Learning from Earthquakes

Preliminary Observations on the Bam, Iran, Earthquake of December 26, 2003

Following the earthquake, EERI sent a reconnaissance team to the affected area in cooperation with the International Institute of Earthquake Engineering and Seismology (IIEES) of Iran. The EERI team was composed of structural engineers Farzad Naeim (team leader), Mike Mehrain, and Mohsen Rahnama; strong-motion specialist Yousef Bozorgnia; environmental engineer Elahe Enssani; geotechnical engineers Ali Bastani and Farhang Ostadan; medical doctor Haasan Movahedi; and remote-sensing specialist Babak Mansouri.

Ron Eguchi, Beverley Adams, and Charles Huyck, remote sensing specialists with ImageCat, Inc., made significant contributions to the reconnaissance effort by preparing detailed satellite-based damage maps and a GPS-based software system that was used by the team at the earthquake site. Satellite imagery was purchased by EERI and the University of California at Irvine.

The IIEES team was composed of Mohsen Ghafory Ashtiany (team leader), Sassan Eshghi, Mehdi Zare, Kambod Amini, Mahmood Hussaini, Kazem Jafari, Behrokh Hashemi, A. S. Moghadam, Farhang Pas, Farokh Parsizadeh, Khaked Hessami-Azar, Kiarash Asadi, Mehran Razaghi, Massoud Ahaari, Mehrtaash Motamedi, Mohammad Reza Mahdavifar, Mohammad Bakhshaiesh, and Massoume Rakhshandeh.

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Introduction

A magnitude 6.6 (*Ms*) earthquake struck the city of Bam in southeast Iran at 5:26:52 AM (local time) on Friday, December 26, 2003. The city's population was about 90,000, with 200,000 total residents in the greater Bam area. The U.N. Office for the Coordination of Humanitarian Affairs (OCHA) indicates that the Bam earthquake caused the deaths of approximately 43,200 residents and injured approximately 20,000. Some 75,600 people (14,730 households) were displaced, and 25,000 dwellings were razed. An additional 24,000 dwellings were destroyed in the rural areas. The vast majority of buildings in the city collapsed, and most of the remaining buildings were severely damaged. In terms of human cost, the Bam earthquake ranks as the worst disaster in Iranian history. In addition, Bam's ancient citadel (Arge-Bam), probably the oldest and largest adobe complex in the world, with 2,000 years of history, was substantially lost.

Prior to the earthquake, Bam was one of the richest cities in Iran. Surrounded by deserts, Bam had a tradition of very successful agriculture, thanks to man-made irrigation systems (*qanats*) built and maintained by locals over many centuries. It produced more than 100,000 metric tons of the finest quality dates per year and a large amount of premium citrus fruits. East of the city, a modern industrial complex was built that, among other things, assembled about 15% of automobiles produced in Iran each year.

Seismicity and Strong Ground Motions

According to the USGS (2003), the earthquake epicenter was located at 29.004 N, 58.337 E, on a predominantly right-lateral strike-slip fault. The focal depth was estimated at 7 km (BHRC 2004). Currently, scientists from Iran, the United States, and the United Kingdom are carrying out comprehensive investiga-

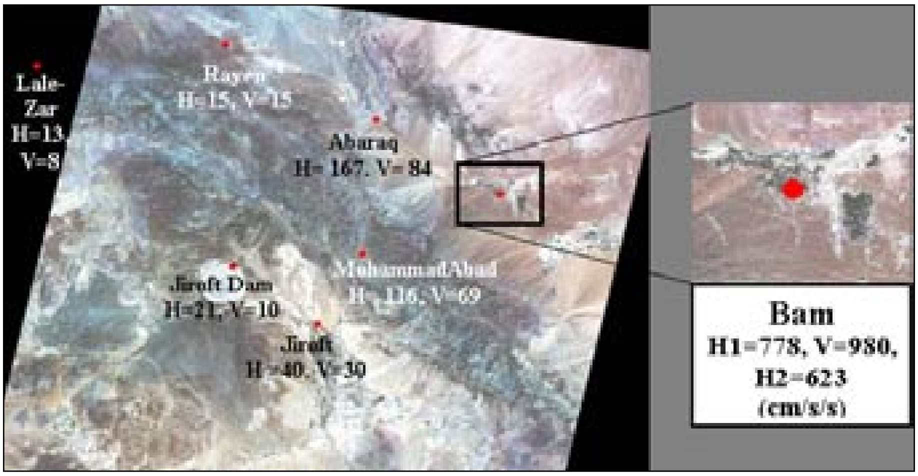

Figure 1 *Satellite image of Bam area. The locations of few strong-motion recording stations are marked. For each station, the larger horizontal acceleration as well as peak vertical acceleration are given. For the Bam station, three peak accelerations are provided. All values are in cm/sec^2 (imagery courtesy of DigitalGlobe,* ***www.digitalglobe.com****).*

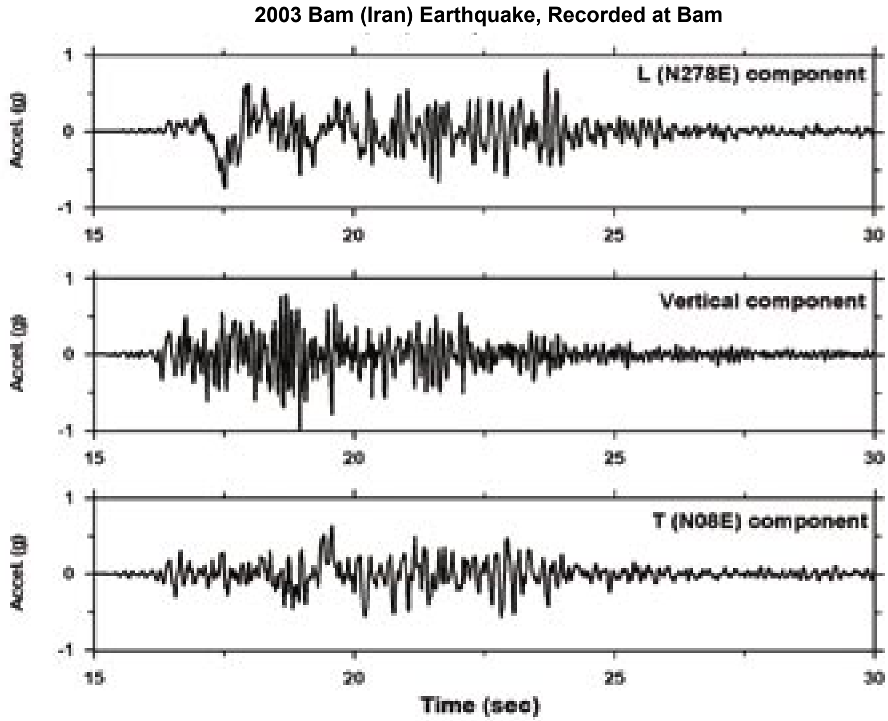

Figure 2 *Ground accelerations recorded at the Bam station.*

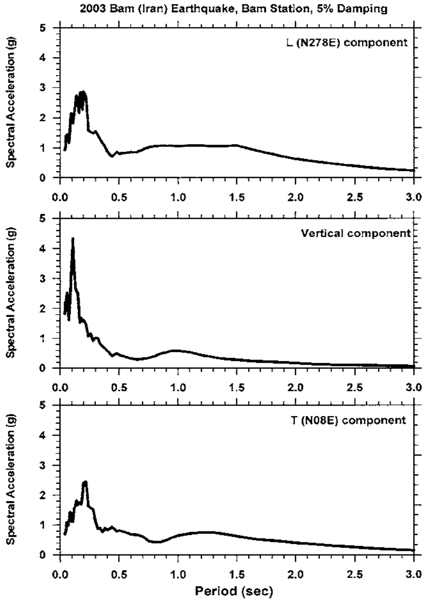

Figure 3 *Response spectra of the recorded ground motions at Bam for 5% damping.*

tions to identify the location and extent of the causative fault of the Bam earthquake.

Southeast Iran has had previous major earthquakes. In 1981, two earthquakes struck the area: in the Golbaf earthquake (Mw 6.6) 3,000 people lost their lives; in the Sirch earthquake (Mw 7.1), 1,500 people were killed. The other significant earthquake in the area was the 1998 Fandoqa earthquake, with a magnitude of 6.6 (Berberian et al. 2001; Walker and Jackson 2002).

Iran has 983 digital strong-motion instruments and 71 SMA-1 analog strong-motion instruments. They are maintained by the Building and Housing Research Center (BHRC). In the Bam earthquake, 24 Kinemetrics SSA-2 digital strong-motion instruments recorded the strong ground motions in the area (BHRC 2004). Figure 1 shows the Bam area, with a few locations of the strong-motion stations.

A tri-axial strong-motion instrument located in downtown Bam recorded important severe near-fault ground motions. The instrument was on the ground floor of the two-story County Building. The building suffered severe damage and partial collapse at two locations, but the instrument room had only minor cracks in its wall. Following the earthquake, the staff of BHRC inspected the instrument room and the SSA-2 instrument and documented their observations (BHRC 2004). They concluded that the instrument was not damaged and did not malfunction during the earthquake.

The recorded ground accelerations at the Bam station are plotted in Figure 2, which shows that the Bam station recorded very severe ground motions. The N278E component, which is roughly in the fault-normal direction, recorded a severe long-period pulse. The pulse corresponds to a high peak ground velocity of about 123 cm/sec (BHRC 2004). The instrument also recorded very strong vertical acceleration with a peak value of about 1g. The response spectra of the uncorrected ground accelerations at the Bam station are plotted in Figure 3. An Evolution of Arias Intensity (AI) for the N278E component of the Bam station is plotted in Figure 4. With a 5-95% evolution of AI, the ground motion at Bam had a strong-motion duration of approximately eight seconds.

In Figure 5, distributions of peak horizontal and vertical ground accelerations are plotted against the seismogenic distance to the Bam fault. The results of Campbell and Bozorgnia (2003) attenuation relations for the stiff soil sites are also plotted for comparison. It is evident that the recorded peak accelerations at Bam exceed the median value of attenuation models for both horizontal and vertical components.

Geotechnical Aspects

Geology and local soil conditions: Surface deposits in the general area of Bam consist of alluvial deposits from major seasonal flooding over time. The thickness of the alluvium ranges from less than a few meters to about 50 m (IIEES 2003), depending on the location. In the northeastern part of the city and

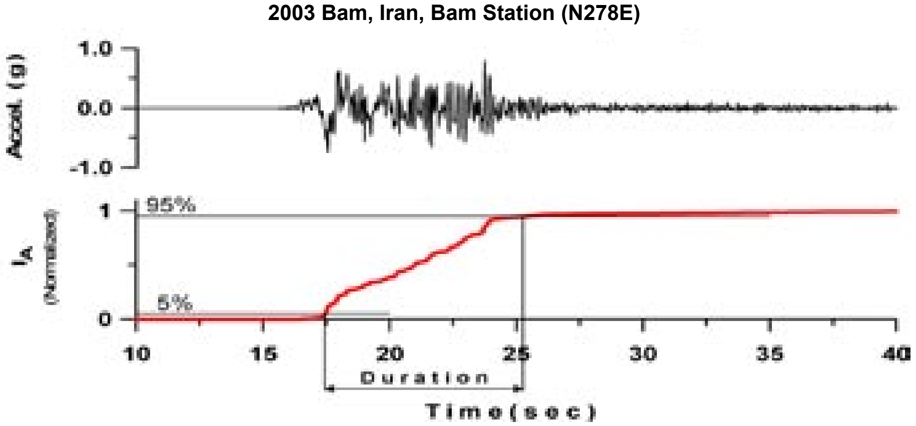

Figure 4 *Evolution of Arias Intensity (normalized) for the N278E component of the strong motion recorded at Bam.*

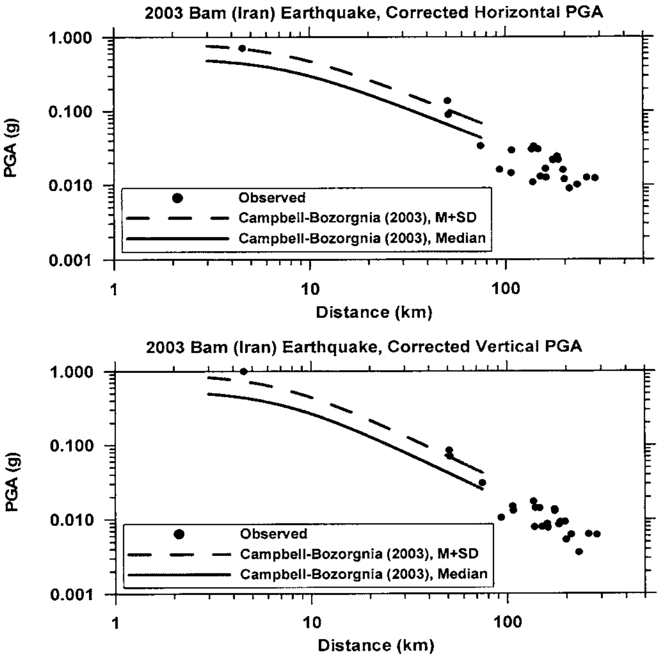

Figure 5 *Distribution of the recorded peak ground accelerations versus seismogenic distance to the Bam fault, for the geometric mean of the horizontal components (top) and vertical acceleration (bottom). The actual site-to-source distances may be less than those shown here, if the causative fault is somewhat west of the Bam fault.*

Arge-Bam, a rock outcrop is visible. The underlying layers consist of recent quaternary alluvium, late quaternary sandstone and siltstone, sedimentary and volcanic rocks. The seasonal riverbed (Posht-Rood), mostly dry, is in the northern part of the city. Due to heavy use of deep water wells, the groundwater table is low — at depths in excess of 30 m.

At the time of the reconnaissance effort (January 2003), drilling was underway near the building where the only strong-motion instrument in the city of Bam was located. The soil layering and properties will be available in near future, and will be very useful for evaluating the local soil effects on the high-intensity ground motion recorded in the city.

Landslides: The area is generally flat, and there are no major man-made earth structures, but there were landslides along riverbanks and man-made channels. A typical riverbank landslide is shown in Figure 6. Large blocks of soils moved and tumbled. Most soil blocks already had tension cracks due to the dry environment. There was no direct damage caused by the landslides, but the soil blocks need to be removed to clear the riverbed for the next seasonal flooding.

Liquefaction: There was no surface evidence of liquefaction due to the depth of the ground water table. There were no reports of any damage or failure caused by liquefaction.

Qanats: A qanat is a horizontal aqueduct system that conveys water from an aquifer in mountainous alluvial fans to lower-elevation irrigated fields, as shown in Figure 7. It consists of a series of vertical shafts in sloping ground spaced between 30-50 m, interconnected with an underground tunnel. The soil removed is placed around the shafts forming a circular

Figure 6 *A typical landslide along a riverbank.*

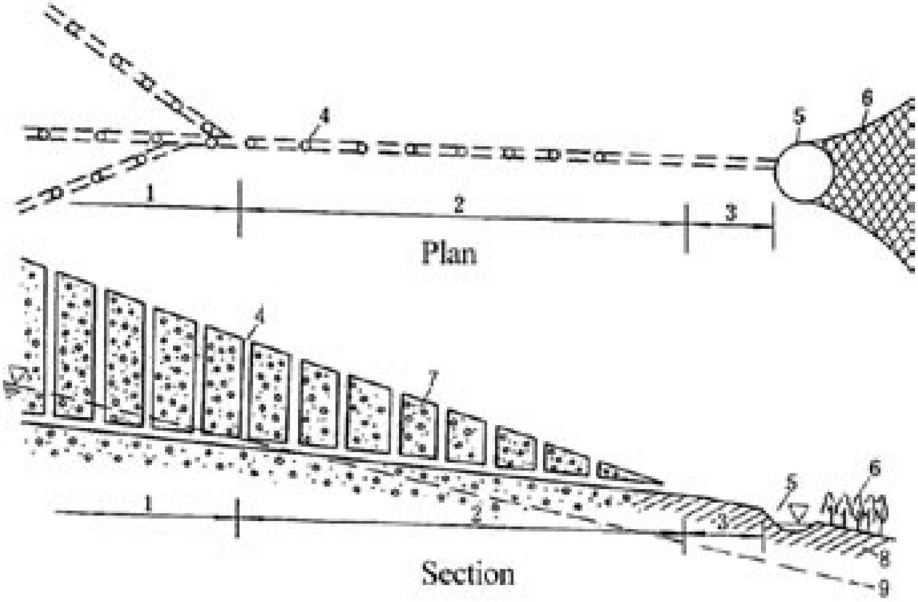

Figure 7 *A typical qanat system: (1) infiltration part of the tunnel, (2) water conveyance part of the tunnel, (3) open channel, (4) vertical shafts, (5) small storage pond, (6) irrigation area, (7) sand and gravel, (8) layers of soil (source:* ***http://www.waterhistory.org/histories/qanats/#figure1****).*

embankment protecting the shafts from surface runoff. Water flows under gravity; no pumping is needed.

Every few years dredging is required to remove the debris in the tunnel area. There are 22,000 qanats in Iran with a total length of 170,000 miles delivering 20,000 gallons per second. It has been documented that qanats in Iran were used 3,000 years ago.

It is estimated that 50% of the water for irrigation around Bam was delivered by 120 qanat systems. About 40% of the qanats were damaged in the earthquake. Visible in the form of sinkholes, the failures were caused by the collapse of the shafts near the ground surface or the tunnel. There are also numerous old qanats in the general area with locations that were unknown at the time of city development. Some of the old qanats failed and caused foundation damage in buildings located close by (see Figure 8). The shafts and qanats need to be repaired and reinforced to prevent extinction of the palm farms, the very livelihood of the city.

Building Performance

Damage was concentrated in a relatively small area of roughly 16 km² around Bam. The United Nations damage assessment team estimated that 90% of the building stock in Bam suffered 60-100% damage, while the remaining 10% had 40-60% damage. Detailed 60-cm resolution optical satellite images obtained by EERI to assist the reconnaissance effort confirmed the widespread damage and destruction in Bam. Satellite photos of a neighborhood in Bam with 80%-100% damage are illustrative. Figure 9 was taken on 9/30/2003 before the earthquake, and Figure 10 was taken on 1/3/2004 after the earthquake.

An isoseismal map developed by IIEES is overlaid on a population map in Figure 11.

Historic buildings: The historic Arge-Bam Citadel is a complex of one- and two-story buildings surrounded by several tall free-standing walls. Figure 12 shows how it looked before the earthquake. The building's adobe is approximately three feet thick with a layer of straw-reinforced mud cover for rain protection. The free-standing walls are thicker, but have the same construction as the building walls. The roofs consist of domes and cylindrical arches constructed of adobe. These structures have little resistance to earthquake motion so the quake caused widespread and significant collapse of the citadel (Figure 13).

Approximately 80% of the buildings experienced total collapse. The collapse pattern in various buildings indicates that the failure initiated in load-bearing walls was followed by roof collapse (Figure 14). There appeared to be no difference in per-

Figure 8
Qanat sinkhole that damaged a nearby structure (IIEES 2003).

Figure 9 *Satellite image taken from a neighborhood prior to earthquake (imagery courtesy of DigitalGlobe,* ***www.digitalglobe.com****).*

Figure 10 *After-earthquake satellite image of the same neighborhood shown in Figure 9 (imagery courtesy of DigitalGlobe,* ***www.digitalglobe.com****).*

formance of domes as compared to cylindrical roofs. Some collapsed walls revealed repairs that may have been made after previous earthquakes (Figure 15).

Because of the historical significance of the citadel, the repair of the structures is under study. The extensive damage suggests that repair decisions should consider seismic resistance in future events.

Traditional buildings: Many Bam residential buildings, from modest houses to large luxury residences, are similar to the historic citadel in their adobe construction. This construction consists of cylindrical or dome-shaped adobe arched roofs spanning approximately ten to 12 feet supported by thick (30”+/-) adobe bearing walls. A two-inch layer of straw-reinforced mud provides protection against rain on roof tops and exterior walls.

Collapse of these structures was widespread (Figures 16 and 17). Most of the 43,000 lives lost were due to their collapse. The mode of collapse appeared to be out-of-plane failure of walls, resulting in loss of support for the roof.

In addition to residential buildings, this structural system was used for some schools and other public buildings. However, due to the time of the earthquake (early morning), loss of life associated with these buildings was relatively low.

Contemporary construction: The majority of contemporary construction uses steel framing with unreinforced masonry brick infill and/or bearing walls. The floors and roofs in these buildings use a “Jack Arch” system consisting of brick arches spanning between webs of steel I-beams spaced at approximately three feet. The floor beams are supported on steel girders. In many buildings, URM bearing walls at the perimeter provide gravity support. The girder system is typically double “I” or double channel sections passing on both sides of columns and supported by top and bottom angles (Figure 18). This system is also used as moment frame for resisting lateral loads in one direction of the building. In the other direction, URM brick walls (in low-rise buildings) or braced frames (in mid-rise buildings) provide lateral resistance.

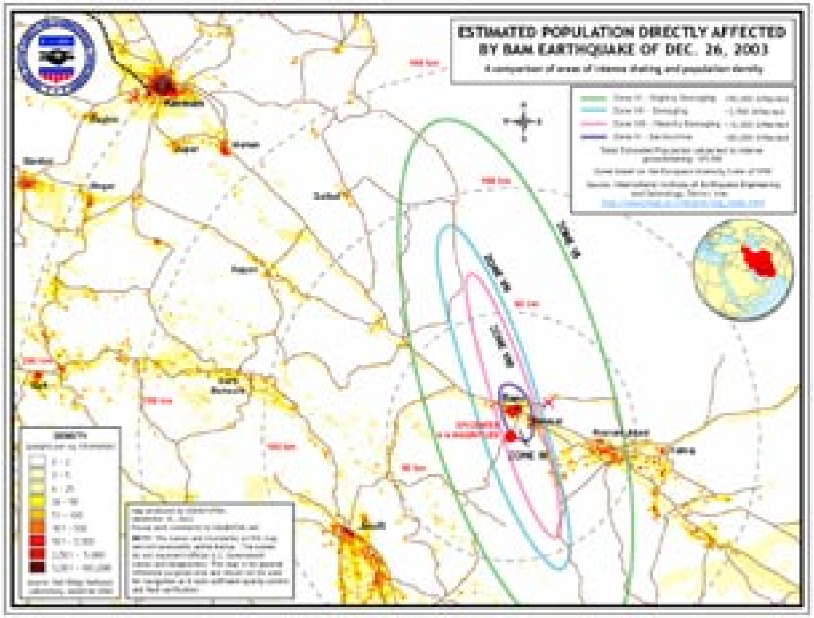

Figure 11 *Isoseismal map and population affected by the earthquake.*

Figure 13 *View of damage to the Arge-Bam historical citadel.*

Figure 12 *View of the Arge-Bam Citadel before the December 2003 earthquake (**www.raphaelk.co.uk/web%20pics/ Iran/Iran.htm**).*

Figure 14 *Out-of-plane collapse of adobe walls in Arge-Bam.*

Figure 15 *Addition of exterior layers to the core adobe walls suggests earlier repair of earthquake damage.*

Figure 17 *Collapse of smaller adobe house.*

Figure 16 *Failure of large adobe house.*

Figure 18 *Typical steel construction with jack arches.*

Figure 19 *Collapse of steel-framed dual-system building at least partially due to deficient welding practice.*

The collapses of low-rise contemporary buildings were primarily due to out-of-plane wall failure leading to floor collapse. In mid-rise construction with braced frames, collapses resulted from bad construction practices or lack of quality control, including improper welding (Figure 19) or nonengineered bracing schemes.

Weak-story collapse mechanism was also observed repeatedly (Figure 20). Infill walls reinforced with steel angles framing around windows seemed to perform well.

Bam also had a few nonductile concrete frame buildings with URM infill. They were damaged due to infill behavior, but did not collapse. There may have been collapses in concrete buildings that will be identified during more detailed investigations. Domes such as those in mosques appear to have performed well, though there was damage to other parts of the same facility.

Essential buildings: The two major hospitals in the city experienced significant structural damage and/or partial collapse (Figure 21). The construction of these facilities is similar to the contemporary buildings discussed above, although some quality control may have been observed. Again, out-of-plane failure of unreinforced brick walls was a predominant behavior.

The city fire station had a weak-story collapse that rendered the fire engines useless (Figure 22). Collapse of the one-story bus depot structure crushed city buses (Figure 23).

Industrial facilities: Industrial facilities performed relatively well. Damage was primarily limited to partition and exterior wall failure. Several large horizontal tanks on braced steel support framing were found to be undamaged. Vertical steel tanks in one industrial facility did not experience elephant foot instability or

Figure 20 *Typical weak-story collapse.*

Figure 21 *Substantial damage to a hospital building.*

damage to the piping system. However, many industrial facilities remained out of operation due to loss of staff.

Lifeline Performance

Drinking water system: The water supply for all of the affected area is groundwater. The Dasht-e-Bam watershed covers an area of 3,900 square miles (10,000 Km²), where the annual rainfall is 2.00 inches (50 mm). This is typical of an arid zone, but for the past two years the Bam area has been experiencing drought conditions, with only 0.4 (10 mm) inches of annual rainfall. The groundwater table in this area is deep: levels range from 260 ft. to 56 ft. (200 m-80 m).

Before the earthquake, the City and County of Bam obtained water from 15 production wells located in the southern section of the city. The depth of these wells ranged from 328 to 656 ft (100-200 m). Eleven of the wells were in production when the temblor occurred, and five had some damage. In 60 nearby villages with 23 deep wells in production, 30% to 50% of them were damaged.

The water is pumped to distribution reservoirs from the wells via 47.5 total miles (76 km) of transmission pipes made of asbestos-cement. About 10% of these pipes were damaged by the earthquake and were repaired within the first two weeks of the event. There were three underground reinforced concrete distribution reservoirs for the storage of water that do not seem to have been damaged. However, two chlorine gas disinfection systems for the distribution reservoirs were damaged, but fortunately there were no reported chlorine gas releases. After the quake, four new liquid chlorine systems were installed.

Gravity flow carries water from the reservoirs into the distribution net-

Figure 22 *Fire engines were crushed under the collapsed fire station.*

Figure 23 *Collapse of the bus terminal roof trapped city buses.*

Figure 24   Small tent-side water tanks provided by local authorities.

work. Immediately after the quake, the outflow from the reservoirs was stopped by closing the exit valves, which prevented flooding of the city. Local engineers had learned about the flooding risk from the 1981 Golbaf earthquake and had incorporated valve closing into their emergency response procedures. Because of the failure of the piping network, the city pumped water out of four operational wells into mobile tankers that filled small portable tanks in the displaced-person camps after the quake (Figure 24).

Between 70% and 80% of the 306 miles (490 km) of the distribution lines were damaged, the ages of which vary from two months to 40 years. The lines of the main grid are asbestos-cement with diameters ranging from 7.87 inches to 27.6 inches (200mm-700 mm). The breakage observed in these pipes was as follows: across the length of the pipe, upper and lower section; across the width of the pipe, upper and lower section; and at the joints. The important question in reconstructing this collapsed distribution system is whether to repair the current system or to replace it with a more earthquake-reinforced material.

Wastewater collection and treatment: There is no wastewater collection and treatment system in the City and County of Bam. Wastewater is collected in 24-33 ft. (8 to 10 m) wells that are common throughout Iran. No damage to these wells was observed or assessed.

Solid waste collection and disposal: Before the earthquake, the city collected solid waste on a daily basis and disposed of it 20 miles (30 km) southeast of the city at Rahim Abad. Because this is where the debris removed from the destroyed sites is currently taken, solid waste collection by the city was stopped after the earthquake.

Electric utilities: There was minor damage to the only electric substation in the city. The transformers were slightly derailed and ceramic insulator fallouts were observed. The substation was out of operation for about 16 hours.

Telecommunications Systems: There was very little damage to the telecommunications system. Mobile phones were out of operation for only two or three hours.

Transportation system: There are no long-span bridges in the affected area. Several concrete bridges over waterways appeared to perform well, although one bridge had minor damage to the bearing support at the wing wall.

Search and Rescue

The earthquake nearly destroyed the emergency response infrastructure. As has been the case in previous earthquakes around the world, trapped people were generally rescued by family members who had escaped without injuries. The work was done mostly by hand, as simple tools such as shovels were scarce. Rescue workers from Kerman and other parts of the province were slow to arrive, and help didn't arrive from Tehran until after the national government met 12 hours post-disaster. In addition to the lack of experienced search and rescue teams, loss of electricity and, hence, light brought all rescue work to a halt on Friday night. This factor, along with the cold weather, probably accounted for the unusually high number of casualties in this disaster.

With the arrival of the national and international rescue teams the following day, an estimated 2,000 victims were rescued in the following 48 hours. At the end of this time period (the third day after the disaster), official search and rescue efforts were called off because of the low probability that anyone else had

Figure 25 *Street-side tents using portable water for washing clothes and dishes.*

survived the cold weather.

Care of the Injured

Because Bam's two main hospitals were virtually destroyed, the injured had to be transported elsewhere for care. The City of Kerman — about 100 miles northwest of Bam — was the main place for the initial phase of receiving and stabilizing the injured. Of the approximately 20,000 injured, 11,000 were transported by car, ambulance, and helicopters to Kerman for treatment, and 5,000 were transported by airplanes to other cities.

Kerman has seven main hospitals: three at universities, one semi-private, two private, and one belonging to the Revolutionary Guard. The information in this report is mainly from the three university hospitals that cared for over 7,500 of the 11,000 taken to Kerman City. Afzalipour Hospital, which is the largest and most modern of the three, had a census of about 250 patients in the days before the earthquake. However, the number of injured they cared for in the ten days after the disaster was close to 3,500, with about 2,000 seen during the first 72 hours. The staff of Afzalipour woke up at 5:30 a.m. Friday morning due to the ground shaking. Not knowing exactly where the quake was, the hospitals nonetheless activated the initial phase of the hospital emergency system. By 7:00 a.m., the dean of the university, the medical chief of staff, the head of nursing, and a few staff physicians were present at Afzalipour and formed the crisis center. The staff of the hospital learned about the location and the extent of the disaster by 9:00 a.m., when the first wave of injured were driven in by their families. This was followed by a larger second wave of injured a few hours later, as more people found means to get to Kerman City.

The Kerman hospitals were well prepared to deal with the disaster because of experience gained during the eight-year Iran-Iraq War. Many people involved in emergency response in Kerman hospitals had dealt with large numbers of injured soldiers in the past. The doctors and staff performed heroically after the quake, but they already knew what to do and did it almost automatically. Considering the magnitude of the disaster and the limitations that existed on the ground, the performance of the hospitals was exceptional.

Shelters

The sheltering arrangement is something of a patchwork. According to public officials of various agencies who talked with the reconnaissance team, more than 110,000 tents were dispersed in Bam by local and international aid organizations (Figures 25 and 26). Some tent camps were established, but tents were also given away. With an option of going to a camp or obtaining a tent and placing it on or next to their property, many people chose the latter. Thus, many of the tent camps were half occupied while thousands of people camped by their properties. This made providing

Figure 26 *Children playing near an established tent camp.*

food and supplies very difficult for the authorities, because the tents are broadly dispersed. There was also no way for authorities to distinguish between who was actually a resident of Bam and who had rushed to the city to take advantage of the situation, because the city infrastructure (official buildings, files, and records) had totally collapsed. As of this writing, work has begun on erecting temporary housing structures, but it is unknown when or whether there will be enough for all the displaced people.

Public Policy Issues

The widespread and almost total devastation of the city of Bam has enormous social and economic consequences that will affect the recovery process. At this writing the government reconstruction policy is still unclear, but there are a number of issues that will need to be addressed:

- As mentioned earlier, Bam is the wealthy center of this region, while surrounding villages are poorer. As a consequence, many villagers have come into Bam to avail themselves of the aid that has been pouring into the city. Anecdotal reports indicate that the population of Bam has now swollen to over 120,000, a remarkable figure considering that more than 40,000 people were killed in the earthquake. More than 100,000 tents have been dispersed. There are reports of villagers coming into the city by day and availing themselves of food and other assistance, and driving back out to their villages at night. Sorting out who is entitled to disaster aid and temporary housing will be a challenge for the government. In fact, at the beginning of March there were riots in the streets in Bam, with aid recipients protesting the lack of assistance. How many of the rioters were earthquake victims is not clear.

- The basic infrastructure of the city, particularly the drinking water system, was seriously damaged. Immediate and major repairs are required to the water system (or construction of a new, improved system) before serious reconstruction work can begin in the city. Until the water situation is resolved, much of life is on hold. Schools are only slowly reopening their doors. In addition to the damaged drinking water system, damage to the irrigation system and qanats means that the date palms, the economic base of this region, may not get the water they need during their growing season. This would have devastating economic repercussions for the region.

- Most residents are currently living in tents and using water from temporary devices, many of which were brought in by international aid agencies. As spring and summer approach, the temperature in Bam will rise to close to 50ºC (122°F), making such temporary living quarters extremely unpleasant and possibly unhealthful. In addition, hot winds called the 100-Day Winds of Sistan will come in the late spring, blowing dust around. There has already been one severe wind storm in mid-March, with 70-mph winds that damaged some of the tents. Typically, people during this time of year spend most of their days indoors, even in basements.

- There is substantial pressure to rebuild the Arge-Bam quickly, as a symbol of the rebirth of the region. As a UNESCO World Heritage site, it is a major cultural treasure that needs careful evaluation and consideration to be rebuilt appropriately. Unfortunately, pressure to make speedy decisions will not allow enough time to study the building history of the site (exposed by the earthquake), and it may result in inadequate attention to seismically resistant adobe building techniques.

- The central government in Tehran is developing a reconstruction plan for the region. They have substantial experience from previous earthquakes and other disasters, and have been consulting with experts from around the world, including India, a country with significant rebuilding experience. The United Nations ISDR office and the U.N. Development Programme are also involved in providing rebuilding advice. Over the next several months, the rebuilding policies should become clearer.

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