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Evaluation of Qanat Subsidence Potential Map in West of Mashhad City NE of Iran

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Abstract

Qanat systems (underground water galleries, kariz) have been used for extracting groundwater in many parts of Iran over centuries. There are 63 Qanat suits in Mashhad city (NE of Iran). In the past, these Qanats were used for extraction of groundwater; however, most of them have dried out today. Cases of land subsidence have been reported due to the collapse of these Qanats in Urban areas. In this paper, the Qanats in the western part of Mashhad city has been studied. The exact locations of Qanats vertical shafts has been determined by aerial photographs with scale of 1:20000 and 1:6000. Qanat characteristics include depth of Qanat underground tunnel and vertical shaft`s diameter has been investigated. The significant factors in Qanats collapse phenomena are soil properties, groundwater table, loadings due to the surface structures, density of vertical shafts and Qanat depth. In this study using of Qanat characteristics and loadings due to the surface structures, a potential map of Qanat collapse hazard and subsidence is presented. According to the field study, several cases of subsidence were recognized in high potential zone that introduced in the potential map.

Keywords: Qanat system, collapse hazard, subsidence, potential map, land use.

1. Introduction

Qanat systems are artificial underground water galleries with up to 3000 years old that used in arid Middle East. This system has been used in Iran for extracting groundwater over centuries (Reyhani and El Naggar, 2006). In Fact, Qanats are gently sloping tunnels dug far enough into alluvium or water bearing sedimentary rock. The Qanat tunnels pierce the underground water table and penetrate the aquifer beneath. Water from the aquifer filters into the upper reaches of this tunnel, flows down their gentle slope and emerges as a surface stream of water at or near a village or settlement (English 1998).

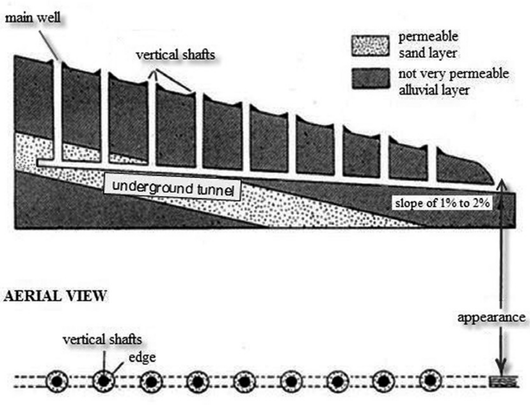

Figure 1: Longitudinal section and different parts of a Qanat suit (Hill and Al-Hassan, 1997)

Figure 1 shows a schematic profile of a Qanat system. In process of Qanat construction some vertical shafts are used for removing of the demolition soil and air conditioning. Qanat is usually dug in regions where there is not sufficient run off (Salih, 2006). In the past decades, huge withdrawal of groundwater using the deep and semi-deep wells led to the decline of groundwater level and dryness of more than 20,000 Qanat suits in Iran (Beckman et al., 1999. Yoshimura et al., 2006). The collapsing of underground tunnel of dry or out of service Qanats will be results to significant subsidence in urban area. The diameter of Qanat vertical shaft is about 1-1.5 meter. But in non-cohesive soils the shafts diameters could be increase up to 10 meters due to repeated collapsing of soil. By development of city over the Qanat suits, vertical shafts are filled by loose and uncompact soil and caused severe damage to surrounding buildings and lifelines.

There are some reports on Qanats collapsing and land subsidence in Iran and other countries (Lightfoot, 1996; Atapour and Aftabi, 2002; Shariatmadari and Fazelian, 2002; Amini Hossein et al., 2004; Hashemi and Hashemi, 2005; Pellet et al., 2005, Reyhani and El Nagger, 2006; Stiros, 2006). This phenomenon is also observed in Mashhad city. Due to the high distribution density of Qanat shafts and the deep Qanat tunnels in the western part of Mashhad city, most of land subsidence happened due to Qanat shafts rather than underground Qanat tunnels. The only support for Qanat shafts and underground tunnels are oval baked clay hoops called "caval". Thus these Qanats are very vulnerable if confronted with earthquake forces which can lead to the destruction of shafts, and Qanat tunnel as well. Similar cases of Qanat damage were happened

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in December 26, 2003 by Bam earthquake (south-west of Iran). 40% of Qanats systems around the Bam city were either destroyed or damaged seriously during this earthquake (Amini Hossein et al., 2004). Moreover, Qanat tunnels in urban areas are likely convert to a sewage channel so these underground tunnel lead to pollution of groundwater (Kazemi, 2010).

2. The effective factors on Qanat instability

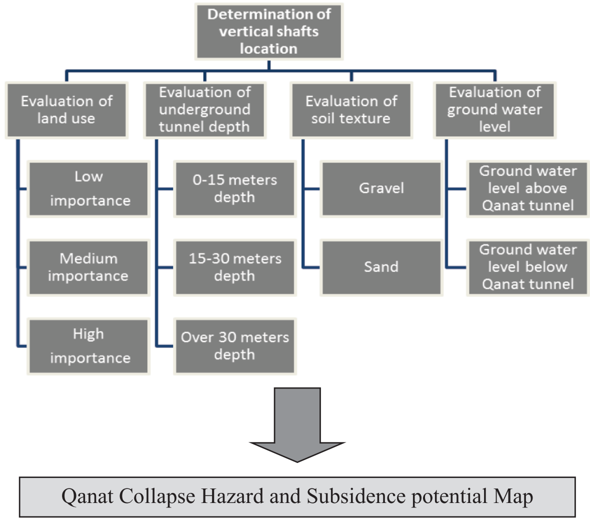
The most effective factors on instability of Qanats are geotechnical properties of soil, groundwater table, loadings due to surface structures and Qanat properties including Qanat depth and Qanat distribution density (Reyhani and El Naggar, 2006). Qanat is similar to a tunnel system. In order to evaluate the stability of Qanats which have not been studied extensively yet, the data regarding tunnels dug in soils were employed. One of the most effective factors on instability of tunnels (such as Qanat underground tunnels) in soft materials is the type and properties of the soil (Vacher et al., 2004).

Figure 2: Soil texture map of the depth of 30 m (average depth of Qanat's well)

Figure 2 shows the soil texture map of the region to the depth of 30 m (Hafezi Moghaddas, 2008). The soils in the study area mostly consist of coarse-grained and low cohesion material of gravel and sand. Huge withdrawal of groundwater led to the decline of groundwater level and dryness of Qanats in the study area. Qanat vertical shafts were commonly filled with demolition wastes which will lead to land subsidence in future especially when saturated. The depth of groundwater in the area is about 60 to 100 m and Qanat suits in the study area are above the groundwater table.

3. Methodology

The main aim of this paper is preparing the collapse hazard and subsidence potential map of the area by GIS software based on two parameters: Qanat properties (include location of vertical shaft and underground tunnel depth) and land use; however geotechnical properties of soil and groundwater table did not considered in this map due to homogeneity of soil and high depth of groundwater. Locations of vertical shafts in study area (District 11 of Mashhad city) were determined by aerial photographs scale of 1:20000 and 1:6000 (National Geographical organization 1966 and 1975). Usually in non-cohesive soil the diameters of vertical shafts increased up to 10 meters by repeat of fall and soil collapse. The uncompact soil filling of vertical shafts lead to land subsidence. In this study the depth of Qanat underground tunnels are calculated by length of Qanat suits and main well depth (the last deepest vertical shaft of Qanat is main well or mother well). In the western part of Mashhad city most of Qanat underground tunnel are situated in high depth; so they rarely collapse. Another effective parameter using in potential map is land use which indicates the pressure of structures. Furthermore, the rupture of water network as the superficial sign of subsidence in the region was employed to correlate the effect of Qanat collapse with land subsidence. The research method is summarized in Flow chart below.



4. Results and discussion

4.1. Evaluation of Qanat systems in the study area:

Mashhad city is considered the second metropolis to Iran. The city area is about 320 km2 and according to statistical survey of 2011, its population is 2,772,287. This city has had a mild growth of population in the last 50 years and a rapid growth in last two decades. Figure (3) shows the development in Mashhad city between 1956 and 2006. As shown in this Figure most of this growth has been toward west and north-west of Mashhad city. Based on this Figure the study area in west of Mashhad city is funded in 1986.

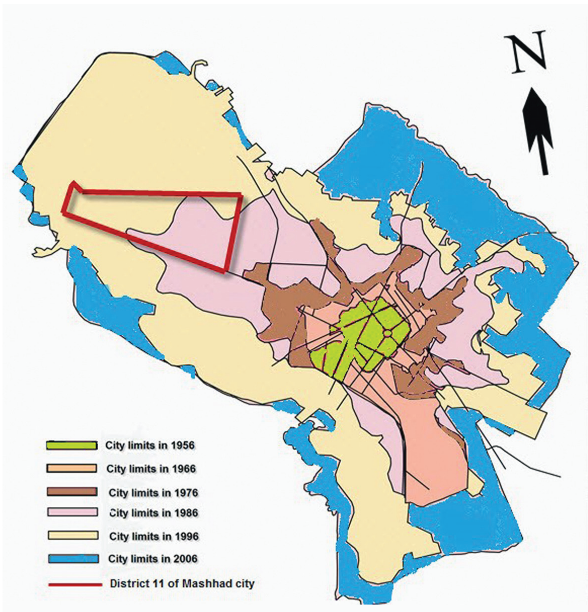


Figure 3: Development of Mashhad city (Khorasan-e-Razavi Housing and Urban development organization 2006)

Based on the aerial photographs and report on Mashhad plain Qanats (Khorasan-e-Razavi regional water company 1964), there are 63 Qanat suits in Mashhad city. Although, these Qanats had been used for many years, currently, only two Qanat suits are active. During the last 50 years, 95% of Qanats in Mashhad city area have dried out. The average depth of main wells of these Qanats (the deepest Qanat vertical shaft is called the mother or main well) is 45 m while the average length of Qanat suits is 5 kilometers. The longest and the deepest one is "Bahrabad Qanat" which has 22 kilometers length and its main well has 133 m depth (Khorasan-e-Razavi Regional water company 1964). Figure (4) shows Qanats in Mashhad city which are determined through the location of their vertical shafts on aerial photographs. Also location of study area has been determined in this map.

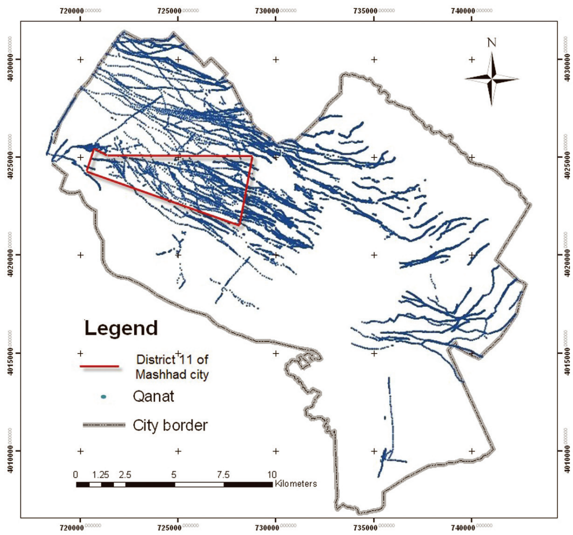


Figure 4: Qanat suits in Mashhad city

There are 19881 Qanat vertical shafts in the region. As shown in Figure (4), most of these Qanats are located in the western parts of the city and the general direction of Qanat suits is from North-west to south-east. Several cases of land subsidence due to Qanat instabilities have been reported in west of Mashhad city. As a noticeable example, a number of residential structures on Andisheh Street in Ghasem abad (west of Mashhad city) which are built on the Qanat shafts have subsequently been damaged (Hafezi Moghaddas et al., 2012) (Figure 5).

Figure 5: A crack in the wall of a building (left part) and tilting a wall (right part)on Andisheh Street west of Mashhad city (Hafezi Moghaddas et al., 2012)

Because, there are no Qanat establishments after 1970, the exact location of the Qanat shafts in study area have determined by the large scale and ancient aerial photographs of 1972 with scale of 1:6000. Figure 6 shows the distributions of Qanat suits and Qanat shaft in the region. The density of Qanats in the eastern part of the study area is higher than the western parts. They extend mostly from north-west to south-east.

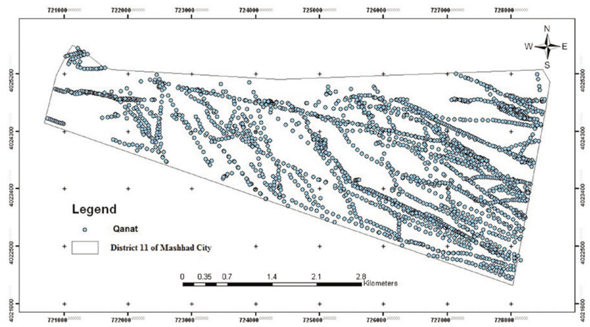


Figure 6: Qanats in District 11 of Mashhad City

Table 1: Characteristics of all Qanats located in Mashhad District11

Qanat name	Absarde	Farah abad	Neka	Mil karez	Sanabad	Nokhodak	Ghasem abad	Malek abad	Saad abad
Depth of main well (m)	65	71	90	80	65	75	43	80	70
Length of Qanat chain (m)	11000	6100	18000	13000	7000	17000	2300	8500	7000
Inflow (L/s) in 1963	45.7	42	8	Dry	9.4	52.59	20	40	Dry

There are 9 main Qanat suits in the area whose properties are mentioned in Table 1. The average depth of main wells of the Qanats in the area is 70 m. The average length of Qanat suits (the distance between main well and appearance of Qanat that water coming out) is 10 kilometers. The average diameter of vertical shafts is about 1-1.5 m and the diameters of underground tunnels are about 1 to 1.2 m. The distances between vertical shafts in the region are varying dramatically, but the average distance between vertical shafts of the area is about 40 m. based on the soil texture in the region, the distance between vertical shafts is longer in coarse grained soils. The average distance between vertical shafts in gravelly soils is 50 m and in sandy soils is 27m.

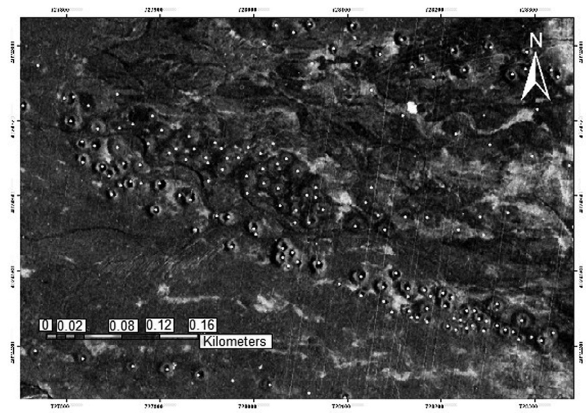


Figure 7: Qanats of the north-east of District 11 in an aerial photograph

The abundance of Qanats in the area is shown in Figure 7. This Figure shows an area of 252,000 m2 in north-east of District 11 on an aerial photograph. Every whit spot in the Figure is an indicator of a vertical shaft. As shown in this Figure in some cases the distance of the shafts is less than 10 m.

4.2. Collapse hazard and subsidence potential map

The collapse hazard and subsidence potential map of the area is prepared based on land use, Qanat shafts density and Qanat depth. Soil properties due to homogeneity in the study area are not considered as effective factors. The land uses in the study area include residential, educational, commercial, health, governmental and cultural and also green and resort areas.

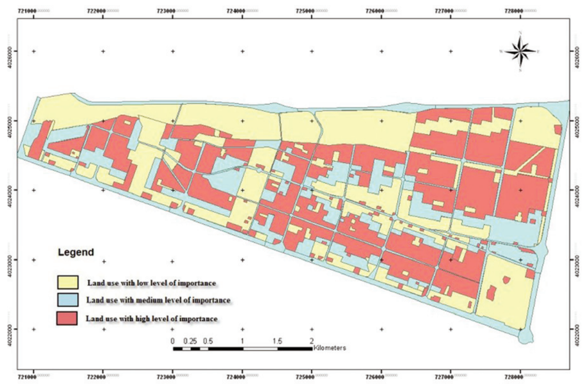


Figure 8: Land use map of the area

In Figure 8 a simplified classification of land use importance in the study area is shown. This classification is based on two parameters: first one is the pressure inverted to the earth by structures. This parameter is determined by height of buildings. The second one is related to the density of population which has a high risk of damaging. The first class is low important regions which includes low density residential areas as well as green and resort areas. The second class is medium important regions includes residential areas with medium density and main streets. The third group with the highest level of importance includes residential areas with high density and educational, commercial, health, governmental and cultural zones. These areas are considered as the most important regions due to their significance and high population. According to Figure 8, regions with high levels of importance cover about 50% of the area.

In order to prepare the potential map, the area was divided into square cells with an area of 10,000 m2 each. Based on the distribution density of Qanat shafts the area was classified into three groups: (1) without Qanat shaft, (2) 1 to 3 Qanat shafts and (3) more than 3 Qanat shafts (Figure 9). Based on this classification, 47.5 % of the cells does not have any shafts, 41% have 1 to 3 and 11.5% have more than 3 Qanat shafts. Although the last group has the lowest area, but these cells usually have 8 to 10 Qanat shafts and in some cases there are 20 Qanat shafts in one cell. One of the cells with high Therefore, the rate of land subsidence due to Qanat collapse in deep Qanat underground tunnel is less than shallow Qanat tunnel. The distribution density of Qanat (about18 Qanat shafts) in the aerial photograph is shown at Figure 9.

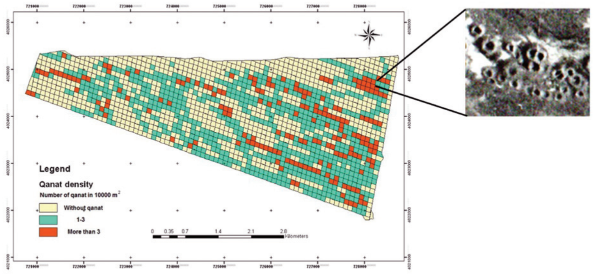


Figure 9: Classification based on the number of Qanat shafts. The photo in the right part shows high distribution density of Qanats

The last effective factor on Qanat instability is Qanat depth. Peck (1969) has expressed that the relation between the depth of a tunnel and land subsidence due to the digging of a tunnel is reverse. According to the depth of Qanat, the study area is categorized into three groups (Figure10).

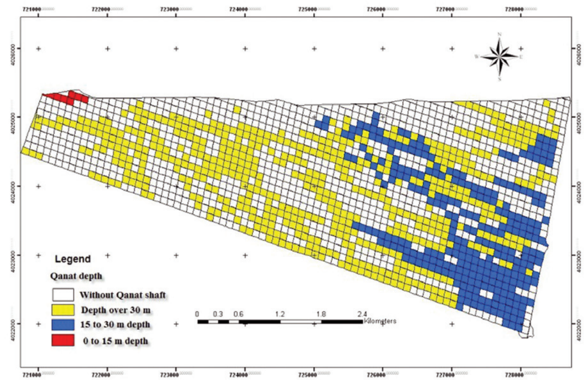


Figure 10: Classification of the area based on the depth of Qanats

The first group of Qanats is at the depth of more than 30 m. The second one is at the depth of 15 to 30 m and the third one is at the depth of less than 15 m. It is assumed that the shallow Qanats have the highest risk of collapsibility.

Table 2: Characteristics of all Qanats located in Mashhad District 11

Land use Number of Qanat shaft in every block	Low importance	medium importance	high importance
No-Qanat shaft	I	I	I
1 to 3 Qanat shafts	II	IV	V
More than 3 Qanat shafts	III	V	VI

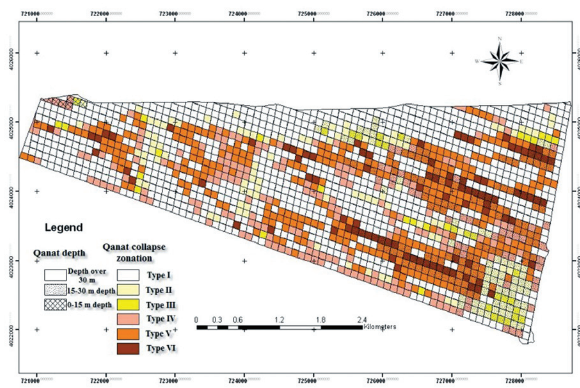


Figure 11: Collapse hazard and subsidence potential map of Qanats in Mashhad District 11

The potential map is prepared by overlaying the three maps of land use, Qanat distribution density and Qanat depth. In Figure 11 the area is categorized into 6 groups based on Qanat collapse hazard and subsidence potential. Groups of type I- VI summarized in Table 2.

The land subsidence and collapse hazard increases from group I to VI, respectively. Cells type I have no collapse hazard. Due to high number of Qanat shafts in cells type VI, these cells categorized in high risky areas. They also have a high risk from point of land use criteria. Cells type VI includes high population centers and their land uses are high density of residential, educational, commercial, health and governmental areas as well as cultural ones. The depth of Qanats has been evaluated in potential map separately (Figure11). As shown in the potential map, half of Qanats of type VI have medium depth. So the risk of collapse in these cells is more than cells with deep Qanats. 47% of total cells of the area are classified in group I, 10% in group II, 2.5% in group III, 12.5 % in group IV, 22.5% in group V and 5.5 % in group VI. Cells type IV, V and VI have the highest Qanat collapse hazard and subsidence potential and cover 40% of the area.

4.3. Reliability of Qanat collapse hazard and subsidence potential map

Field study was conducted in risky areas with high density of Qanats. These areas have been categorized in cells type VI in the potential map and some subsidence has been observed in these areas (Figures 12 and 13).

Figure 12: Round shaped subsidence formed in high-risky cells in potential map

Figure 13: Crescent and round shaped subsidence in risky area with high distribution density of Qanat

Land subsidence due to collapse of Qanat shafts and Qanat underground tunnel in urban area could cause damages in the drinking water network of the city. The location of cracks in main pipes of drinking water has been studied along with Qanat collapse hazard and subsidence potential map (Khorasan-e-Razavi water and Wastewater Company 2009). As Figure 14 shows, most of cracking in water pipes occurred in areas with highest Qanat collapsibility hazard (cells type IV, V, and VI).

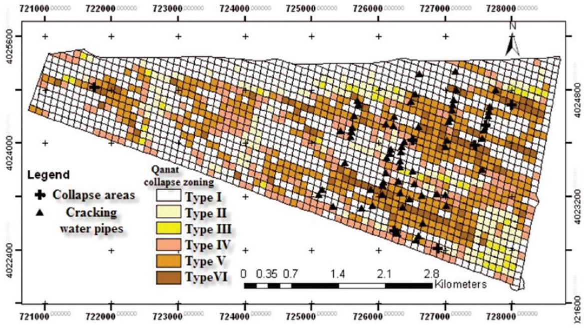


Figure 14: The location map of the main water pipes breaks and collapses in Mashhad District 11

5. Conclusions

In District 11 of Mashhad municipality nine main Qanat suits have been identified with an average of 10 kilometer length and 70 m depth for the main well. Seventy six percentages of the Qanats in the area are deep (more than 30 meters depth) and the others have medium (15 – 30 meters depth) or low depth. The soil texture in the area is non-cohesive coarse grained soil which results to falling of Qanats shafts. The filling of these shafts with disturbed soils and demolition wastes are vulnerable to collapse. Based on Qanat depth, land use and Qanat distribution density, the Qanat collapse hazard and subsidence potential map is prepared and the area is categorized into six groups. Cells of type IV, V and VI in the Qanat collapse hazard and subsidence potential map have the highest risk of collapsibility and cover about 40% of the area. In high-risk areas, many cases of subsidence and collapse have recognized. Also, the damage in urban water pipes has increased in these areas.

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