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Macroseismic survey and isoseismal map of September 2011 Sikkim earthquake

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सार – 18 सितंबर 2011 को भारतीय मानक समय के अनुसार 18:11 पर गंगटोक, सिक्किम (अक्षांस–27.7° उ., देशांतर 88.2° पू.) के 68 कि. मी. उत्तर पश्चिम में जमीन के नीचे 50.0 कि. मी. से अधिक की गहराई में 6.8 परिमाण का भूकंप आया। प्रश्नावली के माध्यम से भूकंप की तीव्रता के बारे में किए गए सर्वेक्षण तथा प्रेस रिपोर्टो का इस्तेमाल समभूकंपीय मानचित्र तैयार करने के लिए किया गया और कार्य के लिए ArcGIS के भूसाँख्यिकीय विश्लेषण की सहायता ली गई है इस क्षेत्र के लिए सर्वे की गई तीव्रता (SI एस. आई.) आँकड़ा और चरम भूत्वरण (पी.जी.ए.) के बीच संबंध विकसित किया गया है

ABSTRACT. An earthquake of M: 6.8 occurred inland at 1811 hrs (IST) on 18 September, 2011, about 68 km northwest of Gangtok, Sikkim (Latitude 27.7 ° N, Longitude 88.2° E) at a deeper depth of more than 50.0 km. Intensity survey conducted through a questionnaire and press reports were used for generation of isoseismal map using geo-statistical analysis tool of ArcGIS. Relationship between Surveyed Intensity (SI) data and Peak Ground Acceleration (PGA) was developed for the region.

Key words – Intensity, Isoseismal, Earthquake, Macroseismic survey.

1. Introduction

On Sunday evening of 18th September 2011; an earthquake occurred at 1811 hrs (IST) about 68 km northwest of Gangtok, Sikkim (Latitude 27.7° N, Longitude 88.2° E) at a deeper depth of more than 50.0 km. Its epicenter was located along the boundary of Indian and Eurasian Plates beneath the mountainous region near India-Nepal border.

Two buildings of the Indo-Tibetan Border Police in the Pegong area of North Sikkim collapsed due to strong shaking. In Gangtok, many government offices and hospitals were left unusable. The heavy shaking destroyed the villages of Lingzya, Sakyong, Pentong, Bay and Tholong. The strongest shaking occurred to the west in Gangtok and further south in Siliguri, although similar ground motions were recorded in many smaller towns such as Mangan across elevated regions. Lighter intensities were reported in the capital of Bihar at Patna and as far southwest as Bihar Sharif. The earthquake was reported felt in Nepal, India, Bhutan, Bangladesh and China. Tremors were felt in Assam, Meghalaya, Tripura, parts of West Bengal, Bihar, Jharkhand, Uttar Pradesh, Rajasthan, Chandigarh and Delhi states of India. In Tibet, the earthquake was felt in Shigatse and Lhasa.

The strong shaking caused significant building collapse and mudslides; at least 111 people were confirmed killed by the effects of the earthquake, and hundreds of others sustained injuries. As the earthquake occurred in the monsoon season, heavy rain and landslides made the rescue work more difficult.

The earthquake caused strong shaking in many areas adjacent to its epicenter reportedly lasting 30-40 seconds. Northern India suffered the most from the earthquake, with at least 75 people killed. 60 people were reportedly killed in Sikkim alone. At least 7 people have died in Bihar, while 6 deaths have been reported from West Bengal. Power supply was disrupted in areas near Sikkim, including Kalimpong of Darjeeling district, and adjoining Jalpaiguri and Cooch Behar districts; the outages were in part blamed on an affected electric substation in Siliguri. Water supply was interrupted in Sikkim. National Highway 31, the major highway linking Sikkim to the rest of India, was damaged. Ten of the dead were workers at a hydroelectric project on the Teesta River. The property damage is estimated to be around 100,000 crore (Times of India dated 19th September, 2011). The focal mechanism of this earthquake showed strike slip faulting with some thrust component (IMD, USGS). The

TABLE 1 (a)

Hypocenter parameter of Sikkim earthquake of September 2011

Agency	Hypocenter			Origin time (UTC)	Magnitude
	Latitude (°N)	Longitude (°E)	Focal depth (km)		
IMD	27.70	88.20	10.0	12:40:47	Mb : 6.8
USGS	27.723	88.064	19.7	12:40:48	Mw : 6.9

TABLE 1 (b)

Source Parameter (IMD Report 2011; USGS) of Sikkim earthquake of September 2011

Agency	Epicenter		Depth (km)	Mw	Origin Time (UTC)	Nodal Plane 1			Nodal Plane 2		
	Lat. (°N)	Long. (°E)				S1	D1	R1	S2	D2	R2
IMD (CMT)	27.73	88.13	58.0	6.9	12:40:47	217	80	15	124	75	169
USGS (W Phase)	27.729	88.082	60.0	6.9	12:40:48	217	75	-4	308	86	-164
USGS (CMT)	27.740	88.113	35.0	6.9	12:40:51.55	220	78	0	130	90	168
Global CMT	27.44	88.35	46.0	6.9	12:40:59.9	216	72	-12	310	79	-162

S1, D1, R1: Strike, Dip, Rake of nodal plane 1 S2, D2, R2: Strike, Dip, Rake of nodal plane 2

hypocenter and source parameter of Sikkim earthquake of September 2011 is given in Tables 1(a&b).

As the earthquake was widely felt and extensive damage was reported from many places near the epicenter, it is important to know the extent of felt area and region of strongest shaking. Seismic intensity is a qualitative method to measure such ground shaking at a specific location determined subjectively during post earthquake investigations and is traditionally used worldwide. Isoseismal (equal intensity) maps provide valuable information to characterize earthquake severity and seismic hazard. Such macroseismic studies are helpful in seismically active regions where seismic instrumentation is sparsely distributed to provide spatial coverage of effect of shaking and hazard due to an earthquake. Intensity data may provide a basis for interpreting or extrapolating strong motion data and in the absence of strong motion data, can help identify regions in which ground motion is amplified by site-specific geologic conditions. Isoseismal maps of modern earthquakes, whose epicenters, depths and other source parameters are determined with instrumental data; help to calibrate intensities from historic, non-instrumentally recorded earthquakes to refine their estimates. Isoseismal maps are also useful to find the orientation of faults instrumentally recorded or geologically mapped.

The Modified Mercalli Intensity (MMI) scale of Wood and Neumann (1931) is one of the widely used intensity scale world over including India. In general MMI depends on numerous factors, including the earthquake magnitude, epicentral distance, local soil conditions and building characteristics. There are 12 levels in MMI scale marked by Roman numerals from I to XII. For the present study macroseismic surveys were conducted by actual field surveys. It is well known that the attenuation of intensities with distances varies in different tectonic domain (Bakun and McGarr, 2002).

2. Data and methodology

A questionnaire (Wald *et al*., 1999 and Dengler & Dewey 1998) of internet intensity map generation was used for conducting the survey through e-mail. A numerical value was assigned to individual answers to each question. On receipt of response to the questionnaire (as e-mail attachments), the answers were numerically evaluated and mean value for each question was calculated from all the responses in the corresponding area. An area Weighted Sum Survey (WSS) was then calculated based on equation proposed by Wald *et al.* (1999):

$$\text{WSS} = 5 \times [\text{Felt index} + \text{Shelf index} + \text{Damage index}] + 3 \times [\text{Furniture index}] + 2 \times [\text{Stand index} + \text{Picture index}] + \text{Motion index} + \text{Reaction index} \quad (1)$$

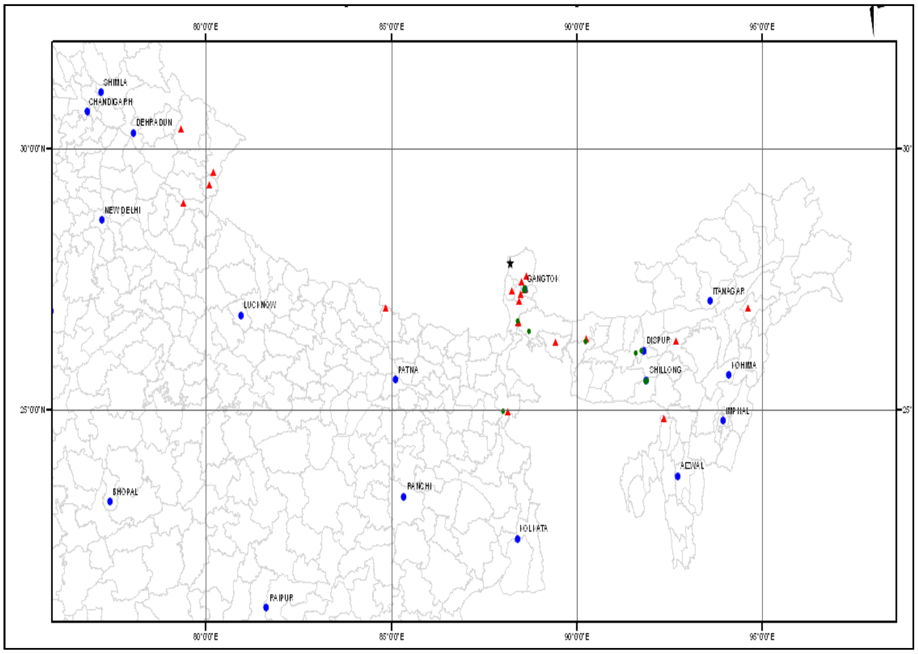

Fig. 1. Location of surveyed sites and SMA (Red triangles : SMA ; Green Circles : Survey Sites and Black Star : epicenter of the earthquake)

TABLE 2

Parameters of the macroseismic survey sites of 18th September, 2011 Sikkim earthquake

Latitude	Longitude	Location	Dis (km)	SI	MMI
25.571112	91.896942	Laitumkhrah, Don Bosco, Shillong	442.63	3.1	III
25.566111	91.855553	3rd Mile Upper Shillong	439.57	4.2	IV
26.101284	91.598480	Guwhati Airport	385.51	3.8	IV
26.141491	91.742325	Lal ganesh, Guwahati	395.77	5.3	V
27.337833	88.609581	Gangtok	65.95	7.5	VIII
27.347500	88.617226	Baluakhani, Gangtok	65.52	6.9	VII
27.312222	88.598892	Tadong	67.70	5.9	VI
27.311112	88.592781	NH31 Gangtok	67.47	7.8	VIII
27.316389	88.601387	Daragaon, Tadong, gangtok	67.45	7.4	VII
26.724443	88.401947	Siliguri	123.14	6.9	VII
26.524351	88.718521	Jalpaiguri	152.28	6.8	VII
25.000557	88.017502	Malda	314.16	3.1	III
26.323889	90.245560	Coochbihar	260.56	6.4	VI

Some of the questions in survey were not used directly in area intensity calculations but responses were collected for consistency in deciding intensity with standard MMI scale. These include questions on whether the observer was inside or outside, perceived duration of earthquake felt/shaking and type of structure in which observer was present during earthquake. We used the regression relationship developed by Wald *et al.* (1999)

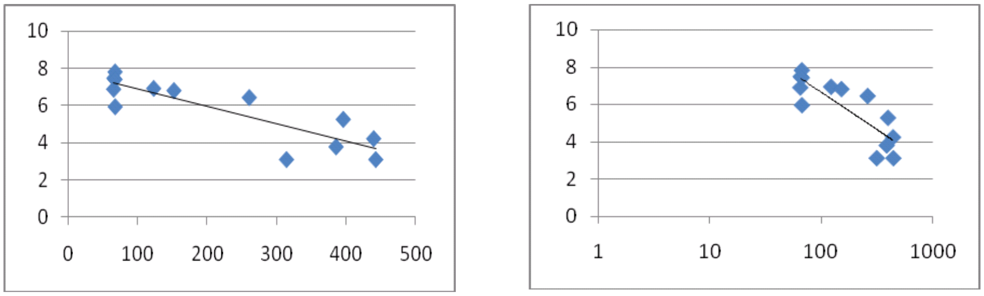

Fig. 2. Intensity - distance relationship for the Sikkim earthquake of 18th September, 2011 (left : linear regression and right : logarithmic regression)

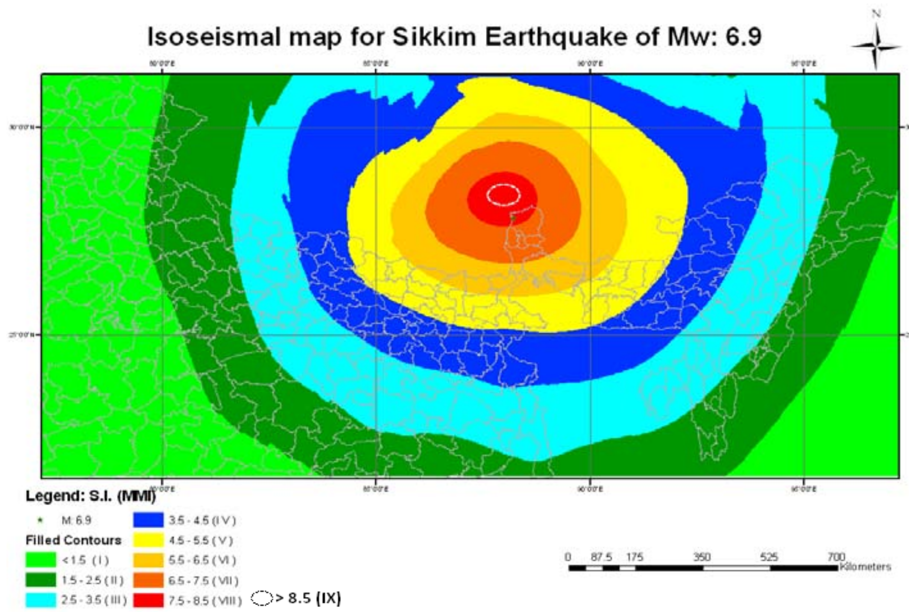

Fig. 3. Isoseismal map for 18th September, 2011 Sikkim earthquake

which was the revised regression to fit the extremes of the intensity values. This is defined in following equation (2).

$$\begin{aligned} SI &= 3.4 \log (WSS) - 4.38 \quad \text{for } WSS \geq 6.53 \\ &= 2 \text{ for } WSS < 6.53 \text{ and felt} \\ &= 1 \text{ for } WSS < 6.53 \text{ and not felt} \end{aligned} \tag{2}$$

where SI is Surveyed Intensity. Here SI is same as community internet intensity (CII) of Wald *et al.* (1999). The SI values were computed to two decimal places and then rounded off to integer values for comparison with Roman numerals assigned to MMI values.

The survey was conducted in the form of feedback collected through e-mails from the residents of the area (Officials of RMC Guwahati, RMC Kolkata, CSO Shillong and MC Gangtok) close to epicenter as well as press reports. The geographic values of survey points were collected from www.wikimapia.org. The location of these points and SMA sites are shown in Fig. 1.

3. Survey results

Table 2 provides the parameters of the 13 sites from where responses were received through e-mail, including geographic coordinates, distance from the epicenter, decimal SI and corresponding MMI intensities.

4. Analysis and discussion

The SI values were estimated at 13 surveyed locations. In order to visualize intensity contour map using

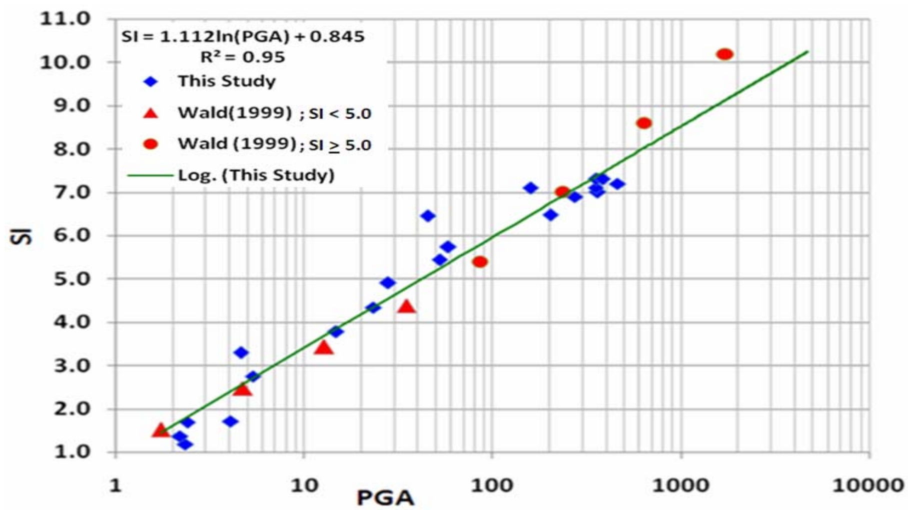

Fig. 4. Correlation of intensities with the maximum horizontal PGAs

TABLE 3

Details of PGHA* at 20 sites and corresponding Intensity

S. No.	Station Name	Station Code	Lat. (°N)	Long. (°E)	ELV (m)	PGA (gal)	SI	Distance (km)
1.	Chamoli	CMO	30.4120	79.3200	1578	2.32	1.2	911.15
2.	Udham Singh Nagar	UDH	28.9970	79.4030	213	2.18	1.4	873.45
3.	Champawat	CHP	29.3340	80.0950	1635	2.38	1.7	813.3
4.	Pithauragarh	PTI	29.5790	80.2070	1538	4.05	1.7	805.99
5.	Sibsagar	SBS	26.9890	94.6310	78	5.33	2.8	639.85
6.	Karimganj	KRM	24.8700	92.3540	35	4.58	3.3	526.54
7.	Naugaon	NAU	26.3490	92.6900	72	14.77	3.8	471.75
8.	Malda	MLD	25.0000	88.1460	44	23.30	4.3	310.5
9.	Raxul	RAX	26.9820	84.8430	50	27.94	4.9	347.12
10.	Kokhrajhar	KOK	26.4000	90.2610	54	52.39	5.4	256.02
11.	CoochBihar	COB	26.3190	89.4400	64	58.11	5.7	202.78
12.	Siliguri	SLG_KGP	26.7010	88.4270	122	45.08	6.5	125.57
13.	Siliguri	SLG_RRK	26.7120	88.4280	131	201.65	6.5	124.38
14.	Melli	MLI	27.1070	88.4520	442	274.40	6.9	82.44
15.	Singtam	SNG	27.2330	88.4890	555	362.60	7.0	70.11
16.	Gangtok	GTK_RRK	27.3520	88.6270	1536	158.33	7.1	65.59
17.	Gangtok	GTK_KGP	27.3200	88.6100	1466	352.80	7.1	67.17
18.	Gezing	GZG	27.3090	88.2500	1879	460.60	7.2	55.83
19.	Chungthang	CHT	27.6000	88.6439	1868	352.80	7.3	47.49
20.	Mangan	MNG	27.4900	88.5299	1137	382.20	7.3	47.16

**Source* : http://moes.gov.in/motion.html

GIS tools, we need to estimate intensity at some points on its boundary. Linear and logarithmic fits of intensity versus epicentral distance were determined with regression coefficient of 0.75 and 0.7 respectively. As the regression coefficients are little less than 1.0 and SI were overestimated (9.8) at few points using log equation [Fig. 2] and under estimated (0.3) at few points using linear fit [Fig. 2]; average of both fits was taken for calculating SI values using following equations;

$$SI = 0.5[14.55 - 1.72 \ln (D) + 7.819 - 0.009(D)] \quad (3)$$

Where, D is distance in km

Intensities were determined at 50 locations of spatial grid using above intensity-distance equation.

The isoseismal map of Sikkim earthquake of 18th September, 2011 is presented in Fig. 3. The eight isoseismal corresponds to the SI < 1.5, 1.5-2.5, 2.5-3.5, 3.5-4.5, 4.5-5.5, 5.5-6.5, 6.5-7.5 and > 7.5, delineating the zones of MMI Intensities I, II, III, IV, V, VI, VII and VIII accordingly. The mean isoseismal radii for the zones VII, VII, VI, V, IV and III are 154.47, 337.70, 517.17, 746.51, 986.80 and 1342.36 km respectively. The mean isoseismal radius for the zones I and II is more than 1750 km which agrees with felt report.

The intensity map was developed using geo-statistical analysis tool with local polynomial interpolation method; having mean and root mean square of prediction error, -0.0626 & 0.75 respectively (Fig. 3). Instrumental Intensity (Im) from SMA and SI were combinedly used for generating isoseismal map as shown in Fig. 3 (Shake Map Manual, 2006). Since surveyed points near the epicenter were not available except newspaper reports, intensity IX has been shown in dotted.

Table 3 lists the observed maximum horizontal PGAs and intensities for 20 strong motion sites, the locations of which are shown in Fig. 1 with triangles. The corresponding intensity-PGA relationship is plotted in Fig. 4. The correlation between the two parameters is very good, with the correlation coefficient close to 1.0 ($R^2 = 0.95$).

5. Conclusions

The results of the macroseismic survey of the 18th September, 2011 Sikkim Earthquake of M: 6.8, with the surveyed dataset allowed establishment of spatial distribution of the earthquake effects in the form of isoseismal map. The mean isoseismal radii for the zones VII, VII, VI, V, IV and III are 154.47, 337.70, 517.17, 746.51, 986.80 and 1342.36 km respectively. Separation of zones VIII and IX was done based on damage reported from news paper reports. The maximum PGA 460.60 gal was recorded at Gezing. The relationship developed for Surveyed Intensity (SI) in this study for SI and PGA is in good agreement with Wald *et al.*, 1999 and Shake Map 2006; and can be used for the region.

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