PROVISIONAL REPORT OF THE DECEMBER 26, 2003 BAM EARTHQUAKE, IRAN

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ABSTRACT: The Bam earthquake of December 26, 2003 (Mw6.5) occurred around the city of Bam in the southeast of Iran. Since the earthquake happened early in the morning at 01:56:56 (GMT, 05:26:26 local time), most of the reported victims of 43,100 were killed in their dwellings. A joint team covering both social and engineering aspects of this killer earthquake was organized among the Japan Association for Earthquake Engineering, Japan Society of Civil Engineers (JSCE) and the Ministry of Education, Culture, Sports, Science and Technology (MEX), with the International Institute of Earthquake Engineering and Seismology (IIEES) as the major Iranian counterpart. This is a quick report prepared by the ERS members covering physical features of the earthquake and damage to dwellings.

Key Words: Bam earthquake, local site effect, utility poles, microtremors, adobe dwellings

INTRODUCTION

An intense earthquake occurred in southeastern Iran at 5:28 local time, December 26, 2003. Though the moderate moment magnitude of 6.5 (Building and Housing Research Center, Iran) – 6.6 (USGS) calculated for this earthquake was not surprisingly large as contrasted with those major earthquakes that ever occurred in this country, Bam, an oasis city in a desert, was seriously ravaged. About 43,100 people were reportedly killed and 1,300 injured making this earthquake the worst that Iran has ever had.

The city had about 100,000 residents according to official figures. Shortly after the earthquake, the officials announced that the possible death would be 28,000. The number was revised down to 26,500 on January 3, but as the rescue crews continued to pull out dead bodies from debris, the death toll increased. On Jan. 15 the official estimates put the number of casualties between 30,000 and 35,000, and up until now the death toll has been increased up to 43,100. Since the earthquake happened quite early in the morning, the majority of the casualties was killed in their dwellings, mostly adobe, unreinforced and/or confined masonry structures.

Several organizations in Japan including the Japan Association for Earthquake Engineering, Japan Society of Civil Engineers (JSCE) and the Ministry of Education, Culture, Sports, Science and

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Technology (MEX) decided to dispatch investigation teams to Iran. After some discussions, a joint engineering team was organized for an efficient reconnaissance survey. Although the major counterpart organization was the International Institute of Earthquake Engineering and Seismology (IIEES), the Building and Housing Research Institute (BHRC) and the University of Tehran (UT) also collaborated during the field survey. The joint team made the first and second reconnaissance trips on Feb. 16–25 and Feb. 23–March 5, respectively, stressing on the evaluation of damage to dwellings, description of the damage in terms of possible intensity distribution, which might have been affected by local and geological site conditions, and discussion with Iranian specialists about possible future collaborations beneficial for both Iranian and Japanese sides.

SOURCE PARAMETERS AND GEOLOGICAL STRUCTURE

Southeastern Iran is a region of widespread active faults (Figure 1a) that take up basically right-lateral shear in this area. The Bam Earthquake measuring 6.51 on the Richter scale occurred on December 26, 2003 at 05:28 local time, with its epicenter located at 29.004 N, 58.337 E, on a predominantly right-lateral strike-slip fault. The focal depth was located 7 to 12 km directly underneath Bam city spreading west behind a pressure ridge formed along Bam fault (Fig. 1b). The presence of a pressure ridge suggests that there are shortening (thrusting) components associated with the strike-slip movement of the fault.

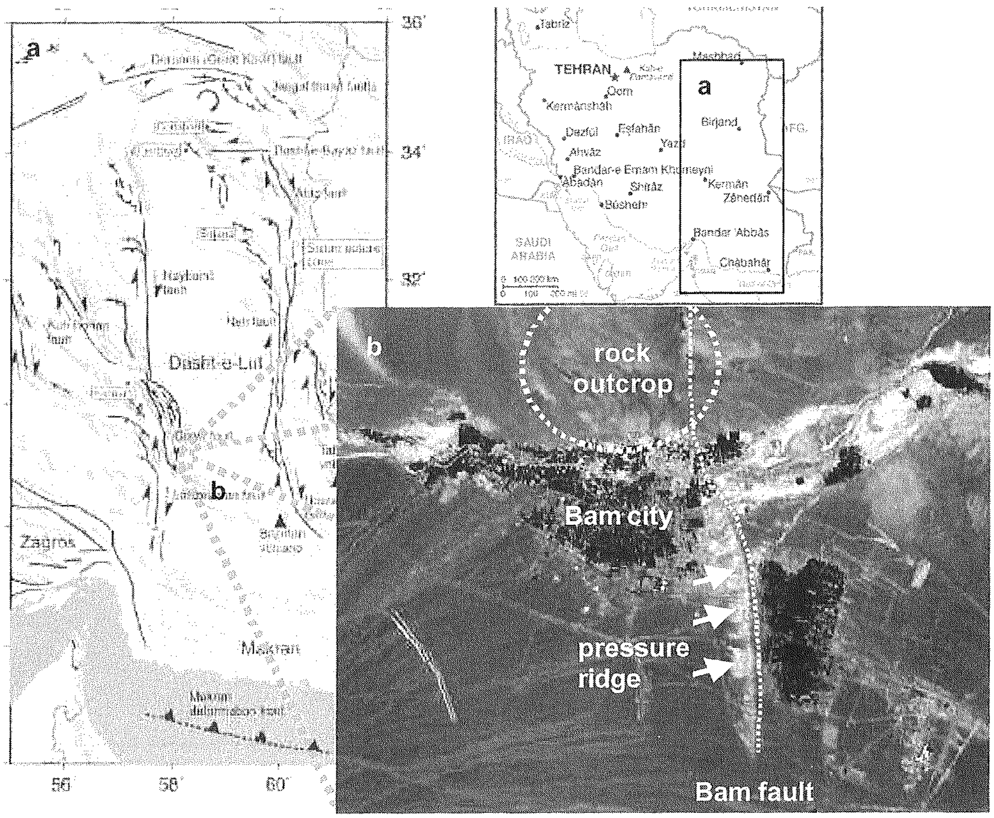


Fig. 1 Location of Bam and its satellite imagery: Bam fault take up basically right-lateral shear in this area. However some shortening component has been responsible for forming a pressure ridge along the fault. Bam city spreads behind the pressure ridge on the hanging wall side. (Satellite imagery from LANDSAT, [1]).

Fig. 1b shows satellite imagery from LANDSAT [1] covering Bam. A volcanic rock outcrop can be seen just north of the city, which dips to the south. The rock is cut in half by Bam fault, which extends from north to south. The 2 km wide pressure ridge has stopped sand, soil and other suspended matters that rivers from mountains have carried over centuries. The area is thus rich of underground water. Taking this advantage, Bam, an old oasis city has been developed with no reported great historical earthquake before this event. The city spreads about 6 km from north to south and 8 km from east to west on the hanging wall side.

The International Institute of Earthquake Engineering and Seismology (IIEES) did seismic profiling along total 10 lines taken in the city after the earthquake [2]. Color bars in Fig. 2 show average soil profiles at these lines. Alluvial soil covers thick the mid to southern part of the city area, while the soil becomes thinner as we go north. Fig. 2 shows inferred layer boundaries of shear wave velocities 155 m/s and 900 m/s respectively, both showing rich variation of soil profile in Bam city.

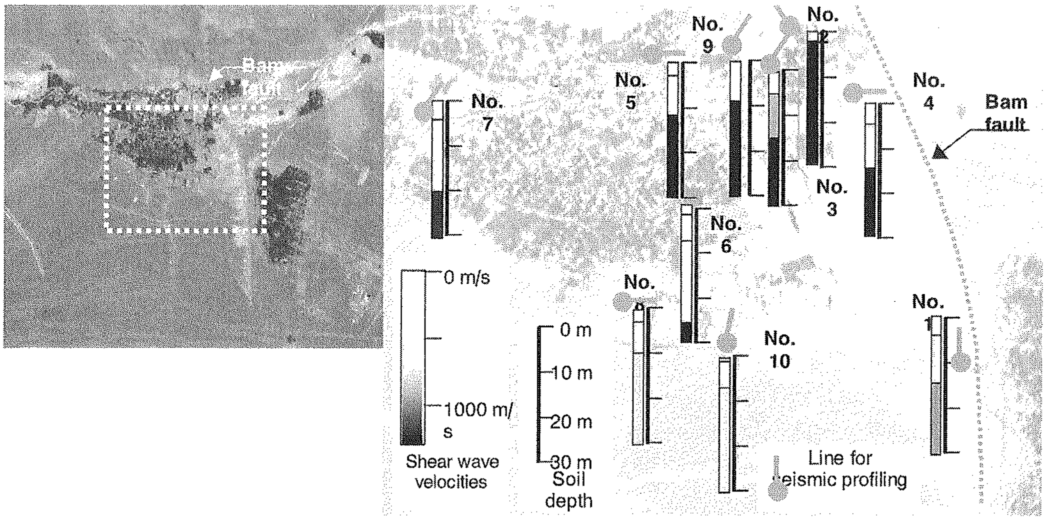


Fig. 2 Seismic soil profilings in Bam: Each marks with a circle on its one end show a line taken for seismic profiling. Circle denotes the point where a blow was given. (Original data from [2])

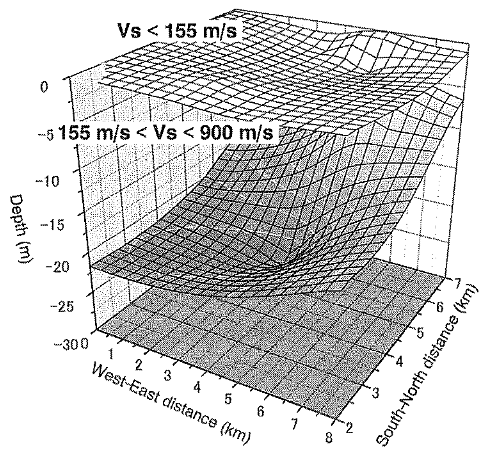


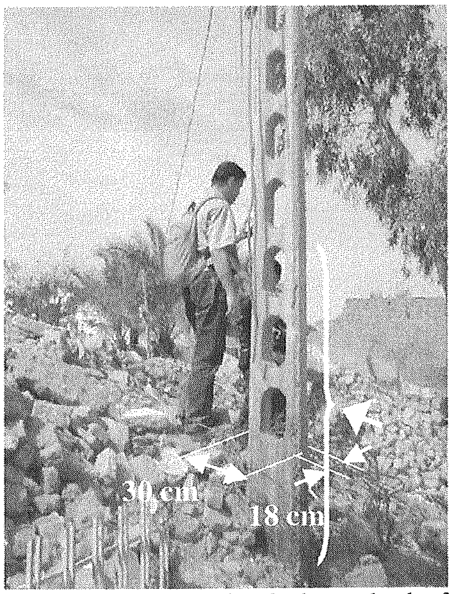
Fig. 3. Inferred layer boundaries of shear wave velocities 155 m/s and 900 m/s respectively.

STRAINS REMAINING ON UTILITY POLES

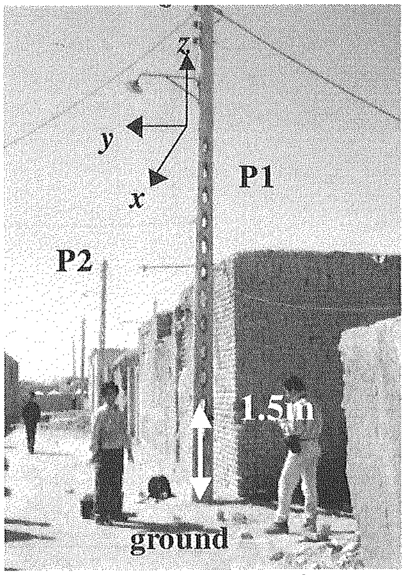
For oasis cities near active faults to be prepared for possible future earthquakes, damage caused by the Bam earthquake is to be discussed in terms of strong ground motion features that dwellings have experienced. However, as was often the case, damage differed from street block to street block, while only one seismometer was available in the city. In countries such as Japan and Iran ranked as the most seismic hazard prone zones in the world, strong ground motion networks are often very dense to describe seismological features of earthquakes, but yet very sparse to describe damage distribution frustrating many attempts for learning lessons from tragedies. Among possible breakthroughs, measuring traces of intense shake remaining in structures, which are seen everywhere and have common features, could be very effective. The authors used utility poles in Bam as this structure. Poles differ in their dimensions from area to area, but a thin pole type, with holes for climbing on, were the most widely used in the city (Fig. 4(a)) and, thus, chosen as the target.

Table 1. Characteristics of the surveyed poles

Name	Height (m)	Remarks
P-1	6.6	Pole with hexagonal holes
P-2	6.6	Pole with hexagonal holes filled with concrete



(a) 8m pole with holes and embedment depth of 2 m



(b) Poles P-1 and P-2

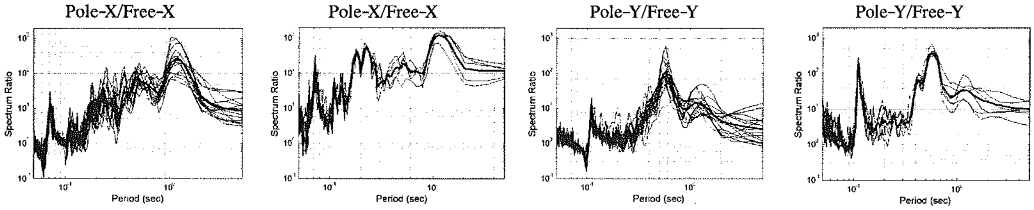
Fig. 4 Poles taken in Bam

In order to examine the dynamic features of this pole type, microtremors were measured at two poles (Fig. 4(b)). Their characteristics are summarized in Table 1. Bottom holes on P-2 pole were filled in to prevent theft.

A pair of 3-components velocity sensors was used for the measurements, one on the ground and the other strapped to each pole at the height about 1.0 to 1.5m above the ground. In each case, the X-axis was taken along the transmission line. Tremors were measured with poles a) subjected to ambient vibration, basically wind; b) hit in X-direction; and c) hit in Y-direction.

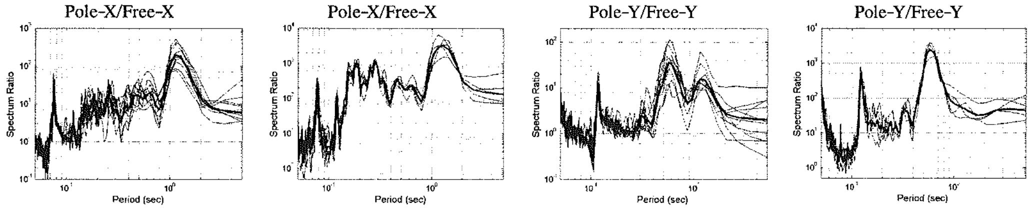
Each time history of the tremor was divided into several 10.24sec pieces. Fourier spectra of all pieces were then calculated and averaged for each time history. In order to obtain transfer functions in the frequency domain, spectra measured on the pole were divided by those on the ground.

Fig. 5 shows the transfer function for P-1. It is clear in Y-direction that there is little change of the predominant periods between the "ambient" and "hit" cases. In both cases, clear peaks are found at 0.105 and 0.57sec, with the main difference being the peak relative amplitudes. When the structure is hit, the lower period amplitude becomes higher.



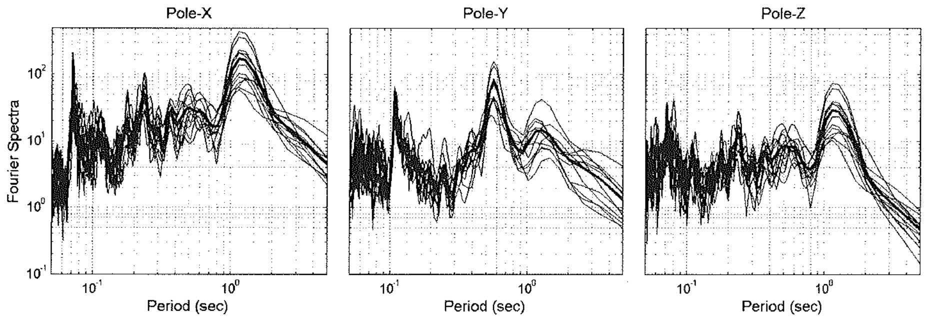
(a) Ambient vibration (b) Hit in X-direction (c) Ambient vibration (d) Hit in Y-direction

Fig. 5. Transfer functions for pole P-1

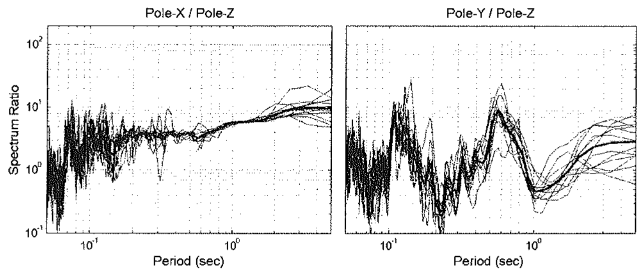


(a) Ambient vibration (b) Hit in X-direction (c) Ambient vibration (d) Hit in Y-direction

Fig. 6. Transfer functions for pole P-2



(a) X-direction spectrum (b) Y-direction spectrum (c) Z-direction spectrum



(d) Comparison among spectrum in different directions

Fig. 7. Comparison of P-1 spectra in three directions

Poles exhibits quite different vibration features in X-direction. As for ambient vibration cases, two peaks at 0.07 and 1.10 sec are distinguished among the others at 0.18, 0.21, and 0.6. When the structure is hit, two clear peaks appear at 0.18 and 0.21s in addition to 0.07 and 1.10s, but 0.6s peak is not clearly seen suggesting that this peak is the crosstalk from Y-component of the pole vibration.

Fig. 6 shows the transfer functions for P-2 pole. The functions have similar shapes as those for P-1 pole in all cases, suggesting that mortar filled in holes had little effect on the dynamic behavior of the pole. Fig. 7(a), (b) and (c) show X, Y and Z components of the pole vibration spectra. It is noted that the spectra for X and Z components are similar with each other, while Y component exhibits some different shape. Fig. 7(d) shows X/Z and Y/Z spectra ratios to highlight this feature. Assuming that the vertical vibrations of the pole were mainly induced by cable oscillations, it may be concluded that a cable has an important effect on the pole's motion along the cable.

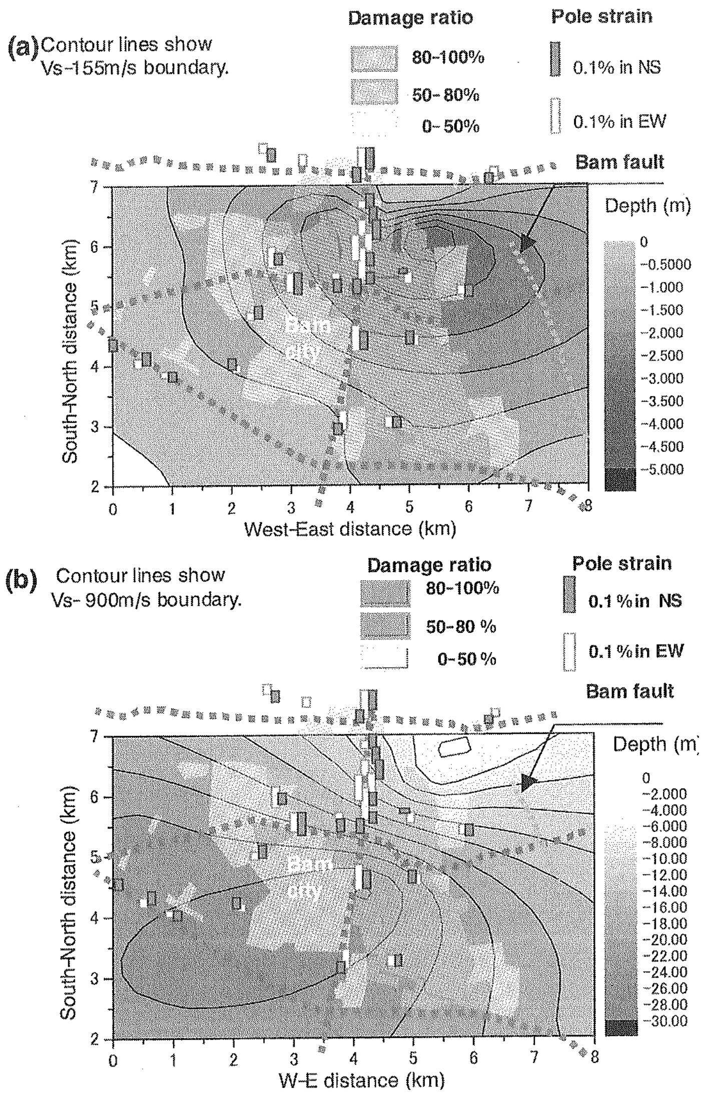


Fig. 8 Strains remaining in poles: (Damage distribution mapped by NCC, Iran [3])

For this reason, crack openings on pole sides without holes were taken to minimize the effect of transmission lines, the cracks caused by poles' motion in Y direction. For each pole, crack openings were added up over about 2m distance near the lower pole end, and then the total openings were divided by the distance to obtain average strain remaining on the pole. Total 270 poles were taken both in the city and its suburbs. The poles were then divided into several tens clusters in such a way that each cluster includes at least one crossing in it. Since the poles in one cluster line up at least two roads crossing each other, both north-south (NS) and east-west (EW) average strains were obtained cluster-wise. Fig. 8(a) and 8(b) show the distribution of remaining average strains in the city. Contour lines in Figs. 8(a) and (b) show inferred layer boundaries of shear wave velocities $V_s = 155m/s$ and $V_s = 900m/s$, respectively (see Fig. 3), and colored zones show percentages of damage mapped by the National Cartographic Center of Iran [3]. Though the strain distribution seems to be consistent with the overall damage distribution pattern, the strains do not tell directly anything about seismic intensity. A calibration is necessary for this discussion, and it will come up in future publication.

BUILDING DAMAGE

Construction practice in Bam City and typical observed damage

Although the Iranian Code of Practice for Seismic Resistant Design of Buildings, Standard No. 2800 [4] prohibits the use of adobe buildings, this is by far, the predominant construction material in the region, especially in the older part of Bam city. Typical houses are one story height with thick walls, up to 900mm, and heavy roofs, which serve as insulation for both hot and cold weather. Adobes are prepared manually as shown in Fig.10 and its typical measures are 250mm×250mm×65mm. Natural fibers are sometimes included in the mud mix. Multi-wythe walls are the most common.

Unreinforced masonry, confined masonry, and steel buildings with masonry infill are also common in the area. Very few reinforced concrete structures are observed. Masonry bricks vary in quality and are produced through both artisan and industrial processes.

Adobe structures were badly damaged as in many previous experiences. Fig. 11 shows a completely collapsed adobe house in the front whereas in the back, a confined masonry structure stands almost undamaged. Some masonry structures are provided with horizontal ties only, i.e. collar beams, as shown in Fig. 12. Although the complete collapse is prevented, the lack of vertical ties causes the failure of the wall corners.

Damage evaluation survey

Considering the damage evaluation [3], which was prepared based on aerial photographs, 33 locations covering Bam and Baravat cities were selected. At each location, three surveyors evaluated two damage levels: complete collapse and non-collapse, corresponding to D5 and D0-D4 damage levels in the EMS-98 scale [5], respectively. The surveyed area approximately corresponded to a circle with radius equal to 50-100m. The surveyed buildings were typified as: adobe houses, adobe walls, unreinforced masonry, confined masonry, steel, and reinforced concrete. The number of buildings of each type and the collapse rate was recorded. Four levels of collapse rate were considered: >80%, 50-80%, 20-50%, and <20%.

As part of the survey, microtremors were measured at all the locations were damage was evaluated in order to estimate the dynamic properties of the underlying soil deposit. Additionally, microtremors were recorded at typical undamaged constructions to determine their fundamental periods. The sensors, with a frequency range 0.5-20Hz, recorded velocities in three directions. Four to six 40.96sec measurements were taken at each location.

Results and discussion

At first the results of the microtremors measured at the building structures are discussed. The data was processed by choosing the portions of the records with fewer disturbances. The Fourier Spectrum of at least 8 windows of 10.24sec were calculated and smoothened with a 0.3Hz width Parzen window. The so-obtained spectra were averaged to evaluate the structure dynamic properties.

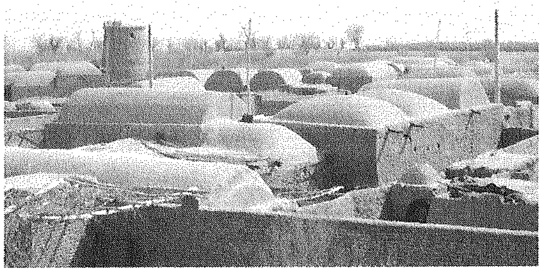


Figure 9. Overview of Darzin City near Bam

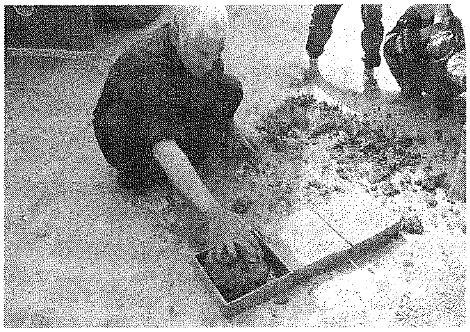


Figure 10. Adobe preparation

Figure 11. Completely collapsed adobe house

Figure 12. Heavily damaged partially confined masonry house

Figure 13 shows one of the surveyed adobe houses in Darzin City. The structure height is approximately 3.8m and the average wall thickness 800mm. The sensor was placed on top of the roof coinciding with a wall alignment. Figure 14 illustrates the analysis results. The blue lines show the spectra of different measurement windows whereas the red line represents the average. The fundamental periods in the longitudinal and transverse directions are 0.1 and 0.09sec, respectively. It is clear that the structure is slightly stiffer in the transverse direction along which several walls were aligned. The transverse direction spectrum shows a peak at 0.1sec, which coincides with the vibration period in the longitudinal direction. This may suggest some torsional vibrations in the structure.
Similar measurements were carried out at other structures. Generally, adobe predominant periods varied between 0.09 and 0.11 sec. On the other hand, masonry houses had typical periods of 0.07 to 0.09sec. Figure 15 shows the results of the adobe house damage evaluation plotted on the damage distribution map published in [2]. From the graph it is clear that the adobe construction predominance is related to the city evolution. The closer the surveyed point is to Arg-e-Bam, the city origin, the larger the number of adobe houses. It can also be observed that the newer the structure, i.e. further from Arg-e-Bam, the lower the collapse rate. As expected the adobe performance was poor. Among 18 observed points where these structures were present, 13 sustained more than 80% collapse rate and 16 sustained more than 50% collapse rate. Very few adobe houses survived the earthquake in the city downtown. Figures 16 to 18 show the damage distribution for unreinforced masonry, confined masonry and steel structures, respectively. From these figures, it is clear that the best performance was achieved by the confined masonry houses. If soundly constructed, steel structures should also have very good performance during earthquakes. Unfortunately, in the case of Bam City, the lack of qualified construction workers led to numerous failures at the welded connections. Poor detailing was also observed in the small size of the plates used for connecting steel elements.

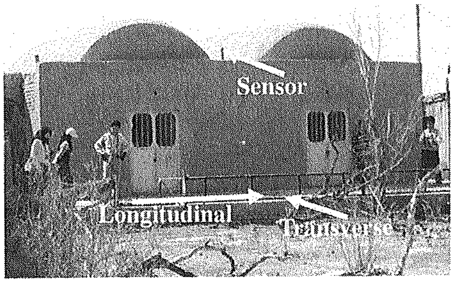


Figure 13. Completely collapsed adobe house

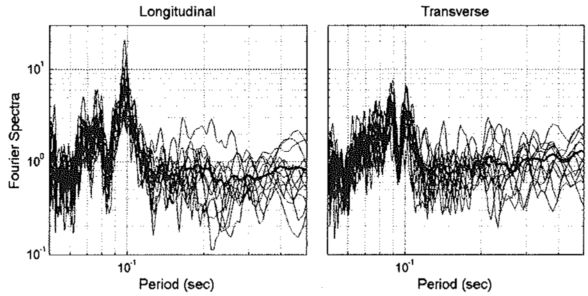


Figure 14.Heavily damaged partially confined masonry house

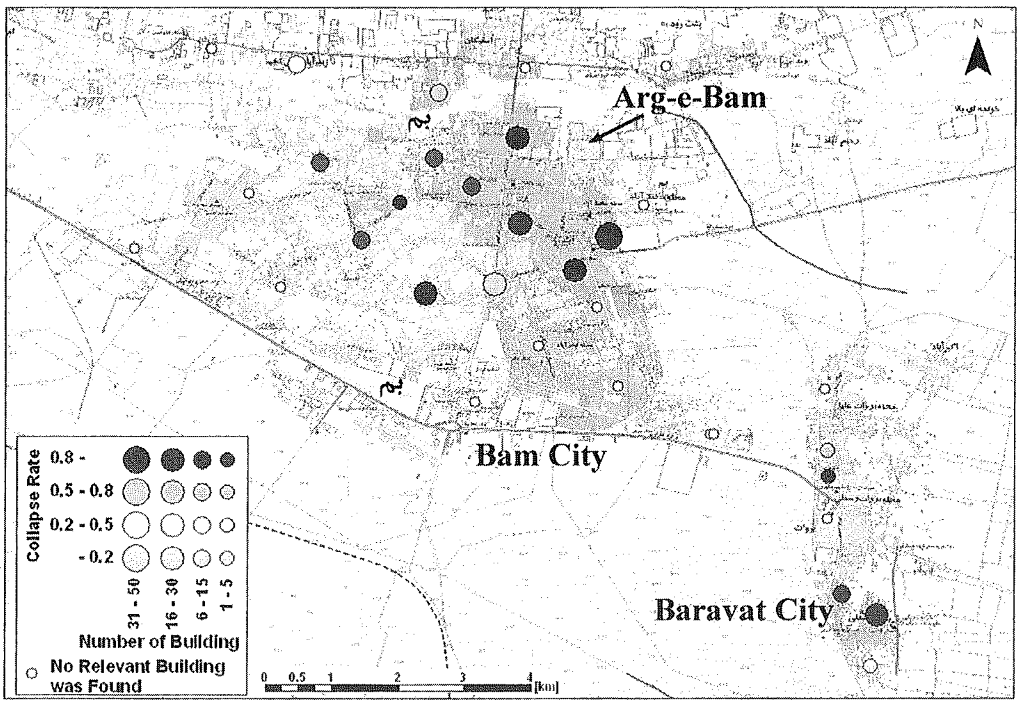


Figure 15. Adobe house damage distribution

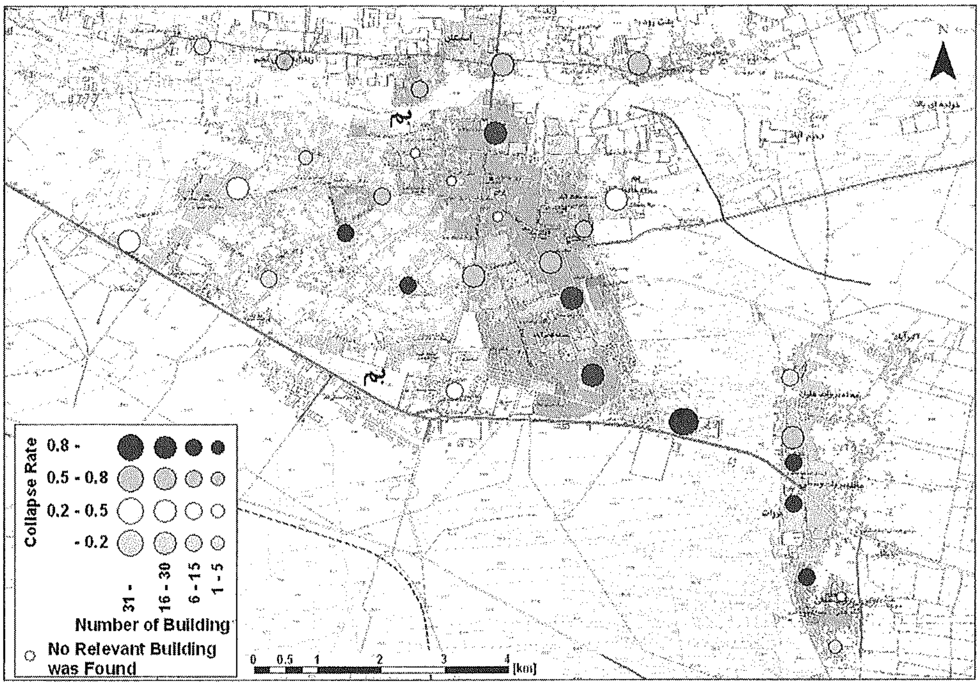


Figure 16. Unreinforced masonry damage distribution

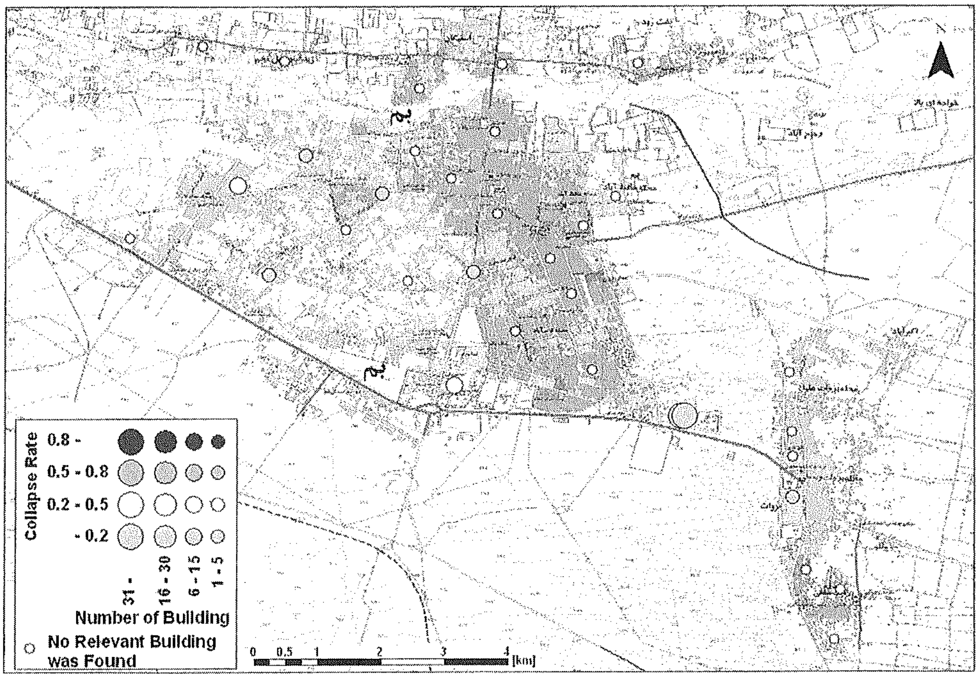


Figure 17. Confined masonry damage distribution

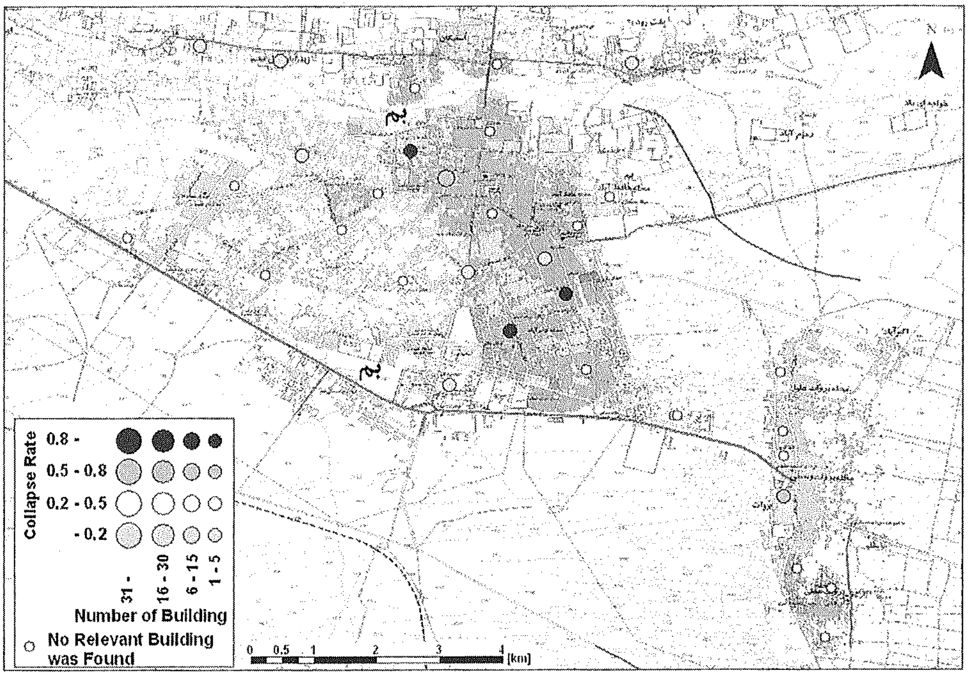


Figure 18. Steel building damage distribution

CONCLUDING REMARKS

Measuring traces of strong ground motions remaining in structures, which are seen everywhere and have common features, may provide useful pieces of information for discussing spatial distribution of damage. Utility poles were taken as the target structures in Bam, the city flattened in the December 26, 2003 earthquake. The obtained strain distribution seems to be consistent with the overall distribution of damage to dwellings, which killed more than 43,000 people.

The Bam Earthquake was yet another evidence of the high seismic vulnerability of adobe and unreinforced masonry structures. It also showed the very good seismic performance of confined masonry. Although it is possible to ban the use of adobe as a construction material, which was actually done by the Iranian Government, this measure is inapplicable, as many people with limited resources will continue to use it. Several constructions practices for improving the seismic performance of new adobe structures have already been devised as well as retrofitting methods for existing structures. Unfortunately, these have not been implemented due to a lack of appropriate information spreading campaigns. This fact underscores once more the stress that should be put not only on technical issues of earthquake engineering but also on the social ones.

ACKNOWLEDGEMENT

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Building and Housing Research Center, kindly provided the team with necessary materials including digital data of strong ground motions from the Bam earthquake. Prof. R Alaghebandian and Prof. A. Ghalandarzadeh, University of Tehran, joined the reconnaissance and helped the team members providing geotechnical and architectural pieces of information. The authors wish to further collaborate with Iranian specialists for possible countermeasures, e.g., reconstruction of damaged structures, retrofitting of existing structures and reducing earthquake hazards.

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