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Earthquake Hazards on Historic Hydraulic Structures: The Qanats of Bam

Abdin Salih, Alireza Salamat and Niloofar Sadeghi
UNESCO Tehran Cluster Office (UTCO)
Tehran - 19894, IRAN
E-mail: tehran@unesco.org

ABSTRACT: Earthquakes are natural hazards which not only demolish buildings and old monuments, but also ruin historic and new hydraulic structures which could be important water supplying systems in the devastated regions. Some of these historic hydraulic structures could also have a cultural heritage value, such as Qanats which are traditional systems for continuous supply of tapped groundwater to agricultural, domestic and industrial use.

A large earthquake stuck Kerman province in the South Central part of Iran in December 2003, causing the demise of approximately 26,000 people, injuring many more and destructing almost all of the buildings of the city of Bam and its surroundings. Before the earthquake, there were over 350 fully functioning Qanats in and around the city of Bam. The devastating earthquake caused significant damage to agriculture and animal husbandry with losses ranging from 30–100 percent. Many Qanats collapsed and water pumps and irrigation channels were ruined.

This paper presents the effects of earthquakes as a serious natural hazard to hydraulic structures. It will focus on the Bam earthquake and the current status and future prospects of the Qanats of Bam viewed from engineering, cultural, archaeological, geological, agricultural and socio-economical view points toward an integrated management approach.

INTRODUCTION

Iran covers a total area of around 1.65 million km^2 and is bordered by Azerbaijan, the Caspian Sea and Turkmenistan to the north, Afghanistan and Pakistan to the east, the Persian Gulf to the south and Iraq and Turkey to the west. About 52% of the country consists of mountains and deserts and some 16% of the country has an elevation of more that 2000 meters above the sea level. The total population is around 68.5 million (2006) of which 40% live in rural areas.

The climate of Iran is one of the great extremes due to its geographic location and varied topography. The temperature varies from over 55°C during summer to minus 30°C in winter.

Annual rainfall ranges from less than 50 mm in the deserts to more than 1600 mm towards the Caspian plain. The average rainfall is 252 mm which is one third of the world's average and approximately 90% of the country is arid and semi-arid. The total agricultural, domestic and industrial water use is around 92%, 6% and 2%, respectively, of the country's annual water use.

The problem of water supply has been a constant pre-occupation since the beginning of the country's history, thousands of years ago. Its inhabitants learnt from old time to design and implement efficient techniques for harnessing limited water resources for their domestic needs and for irrigation. One of these great innovations was the Qanat system which was built and continued to be utilized by Iranian in the past as a major source of irrigation and domestic water supply for centuries.

A Qanat is a gently sloping subterranean conduit which taps a water-bearing formation at a higher elevation than cultivated lands. The conduit is connected to the surface by series of shafts, and uses gravity to bring water from the tapped aquifer to the surface for various uses (Figures 1&2).

Iran is claimed to be the original homeland of Qanats. Their invention dates back to over two thousand years ago, supplying water for the historical expansion of the Persian Empire across the region. It has been estimated that 60% of the world's Qanats are found in Iran, and their know-how were exported to an estimated 36 countries across the globe, including: Afghanistan, Bahrain, Chile, China, Egypt, India, Oman, Pakistan, Qatar, Russia, Saudi Arabia, Spain, Tajikistan, Turkey, Turkmenistan and the United Arab Emirates (Figure 3).

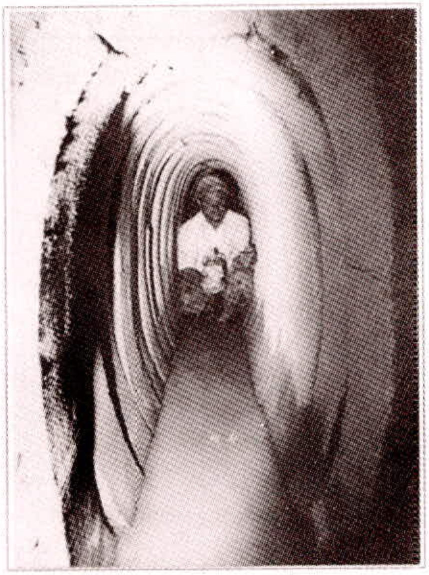


Fig. 1: Qanat Shafts (ICQHS-Yazd)

Fig. 2: Qanat Gallery (ICQHS-Yazd)

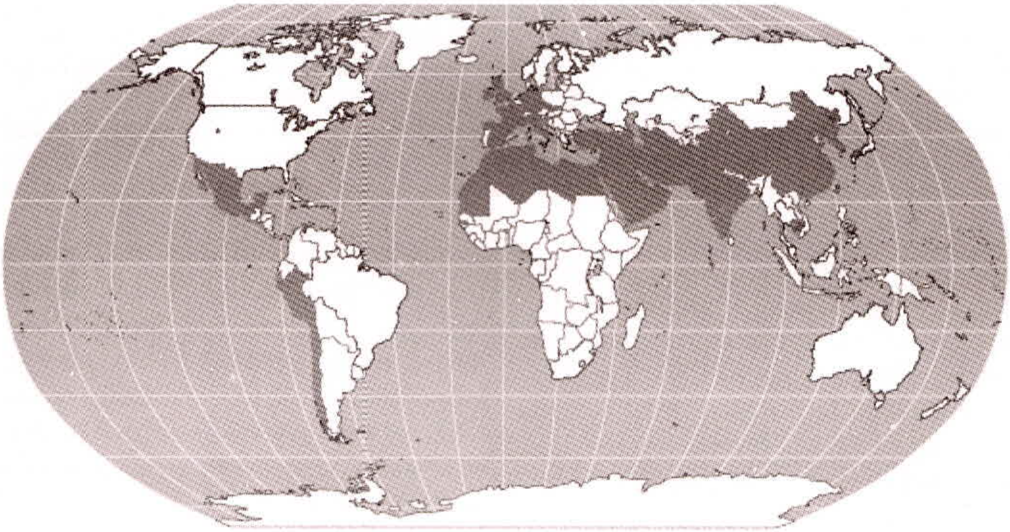


Fig. 3: The darker areas show the distribution of Qanats on the planet

Qanats gave rise to a variety of associated water supply and distribution techniques which were adapted to the climate and local agricultural needs. Entire social, cultural and political systems evolved because of the outstanding irrigation techniques that were based on Qanats presence.

Qanats are also known as Karez, Khotara, Aflaj, Foggare, Kanerjing, Falaj, Galeria and Auyoun, reflecting the widespread dissemination of this ingenious technology.

Qanats are still an important source of water in many countries of the world. According to the official statistics, there are around 32,164 live Qanats in Iran, producing about 10 billion m^3 of water per year (Ministry of Agriculture, 1998).

EARTHQUAKE HAZARDS ON HISTORIC HYDRAULIC STRUCTURES

Earthquakes affect the linear structure of Qanats in two ways—tremors and ground failure. Tremors refer to the vibration of the ground that produces seismic waves. These may cover hundreds of square kilometres around the epicentre and the intensity of the tremor decreases with distance from that point. Any underground tunnel shape structure in ground is affected by this and damage to the structure will depend on its overall design, strength, ductility and flexibility.

Ground failure broadly includes various types of instability such as faulting, landslides, liquefaction, tectonic uplift and subsidence. The best way to mitigate the risk of structural damage is to avoid areas prone to these hazards but since Qanats are often several kilometres long it is almost impossible in highly seismic areas to overcome this problem.

BAM AND THE EFFECT OF ITS EARTHQUAKE ON HISTORICAL STRUCTURES

Bam County is located in the south east part of Kerman province, more that 1200 km far from the capital (Figure 4). It covers 75 km^2 and consists of five districts, namely Baravat and Bam, Narmashir, Rigan, Fahraj and Roudab. Bam district is a typical desert oasis with an arid climate and average annual rainfall of about 60 mm, making irrigated agriculture an important driver for the region's economy.

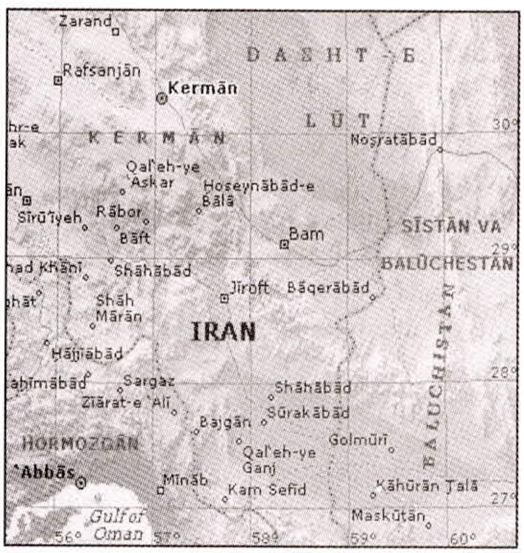


Fig. 4: Geographical setting of Bam city (GSI/Archives)

The worst earthquake in the last decade, hit the ancient city of Bam, in south-eastern Iran, on 26th December 2003 killing 26000 people and making, over 60,000 inhabitants homeless. The devastating 6.5 magnitude quake struck the region at 05:28 am local time; an hour at which almost all the city's 80,000 residents were in bed. The catastrophe brought more than 80 percent of the buildings in the city to the ground. In addition, Bam's historical landmark—a giant medieval fortress complex of towers, domes and walls, all made of mud-brick was vastly destroyed. This Arg-e Bam (Citadel), over 2000 years old, whose strategic location was chosen for agricultural, economic and defensive reasons is the cultural and spiritual land mark of the city of Bam and is considered as one of the wonders of Iran's Cultural Heritage.

There are no permanent surface streams or rivers in or near Bam, although dry riverbeds indicate seasonal floods. The groundwater situation is quite different. The district is surrounded by high mountains that receive precipitation, both as rain and snow, which infiltrates into the alluvial fan and recharges aquifers overlying fine grained and impermeable alluvial deposits. This situation was ideal for the construction of Qanat system. The discharge rates of the Qanats vary widely, in the range of 50–200 lit./second, while well's discharge are in the range of 15–50 lit./second. These two means of exploiting groundwater provide the agricultural water required for irrigation. Both Qanats and wells were damaged to a range of 30–100 percent due to the strong earthquake.

UNESCO EFFORTS TO PROTECT QANATS IN BAM

UNESCO has taken the initiative to support Iranian efforts to rehabilitate, protect and strengthen the management of the Qanats of Bam. Comprehensive studies on the Qanats of Bam from the view points of engineering, archaeology, geology, and socio-economic characterizes have been carried out as summarized below.

Qanats of Bam: A Geological Perspective

According to geological studies, the Bam fault scrap (Figure 5) has greatly contributed to the trapping of groundwater in the upper terrace, where bam city is located, as it forms a sort of underground dam that keeps recharge water in the aquifer. Recent geological studies have shown that the 2003 earthquake did not result in significant displacement of the fault scrap and is not expected to have changed groundwater status in the area.

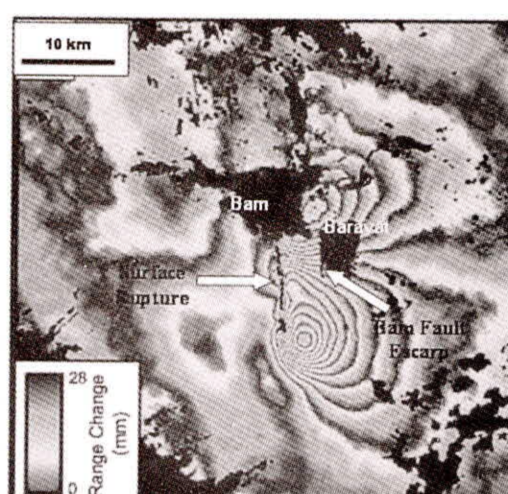


Fig. 5: Bam Fault Escarp (GSI/Archives)

The Bam earthquake measured 6.5 on the Richter scale and its epicentre was on the Bam Fault at 29.00 N, 58.34 E. The focal depth of the tremor was estimated to be 10 km. Ground motion recordings obtained from a digital accelorograph unit in Bam city show maximum corrected Peak Ground Acceleration (PGA) of 0.979 g for the vertical components and 0.778 g for the longitudinal (N–S) and 0.623 g for the transverse (E–W) components. Rapid ground movements during the earthquake led to a striking pattern of damage to buildings which decreased along a path perpendicular to the Bam fault.

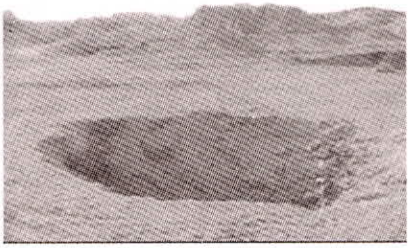
The Qanats of Bam vary in vulnerability and the earthquake damaged them to a lesser or greater extent depending on the geomorphologic context as well as maintenance or structural integrity (Figures 6, 7 & 8).

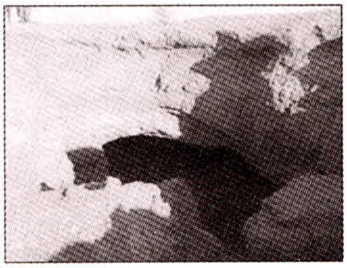
Qanats near the main rupture at the western end of the Bam fault scarp suffered greater damage than others, and this is partly because of the direction of the seismic waves and partly because of the changing engineering properties of materials. Some Qanats were also damaged by landslides and subsidence.

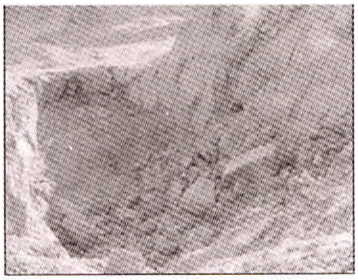
A preliminary evaluation showed that about 40 percent of Qanats had collapsed or been severely damaged. In some cases damages had completely stopped the flow of water. Most of the damage to Qanat systems was because of structural damage or collapse and not leaking through fault lines. Surface displacement as a result of the earthquake was almost 25 cm and hypotheses estimate that this has reached at least a meter in bedrock. Qanats are shallow structures and therefore the maximum displacement is probably the same as that found on the surface. This means that surface faulting has a minimal impact on water yields unless faults directly cut the gallery.

To reduce the impact of earthquakes on Qanats as far as geological aspects are concerned, the following recommendations need to be emphasized:

- The newly found fault west of the Bam fault plays a major role in understanding the mechanism of the Bam earthquake and it needs to be considered in planning the reconstruction of facilities such as Qanats.
- Qanats depend on a combination of geological factors including the existing of a recharge area (Barez and Kafut mountains), aquifer material (alluvial fans), and a seal layer (deposits on the Bam fault scarp).
- The damage to Qanat systems are mostly structural affecting access wells and galleries near the Bam fault scarp and there is minimal leakage as a result of faulting.
- Extensive damage was observed in a narrow band near the Bam fault. Skilled engineers can provide support to galleries and access wells near the Bam fault and reduce the likelihood of damage near the newly found fault line.
- Detailed study of geotechnical and engineering properties of different horizons near Qanats may help to develop aseismic designs in hazardous areas.
- Mapping old Qanats, especially those still yielding water, may help to avoid damage to newer structures and channels. It is also important to restrict construction near Qanat systems and to provide extra support when building near access wells or galleries.







Figs. 6, 7 & 8: The vulnerability of Qanats of Bam (GSI/Archives)

Qanats of Bam: Archaeological Perspective

The present research program, which started the day after the earthquake by requesting new aerial photographs, tends to remedy some of these shortcomings. Although still in its infancy, the study has to some extent clarified the very remote history of Bam by bringing to light new archaeological sites. Furthermore, it supplies indispensable fresh evidences for the knowledge of the general history of world irrigation; one of the man's main acquisitions in his march towards mastering his own food.

The first surveys in the Bam vicinity have indicated that, thanks to a favourable climate, men were already settled in the Bam area by the Neolithic and Chalcolithic Epochs, around the IVth millennium B.C. They were either living in self-sufficient independent entities such as the one in Tall-e Âteshi and perhaps in Bam itself, or in a series of closely interrelated settlements established close together. Probably, when the weather became drier, the local farmers discovered step by step how to extract water stored up in the lands west of Bam's Seismic Fault, imprisoned by its Scarp and fed by rains and melting snows in the mountains surrounding the Bam Basin. At the beginning, the running waters seem to have been abundant enough, and the level of the groundwater sufficiently high to be in both cases collected by canals, but later, water became scarcer and its level dropped. Greatly helped by the sharp fall in the land level next to the Scarp of Bam which could significantly shorten the length of the necessary underground tunnels, settlers naturally found it easier to dig short underground interconnected shallow wells instead of excavating unceasingly to deepen the canals; Qanats were thus invented in the first millennium B.C. Indubitably, the existence of the Scarp which played the role of a dam in gathering the coming waters, and the sharp drop in the level of the Bam-Narmâshir plain caused by the Seismic Fault, not only made the task possible, but made it by far easier in dramatically shortening the length of the first Qanat.

Qanats of Bam, reached its zenith in the early Islamic period, but lost its lustre when by the end of the 12th century ceaseless succession wars among the Seljuq princes together with the destructive invasion of the Ghuz tribes greatly damaged the social and economic forces upon which the Qanat network was functioning in Bam. The system, although weakened, survived, but the town never recovered its former position especially as a textile production centre. Its landscape as a garden town remained however fascinating, still irrigated as it is by a complex and mesmerizing Qanat network in which they survive the vestiges of the oldest Qanats of Iran and perhaps of the world (Adl, 2005).

Qanats of Bam: Engineering Perspective

Qanats are usually dug where there is no surface water. The mother well is generally dug in the mountains deep into the water table (Figure 9). Water flows down a slightly sloping tunnel, gradually increasing in volume until it emerges through the outlet which is called "*Mazhar*". *Mazhar* is the point where people take water and it is generally located in the main square of a village. *Mazhar* is a very important point, it is well kept and cemented and water use is monitored.

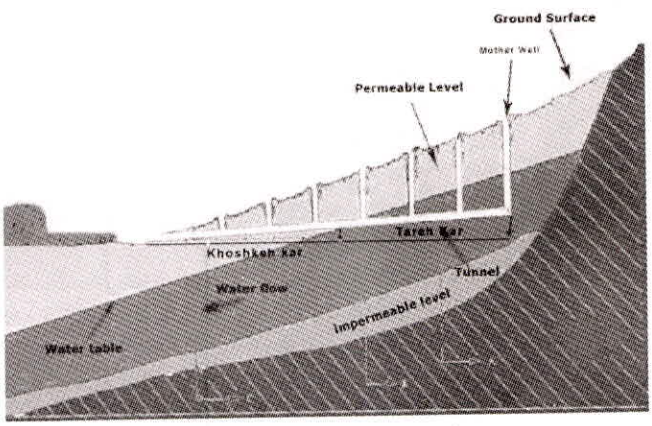


Fig. 9: A typical qanat system

To allow smooth water flow by gravity from the mother well to the *Mazhar* precise levelling is essential. The water appearance of *Mazhar* is usually an open trench, 1 to 4 meters deep, locally named "*Kush*". This depth is gradually reduced till eventually water flows to the surface at the outlet. From this point a ditch, locally named "*Ju*", conveys water to the field or the place of use (Figure 10). Where Qanats are deep, usually two wells are dug nearby, to provide proper ventilation, known locally as "*Joft-e-Badu*" meaning twin ventilators. The ceiling of a Qanat canal is mainly cut semi-arched. Galleries are dug in the wet zone, where water seeps into the tunnel, or in the dry zone, which is the water passage.

To construct the walls and floor of the gallery in dry and wet zones, the slope is kept even, again depending on the length of tunnel and gradient of the ground. In the cases of a tunnel of another Qanat passing underneath, to prevent the penetration of water in to the lower canal, the floor of the upper one is well isolated with cementing material. In this respect, a paste of clay, lime and white part of eggs is spread on the floor and walls, where water is flowing. The shape of ceilings of canals in wet zones in Bam looks like the letter V upside down, Number 8 ("^") in Persian; locally named *Mekenayi*, which is common in Yazd. This type of sharp arch prevent water dripping and causing ceiling collapse; sliding on the walls instead. To construct tunnel in the wet zone, the master practitioner begins with the ceiling first, then the walls and finally digging the floor so that water level does not raise upper than knees; this also is to use the water flow for keeping the slope constant along the tunnel.

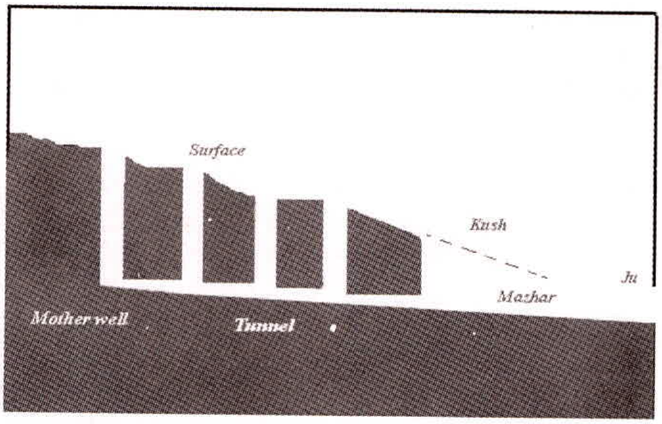


Fig. 10: The appearance (*Mazhar*) of a Qanat

Qanat diggers are called "*Moqanis*", and the master practitioners are "*Ostad Moqanis*". "*Kahkin*" is another name for the practitioners in Kerman region. Qanat digging technique is an ancient and important innovation in Iran. Recognition of its social, technical, operational, managerial and cultural dimensions are vital in understanding the entire system. Digging a Qanat in the past was done by either unskilled diggers, landowners or professional Qanat diggers.

The December 2003 earthquake caused blockage and collapse in many Qanats in Bam, and the discharge increased in some others. Blockage to some Qanats caused water to seep into other Qanats. The immense structural damage has led to changes in the management and supervision of Qanats and acknowledgement of their cultural and social as well as economic and hydrological importance.

Blockages are removed by the moghannis but sometimes tunnels are diverted or, if the wells are shallow, restructured as an open ditch. Qanat restoration work requires great skill and the use of non-professionals can cause problems. For example, 120 m of canal was dug to unblock the tunnel of one of the longest Qanats in Bam region. The new section was dug one meter higher than the original tunnel and water accumulated along the gallery, causing the ceiling and walls to collapse. Due to the topographic conditions of the area, bulldozers cannot be used in some spots and traditional tools must be used.

The case study of Ghonad-Kohneh Qanat, one of the main structures in Baravat-Bam, illustrates some of the problems in post-earthquake reconstruction. The costs of the operation have been divided proportionally among the owners according to an eight-day cycle of 192 hours. Water rights to this Qanat are around two million Tomans (USD 2212) per hour (Semsar-Yazdi, 2005). The earthquake caused considerable damage and workers began by digging a trench 10 m deep and 100 m long from the mazhar (origin) towards the first shaft. Moghannis continued the task, digging four shafts which ran to the center of Bam, where another collapsed section of tunnel was discovered near the city reservoir. The moghannis dug another well in the middle and excavated the soil from both sides. Eight shafts from this point to the wet zone needed repair before the reconstruction was complete.

In order to make Qanat use more sustainable, to preserve them and to optimize the use of water in the Bam region, the following recommendations are made from the engineering point of view:

- Authorities should impose restrictions on the digging of deep and semi-deep wells. Consent monitoring of the Bam-Narmashir Basin is vital and any excess water extraction should be stopped.
- Deep and semi-deep wells should only be permitted when absolutely necessary and new wells should be at least 3 km from existing Qanats.
- Agricultural wells should not be dug in zones reserved for Qanats.
- Qanats and their share-holders should be financially and culturally supported by the government. The Ministry of Jihad-e Agriculture should facilitate grants, loans and incentives for the repair, restoration and reconstruction of Qanats.
- Any work on Qanats must be done with full consultation with communities and they should be encouraged to participate. The mass media should feature Qanat-related issues more prominently and regularly.
- Moghannis must be hired to undertake post-earthquake restoration work and digging in wet zones and their traditional knowledge should be documented.
- After the earthquake, management of many Qanats suddenly changed but there should be compatibility between traditional management systems and new ones. New management structures must fulfil all economical, social and technical needs of communities and Qanat users.

- A comprehensive groundwater monitoring network should be established and this should undertake annual assessments of the active wells and Qanats in the region.
- A Qanat database should be established to document and store information on moghannis, traditional techniques and distribution systems, as well as the experiences of farmers and all those involved in the operation and use of Qanats.
- Traditional techniques should be integrated to modern methods using labour-saving technology.
- Young people should be made more aware of Qanats and Qanat construction technologies and training should be provided to those wishing to pursue the profession of the moghanni.

Qanats of Bam: Socio-economic Perspective

Bam district is both rural and urban in character. Economically, ownership of or access to land, water and date palms has been, and still is, the criterion of social stratification into upper, middle and lower classes. Most of the society may be categorized as middle class, though their attitudes, particularly on gender issues, are different from that of the completely urban middle class of Iran. Besides, the district has for long suffered from widespread drug addiction.

With the prevailing arid conditions in Bam area, it is not hard to imagine that the birth and development of the city and the surrounding oasis for some 2000 years has depended on the construction of Qanats that made water available. This ingenious method of tapping groundwater has also given the local community a sense of pride in their legacy of indigenous knowledge, historic civilization, and scientific advances in hydraulics.

Qanats have also contributed to development of social structure in the area because the hard and expensive work required for Qanat construction meant that it has always been a collective activity, with different beneficiaries helping in different ways, such as by taking part in the construction or providing in-kind inputs or cash money. Access to and management of Qanat water is regulated by a Water User Group, whose members are the water share owners. Members collectively manage the water, take part in maintenance or may pay in cash or kind (labor), and share the water.

The Bam economy is based on agriculture and this, in turn, is highly dependent on groundwater. Around 70 percent of the people living in Bam and surrounding villages are directly or indirectly engaged in agricultural activities. There is no real strong socio-economic separation between the town and its surroundings as many people working in the city have date plantations in the villages.

There are two main types of irrigation in Bam: the traditional Qanat systems and a more recent system of wells/boreholes equipped with pumps. Bam is known for its high-quality dates, citrus corps, henna and dairy products. Many of the surrounding villages and cities have close economic ties with Bam. The 2003 earthquake caused extensive damage to the Qanats and there was a great concern that the valuable date palm plantations would be lost. However, repairs of the irrigation system progressed well and damage to agricultural production has been limited. Nevertheless, the following issues were of concern:

Collapsed Qanat tunnels, some of which were also used for domestic use and livestock as well as irrigation, stopped water flow completely or caused decreased discharge. The earthquake occurred near the time when date palms are manually fertilized. This is a very sensitive time for irrigation when water stress could seriously reduce date production in the short term and have a long term impact because of the loss of trees.

The sudden poverty and lack of cash made rehabilitation activities much harder. Prices increased sharply because of a shortage of labor and materials and supply of both was not adequate to meet demand.

Participation of farmers in rehabilitation of the Qanats or wells was also affected by the fact that shares of Qanat water, both in terms of ownership and access, were not equally divided and therefore some people had little incentive to cooperate. Repeated aftershocks meant that rehabilitation operations became hazardous because of increased risk of tunnel collapse, and also expensive.

The social problems affecting the management of Qanats after the earthquake are:

- Vacuum in know-how due to the death/injury of local skilled Qanat specialists.
- Death/injury of shareholders reduces the number of laborers for the operation and maintenance of Qanats.
- Traumatized community means little interest in participation in collective activities.
- Some dissatisfaction with employment of "non-locals" in rehabilitation operations, partly stemming from competition in job opportunities.
- Dissatisfaction because of low community participation in decision making.
- Drug addiction.

The socio-economic roles of Qanats are:

- Birth and development of the oasis and the city has been dependent on Qanats;
- Local communities take a sense of social pride in Qanats legacy of indigenous knowledge, national historic civilization and scientific advances in hydraulics;
- Contribution to development of social structure through water users group, whose members collectively manage the water;
- Agricultural development of the community;
- Industrial development (agro-industry and tourism);
- Energy saving (water withdrawal) and producing (water mills);
- Qanats are compatible with natural inflow-outflow equilibrium of aquifers, meaning a balanced and sustainable withdrawal of groundwater.

CONCLUSIONS

For many centuries, the Qanats of Bam have been playing a vital role for the inhabitants of Bam region by continuously supplying their water needs for domestic, agricultural and industrial use. The catastrophic earthquake of 2003 caused various levels of damages to these Qanats. Several studies have been carried out by UNESCO on these historic hydraulic structures, which also have a cultural heritage value, for their rehabilitation resulting in many recommendations that are essential for any sound reconstruction, operation and management actions. The most important of these recommendations have been summarized in the text of this paper.

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