake hazard. One of them is the probabilistic seismic hazard analysis (PSHA), which accounts for all possible earthquake scenarios that could affect the site and results in hazard represented by ground motions parameters at reference ground conditions, such as peak ground acceleration and spectral accelerations. The other approach is the deterministic earthquake hazard assessment. In PSHA, de-aggregation involves the determining earthquake variables, principally magnitude, distance and values of other random variables defining seismic events that contribute to a selected seismic-hazard level (McGuire, 1995; Bazzurro and Cornell, 1999).

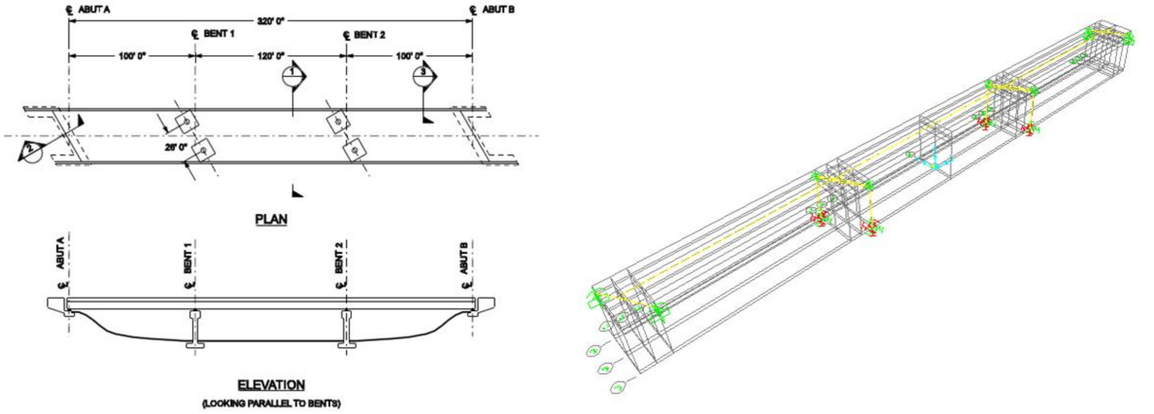


Figure 1. Bridge plan and elevation view of the skewed bridge with its SAP2000 model

For a given ground motion record, ε is a function of T, the ground motion prediction model (attenuation relationship) used and the probabilistic hazard model (Poissonian or renewal). The distribution modal values are the most likely events (M, R and ε to generate a Sa(T)≥ Sa0(T)). Epsilon values may be selected by several ways. In this study epsilon value is selected from PSHA de-aggration. Then, the conditional mean spectrum (CMS) method is utilized to represent Target spectrum select earthquake ground motions where they are associated with a target Spectral value at a single period where it is consistent with the PSHA. Mean spectrum of the selected site with GMPEs and Distance (R), magnitude (M), epsilon (ε0, ε) de-aggregation are shown in Figure 2.

Two site specific spectra are developed to select and scale earthquake records. Scaled earthquake records are used to assess the performance of the bridge. FHWA #4 Bridge is located in California region with latitude 38.079857°, longitude -122.232513 and the shear wave velocity (Vs_{30}) is assumed to be equal to 400m/sec. Location of the bridge and the first site specific spectrum have shown in Figure 3. The response spectrum of the site is the greatest among the spectra calculated for the site, which for this location was the one of the 2008 USGS National Hazard Map for a 5% probability of being exceeded in 50 years.

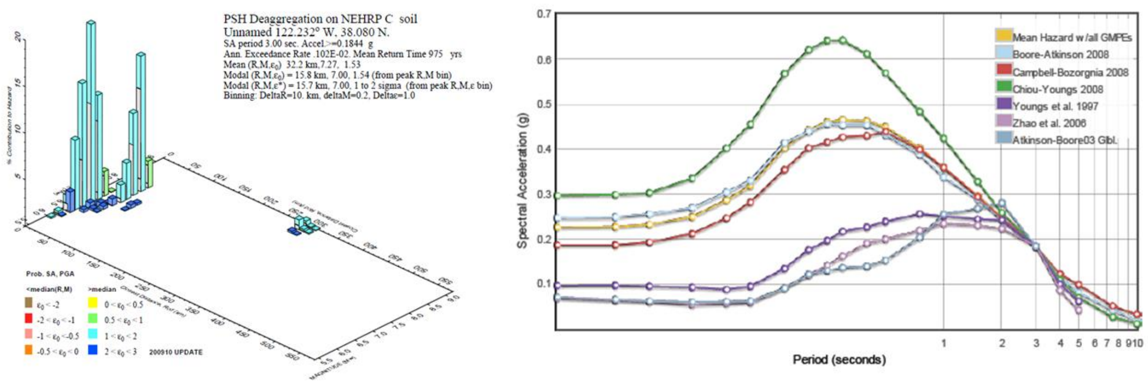
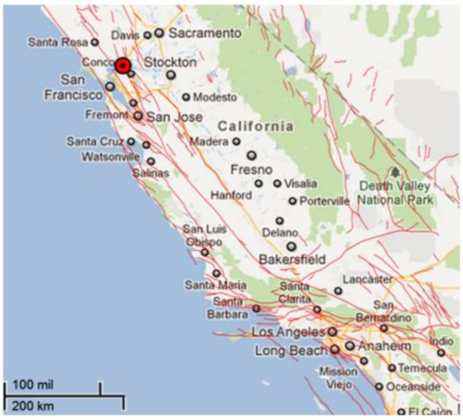


Figure 2. Mean spectrum of the selected site with GMPEs and Distance (R), magnitude (M), epsilon (ε_0, ε) de-aggregation for the site of the bridge on.

Moreover, Caltrans SDC requires a near-fault adjustment factor for sites less than 25 km (Rrup) from the causative fault and adjustment factor has been applied to construct the target spectrum. Site specific response spectrum is available for the bridge site with PSHA deaggregation.



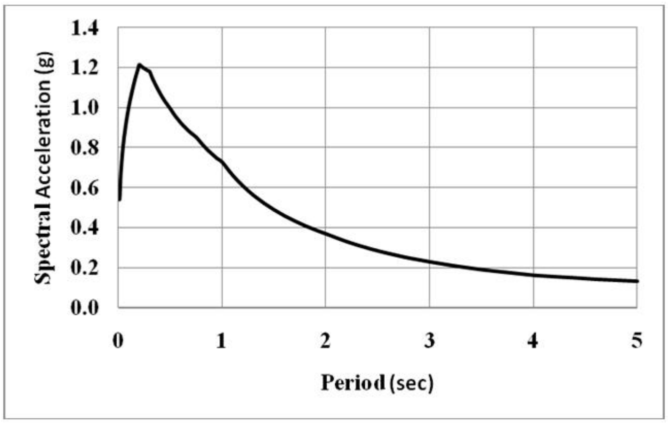


Figure 3. Location of the bridge and site specific DBE spectrum

CMS scaling method applies simple amplitude scaling to ground motions in order to obtain response spectra as close as possible to the target conditional mean spectrum (J.W. Baker, 2010). The CMS represents the expected response spectrum for the determined ground motion scenario, and it is calculated from a target $Sa(T_1)$ value at a single period and the associated M and R values. Mean spectrum of the selected site with GMPEs and Distance (R), magnitude (M), epsilon (ε_0, ε) deaggregation for the site of the bridge are illustrated in Figure 3.

4. SELECTION AND SCALING PROCEDURES

Dynamic response history analysis requires the selection and scaling of earthquake records. Careful ground motion selection can achieve the reduction in bias and variance of structural response as is gained by more advanced measures of ground motion intensity, while allowing the user to process the records using simple measures of intensity such as elastic spectral acceleration (Baker and Cornell, 2006). Different ground motion selection and modification (GMSM) methods currently available for their use in bridge structures.

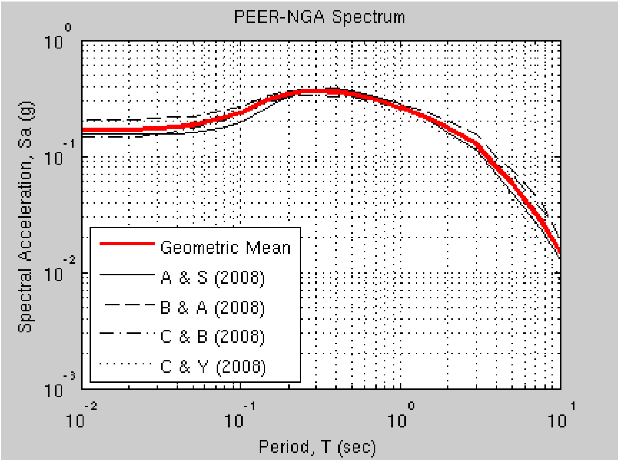


Figure 4. PEER-NGA SPECTRUM is generated on basis of GMPEs and deaggregation

In order to evaluate the scaling methods, bridge model is exposed to 7 pairs of data sets to assess its performance with respect to AASHTO 2010 LRFD design procedure. First set of near-field earthquakes are identical to the design example of FHWA # 4 Bridge in the study of Constantinou et al. (2011). Seven pairs of ground motions were selected same as for scaling in order to demonstrate average results of dynamic analysis. Each pair of the seed ground motions has been rotated to fault-normal and fault-parallel directions. The motions were selected to have near-fault characteristics and list of the records are illustrated in Table 1. Except 1976 Gazli earthquake (Backward-directivity), all other motions are from forward- directivity regions (PEER-NGA database, http://peer.berkeley.edu/nga/).

First set of input is selected on the basis of magnitude, distance and site classes beside directivity effects. The moment magnitudes for the seed motions are between 6.7 and 7.1; the site-to-source distances (Campbell R distance) are between 3 and 12 km; and all the records are from Site Classes C and D per the 2010 AASHTO Specifications, in the first data set. It is worth to note that, each pair of the seed motions from data set 1 (No. 1 through 7 of Table 1) was amplitude scaled by a single factor to minimize the sum of the squared error between the target spectral values of the target spectrum and the geometric mean of the spectral ordinates for the pair at periods of 1, 2, 3 and 4 seconds. The weighting factor at 1second was w1=0.1 and the factors at 2, 3 and 4 seconds were w2=w3=w4=0.3. In a similar way, average of 5% damped SRSS spectra is calculated and the compliance of minimum acceptance criteria in ASCE 7-2010 is ensured for periods in the range of 1 to 4 second. The highest value of final scale factor in the described method above is found as 1.57. In order to make a reliable comparison between scaling procedures, maximum scale factor in CMS method is restricted to the upper limit of 1.5.

Table 1. Near-Field earthquakes in first input data set to assess the performance of isolated bridge

First Input Set					
No	Earthquake Name	Recording Station	Mw	r (km)	Site
1	1976 Gazli, USSR	Karakyr	6.8	5.46	C
2	1989 Loma Prieta	LGPC	6.93	3.88	C
3	1989 Loma Prieta	Saratoga,W. Valley Coll.	6.93	9.31	C
4	1994 Northridge	Jensen Filter Plant ,	6.69	5.43	C
5	1994 Northridge	Sylmar, Coverter Sta. East	6.69	5.19	C
6	1995 Kobe,Japan	Takarazuka	6.9	3	D
7	1999 Duzce, Turkey	Bolu	7.14	12.41	D

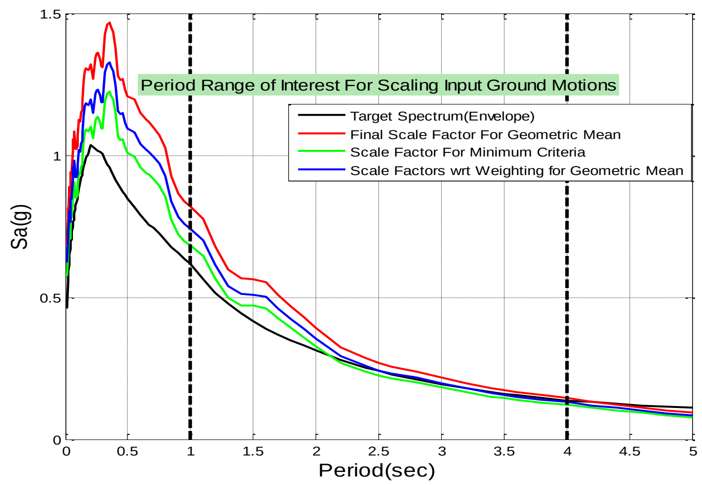


Figure 5. Comparison of Average Geometric Mean Spectra of 7 Scaled Near-Field Ground Motions to Target DE Spectrum

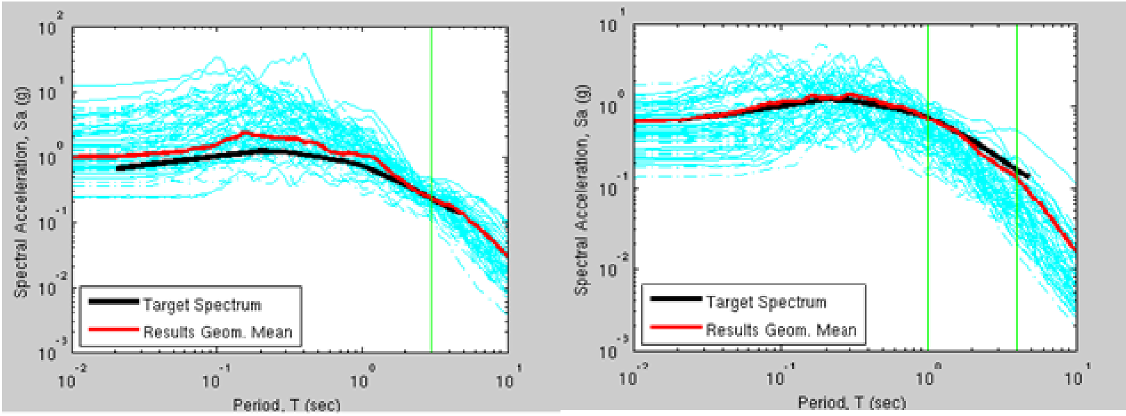


Figure 6. PEER-NGA Spectra for single period scaling and weighted scaling for the interested periods of range

5. SEISMIC ISOLATION APPLICATIONS IN BRIDGES AND METHODS OF ANALYSIS

Methods of analysis of seismically isolated bridges consist of the simplified method, response spectrum and the response history analysis methods. The most accurate result is the response history analysis. However, simplified method is performed to verify the response history analysis and quantify the lower bound values. The two most common bridge seismic isolators in use are lead rubber bearings and friction pendulum bearings.Analysis of seismically isolated bridges should be performed for two distinct sets of mechnical properties. The upper and lower bound values of mechanical properties are determined from nominal values of properties and the use of system property modification factors. Therefore, each data set has been used as an input for lower and upper bound values of seismically isolated bridges.

Note that all criteria for applicability of the single mode method of analysis are met. Specifically, the effective period in the Design Earthquake (DE) is equal to or less than 3.0sec (limit is 3.0sec), the system meets the criteria for re-centering and the isolation system does not limit the displacement to less than the calculated demand. Nevertheless, dynamic response history analysis will be used to design the isolated structure but subject to limits based on the results of the single mode analysis. Typical Force-Displacement relation of the isolation bearings is illustrated in Figure 7. Triple friction pendulum bearing is implemented to described bridge model in section 2.

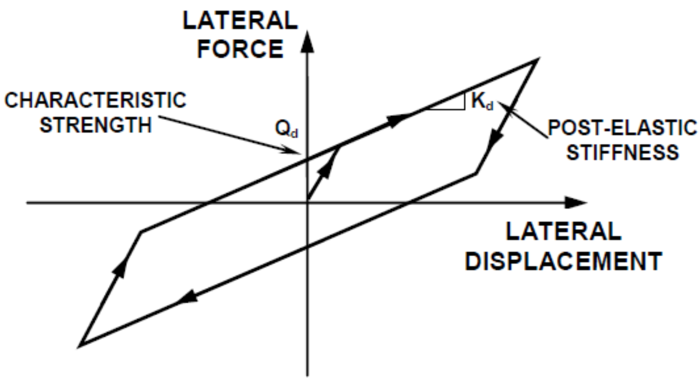


Figure 7. Idealized Force-Displacement Relation of Typical Seismic Isolation

6. TRIPLE FRICTION PENDULUM BEARINGS (TFP)

Friction Pendulum (FP) bearings have Single, Double or Triple configurations. The individual response of the conventional FPS has been established with experimental and analytical research by Zayas et al. (1990). The Triple Friction Pendulum (FP) isolator exhibits multiple changes in stiffness and strength with increasing amplitude of displacement. The construction of the force-displacement loop is complex as it may contain several transition points which depend on the geometric and frictional properties (Fenz and Constantinou, 2008a, b). Geometric and frictional properties of TFP with its force-displacement loop are shown in Figure 8.

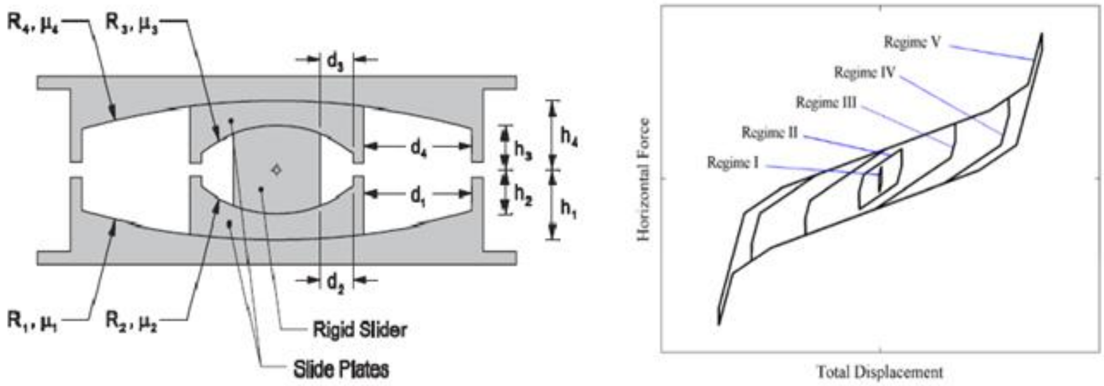


Figure 8. Triple FP Bearing Definition of Dimensional, Frictional Properties and Force Displacement Loops

7. MODELING TRIPLE FRICTION PENDULUM BEARING IN FINITE ELEMENT SOFTWARE

The analysis was performed with the program SAP2000, Version 14.2.2, using the Fast Nonlinear Analysis (FNA) method with a large number of Ritz vectors (129) so that the results are basically exact. The series model has been developed by Fenz and Constantinou (2008d, e) and overall behavior of TFP in 5 regimes is represented through series arrangement of single FP bearing. Second modeling option for TFP is the parallel model with the arrangement of single FP and flat sliding bearing to capture the overall behavior. The parallel model was originally described in Sarlis and Constantinou (2009) which is a much simpler model capable of describing the overall behavior. It has also less computational effort for the special case Triple FP bearing.

8. CONCLUSIONS

The earthquake resistant design of base isolated structures is regulated by several codes with international applications. The earthquake hazard assessment and the definition of the design basis ground motions should conform to these codes. Selection and scaling of real earthquake records for long period structures have to be based on the seismic hazard assessment. Main objective of this paper is to compare the distinct scaling procedures and investigate the performance of long-period structures in close proximity to active faults. The primary concern in near-field regions is the assessment of design basis ground motion for base isolated bridges on rational bases. Apart from the basin response effects, the main factor that influences the long-period ground motion comes from the forward rupture directivity associated with near-fault effects. Thus, first set of input motion is selected on the basis of magnitude, distance and site class as well as directivity effects.

6 set of earthquake records have been used as input for both lower and upper bound values of TFP. Results of FNA indicate that near-field earthquake data set from previous studies (Constantinou et. al, 2011) requires larger displacement demand than the simplified procedures. However, in all cases of

CMS method displacement demand has found smaller than the simplified procedure. Effectiveness of CMS method for seismically isolated bridges should be investigated under extended studies to determine if there is a trend exist or not.

Near future efforts should address the principles for modification of design basis spectra in the long-period range (2-10s) for more reliable analysis; rules for selecting and scaling ground motion while earthquake records address effects of long period earthquakes on bridges.

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