The September 29, 1993, M6.4 Killari, Maharashtra Earthquake in Central India.

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Introduction

Most of the world seismicity is concentrated along the plate boundaries. However, a significant number of earthquakes, including some large and damaging ones, do occur within the plates. Our understanding of intracratonic seismogenesis and the hazard it entails is poor, in part because data are scarce.

The 1993 Killari earthquake in central peninsular India is the latest intracratonic event to be responsible for a large disaster. The positive side of this tragedy is that it will provide new insights into geologic, engineering and cultural factors that control the distribution and degree of damage, which will aid in turn the development of a more effective hazard reduction program for peninsular India and similar intrapolate environments.

This report summarizes our observations during a ten-day investigation of the mesoseismal area of the 1993 Killari earthquake. Several aspects of the earthquake were investigated, ranging from the surface rupture and related deformation to the pattern of damage to engineered and traditional structures. Finally, the rescue and reconstruction efforts following the earthquake brought out important issues that are generally relevant to earthquake hazard reduction in traditional rural settings; these are also briefly discussed.

Key Information

Location

Centered near the village of Killari, Latur district, Maharashtra State, Central India (18.2N; 76.4E)

Main Shock Source Characteristics (USGS):

00:03:53 local time, September 30, 1993 (22:25:53 GMT, September 29); $M_a = 6.4$; $M_b = 6.3$; $M_w = 6.1$; centroid depth = 5km; moment tensor solution yields an almost pure thrust with quasi-horizontal P axis striking N31° E.

Main Shock Effects

Widespread death and destruction in the districts of Latur and Osmanabad, Maharashtra state; complete destruction of stone /mud structures in about 20 villages covering an area about 15km wide centered 5 kms west of Killari. death toll about 10000; highest relative death toll 35% in the villages of Killari and Chincholi-Rebe; mesoseismal area intensity VII-IX.

Precursory Seismicity

A very active swarm between august and October 1992 (125 felt events in Killari); the largest event on October 18, 1992 (m_b=4.5) caused damage to many stone/mud buildings in Killari.

Geologic setting

Located in the ½ km-high plateau of central peninsular India, within the area covered by the Deccan traps, a sequence of late cretaceous basalt flows that cover the central-western portion of the craton; the basement below the trap rock, where the earthquake probably nucleated, is thought to consist of high grade metamorphic rocks of early Precambrian age.

Intracratonic Seismogenesis in India

Most of the well-known large and destructive earthquakes of the Indian subcontinent are related to the Himalayan and Baluchistan arcs, the topographical expression of a collosional plate boundary that marks the northern limit of the shield. Yet, intracratonic seismicity in India is well represented, both in number and in size (*Figure 1*) The 1819 Rann of Kuch earthquake (RK in *Figure 1*) is associated with a surface rupture about 100 km long and a scarp up to 10m high. It permanently altered the shape of the land surface over a very large area and was felt throughout northern India. Other intracratonic Indian earthquakes associated with loss of human life are: Bellary, Karnataka, 1843; Coimbatore, Tamil, 1900;Anjar, Gujarat, 1956 (5.5, 115 killed); Koyna, Maharashtra, 1967 (6.4, 200 killed); and Bharuch, Gujarat, 1970 (5.4, 30 killed).

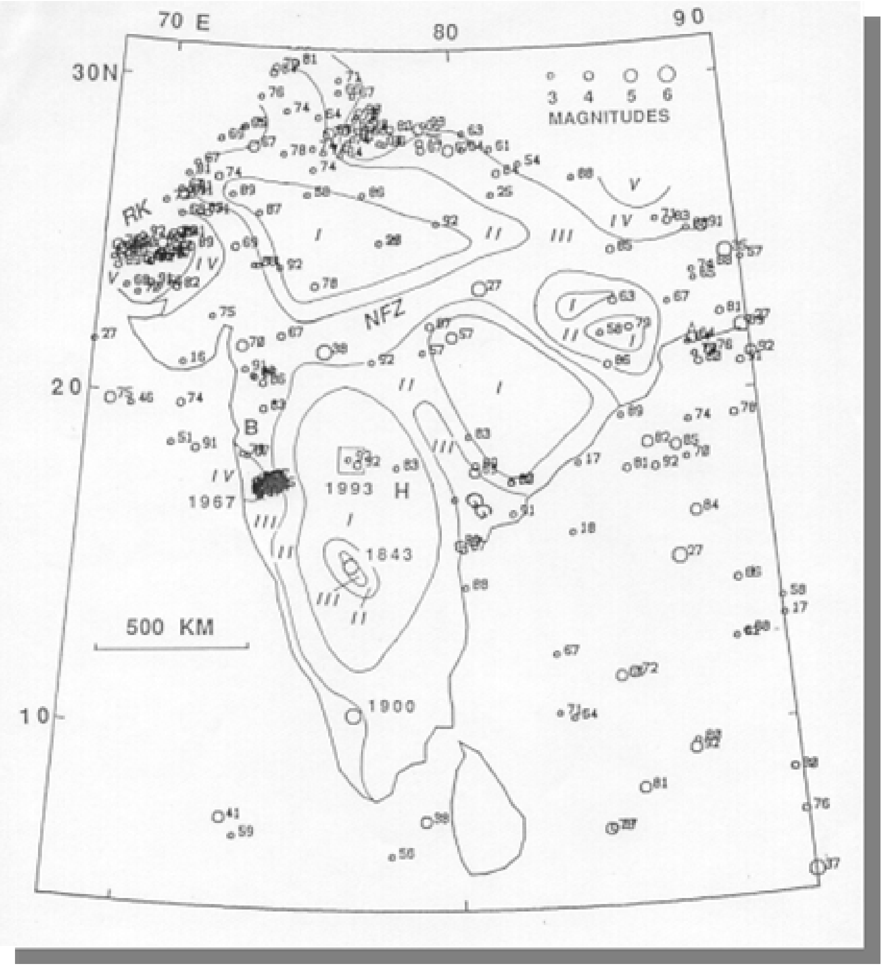

Figure 1: Seismicity (ISC catalog, 1901-1992; epicenters indicated by a circle and last two digits of the year; epicenters along the Himalayan and Baluchistan arcs omitted to avoid clutter) and earthquake hazard zonation in five categories (I to V is lowest to highest, respectively, Geological Survey of India, 1992). The 1993 Killari epicentral area is indicated by a box; the two epicenters within this area are the largest representatives of the very active precursory swarm felt in Killari in 1992. Large and destructive earthquakes near Bellary, 1843, and near Coimbatore, 1900, are also plotted (years indicated in full). 1967 is the year of the largest earthquake from the very active reservoir-induced source zone near Koyna. RK = 1819 Rann of Kuch earthquake; NFZ = Narabada fault zone; GG = Godavari Graben; B = Bombay; H = Hyderabad.

Historic seismicity suggests that casualties and damage from earthquakes with magnitude of 5.5 or grater occur relatively often in cratonic India. Thus, the M_a=6.4 Killari event is statistically consistent with the general level of seismicity in cratonic India, but is unusual in the large number of casualties. The shallow depth of rupture, which reached the surface, is probably an important factor in the dramatic surface effects of the earthquake. Other seismologic and geologic circumstances in this event do not seem exceptional and the cultural setting of the epicentral area is typical of rural peninsular India. The earthquake occurred in the middle of the night when most people were indoors and therefore particularly vulnerable. Worse scenarios, however, can be envisioned; for example, the same earthquake centered under a metropolitan area.

Surface Rupture

The 1993 Killari earthquake ruptured the surface. Three weeks after the main shock, at the time of our field investigation, discontinuous scarps were discernible along a west-northwest zone about 1km long and starting 1.5km west of the village of Killari. Where best expressed, the surface trace of the rupture is very complex; it is multibranched, double vergent, and discontinuous (*Figure 2*). Most scarps trend approximately east west; a few north-northeast trending scarps show evidence of predominant horizontal components of motion. The sense of movement is in each case consistent with their interpretation as “transform” faults connecting different branches of the system.

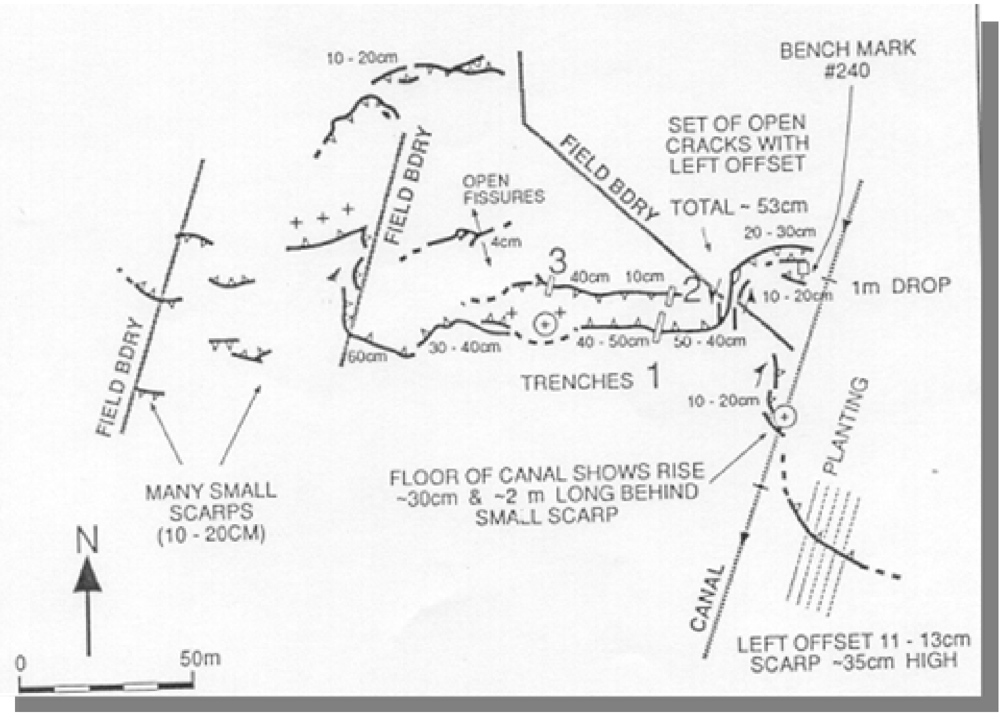

Figure 2: Portion of the surface rupture associated with the 1993 Killari earthquake. This rupture was mapped discontinuously in an east-west zone over a distance of about 1 km. Barbs indicate the uplifted side of the scarps; the approximate height of the scarps is also indicated. Plus signs indicate uplifted area, circled when localized. Note that a 'transform' fault connects a south-facing scarp in the center of the map with a north facing scarp on the right. This 'tranform' offsets a field boundary by 53 cm left laterally, which is a minimum measure of the shortening. The strike of this and other 'transforms' in this map is north-northeast, the inferred direction of shortening.

Results associated with two north-merging scarps and a south-verging scarp were exposed in three 1-1/2 m deep hand-dug trenches. Two distinct modes of faulting could be identified in the weathered basalt exposed in the trenches. In the regions where the fault could not develop along pre-existing fractures, shear was accomplished in a zone, typically 10-20 cm wide, where pre-existing and newly splintered fragments were rotated. These zones had lost cohesion (and probably density as well) and were easily identifiable on the trench walls. The evidence for motion was much more subtle where the fault followed pre-existing fractures. In these cases the movement was often confined to a very small thickness, possibly a single fracture.

Figure 3 shows fatalities relative to the total population in each village. These gruesome statistics are quite effective in delineating the mesoseismical area. In an area about 10 x 10 centered on the Tirna River, 20-30% of the people were killed. Outside this area relative casualties decrease rapidly. This mesoseismical area probably corresponds spatially to the main shock rupture; the surface area of the rupture is along the northern limit of this area.

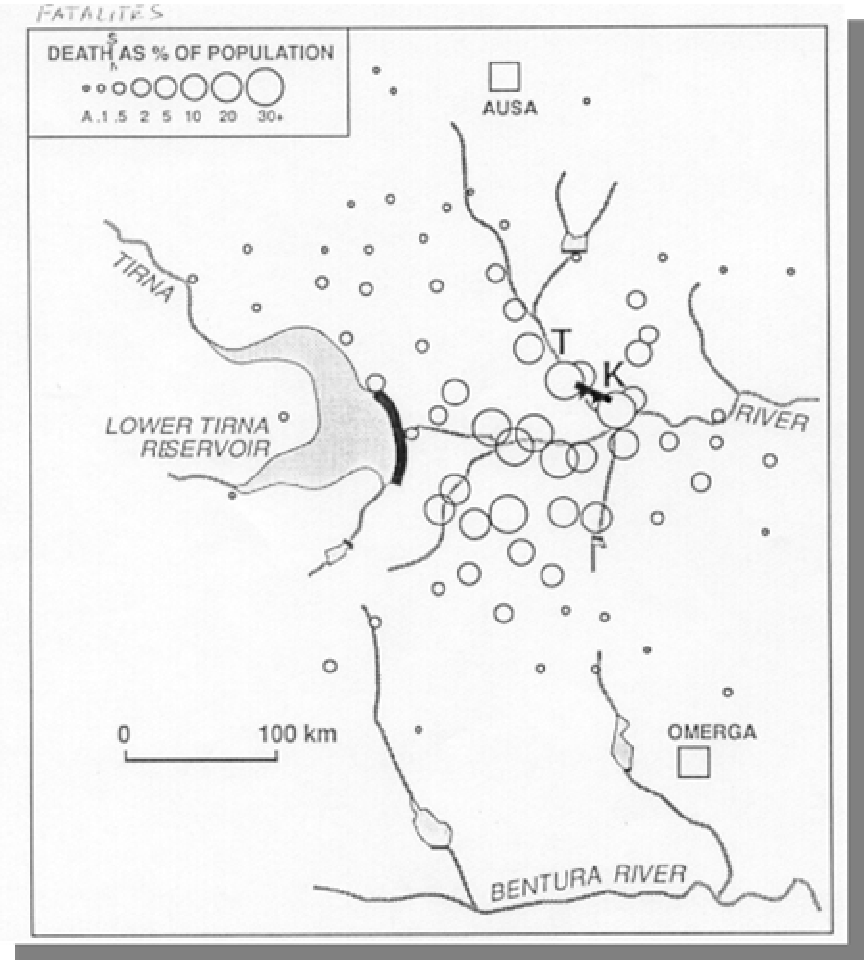

Figure 3: Number of officially recorded fatalities as percentage of population in villages in epicentral area. A surface rupture was mapped near the village of Killari (K) and inferred to extend at least to the village of Talni (T). Surface deformation features reflect a reverse fault dipping to the Southwest. Note that the zone of highest relative fatalities (20-30 %) is centered Southwest of the trace of the thrust, above the inferred rupture. Note also that this rupture is centered about 10km from the Lower Tirna Dam.

A new Fault?

Is the 1993 Killari earthquake rupture one of a sequence of ruptures that have occurred on the same fault? Except for the precursory activity in 1992, the Killari area is not known to have had prior earthquakes during the historic period, not there is evidence of Holocene ruptures or accumulated Neocene deformation in the form of prehistoric scarps or a topographic rise. No evidence of pre-1993 faulting of the late cretaceous Deccan Traps in the Killari area has yet been reported. The 1993 rupture may therefore represent a new fault, although it could have reactivated a pre-Cenozoic fault in the basement below the Traps.

Induced Seismicity?

The Killari earthquake was about 10 km from the Lower Tirna Reservoir (*Figure 3*). The maximum water depth is about 20m, which is at the low end of the range of depths of reservoirs where induced seismicity has been documented. The reservoir level was low at the time of the main shock, which is consistent with the expected negative effect of the loading by the reservoir on an underlying thrust fault. The M=6.4 1967 Koyna earthquake and a related long-term swarm is one of the best-known cases of seismicity triggered by a reservoir. Several other recent earthquakes in peninsular India appear to be located close to reservoirs. Whether the Killari earthquake was triggered by the Lower Tirna reservoir is not known, but it cannot be ruled out at this time. In any case, induces seismicity in Cratonic India may be more prevalent than generally recognized and the distribution of reservoirs may be relevant to earthquake hazard no less than the distribution of historic seismicity.

Response of Buildings

Engineered structures were relatively scarce in the affected area. A maximum intensity level of MM VII-IX could be determined by the performance of the few-constructed brick-and-mortar structures.

The collapse of traditional stone-and-mud buildings in the mesoseismal area was nearly total. The wood-plank roofs of these single-story dwellings typically are topped with a 30-60 cm thick layer of clay to provide protection from rain and heat. All such constructions behaved very poorly due to the heavy mass at the roof and the poor strength of the supporting rubble masonry walls; such houses were the main cause for the high number of casualties.

A number of dwellings in the affected villages had timber columns connected together with transverse and longitudinal beams. The roof planks in these houses were supported by the timber beams and columns rather than the rubble masonry walls. When securely anchored to the floor and to the roof beams, the posts tended to hold up the roof and prevent the inward collapse of the walls, thereby saving the inhabitants.

Some of the poorest people in the villages lived in thatch-type houses consisting of wooden vertical posts and rafters connected with coir rope ties. Roofs are thatch, and thatch panels or a series of small stocks or slit bamboo woven together form the walls. Mud-plaster provided a wall finish in some of these pictures. These houses performed extremely well with only minor cracks in the mud-plaster walls.

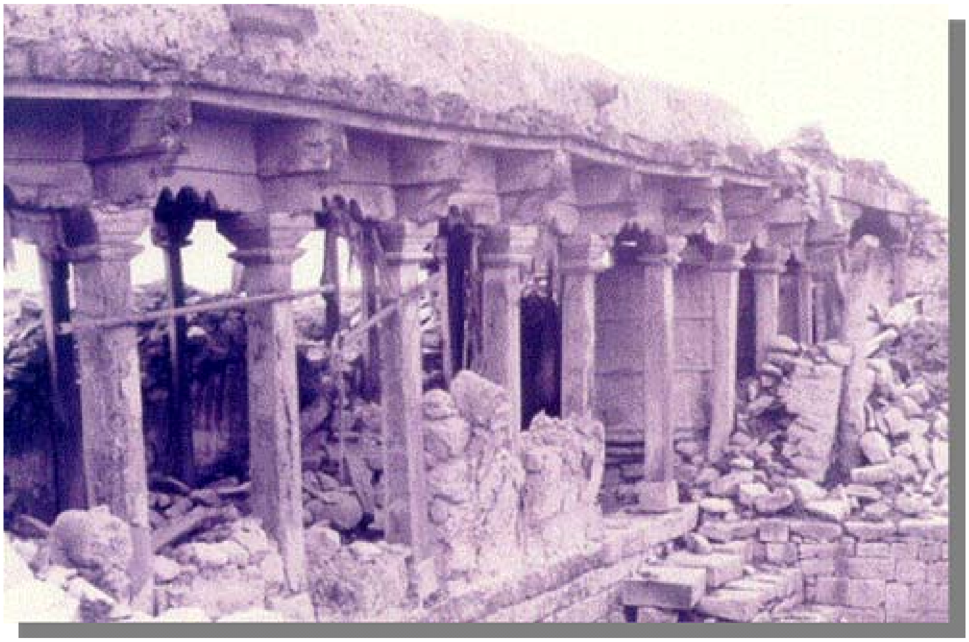

Figure 4: In some buildings, the traditional heavy clay roof was supported on a frame of wood posts and beams. In most cases, the timber columns continued to hold the roof together while the walls collapsed, generally outwards from the timber frame, saving the lives of many occupants

Some houses were made of load-bearing walls of burnt-clay bricks in cement mortar supporting either a reinforced concrete slab or a corrugated sheet roof. These suffered varying degrees of damage, but none collapsed. In a residential colony at Killari, a house supporting heavy reinforced concrete roof sustained severe wall cracks, while the adjoining one supporting a light roof of corrugated asbestos sheets sustained only hairline cracks in the walls. Surprisingly, a few brick masonry houses in the area were found to have concrete lintel bands. The

Indian building code only recommends lintel bands for seismic zones IV and V. Such houses performed very well with no damage.

A one-room 8x8 m school building in the village of Rajegaon had exterior load-bearing walls of brick masonry with cement mortar. The roof consisted of lightweight precast planks 4 m long and 12 cm thick spanning from a light steel truss at the center of the building to the masonry walls. The planks were held together at the line of the truss by steel strips tacked with an epoxy material. No diaphragm action was possible due to the lack of proper connections between the walls and the panels and the truss, and between the panels themselves. The roof panels collapsed, demonstrating, yet again, the seismic vulnerability of precast panels without adequate connections.

Figure 5: A brick masonry school building in Rajegaon collapsed. The roof of precast panels lacked adequate connections

Some of the factors that contribute to the poor performance of the traditional structures are unavoidable, given the materials available within the economic constraints. Some patterns of failure, however, point to improvements that probably could be made within these limitations. For example, stone walls tended to separate along axial planes, with the two faces collapsing in opposite directions. Large stones for cross-wall ties are difficult to procure from the native weathered basalt, but suitable substitutes should be sought out. The heavy roofs used for thermal insulation contributed heavily to destruction and casualties. Vertical wooden posts that supported some roofs saved many lives. Because timber is a scarce resource, some effective alternative should be developed.

Ironically, the poorest houses with thatched roofs and walls were often the only ones to survive unscathed.

Response of Engineered Structures

Figure 6: While most elevated water tanks performed well, this tank of Kautha collapsed straight down into its crumpled supports. Circumferential displacement of about 0.5m suggests that rotational vibration led to its collapse.

For water supply, most of the villages had an elevated water tank consisting of a reinforced concrete container supported on a concrete moment-resisting frame about 10 m high, a standard design of the public health engineering department. Tank capacities ranged from 40 kl to 200 kl. Most of these tanks survived the earthquake with little or no damage. The one tank that suffered a complete collapse came straight down, burying the remains of six supporting columns directly under the bottom dome of the tank. That, and evidence of a circumferential displacement of about 0.5 m, suggest torsional vibrations were the primary cause of the damage.

Several structures in the Lower Tirna river irrigation system were damaged. Cement slabs lining the main canal were often horizontally cracked and buckled toward the axis of the canal. Probably in response to ground in the banks tending to move downward toward the canal. The embankment of the lower Tirna dam suffered longitudinal fissuring along the crest, but spillways and gates were apparently undamaged.

Several bridges sustained minor damage. The bearings on one of the piers of a six-span overpass were damaged when the pier moved away from the abutment by about 4 to 5 cm.

Emergency Response

The affected area does not suffer from floods and was considered Aseismic. The only natural disaster known in the area is drought. Hence, the earthquake took the people and administration by surprise. It took the administration 2 to 4 days to effectively organize rescue and relief operations. What then followed appeared to be well-organized and effective. Civilian as well as military authorities cooperated in the effort. Since the reconnaissance team did not visit the affected areas of Karnataka, the discussion here is based on the response in the districts of Latur and Osmanabad only.

Of all the villages devastated by the quake, only the village of Killari had a wireless connection with the district police headquarters at Latur. Within minutes, the information about the devastation in Killari was conveyed to Latur and from there to the state headquarters at Bombay. Immediately, about 20 policemen stationed at Ausa (28 km) were rushed to Killari, followed by district level administrators (District Collector, Superintendent of Police, etc). About 50 policemen were also dispatched from Latur (42 km). Immediate search and rescue was conducted by the survivors and the limited police rescue teams. As the day progressed, information about equally severe devastation from nearby villages started reaching Killari. By early next morning (Oct. 1), the Indian army took over the task of search and rescue.

By the afternoon of the day of the earthquake, many curious onlookers had arrived in the area. This led to traffic jams and hampered the task of search and rescue. Beginning Oct. 2, entry to the affected area was controlled to allow entrance only to government personnel and members of volunteer organizations.

The task of search and rescue became extremely difficult due to the heavy rains, which immediately followed the earthquake and the enormous quantities of the rubble. In places 2-3 m of rubble has to be removed to extricate the bodies. The narrow village streets were choked by fallen rubble, which further hampered rescue operations.

Mass cremations that were held on the first two days after the earthquake were done without adequate record keeping. This led to confusion about the actual number of deaths. At one time, the newspapers were reporting up to 30000 dead. Later it was discovered that about 9000 fatalities actually occurred.

Recovery

Medical Aid: The number of injured in Maharashtra was about 15500. About 50 mobile teams of doctors were pressed into service; at least – doctor was made available at each of the affected villages. The 125 beds civil hospital at Latur had to convert the nearby Rajasthan School into a hospital ward to care for about 300 indoor patients. On the other hand, the rural medical college and hospital at Ambe Jogai, which is only 60km from Latur, had a 510-bed capacity but only had 86 patients maximum at any given time. On the whole, in a few days, there were more government and private doctors available than could be used.

Food, water, Provisions: Cooked food was provided in the affected villages during the first fortnight by large number of voluntary agencies and the army. After 15 days the community kitchens were closed. Enough rations and other provisions to last a month were provided to the people, requiring them to cook their own food.

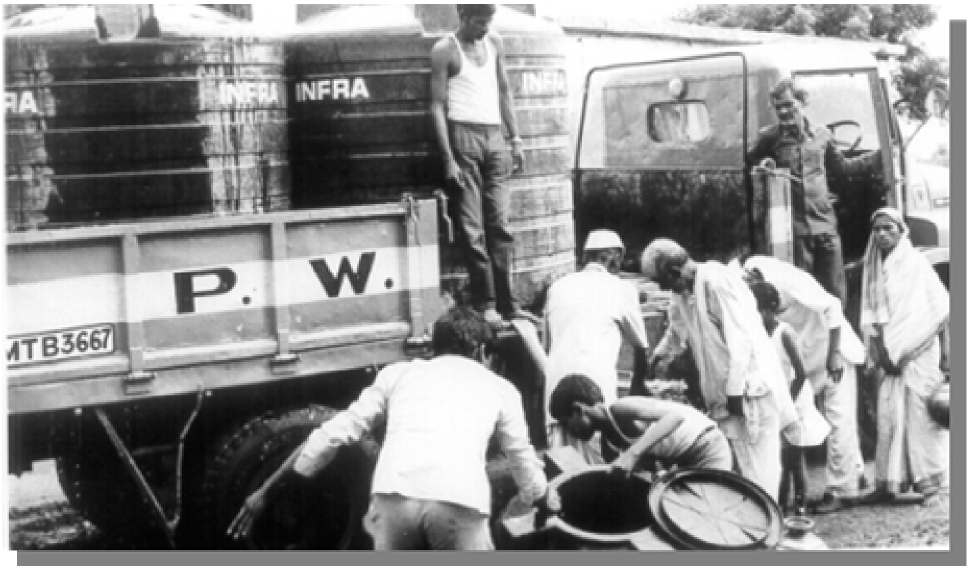

Figure 7: After the earthquake, water was trucked into the region. Generally, each village was assigned a truck requisitioned from unaffected neighbouring districts

Drinking water was supplied regularly by mobile water carrying units, generally one for each village, requisitioned from the neighbouring districts. Water storage tanks (5000 l), donated by UNICEF/CARE, were being used for storing water in villages. In some villages, these tanks were lying upside down while quite a few were still resting in storage yards, indicating excess availability of the tanks. A total of 227 water hand pumps in the earthquake-affected areas of the Latur district were found operative.

Simultaneously, a program for installation of tube wells in the temporary settlements was initiated. In the Latur district, 83 deep-bore wells at the temporary shelter sites needed to be dug. 47 of these had been completed by Oct 19. For this task, eleven deep-bore rigs were mobilized from the other districts of Maharashtra.

Figure 8: Distribution of relief supplies was systematized through the issuance of 'family cards' and 'individual cards' to residents of the affected areas

The government and several voluntary agencies distributed clothes and household goods like utensils, stoves, storage cans, and provisions for daily needs, either through the administration or directly. A team consisting of an officer from the administration, an officer from the police, and a local head of the village issued every affected family a “family card” and every affected person an “individual card” to record and regulate the goods distributed as a relief aid. This, to a large extent, systematized the relief distribution. Spontaneous offers of aid were received from within the country and outside. Bombay International Airport made special arrangements to receive and clear planeloads of clothes, medicine, tents and food. Within about 3 weeks, the relief material available was somewhat in excess of the needs.

Figure 9: Temporary shelters of galvanised iron sheet were rapidly erected. Each provides shelter for five families

Temporary Shelter: Immediate shelter was provided by erecting temporary galvanized iron sheet houses. Each shelter consisted of 5 units of about 15 m^2 areas each; each affected family was offered one such unit. Common toilets and hand operated bore wells were provided. Some families chose to take tents and tin sheets instead and made their own shelters.

Resettlement and Housing: A large number of villages which were totally destroyed are being relocated to places not far away. Most of the sites for relocation have been identified.

Every affected family will be provided a housing unit with a covered area of 20, 40 or 60 m^2 (depending on the needs of the family) and an open area of 15 to 45 m^2 for animal shelters and future extensions. The government will bear the cost of only 20 m^2 of the housing per family. For houses with a larger constructed area, the remaining cost will be treated as a long-term low-interest loan payable on terms similar to those for World Bank loans.

Transportation

The primary mode of transport in the area is bus. The affected area has no rail network. The nearest railway stations are at Latur and Sholapur. The nearest airports are at Hyderabad and Aurangabad. Since there was no damage to roads or bridges, the bus services were not adversely affected, even though the lanes inside the villages were blocked with the rubble of collapsed houses. Most of the villages have been temporarily shifted to new locations to the main roads.

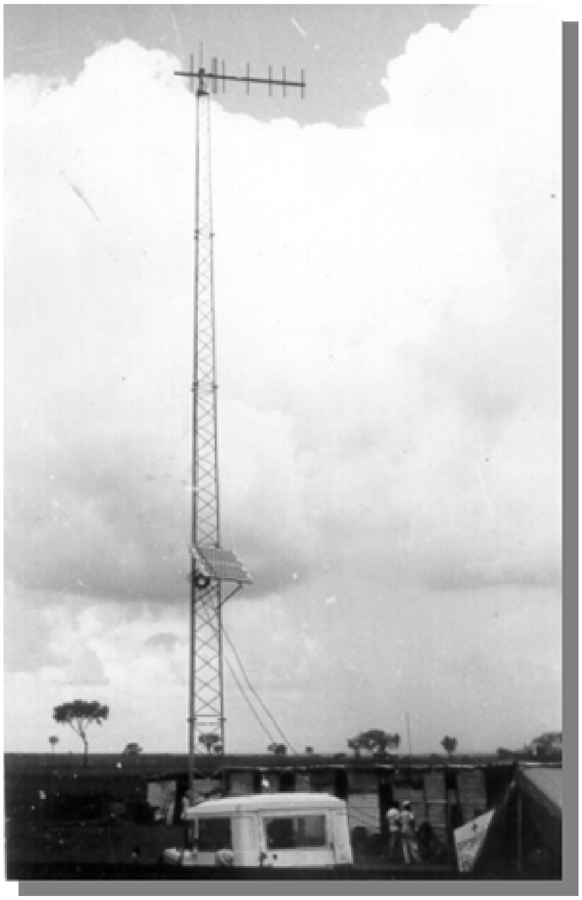

Figure 10: Solar Powered Satellite Communication Towers were brought in to connect the larger villages to the outside world

Communications

An excellent communication network was set up after the earthquake. Initially, a number of HAM sets were called in. Later, solar powered satellite communication towers were installed in most of the bigger villages. The district collectors were provided with a hotline to the chief secretary at Bombay. This enabled the state to take immediate action on the requests from the local administrations for men and materials.

Economic activity

The economy of the area is primarily farm based with very few industries. The only major industry in the region was a sugar factory at Killari Pati, which had closed quite some time prior to the earthquake. It suffered no apparent damage and was being used as a relief distribution center.

A large chicken farm about 15km north of the epicentral area reported that egg production fell substantially after the quake. Production was still down about 7% three weeks later. (No fluctuations in egg laying preceded the quake.)

Though it is harvesting season for the Kharif crop and the sowing season the Rabi crop, the farmers have been unable to resume regular farming activity. This is due to incessant rains, unexpected at this time of year, and the non-availability of farm laborers, who do not seem concerned about daily wages due to the availability of free relief provisions. There are reports that the government may have to help in harvesting by bringing in labor from outside the area.

Earthquake Hazard Maps and the 1993 Killari Earthquake

Earthquake hazard maps for intracratonic areas are usually based on the distribution of historic seismicity. Geologic features which are thought to be preferentially associated with large earthquakes are also a factor in modern maps because the relatively short historic period is likely to give an incomplete picture of the possible earthquake sources. The hazard zonation in *Figure 1* conforms to this state-of-art approach and is based on both seismicity and geology. For example, the earthquakes in 1843 and 1900 as well as the Narabada fault zone (NFZ) and the Godavari Graben (GG) clearly affects the perceived distribution of the hazard. Should we then be surprised that the 1993 Killari epicenter is in an area with the lowest perceived hazard? Probably not, since many similar intracratonic earthquake sequences worldwide have occurred in area with little prior known seismicity and without previously recognized seismogenic structures. This, the 1993 Killari earthquake sequence is a dramatic remainder that criteria currently used to map hazards in intracratonic areas may not be satisfactory.

Is there ground for optimism?

The Killari earthquake offers new opportunities to improve the resolution of hazard maps and the effectiveness of hazard-reduction measures. A current controversy in India is concerned with whether reconstruction in the Killari area should follow improved traditional techniques, or whether it should introduce entirely new techniques and materials. The latter position seems appropriate if the hazard is localized where the earthquake has occurred already. If, on the other hand, the next damaging earthquake is more likely to occur at another “surprising” location, then the emphasis in the reconstruction should be technologies that can be widely applied. The resolution on this controversy will have widespread repercussions on the future seismic safety of non-engineered construction worldwide.

Acknowledgements

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