Performance of Lifeline Systems in Bam Earthquake of 26 December 2003

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ABSTRACT: *At 5:26 am local time, Friday, December 26, 2003, an earthquake with moment magnitude 6.5 hit the city of Bam in southeast Iran. The earthquake caused more than 26,000 deaths, 30,000 injuries, and left 70,000 homeless. It caused extensive damage to residential and commercial buildings and emergency response facilities. In contrast to the inflicted human loss and suffering and extended building damage, lifeline systems, although damaged, performed much better. Transportation systems, i.e., roads, bridges, railways, and the airport, although slightly to moderately damaged, were generally operational soon after the earthquake to support emergency response and recovery effort. There were several breaks in the water distribution systems and minor damage to deep wells. However, the traditional qanat systems, which bring water from foothills tens of kilometers away via underground tunnels, were mostly damaged. The Bam area is served via connection to countrywide electric grid system. There was little damage to high voltage transmission lines and towers and minor damage to electric equipment in the main substation. Numerous concrete poles were damaged in the distribution system. There was nonstructural damage to telecom central offices. The main reason for the good performance of the lifeline facilities was that most of them are located outside the zone that was heavily damaged. Another reason is that they are newer facilities and in general more engineering has been used in lifeline facilities design and construction when compared with that for residential buildings.*

Keywords: Earthquake; Lifeline; Water tank; Qanat; Electrical Substation; Airport

1. Introduction

Continuous functioning of lifeline systems, such as transportation system, water distribution, waste-water and sewage systems, electric generation, transmission and distribution networks, communications systems, and gas and petroleum distribution systems, is essential for the well-being of urban communities. The need for lifeline systems is even more crucial immediately after occurrence of a major natural or man-made hazard such as an earthquake. Thus, proper design, construction and maintenance of lifeline systems with respect to their availability, performance, and reliability during and after natural hazards are critical and needed [1, 2]. Lessons learned from the performance of lifeline systems in natural hazards [3, 4, 5] help support achieving this goal. The purpose of this paper is to summarize the performance of lifelines in the recent Bam earthquake.

On Friday December 26, 2003 at 5:26 *am* local time, a moderate earthquake with moment magnitude 6.5 hit the city of Bam and its surrounding areas in Kerman province in southeast Iran. The epicenter of the earthquake was located at 29.00*N*, 58.34*E* in the ancient city of Bam. The rupture occurred on the known and mapped dipped Bam fault which runs through the city of Bam. The Bam fault, though known, had no known earthquake activity in recent times. The earthquake had a focal depth of 10*km* and an estimated rupture length of 20*km*. There was no evidence of rupture reaching the ground surface. However, there is strong evidence that the fault rupture reached the city of Bam.

The earthquake caused extensive damage to residential, commercial, governmental, religious and educational buildings. In the old parts of the city of Bam more than 90% of traditional adobe buildings collapsed. A large number of new buildings, mostly unreinforced masonry but also engineered buildings, collapsed or had extensive damage, which require their complete demolition. The earthquake impacted area had a total estimated population of 200,000 with about 90,000 in the city of Bam. The earthquake caused more than 26,000 deaths, 30,000 injuries, and left 70,000 homeless. The high ratio of death to injuries is due to the timing of the earthquake, when most people were in bed, and large number of people living in traditional adobe buildings and unreinforced masonry buildings where earthquake motions cause brittle failure and sudden collapse of buildings. In contrast to the devastating human loss and suffering and extensive damage to buildings, the lifeline systems, though damaged, performed relatively better.

By invitation of the Geological Survey of Iran, *GSI* (www.gsi.org.ir), the Norway's Centre of Excellence, International Centre for Geohazards, *ICG* (www.geohazards.no), sent a team of experts on a post-earthquake reconnaissance mission to Bam in January 2004 [1]. The *ICG* in turn invited the first author from Risk & Reliability Engineering, to join the *ICG* team in this effort. The team was in Bam about one month after the occurrence of the earthquake. The team documented its finding on the, earthquake, causative fault, and impact of the earthquake in a report to *GSI* [6]. This paper summarizes damage and performance of lifelines in this earthquake. The lifelines considered in this paper are water systems; transportation networks, including roads and bridges, railways, and airports; electric transmission and distribution systems; and communication systems.

2. Water Systems

2.1. Water Distribution System

The city of Bam uses drinking water from about 12 deep wells. The water is distributed to residential, commercial, industrial and other users via a water distribution system. The system is made of buried pipelines, mostly concrete cement pipes, and several underground and above ground water storage tanks. There is no water treatment plant in Bam. At the locations of several storage tanks chlorine mixture is added to water for chemical treatment [7].

There was report of damage to a number deep wells and also several pipeline breaks throughout the city. Due to collapse of the buildings and breakage of connecting pipes, at users ends, water had to be brought by tanker trucks to the tents and shelters and other users after the earthquake. Overall the storage tanks performed well. Figures (1) shows an elevated concrete water tank, located near the old section of the city close to the earthquake rupture where the damage was high. The tank experienced severe stress and deformation at the column-beam connections.

2.2. Qanat System

Qanats are the traditional water systems used in Iran over centuries. A qanat consists of an underground tunnel dug into competent sediments and a linear series of vertical wells that provide access for inspection and repairs. Figure (2) shows the design principles of a qanat. The underground tunnel would bring water from foothills of mountainous area tens of kilometers away. The wells are typically about 30*m* to 50*m* apart. Sometimes several qanat branches are joined together and continued to the designated area via one qanat branch. Figure (3) shows aerial photo of several qanat branches.

There are 126 chains of qanats in the Bam region, of which 62 to 64 serve the twin cities of Bam and Baravat. The chains of qanats bring water to the city from foothills of mountainous area west and south-west of the city (Jebal Barez) tens of kilometers away, Figure (4). The wells are about 20 to 50*m* apart. The water from each well is led toward the city via the connecting underground tunnel. The wells are about 70*cm* to 90*cm* in diameter, and are as deep as 100*m* closer to foothills to about 5*m* to 15*m* closer to the city. The tunnel cross section is usually in rectangular shape about 70*cm* to 100*cm* in width and 150*cm* to 200*cm* in height. The under ground tunnel eventually reaches the ground surface, and the water is then led to farms and gardens via small manmade creeks, Figure (5). In Bam area the qanat water is mostly used for agriculture and date tree gardens. There are about 1,600,000 date trees in Bam and its vicinity and the export of Bam dates to other parts of Iran and rest of the world is a major source of income and livelihood for citizens of Bam. The qanat water is sometime stored in traditional underground reservoirs, as shown in the last two picture on Figure (5).

More than 55 chains of qanats had various levels of damage mostly to their wells and underground tunnels closer to the city and the quake epicenter. The damage was in the form of failure of the underground tunnel walls and wells, blocking the water to reach the ground

Figure 1. Elevated concrete water tank located in near the old section of the city where the damage was high. The tank experienced severe stress and deformation at the column-beam connections.

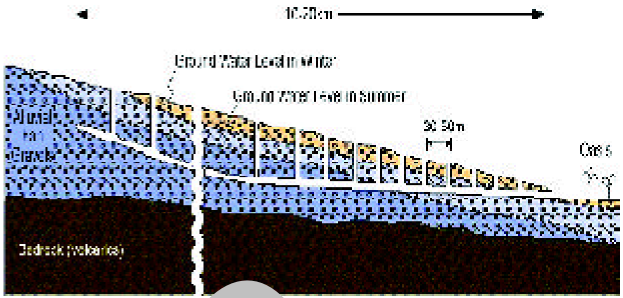

Figure 2. Principles of water transport by a qanat.

Figure 3. Aerial photo of several chains of ancient qanat systems, which typically bring water from foothills of mountainous area to more dried desert towns and villages in Iran.

Figure 4. Snow-capped Jebal Barez mountain range is located in southwest of city of Bam as seen from Azadi hotel in Bam. About 126 qanat chains bring irrigation water from foothills of Jebal Barez to Bam region.

Figure 5. Once the qanat chain arrives at its destination, the underground tunnel reaches the ground surface (top and middle left pictures). From there the water is distributed via man-made channels and brought to farms and date palm gardens. Damage to the channels is noted in the middle and lower right pictures. The qanat water sometime is stored in traditional underground reservoirs (bottom two pictures).

surface. One should note that the wells as well as the underground tunnels are not reinforced and are basically vertical and horizontal holes in the ground. Even without earthquakes the wells and the tunnels need regular maintenance to remove the fallen soil from the well walls and tunnels. At the time of the team visit a number of qanat builders from other parts of Iran had come to Bam area to clean and reconstruct the damaged qanats, see Figure (6). In addition to damage to qanat chains, the distribution surfaces channels were damaged or closed off due to collapsed garden walls or other constructions.

Figure 6. The vertical wells, also used as access wells, are usually large enough for one person to be able to climb down (about 90cm across). Note the use of old tire at the entrance of one well. Damage to the qanat systems included underground tunnel collapse and closure (not shown), access well failure, which in turn causes the closure of the underground tunnel, damage to the channels. At the time of our visit a number of qanat builders had been brought from other parts of country to repair the very important qanats.

3. Electricity

There are no electric generating plants in Bam or the affected area. Bam and its vicinity are connected to the countrywide electric grid system. Main transmission lines, bring electricity from this grid to Bam area. There are four substations in the area: two in Bam, one in Baravat, and one in New Arg. The two in Bam are 230kV and 115kV. Transformers are used to reduce the voltage to 220V for residential and commercial use.

There was no damage to main 230kV transmission lines. There was however damage to concrete poles in the distribution system and streetlights. Part of the damage to the concrete poles was due to collapse of adjacent walls and buildings. We observed series of poles to be out of plumb. Damage to transformers on distribution poles was reported [8], see Figure (8).

The 230kV substation in Bam experienced some damage. There was some damage to porcelain insulators and bushings at this substation. The wall around the substation collapsed. The office/control building in the substation structurally performed well, see Figures (8) and (9). This substation was about 5km distance from epicenter. At the time of our visit (one month after the earthquake), electricity had been restored throughout the city, even in the area where there was severe to complete building destruction.

4. Transportation Systems

4.1. Roads

There is a main two-way highway-connecting city of Bam to Kerman on the northwest and Zahedan and Iranshahr on east and southeast of Bam. This road crosses the Bam fault scarp. Very minor damage to road embankments and surface cracks in the main highway close to Bam fault scarp were observed. For the most part, roads and streets were usable immediately after the earthquake, see Figure (10).

Cross-country bus lines are the main mode of transportation for masses in Iran especially outside the major cities. The last picture of Figure (10) shows the roof of a bus terminal building collapsed onto several busses.

The bridges over a Bam river, called Posht-e-rud, performed relatively well. Figure (11) shows one of the main bridges over the river. There are signs of vertical movement in the base of the support walls/ columns. Damage to the pipeline on the side of the bridge is observed. All of the three main bridges were operational for service after the quake.

4.2. Airport

The main terminal building at the Bam airport had moderate damage, but the runway was operational immediately after the earthquake, see Figures (12). The steel frame terminal building was moderately damaged, but it withstood the quake. The masonry infill walls were damaged. The false ceilings were severely damaged. There was moderate damage to stairway to the second floor. There was nonstructural damage to airport control tower (broken windows). The airport runway had little damage and came to be extremely useful for emergency response and recovery effort. Hundreds of flights from inside of Iran and around the world landed in this airport immediately after the earthquake to bring search and rescue teams and equipment as well as much needed medical, food, blankets, tents and other supplies.

4.3. Railway

The construction of railroad to Bam had just been completed but the railroad had not been used prior to the quake. The passenger terminal located some 25km south of the city was under construction and had some damage. There was no damage to the rail tracks. There was light damage to embankment. The railroad was extremely useful for bringing supplies and help to Bam immediately after the earthquake, see Figure (13).

5. Gas and Petroleum

There is no petroleum pipelines installed in the affected area. Even though a large number of small and large cities in Iran have natural gas distribution system, Bam and the affected area did not have a gas transmission and distribution system at the time of the quake. One should note that, fires following earthquakes are very common and existence of underground gas pipelines and their ruptures due to earthquakes could lead to major conflagration. Even though there were reports of at least seven fires after the earthquake, lack of a natural gas system and wood constructions did prevent a conflagration in the city.

The gas stations and heating gas suppliers bring their material via tankers to the city. Fortunately, there was no gas station in the old section of the city, which experienced severe shaking. The gas stations in the city, Figure (14), were in operation at the time of our visit (one month after the earthquake).

Figure 7. Damage to transmission line towers was not observed. Concrete and wooden poles are used to bring electricity from substations to users. Pole top transformers convert the electricity to 220V. Many distribution poles were damaged. A large number of distribution poles and street light poles were out of plumb after the earthquake.

6. Communications

The team did not get to visit the central offices at Bam and Baravat, but there was report that the telecommunication central offices had mostly non-structural damage as well as damage to unanchored equipment. The main telecom towers mostly survived the quake. Some communication towers located on the roofs of the collapsed buildings were also damaged, see Figure (15).

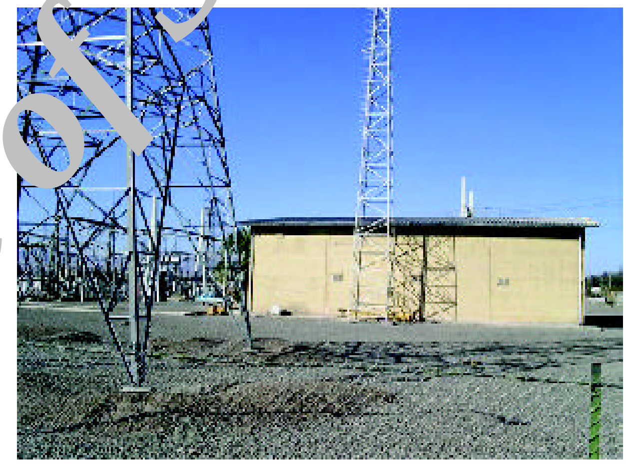

Figure 8. The 230kV substation experienced minor damage. The wall surrounding the facility collapsed. In the process it hit the concrete poles and caused their failure. A number of porcelain isolators were b roken. The office/control room did not seem to have been damaged structurally.

7. Summary and Conclusions

There were minor cracks on the main Kerman-Bam-Zahedan highway close to the Bam fault scarp crossing. The bridges over Posht-e-rud river had none to light damage and were available for use right after earthquake. The airport terminal steel moment resisting frame building had moderate damage, mostly to the masonry infill and non-structural elements, false ceilings, partitions, and architectural features. The runways had minor cracks, but were available for plane taking off and landing and proved extremely

Figure 9. Damage to various electric equipments in the 230kV substation is observed in the above pictures. At the time of our visit (one month after earthquake) the electricity was available throughout the city, even though most of the users' buildings had been severely damaged to use the electricity.

Figure 10. There were minor damage to roads and highways. There were some damage to road embankment and surface cracks cracks in the main highway close to Bam fault scarp. For the most part roads and streets were usable immediately after the quake. The roof of bus terminal building collapsed onto several busses.

Figure 11. A bridge over the Posht-e-rud performed relatively well. There are signs of vertical movement in the base of the support walls/columns. Damage to pipelines is observed.

Figure 12. The engineered steel frame terminal building at Bam airport was moderately damaged. The masonry infill walls were damaged. The false ceilings were severely damaged. The airport runway had little damage.

Figure 13. The passenger terminal was under construction and had minor damage. There was no damage to rail tracks. There was light damage to embankment.

Figure 14. Gas stations in the city of Bam were in operation at the time of our visit.

Figures 15. The main tele[illegible] towers mostly survived the quake. Some communication towers located on roof of the collapsed buildings were also damaged.

useful for bringing immediate emergency management operations to the affected area. The national railway system had been extended to Bam. The passenger terminal building was under construction and had minor damage. The rail tracks had none to light damage (embankment).

The railroad was also available and useful for emergency response and reconstruction effort. There were several breaks in the water distribution systems and minor damage to deep wells. The age-old traditional qanat systems, which bring water from foothills tens of kilometers away via underground tunnels, were mostly damaged. Out of the more than 60 qanat chains that served the twin cities of Bam and Baravat, only a few survived the earthquake. The agricultural activities in the Bam area (mainly date tree and citrus gardens) are totally dependent on the water transported to the area by these qanats from the foothills of Jebal-e-Barez Mountains. The importance of qanats to the livelihood of the people of Bam cannot be underestimated. The city is where it is because the fault that caused the earthquake also provided the conditions for the access to water for agricultural activities (daybreak of the qanats occurs on the surface expression of the Bam lineament).

The area is served via connection to countrywide electric grid system. There was little damage to high voltage transmission lines and towers. There was minor damage to electric equipment in the main substation. Numerous concrete poles were damaged in the distribution system. There was nonstructural damage to telecom central offices.

The damage pattern of the earthquake was nearly symmetric about a line 3 km to the west of the surface expression of the Bam fault, and the damage attenuated rapidly with distance from this line. There was very little or no damage at distances greater than 5 km from the reference line [6]. The main reason for the relatively good performance of the lifeline facilities was that most of them are located more than 5*km* from this reference line (e.g. airport, railway, train station, electrical substations). The qanats were damaged in the area between the reference line and surface expression of the Bam fault. Qanats typically have daybreak at locations where there is a sudden change in the ground elevation level (and the water table). These sudden changes in surface topography usually occur because of the existence of faults underneath. The correlation between access to water and proximity to earthquake-generating faults is a problem that needs to be studied further.

Another reason might be that for the most parts they are newer facilities. In general more engineering has been used in lifeline facilities design and construction when compared with that for buildings (e.g. concrete water tank, airport, railway station, telecommunication facilities). The observations confirmed that well-designed and constructed structures would have survived with only minor damage the severe earthquake shaking levels experienced during the Bam earthquake.

In summary, with the exception of qanats, lifeline systems by far had less damage than buildings. Having said that, there was still significant damage to lifeline facilities. More attention must be paid to non-structural elements and equipment installations in lifeline facilities.

Acknowledgment

The authors would like to express their deep gratitude to *GSI* for inviting the *ICG* team to Iran, and their hospitality and professional arrangement of the visit to Bam. In particular, the tireless effort of the *GSI* team in Bam is gratefully acknowledged.

This paper is the International Centre for Geohazards (ICG) contribution No. 56.

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