The Inferences of Earthquake Fault and Strong Motions in Kutch Earthquake, India of January 26, 2001

Ömer AYDAN[1]

アイダン・オメル[1]

[1] Department of Marine Civil Engineering, Tokai University, Shimizu
[1] 東海大学海洋学部海洋土木工学科

Kutch (Kutch) region in Gujarat State of India was severely shaken by a powerful earthquake, which has been the most damaging earthquake in the last five decades in India. The M7.9 quake caused a large loss of life and property. Although the hypocenter was shallow and both the USGS and HARVARD fault plane solutions indicated predominantly reverse faulting along a moderately dipping, nearly east-west trending fault plane with a slight sinistral sense, there was no well-defined surface fault ruptures. Furthermore, except the strong motion records in Ahmedabad 220 km away from the USGS determined epicenter, there is no strong motion records in the epicentral area. The article attempts to infer the earthquake fault from existing fault outcrops and aftershock data and strong motion distributions from collapsed structures. The validity of inferences on the earthquake fault and strong motions are checked with those determined or inferred from other methods.

1. INTRODUCTION

Kutch (Kutch) region in Gujarat State of India was severely shaken by a powerful earthquake at 8:46 am on 26 January 2001 of the India Standard Time, which has been the most damaging earthquake in the last five decades in India. The M7.9 quake caused a large loss of life and property. Over 20,000 persons are reported to be dead and over 167,000 injured. The estimated economic loss due to this quake is placed at around US$5 billions. The entire Kutch region of Gujarat sustained highest damage with maximum intensity of shaking as high as X on the MSK intensity scale. Several cities and large towns such as Bhuj, Anjaar, Vondh and Bhachau sustained widespread destruction and casualties. The other prominent failures in the Kutch region include extensive liquefaction, failure of several earth dams of up to about 20m height, damage to masonry arch and RC bridges, and failure of railroad and highway embankments. Numerous recently built multistory RC frame buildings collapsed in Gandhidham and Bhuj in the Kutch region and in the more distant towns of Morbi, Rajkot and Ahmedabad). At least one multistory building at Surat collapsed killing a large number of people. The strong motion records obtained from the region at the Passport Office Building in Ahmedabad City indicated a peak ground acceleration of about 0.11g.

The hypocenter of the erthquake was shallow and its magnitude was 7.9, it did not produced a well fault scarp to confirm the fault plane solutions obtained by different institutes. Some research teams from USA and Japan have concentrated their efforts to determine the geometry of the fault planes through aftershock studies.

Although a strong motion network was established in Gujarat State, most of the strong motion stations were destroyed by the earthquake. The records observed in Ahmedabad, Delhi and Roorkee stations were only available, there was no data in the epicentral area of the earthquake.

The author briefly describes some methods to infer the earthquake fault from aftershock data and strong motions from collapsed structures in the earthquake affected area. These methods are then applied to the aftershock data and observations on the structural geological features and the damage state of various structures in the earthquake affected area. The inferences are also compared with those obtained from other researchers and their validity are discussed.

2. INFERENCE OF THE EARTHQUAKE FAULT FROM AFTERSHOCK DATA

(1) The Procedure for Inferring the Earthquake Fault from Aftershock Data

When a fault ruptures numerous aftershocks occur. These aftershocks generally take place on the fault plane and some aftershock activities occur at the edges of the fault due to forking phenomenon so that the fault achieves a stable geometrical configuration under the resulting stress state and geo-mechanical characteristics of the earth's crust. By taking this physical observation into acoount, it may be possible to fit the hypocenter information of aftershocks to a plane through the least square technique as given below

$$f = a + b * LONGITUDE + c * LATITUDE \quad [1]$$

The unit of f is in kms. When the procedure is applied to aftershock data, the region will generally have an rectangular shape. It is desirable to define the boundaries of this rectangular region for a reliable estimate. Although such a designation may be subjective, it would be quite helpful to eliminate the data of aftershocks caused by the triggering effect of the earthquake fault on the nearby faults.

(2) The application of the Procedure to Kutch earthquake Aftershock Data

Indian Geological Survey (IGS) released 250 aftershock data until the end of February 2001. By assuming that the fault was planar, the following equation of the plane was determined by using the least square technique for a region bounded by 69.5-71.0 E & 22.5-24.0 N:

$$f = 936 - 26.52 LONGITUDE + 38.69 LATITUDE \quad [2]$$

From this function, the fault plane has been inferred to be dipping SE with an inclination of 47° and its strike is N53E. Figure 1 shows a three-dimensional perspective view of the determined fault plane with the epicenters and hypocenters of the aftershocks. Although this earthquake did not produce a remarkable fault scarp, the surface trace of the plane should appear along an alignment extending from Khadir Island, passing the north of Chobari and Lodai in Banni plains and it should terminate somewhere 30km the north of Bhuj. This estimation is quite consistent with the surface ruptures, cracks and deformation zones observed in the earthquake area. Furthermore, This fault plane is quite similar to the SE-dipping fault plane inferred from HARVARD and USGS focal mechanism solutions shown in Figure 2. The aftershocks were distributed over a length of 120-130km along the direction of N60-80E. There was not any well-defined fault scarp on the ground surface to confirm the both focal plane solutions and the inferred fault plane presented above. Nevertheless, some fault scarps could be observed along the roadcuts during site investigations. Figure 3 shows a fault scarp near the northern embankment of the Rudramata Bridge 20km north of Bhuj. At the same location, the bedding planes of sandstone abruptly become steeper. From the striations on the fault plane, the mechanism of a possible earthquake inferred from a method proposed by Aydan (Aydan et al. 2001) would look like as shown in Figure 4. The strikes of faults and bedding planes at this location are similar to the general trend of the strike of the Kutch mainland fault. The fault plane solution for this thrust fault strikingly is similar to that of the main shock given by various institutes shown in Figure 2.

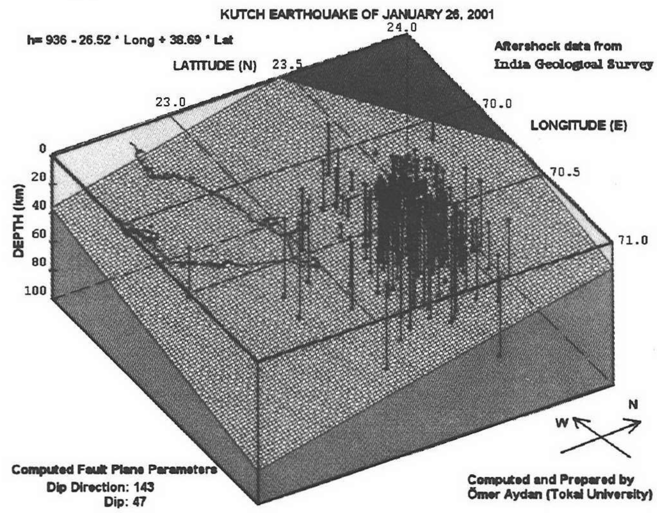

Figure 1: A perceptive view of the estimated fault plane from aftershock data

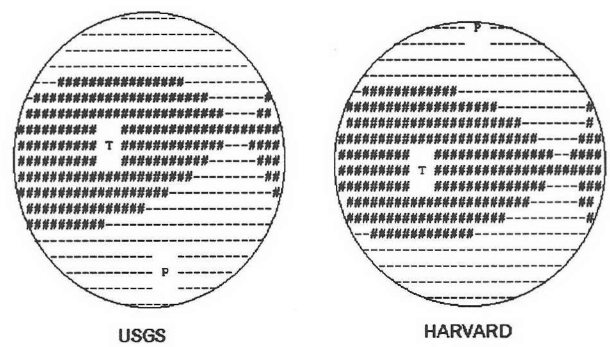

Figure 2: Fault plane solutions for the main shock on January 26, 2001 by various institutes

Figure 3: A thrust fault with striations at the northern embankment of Rudramata Bridge (picture towards north) 20km north of Bhuj

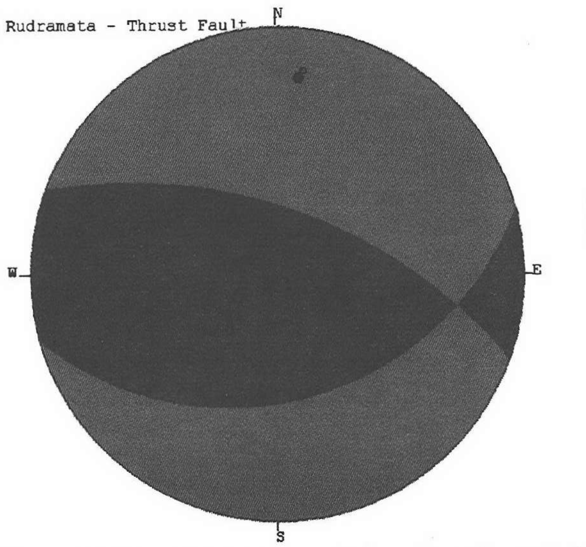

Figure 4: Inferred fault plane solutions for a thrust fault with striations at the northern embankment of Rudramata Bridge

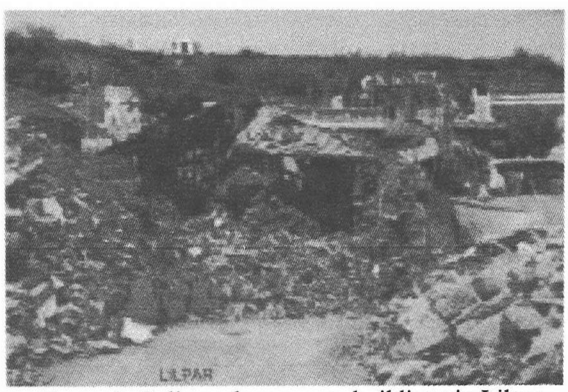

Figure 5: Collapsed masonary buildings in Lilpar

3. INFERENCE OF STRONG MOTIONS

(1) Inference of strong motions from masonary walls

As indicated in the previous section, masonry buildings with mud-mortar mostly collapsed during the earthquake. Since the bonding strength of mud mortar is very small, the seismic resistance of the masonry walls against toppling will mostly depend upon the wall geometry while the seismic resistance against shear will be frictional. The conditions for different modes of failure shown in Figures 5 and 6 derived for a horizontal seismic coefficient as follows (Aydan et al. 1989):

Toppling condition

$$\frac{a}{g} > \frac{t}{h} \quad [3]$$

Sliding Condition

$$\frac{a}{g} > \tan\phi \quad [4]$$

Toppling & Sliding Condition

$$\frac{a}{g} > \frac{t}{h} \text{ and } \frac{a}{g} > \tan\phi \quad [5]$$

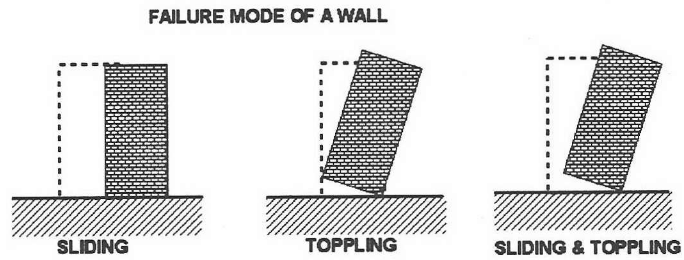

Figure 6 Failure modes of a wall

Figure 7 shows the relation between wall height to width ratio and lateral seismic coefficient. It seems that the walls of masonry buildings will be vulnerable to both toppling (out of plane failure) and sliding failure (X-cracks) in the epicentral area. Such buildings away from the epicentral area may only suffer from toppling failure. The author plotted some observations and the results are shown in Figure 8 together with the bounds for stability against toppling, computed from empirical attenuation relations proposed by Aydan (1997,2001) for various ground conditions. Since the ground conditions in many places are hard soil or rocky ground, the computed results are quite consistent with actual observations.

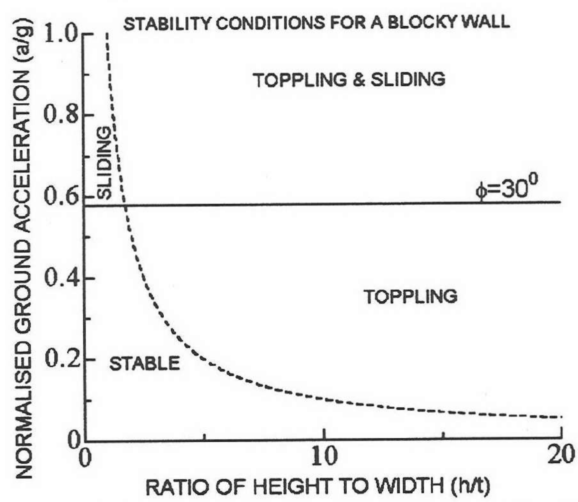

Figure 7: The relation between wall height to width ratio and lateral seismic coefficient

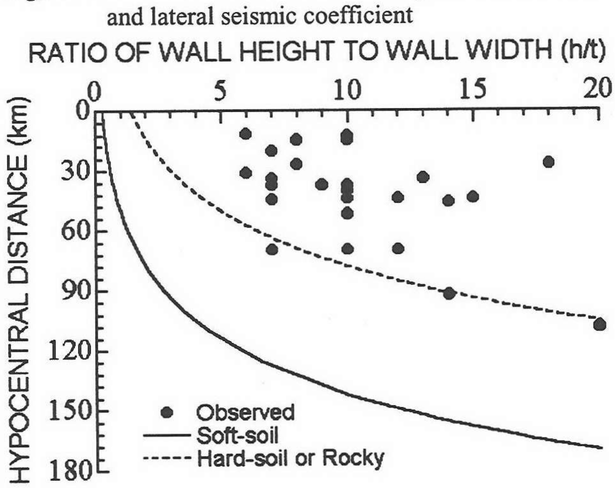

Figure 8: The relation between wall height to width ratio and hypocentral distance

Figure 9: Failure of RC buildings due to soft-floor effect in Bhuj

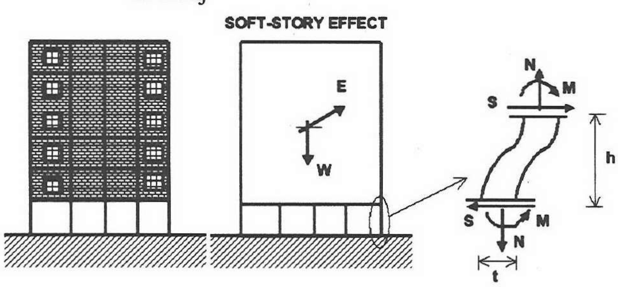

Figure 10: Illustration of the soft-floor effect and its mechanical modelling

(2) Inference of strong motions from Reinforced Concrete Structure

Next, the relation between seismic coefficient and number of floors for RC buildings, which collapsed as a result of soft-floor effect, was investigated. To derive the equations for seismic coefficient for the collapse of RC structures due to the soft-floor effect, the failure modes may involve the shearing of columns or bending as illustrated in Figures 9 and 10. If the load is assumed to be uniformly distributed over columns with a square cross sections and the resistance of the columns against shearing and bending result from the shear and tensile strength of the reinforcing bars and column friction with the basement, one can easily derive the following equations for the seismic coefficients for the bending failure and for shear failure of the columns as:

Bending failure

$$\frac{a}{g} > \frac{t}{3h}\left(1 + \frac{\sigma_b}{\gamma_b h} i_b \cdot i_c \frac{1}{N}\right) \qquad [6]$$

Shear failure

$$\frac{a}{g} > \tan\phi_c + \frac{\sigma_s}{\gamma_b h} i_b \cdot i_c \frac{1}{N} \qquad [7]$$

Where

t: column width

h: floor height

N: number of stories

σ_b :reinforcing bar tensile strength

σ_s :reinforcing bar shear strength

i_b :areal ratio of reinforcing bar to the column area

i_c :areal ratio of columns to the building area

γ_b :average unit weight of the building

ϕ_c :friction angle of columns with base floor

Figures 11 and 12 show the relation between number of stories and lateral seismic coefficient for bending failure and shear failure modes. In computations areal ratio coefficients are changed between 0.01 and 0.02, which are typical values in RC buildings in the earthquake region. The results indicate that the buildings should be more vulnerable to bending failure rather than the shear failure unless the ratio of column width to floor height is large, which should correspond to buildings having shear-wall like columns. Since the ratio of the floor height to column width is generally greater than 6, the failure of RC buildings must had been due to bending failure. The site observations confirmed this conclusion. Furthermore, it is inferred that the damage to low story RC buildings may also occur in the epicentral area due to the soft floor effect while high-rise buildings away from the epicentral area should be more vulnerable to the earthquake shaking.

The author plotted some observations together with the bounds for stability against bending failure due to soft-floor effect, computed from empirical attenuation relations by Aydan (1997, 2001) for various ground conditions, and the results are shown in Figure 13 and Figure 14. The plotted data clearly confirm the statement above. Furthermore if the effect of vertical shaking is considered, it is expected that the damage to buildings due to soft-floor effect can be observed at distances far away from the epicenter. The damage to buildings as observed in Ahmedabad, Morbi, Surat in Gujarat state and Hyderabad in Pakistan far away from the epicenter may also be related ground amplification and the resonance phenomenon in addition to the poor quality of the construction.

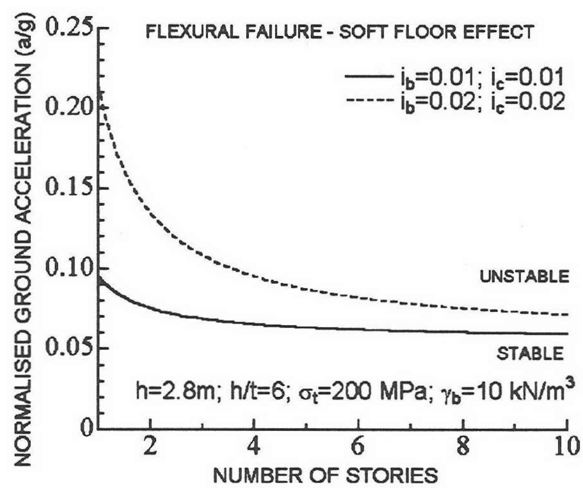

Figure 11: The relation between number of stories and lateral seismic coefficient for bending failure due to soft-floor effect

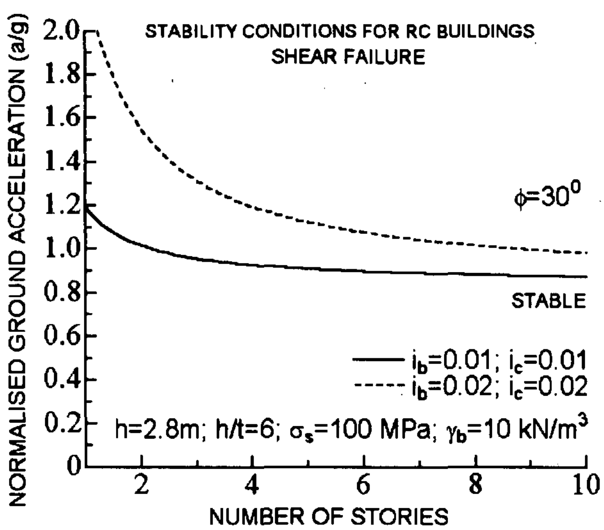

Figure 12: The relation between number of stories and lateral seismic coefficient for shear failure due to soft-floor effect

(3) Inference of Strong Motions from Mercalli Seismic Intensity

As pointed out in the previous section, there is no strong motion available for the epicentral area. Therefore, a relation between Modified Mercalli Intensity and maximum ground acceleration was derived from the empirical relations proposed by Aydan (1997) as follows:

$$a_{\max} = a(e^{0.6834 * I} - 1) \qquad [8]$$

where

I: Modified Mercalli Intensity at the particular location

$a = A * B$;

A:2.8 for soft soil ground and 0.56 for stiff and rocky ground,

$B = e^{-0.025*h}$: h:hypocenter depth. If it is not known, it may be assumed to be 20-25km.

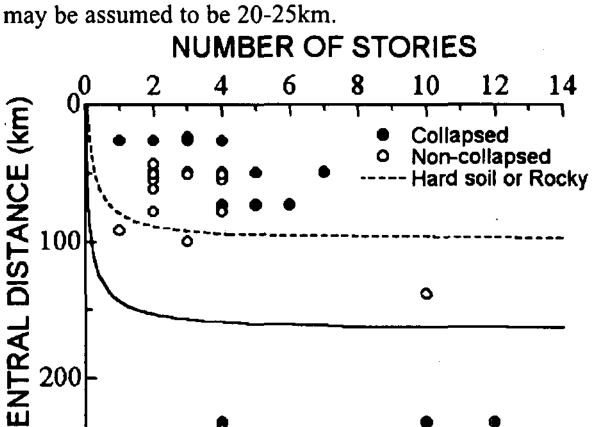

Figure 13: The relation between number of stories and hypocentral distance

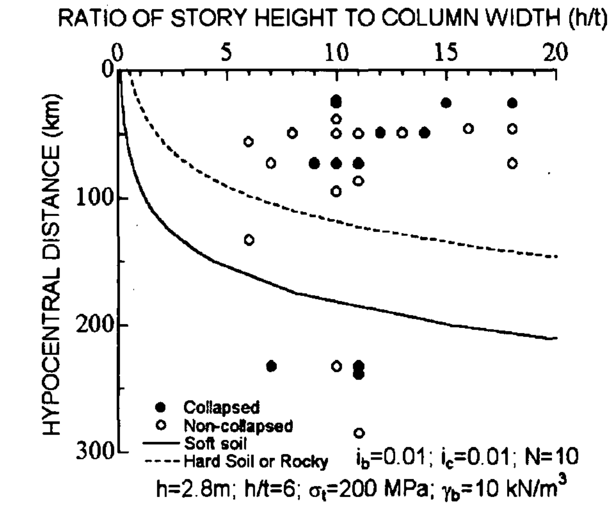

Figure 14: The relation between the ratio of story height to column width and hypocentral distance

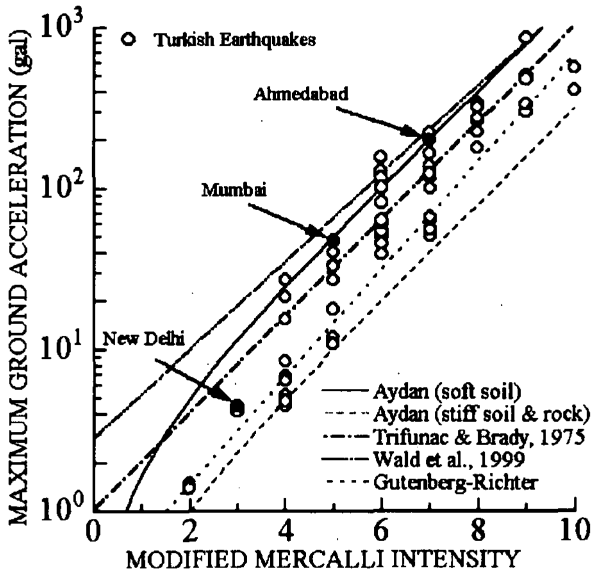

Figure 15: Comparison of empirical relations between Modified Mercalli Intensity and maximum ground acceleration with observations

This relation is then compared with estimations obtained from other empirical relations proposed by Gutenberg-Richter (Rchter 1958), Trifunac-Brady (1975) and Wald et al. (1999) in Figure 15. The actual data between maximum ground accelerations and Modified Mercalli Intensity (I) are from the measurements in Turkish earthquakes including the recent earthquakes. While the relation porposed by Wald et al. (1999) is an upper-bound for the actual data from Turkish earthquakes, the relation proposed in this report by Aydan for stiff and rocky sites provides a lower bound to the same data. It seems that the empirical relation proposed in this article may be used to infer the strong motions in the earthquake area where no strong motion data is available. In the same figure, the data for Ahmedabad, Mumbai (Bombay) and New Delhi are also plotted and the data from these sites almost coincide with the empirical relation proposed in this report for soft ground. From this empirical relation, it is inferred that the maximum ground acceleration could exceed 1g for soft ground and 0.3g for stiff soil and rocky ground in the epicentral area.

4. CONCLUSIONS

The outcomes and conclusions may be briefly summarized as follows:

1) Since there was not any well-defined fault scarp on the ground surface, it was difficult to say which of the fault planes determined from the fault plane solutions corresponded to the causative fault. Nevertheless, the fault plane with the NE strike and dipping south inferred by the method presented in this article could be the causative fault of this earthquake in view of the spatial distribution of the aftershocks and widely scattered surface ruptures.
2) The results for collapsed walls indicate that the masonary walls should had been failed due to toppling and the maximum ground acceleration could be computed from empirical attenuation relations by Aydan (1997, 2001). The ground conditions in many places correspond to hard soil or rocky ground and the computed results are quite consistent with actual observations.
3) Observations on RC buildings indicated that their failure was due to the soft floor-effect and they are confirmed by the computed bounds for stability against bending failure for soft-floor effect, using empirical attenuation relations by Aydan (1997, 2001). Furthermore if the effect of vertical shaking is considered, it is expected that the damage to buildings due to soft-floor effect can be observed at distances far away from the epicenter. The damage to buildings in Ahmedabad, Morbi, Surat in Gujarat state and Hyderabad in Pakistan far away from the epicenter may also be related to ground amplification and the poor quality of the construction.
4) The empirical relation between the maximum ground acceleration and Mercalli seismic intensity proposed in this report may be used to infer the strong motions in the earthquake area where no strong motion data is available. The data for Ahmedabad, Mumbai (Bombay) and New Delhi almost coincide with the empirical relation proposed in this report for soft ground. Therefore, it is inferred that the maximum ground acceleration could exceed 1g for soft ground and 0.3g for stiff soil and rocky ground in the epicentral area.

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