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Numerical simulation and prediction of regional land subsidence caused by groundwater exploitation in the southwest plain of Tehran, Iran

Masoud Mahmoudpour [a], Mashalah Khamehchiyan [a,*],
Mohammad Reza Nikudel [a], Mohammad Reza Ghassemi [b]

[a] Department of Engineering Geology, Faculty of Basic Science, Tarbiat Modares University, Tehran, Iran
[b] Research Institute for Earth Science, Geological Survey of Iran (GSI), Tehran, Iran

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ABSTRACT

This study characterizes land subsidence in southwest plain of Tehran using numerical modeling and predicts the trend through 2018. Excessive groundwater withdrawal has caused severe land subsidence in Tehran; in the past 28 years (1984–2012), groundwater level has decreased 11.65 m. The multi-layered aquifer system in the southwestern plain of Tehran contains three aquifers and three aquitard units. The present model was developed simulation using PMWIN (MODFLOW for Windows). First, groundwater level and land subsidence were simulated for the end of 2004. The model was calibrated using hydraulic head measurements and InSAR data. The simulation results were in fairly good agreement with the measurement results. The calibrated and evaluated model was then used to assess the future evolution of land subsidence and for prediction of subsidence through the end of 2018. Numerical results show that, assuming a constant rate of pumping in the future, land subsidence in the southwestern plain of Tehran will reach 33 cm by 2018. The study confirmed that land subsidence caused by groundwater pumping is a serious threat to southwest Tehran.

1. Introduction

Land subsidence includes both the gentle downwarping and sudden sinking of discrete segments of the ground surface (Galloway and Burbey, 2011). In many areas in the United States underlain by soluble rocks, land subsidence is a common phenomenon. Consequently, the most common type of sudden collapse is from erosion of underground soil and/or rock caused by leakage of sewage pipes or water mains. A second type of sudden collapse results from dissolution of carbonate rocks beneath the surface in these areas (Zeitoun and Wakshal, 2013). Underground mining is another cause for man-induced subsidence. Mining activities that remove materials (such as coal and salt) from below the surface can result in a sudden subsidence (Zeitoun and Wakshal, 2013).

Displacement is principally vertical, although horizontal deformation often causes significant damage. The extraction of groundwater plays a direct role in land subsidence by causing the compaction of susceptible aquifer systems. Subsidence accompanying the extraction of fluids such as water, crude oil and natural gas from subsurface formations is perhaps the best known cause of land subsidence. Subsidence can disturb the existing infrastructure, including buildings, roads, railways and pipelines, and also signifies a major deficiency in sustainable water management (Galloway and Burbey, 2011).

Land subsidence caused by long-term excessive groundwater withdrawal is a worldwide phenomenon. It is often observed in semiarid and arid environments. Over 150 major cities worldwide have experienced substantial subsidence (Hu et al., 2004). The severe consequences to the environment and economy of the global distribution of land subsidence demonstrate that it requires research and technology transfer on an international level (Hu et al., 2004). Geohazards caused by land subsidence from excessive pumping of groundwater have been reported in Jakarta and Samarang, Indonesia (Chaussard et al., 2013), Venice, Italy (Teatini et al., 2012), Mexico City, Mexico (Osmanoğlu et al., 2011; Yan et al., 2012; Chaussard et al., 2014), Shanghai, China (Hu, 2006), Beijing, China (Ng et al., 2011), Tianjin, China (Yi et al., 2011), Antelope Valley, California, USA (Galloway et al., 1998), Houston–Galveston, Texas, USA (Gabrysch, 1984), San Joaquin Valley, California, USA (Ireland et al., 1984), Santa Clara Valley, California, USA (Poland and Ireland, 1988), Bangkok, Thailand (Phien-wej et al., 2006), and Quetta Valley, Pakistan (Khan et al., 2013). In Iran, it has been reported in Rafsanjan (Mousavi et al., 2001; Rahnama and Moafi, 2009), Mahyar, Nayshabour and Kashmar (Lashkaripour et al., 2010, 2007, 2006) and Mashhad (Motagh et al., 2007). Table 1 records recent subsidence rates worldwide.

Land subsidence can be explained by poroelasticity or poroelastic consolidation theory, which was first formulated by Biot (1941). Poroelasticity theory is a valuable method for analysis of the interaction between fluid flow and skeletal-matrix deformation (Hsieh, 1996). The principle of effective stress, first proposed by Karl Terzaghi in 1925, is

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* Corresponding author.
E-mail address: khamechm@modares.ac.ir (M. Khamehchiyan).

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Table 1
Recent worldwide measured subsidence rates for selected locations. Rates represent the local maximum measured rate for the specified period (modified from Galloway and Burbey, 2011).

Location	Rate (mm/year)	Period	Measurement method	Source
Aguascalientes Valley, Mexico	111	1993–2003	Global positioning system	Pacheo-Martínez et al. (2013)
Anthemountas Basin, Northern Greece	23	1995–2001	Differential interferometry	Raspini et al. (2013)
Bandung, Indonesia	230	2006–2009	Differential interferometry	Chaussard et al. (2013)
Bangkok, Thailand	30	2006	Leveling	Phien-Wej et al. (2006)
Beijing City, China	115	2003–2009	Differential interferometry	Ng et al. (2011)
Bologna, Italy	40	2002–2006	Differential interferometry	Bonsignore et al. (2010)
Coachella Valley, California, US	70	2003–2009	Differential interferometry	Sneed (2010)
Datong, China	20	2004–2008	Differential interferometry	Zhao et al. (2011)
Gioia Tauro plain, Italy	23	1992–2006	Differential interferometry	Raspini et al. (2012)
Guangrao, Yellow River Delta, China	65	2002–2008	Leveling	Liu and Huang (2013)
Houston-Galveston, Texas, US	40	1996–1998	Differential interferometry	Buckley et al. (2003)
Jakarta, Indonesia	220	1997–2010	Global positioning system	Chaussard et al. (2013)
Mashhad Valley, Iran	280–300	2003–2005	Differential interferometry	Motagh et al. (2007)
Mexico City, Mexico	380	2002–2007	Differential interferometry	Yan et al. (2012)
Murcia, Spain	35	2008–2009	Differential interferometry	Herrera et al. (2010)
Quetta Valley, Pakistan	100	2006–2009	Global positioning system	Khan et al. (2013)
Saga Plain, Japan	160	1994	Leveling	Miura et al. (1995)
Semarang, Indonesia	130	2007–2009	Global positioning system	Chaussard et al. (2013)
Tehran Basin, Iran	205–250	2004–2008	Differential interferometry	Dehghani et al. (2013)
Thessaloniki plain, Northern Greece	45	1995–2001	Differential interferometry	Raspini et al. (2014)
Tianjin, China	30–40	2007–2010	Leveling	Yi et al. (2011)
Tokyo, Japan	40	1977–1988	?	Hayashia et al. (2009)
Toluca Valley, Mexico	90	2003–2008	Differential interferometry	Calderhead et al. (2011)
West of Villa de Arista, Mexico	184	2007–2011	Differential interferometry	Chaussard et al. (2014)
Yunlin, Taiwan	100	2002–2007	Leveling	Hung et al. (2010)
Zamora, Mexico	128	2007–2011	Differential interferometry	Chaussard et al. (2014)

often used to explain the occurrence of land subsidence as related to groundwater withdrawal (Galloway et al., 1999).

Excessive groundwater withdrawal from aquifer systems causes pore water pressure to decrease and effective stress to increase. The increase in effective stress results in compaction of hydrostratigraphic units, including aquitard and aquifer units, and land subsidence. It is often thought that aquitard units, which consist primarily of clay and silty clay, experience higher compressibility and greater compaction than aquifer units consisting primarily of sand (Calderhead et al., 2011).

Aquifer-system deformation is elastic (recoverable) if the stress imposed on the skeleton is smaller than the previous maximum effective stress. When the stress is greater than the preconsolidation stress, the pore structure (granular framework) of the fine-grained sediments rearranges into a configuration that becomes more stable at higher stress. This results in an irreversible reduction in pore volume and in inelastic compaction of the aquifer system (Sneed et al., 2003). Preconsolidation stress is the maximum effective stress a soil has experienced throughout its life. It separates elastic and reversible deformation from inelastic and partially-irreversible deformation and marks the starting point of high compressibility (Tomás et al., 2007).

Calderhead et al. (2011) have shown that numerical models are useful tools for evaluation of the evolution of land subsidence caused by groundwater pumping. They are at present the most powerful predictive tools for assessing future land subsidence (Cao et al., 2013). MODFLOW numerical modeling has been used to simulate groundwater flow (Mc Donald and Harbaugh, 1988) and the interbed storage package (IBS1) in MODFLOW to simulate land subsidence (Leake and Prudic, 1991), determine the layer compaction coefficient, and estimate the groundwater safe yield in Los Banos–Kettleman City, California (Larson et al., 1999).

Hoffmann et al. (2003a) used inverse modeling in MODFLOW code and the SUB package to simulate land subsidence and estimate the inelastic storage coefficient and time constant for Antelope Valley, California. Taiyuan basin in China was simulated using IBS. The modeling results show that compression of different clay layers contributes differently to land subsidence (Ma et al., 2006). Kihm et al. (2007) analyzed 3D fully-coupled groundwater flow and land deformation caused by groundwater pumping in southeast of Seoul, Korea.

A new 3D groundwater flow model and a 1D instantaneous compaction finite element numerical model were verified and applied to the Toluca Valley in Mexico (Calderhead et al., 2011). Their study showed that the use of different sources of data was beneficial for estimating and constraining the vertical component of the inelastic skeletal specific storage. Also, the study of Toluca aquifer system was carried out for establishment of a management policy for the sustainable development and management of this aquifer for minimizing land subsidence. Simulation results show that much of the land subsidence could have been avoided by implementing water policies to restrict pumping in regions with compressible materials (Calderhead et al., 2012).

A 1D deformation model was developed to simulate deformation for development of groundwater resources under land subsidence control (Shi et al., 2012). Land subsidence analysis in Changhua in central Taiwan was conducted using the COMPAC 1D compaction model. The results provide a key reference for water management in central Taiwan (Hung et al., 2012). Simulation of Hangzhou–Jiaxing–Huzhou plain in China was carried out under transient conditions using MODFLOW 2000 (Harbaugh et al., 2000). The results showed the main cause of land subsidence to be inelastic compaction of the aquifer system resulting from continuously declining water levels (Cao et al., 2013).

InSAR data has been used to calibrate numerical methods that reproduce aquifer deformation due to groundwater withdrawals. The relationship between the temporal evolution of the displacement and the groundwater level changes has been used for model calibration. This method can be found for instance in Tomás et al. (2010); Herrera et al. (2009) and Ezquerro et al. (2014).

In Iran, land subsidence caused by withdrawal of groundwater has occurred in the cities of Tehran, Mashhad, Kashmar, Varamin, Kashan, and Rafsanjan (Sharifikia, 2010). Simulation of aquifer and land subsidence prediction have been applied with PMWIN to the Shirvan aquifer (Mohammadi et al., 2014), Hamedan–Bahar aquifer (Mahdavi et al., 2013), Shiraz plain (Karimipour and Rakhshandehroo, 2011) and Shahryar plain (Fotovat-Eskandari and Karami, 2009). The prediction model indicates that the maximum rate of subsidence recorded in Shahryar plain was 30 cm/year in 2014.