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An investigation on the mechanism of land subsidence in the northwest of mashhad city, NE Iran

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Abstract

Mashhad city is located in Mashhad Plain in the northeast of Iran. Mashhad plain is one of the most important plain in Khorasan Razavi province. In the last decades, rapid population growth coupled with agricultural expansion has tremendously increased pressure on the groundwater resources in the plain. Large increases in water demand with little recharge have strained the plain groundwater resources resulting with 65 m drawdown of water levels in the past 40 years in some part of the plain. Due to declining of the groundwater levels, digging new wells has been forbidden since 1965. As a result of dropping in groundwater levels, land subsidence appears in some parts of the region. For example, intensive dropping of groundwater level has created cracks and fractures on the land and buildings in Tous area in the northwest of the city. This paper deals with declining of groundwater level and mechanism of land subsidence in this part of the plain. Based on land subsidence data available from Tous permanent GPS stations, the annual rate of land subsidence was measured about 20 cm/yr. This rate of land subsidence is confirmed with the results was obtained by the InSAR(Interferometric Synthetic Aperture Radar) method. The results show that land subsidence in the study area is due to compaction of clay beds (Aquitard layers) within the aquifer systems as a result of a decrease in pore-fluid pressure (ground water decline) and resultant increase in effective stress.

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Introduction

Groundwater exploitation is a major cause of land subsidence. The exploitation of groundwater plays a direct role in land subsidence by causing the compaction of susceptible aquifer system. Subsidence accompanying the extraction of fluids such as water, crude oil, and natural gas from subsurface formations is considered the main cause of land subsidence, anthropogenic and natural. Subsidence phenomena cause disturbances in lifelines (roads, railway, pipelines) and sustainable water management (Galloway & Burbey, 2011).

Land subsidence due to overexploitation of groundwater resources has been reported in different parts of the world (Burbey, 2010, Darini, 2007, Burbey,2010, Lixin *et al.*, 2011, Lofgren, 1979). Sneed *et al.* reported that results of InSAR analysis indicated at least 540 millimeters of land subsidence due to aquifer compaction near San Joaquin River and the Eastside Bypass during 2008–10, in southern part of Delta-Mendota in the United State (Sneed *et al.,*2013).

In Iran, land subsidence, as a result of the withdrawal of groundwater, has been reported from many plains, such as Rafsanjan plain in Kerman Province (Solaimani and Mortazavi, 2008), Neyshabour plain in Khorasan Razavi province (Lashkaripour and Ghafoori, 2009). In Rafsanjan plain, for every 10m drawdown in groundwater table, ground surface settle as 42 cm (Rahnama and Moafi, 2009). Excessive groundwater withdrawals have caused severe land subsidence in Tehran, Iran. At present, a maximum land subsidence rate of 36 cm/year is reported for Tehran plain, covering an area of nearly 530 km2 (Mahmoudpour, *et al.* 2013).

In recent decades, excessive extraction from groundwater resources of Mashhad plain led to an excessive pressure on the plain aquifer and land subsidence. Ninety centimeters land subsidence during the 1995–2005 periods for some part of the plain was reported (Lofgren**,** 1979).

A radar interferometry time series analysis of Mashhad subsidence has been done by Dehghani *et al.* between 2003 and 2006. They reported a considerable subsidence rate up to 24 (cm/yr) (Dehghani *et al.***,**2009).

Drawdown of groundwater table caused land subsidence and ground displacement and decrease of water discharge and well destruction in some parts of the study plain, especially in Tous area. In some conditions, land subsidence appears as large cracks on the ground surface. These large cracks which resulted from ground settlement can be seen in Hasan Khordo village in the northwest of Mashhad city (Figure 1). This paper deals with groundwater decline and mechanism of land subsidence in Tous area. Also the relationship between land subsidence and grain size variation of soil in the area has been investigated.

The Mashhad plain is a northwest-southeast (NW-SE) trending plain in northeast of Iran. This plain is a part of Kashaf Roud catchments and it is limited to Hezar Masjid heights in the north and Binaloudmountains in the south. Both mountain chains stretch from north-west to south-east. Total catchment area is 9909 km², out of which 3351 km² is plains and 6558 km² is heights (Darini,2007). The highest elevation in the Hezar Masjed highs is 3040 m and in the Binaloud highs is 3211 m above the sea level. Kashaf Roud river is the most important seasonal river in the plain which has high flooding potential. Mashhad city, the second largest city in the country with a population of about 3,000,000 is located in the southeast of the plain. Figure 1 shows position of the Mashhad plain.

Materials and methods

Decline of groundwater level

Mashhad Plain Aquifer with more than 3000 km² area originates from 10 km the southwest of Ghuchan city and continues in southeastern direction between the Hezar Masjed and the Binaloud ranges. General flow direction of groundwater is from the northwest to the southeast and the main source of recharge for groundwater is flows resulted from rainfalls.

In permeability aspect, the south side of the plain is more permeable and alluvium thick (up to 300m). Due to excessive extraction from groundwater resources since 1970, groundwater table descended about 80 m which this amount during 2003-2008 years was 3.3 m (Figure 2). This drawdown of water table, cases land subsidence and create joints and cracks and destruction in farming wells around the Tous area.

In order to observe surface variations, different methods are used. GPS technique presents continuous observations and accurate leveling of surface variations in a series of points which are stations (Dehghani *et al.*,2006). National Surveying Organization has established 4 permanent GPS (Global Positioning System) stations in Tous, Toroq, Kalat and Vakil Abad Bulevard of Mashhad city for land subsidence measurement since 2005. Received data from these stations indicate vertical, eastern, and northern displacement at each station.

Figure 3 shows vertical data provided from Tous station. Based on the available data from this station, ground settlement amount since installation date during 2005 to 2008 years has been measured averagely 20 cm per year. This vertical movement is accompanied by a horizontal movement of the ground. Also, InSAR results indicate an average settlement rate of 24 cm per year for the Tous area. The InSAR results confirm the data resulted from the Tous GPS station (Dehghani *et al.*, 2009).

Results and discussion

Mechanism of land subsidence

Permanent land subsidence is most likely due to compaction of clay beds (aquitard layer) within the aquifer systems. When an aquifer system is full of water, the gravel and sands are buoyant. As groundwater levels decline from extraction, there is less buoyancy to support the weight of the gravel and sand that was previously full of water. Additional weight from the gravel and sand creates more downward pressure on clay beds that are between the sand and gravel strata from which water has been extracted. When the water held in the clays can no longer withstand the pressure from the increased weight of the gravel and sands above, the clays are compressed and water is squeezed from them (clay consolidation). These clays will never reabsorb the water that has been expelled from them. Permanent subsidence occurs and recharging the groundwater to its original levels will not result in the recovery of the original land surface elevations. It has been recognized that because of their low permeability, the clay interbeds drain more slowly than the coarser layers of the aquifer and that therefore there will be a time-delay between the extraction of the groundwater and the occurrence of the subsidence(Lofgren, 1979, Rudolph and Frind,1991).

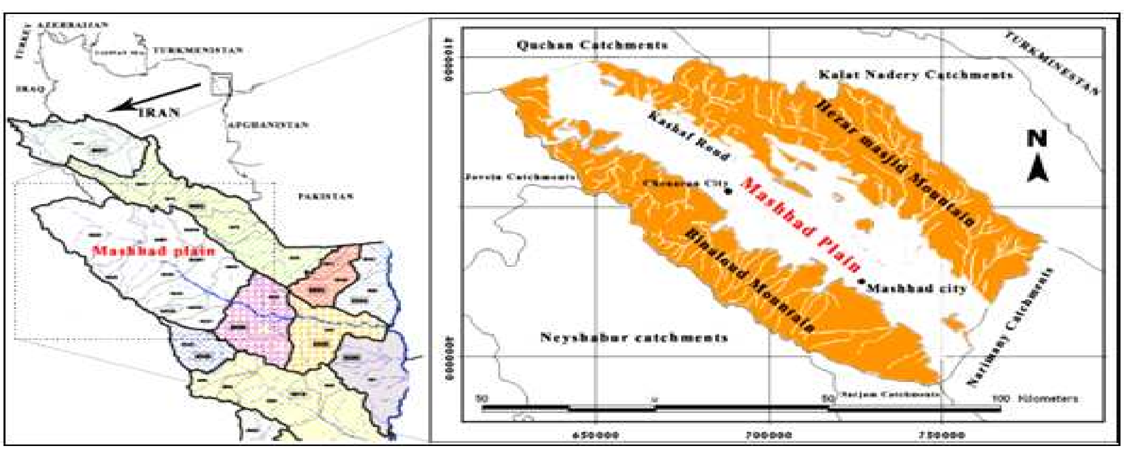

Fig. 1. Position of Mashhad plain.

The relation between changes in pore-fluid pressure and compression of the aquifer system is based on the principle of effective stress (Terzaghi law), Where effective or intergranular stress (σ_e) is the difference between total stress (σ_T) and the pore-fluid pressure (p) (Figure 4).

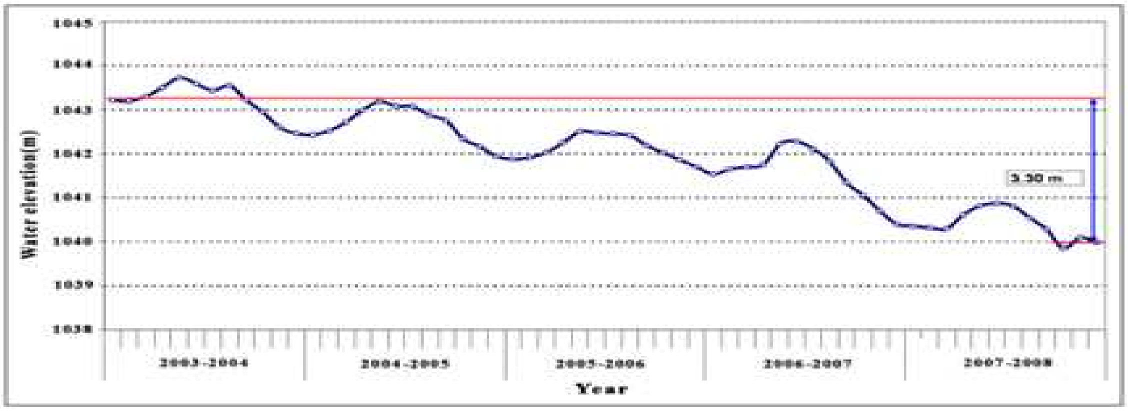

Fig. 2. Unit hydrograph of groundwater in the Mashhad plain during 2003-2008 years**Land subsidencebased on GPS data.**

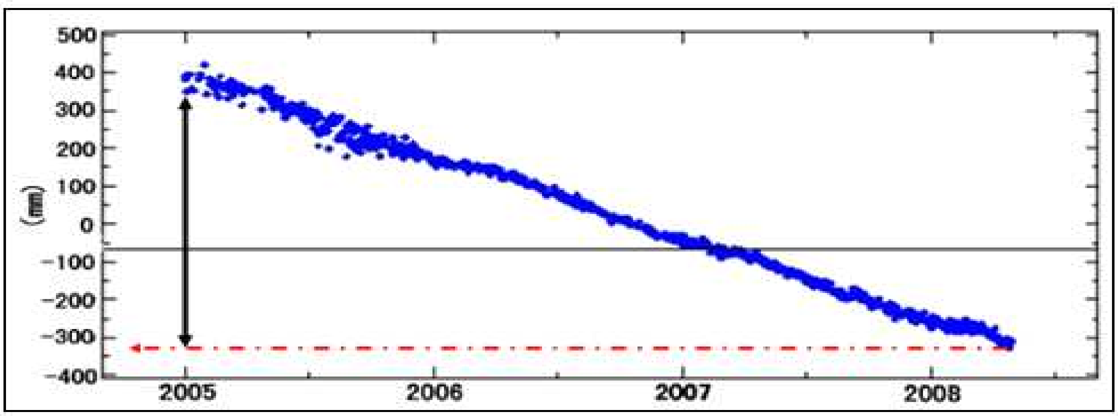

Fig. 3. A diagram showing vertical displacement variation in permanent GPS station of Tous area.

Effective stress increases in fine grain clay and silt layers led (aquitard) to their drainage and therefore create new arrangement in grain size distribution and finally consolidation. Consolidation effects can be observed as decreasing thickness of layers and ground settlement and their effects can be characterized as wellbore slumping, tilting of casing pipes, pipe genesis (exposed casings from the ground surface), and creating deep cracks. Grain size zonation profiles provided from drilling logs in the northwest of the city (Tous area) as an area with high ground settlement and well destruction and Nazerie area of the city as a low problem area, indicate that soil layers in Tous area are finer grains especially in depths below the ground water table as compared to the Nazerie area. Therefore, layering situation and soil grain size in each area have a great effect on land subsidence. Figure 5 shows tension carks due to land subsidence in this area.

In Tous area, problems resulted from ground settlement area more evident and they can be seen as wellbore slumping, tilting and destruction of casings, and pipe genesis (exposed casings from the ground surface). Due to ground slope direction from the highs toward the KashafRoudriver and with respect to available logs from the area, whatever we proceed from the mountain to the river, fine grain materials increase. Grain size differentiation between the Binaloudmountains and the KashafRoud river due to distance is observable so that near the KashafRoud river stratigraphic succession of soil is mostly composed of fine grained materials. In the study area, drilling logs of wells drilled in the city area have been investigated and grain size variation of soil has been determined above and below the groundwater table. In order to provide a grain size zonation map, soil based on grain size variation has been divided to different classes.

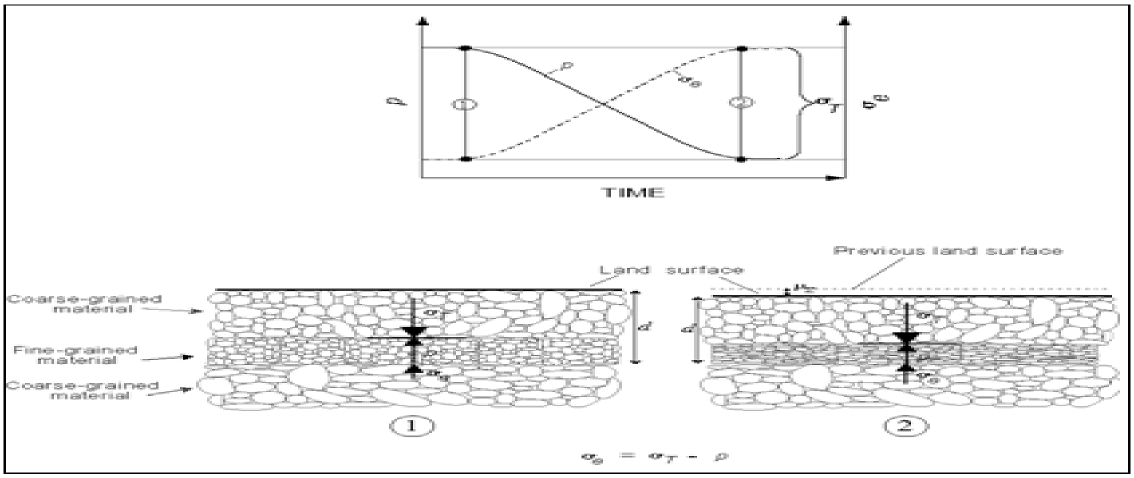

Fig. 4. Principle of effective stress, as applied to land subsidence. Vertical displacement (mz) of land surface as a result of a decrease in pore-fluid pressure (p) and resultant increase in effective stress (σ_e) exerted on a horizontal plane located at depth (d) below land surface in fine-grained material, under conditions of total stress (σ_T) in a one-dimensional, fluid-saturated geologic medium.

Based on available data, zonation map for grain size variation of soil in two conditions, above and below the groundwater table, has been provided for the city area which is indicated in figures 6 and 7.

Fig. 5. Tension carks due to land subsidence in Tous area.

Investigation and comparison of two provided zonation maps indicate that totally with increasing depth below the groundwater table, grain size of soil in the most parts of the city area is becoming finer. Therefore, increase of fine grained soil with continuing drawdown of water table can increase land subsidence in the future.

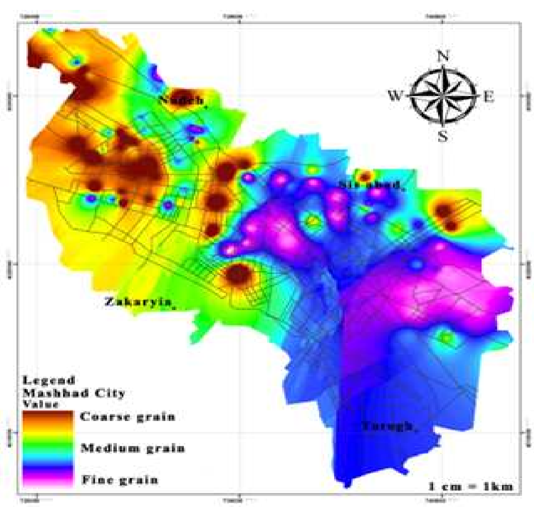

Fig. 6. Zonation maps of soil variation above the groundwater table in the city.

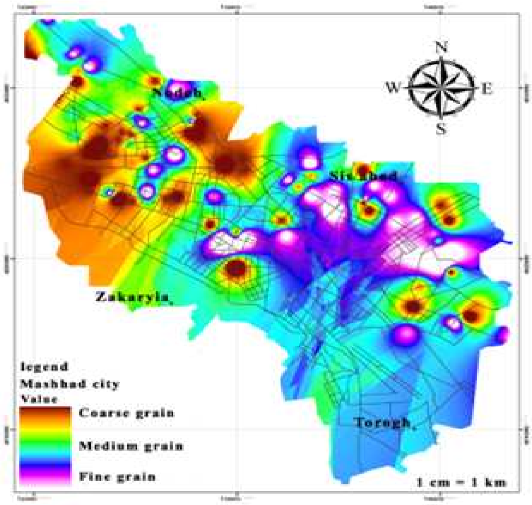

Fig. 7. Zonation maps of soil variation below the groundwater table in the city.

Conclusions

Extensive decline of groundwater in the Tour area has caused land subsidence. Water level decline of as much as 65 m was reported for this region during the four decades. Tous permanent GPS station results indicate a ground subsidence with a maximum rate of 20cm per year. Land subsidence in the region has caused water well casing destruction which its mechanism is different according to layering type and soil grain size. Investigation of grain size profile of soil indicates that well destruction in areas with fine grain soil is accompanied by more drawdown of water table. Generally it can be concluded that coarse grain materials above the groundwater table are more abundant compare to below groundwater table zone.

Overexploitation of the groundwater creates reduction in pore water pressure within the aquifer-aquitard system which is reflected by an increase in the effective stress and compaction of sediments. Effective stress increases in fine grain clay and silt layers led to their drainage and therefore create new arrangement in grain size distribution and finally consolidation. Consolidation effects can be observed as decreasing thickness of layers and ground settlement.

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