Australian Journal of Basic and Applied Sciences, 5(5): 510-518, 2011
ISSN 1991-8178

Stability Analysis of Qanats in the West of Mashhad, North-east of Iran

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Abstract: In the past, many underground water channel systems (Qanats) were used to extraction of groundwater in Mashhad and its surrounding area. Nowadays, most of them have dried out and the city has developed on them. The constructions of tall buildings in recent years increase the potential of Qanats collapsibility in this area. In this paper the distribution of Qantas system in West of Mashhad and their stability's under different loading and support system conditions are investigated. For this, the locations of Qanats wells are mapped using the aerial photograph then the roughly depth of Qanats are estimated based on the few site measurements and existing documents. The stability of Qanats was evaluated based on the elasto-plastic soil models in four depth and different support systems. The results have shown that with increase of Qanat depth the extension rate of plastic zone decreases. Also the effect of the support covers in the plastic zone decrease with increasing the Qanat depth. As it is estimated, for every 1.2 m increase in depth, the bearing capacity of Qanat gallery increases as much as a load of one-storey building.

Key words: Mashhad, collapse of Qanat, plastic zone extension.

INTRODUCTION

Qanat is the traditional underground water extracting system used in Iran over centuries. (Rayhani, El Naggar, 2006). A Qanat consists of an underground tunnel which is connected to the surface by a set of vertical shafts (vertical wells) at specified intervals (Fig 1). In this system, groundwater reaches to the ground surface by gravity and Qanat is usually dug in regions where there is no run off (Salih, 2006). The Qanat's shafts connect the underground tunnel to the surface at specified intervals (Fig 1). The underground tunnel would often start from foothills of mountainous areas (source of fresh water) in order to transfer water from high regions to agricultural lands. This system is planned based on surface topography and ground water slopes and is very sensitive to changes of underground water level (Mustafa, Usman Qazi, 2007; Al-Marshudi, 2007). In the past decades, huge withdrawal of groundwater by deep and semi-deep wells led to decreasing of groundwater level and dryness of majority of Qanat chains. Hence, some researchers stated that Qanat civilization has ended in Iran (Beckman *et al,* 1999; Yoshimura *et.al,* 2006). Nowadays, many of Qanats chains located around the cities were covered results of city developments and results to some problems such as collapsibility and groundwater pollutions (Atapour, Aftabi, 2002; Shariatmadari, Fazelian, 2002; Amini Hosseini *et.al,* 2004; Hashemi Sahi, 2005; Pellet *et.al,* 2005; Rayhani, El Nagger, 2006). Qanats subsidence is consequence of constructions over Qanat shaft or extra loading on the Qanat gallery (Fig. 2).

Mashhad, center of Khorasan Razavi Province, is located in the north-east of Iran. It is considered as the second metropolis of Iran from both area and population-wise. The city area is about 320 km^2 and according to the statistical survey in 2006 its population is 2,420,000 which comprises for a half population of the province (Mashhad Municipality, 2007). Mashhad had a rapid growth in recent years and now it is developing towards the west and north-west over the many Qanats shafts. In the past decades, the Qanats were the most

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important sources of drinking and agricultural water of Mashhad city and the around villages. Nowadays most of the Qanats near the city have dried out and enclosed by urban. In Figure 3, the study area (district 11 of Mashhad Municipality) and Qanat suits that in west of Mashhad which covered by city development are shown.

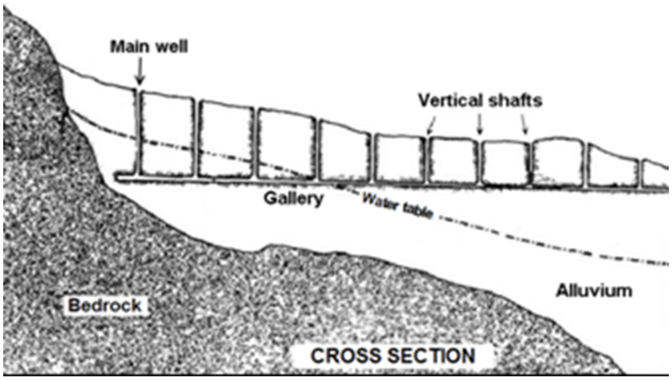

Fig. 1: Cross section and various parts of a Qanat.

Fig. 2: Qanat collapse and its damage to structures in the north-west of Tehran (Rayhani, El Nagger, 2006).

Methodology:

In the first step of this study, the Qanats locations in study area were determined using aerial photographs with scale of 1:20000 and 1:6000 (National Geographical Organization of Iran, 1966 & 1972). Then the characteristics of gallery and shafts such as depth, geometry and soil properties were determined. The software of Plaxis V 8.2 was used for modeling and analysis of Qanats gallery with different depth, loading condition and support system. In each model, plastic zone extension around the Qanat gallery has been evaluated.

The Map of Qanats Suits in Study Area:

Mashhad is situated in an area with arid to semi-arid climate. Therefore, its surface runoff and underground water resources are limited. The average annual rainfall of 24 hours peak is 33 mm based on the statistics published by Mashhad climatology center. Thus, utilization of Qanats in this city was common from the past. The number of active Qanats in Mashhad in 1961 about 63 suits reported (Fig. 3) and during the past 50 years more than 95 percent of them have dried out (Salehi Moteahed, 2010). However, with respect to the position and depth of Qanats in urban area, it’s expected that the gallery of inactive Qanats filled by the sewage.

In table 1, the characteristics of main 9 suits Qanats located in the study area are shown. The galleries of Qanats are usually circular with diameter about 1-1.2 meters and the diameter of shafts is about 1 meter. Figure 4 shows soil texture map of the area in depth of 10 m. As we can see, the main constituent soils are coarse grain gravel and sand soils which have low cohesion. The depth of groundwater is below the Qanat tunnels in ranges from 60 to 110 m below the ground surface.

Table 1: Characteristics of Qanats situated in district 11 of Mashhad (Khorasan Razavi Regional Water Company, 1964).

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) 1963	45.7	42	8	Dry	9.4	52.59	20	40	Dry

Factors Affecting the Qanat Instability:

There are a few case study of Qanat stability. Rayhani, El Nagger (2006) stated that the most important effective factors in Qanat instability are geotechnical properties of soil, groundwater table, loading due to surface structures, Qanat characteristics (such as Qanat depth) and existence or non-existence of supporting system in Qanat gallery.

Another important factor involved in Qanat instability is overloading caused by surface structures and tall buildings. Figure 5 indicates high density residential area (four-storey buildings and more), educational, commercial, hygienic, governmental and cultural. These land uses comprise about 40 percent of the study area, so there is a potential for collapse of Qanats due to the increase in construction of tall buildings in the study area.

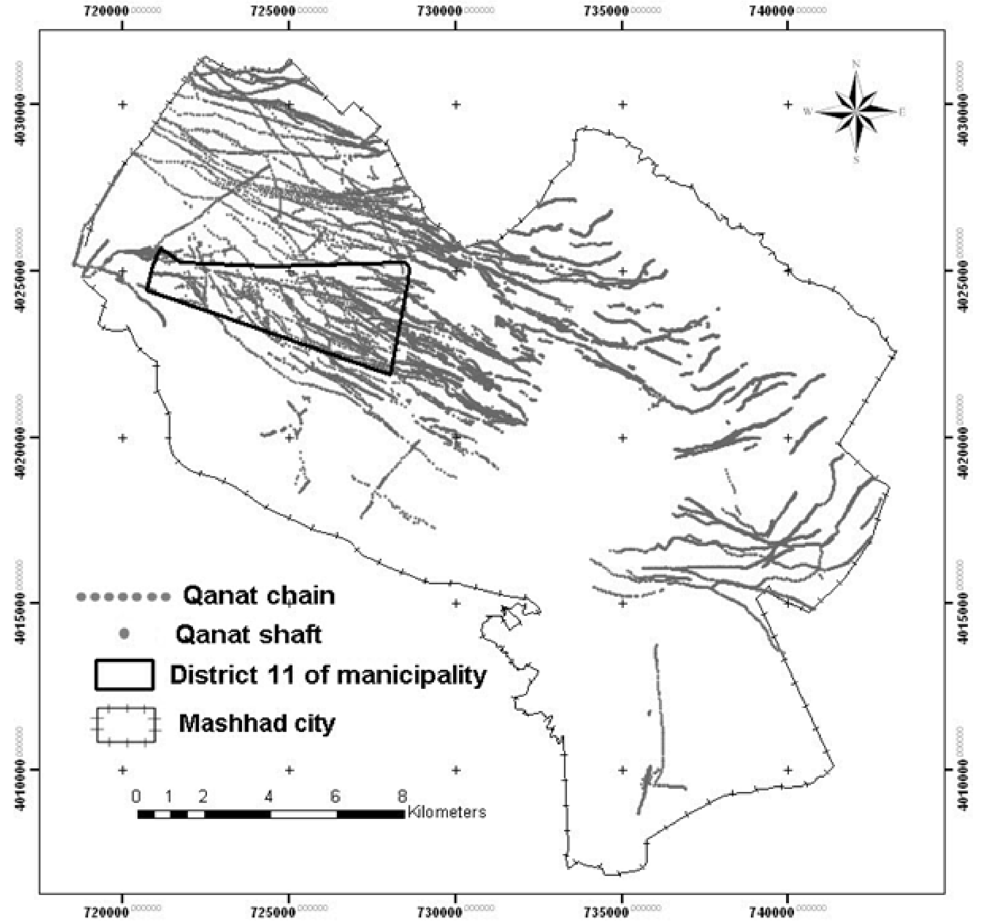

Fig. 3: Position of Qanats shafts in west of Mashhad city

In the past, for protecting of Qanat galleries and preventing water loss, the support system including the elliptical and circular baked clay hoops ("Caval" in Persian literature) or brick have been used(Seyyed Sajedi, 1982). In recent decades, cement Cavals were used instead of baked clay Cavals. The thickness of circular baked clay linings ranges from 4 to 5 cm and the thickness of circular cement linings is 4.5 cm (Behnia, 1988).

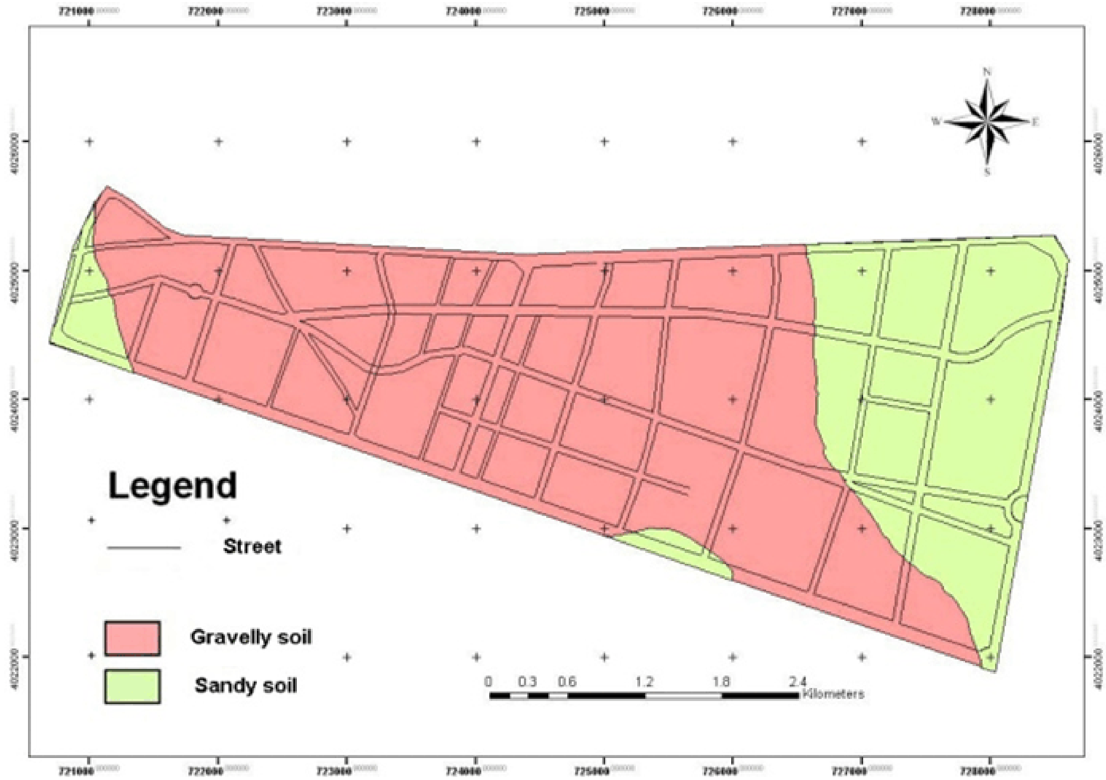

Fig. 4: Soil texture map of study area in 10 m depth.

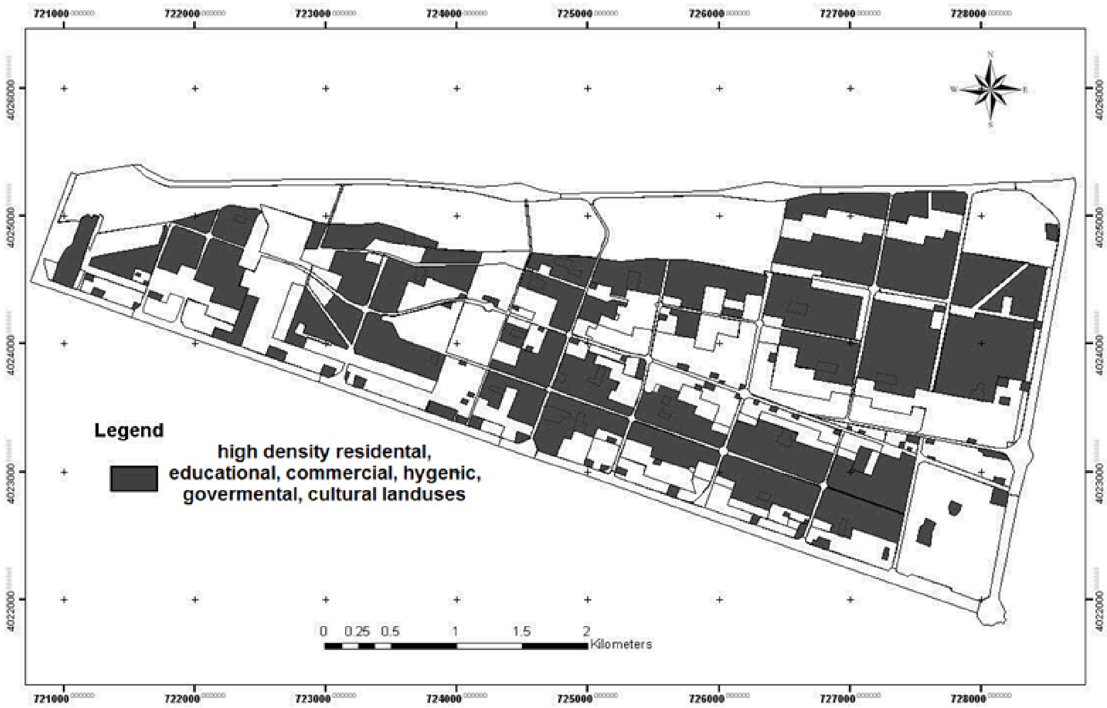

Fig. 5: High density residential, educational, commercial, hygienic, governmental and cultural lands in the area under study.

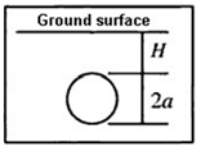

Fig. 6: Depth and radius of tunnel for calculation of critical radius of plastic zone (Yu, 2004).

Qanat Stability Analysis:

One of the applications of numerical models is soil deformation analysis around the tunnel (Gonzalez, Sagaseta, 2001). With respect to coarse grain soil in study area, soil elastic settlement due to loading has been given up and soil plastic deformation around the Qanat gallery due to loading has been investigated. The plastic points are stress points in plastic state. If the plastic point matches with Mohr- Coulomb point, it will indicate that the stress lies on the surface of the Coulomb failure envelope (Manual of Plaxis soft ware, 2002). With increasing loading due to surface structures, plastic zone will develop around the tunnel. It will lead to collapse of tunnel and will cause the settlement of the ground surface. Any change in tunnel depth lead to some changes in plastic zone extension (Lee *et.al,* 2006). Yu (2004) presented the following equation of plastic zone radius for collapse of tunnel in c-Φ soils:

$C=xH+D/2$

In this equation C is critical radius of plastic zone and $a=D/2$ and a and H are shown in Figure 6. $x=0.375$ is suggested for frictional soil.

Qanat Modeling:

For stability analysis of Qanats in the study area, finite elements method as 2-D analysis and plain strain model which lead to simplification of calculations were used with the help of Plaxis V 8.2 software. The soil properties of model are obtained from borehole data in center of the study area and the depth of 5, 7, 9, and 11 m are assumed for Qanat location. The geotechnical properties of soil used in the model are shown in Table 2.

Table 2: Geotechnical parameters of soil layers

Layer number	depth (m)	Soil group	γ_m kN/m^3	γ_{sat} kN/m^3	E_{50}^{re} kN/m^2	C kN/m^2	φ	ψ	Moisture content
1	0-3	GW,GC,GM	20.3	21.95	8500	9	41.6°	11.6°	4.10%
2	3-5	SP,SM	19.2	21.27	7500	9	39.1°	9.1°	3.90%
3	5-9	GW,GC,GM	20.3	21.95	8500	9	41.6°	11.6°	4.10%
4	9<	SW,SC,SM	19.7	21.4	5450	14	37.3°	7.3°	5.40%

The condition of Qanat collapsing with respect to the supporting system type (without lining, brick lining, and concrete lining) and imposed load was analyzed. The soil is modeled using 15-node triangular elements which are very accurate elements and present better results for soil collapse calculations. Loading was assumed as distributed load with 10 m length and 10kN/m^2 load for every story of a building. Loading is carried out at ground level and it is assumed that the structures have shallow foundations. In this study, dynamic loading resulting from earthquake and traffic was not considered. The model is restrained in smooth rigid in horizontal and free in vertical direction; and in rough grid both in horizontal and vertical directions and it is also defined in the lower boundary. In order to prevent any influence of the restrains on Qanat behavior, the restrains of the area under study are defined as 30 meters on every side from the Qanat axis. Considering the Qanat depth, the draw area was set at 60 m × 25 m.

Qanats Supporting System:

Circular form is considered for Qanat gallery. The tunnel with 1.2 m diameter is assumed to have brick or concrete lining with elastic behavior. Axial stiffness (*EA*) and flexural rigidity (*EI*) are the required parameters for tunnel lining modeling. To model the brick lining, common clay brick properties were used. Compressive strength of common brick is 6000 kN/m^2. The modulus of elasticity for brick was calculated with the following equation:

$$E_m = 750 f_m$$

E_m is elasticity modulus of brick and f_m is compressive strength of brick (Approval committee of Building and Housing Center Research BHRC PNS, 2004). Concrete with average compressive strength of f_c=20000 kN/m^2 for concrete lining was assumed and the following equation was used to calculate its modulus of elasticity (Mostofi nejad, 2010).

$$E_c = 4700\sqrt{f_c}$$

Table 3 shows the required parameters for Qanat lining modeling and Figure 7 shows a typical finite element mesh using in this study. This model includes four layers of soil, tunnel, and loading.

Table 3: Qanat lining properties.

Type of lining	EA(Axial stiffness)kN/m	EI(Flexural rigidity)kNm^2/m	Thickness m	Poisson´s ratio	Weight kN/m/m
Brick	225000	46.8	0.05	0.22	0.85
Concrete	1050950	218.59	0.05	0.15	1.15

Analysis and Discussion:

The analysis was performed for 4 phases with plastic calculation. Initial phase includes soil layers which are used to create a primary balance model. In the second phase, Qanat gallery and in the third phase tunnel lining are established. The last phase is related to structural loading. When Qanat is assumed without the supporting system, the third phase is omitted and calculations are performed in three phases. In order to study the collapsing of Qanat due to surface structures loading, plastic zone extension around the gallery was investigated. Figures 8, 9, 10, and 11 indicate plastic zone extension from Qanat axis at 5, 7, 9, and 11 m depths. In this study Qanats was considered to have 3 forms of brick and concrete lining and also without lining. As Figure 8 shows the Qanat in 5 m depth without lining can impose 10 kN/m2 loads which are approximately equal to a one-storey building's load. If this Qanat, would have a brick lining, it could impose a load equal to 4-storey building and if it would have a concrete lining it could impose a load equal to 6-storey building (safety factor=1.5).

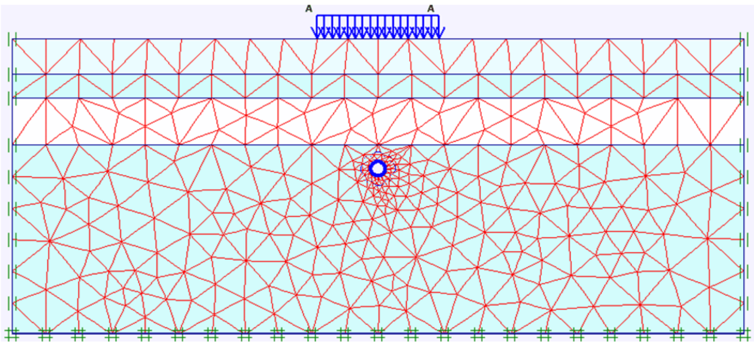

Fig. 7: Finite element mesh used in the numerical analysis for Qanat in 11 m depth.

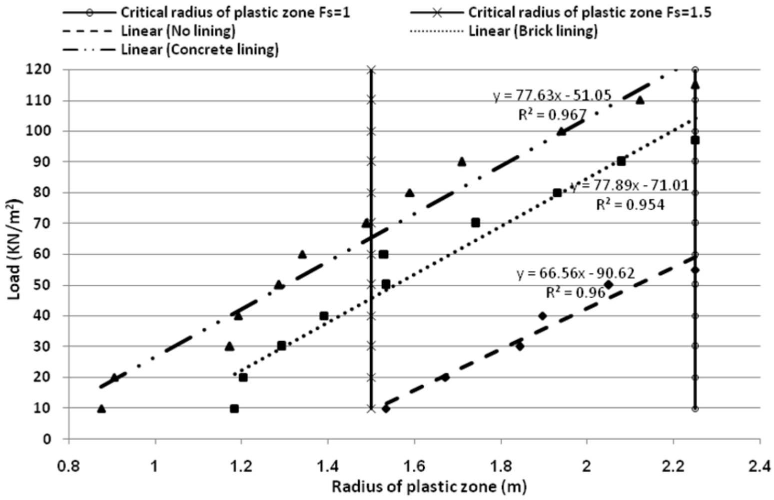

Fig. 8: Plastic zone extension of Qanats in 5 m depth

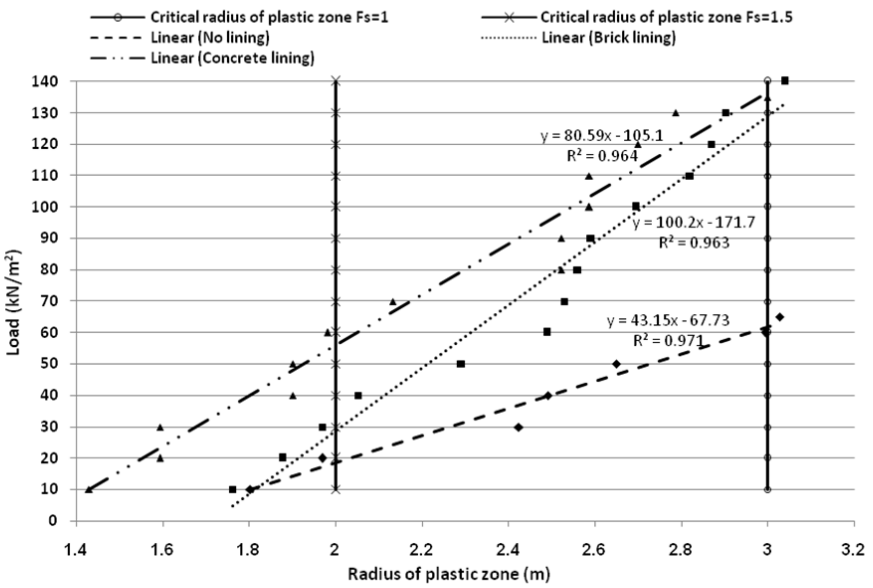

Fig. 9: Plastic zone extension of Qanats in 7 m depth

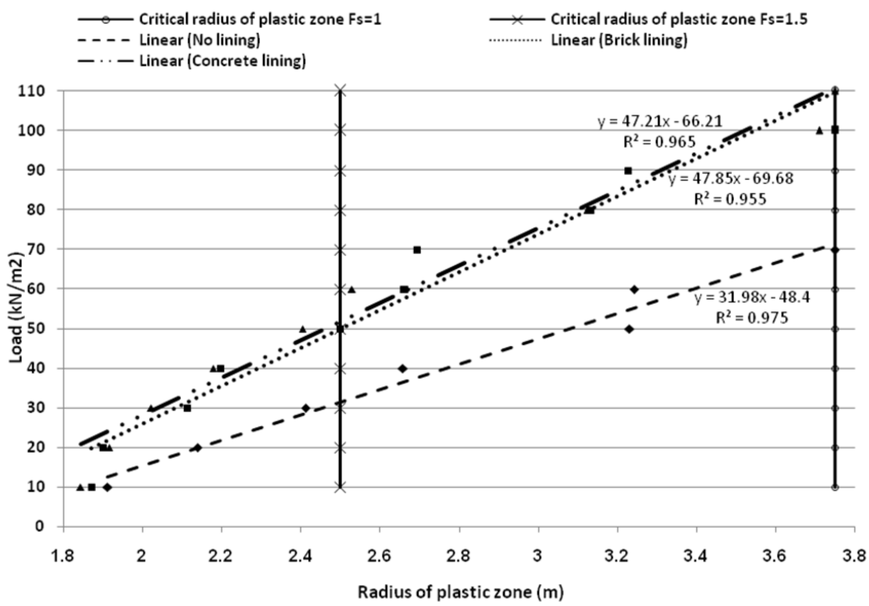

Fig. 10: Plastic zone extension of Qanats in 9 m depth

As it is seen in Figure 11, with assuming safety factor of 1.5, Qanat in 11 m depth without the supporting system could impose a load equal to a 5-storey building. In the case of brick lining, it could impose a load equal to a 7-storey building and in the case of concrete lining it could impose a load equal to an 8-storey building. Comparisons between Figures 8,9,10 and 11 indicate that if Qanat is located in shallower depths, there is an obvious difference in the bearing load by lined and unlined Qanat, but if Qanat is located in deeper, there is a little difference in bearing load by lined and unlined Qanat. For example, Qanat in 5 m depth, with a brick lining could impose a load more than 4 times of an unlined Qanat and that of a concrete lining would be more than 6 times. Also, Qanat in 11 m depth with a brick lining can impose loads 1.3 times and with a concrete lining it would be 1.4 times of an unlined Qanat. Therefore, by increasing depth of Qanat, the effect of supporting system in Qanat stability decreases. This is because of the increase in confining pressure of soil and the decreasing effect of surface loads on Qanat roof while increasing the depth.

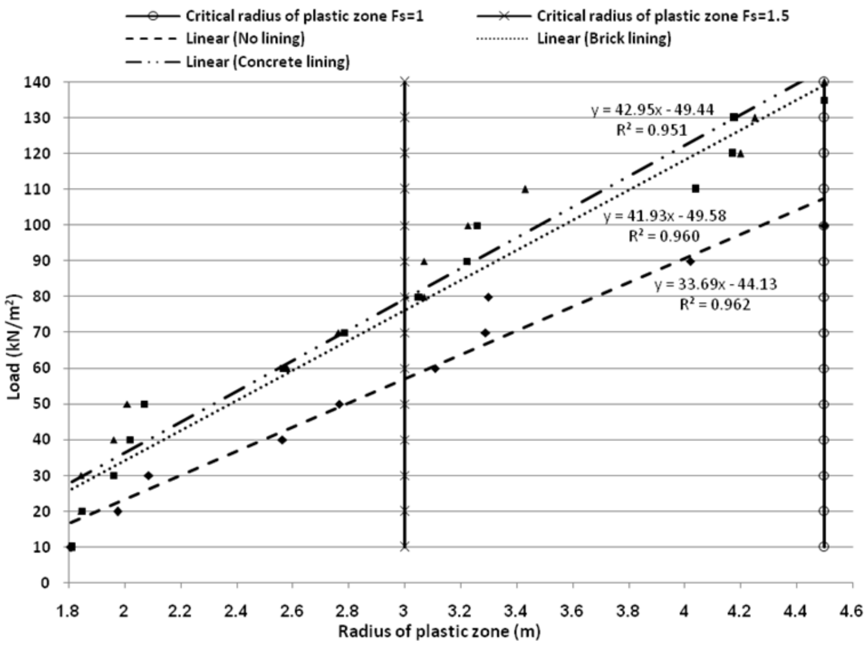

Fig. 11: Plastic zone extension of Qanats in 11 m depth

With regards to Figures 8, 9, 10, and 11, there is a linear correlation between the plastic zone radius and structural loads over the Qanat gallery with a high correlation coefficient (R^2). With increasing the depth of Qanat, the slope of line correlation between the plastic zone and load decreases in both unlined and lined Qanats. In fact, with the increase of depth of Qanat, plastic zone extension rate decreases due to the increasing load.

Because most Qanats in the study area have dried about 40 years ago and they have not been repaired, it is possible that the Qanat lining is damaged or broken and all of Qanats are acts like an unlined Qanat. In Fig. 12, the relationship between the depth of Qanat and maximum bearing capacity by an unlined Qanat has been demonstrated. It is considered that with respect to cohesion and strength properties of soil in the region, unlined or broken lined Qanats are stable in natural conditions. With respect to the Fig. 12, for every 1.2 m increase in depth, Qanat bearing capacity increases as same as about a one-storey building load.

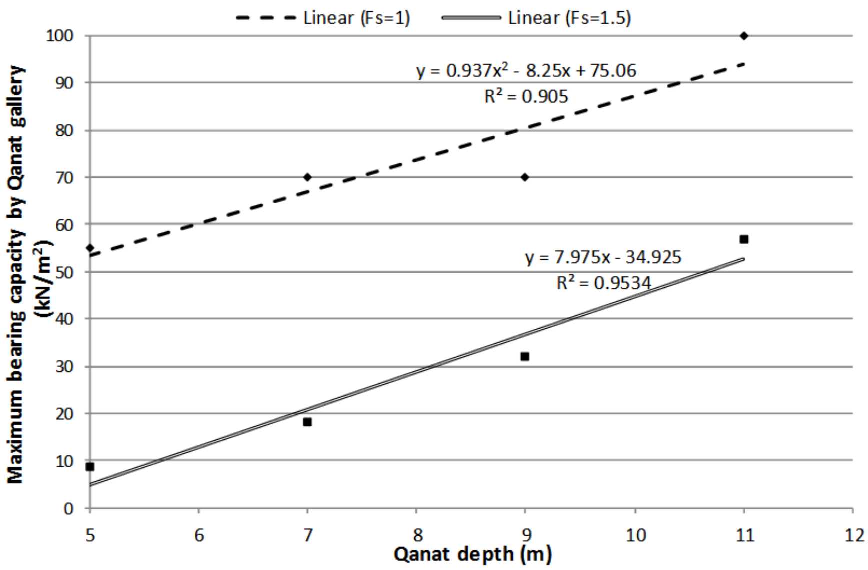

Fig. 12: Maximum bearing capacity by unlined Qanat versus depth of Qanat

Conclusions:

In this study the locations of Qanats shafts in district 11 of Mashhad Municipality in the western part of the city are mapped and their stability was analyzed using the Plaxis software. The results show a linear correlation between the plastic zone radius and load values. Also it shows that with increasing the depth of Qanat, plastic zone extension rate and the effect of supporting system decreases. This study also demonstrate that by assaying a safety factor of 1.5, an unlined Qanat with 5 m depth could suffer a load of a one-storey building and in more depths approximately for every 1.2 m increase in depth, the bearing capacity of Qanat gallery increase about of a load of one-storey building.

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