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Finite Element Analysis of Land Subsidence: A Case Study

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Abstract

In this paper, land subsidence which is caused by groundwater level drop in the Qazvin Plaine, has been investigated. Initially, subsidence was simulated by numerical analysis methods such as the finite element method using the PLAXIS geotechnical software. Numerical simulations were modelled based on hydrogeological information and groundwater level changes provided by the Iran Water Resources Basic Studies Office and geotechnical information obtained from the Geological Survey of Iran. The results were compared with satellite images. Then the subsidence rate in the forthcoming years was predicted according to different scenarios of water level changes over a ten-year period.

Keywords: land subsidence, groundwater level changes, Qazvin Plain, finite element method

1 Introduction

One of the biggest risks threatening Qazvin province is subsidence and sinkhole. In recent years, agricultural development along with population growth, has led to uncontrolled abstraction of groundwater resources and a sharp drop of groundwater levels, which caused Subsidence by making ground cracks and fissures. Subsidence is higher in areas where there are more deep wells made for groundwater abstraction to achieve different purposes. These areas include Buein Zahra, Danesfahan, Shal and Takestan.

Land subsidence is one of the consequences of long-term use of groundwater [1] which causes negative effects such as the destruction of highways [2] airport runways [3] structural and fundamental underground damages such as irrigation and drainage networks [4] reduction of storage coefficient of aquifers [5] alteration in morphology of the earth's surface and emergence of land fissures and mixture of fresh water with salt water [6]. These risks are remarkably affecting Qazvin plain. The area affected by subsidence in Qazvin plain with a maximum rate of 17 (cm) is 2410 (Km^2) and has put 87,900 people at risk of subsidence [7]. Due to the prevalence of this phenomenon in the country and the resulting damage, the study of land subsidence requires more concentration and needs to create more control mechanisms and alarm simulators.

To achieve the fore mentioned goals, several data are needed including hydrogeological information such as the amount of annual rainfall in the area, groundwater recharge and rate of water withdrawal. Furthermore, to provide the possibility for simulate and predict hazards, geological engineering data in subsidence-prone area are needed including the quality and thickness of different layers of soil structure and the depth of bedrock in Qazvin plain.

Then, using different numerical modeling methods, we can stimulate subsidence phenomenon based on conceivable changes in the groundwater level over a period of 10 years (2018 to 2028) or any other desired period.

1.1 Subsidence Mechanism

Underground bases disappear slowly over long periods of time and has variety of factors. Generally, one of the most important factors is the presence of fine-grained sediments [8] in aquifers adjoining sand layers [9] which are under influence of groundwater levels [10]. After excessive groundwater abstractions, decrease in hydraulic pressure between the soil grains causes irreversible compaction in the soil layers in areas that have a thick layer of compactable fine-grained aggregates and these areas will be exposed to subsidence. Therefore, over-abstraction of groundwater in aquifer can be considered as a stimulus to land subsidence [11].

Figure 1: Cracks and gaps in Buein Zahra village [7].

1.2 Geographical location

Qazvin plain is in center of Iran and it covers 15,623 (Km^2) 48¬44′ to 50¬51′ east of Greenwich meridian of longitude and 35¬24′ to 36¬48′ north latitude of the equator. The central and eastern part of the province consist of plains, slope of which extends from northwest to southeast and is 1130 (m) at the lowest point. The lowest altitude is located in the northwest and in the section of Taromsofla and the shores of Sefidrood Lake with an altitude of 300 (m) above sea level [7].

The geographical position of Qazvin plain and the subsidence-prone area in Buin Zahra are presented in Figure (2) and the geological profile of Qazvin plain is presented in Figure (3).

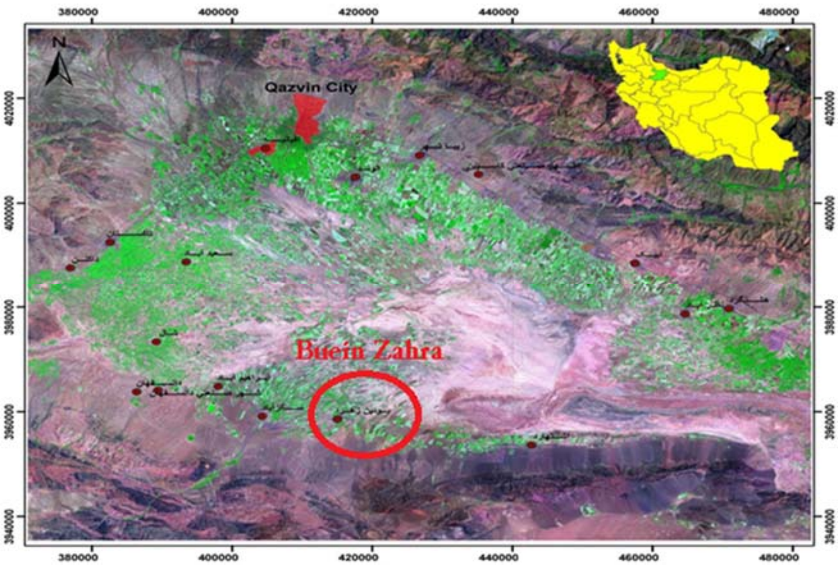

Figure 2: Geographical location of Qazvin plain On the satellite image [7].

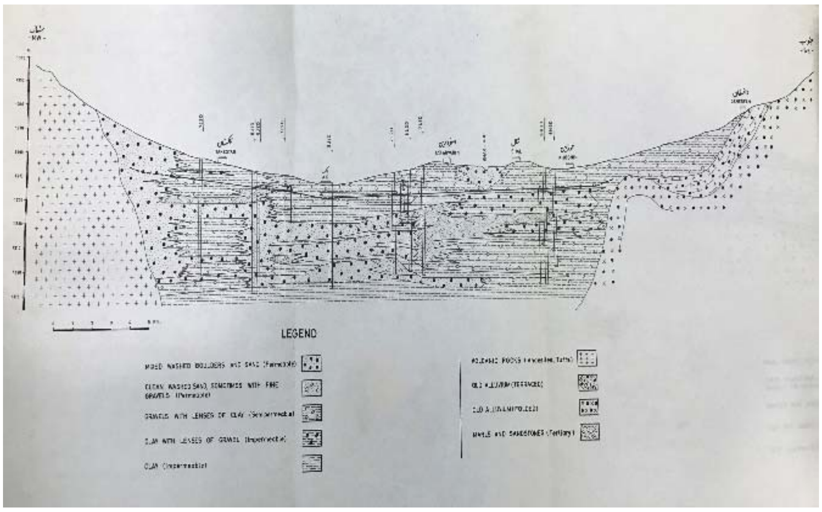

Figure 3: Geological profile of the structure of Qazvin plain formation [7].

To analyse the current rate of land subsidence and forecast subsidence in the future years, Buein Zahra area, position of which is specified in Figure (2), was examined. Due to the lack of geotechnical information obtained from deep boreholes in the area, a borehole with a depth of 100 (m) was considered as a basis for studying and simulating subsidence. The borehole information is gathered through a research done by the Geological Survey of Iran. Results of analysing this borehole and the relevant geotechnical properties are presented in Table (1).

Depth (m)	E (KPa)	C (KPa)	Φ (°)	γ_{dry} ($\frac{KN}{m^3}$)	γ_{sat} ($\frac{KN}{m^3}$)	υ	K ($\frac{m}{s}$)
0-14	19500	221.5	31	16.3	20.6	0.3	10^{-5}
14-25	11671	165.7	25.2	15.8	19.4	0.25	10^{-5}
25-29	17300	193	27.6	12.8	18.5	0.3	10^{-6}
29-33	24950	3280	28.1	13.4	17.3	0.35	10^{-6}
33-37	12200	2050	25	12.6	18.7	0.3	10^{-6}
37-51	17100	2496	26.6	15.3	18.2	0.3	10^{-5}
51-62	17077	2133	22	15.9	17.2	0.25	10^{-7}
62-100	15100	218.6	20.3	13.2	18.6	0.25	10^{-7}

Table 1: Geotechnical properties of borehole

1.3 Hydrogeological information

1.3.1 Seasonal rivers

The surface water of this province mainly flows through two drainage basins. The northern drainage basin (Sefidrood) and the southern drainage basin (shoor). In northern drainage basin (Sefidrood), the water flows into Taleghanrood and Alamutrood rivers, which create Shahroud in the city of Lushan. Southern drainage basin (Shoor) includes Haji Arab, Khorrood and Abharrood rivers and small rivers on southern slopes of Alborz. Haji Arab river originates from the southern mountains (eastern Kharqan) and flows seasonally.

The drainage basin covers 9,376 (Km^2), 3,842 (Km) of which is covered by plains and swamps. North of this area adjoins Shahroud drainage basin , west of this area adjoins Abharrood and Kharrood drainage basins , south of this area adjoins Shoorchai, Qarabolagh Lar and Qarachai rivers and west of this area adjoins Kordan and Karaj rivers [7].

1.3.2 Rainfall

The average annual rainfall in the province varies from 210 (mm) in the eastern parts to more than 550 (mm) in the northeastern heights. The rainiest parts of the province are the northeastern slopes in Alamut region with more than 550 (mm) rainfall. This amount is more or less visible in northern highlands of Qazvin. Furthermore, in the southwestern heights of the province, three are areas with more than 450 (mm) annual rainfall [7].

The driest areas of the province, starting from the southeast of the province and the waste places of Buin Zahra extending to the southern parts of Takestan, receive 210 to 230 (mm) annual rainfall. Also, in the northwestern regions of the province, rainfall exhibits a tendency to reduce due to the decrease in altitude, as far as it reaches 210 (mm) in Lushan and Manjil areas outside the province.The distribution map of Qazvin plain's water resources is shown in Figure (4).

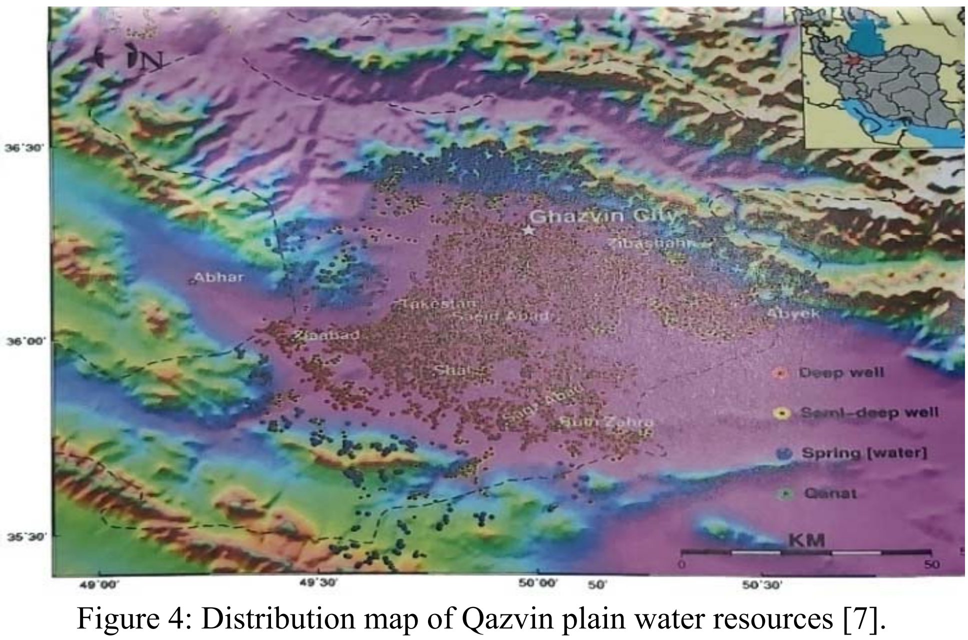

Figure 4: Distribution map of Qazvin plain water resources [7].

1.3.3 Groundwater level changes

Annual fluctuations in groundwater levels in the aquifer of the research area are affected by annual feeding and discharge values. Due to the effect of these two factors, the groundwater level is decreased or increased during the time. This is not the same in different areas of the plain because of the differences in the permeability of the layers and different exploits. Groundwater level changes have been recorded by Qazvin Regional Water Organization, using observation and piezometric wells from 2002 to 2018, and the results have been published by the Office of Basic Studies of Water Resources of Iran. The hydrograph of groundwater level changes is drawn in Figure (5).

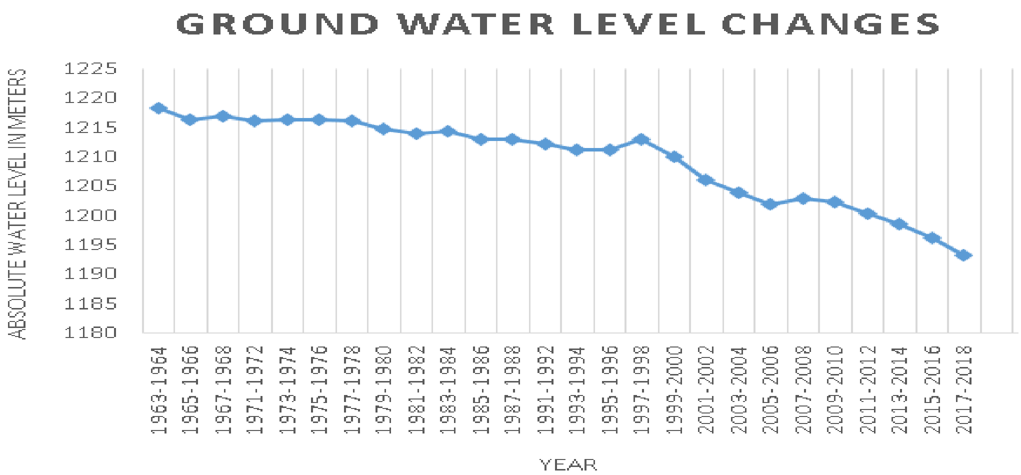

Figure 5: Groundwater level changes in Qazvin plain.

Using these results, hydrographs and water level changes in the intended area were drawn. With regard to the hydrological situation of this area and the way surface water of Qazvin plain is discharged and also the direction of groundwater flow, it is observed that the amount of water intake is very low compared with the discharged water in this area. Therefore, the decrease in water level shown in the area is due to this issue.

1.3 Subsidence values in Qazvin Plain

The National Mapping Organization has evaluated the annual subsidence rate map which is made using radar interference measurement method with high spatial resolution and wide coverage, and integrating its results with numbers obtained from ground levelling stations. The rate of subsidence which is estimated observing the satellite images is shown in Figure (6).

According to the achieved results, the highest land subsidence rate in Qazvin plain belongs to Buein Zahra, Esmatabad, Jovin village, Hyder Abad and the northeastern part of Qazvin plain. Based on these results, the rate of land subsidence in Qazvin plain is 3 - 5 (cm) at minimum and in some areas of the plain reaches 20 - 23 (cm) per year. The estimated rate of land subsidence in Buin Zahra is 7 - 10 (cm) per year.

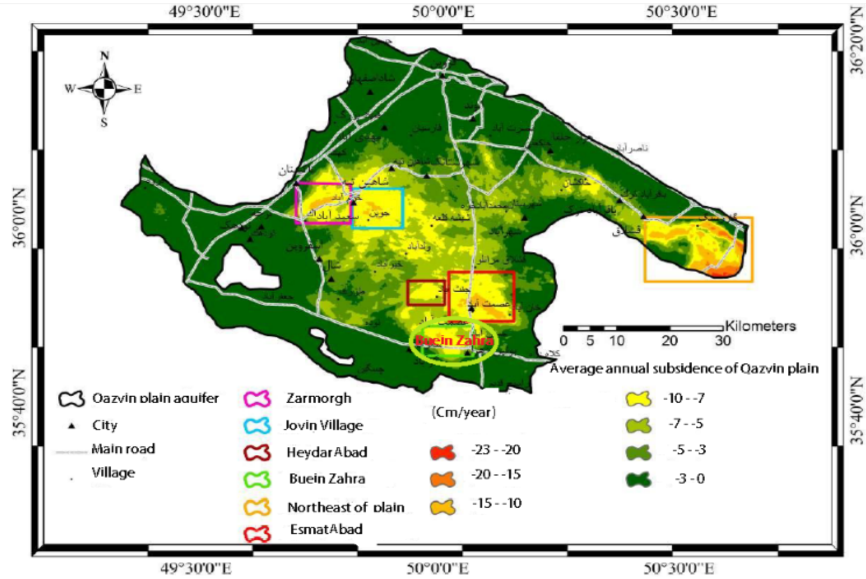

Figure 6: Land subsidence map in Qazvin plain [7].

2 Methods and Results

2.1 Model Description

2.2

In this study, subsidence zones stimulated using finite elements software (PLAXIS) considering the two-dimensional geometry in the plane strain mode. Detection of different soil layers and their thickness in software is provided by separating their colours from each other. At the beginning of modelling, the initial water level is applied and we solve the model to reach equilibrium. After this step, we reset all the settlements in the model elements to zero and then change the groundwater level and solve the model again.

It was observed that when the water level is decreased, the results of simulation shows soil surface subsidence; and at intervals when the water level is increased, the results of simulation end with swelling soils. The swelling rate is about 30% of the subsidence rate with that very water level changes. Therefore, with regard to this issue, subsidence modelling was performed at one-year intervals using the average groundwater level of each year.

This process was done to make the modelling subsidence results and the actual subsidence in each year equal, and at last, the final amount of subsidence was obtained from summing the total subsidence numbers. Given that reduction in aquifer storage coefficient is one of the irreparable damages caused by subsidence [9], we overlook the results of time periods, numerical analysis of which shows soil inflation.

It is worth noting that the behavioural model selected for the soil is the Mohr-Columbus model and the lateral boundary conditions in the modelling were defined in a standard way (displacement in the y direction is allowed and displacement in the x direction is not allowed).

2.3 Simulation in PLAXIS software

2.4

The initial geometry, boundary conditions and the shape of mesh in PLAXIS software are shown in Figure (7), and the deformed geometry of the soil structure caused by the drop in groundwater level is shown in Figure (8).

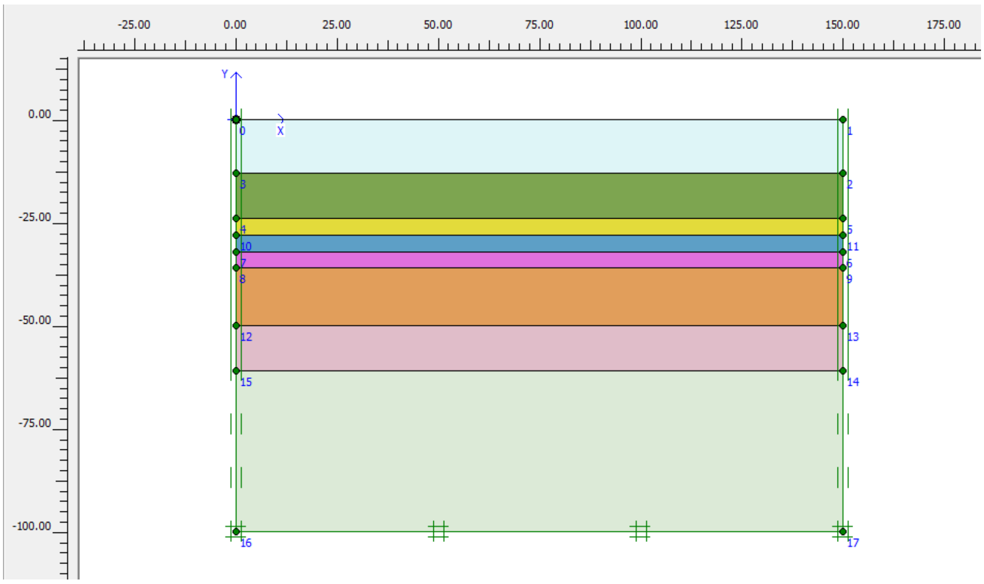

Figure 7: Initial geometry of the model of Buein Zahra area in PLAXIS software.

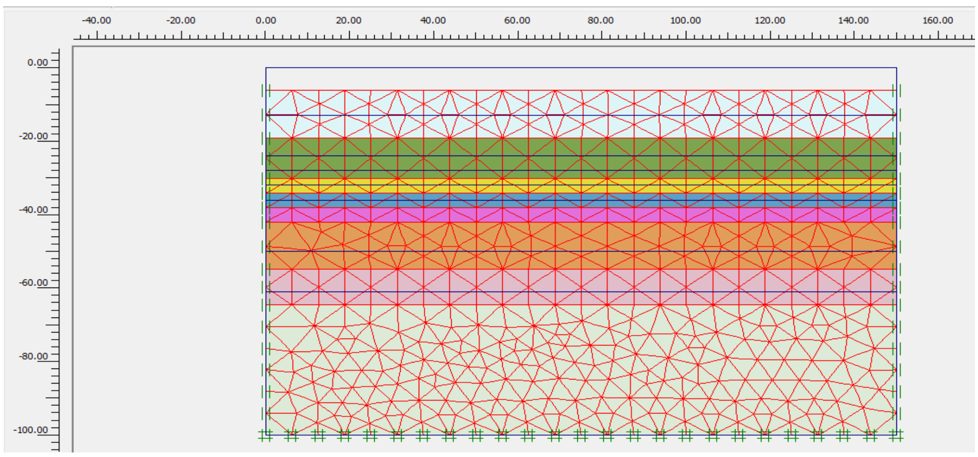

Figure 8: Geometry of the transformed model of Buein Zahra area caused by the decrease in groundwater level in PLAXIS software.

Therefore, we used stimulation to predict the amount of subsidence in future years in the subsidence-prone area. With regard to being uncertain about the amount of groundwater changes in the future years, three different scenarios have been used to predict future land subsidence rates:

- Scenario A: drop of groundwater level is half that of the previous years.
- Scenario B: groundwater level is declined as much as the previous years.
- Scenario C: the drop of groundwater level is twice as much as the previous years.

The obtained result from the above three scenarios are presented in Table (2).

Zone	Comparison of predicted subsidence rates from 2018 to 2028 (cm)		
	PLAXIS		
Buein Zahra	C	B	A
	83.6	40.8	21.9

Table 2: Comparison of predicted subsidence rates obtained from PLAXIS software.

3 Conclusions

The obtained results from numerical modelling by PLAXIS software and comparing their results with satellite images over a period of 10 years are presented in Table (3).

Zone	Comparison of subsidence rate caused by groundwater level drop over 10 years (cm)	
	Satellite Images	PLAXIS
Buein Zahra	70 - 100	40.8

Table 3: Comparison of predicted subsidence rates

The results of numerical modelling obtained from PLAXIS software shows the drop of groundwater level has a direct and significant effect on land subsidence. Furthermore, use of finite elements method in numerical analysis has shown different but close results. This insignificant difference is as a result of differences of methods between the shapes and size of mesh and the type of elements and force transfer. By comparing the obtained subsidence values, it can claim that the results of numerical modelling are in conformity with the results of satellite images. Besides, by comparing the numbers in the table above, it can be claimed that the average drop of groundwater level in recent years in Qazvin plain has increased and consequently the resulting subsidence has intensified. Due to the lack of accurate and up-to-date information on the groundwater level reduction rate and calculation of the actual subsidence rate which is obtained from the analysis of satellite images, and many risks that have arisen in the study areas because of land subsidence, we need an intelligent system which monitors groundwater levels and subsidence and also enables us to analyse and provide accurate information with an extensive coverage more than ever. Also it is possible to numerically model and predict the future status of groundwater levels and land subsidence using up-to-date information of this system.

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