Probabilistic Analytical Benchmarking of Source-Based and Site-Based Ground Motion Simulation Models

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ABSTRACT: Scarcity of the recorded ground motions and their unavailability to meet specified design scenarios have led to an increased use of the simulated ground motions in performance-based earthquake engineering. This paper offers a benchmark study aimed at validating various ground motion simulation models for engineering practice. The ground motion simulation models used in this study cover both site-based and source-based techniques aimed to benchmark their performance using response of single- and multi- degree-of-freedom (SDOF and MDOF) systems to seismic excitation. Source-based ground motion simulation predicts time series using models that explicitly incorporate the physics of the earthquake source and the resulting propagation of seismic waves; Southern California Earthquake Center (SCEC) broadband simulations used in this study represent source-based ground motion simulation technique. Site-based ground motion simulation techniques, on the other hand, use statistical approaches without necessarily solving the mathematical notions that describe the physics of source dynamics and wave propagation to generate ground motion time series. Ground motions simulated from three historic events (Northridge, Loma Prieta, and Landers) are used and applied to a set of SDOF (non-deteriorating), and MDOF (Box-Girder Seat-type bridge) models and their responses are compared with what is observed using recorded ground motions. Evaluation of the efficiency and sufficiency of the synthetic ground motions show that they are in general a good representation of recorded ground motions. Ground motions obtained via the source-based simulation approach provide a more accurate estimation of *RotD50* spectral acceleration (S_a) while site-based simulations provide a better representation of Arias Intensities (I_0). Issues related to variability in response of structures using recorded and simulated ground motion sets are presented.

1. INTRODUCTION

Nonlinear Time History Analysis (NTHA) is one of sophisticated methods currently used in the Performance-based Earthquake Engineering (PBEE) framework to assess the structures response in various seismic hazard regimes. The community of earthquake engineers have been widely dependent on the out-sourced recordings of the ground motions during the earthquake events. Various projects – such as NGA-West2 (Timothy et al. 2014) – provide access to ground motion records which can be used for the NTHA of structures. The deficiency of ground motions representing a given hazard for a location, especially for large magnitude and small distance events, has raised the demands for alternate procedures of obtaining ground motion time series. As a result of this scarcity, practitioners are forced to alter the available ground motion records e.g. scaling them by factors as large as 10 or modify their frequency contents in order to match the hazard level characteristics. Due to these concerns, researchers such as Giarilis *et al.* 2010, do Santos *et al.* (2016) and Mitseas *et al.* (2018) have tried to implement alternative stochastic dynamics-based techniques seismic demand estimation of structures which do not required computationally intensive nonlinear response history analyses. However, in general, there is an increased interest in developing easier methods for generation of synthetic ground motions for design scenarios.

The simulation process of obtaining synthetic ground motions can be broadly classified into two groups: 1) Source-based (also known as Physics-based) and 2) Site-based. Source-based simulation approach is a deterministic technique (randomness is added at an earlier stage for rupture generation, and at a later stage to augment the record with high frequency content) in which uses the three-dimensional representations of Earth structure to spatially correlate the propagation of rupture waves from source to site. On the other-hand, the site-based simulation approach involves a stochastic method to generate a data driven realization of ground motion history at a location. Source-based models can produce realistic accelerograms at low frequencies (typically <1 Hz), but often need to be adjusted for high frequencies by combining with a stochastic or empirical component, resulting in "hybrid" models (Douglas *et al.* 2008). In general, these models tend to heavily employ seismological principles to describe the source mechanism and wave travel path, as pointed out by Stafford *et al.* (2009). They depend on physical parameters that vary significantly from region to region. This limits their use in regions where seismological data are lacking–exactly in places where there is an increased need for generation of synthetic ground motions. In the current practice, most engineers prefer using methods of scaling and spectrum matching of recorded motions instead of incorporating source-based models. This is partly due to lack of understanding about the seismological principles underlying these models, and the fact that they require a thorough knowledge of the source, wave path, and site characteristics, which typically are not available to a design engineer. Hence, site-based models are focused on simulating ground motion histories using parameters that are readily available to practicing engineers; input parameters that are directly related to the earthquake and site characteristics.

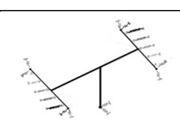
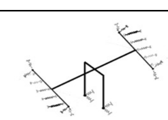
In this study, recordings from multiple stations of three major earthquake events: Northridge (1994), Loma Prieta (1989) and Landers (1992), are used as the validation sets. Using the ground motion records of the stations for these earthquakes, source-based ground motions are simulated using the Broadband Platform (BBP, ver. 17.3.0) provided by the Southern California Earthquake Center (SCEC) (Maechling *et al.* 2015). The source-based simulation methodologies used by BBP generate earthquake strong-motion waveforms over the frequency range 0-10 Hz. At frequencies less than 1 Hz, it uses deterministic methodologies to predict the amplitude, phase and waveform of earthquake ground motions using fully three-dimensional representations of Earth structure, as well as dynamic or dynamically compatible kinematic representations of fault rupture. At higher frequencies (1-10 Hz), the methodologies predict the main character of the amplitude, phase and waveform of the motions using a combination of deterministic and stochastic representations of fault rupture and wave propagation. For the site-based simulations, a data-driven model (Razaeian *et al.* 2010, Dabaghi *et al.* 2016), denoted as *DRD*, is used to simulate the ground motions. The source-based and site-based ground motions are then validated against the recorded ground motions for each earthquake event on the basis of the response of SDOF model with multiple periods (Spectrum) and MDOF model (Box-Girder Seat-type bridges). The validation is conducted through a series of statistical analyses and conclusions are drawn on which type of synthetic ground motions provide better results as compared to the recorded motions.

2. MODELS

The Single-degree-of-freedom (SDOF) model consists of cylindrical non-deteriorating linear elastic element with various fundamental periods. For the Multiple-degree-of-freedom (MDOF) two

California representative RC highway bridge structures are selected for the statistical analysis. Table 1 includes the details of the two ordinary bridges with seat-type abutments. The modelling of the bridges is conducted in the OpenSees (McKenna et al. 2010). The models comprise of: seat-type abutments, shear keys, column bents, elastomeric bearing pads, backfill soil and superstructure. The concrete and steel used in modelling have a Compressive Strength f_c` = 5.0 *ksi* with Modulus of Elasticity E_s = 4030.5 *ksi* and Tensile strength = 68 *ksi* with Modulus of Elasticity E_s = 29000 *ksi*, respectively.

Table 1–Characteristics of Bridge Structures

Bridge	*A*	*B*
Name	*Jack Tone Road Overcrossing*	*La Veta Avenue Overcrossing*
Number of Spans	*2*	*2*
Column Bent	*Single-column*	*Two-column*
Column Radius	*33.1 in*	*33.5 in*
Column Height	*22.0 ft*	*22.0 ft*
Reinforcement of Column Section	*Long: 44 #11 (bundles of 2) ρl = 2.00% Trans: Spiral, #6 @ 3.34 in*	*Long: 44 #11 (bundles of 2) ρl = 1.95% Trans: Spiral, #4 @ 6.00 in*
Site Vs30	*222.95 m/sec*	*187.6 m/sec*
Fundamental Period	*0.61 sec*	*0.83 sec*
Configuration		

The superstructure is modeled with `elasticBeamColumn` using uncracked section properties. To capture the dynamic response accurately, the mass of the superstructure is distributed throughout the length of the deck with each span`s mass being distributed in ten intervals. The bridge columns are modeled using `beamWithHinges` element (two Gauss integration points) with fiber-discretized cross sections to model 1) confined concrete for the core, 2) unconfined concrete for the cover and 3) steel rebars. The plasticity of columns is concentrated at two plastic hinges at the opposite ends connected through a linear elastic element. The cap beam is modeled as a rigid bent using `elasticBeamColumn` element with high torsional, in-plane and out-of-plane stiffnesses. The concrete and steel are modeled using `Concrete01` and `Steel02` materials of OpenSees, respectively. The base of bridge *A* and bridge *B* are simulated as fixed and pinned connections, respectively, with the stiffness of connections arising from piles beneath. The piles under the bridge columns are modelled using elastic springs with the horizontal stiffnesses described as per Choi (2002).

Shear keys are designed and modeled in a brittle/isolated manner using the `hysteretic` spring model available in OpenSees (McKenna *et al.* 2000). The model is defined with a trilinear backbone curve. To determine the Area of Vertical Reinforcement (A_{vsk}), the shear key is designed as per Caltrans SDC (2013). As detailed in the experimental observations of Kottari (2016), the strengths and stiffnesses of the initial, hardening and softening parts of the trilinear backbone curve are determined using the two states of isolated shear keys: 1) shear resistance at first sliding (V_{slid}) and 2) ultimate sliding shear resistance (V_u) right before the rupture of the dowel bars with an assumption of a smooth construction joint

The model of abutment is comprised of: 1) abutment Piles, 2) backfill soil and 3) Elastomeric Bearing pads. Piles of the abutments are modeled through a trilinear `hysteretic` spring model in OpenSees with the backbone curve defined as per Choi (2002). The backfill soil is modeled using the `HyperbolicGapMaterial` material of OpenSees (Mckenna *et al.* 2010) with a Generalized Hyperbolic Force-Deformation (GHFD) backbone (Shamsabadi *et al.* 2005, 2007, Duncan & Mokwa, 2011). Hence, the active resistance of the abutment is provided by the piles while the passive action includes resistance due to the piles and backfill soil. The parameters described by Ramanathan (2012) are used to model the Elastomeric bearing pads using the `Steel01` material. The longitudinal behavior of the abutment is modeled using five springs in parallel connected by a rigid link while the transverse behavior is modeled using one spring on both ends of the abutment.

3. GROUND MOTIONS

The recorded ground motions used in this research are derived from the seismic records of 40, 61 and 31 stations for Landers (1992), Loma Prieta (1989) and Northridge (1994) earthquakes, respectively. The corrected versions of the recorded ground motions for the respective stations are obtained from NGA-West2 (Timothy *et al.* 2014). The source-based and site-based synthetic ground motions are simulated against these recorded motions for the corresponding stations.

The source-based ground motions are obtained from the SCEC`s Broadband Platform (BBP) ver 17.3.0 (Maechling *et al.* 2015). The Broadband Platform (BBP) is an open source computational pipeline platform that contains source-based ground motion models capable of simulating earthquake ground motions across regional distances. BBP contains several source-based ground motion simulation models including: 1) *GP* (Graves and Pitarka, 2010), 2) *SDSU* (Mena et al., 2010), 3) *UCSB* (Schmedes et al., 2012), 4) *EXSIM* (Motazedian and Atkinson, 2005) and 5) *CSM* (Zeng et al., 1994). Each of these models is assembled from one or more processing stages. Since *GP* model simulates distinct time-histories in the three orthogonal directions, in this research, *GP* model is used to generate the synthetic ground motions using the *validation set* option of BBP for the three historic earthquake events.

The site-based ground motions are simulated using the DRD model (Razaeian *et al.* 2010, Dabaghi *et al.* 2017). The DRD model is a parameterized stochastic model which generates ground motion in the two orthogonal horizontal directions. The simulation is conducted by matching the earthquake source and site characteristics of a recorded ground motion, which include: type of faulting (F) i.e. Strike-slip faults or Reverse and Oblique faults, moment magnitude (M_w), depth to the top of rupture plane (Z_{tor}), closest distance between site and the fault rupture (R_{rup}), shear wave velocity of the top 30 m of soil at the site (V_{s30}), directivity parameter (s or d) and directivity angle parameter (θ or ϕ). The *DRD* model is able to account for the major characteristics of recorded ground motion which include the near-fault directivity effects (both pulse-like and non-pulse-like cases); temporal and spectral non-stationarity; intensity, duration, and frequency content characteristics; directionality of components; and the natural variability of ground motions. Thus, *DRD* model generates an 'observed' set of model parameters for different earthquake source and site characteristics. The model is bifurcated into two parts by the virtue of R_{rup}. The model is bifurcated into two parts by the virtue of R_{rup}. For generating near-field ground motions (R_{rup} < 30 km) Dabaghi *et al.* (2017) is used, and the input parameters include: F, M_w, Z_{tor}, R_{rup}, V_{s30}, s or d, and θ or ϕ. For simulating far-field ground motions (R_{rup} > 30 km), Rezaeian *et al.* (2010) is used, and the input parameters include: F, M_w, R_{rup}, and V_{s30}. For this study, the input parameters corresponding to each recoded ground motion are obtained from the NGA-West2 (Timothy *et al.* 2014) flat-file.

4. METHODOLOGY

For each ground motion, the two orthogonal components of the record are rotated through 180 degrees at an increment of 1 degrees for the SDOF model and 9 degrees for the MDOF Bridge models. Hence a total of 5544 (2 bridges x 132 ground motions x 21 angles) nonlinear simulations are conducted for the MDOF Bridge models while a total of 23760 (1 SDOF x 132 ground motions x 180 angles) linear simulations are conducted for the SDOF model. The median value of the spectral acceleration obtained when the 2 horizontal components of ground motions are applied orthogonally and rotated throughout 180 degrees on a Single Degree of Freedom (SDOF) system for each spectral period is termed as *RotD50* (Bozorgnia *et al.*, 2016). The *EDP* for the MDOF bridge model considered in this study is termed as *Rot50CDR*, which is the median value of the vector containing the peak column drift ratios (*CDR*) through intercept angles 0 to 180 degrees with increment of 9 degrees as given in Eq. 1

$$Rot50CDR = median\begin{Bmatrix} CDR_{0^\circ} \\ CDR_{9^\circ} \\ \vdots \\ CDR_{180^\circ} \end{Bmatrix} \quad (1)$$

Conclusively, in this research *RotD50* should not be confused with *Rot50CDR,* while the former is a measure of IM obtained after rotating the 2 ground motions components on a SDOF with varying period, latter is a measure of the EDP (Column Drift Ratio *CDR*) obtained after rotating the two components of ground motions through 180 degrees on the MDOF bridge models. To avoid any confusion and for the sake of brevity, in this study, the *RotD50* spectral acceleration at bridge`s first mode period is termed as S_a Hence, each ground motion is associated with one value of S_a (IM) and one value of *Rot50CDR* (EDP).

Another IM used in this study is the Cumulative sum of *SRSS* of the Arias Intensities, termed as I_0, of the two orthogonal components of ground motion, where *SRSS* of Arias Intensity is the integral $\int_0^{t_{max}} \sqrt{a_1{}^2(t) + a_2{}^2(t)}dt$; $a_i(t)$ represents the ground acceleration at time t in i^{th} orthogonal direction, and t_{max} represents the length of the accelerogram (Trifunac & Brady 1975). Based on the earlier studies (Dabaghi *et al.* 2016, Razaeian *et al.* 2010), Arias Intensity has been hypothesized to be an important predictor of the response of MDOF structures. Though there are numerous other parameters (such as Significant Duration ($D_{5\text{-}95}$), mid-frequency (ω) and slope of frequency at t_{mid} (ω`) that have been used in the regression analysis of estimating the response of structures, this research has been simplified to only two IM parameters as the predictor, *i.e.* cumulative sum of *SRSS* of the Arias Intensities (I_0) and *RotD50* spectral acceleration at bridge period (S_a).

The synthetic ground motions have been claimed to be random realizations of the of a particular earthquake event (Maechling *et al.* 2015, Dabaghi *et al.* 2016, Razaeian *et al.* 2010). This means that for any earthquake event, the synthetic ground motions are the random variables from the same distribution to which the recorded ground motions belong. In this study it is further assumed that for each earthquake event the records at all stations are random realization of the distribution of ground motions of the earthquake event. Therefore, ground motion records of all stations of the same earthquake event, are clubbed together with each ground motion representing a random realization. Then, *efficiency* and *sufficiency* of a single simulation of the synthetic ground motions for each station for each earthquake event is evaluated. The term *efficiency* in this paper is used to describe how close the *RotD50* spectrum of synthetic ground motions are with regards to the parameters of the recorded ground motions for each station and for each earthquake event. And the term *sufficiency* is used to describe whether the relation between EDP (*Rot50CDR)* and IMs (I_0 and S_a) of single simulation of synthetic ground motions are a part of the distribution of the relation between EDP (*Rot50CDR)* and IMs (I_0 and S_a) of the recorded ground motions for each earthquake event.

Thus, for each ground motion, Cumulative *SRSS* of the Arias Intensities (I_0) of ground motions, *RotD50* spectrum of ground motions (using SDOF model) and *Rot50CDR* of the bridge models are computed. The *efficiency* of the synthetic ground motions is evaluated by discretizing the *RotD50* spectrum plots and computing the sum of squared error (*SSE*) of the discretized plots between recorded and synthetic (source-based or site-based), as given in Eq. 2. Hence *SSE* is a vector with dimension (132 x 1) for site-based and source-based cases. In the Eq. 2, $y_{recorded_i}$ is the i^{th} discretized ordinate of *RotD50* spectrum plots of recorded ground motion, $y_{synthetic_i}$ is the i^{th} discretized ordinate of *RotD50* spectrum plots of synthetic ground motion (source-based or site-based) and N is the total number of discretized ordinates of the plots.

$$SSE = \sum_{i=1}^{N}\left(y_{recorded_i} - y_{syntheti\ i}\right)^2 \quad (2)$$

For each earthquake event, the EDPs *Rot50CDR* obtained due to the three types of ground motions (source-based, site-based, and recorded), for all the stations of the event, are plotted against their respective two IMs: I_0 and S_a.Then, a separate linear regression model is fitted for *Rot50CDR* vs I_0 and vs S_a for all the three types of ground motions. By comparing the linear regression models of the synthetic ground motion (source-based and site-based) data against the linear regression model of recorded ground motion data for each Earthquake event, the *sufficiency* of the synthetic ground motions is tested. If the synthetic ground motions, in fact, belong to the same distribution of the earthquake event, then the best estimates of linear regression coefficients of the synthetic type should be like that of the recorded ground motions. In other words, if the synthetic ground motions are the random realizations of same earthquake event then their linear regression model must be close to the recorded linear regression model.

5. RESULTS AND DISCUSSIONS

5.1. Efficiency

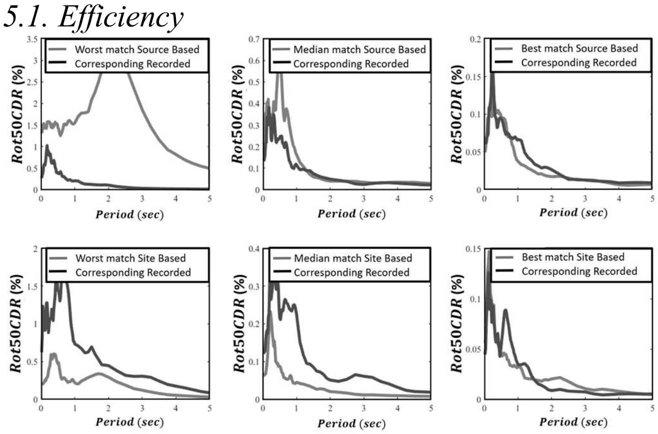


Figure 1:Worst match, median match and best match (left to right) for source-based (top row) and site-based ground motions (bottom row)

To show the results of *efficiency* test, the spectra of synthetic ground motion are termed as *best match*, *median match* and *worst match* based on the values *SSE* between the *RotD50* spectra of recorded and corresponding synthetic ground motion. The spectra with lowest value of *SSE* is termed as *best match*, while the spectra with highest value of *SSE* is termed as *worst match*. The spectra corresponding to the median value of the *SSE* vector is termed as *median match*. This is done for both site-based and source-based ground motions.

The *best match, median match*, *worst match* of the comparison between *RotD50* spectrum of synthetic ground motions (source-based and site-based) and recorded ground motion are shown in Figure 1. It is noticed from the figures that variation of the match between *best match* and *worst match* of the source-based synthetic ground motions is much higher than the variation of the match between *best match* and *worst match* of the site-based synthetic ground motions. It is also observed that the *best match* of the source-based ground motion spectrum is a better fit to its corresponding recorded ground motion spectrum as compared to *best match* spectrum of site-based ground motion with the spectrum of its corresponding recorded ground motions. Furthermore, the *median match* in case of source-based ground motions is better fit to the *median match* of site-based ground motions. This shows that the source-based ground motions are better representative of the *RotD50* spectra of the recorded ground motions and hence have higher *efficiency* than site-based ground motions.

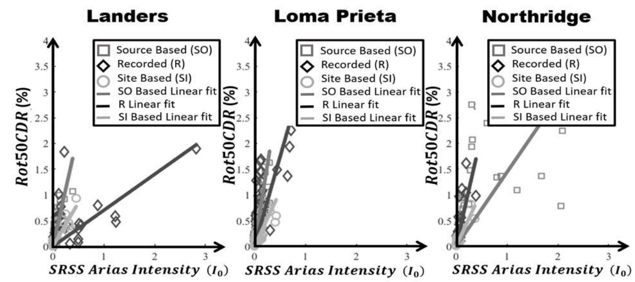
5.2. *Sufficiency*

The linear regression models for synthetic (source-based and site-based) and recorded ground motions for the three earthquake events for bridges A and B are shown in Figures 2 to 5. It is noticed that in case of Figures 2 and 3, which have I_0 as the predicting variable the linear fits of the 3 types of ground motions differ from one another with an exception of Figure 3c, where the linear model of site-based ground motions seems to be aligned with the linear model of recorded ground motions. Overall, site-based ground motions seem to have similar values of I_0 as compared to the recorded ones however, the corresponding EDPs *i.e Rot50CDR* seem to be underestimated by the site-based ground motions. In contrast, in case of source-based ground motions, the Cumulative *SRSS* of the Arias Intensities (I_0) are highly over estimated especially in case of Northridge earthquake. It is deduced that site-based ground motions are better representative of the recorded ground motions in terms of I_0. Furthermore, it is observed in Figures 4 and 5 (*Rot50CDR vs* S_a) that the linear regressions of the 3 types of ground motions are at close proximities to each other with an exception of Figures 4c and 5c. Overall in case of S_a as the predicting variable, source-based ground motions seem to have a closer linear fit as compared to the recorded ones. Whereas, the linear model of site-based ground motions consistently seems to lie below the models of source-based and recorded ground motions. This shows that the site-based ground motions are not good as good as source-based ground motions in predicting the *Rot50CDR* of the ordinary bridges through the predicting variable as S_a .Based on this it is deduced that source-based ground motions prove to better representative of the recorded ground motions in terms of *RotD50* spectral acceleration.

6. CONCLUSIONS

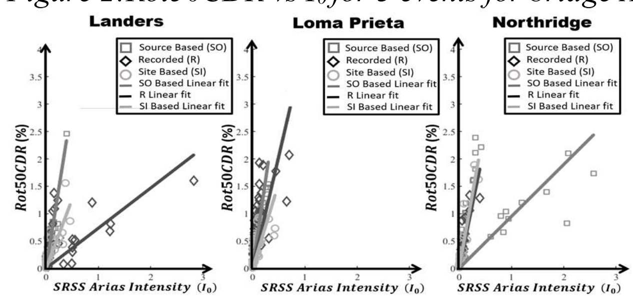
Due to the lack of recorded ground motions representing hazard conditions and to prevent over-scaling of the ground motion records to match the hazard, synthetic ground motions have been a center of attraction for PBEE analysis of structures. The synthetic ground motions are broadly classified into two types based on their simulation techniques: 1) source-based and 2) site-based ground motions.

This study evaluates the performance of the 2 types of synthetic ground motions based on the criteria of *efficiency* and *sufficiency*. The former evaluates the efficiency of the spectra of the synthetic ground motions to match that of recorded ground motions, while the latter investigates the sufficiency of the synthetic ground motions to estimate the EDP of two box-girder seat-type bridges and evaluates whether they belong to same distributions that contain recorded ground motions. It is concluded that the source-based ground motions demonstrate a superior *efficiency* as compared to the site-based ground motions and show better *sufficiency* when *RotD50* spectral acceleration is used as the predicting variable for estimating EDP *Rot50CDR* of the two bridges. However, site-based ground motions show a better *sufficiency* when Arias Intensity is used as the predicting variable for estimating EDP *Rot50CDR* of the two bridges. Furthermore, it is stated that single simulation of the synthetic ground motions for a particular event can cause huge variability in the response of the structures, hence it is suggested that multiple simulations of the same event must be carried and then conclusions shall be deduced.



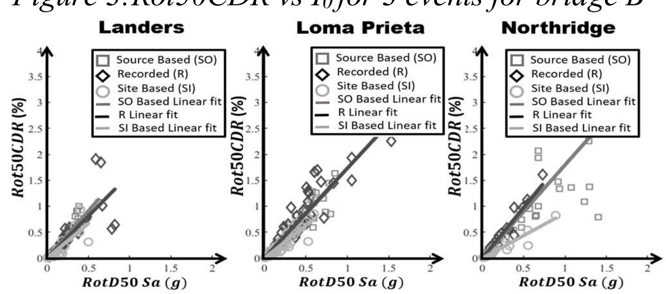
(a) (b) (c)

Figure 2:Rot50CDR vs I_0 for 3 events for bridge A



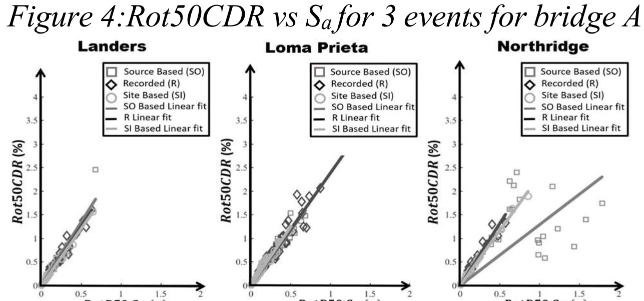
(a) (b) (c)

Figure 3:Rot50CDR vs I_0 for 3 events for bridge B



(a) (b) (c)

Figure 4:Rot50CDR vs S_a for 3 events for bridge A



(a) (b) (c)

Figure 5:Rot50CDR vs S_a for 3 events for bridge B

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