Strong ground motion at Bhuj city during the Kutch earthquake

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In the absence of near field strong motion records, the level of ground motion during the devastating 26 January 2001 earthquake has to be found by indirect means. For the city of Bhuj, three broad band velocity time histories have been recorded by India Meteorological Department. In this paper these data are processed to obtain an estimate of strong ground motion at Bhuj. It is estimated that the peak ground acceleration at Bhuj was of the order of 0.38 g. Ground motion in the surrounding region is indirectly found using available spectral response recorder (SRR) data. These instrument-based results are compared with analytical results obtained from a half-space regional model.

BHUJ city (23.25°N, 69.65°E) in India was severely damaged during the Kutch, Gujarat earthquake of 26 January 2001; the event itself is widely referred to as Bhuj earthquake. According to the India Meteorological Department (IMD)[1], which officially maintains a series of observatories all over India, the epicentre of this quake was at 23.40°N, 70.28°E. Bhuj city is close to the epicentre, located at a distance of about 65 km to its southwest. An important feature of this earthquake was the widespread liquefaction and ground deformation[2] in the epicentral tracts. In nearby places such as Bachau (23.3°N, 70.30°E) and Manfera (23.46°N, 70.38°E) and even in some far-away locations like Kandla (23°N, 70.1°E), structural damage could be attributed as much to ground failure as to vibratory ground motion. From the engineering point of view, the most sought-after data are the accelerograms recorded digitally on a strong motion accelerograph (SMA). Since the time and place of occurrence of a strong earthquake are not known before the event, the present practice is to place several self-triggering SMAs with in-built clocks in a seismically-active region to acquire data as and when an earthquake occurs. Unfortunately, for the Kutch earthquake no such near source strong motion records are available. There was an SMA at the IMD observatory at Bhuj, but this did not produce a record due to cable failure. A three-component record on a strong motion instrument has been obtained by the University of Roorkee[3] at the basement of a ten-storey building in Ahmedabad. The record appears to be affected by the vibrations of the building in which the SMA was located, and moreover the station was some 250 km away from the epicentre. Thus, apart from making educated guesses based on the damage pattern, very little has been understood about the strong ground motion during the Kutch earthquake. The only near source data available are the broad band velocity records from the Bhuj observatory, operated by IMD[1]. The velocity data are processed in this paper, to estimate the ground motion time history at Bhuj. Even though no SMAs were operating in the region, an array of spectral response recorders (SRR) was maintained by the Department of Earthquake Engineering, University of Roorkee[3]. These recorders directly give the peak response of damped simple harmonic oscillators, tuned to specific frequencies, under the earthquake. Here, we use these data to carry out an indirect estimation of peak ground motion at the respective stations. Variation of peak ground acceleration (PGA) with respect to distance gives first-hand information on regional characteristics and also possible spread of damage during future earthquakes. Accordingly, the attenuation of PGA with respect to distance is presented. The ground motion results obtained here are not directly recorded, but are derived indirectly from other instrumental data. Thus, the question arises as to the possibility of validating these results by other means. With this in view, the estimated displacement time history at Bhuj is compared with analytical results based on the source mechanism proposed by Yagi and Kikuchi[4], coupled with a half-space regional model.

The only near source instrumental data available for the main shock are a set of three velocity records from the Bhuj observatory of IMD recorded on a force balance seismometer (STS 20-Q680). As described by Bhattacharya and Dattatrayam[5], this instrument can be used for measuring ground velocity in the range of 0.08–50 Hz, in which interval the instrument has a strictly flat frequency response. The basic three-component velocity signal recorded at the rate of 20 samples per second at Bhuj, is shown in Figure 1. The original data in counts have been

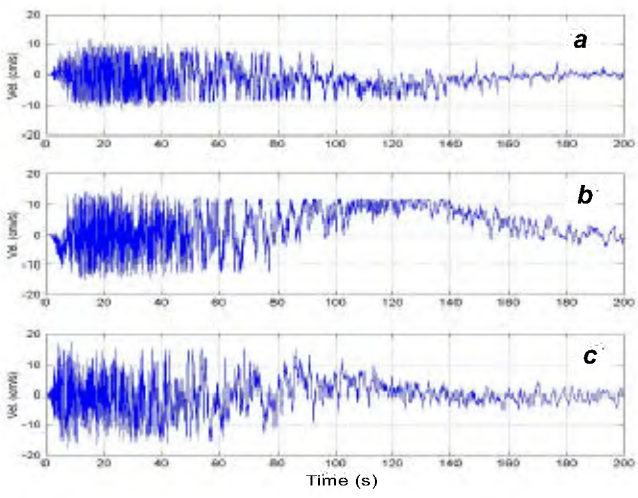

Figure 1. Velocity record (unfiltered) for the main shock of 26 January 2001 recorded at the IMD broadband station in Bhuj: ***a***, EW; ***b***, NS; ***c***, Vertical.

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Table 1. Stability of band pass filtered IMD data

No. of iterations	PGA (cm/s^2)			PGV (cm/s)			PGD (cm)		
	EW	NS	Vertical	EW	NS	Vertical	EW	NS	Vertical
0	338.2	438.6	459.3	11.32	15.87	17.47	267.6	657.5	97.7
1	335.1	406.8	417.6	11.61	16.61	17.83	5.33	10.18	8.83
2	324.4	391.4	410.9	11.65	16.94	18.38	4.76	9.51	7.63
3	317.4	384.1	405.1	11.58	17.04	18.77	4.48	8.83	7.28
4	323.1	383.2	399.3	11.51	17.07	19.01	4.31	8.31	6.99
5	326.9	383.1	393.8	11.44	17.05	19.16	4.18	7.89	6.81
6	329.6	381.8	388.6	11.38	17.03	19.26	4.11	7.55	6.65
7	331.5	380.1	383.9	11.42	17.11	19.33	4.16	7.28	6.53
8	332.8	377.9	379.6	11.45	16.98	19.37	4.06	7.10	6.43
9	333.8	376.9	375.8	11.47	16.95	19.41	4.02	7.10	6.35
10	334.5	375.9	372.3	11.47	16.92	19.42	4.02	6.98	6.29

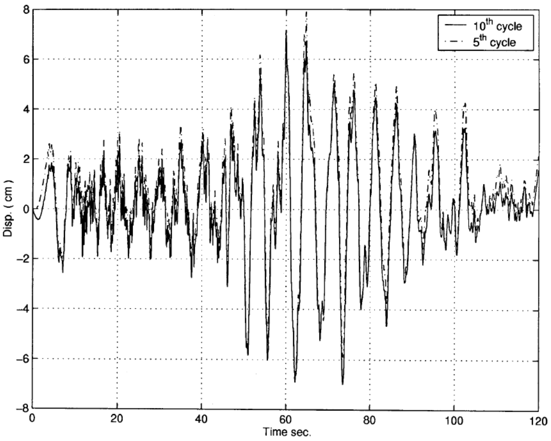

Figure 2. Ground displacement after 5 and 10 cycles of filtering instrumental velocity data of Figure 1 (NS component).

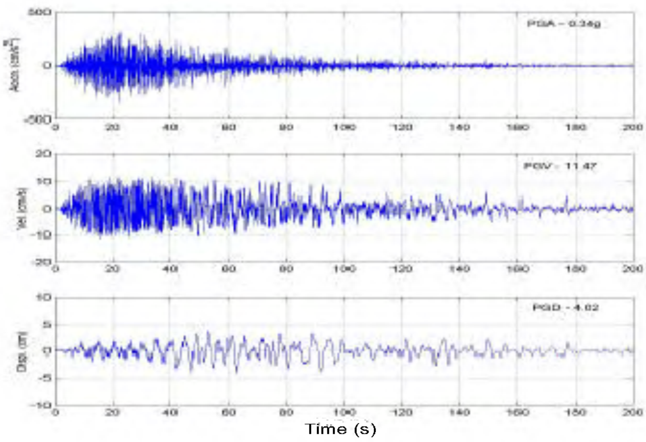

Figure 3. Corrected ground motion data for the main shock of 26 January 2001 at Bhuj, Comp. EW.

converted into velocity units using the instrument constant (1.56×10^{-7} cm/s per count) provided by IMD. It is clear that there is a low frequency drift in the records. It also appears that the data might have got clipped in some intervals. Direct integration of the velocity data indicates unrealistically large displacements of the order of 6 m at the end of the records, which is attributable to the errors in the low frequency end of the record. The low sampling rate of 20 samples per second introduces aliasing errors towards the high frequency end. Thus, whatever is retrievable from these data, as a useful signature, is in the range of 0.1–8 Hz. Accordingly, the velocity data have been band-pass filtered in 0.1–8 Hz range using the MATLAB signal processing toolbox. The filtering is done iteratively keeping the phase spectrum constant, but correcting the amplitude spectrum. At each step the signal is reconstructed using the filtered amplitude spectrum and the original phase spectrum. The stability of the data so balanced is presented in Table 1 in the form of iterated peak ground motion values of the three components. It may be mentioned here that the ground acceleration values refer to numerically differentiated velocity values, whereas ground displacements refer to numerically integrated velocity values. It is observed that after five cycles of filtering, the peak values may be taken to have stabilized. In Figure 2, the NS displacement component after the 5th and 10th cycles of filtering is shown. The closeness of these two iterates over a long time interval demonstrates the robustness of the IMD data in the limited frequency range of 0.1–8 Hz. The complete results for all the three components after 10 cycles of filtering are presented in Figures 3–5. In engineering applications it is normal practice to represent ground motion in terms of an accelerogram. In the present case, the best one could do is to numerically differentiate the velocity time history to arrive at the acceleration. Such a procedure being approximate, the acceleration time histories shown in Figures 3–5 have to be treated as estimates. Another limitation of the basic data is the low sampling rate. The Nyquist frequency for the velocity data is 10 Hz, whereas generally for near source ground motion, the cut-off frequency must be in the range of 50–100 Hz. Thus, not withstanding the fact that the time histories in these figures exhibit characteristic rise, decay and erratic oscillations of strong motion accelerograms, they are deficient in high frequency content. The actual peak ground accelerations at Bhuj might have exceeded the estimated values, namely

0.34 g (EW), 0.38 g (NS) and 0.38 g (vertical). Nevertheless, these records are useful in analysing man-made structures, since the fundamental natural frequency of civil engineering constructions lies within 8 Hz.

Duration of ground motion is an important parameter like peak acceleration and displacement. In the present case, eyewitness accounts indicate a long duration of the order of 90 s or more for the main event. The records presented here corroborate these observations. In the engineering literature the strong motion duration is taken as the length of the accelerogram enclosing 5% and 95% of the total energy[6]. Taking a $T = 200$ s long acceleration sample, $T_{0.95}$ and $T_{0.05}$ are found such that

$$\int_0^{T_{0.95}} a^2 \, dt \bigg/ \int_0^{T} a^2 \, dt = 0.95, \quad (1)$$

$$\int_0^{T_{0.05}} a^2 \, dt \bigg/ \int_0^{T} a^2 \, dt = 0.05. \quad (2)$$

For the EW acceleration component, the duration will be $T_{0.95} - T_{0.05} = 72.74$ s, which is one of the longest strong motions observed in recent times. The corresponding durations for the NS and vertical components are 57.63 and 64.31 s respectively (Figure 6).

The severity of ground motion generally decreases with distance. This is usually quantified in terms of the attenuation of PGA with epicentral distance. In the absence of instrumentally-recorded near field ground motion for the Kutch earthquake, the attenuation of PGA has to be studied by indirect methods. For this purpose, the SRR data[3] come handy. In Table 2 the available SRR data at 13 stations are presented along with the stations and their epicentral distances. The highest peak acceleration response (Sa) of a simple harmonic oscillator depends strongly on the PGA value at the station. A simple empirical approach to understand this relation is to obtain a regression equation between Sa and PGA. Here this is done by considering a global sample of 295 actual strong motion accelerograms and their corresponding response spectra. These data are drawn from the website of Pacific Earthquake Engineering Research Center (URL: http://www.peer.berkeley.edu/). In Figure 7 *a–d*, the scattergrams between maximum of horizontal PGA and Sa for global data are shown. The following least square regression equations are obtained connecting station PGA, with Sa/g.

$$\eta = 0.05;\ T = 0.4 \text{ s}; \quad \log(\text{PGA/g}) = 0.950 \log(\text{Sa/g}) - 0.734; \quad \sigma(\varepsilon) = 0.384, \quad (3)$$

$$\eta = 0.05;\ T = 0.75 \text{ s}; \quad \log(\text{PGA/g}) = 0.860 \log(\text{Sa/g}) - 0.535; \quad \sigma(\varepsilon) = 0.607, \quad (4)$$

$$\eta = 0.075;\ T = 0.4 \text{ s}; \quad \log(\text{PGA/g}) = 0.957 \log(\text{Sa/g}) - 0.518; \quad \sigma(\varepsilon) = 0.348, \quad (5)$$

$$\eta = 0.075;\ T = 0.75 \text{ s}; \quad \log(\text{PGA/g}) = 0.878 \log(\text{Sa/g}) - 0.330; \quad \sigma(\varepsilon) = 0.573. \quad (6)$$

Here, $\sigma(\varepsilon)$ refers to the standard deviation of the error in the regression equation. With the help of the above empirical relations, one can estimate the PGA corresponding to the instrumental SRR value. In Table 2, for the available data, the estimated PGA values at all the 13 stations are presented. It is seen that for each station 4 independent PGA estimates can be obtained. In Figure 8 these estimates are plotted with respect to distance, to get the attenuation of PGA. By least squares fit the expected PGA variation with distance R (km) can be represented as

$$(\text{PGA/g}) = 38.82/R^{1.12}. \quad (7)$$

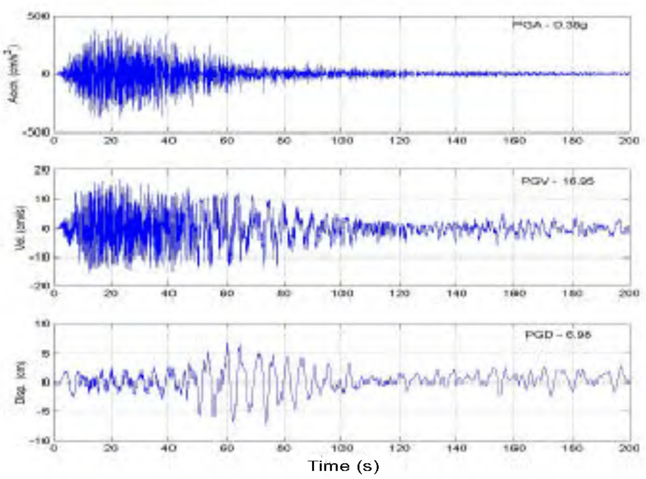

Figure 4. Corrected ground motion data for the main shock of 26 January 2001 at Bhuj, Comp. NS.

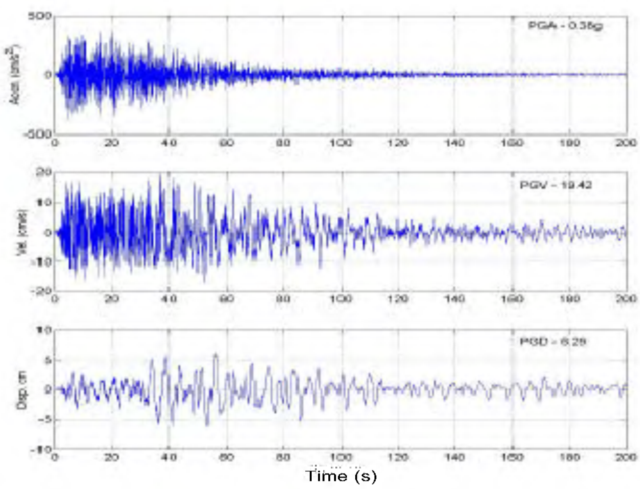

Figure 5. Corrected ground motion data for the main shock of 26 January 2001 at Bhuj, Comp: Vertical.

For Bhuj city, this equation gives a value of nearly 0.38 g, which matches with the previously estimated value of Figure 4. Singh *et al.*[7] have made an indirect estimation of PGA based on several past Indian earthquakes. Their conclusion that for distances less than 30 km, PGA exceeded 0.5 g during the Kutch earthquake, is also supported by the above results.

Earthquake mechanisms are complex and the ensuing ground motion at the surface depends on the details of source, path and site characteristics. However, our knowledge of these is rather limited. For example, it is important to quantitatively describe the fault source in terms of its geometry, rupture velocity and a consistent system of forces. Similarly, the path has to be described in terms of the geology, *P*- and *S*-wave velocities, damping factors and other properties. The site details involve the surface location relative to the buried moving source, local effects such as layering, soft soil deposits and topography. Accurate information is not available on any of these parameters. Moreover, the available analytical models are not capable of handling field data with all their statistical ramifications. Thus, what can be attempted is an estimation of the order of magnitude of ground motion for simple source geometries. With this in background, limited numerical results are presented here for a half-space regional model with a planar rectangular buried fault source (Figure 9). Geometry of the fault plane and the source forces in the form of double couples are taken from the work of Yagi and Kikuchi[4], as reported in the Tokyo University website. The location of the epicentre

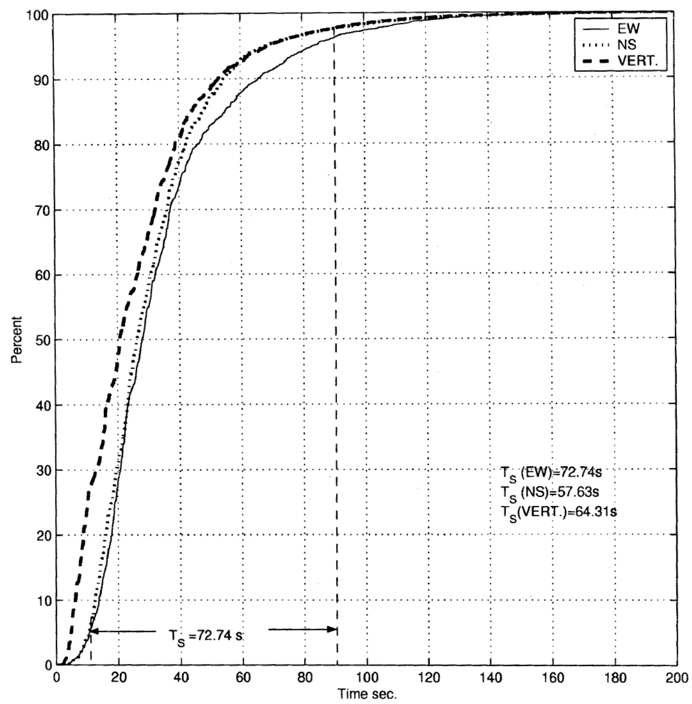

Figure 6. Duration of strong motion for the main shock of 26 January 2001 at Bhuj.

Table 2. Regional PGA estimates from SRR data

Station	Epicentral distance (km)	η = 0.05, T = 0.4 s, SRR Sa/g	η = 0.05, T = 0.4 s, Est. PGA/g	η = 0.05, T = 0.75 s, SRR Sa/g	η = 0.05, T = 0.75 s, Est. PGA/g	η = 0.1, T = 0.4 s, SRR Sa/g	η = 0.1, T = 0.4 s, Est. PGA/g	η = 0.1, T = 0.75 s, SRR Sa/g	η = 0.1, T = 0.75 s, Est. PGA/g	Expt. PGA/g
Anjar	43.8	1.62	0.76	0.70	0.43	0.91	0.54	0.69	0.52	0.56
Kandla	53.2	0.86	0.42	0.57	0.36	0.65	0.39	0.53	0.41	0.40
Niruna	97.0	0.81	0.39	0.65	0.40	0.76	0.46	0.55	0.43	0.42
Naliya	147.1	0.72	0.35	0.22	0.16	0.69	0.42	0.21	0.19	0.28
Khambhaliya	150.2	0.18	0.09	0.07	0.06	0.09	0.06	0.04	0.04	0.06
Jamjodhpur	166.0	0.22	0.11	0.15	0.12	0.14	0.09	0.05	0.06	0.09
Dwaraka	187.8	0.21	0.11	*	*	0.18	0.11	0.11	0.10	0.11
Porbandar	206.6	0.19	0.10	0.25	0.18	0.15	0.09	0.21	0.18	0.14
Junagarh	216.0	0.19	0.10	0.06	0.05	0.10	0.06	0.05	0.05	0.07
Amreli	225.4	0.09	0.05	0.07	0.06	0.07	0.04	0.05	0.05	0.05
Ahmedabad	238.0	0.29	0.15	0.23	0.17	0.24	0.15	0.19	0.17	0.16
Cambay	266.0	0.49	0.24	0.04	0.04	0.29	0.18	0.04	0.04	0.13
Anand	288.0	0.14	0.08	0.06	0.05	0.12	0.12	0.05	0.05	0.07

is taken to be the one reported by IMD[1]. The fault dimensions are 75 km × 35 km, with dip angle of 58°SE and strike of N 78°E. The *P*-wave and *S*-wave velocities are taken as, $C_p = 6.82$ km/s and $C_s = 3.47$ km/s. The damping factor is taken as $Q = 508f^{0.48}$, where f is frequency in Hz. These values are based on the results of Singh *et al.*[8,9] for the Jabalpur earthquake of May 1997. The ground motion felt at Bhuj was for a long duration of 70 s or more. With this in view, rupture velocity of 0.5 km/s has been selected as reasonable for the Kutch earthquake. For faster rupture velocity values, the ground motion turns out to be of shorter duration. To account for the large size of the fault and the long duration, a sequence of 2625 sub-faults each of 1 km × 1 km dimension has been used as causative source. On each sub-fault a double couple of magnitude M_0 is applied, which is the classical Haskell source mechanism[10]. The three components of displacement (u, v, w) at a point (x, y, 0) on the surface, for a double couple source at (0, 0, z) are expressed as 3D Fourier integrals

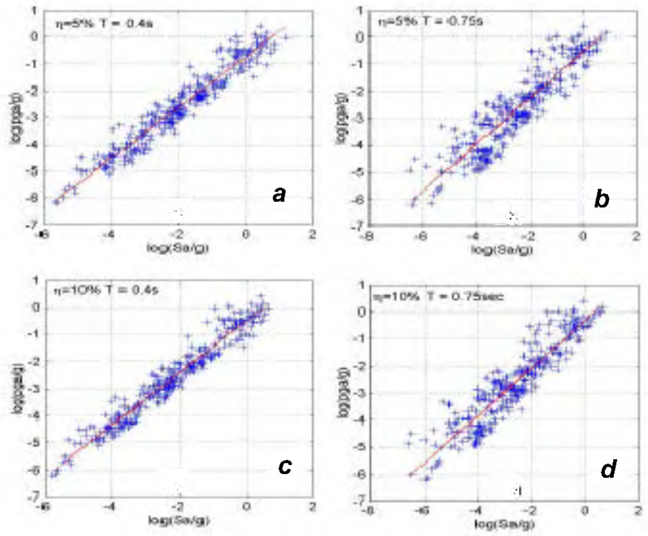

Figure 7 *a–d*. Regression of PGA vs Sa for global data; η, Viscous damping; *T*, Natural period.

$$u(x,y,0,t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{u}(\kappa_x,\kappa_y,\omega)\times e^{-ik_x x-ik_y y-i\omega t}\,d\kappa_x\,d\kappa_y\,d\omega, \quad (8)$$

$$v(x,y,0,t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{v}(\kappa_x,\kappa_y,\omega)\times e^{-ik_x x-ik_y y-i\omega t}\,d\kappa_x\,d\kappa_y\,d\omega, \quad (9)$$

$$w(x,y,0,t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{w}(\kappa_x,\kappa_y,\omega)\times e^{-ik_x x-ik_y y-i\omega t}\,d\kappa_x\,d\kappa_y\,d\omega, \quad (10)$$

$$\tilde{u}(k_x,k_y,\omega)=M_0\tilde{m}(\omega)\,G_x(k_x,k_y,\omega), \quad (11)$$

$$\tilde{v}(k_x,k_y,\omega)=M_0\tilde{m}(\omega)\,G_y(k_x,k_y,\omega), \quad (12)$$

$$\tilde{w}(k_x,k_y,\omega)=M_0\tilde{m}(\omega)\,G_z(k_x,k_y,\omega). \quad (13)$$

Here (k_x, k_y) stand for the spatial frequencies and ω stands for the temporal frequency. M_0 and $\tilde{m}(\omega)$ refer to the double-couple magnitude and Fourier transform of the unit ramp function of Haskell's model. G_x, G_y, G_z are

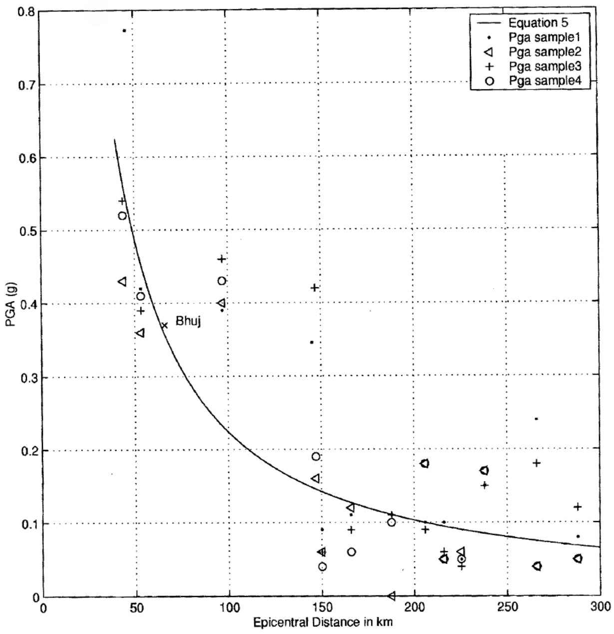

Figure 8. Attenuation of PGA with epicentral distance; **x**, PGA at Bhuj from broadband velocity data.

complex quantities representing the frequency–wave number spectra of the region in terms of P- and S-wave velocities and damping factor Q. The derivation of the analytical solution for a half-space subjected to Haskell's double-couple source model is available in the literature[10], and hence further details of the above solution are not presented here. The ground displacement at station $(x, y, 0)$, due to the complete fault rupture is obtained by summing up the contribution of all the sub-faults. In Figure 10, the analytical displacement time histories corresponding to Bhuj city are compared with displacement components obtained from the IMD velocity data. It is observed that there is an overall match in the order of magnitude of the amplitudes and duration. However, the comparison is not too good in details. This is attributable to the inherent limitations in the simple isotropic half-space model used for the region. Furthermore, the identification of the fault plane according to the results of Yagi and Kikuchi[4] is also debatable.

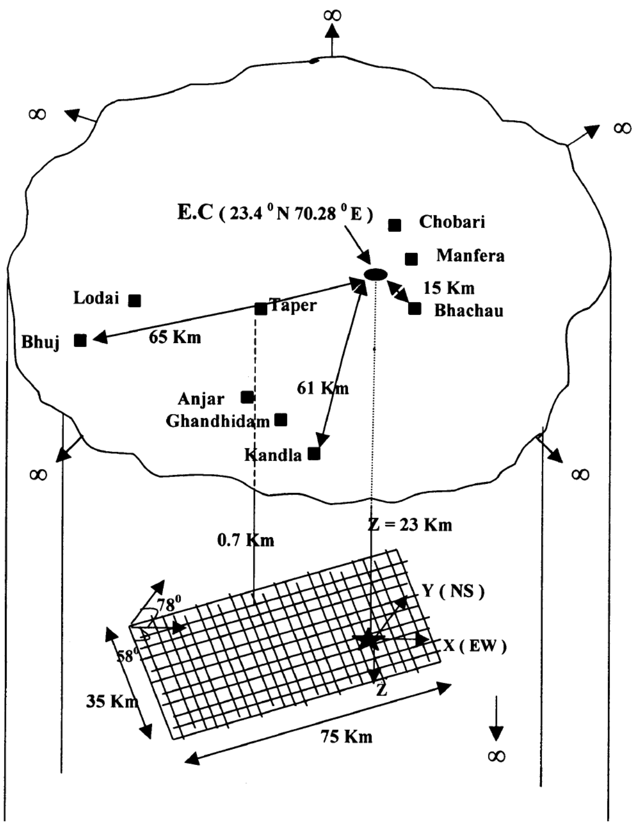

Figure 9. Half-space model and assumed fault plane of Kutch earthquake. Rupture surface of ref. 4 is shown in the grid (not to scale).

Engineering codes for design of structures represent earthquake hazard in terms of expected PGA and a standard response spectrum. The shape of such a response spectrum is supposed to reflect faithfully the frequency domain characteristics of earthquakes expected in the particular seismic zone. Response spectrum is represented as a plot of the maximum response of a harmonic oscillator of natural frequency ω rad/s and viscous damping coefficient η, given by the equation

$$\ddot{x} + 2\eta\omega\dot{x} + \omega^2 x = \ddot{u}(t). \qquad (14)$$

Here, the right hand side represents the ground acceleration. The acceleration spectra defined as $Sa/g = \omega^2|x|_{max}$ during the earthquake is shown in Figure 11, for all the three components of the motion at Bhuj. These show the presence of frequencies beyond 5 Hz in the ground motion. Earthquakes in the stable continental region

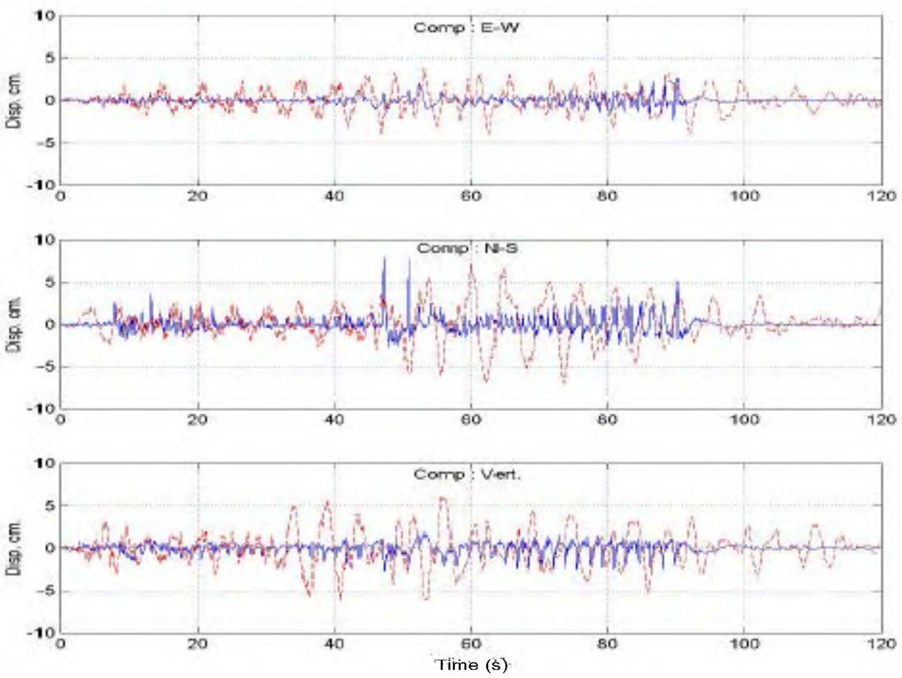

Figure 10. Comparison between analytical and instrumental displacements at Bhuj. —, Half-space model; - - - -, Integrated IMD velocity.

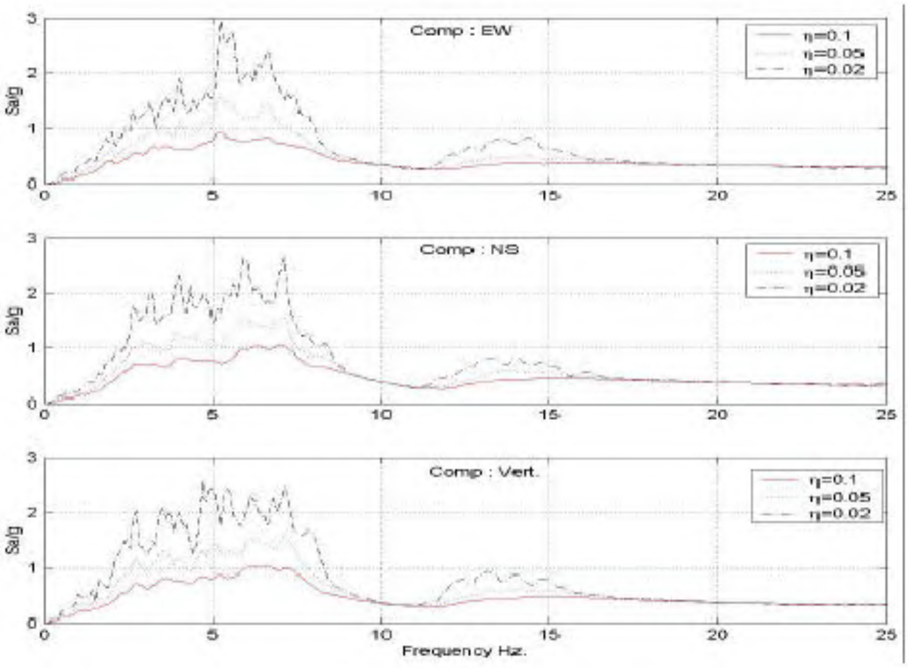

Figure 11. Response spectra for main shock of 26 January 2001 at Bhuj city from IMD broadband velocity records.

(SCR) of India (peninsular shield) are known to show higher frequency content than their counterparts from the Himalayan plate boundary region. For example, the SMAs of the Koyna earthquake of 11 December 1967 show a predominant frequency of 15 Hz (ref. 11). For the recent Killari earthquake of 30 September 1993, there were no strong motion recordings of the main shock. However, an aftershock of magnitude $M_L = 4.3$ was recorded[12] on a SMA. This record shows a high PGA value of 0.11 g, a dominant frequency greater than 15 Hz and a long duration. It is plausible that the Kutch intraplate earthquake ground motion also contained high frequencies, but was not reflected in the IMD data presented previously.

The Kutch earthquake of 26 January 2001 was a devastating event, affecting a large region of India. A scientific and objective understanding of the phenomenon is possible only in terms of the observed ground motion during the earthquake. Teleseismic data recorded far away from the epicentre help us in locating the source of the event, but are not of much help in understanding the behaviour of man-made constructions, such as buildings, bridges, dams and ports in the epicentral region. In this connection, the two most important questions are: How are new structures to be designed? How safe are the existing structures against future shocks? The key information, namely ground motion data with reference to which the above questions can be addressed, are unfortunately missing for this earthquake. The present paper has attempted to fill this gap in our knowledge by studying the available near field velocity data at Bhuj city and SRR data at a few other places. The instrumental data of IMD have been processed to estimate the displacement, velocity, acceleration, time history and response spectrum at Bhuj. The estimated displacement values are validated to a limited extent by a half-space regional model, using the source mechanism proposed by Japanese investigators based on teleseismic data. An empirical approach, to find the attenuation of PGA during the earthquake using spectral response recorder data, has been presented. This approach, based on global data, indicates 0.38 g to be a good estimate of the PGA at Bhuj city.

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