Geotechnical Instabilities Occurred During the Bam Earthquake of 26 December 2003

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ABSTRACT: *This paper describes the geotechnical instabilities such as landslide, liquefaction, and ground subsidence caused by the Bam earthquake. Based on the results of geotechnical investigations, after the Bam earthquake, land subsidence due to collapse of Qanats (underground irrigation tunnels), local toppling, and block slides along riverbanks or man-made channels were the most dominant geotechnical instabilities of the event. These effects will be introduced and discussed in this paper and the distribution of them will be presented based on the study of aerial photos and site investigations. In addition, the geological setting of the area based on field investigations and evaluation of some geophysical data will be discussed.*

Keywords: Bam; Geological settings; Qanats; Landslide; Liquefaction; Sinkhole

1. Introduction

Bam Earthquake, which occurred at 01:56:56 (*GMT*) on 26^{th} December 2003, destroyed the city of Bam, Baravat, and some small villages at the area (southeast of Iran) and caused around 26,500 deaths and thousands of disappeared and injured. The *Ms* of this destructive event was equal to 6.5 (*IIEES*) and focal depth evaluated to be about 8*km*. The corrected *PGA* values of this earthquake recorded at Bam station are equal to 992, 775 and 623cm/sec^2 for vertical, lateral and tangential components [3].

Besides the structural damages, Bam earthquake has been accompanied with some geotechnical instabilities such as landslide, land subsidence and ground fissures, however based on the surface evidences, no effects of liquefaction observed at the area that can be related to the level of ground water and type of the soil and its characteristics.

In the first part of this paper, a summary about the geological and topographical conditions of the Bam area will be presented and in the second part the instabilities and geotechnical aspects of this event will be discussed.

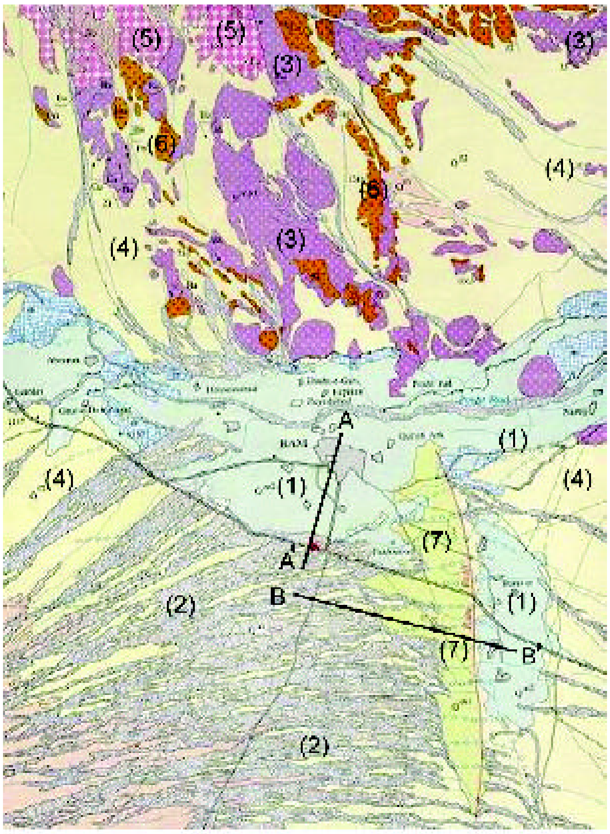
2. Geographical Situation

The city of Bam is located in the southeast of Iran at 175^{th}*km* of the main road of Kerman to Zahedan. The area of the city is about 5400 Hectares having a nearly flat topography and smooth morphology. The altitude of the city is approximately 1050 meters above sea level in average. The main topographical features of the city are the volcanic hills located at the north and south west of Bam.

Climatologically, the area is located at an arid region having dry weather. The total amount of annual rainfall is not considerable especially during the recent years. There is one seasonal river passing through the Bam city called Posht-e-Rood that is nearly dry most of the year but water from some Qanats flow in this river. Due to small amount of rainfall and surface water, the main resource to supply water for drinking and irrigation purposes is the underground water that are extracted mainly by using deep wells and Qanats. In the recent years, due to heavy use of deep wells, the ground water table is lower than 30 meters in most parts of Bam and its vicinity.

3. Geological Setting

Figure (1) shows a schematic view of the 1:100,000 geological map of the area prepared by Geological



1. Light Brown Gravel, Sand and Silt (Q^{m2})
2. Alluvium Fans and Young Terraces (Q^{t1})
3. Ash Flow Tuffs (E^{v3t})
4. Alluvial Fan Deposits (Q^{f2})
5. Dacite, Rhyolite and Andesite Lavas (E^{v2d})
6. Trachyandesitic and Basaltic Lavas (E^{v3a})
7. Yellow to Brown Siltstone and Sandstone (Q^{m1})

Figure 1. Geological setting at Bam and Baravat based on the 1:100,000 geological map.

Survey of Iran. Due to the scale problem, the borders are not exactly mapped and some differences can be observed between aerial photos and the prepared map.

In order to improve the existing data about the geological conditions, a complementary program of site investigation has been arranged in Bam and its vicinity by *IIEES*.

Based on the results of these investigations and the previous available data, five different lithologies have been characterized at the area including: recent and late Quaternary alluvium, Paleogene sedimentary rocks, Eocene volcanic rocks, and intrusive igneous rocks (Granodiorite).

Most parts of the city of Bam have been constructed on Quaternary alluvial. Arg-e-Bam located at the northwest of the city, is the only site where a rock outcrop can be observed. This outcrop is consisted of Andesite and Basalt without considerable effects of weathering. Of course at the vicinity of the fault these layers have been eroded and weathered considerably, see Figure (2).

The alluvial sediments in most parts of Bam and Baravat are related to the Quaternary including the following types: yellow to brown sand and silt (Q^{m1}), brown gravel, sand and silt deposited due to seasonal flooding (Q^{m2}), coarse grain gravel of alluvial fans (Q^{f2}) and coarse grain deposits of the rivers. These types of deposits covered nearly most parts of Bam and Baravat.

Figure 2. Erosion and weathering in Andesite and Basalt at the vicinity of Bam fault.

The deposit (Q^{m1}) can be observed along the Bam fault having about 5 degrees dip toward east. The density of this layer is lower than the other deposits, although it is older. Deep erosions on this layer can be observed frequently at the site. Figures (3) and (4) depict some features of these layers at different parts of Bam and Baravat.

As it is shown in Figure (1), most parts of Bam and Baravat are covered with Q^{m2} deposits including gravel, sand and silt. There are some thin layers of fine grain sediments as lenses inside these deposits. The

Figure 3. Deposits of (Q^{m1}), West of Baravat.

Figure 4. Deep erosion at (Q^{m1}), South of Bam.

thickness of these dense layers is from a few meters to more than 50 meters, depending on their location. A weak cementation caused by infiltration of surface water, can be observed in some parts of these deposits. Shear wave velocity at this layer is about 600*m/s* at depth of 5 meters, based on geophysical measurements carried out by *IIEES*.

The alluvial fan (Q^{f2}) is another quaternary deposits extended at the eastern part of Bam. It is formed by coarse grain sediments having thickness up to 100 meters.

Finally, the youngest layers of alluvium at Bam area are alluvium fans and terraces (Q^{al}) extended along the seasonal river. These sediments are quite loose without cohesion and cementation.

In order to have better understanding about deep geological setting, several geophysical explorations have been carried out at the area by geophysical group of *IIEES*. Figures (5) and (6) present two schematic geological sections prepared based on the collected data

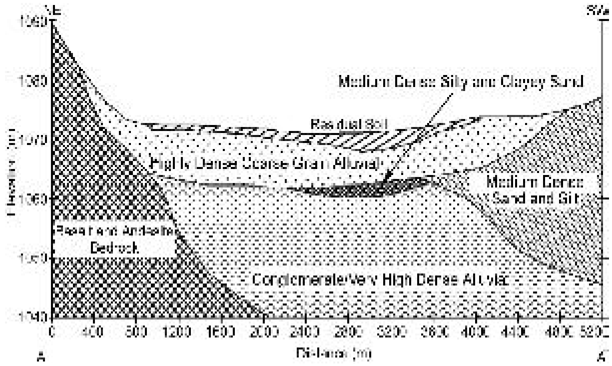


Figure 5. Geological profile of section A -A' shown at Figure (1).

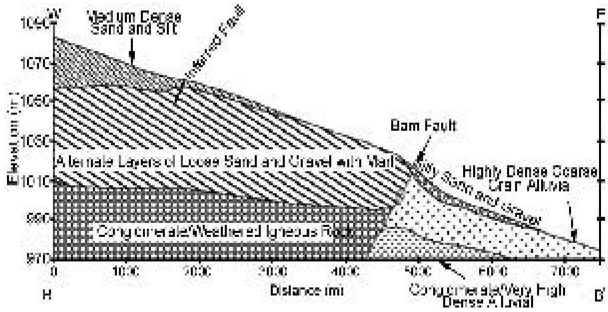


Figure 6. Geological profile of section B-B' shown at Figure (1).

during site investigation and geophysical explorations. As it can be observed there is a complex geological condition at the area that could affect the site response to earthquake. This subject is now under further study and its results will be presented later on.

4. Ground Subsidence Due to Qanat Collapse

4.1. A Summary About Qanats

Qanats are one of the traditional irrigation systems developed in Iran thousands years ago and it is still one of the best economical methods to transport water in the arid and semiarid regions. A Qanat is a horizontal underground gallery including several shafts that conveys water from an aquifer in pre-mountainous alluvial fans to lower-elevation irrigated fields, see Figure (7).

The first shaft is usually sunk into an alluvial fan to a level below the ground water table. Other shafts normally excavate at intervals about 20-30 meters to supply air for the diggers and also to take out the excavated soil. The soil is dumped around the opening of the shaft to form a small mound to keep surface runoff from entering the shaft bringing silt and other contamination with it.

The Qanat gallery has a gently slope and water can

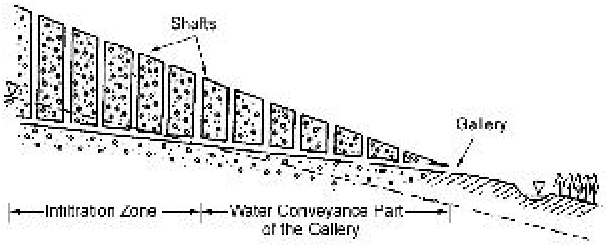


Figure 7. Schematic views of different parts of a Qanat [7].

flow into the gallery only by gravity force. As water passes most of its route underground, the seepage and evaporation of water will be much less than the open channels.

The diameter of vertical shafts and the galleries normally are between 80-150*cm*. If the soil is firm, no lining is required for the tunnels and shafts but in loose soil, reinforcing rings are installed at intervals in the tunnel to prevent cave-ins. These rings are usually made of burnt clay. Figure (8) shows the method of excavation of a Qanat.

4.2. Qanats in Bam

Qanats are one of the main sources of drinking and irrigation water in Bam. Before the earthquake, about 50% of the required water of the area have been supplied by 67 Qanats among the Bam city and 370 Qanats in the Bam region [6]. Most of these Qanats can be observed at the aerial photos, see Figures (9) to (11). In addition there are some galleries and shafts related to the very old Qanats that their locations are unknown. Of course these old Qanats are now dry and partially collapsed, but there are still some cavities remained at their galleries and shafts that could make the risk of collapse and inducing small sinkholes.

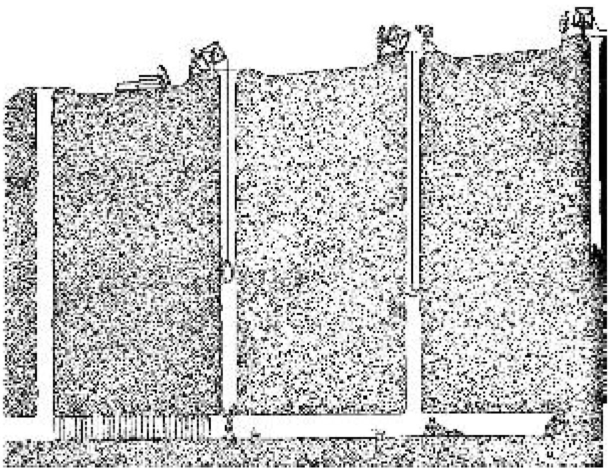


Figure 8. Excavation of a Qanat using reinforcing rings [7].

The depth of Qanat's galleries and shafts in Bam city and its vicinity is different and varies from 3-40 meters depending on length and location of irrigation. Some of these Qanats have been supported by hand made rings called “Kaval” especially those which pass through the soft and collapsible layers, see Figure (12).

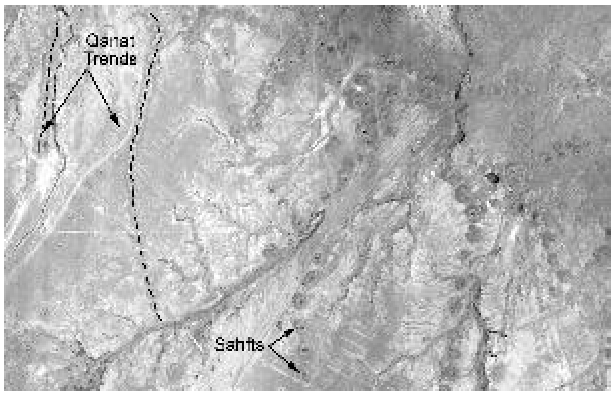


Figure 9. The Location of some Qanats on aerial photo (West of Baravat).

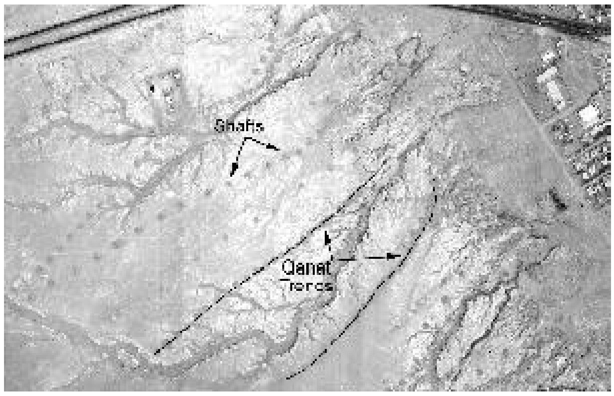


Figure 10. The location of some Qanats on aerial photo (South of Bam).

Figure 11. A Qanat trend near Bam city (The photo has been taken during pilot study by helicopter).

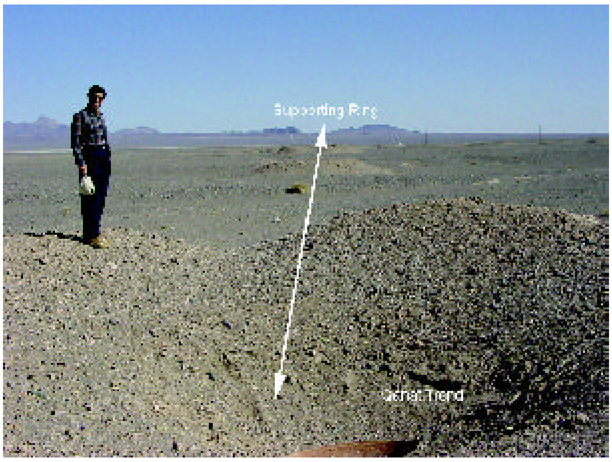


Figure 12. A Qanat trend at the 8th *km* Bam to Kerman road supported by burnt clay rings.

4.3. The Behavior of Qanats During Strong Earthquakes

Although underground openings and tunnels assumed to be more stable against earthquake and seismic waves in comparison with the above ground constructions, there are several evidences of damaging to Qanats or collapse of shafts and galleries during the historical or recent earthquakes occurred in Iran.

In some cases due to partial or complete collapse of the Qanats galleries or shaft, as result of an earthquake, water can not flow any more along the Qanat and this makes a Qanat to be dried. Another main effect of earthquake on Qanats is land subsidence in form of sinkholes that can be observed on the ground surface in different sizes. These features may cause secondary damages on building or lifelines as will be discussed in the next parts. A summary about the damages to Qanats due to historical and recent earthquakes of Iran is presented in Table (1). Most of the strong earthquakes of Iran occurred at arid or semi-arid regions caused damage to the existing Qanats. These damages are more severe when Qanat is close to the epicenter of the event.

Table 1. The Qanat's behavior during historical and recent earthquakes in Iran [1].

Date	Location	Damage to Qanat
856	Ghomes	Blockage of Water Flow
1780	Tabriz	Blockage of Water Flow
1853	Shiraz	Collapse
1893	Ghochan	Collapse and Long Ground Fissures (5-8m)
1895	Ghochan	Collapse in 5km of Qanat Length
1923	Laleh Zar	Collapse
1929	Kopeh Dagh	Collapse
1930	Ab-Mobarak Abad	Collapse
1933	North Behabad	Crack Along an Old Qanat
1947	Doost Abad	Collapse and Blockage of Water Flow
1948	Gavak	Blockage of Water Flow
1968	Dashte Bayaz	Collapse
1968	Ferdoos	Collapse
1972	Ghir-Kazerin	Collapse of 5km Qanat Tunnel and 180 Access Wells
1979	Karizan-Khavaf	Collapse

4.4. The Behavior of Qanats during Bam Earthquake

Bam Earthquake affected the existing Qanats at the area of Bam city and its vicinity considerably. Based on the preliminary evaluations, about 40 percent of the Qanats at Bam and its vicinity collapsed or have been severely damaged due to the earthquake. In some cases the collapse of the Qanats blocked the water flow inside their galleries completely. As the water of Qanats is the main supply of the irrigation water for palm and citrus gardens at the area, these damages may cause considerable secondary economic losses. At the moment several workers and diggers are working on the Qanats to repair them and open the galleries to provide necessary water for irrigation purposes.

Site investigations carried out during the first days after the earthquake showed different levels of damages to Qanats. In addition, at some locations the collapse of the Qanats caused some secondary damages on the buildings and lifelines of the area and increased the losses. These features will be discussed in the following sections.

4.4.1. Land Subsidence Above the Qanats

Based on the site visits and evaluations of aerial photos taken after the Bam Earthquake, the most important effects of the event on Qanat systems are damages to their shafts and tunnels. Several sinkholes induced as a result of the earthquake along the Qanat's galleries due to the collapse of overburden layers. Most of the observed damage were related to the collapse of shallow Qanats, but some sinkholes induced on deep Qanats too. Although most of the Qanats at the area have been supported by hand made rings, these systems could not improve considerably the stability of Qanats against applied dynamic loads due to earthquake. In some locations because of existing close galleries, very large sinkholes induced at the ground surface, due to their collapses.

Near the Bam Fault the damages were more severe and several small and large sinkholes could be observed at the vicinity of the Fault. Far from the fault the effects of earthquake on Qanats are less considerable and only some fissures and cracks can be observed along the galleries and shafts that can be related to the small settlement or partial collapse of some parts of the Qanats. Figures (13) to (18) depict some sinkholes induced by Bam earthquake.

4.4.2. The Effects of Earthquake Induced Sinkholes on Structures and Lifelines

The sinkholes induced during Bam Earthquake caused some damage on the structures and lifelines. These damages were more severe at Baravat and south parts of Bam. At these parts several buildings and main and bypass roads constructed on the old Qanats, have been damaged considerably. Due to the dynamic loadings of the event the stability of these underground openings decreased and collapse occurred in many places. These collapses then made some minor to severe damages to roads and buildings in the area.

Figure (19) shows damage to one of the access

Figure 15. Large sinkholes at northeast of Bam; (The photo has been taken during pilot study by helicopter).

Figure 13. Sinkhole induced due to the collapse of a Qanat gallery; west of Baravat

Figure 16. Large sinkhole; south of Bam.

Figure 14. Sinkhole induced due to collapse of a Qanat gallery; west of Baravat

Figure 17. Large sinkhole observed at west of Baravat.

Figure 18. Collapse of shafts and tension crack along the galleries of old Qanats, west of Baravat.

Figure 19. Sinkhole induced due to collapse of an old Qanat on one of the bypasses at Baravat.

roads to Baravat due to collapse of an old Qanat. Such sinkholes could be observed in this area under the main and bypass roads, and made some difficulties for rescue and relief teams to reach the area after the earthquake. The main road from Kerman to Zahedan passing south of Bam was also damaged severely because of a sinkhole. At the time of the visit, this sinkhole has been filled but the same sinkholes around the road remained without changes, and one sample is shown in Figure (20). Based on the reports, the sinkhole induced under the main road caused a heavy traffic in this part after the event. Considering the importance of first hours after an earthquake for rescue, it is obvious how such sinkholes can affect these activities.

Besides of the effects of sinkholes on roads, there are some damages to the buildings and constructions due to collapse of Qanats specially at Baravat. Figure (21) shows the damage to a building at Baravat due to

Figure 20. Sinkhole observed close to the main road of Bam to Zahedan near Baravat: same sinkholes induced under the road at the time of earthquake that affected the access of rescue and relief teams to the region.

Figure 21. Damage to a building due to collapse of an old hidden Qanat (Baravat).

collapse of an old Qanat during the earthquake. As it can be observed, this sinkhole caused severe damage to this house.

Figure (22) presents damage to a religious arc due to collapse of a hidden Qanat under its column. Along the trend of this hidden Qanat, several sinkholes were observed at the area.

4.5. Distribution of Collapsed Qanats at the Bam Area

In order to get a better idea about the distribution of collapsed Qanats at Bam and Baravat, a *GIS* based map has been prepared based on the data collected during the site investigation and study of aerial photos. Figures (23) and (24) show these maps. As shown in Figure (24), the area of concentration of damage to Qanats is around the Bam fault, in which

Figure 22. Damages to road and a religious arc due to the collapse of a hidden Qanat (Baravat). Photo has been Taken by Dr. M. Zare one day after the event.

several sinkholes can be observed along the existing Qanat trends. This fact may help seismologist to get a better idea about the source of Bam Earthquake, as a sharp surface rupture has not been reported at the area after the earthquake. It should be also considered that the concentration of Qanat in this area is higher than the other parts.

5. Landslides Triggered by Bam Earthquake

The Bam Earthquake induced more than 3000 block

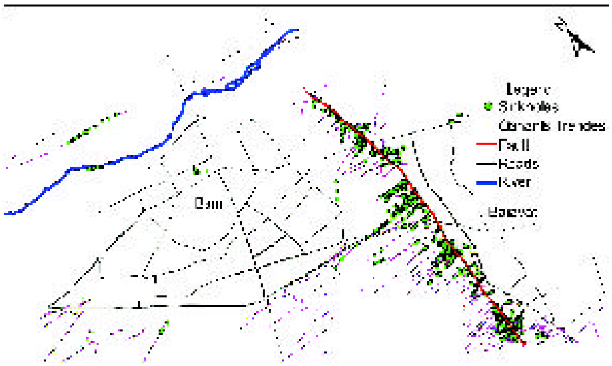


Figure 24. Distribution of sinkholes and trends of Qanats in Bam and Baravat.

falls and landslides over an area 61km^2, in which most of them were concentrated in 18km^2, especially at the east of Bam and west of Baravat. These block falls and landslides have been documented before based on the site investigation and study of aerial photos [2]. In order to prepare the base map of the landslides triggered by the earthquake, these points were digitized and some computer-generated maps have been prepared and evaluated.

In this section, the distribution of block falls and landslides in the area will be presented and a brief description about the prepared landslide map and factors affecting the landslides distribution will be discussed.

5.1. Landslides Map of Bam Area

Field investigations to document earthquake-triggered landslides were initiated 4 days after the earthquake. In that study, based on the distance to the epicenter, concentrations of landslides (included small rock and

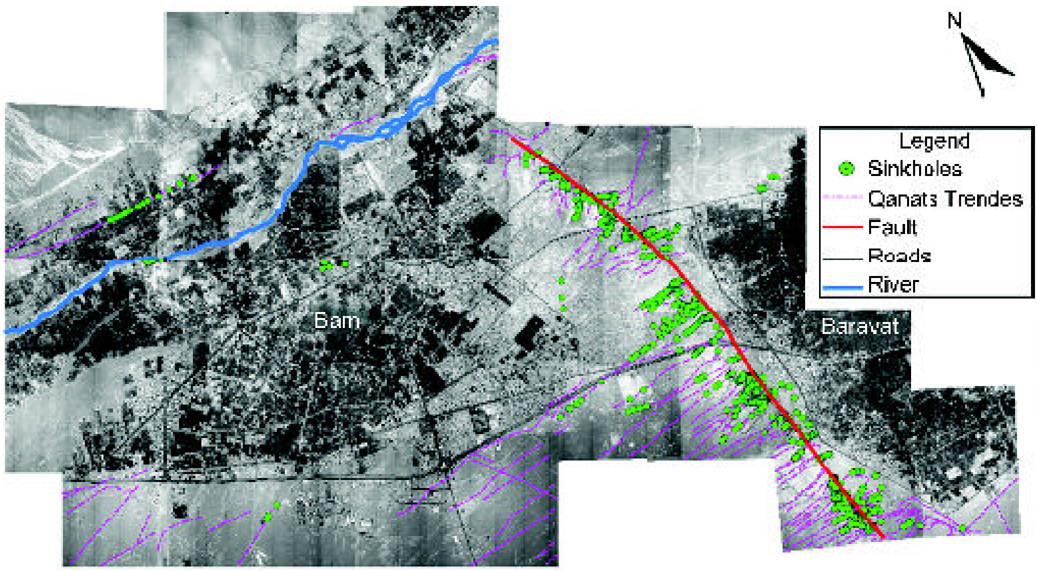


Figure 23. Photo mosaic used to locate the distribution of Qanat in Bam and Baravat.

soil block falls to very large blocks at the river banks and man made channels) have been investigated. In addition high-resolution aerial photos (nominal scale 1:10000) of Bam and Baravet that were taken two days after the event by the National Cartographic Center of Iran were evaluated and used to map new and fresh landslides at the area. These maps has been printed in 1:2000-scale and due to their high qualities and the time of photography were quite useful to locate geological instabilities as well as damage to the buildings. Figure (25) shows one of these photos in which the location of some blocks and landslides have been marked.

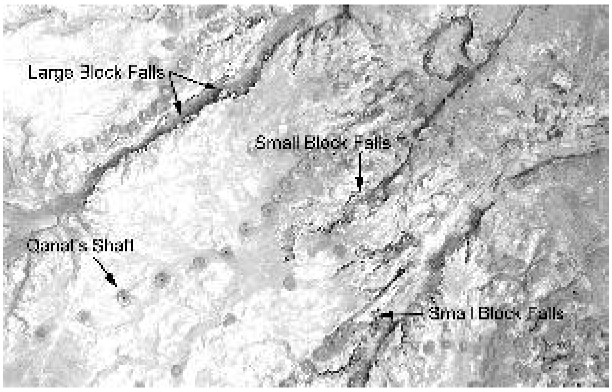


Figure 25. Some small and large block falls and landslides shown at one of the aerial photos; West of Baravat.

Based on these evaluations, more than 2370 individual blocks and landslide have been located on 1:50000 scale map, adopted as the base map, and by using Geographic Information System (*GIS*) all collected data have been entered to its database. Depending on size and distribution of blocks and landslides different methods have been used. The final map contains all data related to the block falls and landslides triggered by earthquake at Bam and Baravat.

5.2. Distribution and Types of Landslides

The most concentrated zones of block falls and landslides are around the Bam fault, see Figure (26). As mentioned before the main geological formation in this area is alluvial sediment having weak cementation (Q^{m1}). This part has been folded and uplifted due to the tectonic deformations resulting by Bam fault activities. These young and weak materials do not have significant tensile strength and so can be weathered and eroded easily. This procedure can make steep-walled narrow valleys. The combination of low strength materials and steep relief makes these slopes

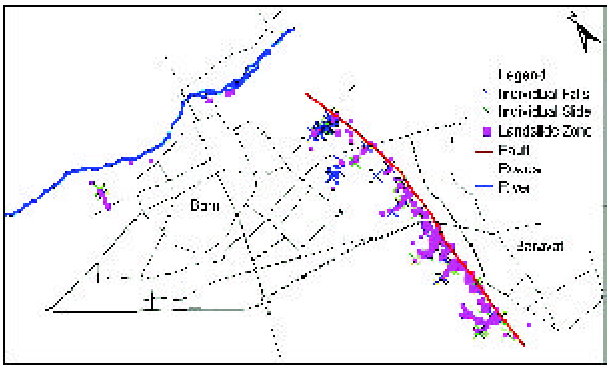


Figure 26. Areas of concentration of landslide triggered by the Bam earthquake

quite susceptible to sliding during shaking.

Along the riverbanks of Posht-e-Rood River in the north of Bam, landslides are more scattered due to the relative long distance from causative fault and the strength of existing layers, that is a bit higher at this place as described before. Few landslides can be observed in the northern and southern mountains, which consist of more competent rocks.

The most common types of landslides triggered by Bam Earthquake can be categorized as: highly disrupted shallow falls, soil block slides and rock block toppling.

- ***Shallow, Disrupted Landslides***

The hills located at the west of Baravat and in the east of Bam are extremely susceptible to failure during seismic shaking. In this area, more than 75 percent of the slopes were affected by the earthquake and several shallow disrupted landslides induced as a result. The main characteristics of landslides at this area are their small sizes, shallow deeps and their dry, highly disaggregated material accumulated at down slopes in a flatter area. The volumes of these slides vary from a fraction of a cubic meter to hundreds of cubic meters, see Figure (27).

At the northwest of the earthquake epicenter, fewer and more scattered rock falls can be observed specially at the Posht-e-Rood Riverbanks, which consist of recent quaternary deposits. However there is an exceptional site along the Posht-e-Rood River bank called Rahmani village where many landslides have been induced by the earthquake.

- ***Deep, Coherent Landslides***

Few deep, coherent landslides have been induced by the earthquake. These slides having volumes of several hundreds to thousands of cubic meters can be

Figure 27. Soil block falls triggered by Bam earthquake at west of Baravat. (The photo has been taken during pilot study by helicopter).

Figure 28. Deep tensional crack and soil blocks fall induced during the earthquake, North of Rahamani village.

Figure 29. Soil blocks falls and slide due to earthquake, west of Baravat.

Figure 30. Damages to a building located at top of an excavation due to landslide, Esfikan village, Northeast of Bam.

observed mostly in more competent sedimentary units at Bam and Baravat. In addition several deep landslides were triggered at the north of Rahmani village, see Figures (28) and (29).

5.3. Effects of Earthquake-Triggered Landslides on Building and Lifelines

Landslides induced during the Bam earthquakes did not have any considerable direct effects on the life and properties of inhabitants at the area, as no important lifelines or structures were constructed at the landslide prone zones. Of coarse it would be necessary to remove the soil blocks to clear the riverbed for the next seasonal flooding.

The only damage observed due to the landslide was related to the collapse of a house located at the top of an excavation at Esfikan; north of Bam, see Figure (30).

6. Liquefaction

The liquefaction potential of Bam area has been evaluated using geological data, ground water level and soil conditions based on the geological information and field investigation. Although the soil condition in most parts of Bam city and its vicinity shows high percentages of fine grain sediments such as fine sand and silt, but due to low level of ground water, the risk of liquefaction is not considerable in most parts of the city.

In some locations there was some saturated zone due to existence of small ponds, see Figure (31), or flow of Qanat's water through the channels, but no evidences of liquefaction have been observed in these sites, and this can be due to the small thickness of sand layers and its compaction.

Figure 31. Small pond at Esfikan, Northeast of Bam.

7. Conclusion

Based on the observations and evaluations carried out after the Bam earthquake, Qanats instabilities are the most important geotechnical instabilities occurred at the area. In addition several blocks and landslides have been triggered by the event. Both of these effects were more severe at the vicinity of Bam fault. Far from the fault (except in Rahmani Village), the instability of Qanats and slopes are rarely reported. In addition there were no evidences of liquefaction at the area due to the depth of ground water table and the type and compaction of the existing soil layers.

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