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INTRAPLATE SEISMIC SOURCES AND WAVE PROPAGATION: A CRITICAL COMPARISON

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Abstract

We studied the excitation, propagation, and site effects in the Kachchh basin of India by using ground-motion recordings from a temporary seismograph network deployed to study aftershocks of the Mw 7.6 Bhuj earthquake of 26 January 2001. The Kachchh basin has been proposed as a useful analog region for studying hazard in other earthquake-prone but slowly deforming regions, such as the central United States. The earthquakes we studied ranged in size from about M 2 to M 5.2, and travel paths ranged from a few kilometers to about a hundred kilometers. There was a broad range of focal depths among the aftershocks, so the data were divided into two overlapping subsets to test the sensitivity of the derived propagation and source parameters to focal depth. Parameters we constrained include the source excitation terms (related to stress drop), a frequency-dependent attenuation operator, a geometric spreading function, and an operator to account for site effects. Our results indicate that seismic-wave attenuation in Kachchh crust is very low, similar to other continental intraplate areas such as central and eastern North America. We also estimated seismic moments and stress drops for the earthquakes by fitting single-corner-frequency source-model spectra to the observed spectra, corrected for propagation by using our derived parameters. Stress drops were found to scale with seismic moment and to be rather high overall. By using a stochastic point-source model to estimate mainshock ground motions, we found that the distance decay of expected peak ground motions, assuming a stress drop of 15-20 MPa, compare well with the scant observations for the Bhuj earthquake. Ground-motion predictions for Kachchh, based on Bhuj aftershock data, support the idea that the region may have similar hazard to proposed analog areas in North America.

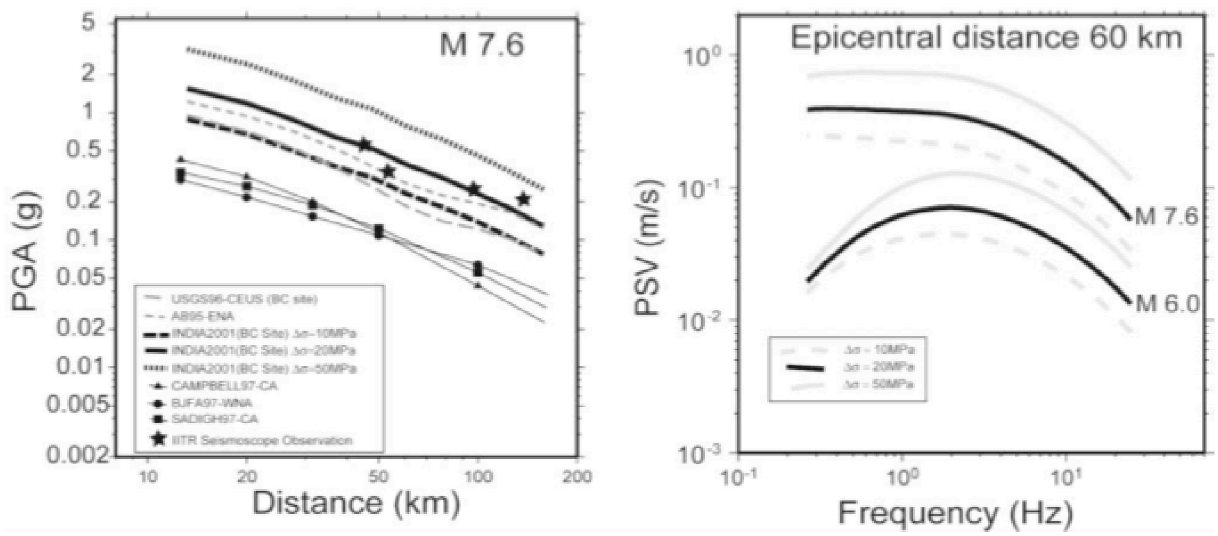

Figure 1. Ground motion predictions. The left panel compares predicted values of PGA as a function of distance for an Mw 7.6 earthquake, based on RVT synthetics. The calculations employ parameters derived by several different studies for several different regions. The three curves for India 2001 are based on the parameters we present in this study, assuming three different values of stress drop (from lower to higher curve: 15, 20, and 50 MPa). The USGS96-CEUS curve was derived for the central United States by Frankel et al. (1996), and the AB95-ENA curve was derived for all of eastern North America by Atkinson and Boore (1997). The three lower curves are estimates,

using either western-U.S.- or California-derived parameters. Stars indicate the estimated PGA values from seismoscope recordings of the mainshock from Cramer and Kumar (2003). The right panel shows predicted spectra of pseudo-spectral velocity for Mw 7.6 and and Mw 6.0 earthquakes in Bhuj at a distance of 60 km on the basis of the parameters we derive in this study. Three different curves for each size of earthquake reflect the same three different choices of stress drop, as in the right panel.

Several sources of uncertainty about the predicted ground motions in Figure 1 must be understood to preface a discussion of possible mainshock ground motions of the Bhuj mainshock. First, we computed a range of predictions over several possible values of the stress drop of the mainshock, because the dynamic stress drop that presumably controls peak ground motions is not known. Second, for comparing different regional attenuation models, we referred all predictions to a uniform site class (NEHRP BC), yet we do not claim that this is appropriate for the Bhuj mesoseismal region. Third, we caution that the models shown in Figure 1 are basically point-source models, and we expect that the assumptions of a point source breaks down at distances closer than about a rupture dimension (in the case of Bhuj, ~50 km; Bodin and Horton, 2004). This is because ground motions in the near field are sensitive to details of the rupture process (e.g., Archuleta and Hartzell, 1981).

One of the questions motivating our study was to what extent could the Bhuj earthquake sources and seismic-wave propagation in the Kachchh region be regarded as an analog of seismic hazard in other seismically active continental-plate-interior regions. The table below compares results of our analysis of Bhuj aftershocks with the same types of analysis performed for other areas. The table also contains comparable estimates of crustal propagation by using other techniques in India and in the central and eastern United States.

Region	Reference	Q_0	{eta}	K0 (sec)	Distance Range (km)
Kachchh Shallow	This study	790	0.22	0.01	0-100
Kachchh Deep	This study	790	0.35	0.01	20-100
New Madrid Seismic Zone	Samiezadé-Yazd et al. (1996)	900	0.30	N/A	0-500
Central Europe	Malagnini et al. (2000b)	400	0.42	0.05	40-600
W. Alps	Morasca et al. (unpublished manuscript)	310	0.2	0.015	
NE Italy	Malagnini et al. (2002)	260	0.55	0.045	0-200
Apennines	Malagnini et al. (2000a)	130	0.1	0.00	0-300
Umbria-Marche	Malagnini and Herrmann (2000)	130	0.1	0.04	0-40
Southern California	Raoof et al. (1999)	180	0.45	N/A	15-500
Pacific Northwest	Samiezadé-Yazd et al. (1996)	160	0.64	0.04	0-150
Southern Great Basin	Samiezadé-Yazd et al. (1996)	230	0.6	N/A	10-500
Utah	Jeon (2000)	150	0.65	0.045	10-500
Erzincan, Turkey	Akinci et al. (2001)	40	0.45	0.02	0-50
Estimates of Seismic-Wave-Propagation Parameters in India and Central and Eastern North America from Other Studies					
Himalayan Arc	Singh et al. (2003)	508	0.48		
Eastern U.S.	Atkinson and Boore (1995)	680	0.36		
Central and Eastern U.S.	Frankel (1996)	680	0.36		

The attenuation characteristics of Kachchh that we present clearly separate it from tectonically active regions of California, Turkey, and Italy. Q_0 values in these active regions range between 100 and 300. Our estimate of $Q_0 = 790$ for Kachchh, however, means that seismic-wave amplitudes decay much more slowly with distance in Kachchh than in plate-boundary regions. The location with ground-motion attenuation most similar to Kachchh is the New Madrid seismic zone in the central United States, with a Q_0 of 900. Central Europe seems to lie between the actively deforming regions and the seismically active craton areas of Kachchh and New Madrid. At the same time the frequency dependence, as parameterized by the exponent {eta} in equation (4), is generally smaller in Kachchh and in New Madrid than in other areas (excluding the Apennines). Thus differences in Q between the continental-plate-boundary and continental-plate-interior regions that have been studied with this method are (although still large) smaller at higher frequencies than at lower frequencies.

For India, we are aware of only a few relevant observations for comparison. Singh et al. (1999) calculate a Q(f) = 580 f0.48 for northern India, based on analysis of ground-motion recordings at distances in general greater than 100 km from moderate-sized earthquakes in the Himalayan fore-land. Singh et al. (2003) also suggest a possible direct relationship between stress-drop and source depth. Cramer and Kumar (2003) do not explicitly develop an attenuation relationship for Indian crust but rather compare several seismoscope recordings of the Bhuj mainshock with attenuation models from North America.

Figure 1 shows RVT-generated ground-motion predictions for moderate and large earthquakes based on our observations. The predicted decay of peak ground acceleration (PGA) with distance from an Mw 7.6 earthquake clearly classes Bhuj with ground motions predicted for central or eastern North America rather than with the tectonically active western United States. This supports the idea that the Bhuj earthquake provides a model for ground motions from future large eastern North America earthquakes.

Given these caveats, we can discuss these predictions with respect to observations for Bhuj, both instrumental (Cramer and Kumar, 2003) and intensity (Hough et al., 2002), and other predictions as well (Singh et al., 2003). The only instrumental records of which we are aware within the distance range we covered are seismoscope recordings at four sites (at most) within our predicted distance range; these values are also shown in Figure 1 and are consistent with our predictions for an M 7.6 earthquake with a stress drop of 15-20 MPa. The conversion of the seismoscope observations to PGA has significant uncertainties (Cramer and Kumar, 2003), so we do not want to over-interpret this agreement, but it is a comfort that there is not wide divergence! Singh et al. (2003) use the crustal attenuation derived by Singh et al. (1999) and the stress-drop estimates based on analysis of sparse ground-motion recordings of only a handful of moderate to large earthquakes in the Indian shield. They use finite-source stochastic (RVT) models to predict ground motions from the Bhuj mainshock. In particular, because the predictions of Singh et al. (2003) account for source finiteness, they tend to be smaller than ours at very small distances (for example, a PGA of ~0.8-0.9 g for $\Delta\sigma$ = 20 MPa at a distance of 20 km, compared with our ~1.0-1.1 g). However, they are also significantly smaller at greater distance (0.1 g at 100 km, compared with 0.2-0.25 g), presumably due to differences in propagation models. The intensity of ground motions in the region, based on damage and observer descriptions (Hough et al., 2002), is also broadly consistent with the mainshock ground motions we estimate for $\Delta\sigma$ = 15-20 MPa), based on aftershock recordings. In particular, the widespread liquefaction, out to distances exceeding 100 km (e.g., Tuttle et al., in press), suggests very high levels of ground motion at these distances.

What can be learned about absolute site effects on ground motions, with no geotechnical information available, in a very poorly instrumented region? In addition, can reliable source spectra be computed at a temporary deployment? These challenges motivated our continuation study of aftershocks of the 2001 Mw 7.6 Bhuj earthquake, in western India, where we decouple the ambiguity between absolute source radiation and site effects by first computing robust estimates of coda-derived moment-rate spectra of about 200 aftershocks in each of two depth ranges. Crustal attenuation and spreading relationships, based on the same data used here, were determined in the earlier study.

Using our new estimates of source spectra, and our understanding of regional wave propagation, for direct S waves we isolate the absolute site terms for the stations of the temporary deployment. Absolute site terms for each station were determined in an average sense for the three components of the ground motion via an L1-norm minimization. Results for each site were averaged over wide ranges of azimuths and incidence angles.

The Bhuj deployment is characterized by a variable shallow geology, mostly of soft sedimentary units. Vertical site terms in the region were observed to be almost featureless (i.e., flat), with amplifications slightly <1.0 within wide frequency ranges. As a result, the horizontal-to-vertical (H/V) spectral ratios observed at the deployment mimic the behavior of the corresponding absolute horizontal site terms, and they generally overpredict them. This differs significantly from results for sedimentary rock sites (limestone, dolomite) obtained by Malagnini et al. (2004) in northeastern Italy, where the H/V spectral ratios had little in common with the absolute horizontal site terms.

Spectral ratios between the vector sum of the computed horizontal site terms for the temporary deployment with respect to the same quantity computed at the hardest rock station available, BAC1, are seriously biased by its non-flat, nonunitary site response. This indicates that, occasionally, the actual behavior of a rock outcrop may be far from that of an ideal, reference site (Steidl et al., 1996).

Contact Information and Data Availability
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Educational Impact of Project
Funding from this award was used to partially support the thesis work of one Ph.D. student, Andrea Raphael. In addition, the award provided support and educational experiences for several undergraduate students.

Bibliography of Publications Resulting from Project
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