CHARACTERIZING SEISMIC HAZARD IN THE BASIN AND RANGE PROVINCE: CASE STUDY FOR RENO, NEVADA

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ABSTRACT

Deformation rates determined for the Basin and Range province using geodetic data agree within uncertainties with scalar moment rate estimates from a 146-year earthquake catalog. This agreement suggests that the rate of historic earthquakes within the province, taken as a whole, provides a reasonable estimate for the long-term rate of seismicity. The spatial distribution of moderate earthquakes (M$\geq5$) matches the geodetic pattern of deformation: concentrated in a zone along the western boundary which widens to the north. These results show that deformation rates from space geodesy agree with earthquake recurrence rates for a large enough region (area $\Sigma$) with a long enough period of observation (T). A preliminary estimate is that the observation period is long enough when the catalog adequacy parameter $Z = T \Sigma \dot{\varepsilon}$ is greater than about 1.5 km$^2$, where $\dot{\varepsilon}$ is the mean strain rate in the region. Geological estimates of deformation rates are lower than that of geodesy or seismicity due to limited data.

We focus on a particular, small sub-region for more detailed seismic-hazard analysis. The analysis has been conducted for the Reno-Sparks urban region (population $\sim$400,000), located within the western Basin and Range, using independent geodetic, geologic, and seismological inputs. The geodetic input predicts the highest hazard in this region, followed by the historical seismicity, and the geological model which predicts the lowest hazard. Reno-Sparks are located in a fault-controlled basin that is about 13 km wide and 21 km long. Both data and synthetic modeling show that the 3D basin structure strongly influences the ground motion within the basin.

Introduction

Earthquake occurrence rates are an essential part of seismic hazard analysis. There are now three major types of data available to estimate these occurrence rates: historical seismicity, geological slip rates on active faults, and geodetic deformation rates. Each approach has

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limitations, but in principle they should all yield similar estimates when averaged over a long enough time interval. To compare the three methods, we compile the best available GPS, geology, and seismicity data in the Basin and Range province of the western United States (Pancha et al. 2005). We compare deformation rates from these three approaches for the region as a whole and within sub-domains along the highly deforming western margin. We also use these three seismicity inputs to compare and assess probabilistic seismic hazard analysis (PSHA) estimates for Reno, Nevada, located within the Basin and Range province.

The Reno-Carson region is the second most populated area in Nevada and lies in one of the most seismically active parts of the state. While recent seismicity is low, this region has experienced thirteen earthquakes of $M \geq 6$ since 1850 (DePolo et al. 1997; Pancha et al. 2005).

The Basin and Range province extends from the rigid Sierra Nevada block in the west to the Colorado Plateau in the east (Figure 1). The province is an actively deforming region of Cenozoic extension and shear, dominated by normal faulting throughout with strike-slip deformation superimposed primarily along the western margin, in a geological province called the Walker Lane (Stewart 1988). Geodetic measurements show concentrated deformation at the eastern (~50 km) and western (~200 km) margins of the Basin and Range, coinciding with regions of modern seismicity, with little deformation in between (e.g. Dixon et al. 1995; Thatcher et al. 1999; Dixon et al. 2000; Svarc et al. 2002; Bennett et al. 2003; Hammond and Thatcher 2004). Approximately 25% of the Pacific–North American relative plate motion (~12 mm/yr) is taken up by displacement and deformation in the Basin and Range province (e.g. Dokka and Travis 1990; Bennett et al. 2003). Strain rates also increase from north to south along the western boundary of the region (Bennett et al. 2003) because of narrowing of the high deformation zone from the 200 km wide northern Walker Lane to the narrow Eastern California Shear Zone (ECSZ) in the south.

1. Basin and Range Moment release rates

Figure 1 outlines the study area, within which geodesy, geology, and seismicity are used to estimate earthquake occurrence rates. The southwestern boundary of the study area runs down the crest of the rigid Sierra Nevada Range, California, and extends along the same trend to include regions in the Mojave Desert where deformation is more related to the northward motion of the Sierra Nevada Mountains than to the main motion of the San Andreas Fault.

Pancha et al (2005) model the present-day geodetic deformation field by means of a continuous, but spatially variable, strain rate field based on GPS velocity observations from all available stations in the Basin and Range. Estimates of slip rates on the most active faults characterized are obtained from input to the 1996 and 2002 USGS seismic hazard maps (Frankel et al. 1996, 2000; Haller et al. 2002). To characterize the historical seismicity, seismic moment rates have been estimated from a new 146-year catalog, complete for $M \geq 5$ (Figure 1). The catalog was compiled from 15 preexisting catalogs, supplemented by the review of 44 journal articles (<http://www.seismo.unr.edu/htdocs/BandR.html>). Strong emphasis was placed on obtaining the most appropriate moment magnitude ($M_W$) for each event (Pancha et al. 2005). The final catalog contained a total of 800 earthquakes since 1855. Of the total moment, 76% was released during 10 earthquakes of magnitude $M_W \geq 6.79$ (Table 1).
Figure 1: Map of the western United States, showing topography and earthquakes with $M \geq 4.8$ (blue circles proportional to magnitude). The study area is outlined with a bold outer polygon. The domains A-D are considered in Figure 3. The red rectangle indicates the Reno-Carson region considered in Figure 4, with the yellow star at Reno, NV.

Table 1. Ten largest events in the compiled catalog.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Hour</th>
<th>Min.</th>
<th>Lat.</th>
<th>Long.</th>
<th>$M_W$</th>
<th>Earthquake Name</th>
</tr>
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<tr>
<td>1872</td>
<td>3</td>
<td>26</td>
<td>10</td>
<td>30</td>
<td>-118.10</td>
<td>-118.10</td>
<td>7.58</td>
<td>Owens Valley</td>
</tr>
<tr>
<td>1915</td>
<td>10</td>
<td>3</td>
<td>6</td>
<td>53</td>
<td>40.50</td>
<td>-117.50</td>
<td>7.15</td>
<td>Pleasant Valley</td>
</tr>
<tr>
<td>1932</td>
<td>12</td>
<td>21</td>
<td>6</td>
<td>10</td>
<td>38.80</td>
<td>-117.98</td>
<td>7.10</td>
<td>Cedar Mountain</td>
</tr>
<tr>
<td>1954</td>
<td>8</td>
<td>24</td>
<td>5</td>
<td>51</td>
<td>39.60</td>
<td>-118.50</td>
<td>6.76</td>
<td>Stillwater</td>
</tr>
<tr>
<td>1954</td>
<td>12</td>
<td>16</td>
<td>11</td>
<td>7</td>
<td>39.20</td>
<td>-118.00</td>
<td>7.12</td>
<td>Fairview Peak</td>
</tr>
<tr>
<td>1954</td>
<td>12</td>
<td>16</td>
<td>11</td>
<td>11</td>
<td>39.67</td>
<td>-117.90</td>
<td>7.06</td>
<td>Dixie Valley</td>
</tr>
<tr>
<td>1959</td>
<td>8</td>
<td>18</td>
<td>6</td>
<td>37</td>
<td>44.88</td>
<td>-111.10</td>
<td>7.32</td>
<td>Hebgen Lake</td>
</tr>
<tr>
<td>1983</td>
<td>10</td>
<td>28</td>
<td>14</td>
<td>6</td>
<td>44.96</td>
<td>-113.90</td>
<td>6.93</td>
<td>Borah Peak</td>
</tr>
<tr>
<td>1992</td>
<td>6</td>
<td>28</td>
<td>11</td>
<td>57</td>
<td>34.20</td>
<td>-116.44</td>
<td>7.29</td>
<td>Landers</td>
</tr>
<tr>
<td>1999</td>
<td>10</td>
<td>16</td>
<td>9</td>
<td>46</td>
<td>34.59</td>
<td>-116.27</td>
<td>7.12</td>
<td>Hector Mine</td>
</tr>
</tbody>
</table>
Scalar moment rates for the Basin and Range province from the seismic, geodetic, and geological methods are compared in Figure 2. Methods used to obtain these rates are discussed in detail by Pancha et al. (2005). The moment rates based on geodesy and seismicity are intended to display the full range of uncertainties. As the geological rates are based on a single model, uncertainties are not displayed for this method. Within uncertainties, seismic and geodetic rates are in agreement. Geological rates are much lower than the seismicity and geodetic rates. This is not surprising considering the limiting paleoseismic data, which is necessarily based only on faults that have been well-characterized – a minority of all the faults in the Basin and Range. Overlap of the range determined from geodesy with seismicity suggests that the rate of historical earthquakes within the Basin and Range province, taken as a whole, provides a reasonable estimate for the future rate of seismicity.

Figure 2: Comparison of the range of moment rates determined from the historical seismicity with those determined from geodesy and geology. Both the extreme values (thin line) and the most likely bounds (thick line) on the seismicity rate are shown.

Extending previous suggestions by Smith (1976) and Ward (1998), Pancha et al. suggest that when the catalog adequacy parameter $Z = T \Sigma \dot{\epsilon}$ is greater than about 1.5 km$^2$, where $T$ is the period of observation, $\Sigma$ is the area of the region, and $\dot{\epsilon}$ is the mean strain rate in the region, the observation period in the seismicity catalog is likely to be long enough to yield a stable estimate of the rate. For smaller domain regions (A-D; Figure 1), using the same procedure, $Z \sim 0.1-0.25$, and since within these areas the historical and geodetic moment rates do not agree well, these values of $Z$ are apparently too small. The threshold is a purely empirical estimate based on this study, and needs to be refined through further research.

Pancha et al. (2005) also consider whether recent suggestions in the literature regarding the maximum magnitude of earthquakes within the Basin and Range are consistent with our results. With consideration of moment rates from historical seismicity and geodesy, modeling using the three functional forms of the Gutenberg-Richter curves of Anderson and Luco (1983) imply that there is no reason to expect an earthquake in the Great Basin with magnitude greater than $M_{\text{max}} \approx 8.2$. This is inconsistent with the suggestions of Wernicke (1995) and Kagan (1999) who through separate lines of evidence suggest $M_{\text{max}}$ of the order of 8.5-9.0. Even $M_{\text{max}} \approx 8.2$ is a large extrapolation based on hypothetical shapes that lack a sound physical basis at the upper magnitude limit, is much greater than the largest observed historical earthquake ($M_W \approx 7.6$), and is much larger than what is expected based on the size of the largest faults in the region.
Figure 3: Profiles through Domains A (a), B (b), C (c), and D (d) (Figure 1). For each domain, the top plot shows the cumulative number of earthquakes, the center plot shows the magnitude of velocity from GPS, and the bottom plot shows cumulative seismic moment of all events within the domain located at a distance greater than $X_{SW}$ from the southwestern boundary. The thin line in Figure 2(b) gives the cumulative moment with the $M_w = 7.58$ Owens Valley event removed. Right axes show normalized values.

Figures 3(a-d) point out the similarity of spatial patterns of seismic activity, seismic moment release, and geodetic deformation along profiles through domains along the western margin of the province. All profiles show a northward widening of this western deformation zone. To quantify the similarity of the profiles, we compare the distances from the south-west boundary to the point along the profile within which 75% of the total of each activity measure occurs (red lines). For profiles A, C, and D these widths agree within 20%. Across domain B
(Figure 3(b)), 75% of the earthquake numbers and the geodetic deformation occur within a zone about 90 to 113 km wide, but the moment release is concentrated by the 1872 $M_W = 7.58$ Owens Valley event, the largest event in the catalog. Removal of the 1872 event results in improved correspondence between the three curves (Figure 3(b)). The 1915 $M_W = 7.15$ Pleasant Valley (domain D) and 1872 Owens Valley (domain B) events occurred prior to when seismic instrumentation was capable of observing aftershocks. If those aftershocks could be included the distribution of earthquake numbers could change.

The spatial consistency of the distribution of small earthquakes, deformation, and moment release shown in Figure 3 is interesting, and given the shortness of the catalog duration, not necessarily expected.

2. Seismic Hazard in the Reno-Carson Metropolitan Region

A multidisciplinary approach to seismic hazard analysis is being conducted for the Reno-Carson metropolitan region (Figure 1) using independent geodetic, geological, and seismological inputs (Su et al., 2004). The area of this region is about $6 \times 10^4$ km$^2$, and the catalog adequacy parameter is only about 0.3, so the observation time is much too short to expect that the historical seismicity rate will be well constrained and consistent with geological and geodetic observations. Fault slip rates give an estimated moment rate of $0.37 \times 10^{25}$ dyne-cm/yr for this region. Moment rates from geodesy reported by Su et al. are $1.01 \times 10^{25}$ to $3.62 \times 10^{25}$ dyne-cm/yr, 3-10 times greater than the geological estimates. The range comes from various conversion methods from strain rate to moment rate (Pancha et al. 2005), and various interpretations of the geodesy data (including interpretations superceded by Pancha et al.). The moment rates implied by the model in Pancha et al are in the range from $1.11 \times 10^{25}$ to $1.79 \times 10^{25}$ dyne-cm/yr. Moment rates from seismicity are intermediate, at about $0.83-1.04 \times 10^{25}$ dyne-cm/yr. The agreement could be worse, but these results suggest that paleoseismic data is incomplete, while the duration of historical seismicity is insufficient.

To investigate the impact and uncertainty in hazard estimates, Su et al. (2004) calculated probabilistic seismic hazards using seismic source models based on the independent geodetic, geological, and seismological inputs. Hazard curves are computed with the computer code used by the USGS in their National Seismic Hazard Map generation. Geologic and seismicity inputs use the same models as for the Basin and Range as a whole, described above. Combined GPS velocities from multiple studies in the Reno-Carson area used a strain-rate field with moment rate of $2.72 \times 10^{25}$ dyne-cm/yr. This value is roughly twice the rate that comes from the latest studies reported in Pancha et al.

The hazard curves reported by Su et al. (2004) are shown in Figure 4. As expected from the relative moment rates, these results indicate the geodetic input predicts the highest hazard, historical seismicity is intermediate, and the geological estimate is lowest. The USGS model, also shown, is a hybrid of the other three, and estimates the hazard are between the seismicity and geodetic models. Since the hazard curve is approximately proportional to the earthquake occurrence rate, a first estimate of the effect results to be expected when the new model is run in the seismic hazard analysis is to shift the geodesy curve downwards by a factor of two. When that is done, it approximately coincides with the USGS model. The geodesy curve is sensitive to
other parameters as well. In the new model the distribution of strain is somewhat different from what was used by Su et al. The level of the curve is quite sensitive to the choice of b-value. Nonetheless, subject to potential revisions resulting from our ongoing work in readiness for the next generation of the national seismic hazard map, it appears that the USGS results may turn out to be reasonably similar to the hazard inferred from geodesy.

Figure 4: Plot of the seismic hazard curves we calculated in downtown Reno using different hazard models, from Su et al. (2004). The green line is calculated from seismicity. The black line is from faults, and blue line is from geodetic input. The red line is from USGS national hazard model. These results are preliminary, and the curve from geodesy is particularly likely to be revised as discussed in the text.

3. GM and Amplification within the Reno Area Basin

The cities of Reno and Sparks, Nevada, are located in a fault-controlled basin that is about 13 km wide and 21 km long. The small basin size, and the growing Advanced National Seismic System (ANSS) network within it, makes this area a very attractive location for improving basin modeling techniques. Our objective is to ascertain if 3D basin effects are significant, and identify areas of the basin more prone to high amplification. These results will supplement the PSHA studies described above, which are nominally appropriate for sites on rock.

Ground motions from an earthquake with $M_W = 4.4$ on Dec. 2, 2000, located about 60 km west of Reno, are used in an initial test case (Pancha et al. 2004). Strong motion data and 1D and 3D synthetics in the 0.2 Hz to 0.6 Hz frequency band are shown in Figure 5. 3D simulations were made by the fourth order, 3D staggered grid elastic finite-difference code E3D (Larsen and Schultz 1995). The 1D synthetic Green's function in a layered elastic solid are much simpler than either the data or the 3D synthetics, demonstrating that 3D basin effects are significant. 3D simulations do not match the phases of the observations, but they reproduce the greater amplitudes and longer durations observed within the basin than on rock sites. Spectra of the
recorded ground motion are amplified over broad bands of frequency by factors of 5 to 10 at the deepest basin sites.

Figure 5: Modeled ANSS seismograms: RF10 is located on bedrock. The colored background highlights stations within the basin, in order of increasing sediment depth. 1D and 3D synthetics are shown along with the ANSS data. The 3D finite difference synthetics match the durations of the data (as in A) and may anticipate some of the later arrivals (as in B).

**Conclusions**

Consistency of moment rates of earthquakes from geodesy with the historical seismicity estimate for the Basin and Range Province suggests that the rate of historical earthquakes in this region is the rate that should be expected in the future. We suggest that agreement of regional rates is to be expected from catalogs that have a large enough catalog adequacy parameter. Figure 3 suggests that spatial distribution of moderate-sized (M~5) earthquakes and moment
release are correlated in this region. If true, this implies that earthquake numbers and moment release could be used to constrain the geodetic deformation field, and conversely, be predicted from geodetic strain rates. Kreemer et al. (2002) have suggested this to be true on a global scale, while Masson et al. (2005) find this relation does not hold at a regional scale for Iran. We suggest that it is worthwhile to investigate conditions for the similarity of seismicity and geodesy patterns to hold on regional scales.

A challenge facing seismic-hazard assessment in the Reno area is to reconcile inconsistencies among estimates of moment release obtained from geodetical, geological, and historical seismicity. By understanding the limits of these independent deformation estimates, PSHA estimates can become more robust. The ground motions from these PSHA estimates, which are nominally appropriate for sites on rock, need also to be modified because of local basin effects, which are significant for the Reno-Sparks area despite the small basin size and depth.

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