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The Selection of Earthquake Records for Pseudo Dynamic Tests of an old Highway Bridge

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ABSTRACT: Bridges constitute the critical part of transportation systems and their functionality should be preserved during major earthquakes. The implementation of comprehensive guidelines for the seismic assessment and retrofit of existing bridges requires the understanding of complex local and global behavior under moderate to large earthquakes. The RETRO TA project has been funded by the European commission within the SERIES project and it focuses on an old portal frame bridge (Rio-Torto Viaduct), not properly designed for seismic actions. Main objectives of the current research activity are to assess the seismic vulnerability of Rio-Torto Viaduct through Pseudo Dynamic (PsD) testing and perform numerical analysis to investigate the effectiveness of the proposed retrofitting techniques. A proper Seismic hazard assessment (SHA) is one of the key steps that needs to be conducted to guide the selection of earthquake ground motion records for nonlinear time-history analysis and similitude laboratory tests. This paper elaborates the selection and scaling procedures of the ground motion records within a performance-based design framework as defined in NTC-08.

1. INTRODUCTION

The seismicity of Italian territory and past experiences highlighted the earthquake risk in terms of casualties and economic losses. In order to reduce the losses due to earthquakes, Italian Civil Protection (DPC), with the seismological and engineering support of the National Institute for Geophysics and Volcanology (INGV), ReLuis and EUCentere, a broad-spectrum nationwide seismic risk mitigation scheme has been launched (Dolce, 2012). Most of the bridges in Italy were mainly built in the late 60s and early 70s, and lack of adequate seismic design considerations.

Various of retrofit applications have been developed for the improvement of strength and ductility characteristics of bridges or bridge components to ensure the safety of the structure and compliance with code requirements. The protection can be provided by applying conventional methods, such as the concentration of significant inelastic action (energy dissipation) in the selected structural components, installation of restrainers, jacketing or by introducing innovative retrofitting techniques like installation of isolation/energy dissipation devices. To this end a comprehensive research program was initiated to formulate pre-normative European guidelines by Italian ReLuis consortium (Pinto and Mancini, 2009) for the performance assessment of existing bridges. Rio-Torto Viaduct can be considered to represent the old bridges in Europe stemming from its material characteristics and design that are not compliant with the contemporary considerations.

Contemporary seismic design guidelines require nonlinear dynamic analysis of critical structures. It is essential to represent a site-specific demand spectra and appropriate ground motion sets for the nonlinear dynamic analysis to verify the performance criteria. Needless to say, the uncertainties associated with the location, magnitude, time of occurence of earthquakes affect the selection of ground motion sets.

The main objectives of RETRO project are to assess the seismic performance of an old reinforced concrete bridge through a large scale PsD tests and evaluate the effectiveness of innovative retrofitting techniques. The test results will also contribute to the development of seismic retrofitting guidelines of existing bridges in Europe. Retrofitting methods addressed in this study include installation of friction pendulum devices and energy-dissipation devices. The RETRO project is funded as a TA facility of the Seismic Engineering Research Infrastructures for European Synergies (SERIES) which was financially supported by the Seventh Framework Programme of the European Commission. Testing campaign took place in ELSA Laboratory of JRC (Ispra, Italy) and two piers (scale 1:2.5) were built and tested by means PsD substructuring technique. This paper focuses on the selection and scaling procedures of real earthquake records for the performance assessment of the bridge by numerical analyses and experimental studies.

2. DESCRIPTION OF THE RIO-TORTO VIADUCT

The Rio-Torto Viaduct is an old RC bridge located in Emilia-Romagna region as a connection link between Florance and Bologna with a total length of 421.1m (Figure 1). It consists of 13 spans with two independent roadways which were supported by 12 pairs of portal frame bents where piers of the bridge are composed of circular solid and hollow sections with varying diameters. Piers of the viaduct are connected to cap beams at the top of each bent and the height of piers are in the range of 13.8m to 41 m as illustrated in Figure 2. Rio Torto viaduct is considered as a critical structure with class of IV and nominal life of 100 years with respect to the seismic design code of Italy (NTC-08).

Figure 1. (a) Location of Rio-Torto Viaduct (b) General view of piers (c) Deck Geometry

The most recent Emilia earthquake that struck the region also supported the idea of assessing the seismic resistance of Rio Torto bridge in case of major to moderate earthquakes. Particular emphasis to Emilia earthquake is considered by using the recordings of the seismic event as input signals in PsD tests of RETRO project.

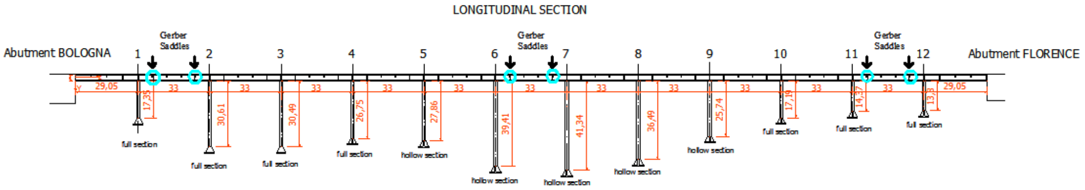

Figure 2. Layout of Rio-Torto Viaduct

3. Representation of the Seismic Demand and Review of Code Provisions in Italy

Ground motion selection procedures are often associated with a target response spectrum which depends on the proper identification of the seismic hazard. There are generally two well-known approaches for the quantification of seismic 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).

PSHA study in Italy was conducted by INGV and findings of seismic hazard assessment are utilized in NTC-08 for 9 return periods. The latest seismogenic zonation of Italian territory in ZS9(INGV) and earthquake catalogue of CPTI04(INGV) are utilized together with ground motion prediction equations (Ambraseys et al.,2003, Sabetta and Pugliesse,1996) for the PSHA study to represent the design spectra in NTC-08. NTC-08 introduces four design spectra named as SLO, SLD, SLV and SLC for serviceability and ultimate limit states as shown in Figure 7 (a). (SLO = Operational Limit State; SLD = Damageability Limit State; SLV = Life Safety Limit State; SLC = Collapse Prevention Limit State).

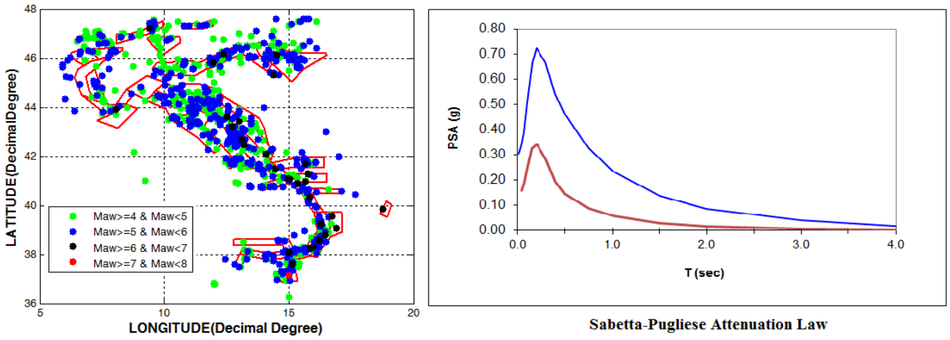

Figure 3. (a) ZS9, Seismogenic zones and seismicity of Italian territory wrt CPTI04 catalogue (b) Prediciton of g.m for Magnitude range=5-6 and Repi=5 km by performing Sabetta and Pugliese Attenuation Law(1996)

Input parameters of the design spectra are computed at each node which has regular grids with approximately 5km spacing. The Annex B of NTC-08 provides ag, Fo and TC* (i.e., the TC value for type A site class) values for each node of the national territory. Fo is an amplification factor (equal to the ratio between the maximum spectral ordinate and the ag value) and TC equals to Cc times TC*(Corner period value for site class-A). Values of Cc depends on site classes. New tool is created in Matlab to extract the specified peak ground motion and spectral acceleration values in the vicinity of the geographical location of Rio Torto bridge automatically as shown in Figure 4 and Figure 5.

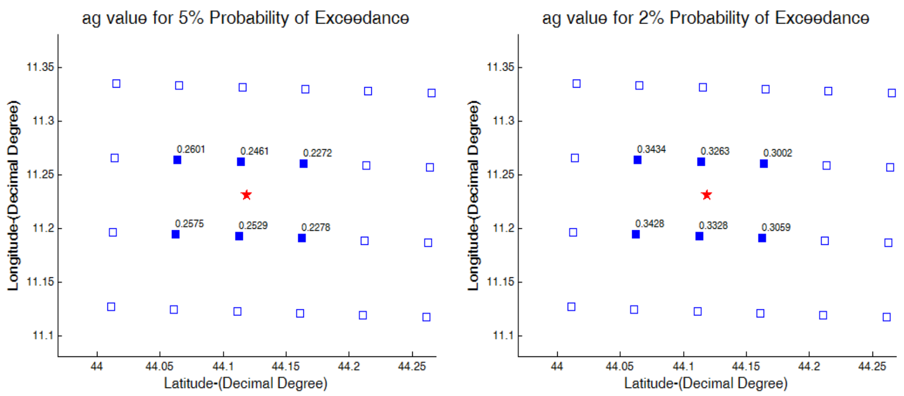

Figure 4. Location of Rio-Torto Viaduct and Expected PGA values in close proximity (INGV)

If the considered return period is not specified in NTC-08, required parameters of the generic return periods are computed for two consecutive return periods of the seismic design code where the unspecified intermediate one falls between.

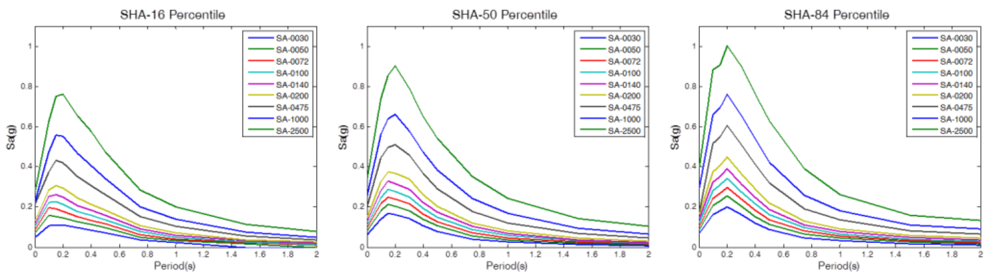

Figure 5. UHS (Uniform Hazard Spectrum) for 16-50-84 percentile in the vicinity of Rio Torto

4. Different Selection Strategies for Real Earthquake Records

Dynamic response history analysis and testing of large scale structures require the proper selection and scaling techniques for real 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 methods (GMSM) are currently available to use for bridge structures. The key steps herein are to quantify and correlate the damage on the basis of Earthquake Demand Parameters (EDP) from time-history analyses. When selection of real records for seismic design of structures is concerned, the current state of best engineering practice is based on the Uniform Hazard Spectrum (UHS) which is an elastic spectrum defined by means of the seismic hazard at the site where the structure is supposed to be located (Cornell, 2004, 2005). In this study UHS are provided by NTC-08 and PSHA studies of INGV.

Current practice and tendency for record selection stand in need to de-aggregate the uniform hazard spectrum (or spectra) at the first mode period of the structure (T_1), determine the modal magnitude (M) and site-to-source distance (r) pair, and select recorded ground motions corresponding to the modal [M, r] pair and local site conditions. In order to achieve the minimum manipulation on the selected input motions only real earthquake records with linear scaling procedures were considered.

In order to achieve the amplitude and/or frequency scaling of ground motions to match a uniform hazard spectrum, two well-known approaches have been commonly used in practice. First one considers the amplitude or frequency scaling of single-component ground motion to exactly match to a target spectrum. This procedure was originally developed for nuclear power plants. In contrast, second procedure for the amplitude scaling of pairs of ground motions computes the average value of the square root of the sum of the squares of the 5-percent damped spectral ordinates for values not less than 1.3 times of the 5-percent damped target spectrum between 0.2 T_1 and 1.5 T_1 period ranges (FEMA 2004, ASCE 2006). The latter procedure was originally developed for seismically isolated structures.

There are different existing strategies for selection and scaling of seed motions which match the target spectrum best after scaling or without scaling. As a preliminary selection methodology minimum deviation of spectral values are aimed in the period range of interest in this study. In addition to mentioned selection procedure, weighted scaling methods are also applied with /without scale factors for unidirectional and bidirectional loading. The simplest case for practicing engineers is to use unscaled records that have scale factor of 1.0. Therefore, results of the weighted scaling procedures were not covered in the scope of this paper. After obtaining suitable sets of records with scale factors equal to 1, response history analyses were performed for simplified analytical models as well as refined 3D models of Rio Torto.On the basis of pseudo-dynamic testing protocol in ELSA laboratory, uniaxial loading will be applied to two bents of Rio-Torto viaduct. Simplified analytical models of the bridge for linear and nonlinear characterization and refined 3D models were generated in OpenSees Software (McKenna et al., 2007). Details of the 3D model will be explained in the accompanying paper (Paolacci et al., 2013).

Four different databases are sought to find representative input motions that fit to code-based NTC-08 spectra. The European Strong Motion Database (Ambraseys et al., 2003) have a tool that searches records in the database with the spectral shapes similar to the target spectrum by using equation(1). The stated equation gives the average root-mean-square difference that is anchored to PGA value. However, most of the engineering structures are investigated through a broader period range of interest. Therefore, proposed method in the tool of European Ground motion database was modified to search records with respect to SA values between the specified periods rather than only checking the PGA anchored values. For each record a scale factor , f was determined for minimizing the root-mean-square difference D_{RMS} between the scaled geometric mean spectrum of the real record and the target spectrum. In our case f=1 for the selected records.

Most of the seismic design guidelines recommend the period range of interest to be between $0.2T_F$ and $1.5\ T_F$ for the fixed base structures. . Upper bound values of period range of interest can be extended due to derived ductility parameter. In contrast, $0.5T_D$-$1.25T_M$ values are recommended for the isolated cases to find earthquake records that are compatible with the target spectrum. T_D and T_M represent the fundamental period of the isolated system under Designed Based Earthquake (DBE) and Maximum Credible Earthquake (MCE), respectively. Earthquake records are selected with respect to their spectral shape and seismological parameters as shown in Figure 6. Average of the selected earthquake records shall not be lower than 10% of the Target Spectrum (SLC).

$$D_{RMS} = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\frac{Sa_R(Ti)}{PGA_R} - \frac{Sa_T(Ti)}{PGA_T}\right)} \qquad (1)$$

where $Sa_R(Ti)$ is the spectral acceleration of the real record at the period Ti, PGA_R the peak ground acceleration of the real record, $Sa_T(Ti)$ is the spectral acceleration of the target record at the period Ti, PGA_T the target peak ground acceleration and N, the number of periods at which the spectra are defined.

The Emilia earthquakes of May 20, 2012 (ML 5.9, INGV; MW 6.11, and May 29, 2012 (ML 5.8, INGV; MW 5.96) struck the Emilia-Romagna region. The national reference seismic hazard model MPS04(INGV) is characterized by the expected PGA with a 10% probability of exceedance in 50 years that ranges between 0.10 g and 0.15 g which is a medium level of seismic hazard in Italy (Meletti et al., 2012).

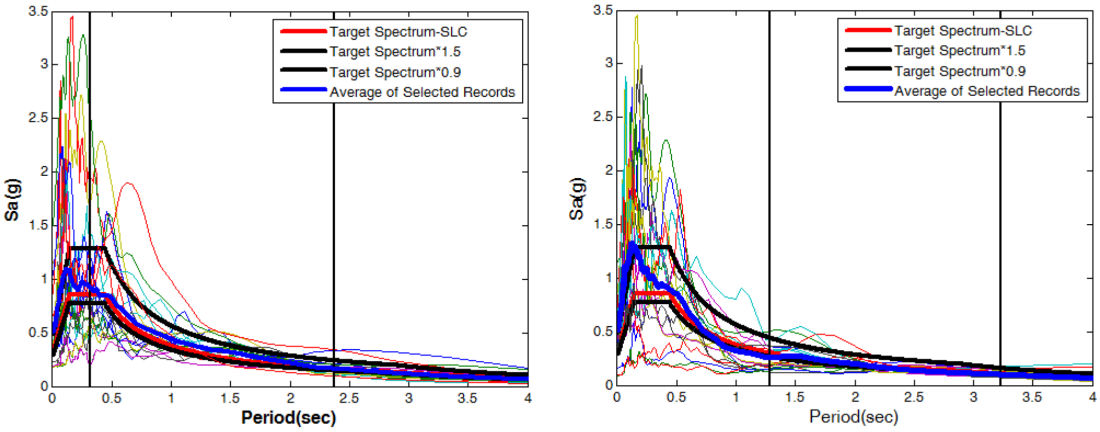

Figure 6. Selected Earthquake Records from 3 Different Databases for Nonlinear Analyses of Rio-Torto Viaduct at Fixed Base and Seismically Isolated Cases

Due to close proximity of Rio Torto bridge to epicenter of Emilia earthquake, earthquake recordings of the seismic events are intentionally included in the input signal sets at two design level earthquake (Figure 7. (b).

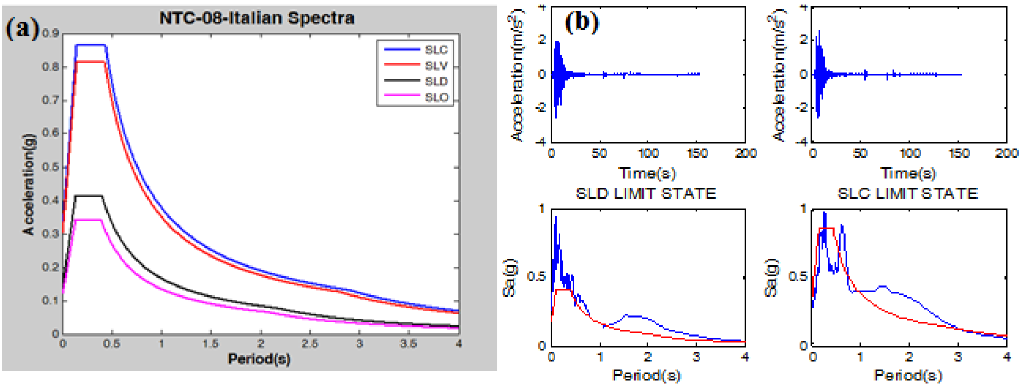

Figure 7. (a) NTC-08 Design Spectra at four limit states (b) Input Signals from Emilia Earthquake for Serviceability and Ultimate Limit States

5. Analytical Models of the Rio Torto Viaduct

The bridge piers consist of moment-resisting frames with transverse beams connecting the columns of each bent. All bridge piers have plain steel bars and further investigation is considered in the task of RETRO project. Results of previous experimental tests and numerical analyses were exhibited that transverse beams are susceptible to shear failures (Giannini and Paolacci, 2009). The stated case is not acceptable for critical structures and most efficient retrofitting schemes are in the scope of RETRO project. Previous quasi-static test results for Pier 12 are implemented to analytical model. In the preliminary analysis phase, SDOF bilinear model that accounts for strain hardening behavior and simplified linear and nonlinear Opensees models are used to evaluate the damage potential of records. Simplified and refined bridge models are generated in OpenSees (McKenna et al., 2007). Results of bilinear SDOF model and simplified analytical models of the as-built configuration are evaluated on the basis of damage potential of the selected set of earthquake records. Four limit states are checked during the performance assessment of Rio Torto Viaduct by assigning suitable sets of real earthquake records. Modifications on the model were done on the basis of findings from nonlinear response history analysis and experiemental results. Hysteretic and Pinching elements are used for nonlinear characteristics of piers in the simplified model (Figure 8). Displacement response histories of piers and envelope displacement profile of an as-built model under one of the selected records are shown in Figure 9 respectively. Finally, a refined three-dimensional nonlinear finite-element model with fiber elements of the Rio Torto bridge was developed in Opensees(McKenna et al., 2007). Results of 3D refined model were used as baseline in the parametric studies for the verification of findings by PsD tests.

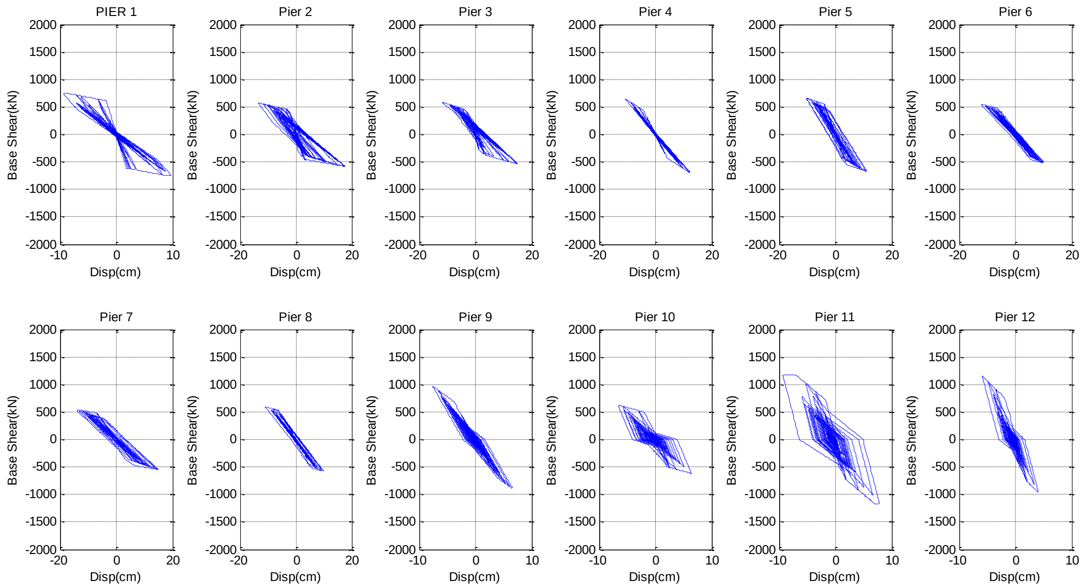

Figure 8. Force-Displacement hysteresis of piers for fixed base condition under a selected ground motion

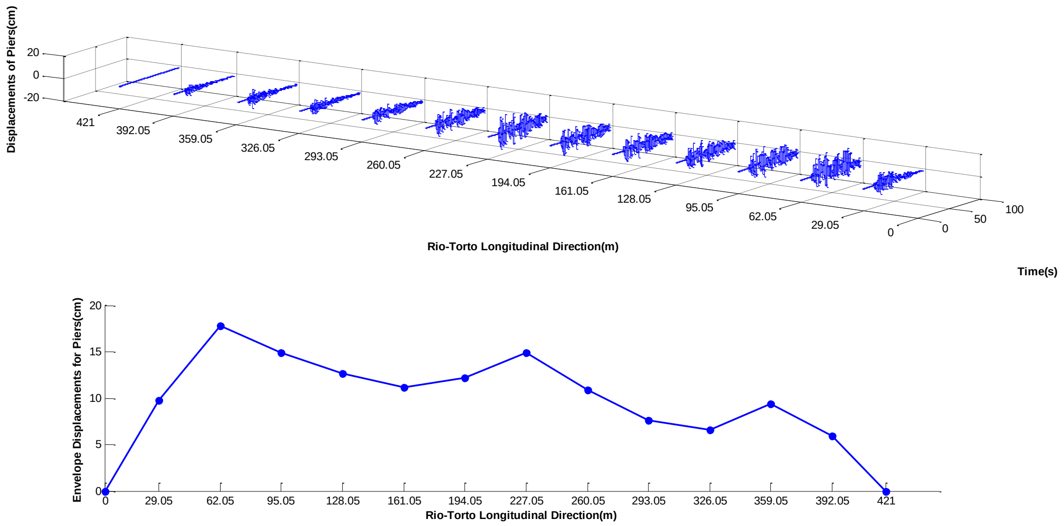

Figure 9 (a) Displacement time histories at pier locations (b) Envelope Displacement Profile of the bridge

6. PsD Test Technique and Input Signals

The loading protocol of PsD test was based on pre-test analytical studies Similitude requirements were applied to represent the characteristics of the full scale structure. It utilizes the sub-structuring technique which simulates the behavior of the bridge by performing numerical analysis for the selected components of the bridge(deck + 10 piers). By this way, full 3D model of the bridge would entail a high computational effort to exhibit the extensive nonlinear beahvior of piers that are expected during the PsD test. Therefore, generation of simplified models of the bridge was essential to have reliable results and controlling the PsD test results during the test.

7.Conclusion

Selection and scaling of seed motions regarding to conducted SHA have a prominent role in the design and retrofitting scheme of bridges and the current state of art are briefly presented in this study. Project partners of RETRO project are actively involved in the development of analytical models and experimental specimens of Rio-Torto Viaduct. Number of earthquake records are limited to 3 input signals at two design levels for testing campaign. Developed analytical models in OpenSees (McKenna,2007) and Matlab codes served to evaluate the damage potential of the suitable sets of records and representation of the average response of the bridge with the selected sets of earthquake recordings without any scale factors(f=1). Further studies relevant with record selection of RETRO Project will cover the orientation of ground motion components and correlation of the damage with IMs by elaborating findings from numerical and experimental studies of Rio Torto Viaduct.

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