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IMPACT OF VARIOUS SITE CONDITIONS AND SHALLOW SITE RESPONSE CALCULATION DIFFERENCES ON LOSS ANALYSIS FOR THE 1812 NEW MADRID TYPE EARTHQUAKES

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ABSTRACT

Regional earthquake ground motion prediction equations, local site conditions, and the procedure for calculating the shallow soil site response all play important roles in regional hazard and loss analysis. Changes in the local site conditions and amplifications can dramatically affect regional earthquake ground motion, hazard, and loss estimates. In recent years, there have been a new set of predicted ground motion (attenuation) relations developed for the central and eastern US which have been used by the USGS for the 2008 National Seismic Hazard Maps. These equations are developed based on various stochastic seismic-source models that include rather large uncertainties on their related input parameters. This creates large epistemic uncertainty in the regional prediction of earthquake ground motions in CEUS. Also, in recent years there have been new developments both in regional site characterization and local site amplification analysis. The recent formulation of the site conditions based on topography can improve the characterization of site conditions where there is lack of data. Regarding the site amplification issue, one of the interesting product of the Next Generation of Attenuation (NGA) has been the development of a new set of equations for direct estimation of the shallow soil site response for any given average shear wave velocity of shallow soil layers. The formulation is general that can be applied to the site amplification analysis in any region. However, it is important to evaluate its impact on regional earthquake loss analysis relative to the NEHRP state of the practice. We selected the New Madrid Seismic Zone (NMSZ) area to evaluate the effects of these new developments on the regional loss estimates. The objective of this study is first to evaluate the effects of different attenuation relations on regional loss estimates for the New Madrid type earthquake. We also evaluate the effects of new site characterization and site amplification procedures on regional loss analysis for the 1812 New Madrid type earthquake scenarios.

Introduction

For many years, the state-of-the-practice for site amplification analysis followed the National Earthquake Hazard Reduction Program (NEHRP) procedure, in which short and long

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period amplification factors were defined for different categories of site conditions as a function of the ground motions at a reference site. The NGA equations, which were developed in 2008, allow direct calculation of the site amplification for any given average shear wave velocity of shallow soil layers. These equations are based on a comprehensive and critical evaluation of observed ground motion data from many earthquakes with different site conditions. They provide methods for calculating ground motion site amplifications that are an alternative to the NEHRP approach.

Several site maps have been developed for the New Madrid Seismic Zone (NMSZ) region. They include a site condition map for eight states in NMSZ, produced by the Central U.S. Earthquake Consortium (CUSEC), which is based on a 1:1,000,000 surficial geological map. A more detailed map for southern Illinois was recently developed by geologists at the Illinois State Geological Survey. Even more recently, a new site condition map was created for the central and eastern US using topographic slope data (Wald and Allen 2007). Due to shortcoming of slope and geological maps, we developed a procedure that uses available geologic and topographic data to create a new site condition map.

In order to evaluate site condition maps and ground motion site amplifications (in terms of regional loss analysis) in the NMSZ, we use a set of simulated New Madrid-type earthquakes extracted from a hundred thousand year stochastic earthquake catalog. The catalog consists of a set of correlated and uncorrelated events on the three fault trace segments, with different magnitude and recurrence-interval distributions for the northern versus the central and southern segments. Meanwhile, uncertainties in the predicted level of intensity and its effect on regional loss variations in the central and eastern US has been demonstrated using individual attenuation relations that were recommended by the NSHM (Petersen et al. 2008).

Site Amplification Analysis

A new empirical site amplification algorithm, based on the latest studies on the non-linear and linear response of shallow soil layers to ground shaking, was developed as part of the NGA project in 2008 (Power et al. 2008). During the NGA project, many researchers were involved in developing analytical and parametric site response studies. For example, amplification factors computed from the equivalent linear method using the Random Vibration Theory (RVT) (Silva and Lee 1987) are used to develop constraints on the nonlinear soil response for possible use by the NGA ground-motion model developers (Walling et al. 2008). The site response computations covered site conditions with average shear-wave velocities for the upper 30 meters of the ground's surface (Vs30). Simple parametric models of the nonlinear amplification factors, which are functions of the Peak Ground Acceleration (PGA) on rock and Vs30, were developed and validated against analytical functions (Walling et al. 2008). The NGA equations for ground motion calculation use Vs30 to quantify the effects of soil amplification on ground motions at the surface. This became a standard practice for the consideration of site conditions since the studies of Borcherdt (Borcherdt 1994), which show a consistent relationship between the site response and Vs30. For each strong motion recording station in the NGA database, Vs30 values are assigned based on observed borehole and site observations, which are combined with age and other geological and geotechnical information. Figure 1 shows the results of the NGA site amplifications compared to the NEHRP procedure, for different level of input ground motions at long periods.

Maps of Site Characteristics

The velocity of ground surface soil layers can be directly measured, or estimated, using geophysical or geotechnical approaches such as borehole logging, subsurface seismologic surveys, or standard penetration tests (SPT). These geotechnical approaches are relatively reliable, but they are also expensive and are therefore only used in site-specific earthquake engineering studies. A more practical approach to quantify site conditions in large regions is to use geological maps and the correlation between geologic units and measured Vs30 (Borcherdt 1994; Wills and Silva 1998; Martin 1994; Wills et al. 2000). Recently, a new approach to estimating Vs30 using topographic slope information has been proposed (Wald and Allen 2007). Wald and Allen developed a correlation between the topographic slope and the Vs30 for active crustal regions and the stable continental. Their approach provides a simple yet effective method for estimating the Vs30 at any site using publicly available topographic data.

The general correlation between observed shear-wave velocity and slope data and also between soil types inferred from surface geology and slope, both indicate that slope information can be used as a reasonable proxy for estimating site conditions. However, for sites that have the same type of soil conditions, the slope range may be wider than can be predicted by a simple relationship. Such variations can be due to natural reasons. For example, the steep slope corresponding to the shear-wave velocity in soils of type C or B (Wald and Allen 2007) can be clearly seen at the two sides of Mississippi River channel in Arkansas or Mississippi on the 9 arc-second topographic map, while the entire Mississippi river floodplain itself is very flat and can be classified as soft soil, of type D or E. The variation of slope on the given soil types estimated from the surface geology may also be due to lack of knowledge about the velocity-sensitive properties of the geological units, such as the texture or thickness of the sediments. Another reason for the variation may be that the geologic units are grouped according to age and depositional environment rather than velocity-sensitive properties such as grain size, density, and thickness.

In regions for which the geologic maps lack details, we have chosen to merge the soil maps estimated from geological data with the soil maps estimated from the slope. The digital geologic maps in many central and eastern US states (the base soil maps) are of the basement geology of pre-Quaternary maps. Surficial geologic units deposited in recent geologic time periods (Holocene and Pleistocene) were generally omitted and therefore do not represent soil conditions at the surface. For this reason, we have created a new soil map for the central and eastern US using the following merging rules:

1. If the slope at a site is steep (corresponding to type B or harder), the soil type inferred from the geologic map is used.

2. If the site is classified as type D to E from geologic data, then that type remains for the site. This rule acknowledges the facts that a) young surficial geologic units are most likely mapped onto the geological data at the site; b) the slope could vary on a surface of soft sediments such as a river flood plain; c) Topographic data cannot definitively resolve

slopes lower than 0.001, and therefore cannot resolve type DE or E.

3. If slope-estimated soil type is D or softer, it will replace the soil type that is estimated based on geological data, unless it meets the condition in rule 2. This rule acknowledges the fact that the slope-based method can reasonably identify lower land depositional environments such as river banks, river flood plains, or basins, especially in areas where the topography is still rapidly evolving.

4. If the soil type is estimated as BC or C based on geology, the average of the geology-based soil type and the slope-based soil type will be used (unless the site meets the condition in rule 3).

State geologists at the Central US Earthquake Consortium (CUSEC) produced a regional Soil Site Class map (NEHRP Soil Profile Map) for the eight states in the New Madrid Seismic Zone (to be used for the Catastrophic Planning project). The base map for this work is from the *Map of Surficial Deposits and Materials in the Eastern and Central United State* (Fullerton, D.S., C.A. Bush, and J.N. Pennell, 2003, USGS I-2789). There are several shortcomings with this soil map: 1) The soil map was derived from a small scale geologic map (1:1,000,000); 2) and shows sharp contrasts in soil types at some state boundaries, such as the one between Tennessee and Alabama. This is partly due to the fact that the geological survey for each state produced its own soil maps; 3) Geologic units were pre-grouped into fewer units based on soil properties at the surface. This greatly reduced the flexibility of subdividing the surface geologic units according to Vs30-sensitive parameters such as sediment thickness and texture. Figure 2 shows a new integrated soil map and compares it to a site condition map inferred from geologic maps. As can be seen in the figure, new integrated site condition maps correlate well with borehole velocity measurement results (Williams et al 2003; 2007).

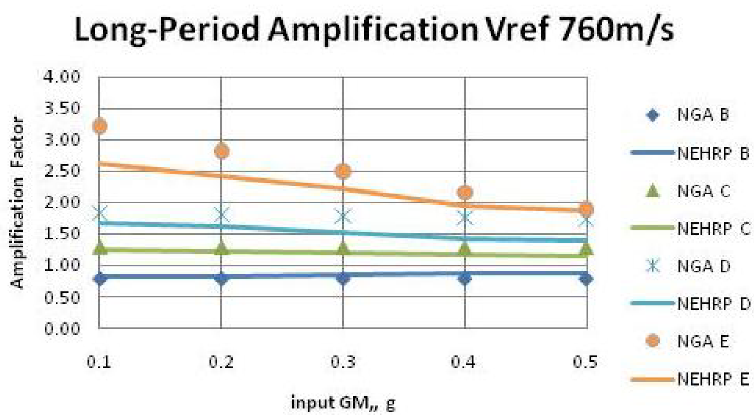


Figure 1. Comparison between the NGA and NEHRP site amplification factors (with respect to a reference engineering rock site) for long-period.

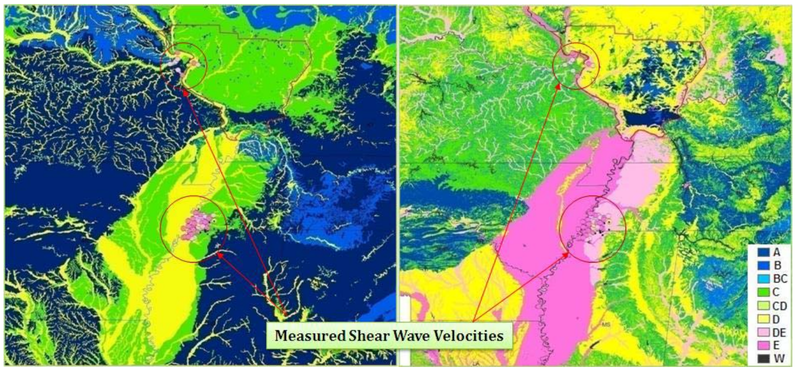
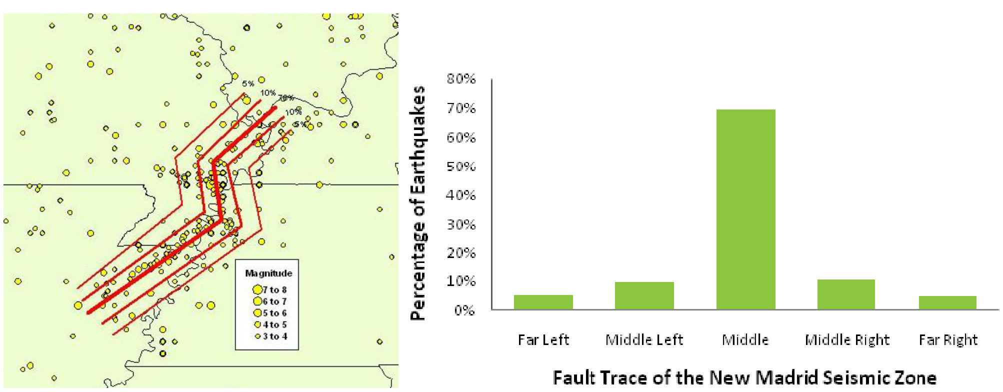


Figure 2. Site condition maps for the NMSZ region based on (left) geologic maps and (right) integrated topographic and Sates surficial geologic maps.

New Madrid Type Earthquake Scenarios

To examine both effects of site-amplification and site-condition maps in loss analysis we extract a simulated set of New Madrid type earthquake scenarios from a hundred thousand years of simulated US earthquake catalog and loss simulation algorithms, both developed at AIR. Due to the lack of detailed knowledge about the causative faults and faulting mechanisms in the central and eastern US, the seismicity of this part of the country is modeled using time-independent rates. The historical catalog contains only one very large historical event for this part of the country, in the NMSZ.

In the new USGS maps the single New Madrid "event" is now treated as three separate earthquakes. As shown in Fig. 3a the USGS proposes five different possible fault traces, each of which has a weighting factor that indicates, in catalog terms, the percentage of earthquakes occurring on that rupture. The rupture trace in the center has the highest weighting factor of 0.7, or 70%. The two traces on either side of the middle trace have weighting factors of 0.1 each, or 10%., and the two outer traces have weighting factors of 0.05, or 5%. **Error! Reference source not found.** 3b shows the percent distribution of simulated earthquakes over the five rupture areas based on the counts from the AIR stochastic catalog. The figure shows complete agreement between the AIR model and the USGS recommended weights for different rupture traces.



(a) (b)

Figure 3. a) Historical seismicity and USGS-modeled New Madrid hypothetical faults and b) percentage of earthquakes on each branch of the New Madrid Seismic Zone compatible with the USGS recommended weights for different rupture traces.

Predicted Ground Motions Used in NMSZ

In order to analyze the damage and loss for each simulated New Madrid-type earthquake, the ground motion intensity at each affected surface location must be calculated. For loss analysis, we use the weighted average of the median ground motion of the sets of attenuation equations, use by USGS for national hazard mapping of the central and eastern US, (with a reference shear-wave velocity of 760 m/s), with weighting factors defined by the USGS logic trees. The use of these different set of attenuation equations captures the epistemic uncertainty in the calculated ground motions. Peak ground acceleration and 0.3 s and 1.0s spectral acceleration (Sa) values are used to formulate the response of buildings to the earthquake ground motions. Figure 4 shows plots of 0.3s Sa versus distance for these set of attenuation equations. From this figure it can be seen that there is a large epistemic uncertainty on 0.3s Sa estimates by these attenuation equations. Similar observation also can be made on other ground motion components. The scale of the epistemic uncertainty observed here is much larger than epistemic uncertainty for the NGA equations for the western US. This is due to the fact that attenuation relations for stable regions such as the central and eastern US are usually based on a stochastic analysis of regional seismologic parameters, such as quality factor and stress drop, which have a wide range of uncertainty.

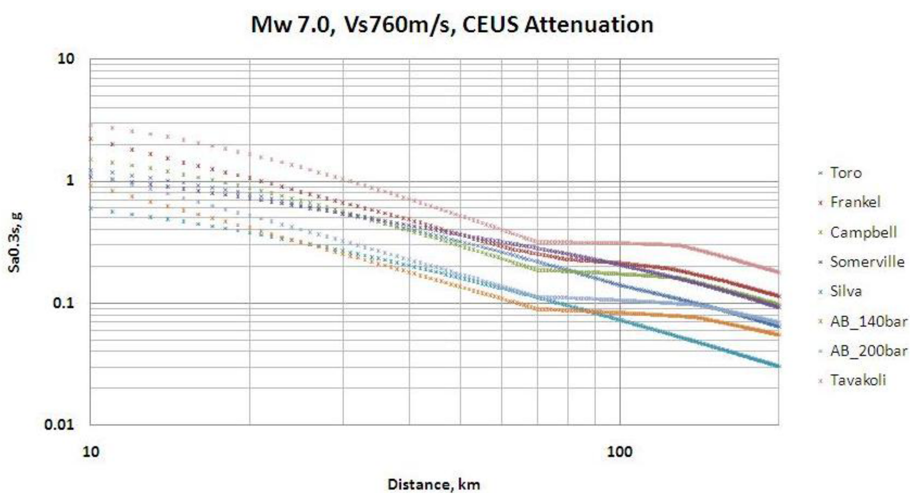


Figure 4. Most recent predicted ground motion (attenuation) relations for the central and eastern US.

Results and Discussions

The AIR industrial exposure and loss calculation algorithm was used to evaluate the regional loss variation of a New Madrid earthquake scenario using different attenuation equation. For this analysis, we used a three-segment fault scenario for the 1812 New Madrid earthquake. Figure 5 shows a histogram of the normalized relative loss change for each attenuation relation, assuming other variables such as site condition maps and site amplification procedures remain constant. As can be seen from this loss histogram, the choice of attenuation equation plays an important role in regional loss analysis. This histogram clearly indicates that an extreme variation in loss due to the selection of a particular attenuation equation can be expected to exceed two-fold the median loss value for a typical 1812 New Madrid earthquake scenario. It should be noted that when weighted average ground motion equation for the CEUS are used, the same weights that are used by USGS for national hazard mapping, the loss falls close to the median loss distribution.

Figure 6 demonstrates the footprints for 0.3s Sa for two extreme cases using attenuation equations of Tavakoli and Pezesh (Tavakoli and Pezeshk 2005) and Atkinson and Boore (Atkinson and Boore 2006). For comparison purposes, the figure also shows the footprint of the weighted average of all eight attenuation euqationss for 0.3s Sa. The figure clearly demonstrates the sensitivity of selecting different seismologic parameters, such as regional Q and stress drop on the expected regional footprint of earthquakes when the attenuation equations are not constrained by observed ground motion data, as is the case for CEUS. For example Atkinson and Boore used lower stress drop value of 140 bars in their stochastic point-source simulated model while Tavakoli & Pezeshk used a magnitude dependent variable Brune stress drop that weights a higher stress drop for large magnitudes. Tavakoli and Campbell (Campbell 2003) both used similar magnitude scaling and the assumptions on regional Q for developing hybrid attenuation equations. However, their assumptions on the Brune stress drops and source models for earthquakes in Western North America (hereafter host region) results in very different predicted ground motions in the Eastern North America (hereafter target region). Campbell used a constant stress drop value of 100 bar for all magnitudes to predict ground motions in the host region while Tavakoli used variable stress drops based on single- and double-corner point sources ranging from 60 bars to 90 bars (for DCPS) and 120 bars to 90 bars (for SCPS) to predict the host region ground motions. These assumptions affect the theoretical corrections they introduced to convert the ground motion of the host region to those of the target region.

If we look at ground motion (GM) variations at near source distances (e.g. up to 50 kilometer from fault plane) Tavakoli's equation produces higher level of GMs by a factor of 70% relative to the median of the weighted average of eight GM relations. The corresponding loss change is about 40%. However, at far distances, for example at 150 km source-site distance, Tavakoli's equation predicts about 50% higher GM than the average GM while its overall loss estimate within 150 km region is more than 200% higher. The discrepancy between the relative contribution of GM to loss estimates at close and far distances is the consequence of the nonlinear shape of the damage functions. For example by increasing 50% on level of GM, loss change increases about two-fold. Buildings at sites close to the fault experience high levels of GM and, considering the typical shape of damage functions, mostly experience damage according to the linear parts of the damage functions. Whereas, buildings at large source-site distances, experience low levels of GM and are mostly damaged according to the nonlinear parts of the damage functions (Mahdyiar et al. 2006).

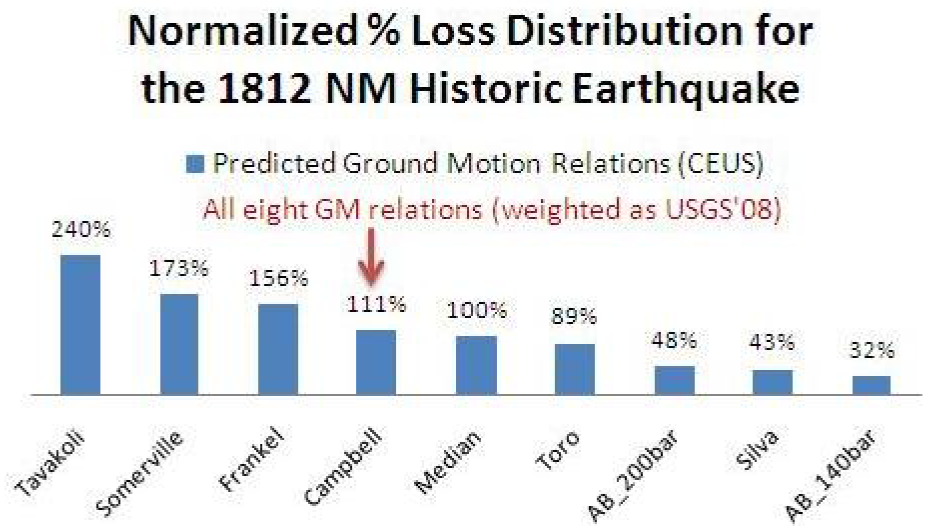
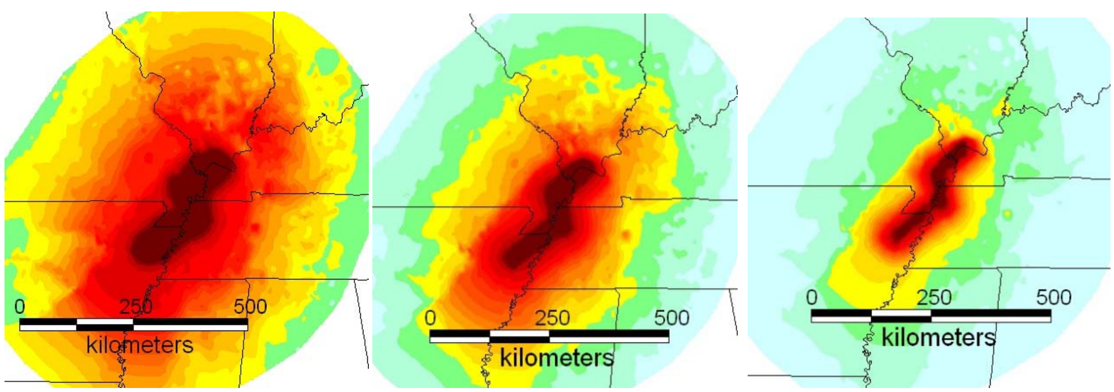


Figure 5. Loss variation for the 1812 New Madrid historic earthquake scenario due to use of individual attenuation relations developed for the central and eastern US.



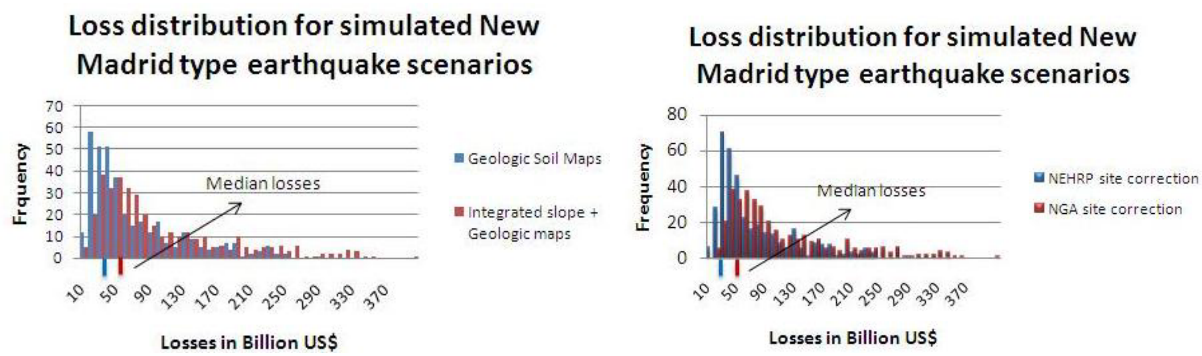
(a) (b) (c)

Figure 6. Spatial variation of spectral acceleration using different attenuation relations for the central and eastern US after correcting for site conditions, a) Tavakoli and Pezesh 2005 relationship, b) weighted average of eight attenuations, & c) Atkinson and Boore 2006 attenuation relation using a stress drop of 140 bar.

To evaluate the effects of site condition maps and different site amplification procedures on regional loss analysis in the NMSZ region, we selected a set of simulated New Madrid type earthquake scenarios from AIR's hundred-thousand year stochastic catalog. As explained earlier, loss analysis was performed using identical weighted-average ground motion relations for the CEUS and NGA site amplification procedure. This analysis was done, first for integrated site condition maps that were inferred from topographic slope information and surficial geologic maps, and then for site condition maps based only on geologic information maps.

Figure 7a shows loss distributions for the set of New Madrid type earthquake scenarios based on two different site condition databases using the NGA-related site amplification. Combining the high-resolution topographic slope with the surficial geologic information site condition map (which has been modified and verified against available borehole data) gives a more realistic picture of local site variability than the geologic maps in which geologic units in the recent geologic time period were omitted (see Fig. 2). As Fig. 2 demonstrated earlier, many site conditions in the integrated site condition map tend to have softer soil categories, which contribute to larger losses in the region. Figure 7a shows that the effects of integrating the high-resolution topographic slope with the surficial geologic information for site amplification analysis translate to about 50% increase in the median loss for this set of earthquake scenarios.

Figure 7b shows the effects of different site amplification algorithms for the same set of earthquake scenarios, using the integrated site condition map for the NMSZ region. As shown in Fig. 1, the long-period NGA site amplification for soft soil conditions (especially for weak input ground motions) shows a higher level of amplification compared to those obtained from the NEHRP site-amplification procedure. This and other differences in the site amplification effects increased the median loss value by two- fold   The differences in the NGA and NEHRP based weak motion site amplifications become especially important in regional loss estimates, considering the differences in the GM estimates at far distances by the regional attenuation equation, as was discussed earlier.



(a) (b)

Figure 7. Histogram of loss distribution for the simulated New Madrid type earthquake scenarios, a) due to the integrated vs. geologic site condition maps b) using the NGA site amplification vs. the NEHRP procedures.

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