



## **BAM, IRAN EARTHQUAKE OF 26 DECEMBER 2003, MW6.5: A STUDY ON THE STRONG GROUND MOTIONS**

**Mehdi ZARE<sup>1</sup>**

### **SUMMARY**

The Bam earthquake of 26 December 2003 (Mw6.5) occurred at 01:56:56 (GMT, 05:26:56 local time) around the city of Bam in the southeast of Iran. The Bam earthquake of 26/12/2003 (Mw6.5) has demolished the city of Bam, having a population of about 100000 at the time of the earthquake. The Bam fault - which was mapped before the event on the geological maps - has been reactivated during the 26/12/2003 earthquake. It seems that a length of about 10km (at the surface) of this fault has been reactivated, where it passed exactly from the east of the city of Bam. The fault has a slop towards the west and the foci of the event was located closed to the residential area (almost beneath the city of Bam). This caused a great damage in the macroseismic epicentral zone; however the strong motions have been attenuated very rapidly, specially towards the east-and west (fault normal) direction. The vertical directivity effects caused the amplification of the low frequency motions in the fault-normal direction as well as the greater amplitude of the motion on the vertical direction.

### **INTRODUCTION**

The Bam earthquake of 26/12/2003 (Mw6.5) demolished the city of Bam in the southeast of Iran (Figure-1). The earthquake happened at 5:26 am local time when most of the inhabitants were slept, that can be one of the causes of the great life losses. The number of victims was declared officially to be more than 40000 at the time of the preparation of this article (19/01/2004). More that 50000 people are injured and about 100000 people remained homeless.

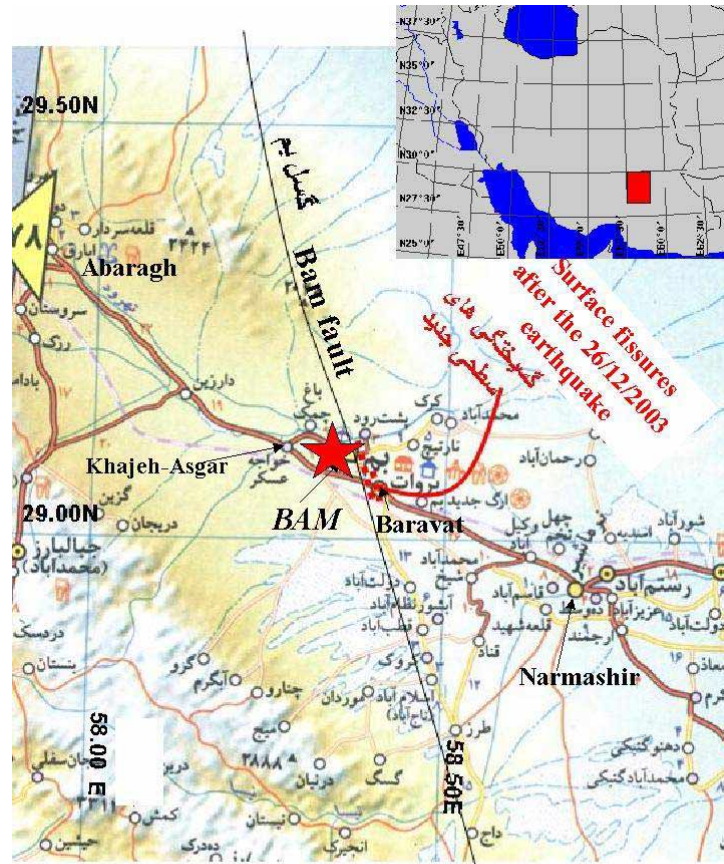
The Kerman province is one of the greatest provinces in Iran, with an area of 186,422 km<sup>2</sup> that is located in southeast of the country. The population of Bam and its suburbs was about 100,000 at the time of the earthquake in 2003. The damages were limited to the city of Bam and then to a smaller city, Baravat, which is located in the east of Bam. However the inhabitants of the villages located nearby Bam have left their house after the earthquake, due to the fear of the greater earthquakes (aftershocks) and according to the extensive to moderate damages to their buildings.

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<sup>1</sup> Engineering Seismologist, Assistant Professor, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, P.O.Box: 19395/3913, Iran, e-mail:[mzare@iiees.ac.ir](mailto:mzare@iiees.ac.ir)

The city of Bam is well-known by the historical citadel of Arg-e-Bam which is about 2000 years old that is mostly destroyed in the 26/12/2003 Bam earthquake (Figure-1) (Zaré [1]). Arg-e Bam is the biggest mud-brick complex in the world. This historical monument is located on an igneous hill, on the verge of the Silk Road. It has an area of some 240,000 square meters. There is no information about the exact date of its construction but according to Persian history it goes back to 2000 years ago and has been repaired several times, and was residential till 150 years ago. Since there is no report of the earthquake occurrence for the city of Bam in the Iranian historical earthquake catalogue, it seems that it was the first time during the last 2000 years that a disastrous earthquake has taken place due to the reactivation of the Bam fault. The date(s) of the previous earthquake(s) should be determined in the paleoseismological studies on the Bam fault.

This paper is prepared to summarize the latest studies performed in view point of strong ground motions. The strong motions recorded in this event are introduced and most of the paper is focused on the source parameters and the frequency content of the accelerogram recorded in Bam station, which was located in the Bam city center.



**Bam Earthquake of December 26, 2003,  
Mw 6.5**

Figure-1: The location map of the Bam earthquake epicentral region in SE of Iran.

## SEISMOTECTONIC OF THE STUDIED AREA

The Bam earthquake prone area in SE Iran is an active seismic zone (Figure-2). The Bam city itself had no reported great historical earthquake before the event of 26/12/2003 (Ambraseys and Melville [2]). Towards the northwest of Bam, 4 major earthquakes with the magnitudes greater than 5.6 have stricken the cities and villages since 1981 until 1998 (NEIC [3]). The trends of the main faults (including the Bam fault) in this region is North-South, and NW-SE (Figure-1) (Zaré [1]). These two systems intersect in western Lut area. The NW-SE faults (Kuhbanan and Ravar faults) and the north-south faults (Nayband, Chahar-Farsakh, Anduhjerd, Gowk, Sarvestan and Bam faults) have determined the border of the north-south structures in the Lut area with the NW-SE structures. These intersection zones are of the main sources for the disastrous earthquakes. The Gowk fault system is representative for its surface ruptures during 1981, 1989 and 1998 earthquakes as well as a hot spring system nearby Sirch. In the west of Golbaf-Sirch valley, there is the Lut depression, where a vertical topographic offset of more than 4000 meters is evident. Four great earthquakes have stricken the region during the recent years: Golbaf earthquake of 11 June 1981, Ms6.6, Sirch earthquake of 28 July 1981, Ms7.0, South Golbaf earthquake of 20 November 1989, mb5.6 and the North Golbaf (Fandogha) earthquake of 14 March 1998, Mw6.6. The Golbaf earthquake of 11/06/1981 has stricken the region of Golbaf in the southern parts of the Golbaf valley (with the strike of N5-15E). This earthquake which was associated with a fault rupture along the Gowk fault left a life loss of 1071 persons. The event caused great damages in Golbaf region. The Sirch earthquake of 28/07/1981 has occurred 49 days after the Golbaf earthquake and caused 877 life losses. It seems that it was originated as the secondary faulting along the Gowk fault (N-S trend) or the triggering of the rupture from activation of the Gowk fault in the hidden continuation of the Kuhbanan fault (NW-SE trend), in their intersection zone. Such situation might be the reason for the great earthquakes around Sirch in 1877 and 1981 (both with magnitudes greater than 7.0). South Golbaf earthquake of 20/11/1989 caused 4 people killed and 45 injured and some damages in Golbaf. Some surface faulting and folding have been reported to be related to this event. The North Golbaf earthquake of 14/3/1998 caused a death loss of 5 killed and 50 injured, and was associated with surface faulting (about 20km length) in northern Golbaf. The focal mechanism of these earthquakes show the compressional and strike slip mechanisms along the Gowk and Kuhbanan fault systems (Figure-2).

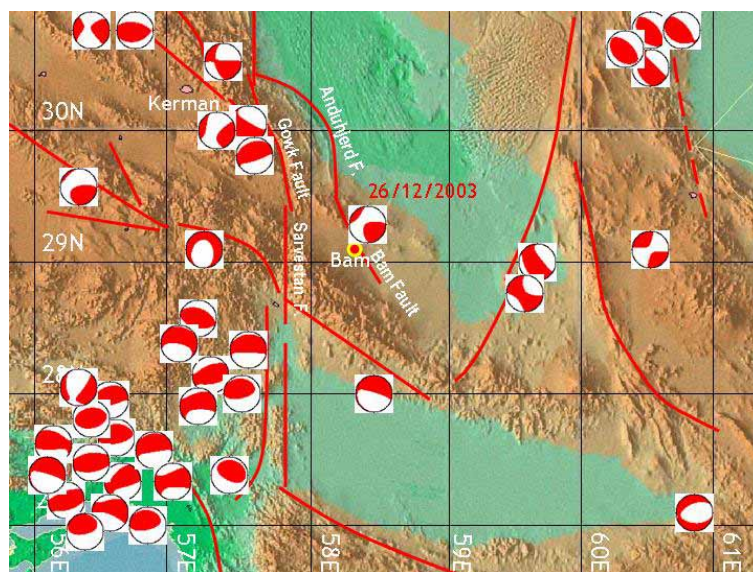


Figure-2: The seismotectonic map of the Bam Region (The base topographic map from USGS Global Digital Data Series [4], focal mechanism from: CMT solutions, Harvard University website [5]).

### **Focal Mechanism**

The focal mechanism of the Bam 26/12/2003 earthquake was reported as strike slip fault (CMT solution, Harvard university, web site [5], Figure-2), which coincides well with the surface evidences of right-lateral strike slip movement of the Bam fault. The reactivated fault plane had a near north-south direction and slop towards the west. The focal mechanism reported by Harvard University shows a small reverse component for the fault plane as well. The focal mechanisms reported for the earthquakes occurred in the region around Bam (Figure-2) show that most of the earthquakes occurred since 1975 till 2003 had strike-slip to compressional mechanisms.

### **Bam Fault Scarp**

The Bam fault has created a major topographic dislocation in the eastern Bam plain towards Baravat (Figures-3 and 4). This fault scarp shows the vertical displacement of about 10 to 20 meters in different places and is consisted of 3 major segments which are lengthened totally about 100km. The fault escarpment is visited several times after the earthquake but no major earthquake related displacement was found in its vicinity. The surface fissures, however, are found along this fault zone.



Figure-3: The Bam fault scarp from air.

The earthquake induced surface fissures are found in a region between Bam and Baravat and in the vicinity of the Citadel of Arg-e Bam, as well as the eastern parts of the city of Bam. The appearance of the surface displacement on the surface was impossible due to the depth of the earthquake (8km) and the dimensions of the source according to the earthquake magnitude (Mw6.5).

### **Source Parameters**

Based on a preliminary estimation of the seismic moment, a Mw=6.5 is assessed for the Bam earthquake. The focal depth of the Bam earthquake of 26/12/2003 is estimated to be 8km and the hypocentral distance for the record obtained in the Bam station was 12km (based on a S-P estimation on the

record obtained from the mainshock). The seismic moment is estimated by the author to be  $M_0 = 0.92 \times 10^{19} (N - m)$  based on the fast Fourier transformations using the Haskell method [6] applying the accelerogram recorded in the Bam station. The stress drop is estimation as well to be 480 bars.



Figure-4: The Bam fault scarp that caused a major topographic border in the east of Bam and west of Baravat (the region covered by palm trees in the horizon of the photograph).

### Seismic Gap

The existing records on historical seismicity indicate no major earthquake in Bam since the historic time. It seems that Bam earthquake of 26/12/2003 has ended a seismic gap along the Bam fault. This seismic gap could be verified with the Arg-e Bam castle, which is constructed about 2000 years ago and not demolished at all since then, until the 2003 earthquake of Bam. However the archeologists believe that the citadel was rebuilt several times during the history and they are dubious about at least one of these reconstructions to be performed according to a probable historical earthquake (that is certainly not mentioned in the historical books). Such estimations are preliminary and should be verified in the detailed investigations in the future.

### Aftershocks

The aftershocks recorded by 25 stations of a temporary network installed by IIEES within 3 months after the earthquake are mostly located towards the west of the Bam fault, which could be justified according to the slope of the Bam fault towards the west. Most of the focal mechanisms estimated for these aftershocks (that are estimated for the events having at least 5 well recorded data) show similar mechanisms to that reported as a CMT solution (Harvard University, Figure-2) for the mainshock. Therefore, the reactivated Bam fault (with a slope towards west and a strike of NNW-SSE) seems to be active for 3 months after the

mainshock, and most of the aftershocks are focused in the central and southern parts of the Bam fault (east to south of Bam).

## STRONG GROUND MOTION

The strong motions in this event are recorded in 22 stations of the national Iranian strong motion network (according to Building and Housing Research Center, BHRC web site [7]). The strong motion records are studied and filtered and the preliminary results are presented mostly based on the mainshock and aftershock records obtained in Bam station. All of the strong motion data obtained during the Bam earthquake are recorded by the digital Kinemetrics SSA-2 accelerographs. The attenuation of the strong motions is studied as well based on the records with good signal to noise ratio in 6 stations. The isoseismal map of the region is presented as well according to the site visit performed in the region.

### Bam Strong Motion Record

The record obtained in Bam station (Figure-5) - after a band-pass filtering between 0.11 and 40Hz - shows the greatest PGA of 775 and 623  $\text{cm}/\text{sec}^2$  for the east-west horizontal and north-south horizontal components, respectively, and 992  $\text{cm}/\text{sec}^2$  for the vertical component. This processing is performed based on the estimation of the signal to noise ratio (Figure-6). The fast Fourier transformation (Figure-7) shows the longer period for the fault normal horizontal component. Zaré et al [8] showed that the assessment of H/V ratio may show the fundamental frequency of the site and could be taken as the criteria to classify the site response to earthquakes.

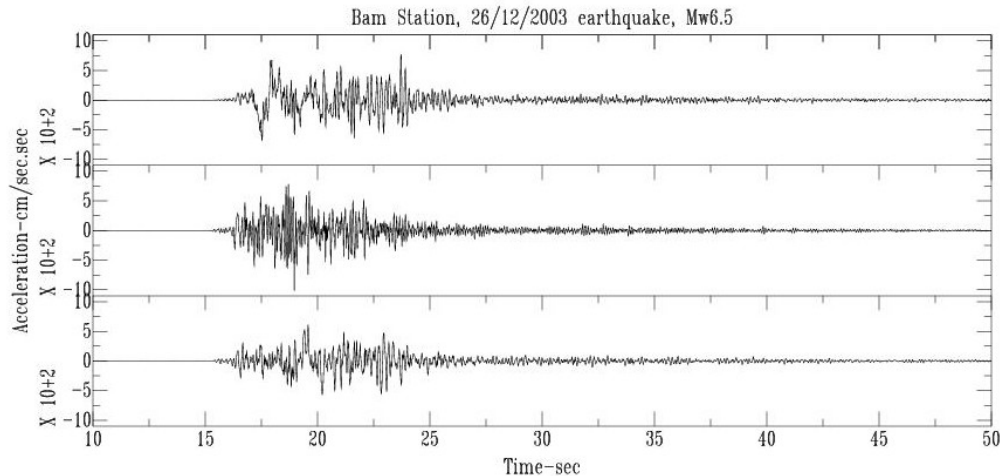


Figure-5: The Bam accelerogram after filtering (between 0.11 and 40Hz).

The comparison of the H/V ratio obtained in Bam station during the mainshock and 13 aftershocks occurred in the first 24 hours after the earthquake (Figure-8) shows very well a low frequency amplification between 0.1 and 0.2 Hz which is evident in the mainshock and it is not evident in the aftershocks. This may be taken as an evidence for the vertical directivity effect. This effect can be assigned to the Bam earthquake fault rupture propagation towards the surface and obliquely towards the north. A strong fault-normal (east-west) motion is created during the mainshock as well. The demolished walls and buildings of Bam are representative for such effects in the up-down (vertical) and east-west directions (fault-normal). The Bam residents that survived the quake explained for the reconnaissance team members that they felt strong up-down displacements during the mainshock. The site class however

may be taken for class '3' since the site fundamental frequency was about 2 to 5 Hz (equal to a site condition having the average shear wave velocity of about 300 to 500 m/sec in the first 30 meters of the deposits, Zaré et al [8]).

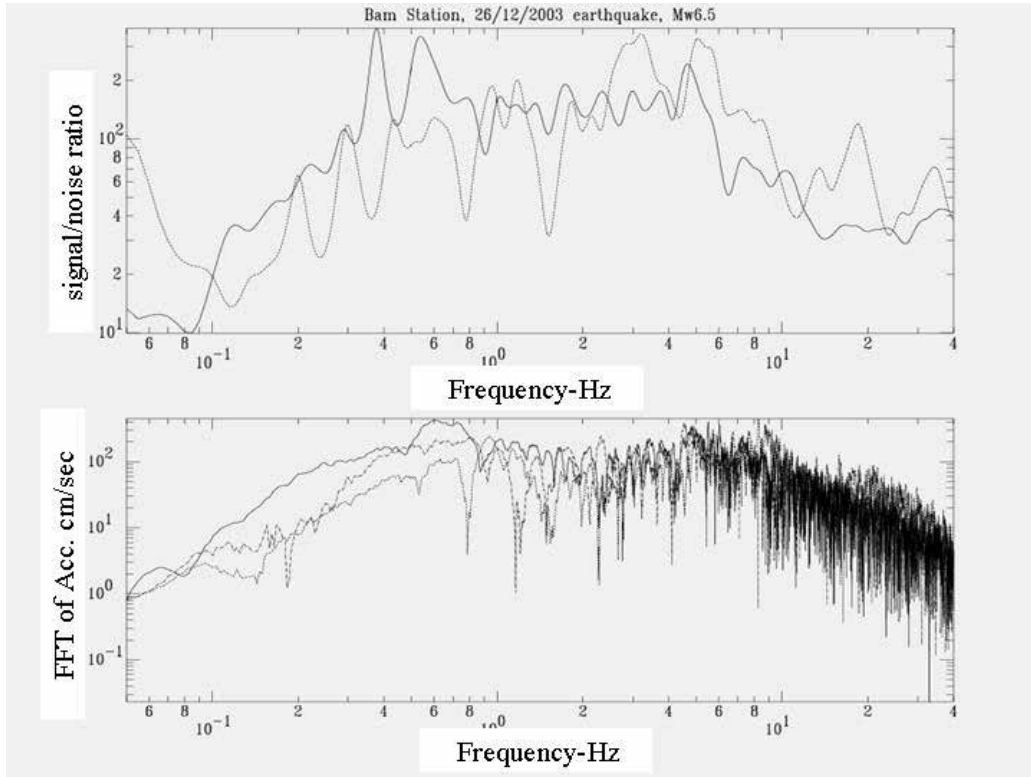


Figure-6: The signal to noise ratio (up) and the FFT of acceleration (down) for the three-components record of Bam.

The velocity and displacement time-histories of the Bam record obtained based on single and double integration of Bam accelerogram are shown in figures 8 and 9, respectively. These time-histories show a great pulse specially in the fault-normal component, which may be related to the directivity effect, as is explained above.

The spectral accelerations for 5% damping are shown in figure-10 for three-component accelerogram obtained in Bam station. This figure shows very well the predominant periods of 0.1 second for vertical and 0.2 second for 2 horizontal components. Figure-10 shows as well the higher spectral ordinates for the vertical component and for the fault-normal horizontal component as well.

### Attenuation of Strong Motions

The Attenuation of strong motions are studied based on the processed records obtained in 6 stations (having the accepted level of signal to noise ratios) of Bam, Abaragh, Mohammadabad-e Maskun, Jirof, Golbaf and Sirch. The attenuation of strong motions was studied by Zaré [9] in Iran based on the strong motions recorded between 1974 to 1996. The catalogue of Iranian strong motions is published in Bard et al [10]. The attenuation of strong motions recorded in these 6 stations are compared with the values obtained by the empirical relationships (Zaré [9]) obtained for the Mw6.5 earthquake for horizontal and vertical

components, that are shown in figures 11 and 12 respectively. These figures show very well the coincidence of the estimated and observed values specially for the far-field records. However the Bam record (obtained in the hypocentral distance of 12km) could not be estimated properly with the previously developed attenuation laws, since very few near-field records were available when those attenuation laws were preparing.

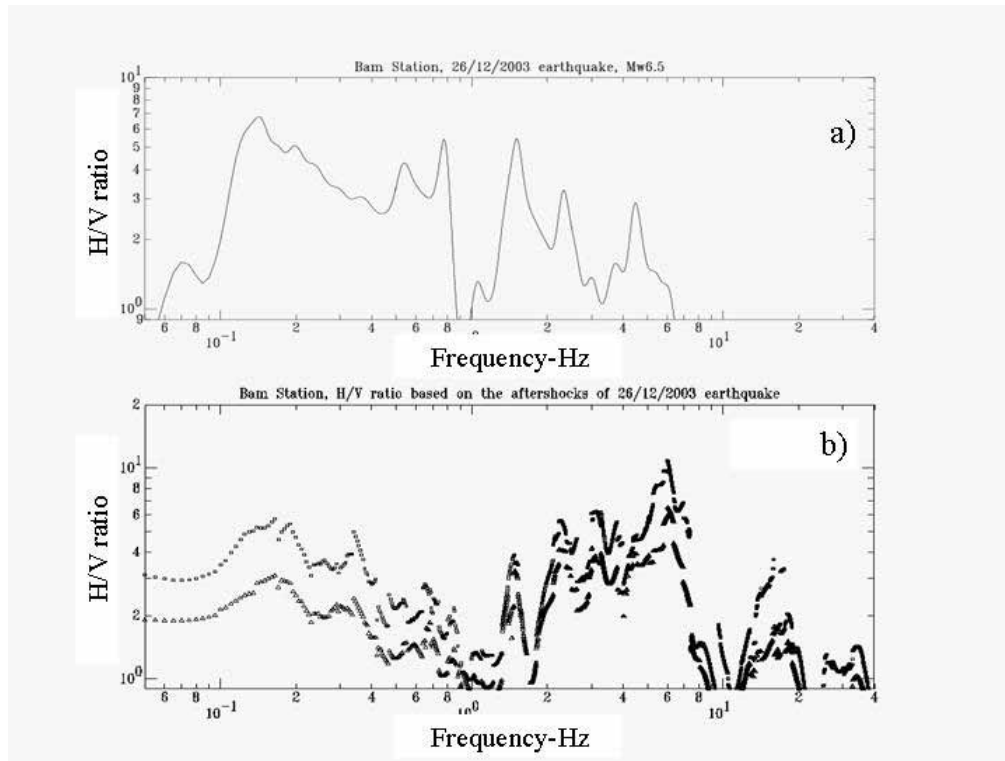


Figure-7: The H/V ratio for a) the mainshock and b) aftershocks recorded in Bam strong motion station.

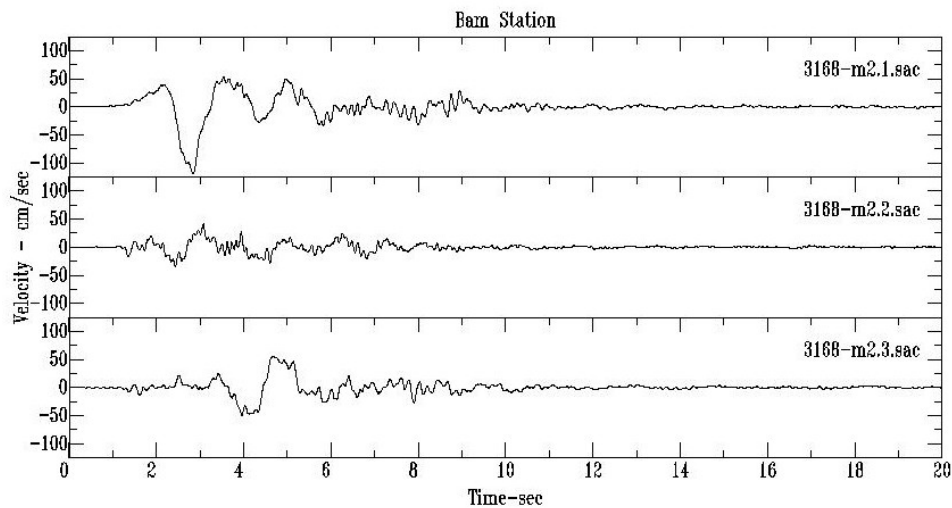


Figure-8: The velocity time-history based on single integration of accelerogram recorded in Bam.

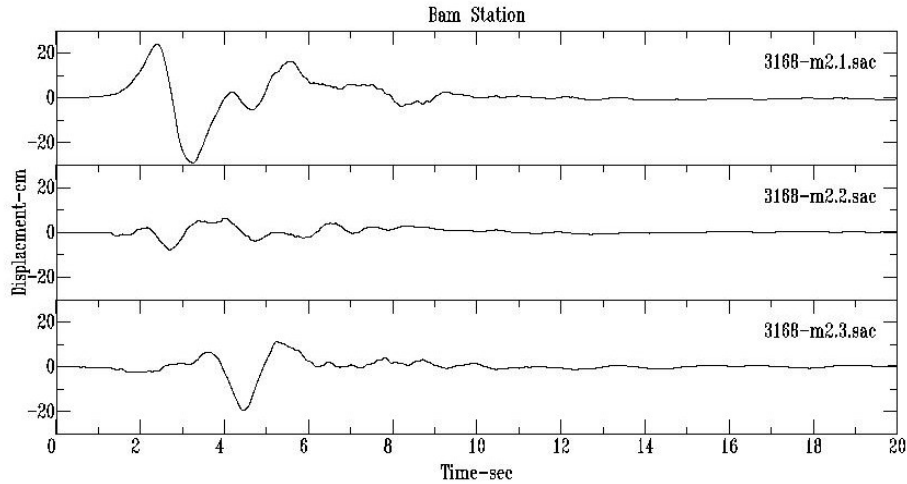


Figure-9: The displacement time-history, estimated based on double integration of the Bam station accelerogram.

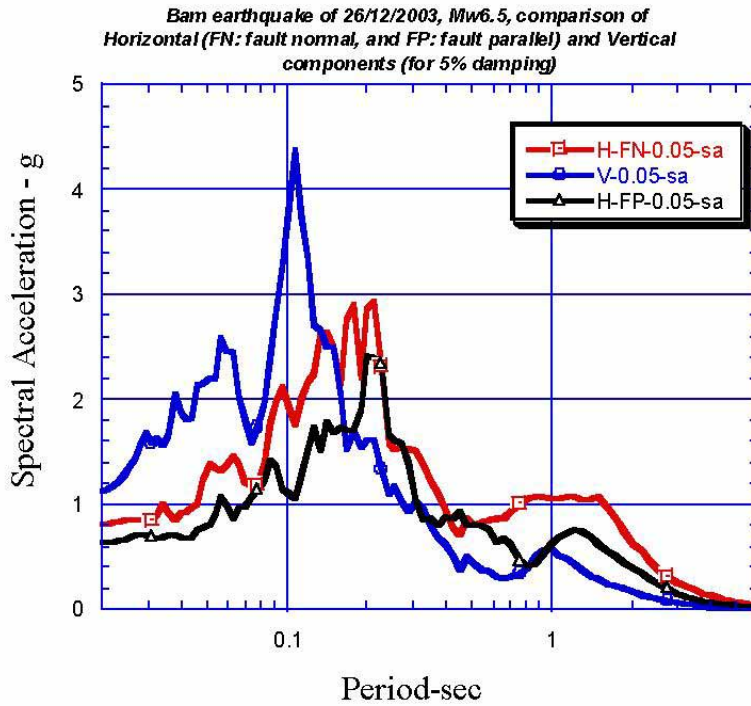


Figure-10: The spectral acceleration for 5% damping, the values for horizontal-fault normal (FN), fault parallel (FP) and vertical components are shown.

### Macroseismic Intensity and Isoseismal Map

The eastern northern parts of Bam are demolished more during the earthquake. The damage distribution map (Figure-13, SERTIT European satellite image), shows higher damages in the northern Bam, where it

could be related to bad construction material and older building concentrated in these parts of the city. The higher damages in eastern Bam, however, could be related to the construction in the near-fault conditions, that can be justified as well based on the fault slop towards west.

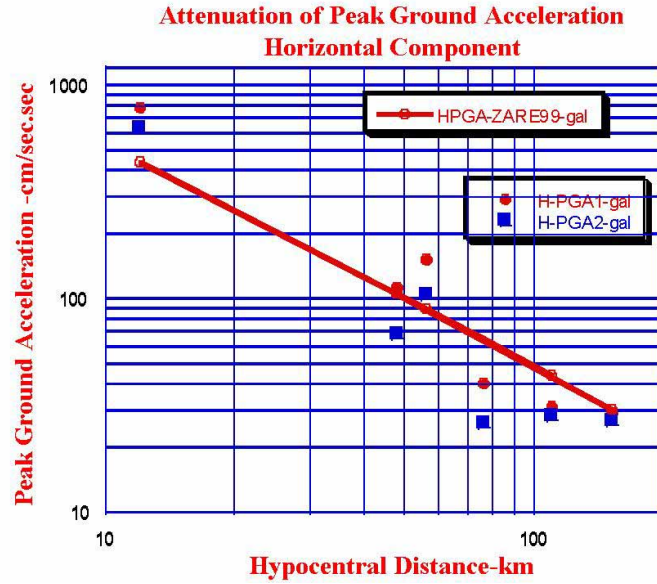


Figure-11: The attenuation of strong motion estimation by Zaré [9] attenuation laws for the horizontal component compared with the observed values in Bam earthquake in 2 horizontal components of 6 selected records.

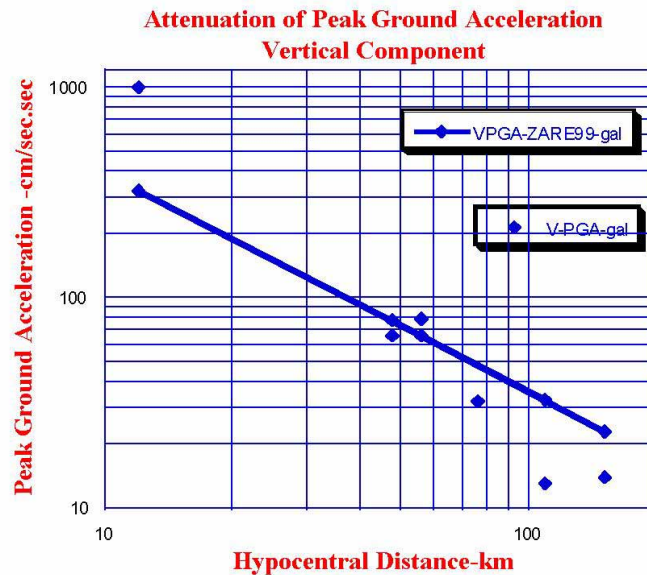


Figure-11: The attenuation of strong motion estimation by Zaré [9] attenuation laws for the vertical component compared with the observed values in Bam earthquake in vertical components of 6 selected records.

The isoseismal map of the Bam earthquake is prepared based on a field reconnaissance study [Eshghi et al [11]) performed in the prone area immediately after the event (Figure-14). Based on this study, the macroseismic intensity of the earthquake is estimated to be  $I_0=IX$  (in EMS98 scale), where the strong motions and damaging effects seems to be attenuated very fast specially in the fault-normal direction. The intensity levels are estimated to be VIII in Baravat, VII in New-Arg (Arg-e Jadid) and airport area. The intensity level was estimated to be around IV-V in Kerman and Mahan.

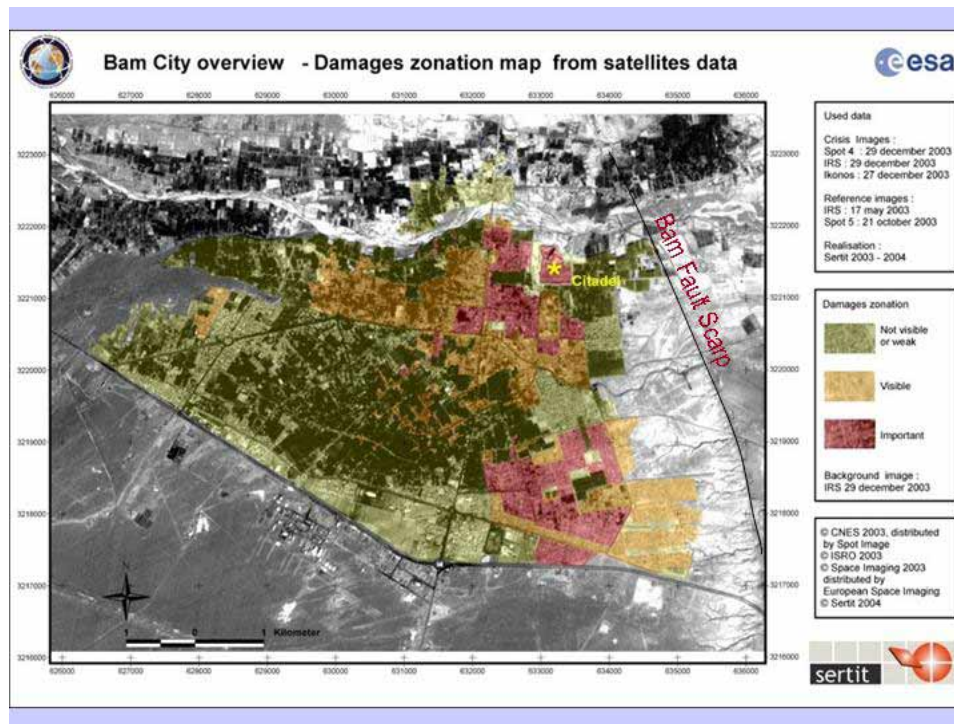


Figure-13: The damage zoning map estimated ESA using the SERTIT European satellite. The trace of the Bam fault scarp is shown by the author on the image. The red-shaded parts of the city are representative for the important damages where the brown and green parts are showing the moderate and lower damages.

## DISCUSSION

The Bam earthquake cause greatest human disaster in 2003 according to a life loss of about 45000 victims and the demolishing of the city of Bam. The 22 strong motion records obtained in this event are studied and six records are selected based on the estimation of signal to noise ratio. The vertical directivity effects could be observed based on the greater damages along vertical and fault-normal horizontal directions, as well as the long period amplification in 5 to 10 seconds in the mainshock. The attenuation of strong motions in the fault normal direction was higher than the fault-parallel direction and the attenuation rate was very high. The higher attenuation rate could be related to the high stress drop estimated for this event and low duration (about 10 seconds).

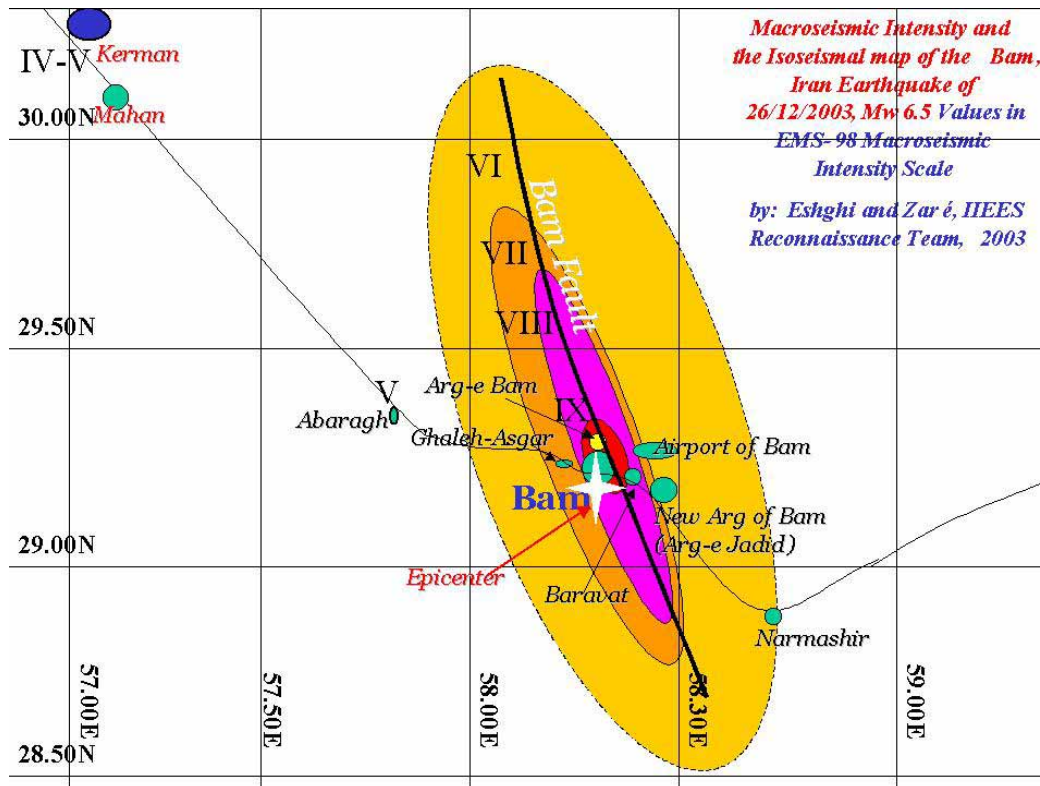


Figure-14: The isoseismal map prepared by the IIEES earthquake reconnaissance team (Eshghi and Zaré [11]). The intensity values are given in EMS-98 scale.

## CONCLUSION

The strong motions records and intensities observed in the Bam earthquake records are representative for a very strong but short earthquake that had the great vertical and fault-normal direction near-fault effects. This earthquake had no visible surface fault displacement, but some surface fissures created during the earthquake are observed along the Bam fault scarp. The shallow depth (8km) and the location the epicenter (nearby the city of Bam), along with the old and weak buildings caused the high level of life and property losses during this event.

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