J. Ind. Geophys. Union (October 2007)
Vol.11, No.4, pp.175-180

Demarcation of liquefaction zones by Bouguer Gravity and Electrical Resistivity method

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ABSTRACT
Of all the disasters the mankind faces, perhaps those due to the earthquakes are most severe. The danger to life and other damages are enormous due to soil liquefaction triggered by earthquakes. Prediction and demarcation of liquefaction zones in high seismicity regions will be a great help to mitigate hazards. In the present communication, it has been demonstrated for 1934 Bihar-Nepal and 1993 Killari earthquakes that Bouguer and electrical resistivity methods (only for Killari) can be of help to delineate the liquefaction zones. With this backdrop, we believe that in conjunction with soil and sediment characteristics indicating high susceptibility to liquefaction, gravity and resistivity anomalies will provide vital information to predict and identify the liquefaction zones.

INTRODUCTION

The present note makes an attempt to identify liquefaction-prone zones by geophysical methods. The first case-study chosen for this purpose is the Indo-Gangetic plains in north Bihar, the liquefaction zones or the "slump belt" of which were delineated by Dunn, Auden & Ghosh (1939) for the 1934 Bihar-Nepal earthquake (8.0) in their pioneering work. The second case is from the recent 1993 Killari earthquake (6.1), Maharashtra where there was a small patch of slumped zone along river Tirana. The gravity and electrical resistivity methods were employed for these investigations.

The term "liquefaction" is a mechanical process by which the saturated sandy soil is rendered cohesion-less due to repeated shaking by the vibrations of the earthquake waves. Without the clay component that binds the soil, the solid-state soil behaves like liquid swallowing men, animals and their properties over a very large area. The "slump zone" or the zones of liquefaction need not be confined only to the epicentral region. These zones may be induced several hundred kilometers away from the epicenter. For example, the 1897 Shillong earthquake (8.1) triggered "slump belt" in the Gangetic plains in North Bihar, near Madubani and Motihari about 650 km away from the epicenter. The 1995 Kobe earthquake (6.9) in central Japan created liquefaction zones in southern islands close to 200 km away.

The recent earthquakes in Latur (6.1, 1993) and Bhuj (7.7, 2001) have induced "slumped zones". While this zone was not far from the epicentral regions in case of Latur, the Bhuj earthquake, it may be recalled, brought greater damage to buildings and other constructions in Ahmedabad, about 250 km away from epicenter. The newly reclaimed land in Ahmedabad easily gave way to the earthquake waves.

1934 BIHAR-NEPAL EARTHQUAKE

Next, we consider in some detail the liquefaction zones and the seismicity mapped and reported by Dunn, Auden & Ghosh. (1939). Figure 1 is the location map showing the "slump zones" in Bihar due to 1934 Bihar-Nepal earthquake. The 1897 Shillong earthquake also created slump zones in the same region. Gupta et al., (1995) have used remote sensing technique to identify the liquefaction-prone regions in Indo-Gangetic plains.

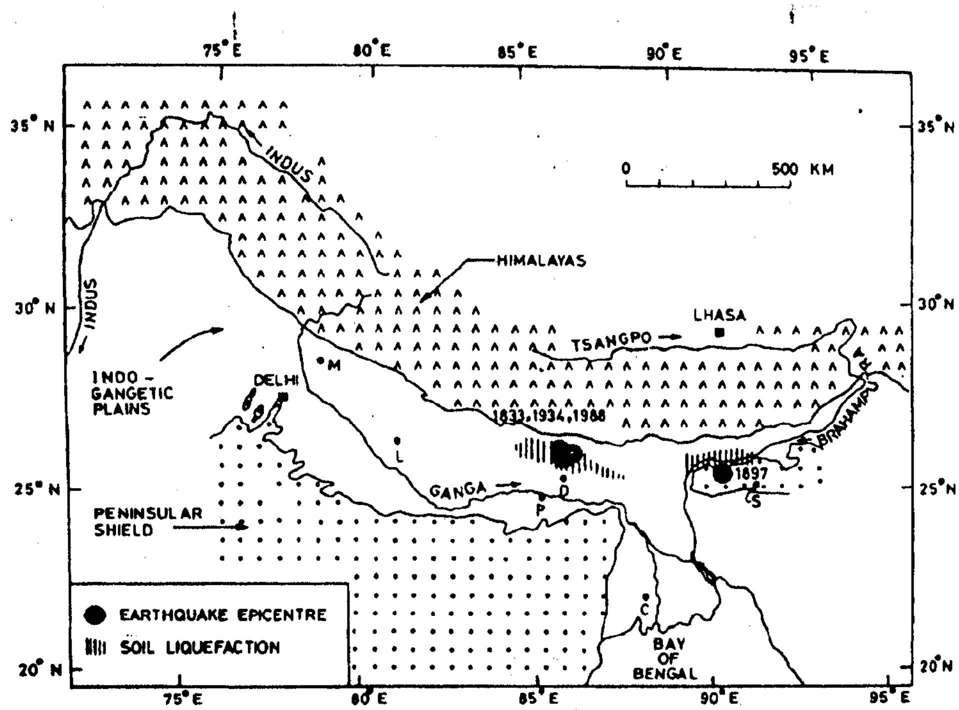

Figure 1. Location map along with slump zones in Bihar due to 1934 Bihar-Nepal earthquake (after Gupta et al., 1995). Slump zone due to 1897 Shillong earthquake is also shown. C-Calcutta, D-Darbhanga, L-Lucknow, M-Moradabad, P-Patna, S-Shillong.

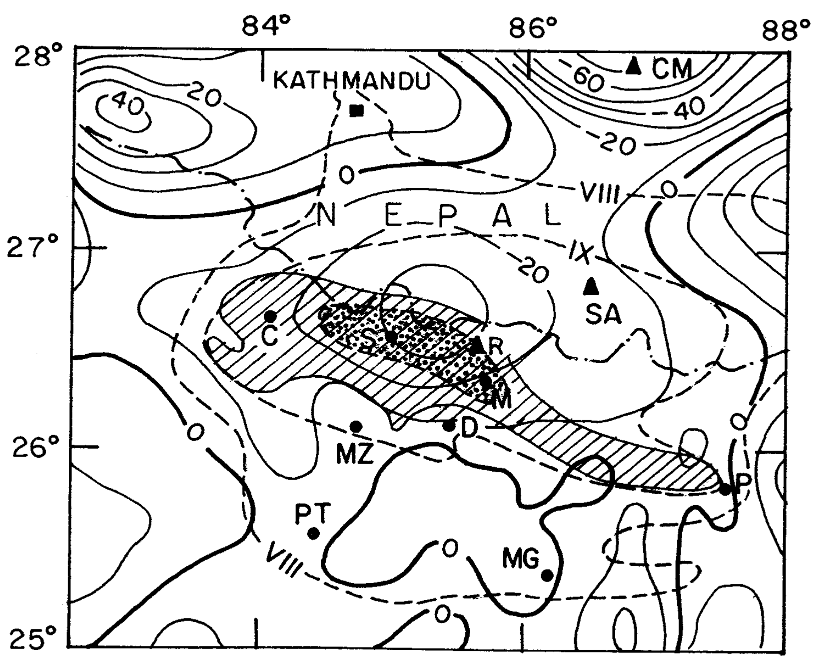

Figure 2. Residual gravity (continuous line) and isoseismal (broken line) contours along with liquefaction or slump zone (in hatches) for 1934 Bihar-Nepal earthquake. The shaded region inside the slump zone corresponds to isoseismal zone X.

Figure 2 shows (i) the epicenter of the 1934 earthquake, (ii) the isoseismal contours, (iii) the liquefaction or slump zone and (iv) the residual gravity anomaly contours covered by Latitudes: 25 and 28 N and Longitudes: 83 and 88 E. The epicenter by the earliest study (Roy 1939) is marked R, north of Madhubani (M), whereas Chen & Molnar (1977) placed it very far on the north-east corner (CM). Seeber & Armbruster (1981) had indicated yet another location (SA) for the epicenter. If the ambiguity in locating the epicenter can be such, how can one compute other parameters of the earthquake? This goes on to show how complex the earthquake processes could be.

It may, however, be noted in Figure 2 that all the three probable epicenter locations fall in regions where the residual gravity anomalies are negative. In such zones, the process of uplift is active.

The isoseismal map based on Mercalli Scale has been prepared by GSI (1939). The isoseismal X with a NW-SE trend, shown as a shaded zone, lies near Sitamarih (S) and Madhubani (M), and almost encloses the epicenter (R), estimated by Roy (1939). The other two isoseismals, IX (elliptical) and VIII (almost circular, except the region enclosing Kathmandu) cover a large region, indicating the severity of the earthquake effects.

The liquefaction zone or the "slump belt" as called by Dunn, Auden & Ghosh. (1939) has a NW-SE trend and spreads from west of Champaran (C) to Purnea (P) on the east, a distance of about 300 km. It is much wider on the western side compared to its width on the east, covering vast area of 46,000 sq km.

Figure 2 shows also the residual gravity anomalies, computed by a recent technique based on finite element concept (Mallick & Sharma 1999; Sharma, Rao & Mallick 1999; Vasanthi & Mallick 2005). It is interesting to note that the negative residual gravity

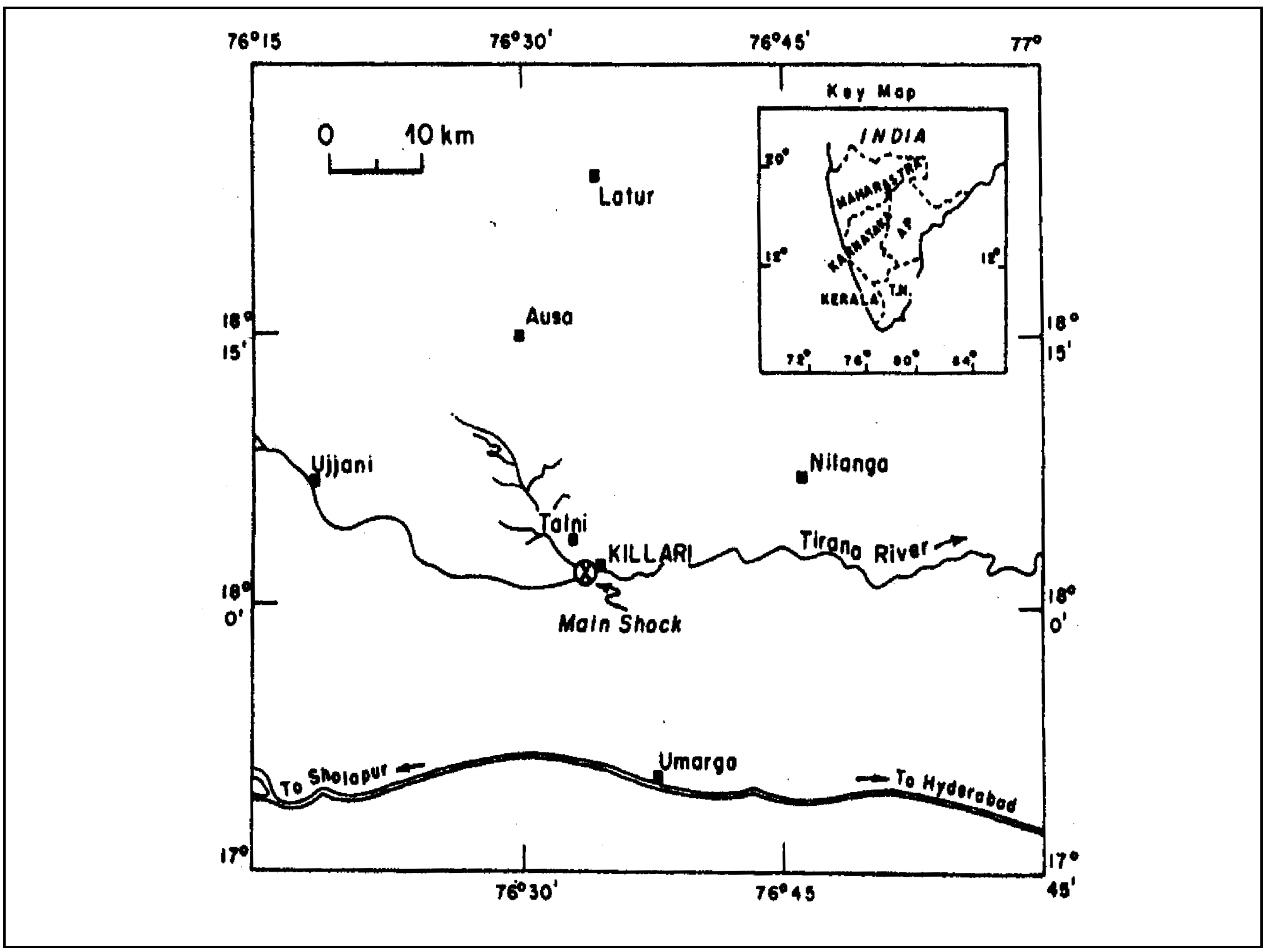

Figure 3. Location map of Killari earthquake of 30 September 1993 in Latur region, Maharastra, India (after Narayanpethkar et al., 2001).

anomalies (-40 mGal and less) cover an area which exhibits the "slump zone". This correspondence between negative gravity residual anomalies and the liquefaction zones may be of great importance, besides demarcating, in predicting zones well in advance that may yield to slumping in the earthquake zones in general, and in Indian context, such as in Bhuj, Jabalpur, Koyna, Iddukki and Latur etc in particular.

The vast sedimentary basin spreading from the west to east shows both positive and negative gravity residual anomalies. Do the negative residual gravity anomalies in certain areas have their origin mainly due to thick sedimentary rocks, or are there any other deeper processes that can play a role?

It is well known that negative residual gravity anomaly usually corresponds to the uplift of a region, for example, Fenno-Scandinavia and Swiss Alps (Lowrie 1997). If so, is it logical to think that the region covered by negative residual gravity anomalies over the entire Bihar plains may be experiencing some sort of tectonic readjustment, possibly isostatic, giving rise to uplift. The process of uplift may bring in instability, and does this process change the soil characteristics so as to facilitate the formation of slump zones? Uplift brings in expansion and thereby weakens the soil as is observed in Scandinavian region which is bouncing up after the glacial denudation. The soil expansion loosens the binding between sand and clay, thereby helps the earthquake waves to make the soil cohesionless leading to liquefaction.

1993 KILLARI EARTHQUAKE, MAHARASTRA

Next we consider the 1993 Killari earthquake (6.1) in Maharastra. The literary meaning of Killari is "lost fort", perhaps implying possible liquefaction of the soil. As per legends, animals, structures including a fort went underground following the earthquake some time in the past.

Figure 3 is the location map showing the epicenter and the slumping zone along the Tirna river embankment. The entire area is basaltic, excluding the alluvial patch along the river. Prior to this major event, there were frequent shakings between 2 August

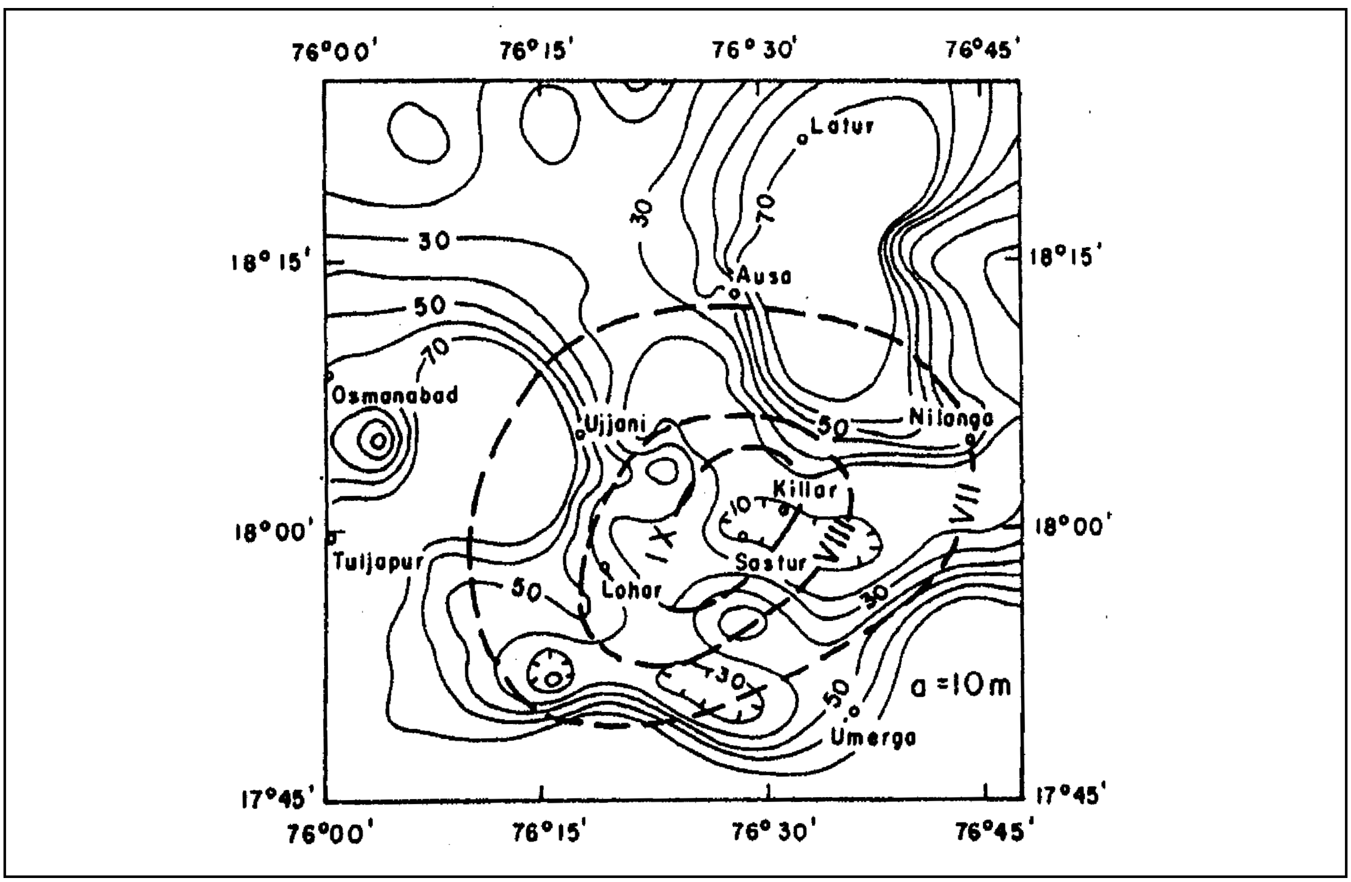

Figure 4. Isoseiemal (broken line) and electrical resistivity (continuous line) contours for Wenner electrode separation of 10m in and around Killari region. Epicentral region shows the lowest resistivity of 10ohm-m. Contour interval: 10ohm-m (after Narayanpethkar et al., 2001)

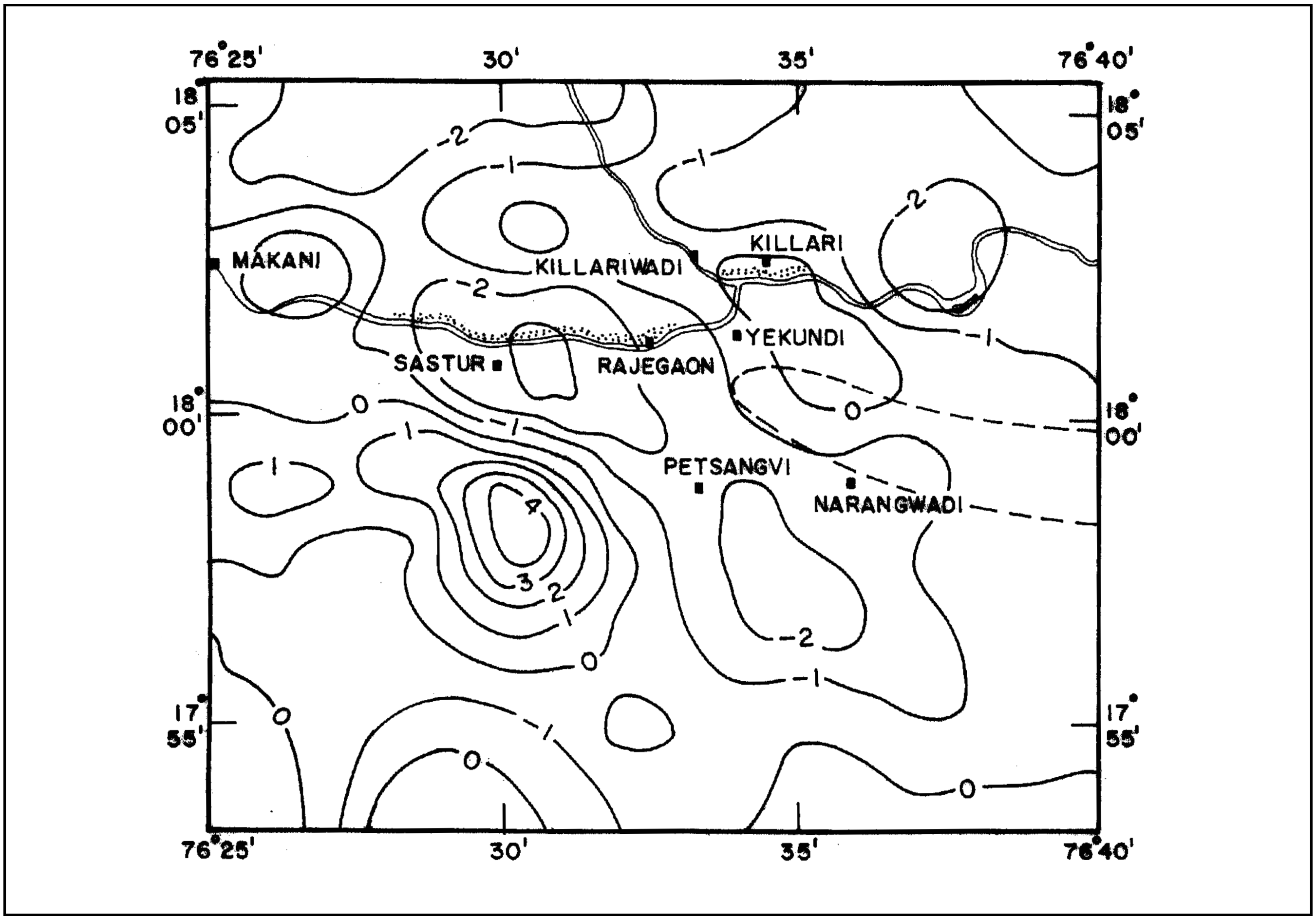

Figure 5. Residual gravity along with the liquefaction or slump zone for 1993 Killari earthquake

1992 and March 1993. During this period, the tremor on 18 October 1992 with magnitude 4 was the strongest. In the months of October and November 1992 alone, the seismological observatory at the National Geophysical Research Institute (NGRI), Hyderabad has recorded as many as nine tremors.

The electrical resistivity in Ujjani, about 25 km west of the epicenter of the Killari earthquake, recorded a sharp decay beginning from October 1992. Prior to these recent indications, the isoseismal maps, seismic zoning maps and maximum earthquake magnitude and peak horizontal ground acceleration maps of this region were prepared by NGRI. Based on this information the Latur region was classified as a high seismicity zone. The magnitude of 30 September 1993 Killari earthquake (6.1) is comparable with some other intraplate earthquakes like Tenant Creek (Australia) earthquakes of 22 January 1988 with magnitudes 6.3, 6.4 and 6.7 with in a span of 12 hr and Ungava (Canada) earthquake of 25 December 1989 with magnitude 6.3 and Koyna earthquake of 10 December 1967 with a magnitude 6.3 in India.

We had a great opportunity to have electrical resistivity data in the vicinity of September 30, 1993 Killari earthquake (6.1) in Latur district of Maharastra due to an on-going program for groundwater exploration by electrical resistivity method since 1983 till 2000 and beyond. Therefore, these resistivity sounding data became handy to bring out a correspondence between resistivity values and the seismicity, the former reflects the rock and soil conditions on one hand and the latter represents the degree of earthquake hazards.

Figure 4 shows the seismicity and electrical resistivity distribution. The isoseismal contours (broken line) with intensity IX in the central part, VIII and VII are elliptical with NE-SW trend. The electrical resistivity contour maps were prepared for various Wenner electrode separations, a=10, 25, 50, 75 and 100 m. As an example, the resistivity contour map with a=10 m is shown in Figure 4.

Here we can note two important features. First, the isoseismal contours show good correspondence with the regions of low resistivity, particularly in the central and south-west regions. Second, and more importantly, the liquefaction zone (shaded in Figure 4) close to Killari and Sastur is marked by a resistivity low.

Next, we examine the gravity residual map (Fig.5) covering the epicentral area.

Half of the area lying on the northeast side of the map shows negative residual gravity anomaly. The "slump zone" was observed in an elongated east-west tract north of Sastur, Rajegaon and near Killari, where the gravity residual is negative, as it was in the case of the liquefaction zone due to the Bihar-Nepal earthquake.

The two above examples, one historic in Bihar-Nepal border and the other, a recent one in Killari, Maharastra, gave us confidence to suggest the application of geophysical techniques, namely gravity and resistivity, to delineate zones of considerable damage in general and possible regions of slumping or liquefaction due to earthquakes in particular.

Besides delineating the liquefaction zones created by earthquakes, it is quite possible to demarcate well in advance such zones in the earthquake-prone areas. Therefore, it is strongly recommended that gravity and electrical resistivity information should be incorporated in seismic zoning mapping for different cities and high seismicity regions like Koyna, Bhuj, Jabalpur, Latur, Chamoli and other selected places in India.

ACKNOWLEDGEMENTS

We thank Vice-Chancellor, Solapur University and Dr. V.P.Dimri, Director, NGRI for their constant support throughout. Partial financial assistance was provided by CSIR.

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