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SEISMIC PERFORMANCE OF EXISTING BUILDINGS DURING THE 2003 BAM EARTHQUAKE

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SUMMARY

On 26 December 2003 at 1:57 GMT, the historical city of Bam, located in the southeastern region of Kerman province in Iran, was shaken by a relatively strong and destructive earthquake. The earthquake located at 29.0^{o}N and 58.26^{o}W had a M_b of 6.3 by Geophysics Institute of the University of Tehran and a M_s of 6.7 estimated by the U. S. Geological Survey (USGS). The epicenter of the earthquake was located about 10 km southeast of the city of Bam. The main shock killed nearly 45000 people, left more than 50000 homeless, and destroyed virtually all buildings in the region.

Based on the reconnaissance visit by the authors, most common types of damaged buildings in the earthquake-affected area were, non-engineered adobe, unreinforced masonry houses and steel buildings. Most houses in the epicentral area were of adobe construction, made of sundried clay brick walls, and heavy domestic roofs or vaults with clay or mud mortar. Most problems were due to the collapse of these abode and brick buildings. This earthquake clearly demonstrated that combination of relatively rigid load-bearing external brick walls and flexible internal steel columns, existing similarly in most regions of the country, is quite hazardous. Also use of steel beams and columns in buildings without observing proper provisions for earthquake resistance showed no improvement over non-engineered buildings. In this paper after summarizing the seismological and engineering field investigations of the devastating earthquake, the performance of unreinforced and reinforced maonry buildings, steel buildings during the earthquake is also reviewed.

INTRODUCTION

On Dec. 26, 2003 at 01:56:56 GMT, (05:26:26 local time) a destructive earthquake hit the city of Bam in Kerman province and caused near source effects. The Kerman province is one of the largest provinces in Iran, with an area of 186,422 km^2, located in southeast of the country. The population of Bam was about 100,000 at the time of the earthquake in 2003[1]. Starting 10 days after the earthquake, the authors spent 4 days in the region to study the earthquake effects on the ground and building structures. This paper summarizes the seismological and engineering field investigations of the devastating earthquake.

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The epicenter of destructive earthquake is located at 29.01°N - 29.01°E, 10 Km, southwest of Bam city. Its magnitude was measured with M_b of 6.3 according to the Geophysics Institute of the Univ. of Tehran and M_s of 6.7 estimated by the U. S. Geological Survey (USGS). According to the official reports, this earthquake took the lives of around 45000 people. Also more than 50000 people are declared to be injured. The earthquake happened at 5:26 am local time when most of the inhabitants were sleeping, which could be one of the causes of the great life loss.

The macroseismic intensity of the earthquake is estimated to be I_0=IX in Bam city (in the EMS98 scale), where the strong motions and damaging effects seem to be attenuated very fast especially in the fault-normal direction (Fig. 1). Most of the buildings in the region were destroyed completely and the rest were damaged from 30 to 70 percent [1]. The intensity levels are estimated to be VIII in Baravat, VII in Modern-Arg (Arg-e Jadid) and the airport area. The intensity level was estimated to be around IV-V in Kerman and Mahan.

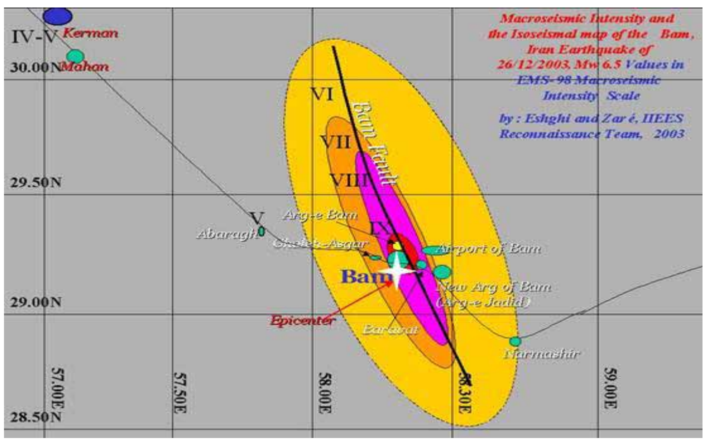

Fig. 1. Intensity map of the damaged area [1]

The existing records on seismicity history indicate no major earthquake in Bam since the historical time. It seems that the 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, constructed about 2000 years ago and since then, until the 2003 Bam earthquake, remaining unaffected. The Bam fault with a near north-south direction passes from the vicinity of the city of Bam (less that 1km distance to the east of Bam, and between the cities of Bam and Baravat as shown in Fig. 1). The focal mechanism of Bam earthquake was reported to be strike slip and its focal depth was estimated to be 8 Km. The strong motions in this event were recorded in stations of the national Iranian strong motion network [2]. The record obtained in the Bam station shows the greatest PGA of 0.8g and 0.7g for the east-west horizontal and north-south horizontal components, respectively, and 0.98g (relatively high acceleration) for the vertical component. The Bam residents that survived the quake explained to the reconnaissance team members that they felt strong up-down displacements during the main shock. The accelerographs of the Bam earthquake are shown in the Fig. 2.

Most popular type of buildings in the region are, nonengineered adobe, unreinforced brick buildings and steel buildings. Similar to most of the dry areas in the country, reinforced concrete buildings are rare in the Bam. Therefore these structures are not discussed in this paper. With a few exceptions, all buildings in Bam, mostly nonengineered adobe or unreinforced brick buildings, were damaged and more than half of them collapsed.

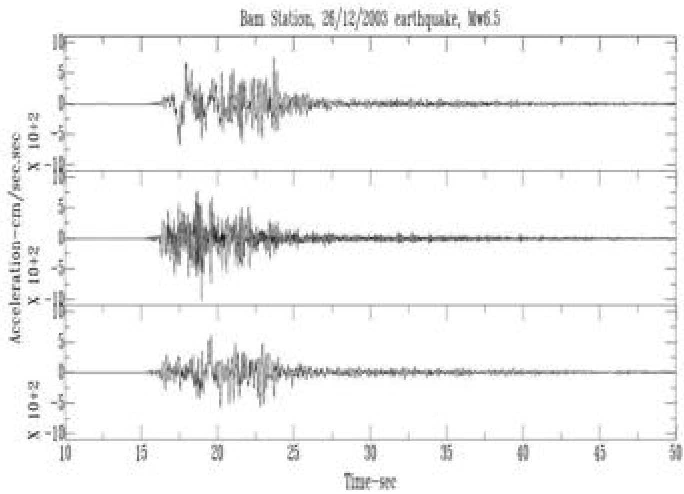

Fig. 2. The accelerographs of the Bam earthquake

GEOLOGY AND TECTONICS

Iran lies on the Alpide earthquake belt which runs west-east from the Mediteranean to Asia. Major geological structures of iran are the Alborz Mountains in the north, the Zagros belt in the west and south, the Kopet-Dagh range in the northeast, and the depressions of Great Kavir in the center, Lut in the east, and the Caspian sea in the north. Recent geological investigations have suggested the existence of various tectonic subplates in the region moving northward at different rates. Underriding of the Persian plate by the Arabian plate along the Zagros thrust fault is the most conspicuous tectonic feature of the region[3].

Central Iran was folded and faulted by the Alpine diastrophism in Tertiary time. This area is fragmented by a series of Quaternary fault systems. The oldest exposed geological features of the region consists of old Paleozoic rocks including dolomite-gypsum series together with porphyritic and acid volcanics, red stones, and trilobite limestone. But Jurassic and Quaternary rocks cover most of the region.

The province of Kerman is surrounded by the depressions of Great Kavir in the north and Lut in the east, and Zagros ranges in the south and west. Due to the complexity of geology, tectonics of the region has been a controversial subject in the literature. The major Quaternary faults in the area are the Kuhbanan fault, apparently a high angle reverse fault, with northwest-southeast direction and Nayband fault with north-west trend. Some other faults in the region are Chahar-Farsakh Anduhjerd, Gowk, Sarvestan and Bam faults. The NW-SE faults (Kuhbanan and Ravar faults) and the north-south faults (Nayband, Chahar-Farsakh, Anduhjerd, Gowk, Sarvestan and Bam faults as shown in Fig.3) have determined the border of the north-south structures in the Lut area with the NW-SE structures. These intersection zones were some of the main sources for the disastrous earthquakes. The Gowk fault system is recognizable for its surface ruptures during the 1981, 1989 and 1998 earthquakes as well as a hot spring system. In the west of the Golbaf-Sirch valley, there is the Lut depression, where a vertical topographic offset of more than 4000 meters has occurred   However tension is predominant in the earthquake of central Iran. Therefore faultings in this region are mostly dip-slip normal or strike-slip, and the horizontal components of displacements are right lateral [1].

SEISMICITY OF THE REGION

In addition to the recent earthquake , 12 other destructive earthquakes of Richter magnitude greater than 7 have hit Iran during the 20th century. On the average, at least one earthquake of Richter magnitude equal or greater than 6 has struck Iran every year during this century. Around 200,000 people have died in earthquakes in Iran during the last 100 years [3].

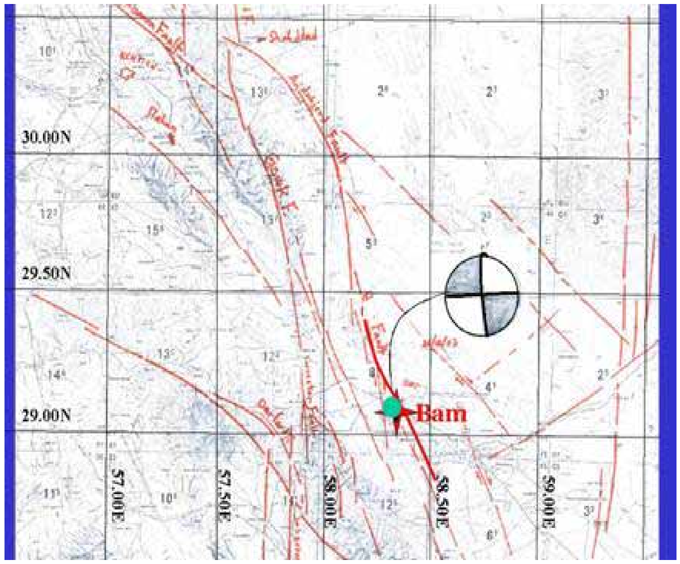

Fig. 3: The fault map of the Bam earthquake prone area of the 26/12/2003 earthquake[1]

Seismicity of central Iran, including Kerman, during the twentieth century does not have a linear pattern. It is sporadic and is interspaced with long periods of relative quiescence. However, several major earthquakes have struck the province of Kerman during the twentieth century.

An earthquake of magnitude Ms=6.5 hit near the town of Bahabad on 18 April 1911. on 22 September 1932 an earthquake of magnitude Ms=6.5 to 6.9 struck Ghaleh Asgar, killing at least 260 people. This earthquake caused damage in the cities of Baft, Sirjan, Kerman, and Rafsanjan. Another earthquake of magnitude Ms=6.3 occurred at Bahabad on 28 November 1933. This earthquake was associated with Kuhbanan fault, destroyed three villages, and killed 4 people. On 2 September 1969, EAST OF Kerman including Anduhjerd, Khizrud, and Shahdad was shaken by an earthquake of magnitude Ms=5.3. on 19 December 1977 northeast of Zarand, was shaken by an earthquake of magnitude Ms=6. This earthquake had a focal depth of about 10 Km and killed 522 people[3].

Four great earthquakes have struck the region during the recent 20 years: The Golbaf earthquake of 11 June 1981, Ms6.6, the Sirch earthquake of 28 July 1981, Ms7.0, the South Golbaf earthquake of 20 November 1989, M_b5.6 and the North Golbaf (Fandogha) earthquake of 14 March 1998, Mw6.6. The Golbaf earthquake of 11/06/1981 has struck 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, caused 1071 fatalities . The event caused great damage in the Golbaf region. The Sirch earthquake of 28/07/1981 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 a situation might be the reason for the great earthquakes around Sirch in 1877 and 1981 (both with magnitudes greater than 7.0). The South Golbaf earthquake of 20/11/1989 caused 4 fatalities 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 5 fatalities and 50 injured, and was associated with surface faulting (about 20km length) in northern Golbaf. The focal mechanism of these earthquakes shows the compressional and strike slip mechanisms along the Gowk and Kuhbanan fault systems [1].

EARTHQUAKE EFFECTS ON THE GROUND

The focal mechanism of the Bam 26/12/2003 earthquake was reported as strike slip fault, which fits in well with the surface evidence of right-lateral strike slip movement of the Bam fault. The focal depth of the Bam earthquake of 26/12/2003 is estimated to be 8km. Bam earthquake has been accompanied by some geotechnical phenomena such as landslide, liquefaction and land subsidence [4].

Since annual rainfall in Bam is not considerable, the main source to supply drinking and agricultural water for Bam and its vicinity are underground resources. Underground water is extracted mainly by using deep wells and Qanats (underground irrigation tunnels). Lots of the Qanats have been excavated at the area during the past decades. Before Bam earthquake there were about 126 active Qanats at the area to supply 50% of the required water for the city. The rest of the required water supplied with deep wells. On the other hand Qanats are vital for people of Bam [4].

Bam Earthquake has considerable effects on a lot of Qanats that excavated at the Bam area and its vicinity. Based on the preliminary evaluations, about 40 percents of these Qanats have been collapsed or experienced severe damages due to the earthquake. In some cases the collapse of the Qanats stopped the water flow completely.

Fig. 4: Sinkhole due to collapse of a Qanat tunnel at west of Baravat [2]

The most important effects of Bam Earthquake on Qanat systems are damages to the access wells and tunnels. Several sinkholes induced due to the earthquake above the tunnels and wells due to the collapse of underground openings (Fig. 4).

Based on the previous experiences, underground openings should be more resistant against seismic loads, but the damages to the Qanats of Bam area were severe. Most of the damages observed at the access wells but near the Bam Fault underground tunnels also have lost their stability and collapsed. It should be considered that most of the Qanats of the area have been supported with hand made arcs, but these supporting systems could not affect considerably on the stability of Qanats when dynamic loadings applied on them.

High concentration of sinkholes observed at the vicinity of the Bam Fault. Most of the occurred collapses were also observed in a narrow band close to the Bam Fault. Of course it should be considered that other damages to the structures and lifelines were also in a limited zone around the Bam fault. Far from the Bam Fault the effects of earthquake on Qanats are less important and only some fissures and cracks can be observed along the tunnels of access wells.

SEISMIC PERFORMANCE OF BUILDING STRUCTURES

Although there is an updated building design code that is comparable to the Uniform Building Code (UBC) of the United States and it is mandatory for practicing civil engineers, its application has been mostly limited to larger cities and for major building structures. In smaller towns and villages, however, current standards for seismic design and construction of buildings have not been properly considered. They usually build their own houses at minimal cost and thus sometimes with insufficient safety measures in place. As a result, severe damage is expected during even a moderate earthquake.

As mentioned before most common type of structures in the city of Bam, are non-engineered adobe, unreinforced masonry buildings and steel building structures; however, reinforced concrete buildings are rare in Bam. Therefore, the behavior of these 3 types of structures during Bam earthquake are briefly reviewed here.

Adobe Houses

Most houses in the epicentral area are abode construction, usually one-story made of sun-dried brick walls, and domed roofs or vaults with clay or mud mortar. This type of construction is common in the dry areas of Iran because abode houses need only local materials and can be built by farmers when their work is tax. The walls and roofs of these houses are thick (usually 40 to 80 cm) and heavy so that they easily protect their inhabitants from the cold and hot weather, but they are very weak in resisting horizontal vibrations particularly at the junctions of vertical walls and domed roof (Fig. 5).

Fig. 5: Heavy walls, thickness of wall in some abode houses reaches to about 1 m

Based on the reconnaissance visit, most abode houses in the epicentral region are either partially or totally collapsed. Their failure normally started in a corner by separation of the walls from the domed roof. In some region the ground shaking was so severe that the abode houses were turned into their original sun-dried bricks (Fig. 6).

Fig. 6: ground shaking was so severe that the abode houses were turned into their original sun-dried bricks in the Bam 26.12.2003 earthquake.

Masonry Buildings

Masonry buildings are the second most common type of buildings in the earthquake-affected area. They normally consist of kiln brick walls with shallow Jack arch roofs supported by steel **I** shaped beams. The steel beams are laid at a distance of 90 to 100 cm apart, and shallow brick arches fill among them. The mortar used in these buildings is sand-lime-cement, or sometimes sand-cement. The performance of unreinforced masonry buildings was not any better than abode buildings. The common modes of failure of these buildings were shear failure of walls, separation of walls from the roof, and separation of roof beams from each other (Fig. 7). In most cases the steel beams of the roof were not braced together by steel re-bars or joists (Fig. 8). As a result, dropping of the bricks between them during the earthquake, could be expected.

Fig. 7: shear failure of walls, separation of walls from the roof, and separation of roof beams from each other are observed in typical brick buildings.

Fig. 8: In most cases the steel beams of the roof were not braced together well by steel re-bars or joists

A number of reinforced masonry buildings, with vertical and horizontal reinforced beams, were recently built in the city. The performance of these structures was good and in many cases saved the lives of their inhabitants (Fig. 9).

Fig. 9: an example of reinforced brick buildings in the earthquake-affected area with a relatively good performance.

Steel Buildings

Many modern residential and office buildings in Bam are steel building structures that can be divided into two groups. The first group includes buildings with steel internal columns, load-bearing external brick walls, and roofs, often, made of shallow Jack arches with steel **I**–beams. The performance of this type of construction as a sort of unreinforced masonry structure was very poor. The flexible steel columns tended to displace much more than the rigid external walls resulting in inclining of the steel columns and mostly the collapse of the whole structure (Fig. 10). This earthquake clearly demonstrated that the combination of relatively rigid load-bearing external brick walls and flexible internal steel columns is very hazardous. This type of structure is not limited to Bam, and it can be easily observed in most of the cities in the country.

Fig. 10: first group of steel buildings, combination of steel internal columns and load-bearing external brick-walls.

The second group of steel buildings consists of steel frames only in one direction with bracing in one or two directions. They are actually designed for some horizontal forces. The performance of this type of construction was generally satisfactory (Fig. 11). Exceptions are made when the bracing were placed eccentrically or incorrectly (Figs. 12 and 13). In these cases, the infill or curtain walls usually experienced severe damage.

Fig. 11: steel building with good performance during the Bam 26.12.2003 earthquake

This earthquake proved that use of steel beams and columns in building structures without observing proper code provisions for earthquake resistance showed no improvement over non-engineering buildings.

Fig. 12: incorrectly bracing system and its gusset plate

Fig. 13: Unacceptable bracing system, the cross-section of bracing member is insufficient.

CONCLUSION

The tragic event of 26/12/2003 in Bam with a M_s of 6.7, was the most destructive earthquake in recent century in the country with a loss toll of about 45000 people, after the Manjil earthquake of 20 June 1990 with a M_s of 7.2 that took lives of about 40000 people. Most casualties in this earthquake were due to the collapse of the adobe houses. The common modes of failure of masonry buildings were shear failure of walls, separation of walls from the roof, and separation of roof beams from each other. In steel buildings there were two great problems. One refers to combination of steel internal columns and load-bearing external brick-walls that this earthquake showed that it is very dangerous, and the other major problem of steel building is lock of observing proper provisions for seismic design and construction.

Although the earthquake magnitude was high, it was generated in a shallow depth, and it induced near source effects on the city, nonetheless, the main reason for serious destruction was due to the poor design and construction and the selection of poor building materials. Considering frequently occurrence of strong earthquakes in the country, serious measures must be taken to control and improve the seismic design and construction of new building structures and also to retrofit existing ones. Incidently, this earthquake proved that the vertical component of earthquake needs more attention in design. A considerable part of damage in the earthquake-affected area is related to vertical component.

REFERENCES

1. Eshghi, S. and Zaré, M. "Bam (SE Iran) earthquake of 26 December 2003, Mw6.5: A Preliminary Reconnaissance Report", International Institute of Earthquake Engineering and Seismology, 2003.
2. Building and Housing Research Center- Iran Strong Motion Network (2003), "The very urgent preliminary report on Bam earthquake of Dec. 26, 2003".
3. Adeli, H. "the Sirch (Kerman-Iran) earthquake of 28 July 1981- a field investigation", bulletin of the seismological society of America, Vol. 72, No. 3, pp. 841-861, 1982.
4. mini Hosseini, K., Mohammad Reza Mahdavifar, M.R., Bakhshayesh, M.K., Rakhshandeh, M. "Engineering Geology and Geotechnical Aspects of Bam Earthquake ", 2004.