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Investigation of Mashhad Plain's Subsidence Potential Due to Soil Layers Consolidation

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ABSTRACT

In this study, a flow – consolidation integrated model in a 3D axially symmetric form and using finite element numerical method for calculating ground subsidence has been provided to assess this phenomenon using elastic porous media theory. Between the years 1995-2005 a subsidence as large as 90 centimeters has been reported in the Mashhad plain. Ground subsidence is usually caused by groundwater-related phenomena. Analyzing piezometric data gives us the huge drop in groundwater level in the aquifer system as the reason for subsidence in the Mashhad plain. Groundwater level has gone down more than 65 meters since the 1960s. Information from InSAR shows that almost 70 square kilometers of Mashhad plain including a part of North-West Mashhad, has been subsiding with a rate of more than 15 centimeters per year between 2004 and 2006. Field Data show that a one meter drop in groundwater level in the aquifer results in 12 centimeters of subsidence in the surface. According to the model it can be said that the total subsidence in the last 25 years between 1983 and 2008 is 4.46 meters, and assuming constant groundwater level drop of 1.5 meters per year, a subsidence as large as 2.4 meters has been estimated in the piezometers near Tous GPS station in the next 22 years, bringing the total subsidence between 1983 and 2030 to 6.86 meters.

KEYWORDS: subsidence; modeling; elastic porous media; groundwater

INTRODUCTION

It has been a few years since ground surface subsidence due to excessive groundwater extraction was as a danger for those regions of the world that use groundwater a lot [1-8]. Ground subsidence can have destructive consequences, including changes in surface water and groundwater flow patterns, decrease in storage capacity and limiting pumping in the areas prone to subside, occurrence of local floodwater, destruction of well's walls and changes in channel's slopes or structural shearing [9]. On the other hand in coastal areas, excessive drop in groundwater level causes seawater permeation resulting in lower quality groundwater and the conversion of a large quantity of groundwater to salt water [10].

In fact, ground subsidence is a gradual or sudden subsidence of ground surface due to the movement of underground material. This phenomenon mainly happens due to three different water-related procedures: compression (compaction and consolidation) of aquifer's clay and silt layers, drainage and oxidation of vegetal soil and the collapse of rocks that are on the verge of dissolution.

Some of the serious dangers of ground subsidence include lowering the free height of levees resulting in a lower factor of safety from floods, a change in water transfer channels' slope and a change in groundwater patterns and damage to roads and bridges. Knowing about and discovering ground subsidence in the earlier levels is important to prevent these structural damages [11]. This phenomenon is threatening gas transmission facilities and the Tous Power Plant in the Mashhad plain.

Permanent ground subsidence is mainly due to clay and silt layers compression in the aquifer. Consolidated clay layer never regains its lost water resulting in permanent ground subsidence, therefore recharging the groundwater reservoir to reach its primary levels will not return ground surface to its former heights [11]. A decline in pore water pressure in clay which is time-dependent causes it to consolidate (compress with delay). These clay layers' compression has a big role in total subsidence on the ground's surface [12]. The relationship between groundwater level decline and subsidence is explained by the effective stress principle. In an aquifer, pore water pressure is equal to head pressure in a balanced state. Even if the total stress is constant, effective stress in the aquifer increases as water goes down in the aquifer and the piezometric head lowers down. Effective stress increase is the cause of soil compression and subsidence [13]. If the hydraulic head is lower than the lowest head in the past, then the soil compression would be inelastic. Inelastic compression is a result of soil grains' irreversible stacking, and when the head goes back to a value higher than the lowest in the past, elastic return occurs as a result of elastic expansion of soil grains [14].

In this study a flow – consolidation integrated model in a 3D axially symmetric form using finite element method has been provided. This model is very suitable for calculating local effects of taking water from a well because it has a high accuracy and conveniently simulates water decline's effect at the soil mass around the well while having a significantly lower calculation cost comparing to the full 3D model. Axially symmetric model is also pretty useful for modeling vertical drains. In the axially symmetric model, we can't generally calculate ground fissure's effects.

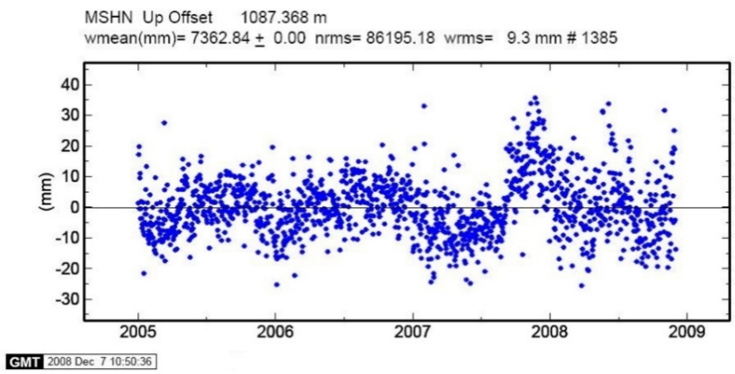
GEOLOGICAL AND GEOTECHNICAL ASSESSMENT OF MASHHAD PLAIN

Geotechnical information of Mashhad plain is available only sporadic and occasional. To get an estimation of Mashhad plain's geotechnical state, exploratory bores in construction projects have been used. This information was gathered with Khorasan Razavi's regional water authority's cooperation and searching in the organization's archives which include geotechnical studies and experimental injection of Akhlamad's historic dam project [15], artificial recharging of Jamab on Farizi river in Chenaran's development plan [16], Radkan's reservoir dam project [17], and geotechnical studies of Ardak's storage dam's second phase [18,19]. According to existing geotechnical data, assessing engineering specifications of fine-grained soil in Mashhad city has shown that clay soil in this area is generally of the kind with low plasticity. Density of fine-grained silt-clay soil ranges from the minimum of 1.5 to 1.8 gr/cm3. Also by studying coarse-grained sandy soil, it was revealed that coarse-grained soil's density ranges from 1.7 to 2.0 gr/cm3. As expected, soil density increases with depth and more soil compression [20].

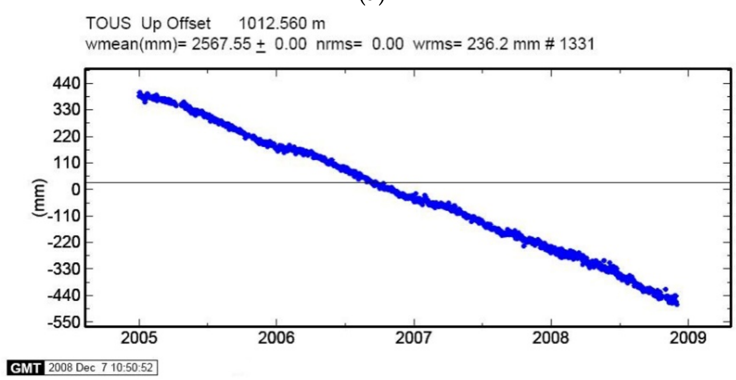
SUBSIDENCE ANALYSIS IN MASHHAD PLAIN

There are four GPS stations in Mashhad plain which constantly record their local information in regular time intervals. The first station was deployed in 3/29/04 in the city of Mashhad. After that, on 12/23/04 the Tous station was installed and set up. Golmakan station joined the country's geodynamic cartography organization on 11/30/05. Due to Ferdowsi power plant's sensitivity as well as the need to know about the power plant's development plans a station was set up there on 9/19/07.

As the recorded information shows (Figure -b), the Tous station in the Mashhad plain reports a considerable and constant subsidence. In the four years of subsidence measurement between 2004 and 2008, a subsidence of 82 centimeters has been reported in this station which means a whopping 20 centimeters subsidence per year. Moreover, accurate benchmarking has been carried out in the years 1995, 2002 and 2005 which has recorded a subsidence as big as 90 centimeters meaning 9 centimeters of subsidence per year in this period. Therefore by comparing the subsidence in the 10-year period (Between 1995 and 2005) with the 4-year period (Between 2004 and 2008), we can see that yearly subsidence has increased from 9 centimeters to 20 centimeters.



(a)



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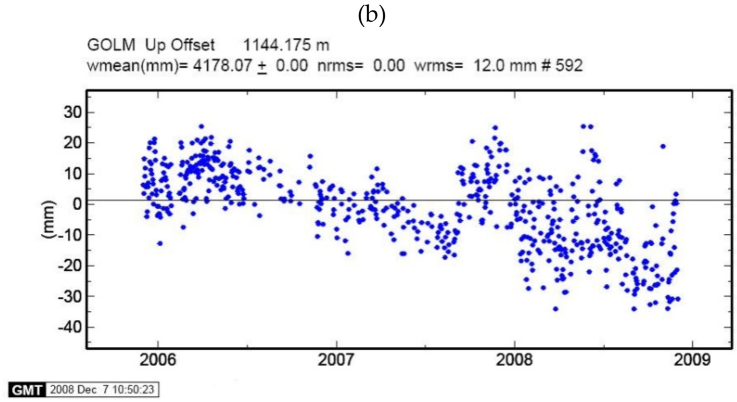
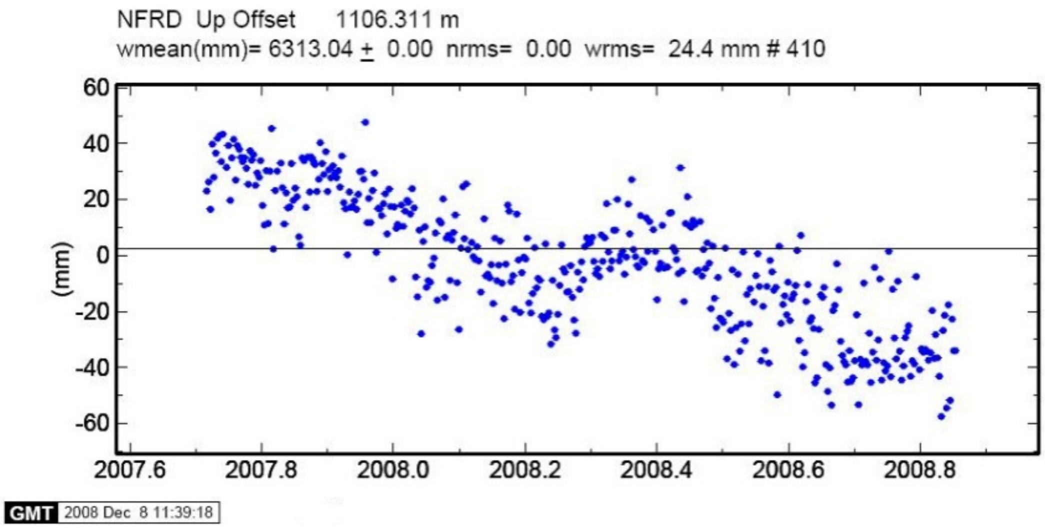


(c)

Figure 1: *Continues on the next page→*



(d)

Figure 1: Recorded height differences in GPS stations: (a) Mashhad; (b) Tous; (c) Golmakan; (d) Ferdowsi power plant [21].

Ferdowsi power plant's station has reported a considerable subsidence of about 8 centimeters during one year (Figure -d). The other stations in Mashhad plain show periodical changes but revert to their preliminary values (Figure -a, Figure -c).

Unfortunately, there are no satellite information (InSAR) of Mashhad plain available and Khorasan Razavi's cartographic center doesn't have direct access to this information. The very first satellite photography of Mashhad plain was done in 2003. These observations where done again in the next years by the Enivsat satellite and very useful information about the subsidence pattern, value and speed in the Mashhad plain were gathered [22].

Groundwater Level in Mashhad plain

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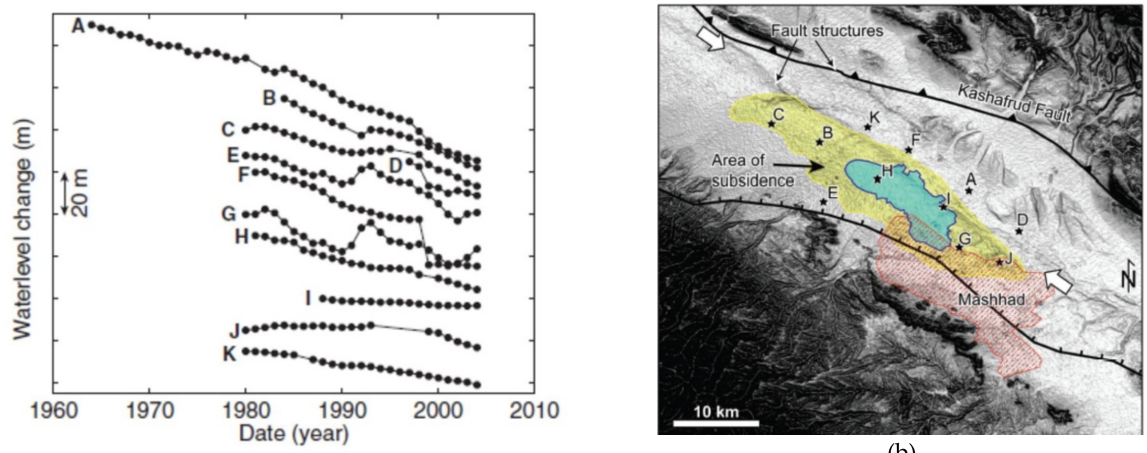
Khorasan Razavi's regional water authority has gathered nearly perfect information of groundwater level in the Mashhad plain in the last 50 years. Figure shows the amount of groundwater level drop in the Mashhad plain. The highest amount of water level drop is about 65 meters which is shown in the piezometer A in Figure . Generally, the subsidence value observed in the surface is related to the drop in groundwater level drop. But as it is shown in Figure , piezometers A, D, F and K show a considerable water level drop, but are out of the critical subsidence zone, also piezometer I which is in the critical subsidence zone (more than 15 centimeters per year), doesn't show a considerable groundwater level drop in the last 20 years (Figure -a). The reason for this incompatibility is the existence of a fault in the white arrow path shown in Figure -b (Motagh et al., 2006).



(a) (b)

Figure 2: Water level drop in the Mashhad plain aquifer. (a) Water level drop in Mashhad plain's piezometers, (b) Location of the studied piezometers and the subsidence range in Mashhad plain. Pink shows the city of Mashhad, while blue shows the area in which subsidence has occurred with a rate of more than 15 centimeters per year between 2003 and 2005. Yellow shows subsidence rate of about 5 centimeters per year. White arrows mark the fault which has limited the subsidence mechanism from the north [22].

STUDY FINDINGS

The Model Provided in the Study

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Due to this study's goal of reviewing subsidence consequences and with a knowledge of this phenomenon's factors and complications and also its vastness, we can suggest different models. In the available studies in order to solve these problem's equations, mostly the finite element method or the finite difference method were used, each of them having their own advantages. One, two, and three-dimensional models were presented with the aim of analyzing this problem based on the finite element method. Generally, subsidence complications include asymmetric ground subsidence, earth fissures or damages done to other structures. One-dimensional models are mainly used for predicting the ground subsidence value and estimating the effect of changing the water drainage pattern or artificially recharging the aquifer. Although these models don't have the ability to calculate local subsidence, they are used a lot for providing solutions to stop subsidence in the area under study [12]. 2D models have been used to analyze surface fissure mechanism and predict its costs [23]. Complete 3D models have the modeling abilities of the previous two forms and can predict the damage done on structures and calculate local subsidence besides that, while also they are very useful for utilizing groundwater management plans. 3D models can determine the best water drawing patterns. These models also can present the most economic combination of solutions for subsidence including correct groundwater drawing patterns and artificial recharging. For example, these models can help in choosing the best locations, efficient number of wells, the most suitable depth and pumping flow and also the required sequence and time interval in order to artificially recharge the aquifer. Since in this study focuses on the local effects of subsidence due to drawing water from a well, the 3D model based on equations governing elastoplastic porous media using finite element method was chosen. With the help of this model, we can analyze reversible and irreversible subsidence in the aquifer due to groundwater level drop.

Model Properties

Model Properties

Since Sarasiab Ferdowsi and Kalate Barfi's wells are near the Tous GPS station, these wells were chosen to check the water level in the aquifer and simulate it in the model and also to predict the subsidence in the future. The position of Sarasiab Ferdowsi and Kalate Barfi are specified with F and H in Figure . The aquifer's depth is not fully identified in this area, but it's estimated at more than 230 meters and selected as 300 meters for modeling. In a similar study in Japan, it is seen that deep layers of soil are inconsiderably affected by the soil surface's transformations [24], therefore a maximum depth of 300 meters is sufficient for modeling. Due to the geological time scale, clay layers are in the aquifer's surface and in the deeper layers, a mixture of fine-grained and coarse-grained sediments are found. In the soil pattern maps of the city of Mashhad's area, similar layering was reported. In table 1 the geotechnical properties assumed for the layers is shown. These numbers were acquired by analyzing the properties of the material seen in the aquifer.

Table 1: Geotechnical properties' parameters of the model in Tous GPS station's subsidence analysis

Layer	Soil Type	Depth (m)	Elasticity modulus (kPa)	Poisson ratio	Permeability (m/s)	Angle of internal friction	Cohesion (kPa)
1	Fine	0-100	6200	0.2	2.32 × 10-8	5	10
2	Coarse	100-300	20000	0.25	1.11 × 10-6	25	5

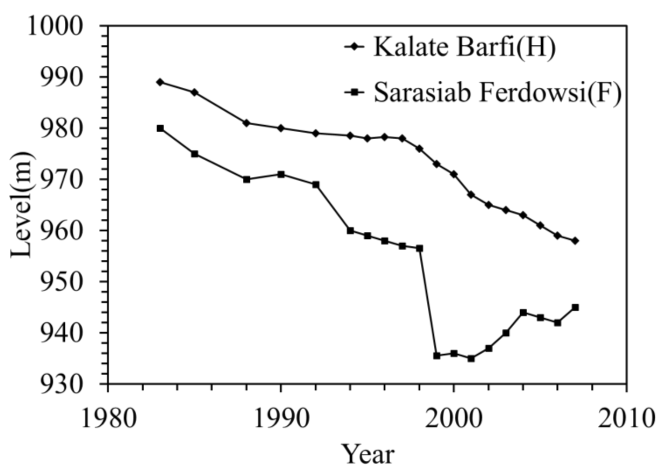

Figure 3: Annual water level average in Sarasiab Ferdowsi (F) and Kalate Barfi (H) piezometers from 1983 to 2007 [21].

In Figure 3 the groundwater level in Sarasiab Ferdowsi (F) and Kalate Barfi (H) piezometers' time series is presented. According to the information provided here, it is shown that from 1983 to 1998 the rate of water level drop was almost monotonous in both piezometers at about 1.5 meters per year. This rate is seen in the piezometer H until the end of 2007, but from 1998 to 1999 a huge water level drop of 21 meters has been reported in piezometer F which is equal to the drop in the previous 15 years. From 1999 to 2007 a period of water level rise is seen in this piezometer such that the water level has risen 1.00 meter per year on average.

Geometry and Elemental Gridding of the Provided Model

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According to the information presented in table 1, two layers have been considered for the model. According to geological observations, the upper layer has been assumed as fine-grained (aquitard) and the lower layers has been assumed as coarse-grained (aquifer).

First in order to get an estimation of subsidence value and maximum pore water pressure as a result of groundwater level drop between 1983 and 2008, an elastoplastic analysis with Mohr-Coulomb criterion was carried out on the basis of average annual groundwater level in piezometer (H), the results of which can be seen in Figure . Total subsidence in the 25 years between 1983 and 2008 was given as about 3.45 meters in this model. Also, the maximum pore water pressure calculated in this time period was in 2001 and equal to 20.5 kPa. Since the observed subsidence in Tous GPS station in only available from 2005 to 2008, in the next step in order to check the integrity of the model, the subsidence value for this period was calculated on the basis of average monthly groundwater level (figure 5) and compared to the subsidence value observed in Tous GPS station (figure 6). As we can see in figure 6, monthly groundwater level goes down in harvest seasons and goes up in raining months. The general trend of the fluctuations is descending and it is seen in this figure that the water level in the piezometer H in Mashhad plain's aquifer goes down about 1.5 meter per year on average.

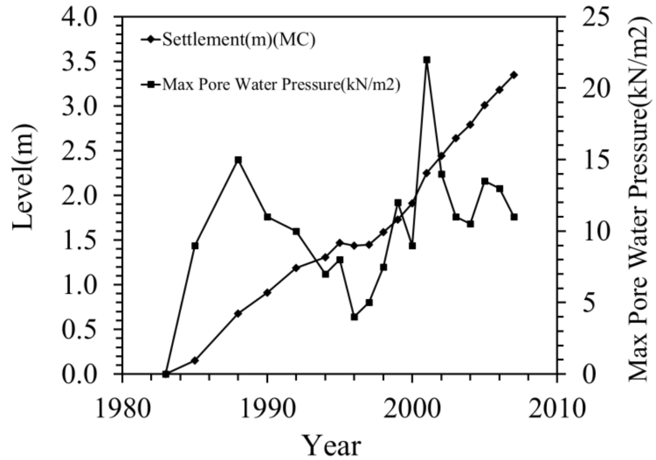

Figure 4: Soil surface subsidence and maximum pore water pressure in soil media according to the analysis of Kalate Barfi piezometer's (H) annual data, using primary Mohr-Coulomb model.

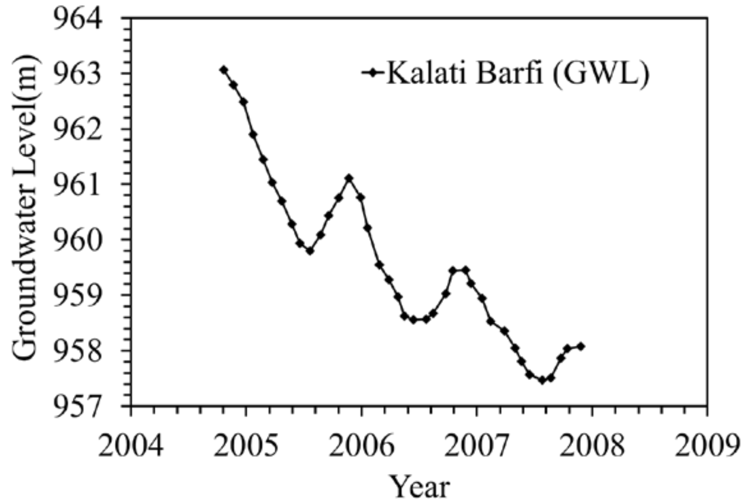

Figure 5: Monthly average water level in Kalate Barfi piezometer (H) from 2005 to 2008 [21].

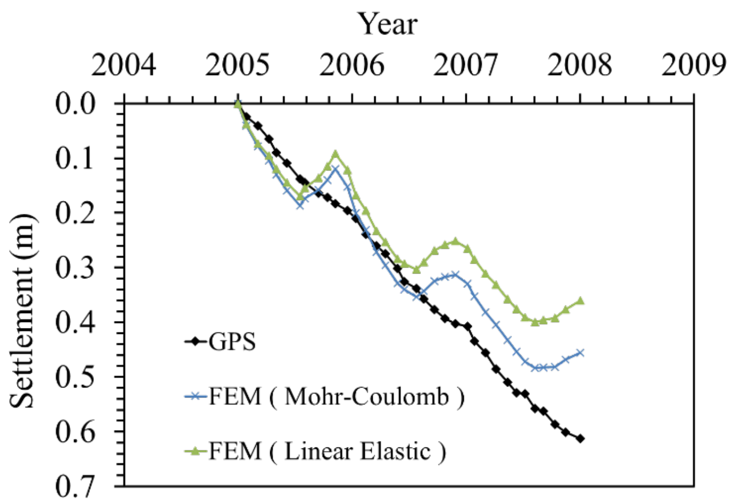

Figure 6: Comparing the subsidence value obtained from the primary model and the observations (GPS) between 2005 and 2007.

As it is expected and shown fairly well in figure 6, the Mohr-Coulomb elastoplastic model gives better subsidence value results compared to the linear elastic model. In the Mohr-Coulomb model, the maximum absolute error and the average absolute error are 0.13 and 0.04 respectively, while in the linear elastic model these numbers are 0.2 and 0.07 respectively. Comparing the line's slope in the elasto-plastic model with the GPS observed data in annual loading mode (between the first and the seventh month) as a result of groundwater level drop, we can conclude that the model gives a good estimation of the loading behavior but in the unloading mode (between the seventh and the twelfth month), the model calculates the return-to-surface values excessively which is one of the biggest weaknesses of elastoplastic models based on the Mohr-Coulomb criterion.

Recursive Analysis

Recursive Analysis

Due to the uncertainties of soil parameters, we can correct the model using recursive analysis and field observations. This method helps to make the subsidence value estimation in the future and the past closer to reality. There are many ways to do a recursive analysis and most of them correct model parameters automatically and like a chain. In the provided model, recursive analysis is done manually by trial and error and with the help of plotting subsidence against time and comparing it to Tous GPS station's observations, lowering error. Table 2 shows the values obtained from recursive analysis. In figure 7 subsidence value obtained from recursive analysis is provided which has a good correlation with field observations (Tous GPS station), in the corrected Mohr-Coulomb model, maximum absolute error and average absolute error are 0.09 and 0.03 respectively.

Using the corrected model we can calculate total subsidence from the start of piezometer readings up until now. In this way, the corrected total subsidence in the 25 years between 1983 and 2008 was calculated as 4.46 meters (figure 8) which equals 18 centimeters of subsidence per year. Therefore we can say that in the Mashhad aquifer every 1 meter water level drop causes 12 centimeters of subsidence. This amount of subsidence due to a meter of water level drop in the aquifer checks out with field measurements. Subsidence value prediction for the next 22 years (2008 to 2030), assuming constant annual groundwater level drop (1.5 meters per year) is shown in figure 9. According to the provided model's prediction, there would be about 2.4 meters of subsidence between 2008 and 2030. Therefore total subsidence from 1983 to 2030 is predicted as 6.86 meters.

Table 2: Soil parameters obtained from the recursive analysis

Layer	Soil Type	Depth (m)	Elasticity modulus (kPa)	Poisson ratio	Permeability (m/s)	Angle of internal friction	Cohesion (kPa)
1	Fine	0-102	5500	0.20	2.32 × 10-8	1	12
2	Coarse	102-300	25000	0.25	1.11 × 10-6	25	1

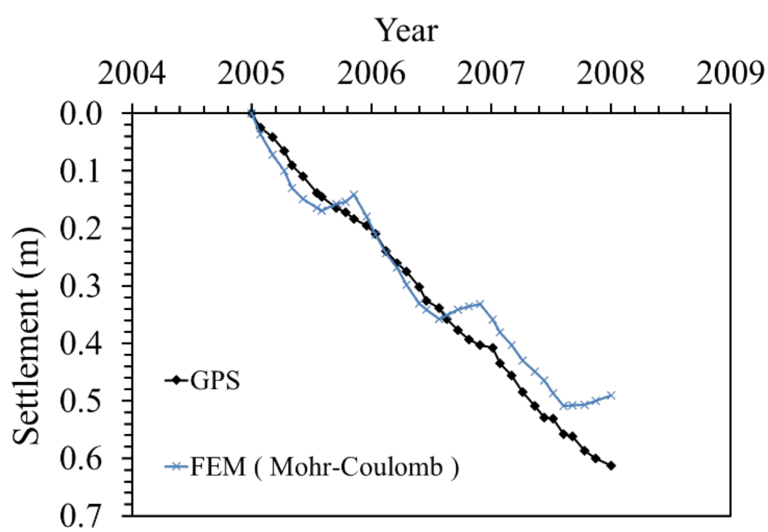

Figure 2: Correcting Mohr-Coulomb model using recursive analysis

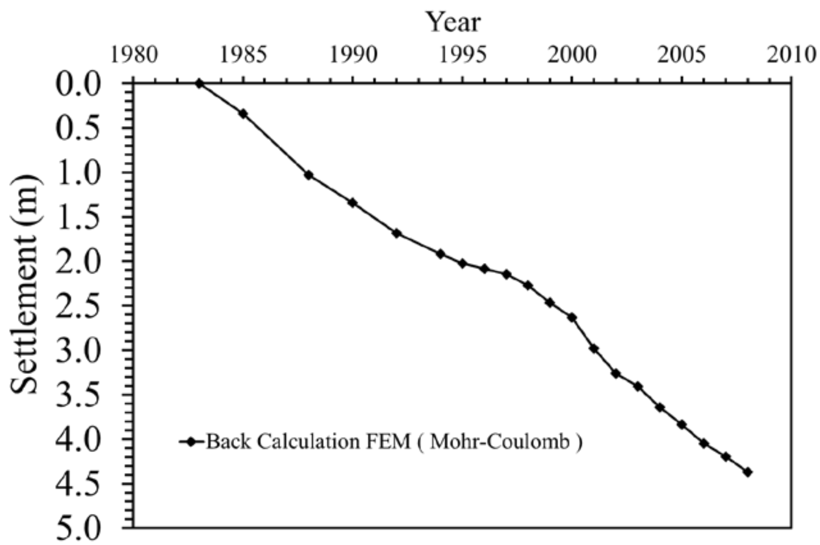

Figure 3: Estimating subsidence using the corrected model for a 25 years period of 1983 to 2008

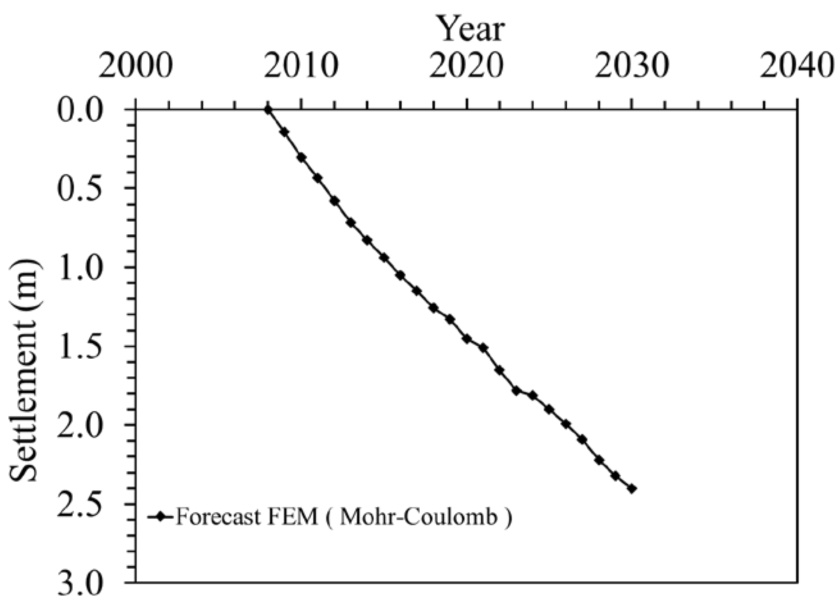

Figure 4: Predicting subsidence for the next ten years (2008 to 2030) assuming annual groundwater level drop of 1.5 meters using the corrected model.

DISCUSSION AND CONCLUSION

Ground subsidence is a gradual or sudden subsidence of earth's surface due to the movement of material beneath it. This phenomenon mainly happens due to different water-related procedures. In this study GPS data from 2005 to 2009 of the Mashhad plain was used. Tous GPS station located at 8 kilometers northwest of city of Mashhad shows a subsidence of more than 20 centimeters per year. In other studies using satellite data (InSAR) a subsidence of 28 to 30 centimeters per year has been reported in some areas of the Mashhad plain, making it have one of the highest rates of subsidence in the world. Unfortunately, satellite data was not available to Khorasan Razavi’s cartographic center and this study.

Ground subsidence has been reported in more than 150 cities in the world, with the central valley of northwest Mendota in America having the highest subsidence, with 8.80 meters from 1925 to 1997. Other countries that face subsidence in some of their cities include Spain, Italy, Thailand, China, Japan, Mexico and Greece. Water utilization management is the most important action done by these countries in order to fight subsidence. In order to reach this goal, different subsidence and piezometric level change in the aquifer measurement methods have been innovated and using these measurements, different models have been provided to analyze their behavior and offer a good solution.

Among famous soil models, there are Mohr-Coulomb model, hardening model and softening model, each of them having a usage of their own. In this study, we used the Mohr-Coulomb model. Even though the hardening model or the hyperbolic model are more able in explaining the studied behavior, we don’t have the desired parameters for these models or more complex models. Finite element numerical method is a very versatile, accurate and organized tool in solving complex differential equations. Finite element method can provide results that are very close to reality. Considering the analysis in this study we can say that the provided model for elastic stress-strain behavior (dry soil element) fully matches the closed form solution and the model results are very close to simulations too. Moreover, the comparison between the elastic 1D consolidation model and elastic 3D consolidation shows that 1D consolidation estimates pore water pressure higher, which could be due to simplifications Terzaghi has done to his equations.

After studying different boundary conditions in the 3D consolidation equations based on the elastic porous media theory it was known that drainage subsidence is the limit for consolidation subsidence for the consolidated layer. This theory also considers pore water pressure in soil mass during loading and pore water suction during unloading, which causes the subsidence done during the load to disappear after unloading and doesn’t consider a lasting subsidence in the soil mass. Studies done in the Mashhad plain has shown that this aquifer is of the unlimited type which has different soil layers with different permeability. So far no layer has been identified that works as a complete limiter. The alluvium accumulated in this aquifer is of river alluvium type. In general, groundwater flows from northwest to southeast, which is a function of the plain’s general slope. By studying soil patterns around the city of Mashhad it was determined that generally, the rate of change in soil patterns is a function of factors such as rainfall, change in streams’ direction, and tectonic factors that cause subsidence or upheaval in sedimentary basins. Generally, layers on the ground surface have finer patterns and deeper layers have coarser patterns.

Assessing the engineering properties of fine-grained soil in the Mashhad plain showed that clay in this area is mainly of the low-plasticity kind. Density of fine-grained silt-clay soil ranges from 1.5 to 1.8 grams per square centimeters. Also studying coarse-grained sandy soil shows that the density of coarse-grained soil ranges from 1.7 to 2.0 grams per square centimeters, and as expected as we go deeper and the soil becomes more compressed, soil density increases. According to the model results, for every meter of water level drop in the aquifer there is a subsidence of 8 centimeters. Also, the total subsidence in the last 25 years from 1983 to 2008 equals 4.46 meters and assuming constant annual groundwater level drop (1.5 meters per year) a subsidence as big as 240 centimeters has been estimated for the next 22 years. Comparing calculation results and observations between 2005 and 2008 we can conclude that the model gives a good estimation of subsidence behavior in the studied area. To have more accurate estimations, more accurate models like hyperbolic elastoplastic models will give a good performance because these models permit us to choose loading and unloading properties separately. But one should note that more complicated models need more parameters that should be carefully obtained from experiments and field studies. Also by obtaining more information about the subsidence process in the past, we can predict future subsidence better.

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