Development of an Earthquake Hazard Map for Maharashtra

As part of the overall rebuilding project, the Government of Maharashtra (GOM) supported development of an earthquake hazard map specifically for the state. Up to this point, all the states in India relied on the national map of earthquake hazard provided by the central government. The new map for the state of Maharashtra is derived from a modern and widely tested methodology that expresses hazard as the level of shaking expected with a given probability (McGuire, 1976; Frankel, 1995). This map introduces an innovation in taking into account the contribution to hazard from earthquakes triggered by reservoirs. The distribution of future seismicity is inferred not only from geologic data and historic seismicity, but also from the distribution of reservoirs. Because the number and location of reservoirs changes over time, the seismicity and the hazard are also time-dependent variables.

The proximity of the catastrophic Killari earthquake to a reservoir and the subsequent process of developing a new hazard map have spurred state officials to consider the role of human activities in triggering earthquakes. Koyna Dam is also in Maharashtra and is associated with a magnitude Ms=6.3 earthquake in 1967. This earthquake killed more than 200 people (Gupta, 1992) and is one of the largest known earthquakes anywhere that was, beyond doubt, triggered by a reservoir. The seismicity of peninsular India has increased substantially in the last 40 years. The hazard map is based on the assumption that this increase is at least partly the consequence of triggered seismicity. The state, and to a lesser extent the central government, have critical roles to play. Small earthquakes continue to be felt throughout Maharashtra, and the GOM must continually answer to the public about plans for the next disastrous earthquake. The persistent seismicity keeps the threat of another earthquake in the public's mind and provides the impetus to improve understanding of the earthquake hazard.

The 1993 Killari earthquake occurred in an area of India that had been zoned least hazardous (Zone 0) on national maps. This area, along with the rest of peninsular India, is a stable continental region (SCR). Seismicity in SCRs is generally much lower than at plate boundaries, such as along the Himalayas. But the advantage of fewer earthquakes occurring is partly offset by a poor understanding of where these earthquakes are more likely to happen. Residents of Maharashtra and of peninsular India are generally more familiar with the hazard of flooding and drought than with earthquakes. About a year prior to the September 30, 1993 mainshock, however, local villagers felt many tremors. These earthquakes included a M4+ event that caused damage in Killari. Villagers were concerned enough to begin sleeping outdoors and to consider relocating the town, but they were reassured by local scientists that these small earthquakes were not signals for a possibly larger event (Seeber, et al., 1996, 1997).

Small tremors continue to be felt at various locations throughout the state, including Mumbai. After the September 1993 mainshock, the government and scientific communities realized their understanding of the earthquake hazard in this area was inadequate. The possibility that a newly built reservoir in the epicentral area, the Lower Terna Reservoir, could have triggered at least some of the smaller earthquakes before the mainshock is being considered by some scientists. As a result, the GOM has been increasingly pressured to demonstrate a better understanding of earthquakes and, more generally, of geologic hazards.

Innovative Database Factors in Seismicity Induced by Reservoirs

With the support of the World Bank, the GOM contracted with the Lamont Doherty Earth Observatory of Columbia University to prepare a new earthquake hazard map for the state. The Lamont team developed a new approach for the preparation of the hazard map, and in July 1998 unveiled drafts of these new maps at the International Workshop on Disaster Management in Mumbai.

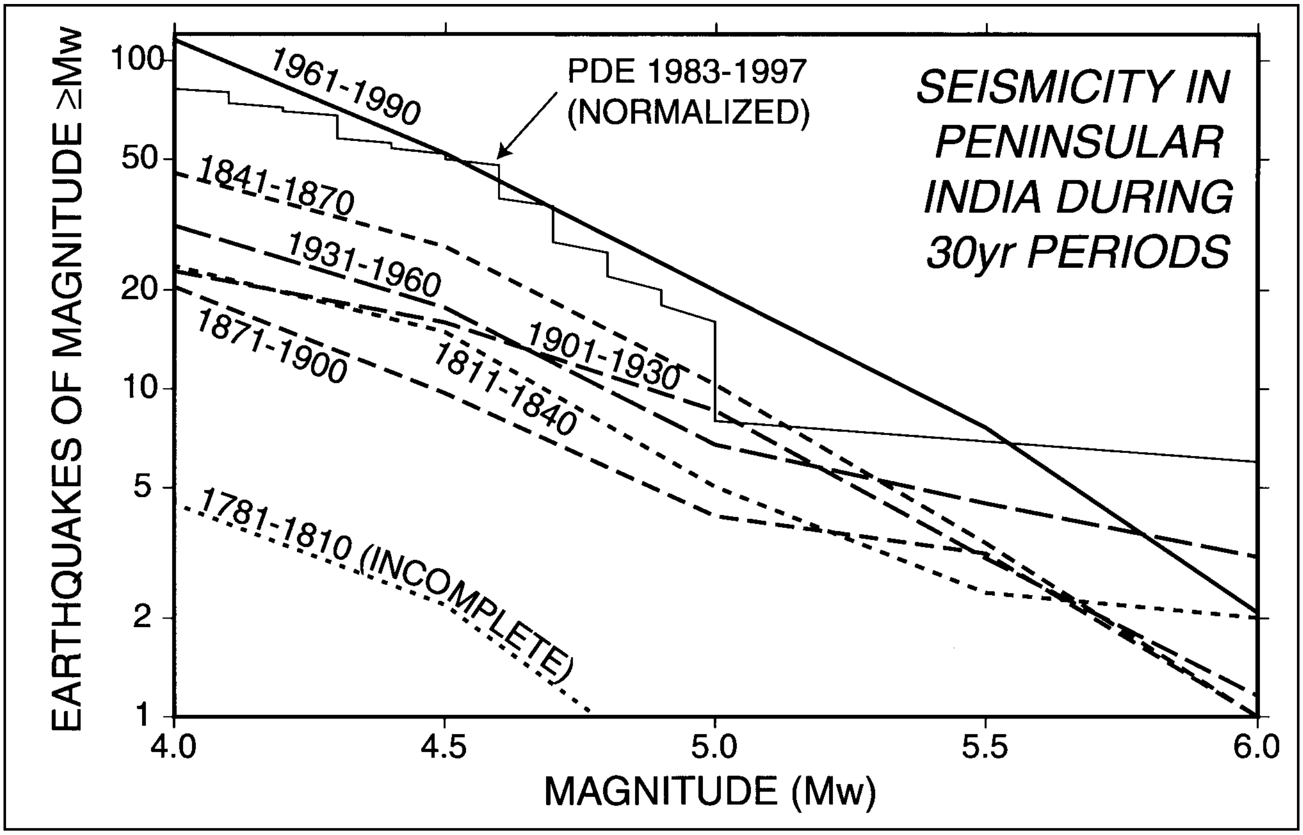

Figure 53 *Rate of known earthquakes in peninsular India through the historic period. The rate was steady up to 1960, but rose significantly afterwards.*

The main innovation introduced by the Lamont Doherty team is in the criteria to infer the distribution of future earthquake sources. To seismicity and geology, the classical databases for this task, they added water reservoirs. This new approach is designed according to general characteristics of tectonically SCRs, as well as to specific circumstances in Maharashtra. Earthquakes are rarer, but more likely to be triggered by engineering activities in SCRs than in tectonically active regions (Seeber, 1999). Very small perturbations can trigger these earthquakes. Several types of engineering activities may perturb the natural stress field sufficiently to trigger earthquakes, including water reservoirs, oil extraction, mines, quarries, waste fluid injection in deep wells, and any other operation that involves changing the pore pressure and/or the stress affecting the upper crustal layer where earthquakes nucleate (McGarr and Simpson, 1998). While the level of natural seismicity depends on the tectonic strain rate, the likelihood of triggered earthquakes depends on the proximity to failure of the natural stress level. The upper few kilometers of the crust in SCRs are characterized by stresses near failure and by rocks that are sufficiently strong to generate large and damaging earthquakes like the one in Killari. Relatively abundant triggered seismicity in SCRs, therefore, can be ascribed to the combination of high density of stored elastic energy and near-failure conditions at shallow depth, where human activities are more likely to cause significant perturbations (Seeber, 1999).

The Lamont Doherty team mapped a probable earthquake hazard in Maharashtra by taking stock of a threefold increase in the level of seismicity in peninsular India starting in about 1960 (Figure 53). They assumed that current seismicity includes a component of natural earthquakes that continue to occur at a constant rate equal to the rate of all seismicity prior to 1960. The current excess seismicity is then divided into a half associated with known reservoirs, and another half that may also be triggered, but is not assumed to be so, in the procedure. The hazard calculation, therefore, assumes three classes of sources that produce seismicity at equal overall rates, but have different spatial distributions.

The spatial distribution of expected future of sources of natural seismicity was determined from the distribution of all available data weighed according to time. This seismicity was partitioned equally among two source distributions, one based on geology and the other based on the actual spatial distribution. They were defined according to the global subdivision of intraplate continental areas into paleorifts, with maximum magnitudes M_w7.5, and stable continental regions, with maximum magnitudes M_w6.5 (Johnston et al., 1994; Frankel et al., 1996).

The level of seismicity in each zone (the “a-value”) was measured from the historic data. The magnitude distribution (the “b-value”) was obtained from the pre-1960 data and was assumed to be the same for all zones. The other half of the natural seismicity was assigned sources as observed in the historic seismicity. This seismicity was assumed to be uniform within each 0.5x0.5 degree area. The level of seismicity was measured in each area and differences between adjacent areas were smoothed. Maximum magnitudes were assigned according to the geologic zonation. The procedure used for the natural seismicity in the hazard map for Maharashtra was similar to the procedure used for hazard maps in the eastern U.S. by the USGS (Frankel et al., 1996).

Current seismicity exceeds the 1960 level by approximately three times, and of that, half was derived from sources associated with known reservoirs, according to a compilation proposed by Gupta (1992). Following Gupta, the team differentiated between major and minor reservoirs and between seismically “active” and “inactive” reservoirs, and weighed them accordingly. In this weighting scheme, major and active reservoirs are most likely to contribute seismicity, while small and inactive reservoirs are assumed to contribute no seismicity.

One third of the seismicity in the near future for peninsular India is associated with 20 reservoirs in Gupta’s list. This seismicity was assumed to stem from relatively small source areas centered at the reservoirs. Finally, the second half of the excess seismicity is probably also triggered, but the procedure treats it as if it were natural. The distribution of sources for this seismicity is determined from the distribution of post-1960 seismicity by the same approach used for pre-1960 seismicity (see above).

The Indian subcontinent is primarily a SCR. The Himalayan arc of continental convergence is one of the most prominent and active continental plate boundaries and bounds the Indian craton to the north. Many reservoirs have been impounded in both the SCR and the plate boundary part of the subcontinent. Even though the Himalayan boundary generates most of the natural seismicity and is host to the largest reservoirs, most of the reservoir-induced seismicity is found in the SCR of India (Gupta, 1992). A series of huge earthquakes along the Himalayan boundary caused widespread destruction during the first half of this century (e.g., Seeber and Armbruster, 1981), but several SCR earthquakes south of the Himalayas were also destructive. One example is the 1967 Koyna earthquake that killed more than 200 people (Gupta, 1992) and damaged a 100-meter high dam near Koyna.

Two decades later, the Koyna area is still active with damaging events. This persistent source of earthquakes is considered a classical example of seismicity triggered by a reservoir (Gupta, 1992). The impounding of a reservoir was also closely associated in time and space with the Killari earthquake, but this reservoir is relatively small and the stress change on the fault that ruptured in the main shock may seem too small to be significant. However, this sequence is representative of the large family of SCR earthquakes for which triggering by human activities is thought possible by some (Seeber et al., 1996; Seeber, 1997) and impossible by others (Rastogi, 1994).

The relative level of current triggered seismicity in the SCR of India can be assessed by comparing the location of damaging earthquakes during the 1980s listed by Rastogi (1992) with the sources of reservoir-triggered seismicity recognized by Gupta

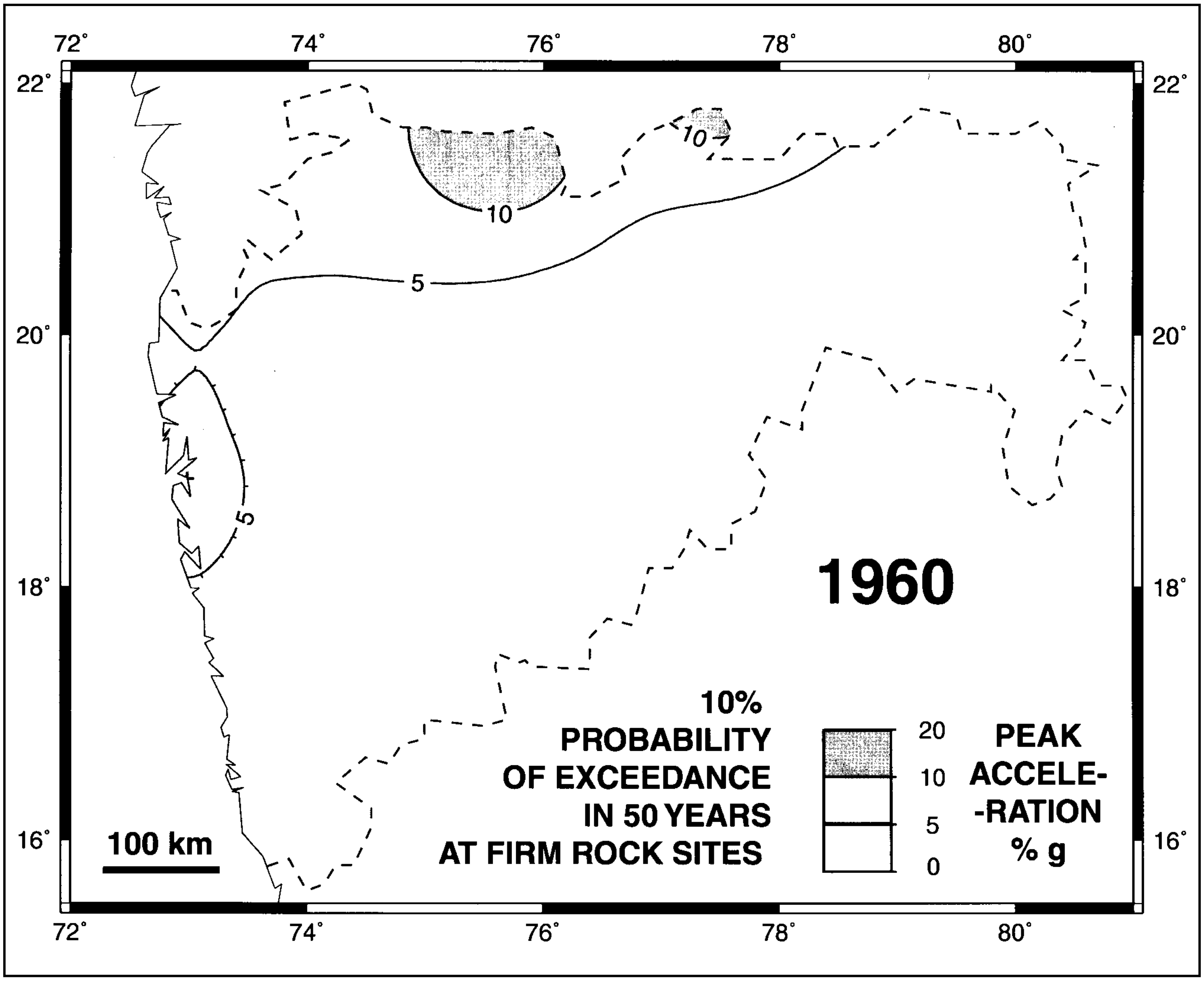

Figure 54 *Hazard map for the state of Maharashtra constructed from seismicity prior to 1960.*

(1992). Half the damaging events are from recognized sources of triggered seismicity. The ratio between triggered and natural earthquakes is obviously much higher in SCR India than along the Himalayan boundary.

The introduction of reservoirs as a potential source of triggered seismicity allows for consideration of a time-dependent component in earthquake hazard maps in SCRs. Human activities that could trigger earthquakes are localized in time and space and can be accurately monitored. Hazard maps can be updated to include the latest changes. Had the proposed methodology for mapping hazards been applied in 1992, Killari would have been viewed as one of the most likely sources of future damaging earthquakes in Maharashtra (compare Figures 54 and 55).

Implications for Mitigation

The possibility of reservoir-induced seismicity poses a challenge for the GOM, given the importance of dam building for electricity and water supply. The GOM remains unconvinced that reservoirs contrib-

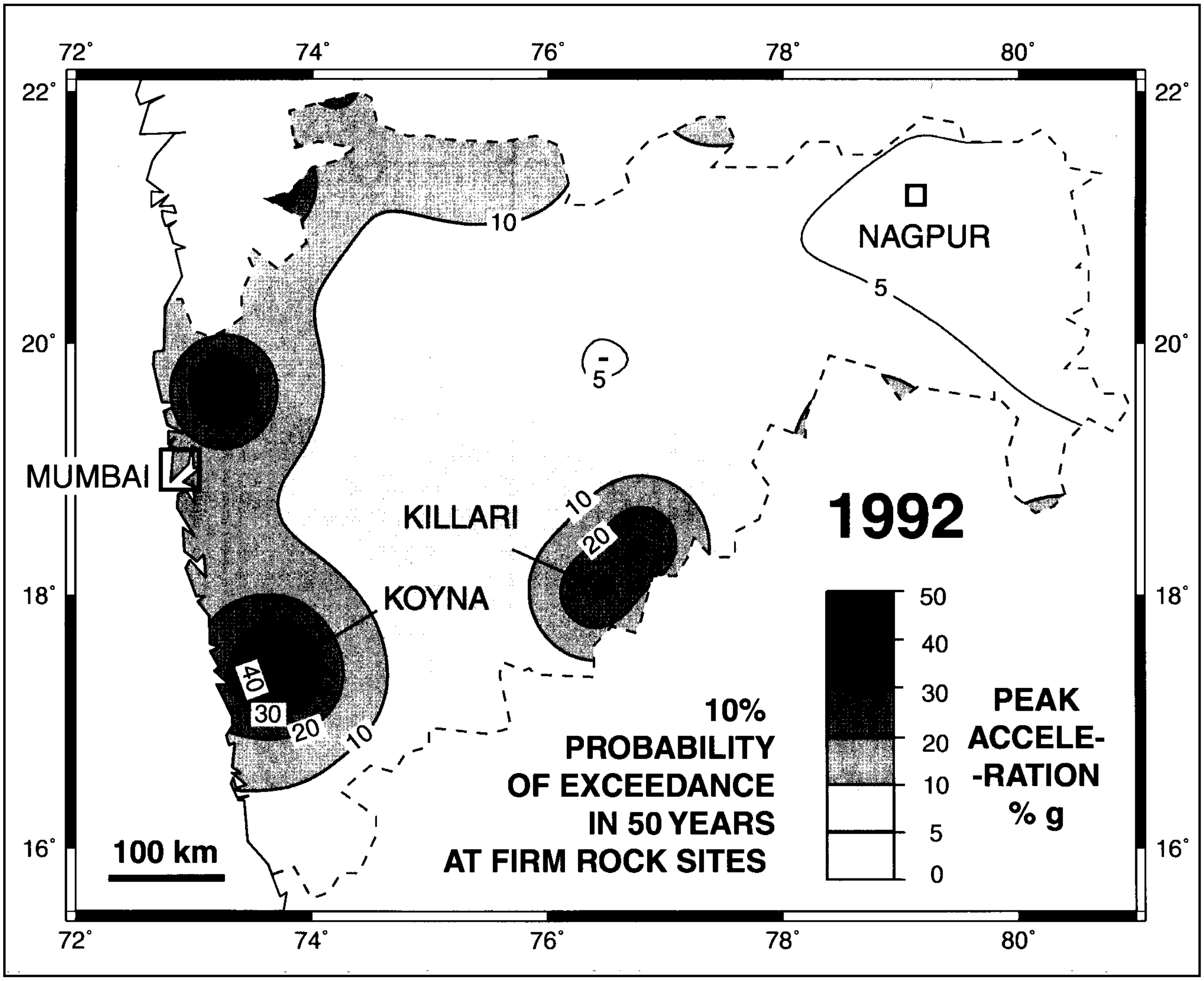

Figure 55 *Hazard map constructed from seismicity prior to 1993, based on the assumption that future seismicity is partly derived from sources associated with specific reservoirs.*

ute to the increased seismicity, but is committed to understanding and responding to the continuing seismic activity in the state.

Of particular interest to the state is combining and synthesizing all the knowledge that is available to get a better understanding of the probability of future earthquakes and to guide decisions about mitigation, such as possible revisions to the building code and changes in land use practices.

To that end, the state is in the process of creating the Earthquake Research and Mitigation Center, which will bring together the scientific and policy communities in Maharashtra to evaluate information regarding earthquake risk.

This is an important institutional development that has resulted from the MEERP project, and may ultimately prove to be a useful model for other states dealing with the particularly difficult issue of earthquake risk in stable continental regions.