SHAKEMAP AS A TOOL FOR UNDERSTANDING EARTHQUAKE HAZARD IN NEVADA

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ABSTRACT

ShakeMap is a mapping and display tool developed by the United States Geological Survey for displaying measured and predicted strong ground shaking. This paper reports on the implementation of ShakeMap in the real-time seismic network operations of the Nevada Seismological Laboratory at the University of Nevada Reno. The Nevada Seismological Laboratory was the first network to integrate ShakeMap into the Antelope Real-Time System, a seismic network acquisition and operations package written by Boulder Real-Time Technologies. The Advanced National Seismic System initiative has provided over 35 new strong-motion recorders for the populated regions of Nevada, so ShakeMaps can now be constructed for both the Las Vegas and Reno-Carson City areas. ShakeMaps are designed to help emergency responders decide where to direct resources in the period shortly following a damaging earthquake, to guide engineers in post-earthquake response, and as a resource for loss estimators that need to evaluate how significant the earthquake may be in economic and social costs. ShakeMaps are also useful for generating scenario earthquakes to assess potential impact of slip on known or suspected faults. We demonstrate this capability by presenting scenario earthquakes on three discrete faults identified in the USGS National Seismic Hazards Mapping Project as being the most significant for seismic hazard in Reno.

INTRODUCTION

The U. S. Geological Survey (USGS) developed ShakeMap as a tool to synthesize recorded and predicted strong ground motions and to present them in map views useful for emergency response, loss evaluation, and public information (Wald and others, 1999b). ShakeMaps are being made by regional seismic networks in California, Utah, and the Pacific Northwest, typically within minutes after M ~3.5 and larger earthquakes (http://earthquake.usgs.gov/shakemap). This paper discusses the recent implementation of a real-time ShakeMap capability at the Nevada Seismological Laboratory (NSL), and presents potential applications of ShakeMap for understanding earthquake hazards in western Nevada.
SHAKEMAP - AN OVERVIEW

A ShakeMap is initiated when automatic network software determines that an earthquake larger than some threshold magnitude has occurred in the coverage area. A data retrieval process is then initiated that predicts S-wave arrival times at strong-motion stations and retrieves peak ground motion amplitudes in a window around the predicted arrivals. On-scale velocity recordings are used in the Nevada implementation to supplement strong-motion station coverage and improve regional coverage.

How It Works

A brief description of how ShakeMap works will facilitate understanding of its map products. The core of ShakeMap, a routine called grind, determines the ground motions that are actually contoured and presented in final maps. Grind begins by using a reported earthquake magnitude and location to predict ground motions at hypothetical rock sites on a grid of pseudostations throughout the coverage area. The spacing of this prediction grid is configurable, but a spacing of 10 to 30 km is typical. Rock-site ground motions are predicted using empirical attenuation regressions. When a grid point falls near an instrumented strong-motion site, the station location is used instead. Measured peak ground motions are corrected for site conditions, if known, to give the corresponding equivalent rock ground motions at the site. Measurements are then compared to the predictions, and the entire map may be shifted upward or downward to adjust for any small systematic bias. This correction can compensate to some degree for a biased estimate of earthquake magnitude. A sanity check can be applied, where if an individual measurement strongly disagrees with the prediction, the station value can be overridden by the prediction. The grid of predicted pseudostation and measurement sites is then contoured to a surface of rock ground motions. These surfaces are then resampled at a finer grid spacing, and the finer grid is projected through a gridded map of local site conditions to produce a grid of surface ground motions. The grids of surface ground motions are then handed off to mapping utilities that contour them and develop final maps of ground motions and derivative products such as Mercalli Intensity.

Because of the nature and number of interacting parameters, results are most stable in well-instrumented areas. Significant errors in location or magnitude can lead to poor maps or in extreme cases, no maps at all. Consequently, configuration of ShakeMap for reliable automatic operation requires adjustments and regular attention, and unreviewed maps should be viewed with this in mind.

Region-specific attenuation regressions are readily accommodated by implementing them as modules meeting the necessary interface requirements. NSL uses Pankow and Pechman (2004) for large earthquakes, and a generic regression for earthquakes of M<5.3. The Pankow and Pechman (2004) relations modified relations of Spudich and others (1999), which were developed for use in extensional tectonic regimes. Other standard regressions, such as those of Boore and others (1997), are available in the standard ShakeMap distribution. As of this writing, no earthquakes of adequate magnitude near strong-motion instrumentation have occurred by which to compare Nevada accelerations to those predicted by the Pankow and Pechman (2004) regression.

Unique to Nevada: ShakeMap Integration with the Antelope Real-Time System

The University of Nevada Reno implementation of ShakeMap was the first to be integrated with the Antelope Real-Time System software. Antelope is a commercial seismic network acquisition and processing product developed by Boulder Real-Time Technologies in Boulder, Colorado (www.brtt.com). The Antelope
Real-Time System integrates modules including datalogger control, data input and archiving, automatic arrival detection, picking, association, event location, web and mail notification, and data exchange with other networks. A full suite of integrated post-processing tools is also included. Antelope strengths include a high level of software and systems engineering and a fully integrated, easy-to-use database. The database model enables uniform access to the data in both real-time and post-processing environments. Antelope comes with an extensive set of application programmer interfaces (API's), so that one can access real-time or archive databases and data from a variety of high-level programming languages including C, Perl, Tcl/Tk, Fortran, Java, and Matlab. This facilitates research and new application development. Antelope is being used by the Earthscope US Array program (www.earthscope.org) to integrate their backbone and 400 element transportable array now being deployed in the western United States. The Antelope APIs greatly facilitated ShakeMap implementation in Nevada.

The integration of ShakeMap with Antelope was implemented in Perl. Two main code pieces were developed, an event selection and queuing module and a data retrieval and formatting module.

Figure 1. Strong-motion station maps for the Reno-Carson corridor (left), and Las Vegas Valley (below). Stations shown would contribute accelerations from strong ground shaking to ShakeMaps. Instrumentation includes Kinematics Eta and K2 recorders, and Reftek RT130-ANSS units. Strong-motion instruments were obtained through a combination of Federal Emergency Management Administration and Advanced National Seismic System funding. Squares and upright triangles are presently telemetered. Inverted triangles are planned for telemetered operation by early 2005. Circles mark stations with no telemetry.
Figure 2. Mercalli Intensity ShakeMap for a scenario involving an M6.7 earthquake on the Mount Rose fault system. Rupture on this fault accounts for 54% of the 2% in 50 year hazard for Reno - by far the largest single contributor.
The event selection and queuing module takes in events generated by the automatic system, screens candidates on magnitude and location criteria, and on finding one or more suitable, begins a broader database retrieval. The data retrieval module is more extensive, as it reads waveform segments from disk, corrects them to actual ground motion amplitudes, and extracts peak ground motion parameters. It also computes derivative products such as peak velocity and pseudo-acceleration peaks at three periods. Finally it produces the formatted XML file of station parameters that ShakeMap actually uses as input. The Antelope ShakeMap utilities are available from the Antelope contributed-code repository at http://www.indiana.edu/~aug.

**Data Sources in Nevada**

The USGS Advanced National Seismic

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*Figure 3. Peak ground acceleration ShakeMap for the scenario Mount Rose earthquake. Peak accelerations in excess of 0.4 g are predicted for portions of the hanging wall above and east of the rupture area, where river sediments are generally thicker, finer, and younger than to the west (Scott and others, 2004b).*
System (ANSS) initiative has provided significant new instrumentation (figure 1) and development funding to regional seismic networks, especially in the western United States where seismic risk is concentrated. In Nevada the ANSS program has provided 35 new accelerographs and related support to enable several existing strong-motion stations to be integrated into the real-time data stream coming into NSL. Figure 1 shows that coverage is divided between the Reno-Carson City urban corridor and the Las Vegas Valley, commensurate with the hazard. Using the informal standard of having at least ten contributing stations, NSL is able to make instrumental ShakeMaps for the urban areas in which the vast majority of Nevadans live.

Strong-motion station telemetry includes a mixture of methods, including direct radio links, semi-private internet via Virtual Private Networking, IP over analog microwave, and shared public internet. NSL does not presently use dial-up

Figure 4. Peak ground velocity ShakeMap for the Mount Rose scenario rupture. Contour interval is 10 cm/sec. Peak velocities are predicted to exceed 60 cm/sec in much of the valley. The Reno-Tahoe International Airport is near the north end of the scenario rupture in the region of peak predicted velocities.
as a data retrieval method. Continuous data have the great advantage of providing data from moderate earthquakes that often do not trigger the station, but never-the-less are recorded at a good signal-to-noise level. Moderate earthquake recordings are valuable for site effect studies and as some assurance that the instrument will function well when a larger earthquake happens. Beside their uses for Nevada, northern Nevada strong-motion instruments also contribute to ShakeMaps in easternmost California, including earthquakes in the Truckee-Tahoe area.

**SHAKEMAP AS A PLANNING AND PREDICTION TOOL**

Figure 5. Pseudo-acceleration maps for (a) 0.3 s, (b) 1.0 s, and (c) 3.0 s periods for a M6.7 scenario earthquake on the Mount Rose fault in western Nevada. Pseudo-acceleration provides an assessment of damage potential for structures of various heights. In this case accelerations are predicted to exceed 1.1 g locally at 3.3 Hz.
The forward prediction facilities that enable ShakeMap to estimate ground-shaking at pseudo-stations for an actual event make it useful as a tool for evaluating the effects of scenario earthquakes. Figure 2 illustrates a scenario intensity map involving a "characteristic" rupture of the Mount Rose fault, a range-bounding, east-dipping normal fault that extends from the northern Carson Valley to near downtown Reno. The fault geometry, likely magnitude, and length were taken from the USGS National Seismic Hazards Mapping Project database. ShakeMap in automatic mode uses a point source at the earthquake hypocenter, but with analyst input, can use a finite-length source such as the one shown. The map-view width of the fault reflects the horizontal extent of the dip of the fault. Thus a vertical fault would be displayed as a line. Ground motions are estimated from the least distance to the surface trace of the fault.

Figure 2 shows that the scenario Mount Rose characteristic event could produce Intensity VIII shaking throughout the Reno and north Carson areas. The Instrumental Mercalli Intensities are determined from a regression against peak ground acceleration and peak ground velocity values as described in Wald and others (1999a).
Amplification effects are predicted throughout the valley areas, especially in the hanging-wall region in and east of Reno. At least light damage can be predicted for the majority of the region shown. Figure 3 shows predicted peak ground accelerations for the Mount Rose fault scenario event. Horizontal peak accelerations are predicted to reach over 40% of gravity for much of the hanging-wall region of the rupture - in this case the most populated portion of the valley. Figure 4 shows the corresponding ground velocities, which are predicted to locally exceed 70 cm/sec. Ground motions of this magnitude pose a serious hazard to life and property. 

Figure 7. Scenario characteristic rupture of the North Peavine fault. The scenario assumes a rupture length of 10 km, and a moment magnitude of 6.2. Ramelli and others (2004) recently excavated the North Peavine fault and found Holocene ground ruptures with offsets consistent with the scenario magnitude. Accelerations in Reno could exceed 0.20 g for much of the downtown region for this scenario rupture.

Figure 8. Scenario Spanish Springs fault rupture assuming a rupture length of 18 km and a scenario magnitude of 6.6. This fault is a minor contributor to hazard in downtown Reno, but runs through one of the fastest growing regions of northern Nevada. Peak accelerations associated with this scenario reach 0.4 g near the fault.

Figure 3 shows predicted peak ground accelerations for the Mount Rose fault scenario event. Horizontal peak accelerations are predicted to reach over 40% of gravity for much of the hanging-wall region of the rupture - in this case the most populated portion of the valley. Figure 4 shows the corresponding ground velocities, which are predicted to locally exceed 70 cm/sec. Ground motions of this magnitude pose a serious hazard to life and property. dePolo and others (1997)
developed a ground-shaking scenario for the Reno area based on a similar earthquake, and showed that it would present a significant hazard, especially to the city's unreinforced masonry buildings. Since the majority of the region's emergency responders live in the region that could see damaging levels of shaking, preparation for such an event should consider potential difficulties in mounting an emergency response.

While not shown here, the ShakeMap program also generates files formatted for input into HAZUS. When ground shaking such as in figure 3 is overlain on coverages of building density and fragility, reasonable estimates of the scope of damage and cost can be developed. While the integration is still in work at UNR, similar connections of ShakeMap and HAZUS in California are exercised routinely by the California Office of Emergency Services. In a related vein, GIS tools have been developed for California users to allow individual stakeholders such as power companies to integrate structural fragilities in real-time; these tools will eventually be available from regional seismic networks that produce ShakeMaps. The application, called ShakeCast, is designed as a client to be run by users that pulls in ShakeMaps from a central server in a format useful for overlay and rapid damage assessment.

ShakeMap also supports quick-look engineering assessments of possible damage. Figure 5 shows pseudo-acceleration spectra from the M6.7 Mount Rose fault scenario for three free periods. Pseudo-acceleration estimates used in making ShakeMaps are calculated from ground motion regression relations such as Pankow and Pechmann (2004) or Boore and others (1997). Physically, the pseudo-acceleration time series is the convolution of a one-degree-of-freedom harmonic oscillator with an input acceleration. The pseudo-accelerations thus provide a quick-look assessment of the demand in multi-story structures with commensurate free periods. In this example at 3.0 seconds, pseudo-acceleration spectra are less than 20% g, but reach to over 110% g at 0.3 seconds. The latter period is relevant to much of the mid-rise construction in Reno.

**ShakeMap in Seismic-Hazard Analysis**

The above examples consider the seismic potential of a single fault. Seismic-hazard analysis methodologies, however, require that all faults capable of contributing to the hazard be included in the analysis. The USGS National Seismic Hazards Mapping Project provides the capability to do probabilistic seismic hazard deaggregations for specific points. To illustrate how ShakeMap might contribute to the seismic-hazard assessment process, we deaggregated the hazard (figure 6) for a point just west of downtown Reno. Three faults contribute more than ~1% to the 2% in 50 years (2475 year return period) hazard: the Mount Rose fault zone, the North Peavine Mountain fault, and the Spanish Springs Valley fault. By far the largest contributor (54% of the total) comes from the Mount Rose fault zone. Within the present understanding of relative fault activity, the Mount Rose fault rupture scenario is the most severe likely event in the long-term future for the Reno-Carson City urban corridor.

Earthquakes on each fault were run as scenario events assuming characteristic magnitudes in ShakeMap (figures 3, 7, 8). ShakeMaps provide a visual context of the respective hazards that is not readily apparent from the deaggregated hazard plots. Figures 7 and 8 from, respectively, the North Peavine Mountain and Spanish Springs faults, are greater hazards for communities north and northeast of Reno, but still contribute predicted accelerations near downtown Reno of about 0.25 g. While not changing the hazard, per se, ShakeMaps do allow the hazard to be better understood by engineers and stakeholders.

Scenario evaluations of shaking for seismic-hazard analysis highlight the need for more detailed
site characterization in urban valleys. Probabilities of ground motion and predicted amplifications presently depend on limited field estimates based on gravity and local seismic investigations. Some progress in this area is being made (Scott and others, 2004a, 2004b), but much work remains to characterize basin response with any real confidence.

**Conclusion**

ShakeMap has become an integral part of the NSL real-time seismic network operations. Strong-motion station coverage realized through ANSS funding and support will constrain estimates of strong shaking in the urbanized areas of Nevada where seismic risk is greatest. Real-time telemetry of acceleration data allows recording of smaller earthquakes that are no hazard to people but are useful for characterization of site amplification and instrument sensitivity. Integration around Antelope data acquisition and analysis software means that data are available from a database in a uniform and easily accessed manner.

The ShakeMap scenario capability is useful as a tool for visualizing seismic hazard from known or hypothesized faults. When applied to known faults, scenario shaking maps facilitate understanding of and planning for what could happen should such an earthquake actually occur. When applied to hypothesized faults, the social consequences can be assessed, and the value of further study evaluated. In both cases, interacting with ShakeMaps can develop familiarity and confidence in the mapping products should a strong earthquake hit in Nevada.

**References**


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