LAND SUBSIDENCE MODELING DUE TO GROUND WATER DRAINAGE USING "WTAQ" SOFTWARE

KAVEH KUMARCI
Sama Organization (Affiliated With Islamic Azad University), Shahr-e-Kord Branch
IRAN
KUMARCIKAVEH@YAHOO.COM

ARASH ZIAIE
Civil Engineering Department
University of Kerman
22th of Bahman Ave, Kerman University, Kerman
IRAN
ZIAIE111@YAHOO.COM

ARASH KYIOUMARSI
Electric Engineering Department
University of Isfahan
Hezar Jerib Ave., Isfahan University, Isfahan
IRAN
KIUMARSI_AR@YAHOO.COM

Abstract: - Subsidence is settling of the earth's surface because of different factors. Ground movements, mining activities, gas, oil and water, withdrawal are some examples that can causes ground subsidence. In recent years it has been proven that in dry areas because of extensive ground water withdrawal, the rate of subsidence increases rapidly (more than 10 centimeters in a year). A decrease in ground water level will causes an increase in effective stresses at clay layers which results consolidation of lower layers. The behavior can be modeled using finite element technique to predict the future settlement. In this paper the relationship between classical soil parameters and parameters used in numerical is driven for a single well water table lowering. It is possible to approximate the model by assuming elastic time dependent behavior due to decrease in water table level that calculates with a computer software that's name is 'WTAQ'' (Water Table Aquifer). For this purpose specialized finite element model was established and related to classical soil mechanics consolidation parameters. In this research subsidence of different lands in Sirjan and also Shahrekord are compared.

Key-Words: - Subsidence- Finite Element- Single Well- WTAQ- Ground Water- Drainage

1 Introduction

Excessive ground water withdrawal, especially in unconsolidated clays can cause land subsidence and earth fissures. In recent decades land subsidence because of its destructive results such as differential settlement and earth fissures in many part of the world, such as desert areas like Kerman province and some other parts of the world become a major consideration.

Earth fissures and subsidence around a single pumping well of Sirjan land in Kerman province are shown respectively in figure 1and figure2.

The considered land subsidence in this research is mainly due to excessive ground water withdrawal.

So because the natural water table level is one of the important factors of the amount of the related subsidence, due to the relation between water table decline around the well and also the effective stress at soil layers and the vertical shrinkage which causes land surface consolidation and subsidence.

So in some areas with larger amount of rainfall and higher level of ground water land subsidence value and rate is so smaller than first desert type one with the lower level of ground water. The results of this investigation, which are presented later, for compairing the two mentioned aquifers confirm this matter.

The other important factors in this filed are soil properties.
In this paper land subsidence of two different areas are obtained, considering the ground water level and also the soil properties of these two areas, and then the results of these two areas are compared with each other.

Fig.1. earth fissures caused by differential settlement of Sirjan land

It has been conformed that land subsidence due to consolidation of soil layers, caused by extensive groundwater withdrawal for agriculture development will tend to huge damages in future.
A semi-complete field investigation was first undertaken by Rahmanian about the land subsidence and the related decrease in ground water drainage in one of the desert provinces of Iran (Kerman)[1, 2,3].

Fig.2. earth fissures caused by differential settlement of Sirjan land

Fig.3.Subsidence around a pumping well in Sirjan

His results shows that subsidence and earth fissures were related only to heavy pumping of the ground water and subsequent continued decline in the water table.Later this investigation was continued by Toufigh and Shafeiei [3, 4].
They provide a prediction model in order to simulate the future settlement. A single well under

operation was modeled based on finite element formulation by Toufigh [5].Also Prediction of Single Well Land Subsidence due to ground water drainage, is another effort which is done by Ziaie. Et al. [10].
Sroka, Et al. has another prediction of geometrical changes on the surface and in the rock mass for deep extraction of solid, liquid and gaseous minerals [11].
A case study also is expressed by Sun. H., et al. as, land subsidence due to groundwater withdrawal: potential damage of subsidence and sea level rise in southern New Jersey, USA, [12] and also by Wolkersdorfer., Ch, et al., as ground water withdrawal and land subsidence in northeastern Saxony ,Germaney[13].
The study of Papaioannou, A., et al. about the soil and ground water and hydrogeological profile of Drama's prefecture in north Greece, is also another kind of study and predict of the effect of ground water in this area [14] and also the two other recent studies of Ehret et al. and Tsang et al. are another useful efforts in this filed for modeling of site effects of groundwater level changes [15], and also theoretical formulae for estimating of these kinds of site effects [16].
In this study water level decline will be determine by a computer program (WTAQ). This software, which is based on Theis's theory and the assumption of continunity of flid flow and also governing of the equilibrium equations, shows the water level around a single well using a numerical method in base and analyzing the aquifers data, applying the soil properties and boundary conditions.
In order to simulate and predict the subsidence in a given single well, the authors developed an axisymmetric fully coupled finite element model, to show that it is possible to obtain satisfactory results. The related results for two different aquifer of Sirjan and Shahrekord are obtained and compaired in this study.
Formulation of finite element was based on Biot's three-dimensional consolidation theory [9].
As excess effective stress due to water withdrawal in whole scale is small, behavior of soil skeleton was assumed to be elastic, but it should be noted that pore water pressure variation is still function of time, depth and other properties and boundary conditions.

2 PROBLEM FORMULATION

The basic formulation presented here is based on Biot's consolidation theory. In the theory of Biot the soil skeleton treated as a porous elastic solid and the laminar pore fluid are coupled by the conditions of compressibility and of continuity.
In the computations cylindrical coordinates were assumed, and when water is pumped out from the aquifer through wells, both radial and axial flow can take place, which are symmetric.
In order to simulate this condition by finite element the exact behaviour should be achieved by actual mathematical equations [6, 7].
For each reason Biot's governing equation was selected; which is:

$$C_r\left(\frac{\partial^2 u_e}{\partial r^2}+\frac{1}{r}\frac{\partial u_e}{\partial r}\right)+C_z\frac{\partial^2 u_e}{\partial z^2}=\frac{\partial u_e}{\partial t}-\frac{\partial P}{\partial t} \quad (1)$$

Where u_e=excess pore water pressure,
P= mean total stress,
z and r = axial and radial directions,
t = time,
and C_r, C_z= coefficient of consolidation in radial and axial directions, respectively.
The equilibrium equation with assumption of zero volumetric force can be written as follows:

$$\begin{aligned}\frac{\partial \sigma'_r}{\partial r}+\frac{\partial \tau_{rz}}{\partial z}+\frac{\partial u_e}{\partial r}=0\\ \frac{\partial \tau_{rz}}{\partial r}+\frac{\partial \sigma'_z}{\partial z}+\frac{\partial u_e}{\partial z}=0\end{aligned} \quad (2)$$

The stress-strain relations for such condition can be written as follows:

$$\begin{Bmatrix}\sigma'_r\\ \sigma'_z\\ \tau_{rz}\\ \sigma'_\theta\end{Bmatrix}=\frac{E(1-\upsilon)}{(1-\upsilon)(1-2\upsilon)}\times$$

$$\begin{bmatrix}1 & \frac{\upsilon}{1-\upsilon} & 0 & \frac{\upsilon}{1-\upsilon}\\ \frac{\upsilon}{1-\upsilon} & 1 & 0 & \frac{\upsilon}{1-\upsilon}\\ 0 & 0 & \frac{1-2\upsilon}{2(1-\upsilon)} & 0\\ \frac{\upsilon}{1-\upsilon} & \frac{\upsilon}{1-\upsilon} & 0 & 1\end{bmatrix}\begin{Bmatrix}\varepsilon_r\\ \varepsilon_z\\ \gamma_{rz}\\ \varepsilon_\theta\end{Bmatrix} \quad (3)$$

where E = modules of elasticity,
υ = Poisson's ratio,
σ' = effective stress,
ε = strain, and

$$\begin{Bmatrix} q_r \\ q_z \end{Bmatrix} = \frac{1}{\gamma_w}\begin{bmatrix} K_r & 0 \\ 0 & K_z \end{bmatrix}\begin{Bmatrix} \frac{\partial u_e}{\partial r} \\ \frac{\partial u_e}{\partial z} \end{Bmatrix} \quad (4)$$

where $q_r, q_z =$ volumetric flow rates per unit area into and out of the element,
and $K_r, K_z =$ Coefficient of permeability in redial and axial directions, respectively.
For fully saturated soil and incompressible fluid condition, outflow from an element of soil equals the reduction in volume of element. Hence:

$$\frac{\partial q_r}{\partial r} + \frac{\partial q_z}{\partial z} = \frac{d}{dt}\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z}\right) \quad (5)$$

Where u and v = displacements in r and z directions, respectively.
Combining Equations (4) and (5):

$$\frac{K_r}{\gamma_w}\frac{\partial^2 u_e}{\partial r^2} + \frac{K_z}{\gamma_w}\frac{\partial^2 u_e}{\partial z^2} + \frac{d}{dt}\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z}\right) = 0 \quad (6)$$

As usual in a displacement method σ, ε are eliminated in terms of u, v so that the final coupled variables are u, v, u_e.
These are now discretized in the normal way:

$$u = Nu \\ v = Nv \\ u_e = Nu_e \quad (7)$$

where N is the vector of shape function.
When discretization and the Galerkin process are completed, Equations 2 and 6 lead to the pair of equilibrium and continuity equations, which are:

$$KM_r + Cu_e = F \\ C^T \frac{dr}{dt} - KPu_e = 0 \quad (8)$$

where, for a four-nodded element,

$$r = \{u_1,\ v_1,\ u_2,\ v_2,\ u_3,\ v_3,\ u_4,\ v_4\}^T \\ u_e = \{u_{e1},\ u_{e2},\ u_{e3},\ u_{e4}\}^T \quad (9)$$

KM is the elastic stiffness matrix and is

$$KM = \iint B^T DBrdrdz \quad (10)$$

where, B = AN,
N = vector of shape function, and

$$A = \begin{Bmatrix} \frac{\partial}{\partial r} & 0 \\ 0 & \frac{\partial}{\partial r} \\ \frac{\partial}{\partial z} & \frac{\partial}{\partial r} \\ \frac{1}{r} & 0 \end{Bmatrix} \quad (11)$$

KP is the fluid stiffness matrix ;

$$KP = \iint\left(C_r \frac{\partial N_i}{\partial r}\frac{\partial N_j}{\partial r} + C_z \frac{\partial N_i}{\partial z}\frac{\partial N_j}{\partial z}\right) rdrdz \quad (12)$$

C is a rectangular coupling matrix, can be written as follows:

$$C = \iint N_i \frac{\partial N_j}{\partial r} drdz \quad (13)$$

and F is the external loading vector.

Equation 8 could be integrated in time.To integrate equation 8 with respect to time, there are many methods available. But we consider only the simplest linear interpolation in time using finite difference.
Thus:

$$\begin{aligned}\theta KMr_1+\theta Cu_{e1}&=(\theta-1)KMr_0+(\theta-1)Cu_{e0}+F\\ \theta C^T r_1-\theta^2\Delta tKPu_{e1}&=\theta C^T r_0-\theta(\theta-1)\Delta tKPu_{e0}\end{aligned} \quad (14)$$

In above equations, if $\theta \geq 0.5$, the system will be stable without any condition, in the Crank-Nicolson type of approximation, θ is made equal to 0.5, or in the Galerkin approximation θ is equal to 0.67.
By using θ = 0.5 in Crank-Nicolson method, Equation 14 can be written as follows:

$$\begin{bmatrix} KM & C \\ C^T & -\dfrac{\Delta t}{2}KP \end{bmatrix}\begin{bmatrix} r_{n+1} \\ u_{e_{n+1}} \end{bmatrix}=\begin{bmatrix} -KM & -C \\ C^T & \dfrac{\Delta t}{2}KP \end{bmatrix}\begin{bmatrix} r_n \\ u_{e_n} \end{bmatrix}+\begin{bmatrix} 2F \\ 0 \end{bmatrix} \quad (15)$$

Therefore values of unknown can be calculated at time $t = t_{n+1}$ based on known parameters at time $t = t_n$.. For initial conditions at time $t = 0$ all values are known.
After finding governing matrix equations for a single element, the assembled matrices for total elements can be obtained and boundary conditions can be introduced.
Solving such equations at any time, horizontal and vertical deformations (u, v) at various nodal points can be found and strain values for each element can be calculated.
The equivalent external load due to water table decline can be computed from figure 4 which shows the Sirjan aquifer properties. Also for Shahrekord aquifer the related properties are given in figure 5.

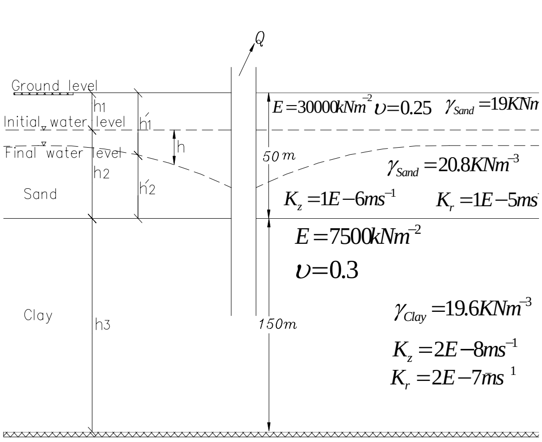

Fig.4 Declined Water Level and Sirjan Aquifer Soil Profile

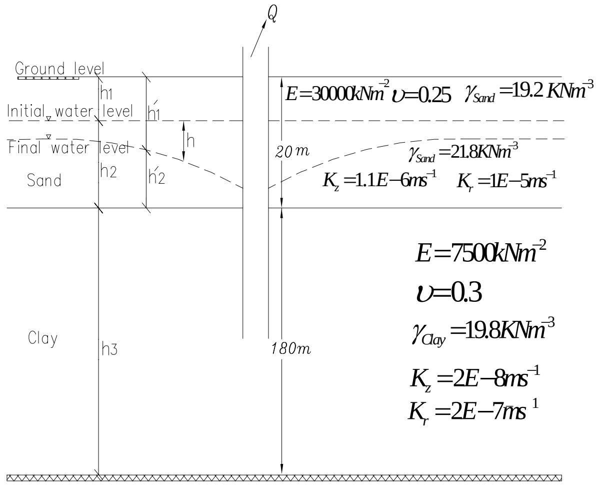

Fig.5 Shahrekord Aquifer Soil Profile

If water table drops equal to h, then:

$$\begin{aligned}&h=h_1'-h_1=h_2-h_2'\\ &\sigma_{v0}'=\gamma_{sand}h_1'+(\gamma_{sat}-\gamma_w)h_2\\ &\sigma_{v1}'=\gamma_{sand}h_1'+(\gamma_{sat}-\gamma_w)h_2'\\ &\sigma_{v1}'=\gamma_{sand}(h_1+h_1')+(\gamma_{sat}-\gamma_w)(h_2-h_1)\\ &\Delta\sigma_v'=\sigma_{v1}'-\sigma_{v0}'=[\gamma_{sat}-(\gamma_{sat}-\gamma_w)]h\end{aligned} \quad (16)$$

where $\sigma_{v0}' =$ initial vertical effective stress,
$\sigma_{v1}' =$ final vertical effective stress, and
$\Delta\sigma_v' =$ estimated vertical load at top layer of clay.

In a single pumping well under operation ground water level draws down causing a hydraulic gradient that cause the well ground water flow. There are some different analyzing models for this flow such as Moench, that is a combination of Neuman and Boulton model by assumptions that, uniform aquifer and constant pumping rate, constant physical properties[8].
In this situation ground water flow around a supposed single well such as figure 6 can be computed by following equations [8]:

$$\frac{\partial^2 h}{\partial r^2}+\frac{1}{r}\frac{\partial h}{\partial r}+\frac{K_z}{K_r}\frac{\partial^2 h}{\partial z^2}=\frac{S}{bK_r}\frac{\partial h}{\partial t} \quad (17)$$

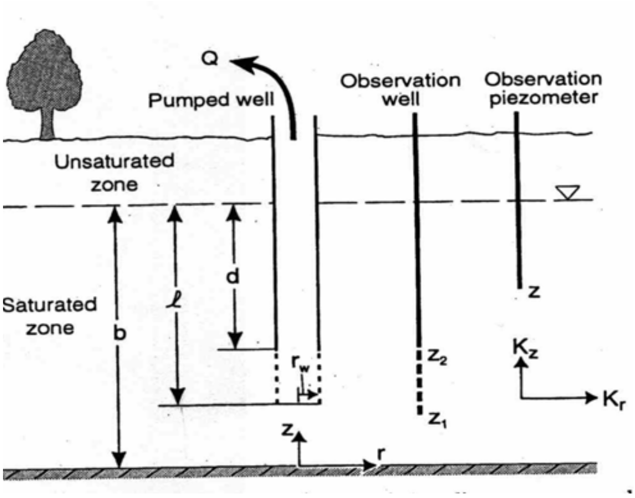

Fig.6 Supposed single well in a uniform aquifer

Solving the above equation, applying the initial conditions [10], we will obtain the following equation:

$$\bar{h}_D(\gamma,\beta,\sigma,z_{D1},z_{D2},p) = \frac{1}{(z_{D2}-z_{D1})}\int_{z_{D2}}^{z_{D2}} \bar{h}_D(\gamma,\beta,\sigma,z_D,p)\, d_{zD} = \sum_{n=1}^{\infty} \frac{2K_0(x_n)\{\sin[\varepsilon_n(1-l_D)]-\sin[\varepsilon_n(1-l_D)]\}[\sin(\varepsilon_n z_{D2})-\sin(\varepsilon_n z_{D1})]}{p(l_D-d_D)\varepsilon_n[0.5\varepsilon_n+0.25\sin(2\varepsilon_n)]} \quad (18)$$

Table 1 shows the parameters of equation (18) without dimension.

Table 1. Equation parameters

t_D	Tt/r^2S
t_{Dy}	Tt/r^2S_y
h_D	$4\pi T(h_i-h)/Q$
r_D	r/b
z_D	z/b
K_D	K_z/K_r
l_D	l/b
d_D	d/b
β	$K_z r^2{}_d/K_r$
σ	S/S_y

3 Problem Solution

Formulation of finite element analysis for subsidence problem was discussed in previous section. A computer program, which named SACII, was developed to predict and examine various soil behavior and conditions.

This formulation make the simulation of land subsidence be possible, using an axi-symmetric fully coupled finite element consolidation theory.

Based on biot's three dimentional consolidation theory, the soil skeleton treated as a porous elastic soil and laminar pore water is coupled to the solid phase.

In order to verify the used computer model, analysis for simple behavior such as one-dimensional consolidation was performed.

As an example for examination of model, properties of Sirjan aquifer in Kerman province and also Shahrekord aquifer were considered (fig.3, 4) and the output results are compared.

It should be noted that values of E and other material properties can be varied in depth or other directions. Values of C_r C_z are functions of K, E, ν, γ and Δt and was chosen from 30 minutes to one day depend on required accuracy and the problem.

A section with height of 200 meters and width of 1000 meters was discretized to 160 rectangular elements with 189 nodes and analyzed with the mentioned computer program.

For complete study two stages of analysis were performed in this research.

At first stage actual consolidation process which is three-dimensional in the field pumping problems,

the water table determined by 'WTAQ' computer program assuming a constant pumping rate.
In this situation water flows in axial and radial directions under axi-symmetric conditions.
This simulation is very close to actual filed condition under pumping of groundwater through wells. The analysis for this case is shown in Figure 7.

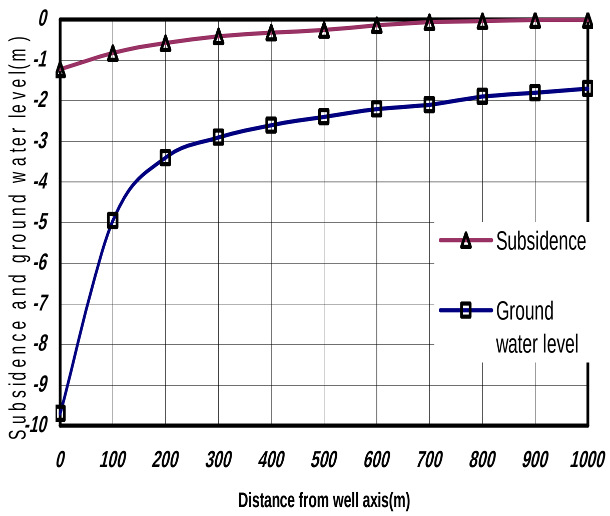

Fig7. Subsidence and ground water level

It can be seen from Figure 7 that subsidence rate around the well axis is higher than farther areas.
Also there is a rough ratio of one tenth for subsidence and its related amount of water decline near the well axis and the shape of subsidence around the well are close to ground water decline cone's shape, but in a much smaller scale.
Using Biot's three-dimensional equation of consolidation it is also possible to estimate differential settlement in various distances from wells.
Figure 7 shows subsidence versus distance after one year for sudden water table drop of one meter.
It can be seen that higher settlement occurred at areas surrounding the wells.
This can be explained on the basis that at areas close to well, with higher water drop and, radial drainage causes dissipation of pore water pressure, which resulted in faster settlement.
In this shape also it can bee seen that the amount of subsidence in situation 1,(Sirjan area) is larger than situation 2,(Shahrekord area).

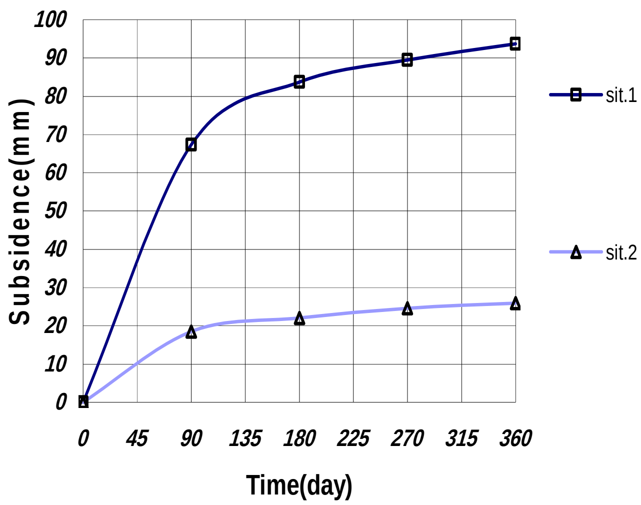

Fig.8 Subsidence Due to 1 meter Water Table Decline after One Year

At the second stage, it is assumed that water table drops at the rate of one meter per year which is equivalent to pistachio farming area at Sirjan aquifer. One of the main advantages of developed computer program is considering the actual slow drop of water table level.
In other words, the subsidence problem considered is time dependent in terms of pore water pressure condition and also time dependent in terms of load application.
For this conditions, the water also time dependent in term of load application. In the mentiond case, the water continuously drops at the rate of 1 meter per year for five years and relation between subsidence and time (at a determined distance from well) is shown in Figure9.
It can bee seen that situation 1 has larger amount of subsidence comparing to situation 2, it really happens because of the special and different conditions of two situations.
For example the difference between ground water level of Sirjan aquifer and Shahrekord aquifer causes different amount of subsidences. Also the different properties of the soil of two aquifers will cause more difference inn results.

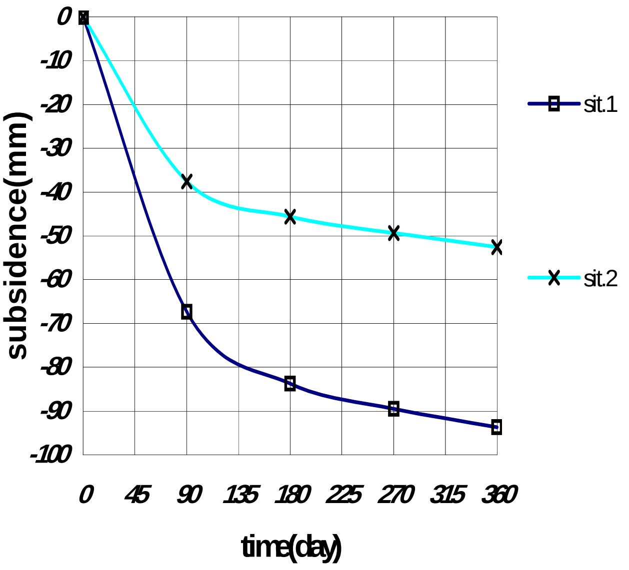

Figure9. Relationship between Subsidence and Time at a determined Distance from Pump Station

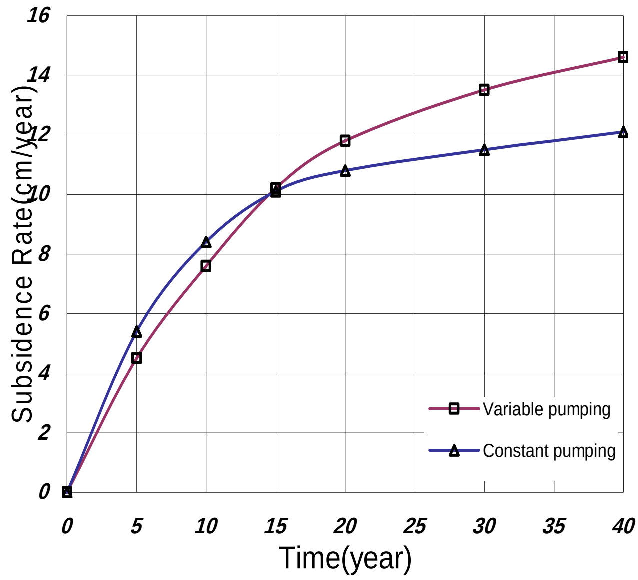

Fig. 10 Relationship Between subsidence rates in constant and variable pumping

Regarding above, Figure 9 modeled the actual and better simulation of the field pumping problems.
In this case it is assumed the rate of the water drop at the pumping station is 105 cm per year and 95 cm per year drop at distance of 1000 meter from pumping station.
From these result it can be concluded that rate of differential settlement increases with passage of time and the corresponded amount of this settlements can also be achieved in this figure.
This will be happened because after each year, the water declination increases cumulatively and this will causes the results in higher settlements and also higher rates of differential settlement.
Figure 9 shows that the results of subsidence rate vs. time at different distances from the well.
It can be seen, expectedly, that the settlement rate near the pumping station is higher than at the other location. This is mainly due to faster drainage near the well casing which causes more settlement.
The obtained amount of the results of this analysis can be confirmed by field data that after 20 years of pumping, the measured rate of settlement at the well is about 10 cm, which is almost equivalent to numerical expressed analysis.
The results of subsidence rate vs. time for constant and various pumping are given in Figure 10.

Various pumping is more probable than the constant one and it means that pumping rate is changed by the time.
It can be seen that generally after pumping in constant pumping subsidence velocity is higher than variable one, and by the time 15 years after continues drainage, the amount of subsidence in two cases of constant and also variable pumpage will meet each other.
But passing the time, variable pumping can produce larger amount of subsidence in a determined time period, as it seen in figure 10.
These results shows almost 10 centimeter per year subsidence rate after abut 15 years of pumping in both two kinds, (various and constant pumping), that is equal to the amount of measured subsidence in Sirjan, so we can see that the related field data in Sirjan confirm this amount well.
In the other discussed aquifer, situation 2, because of the upper ground water table and also better soil profile, we can see smaller amount of subsidence here, but this result also are close to the actual amount of existed filed data in the related area such as the obtained results, neglecting the small existed error, can be confirmed by filed data. It can be seen that the measured field data of the aquifers are very closed to the calculated results of the mentioned methode of this investigation as they appeared in the paper.

Conclusion

The developed computer program based on Biot's three-dimensional consolidation theory gave satisfactory results in subsidence computation and also prediction.

At first stage, the proposed method was examined with classical and one dimensional consolidation theory and then extend to more complicated causes of three dimensional one in order to achieve the results which still confirmed field data. Using the computer program WQAT (Water Table Aquifer), under ground water table can be obtained and this under ground water table is used in the next stages of this research as an input data.

Finally based on the mentioned stages of this study the prediction of future settlement, in different aquifers with different conditions of soil properties and also different under ground water tables, can be obtained. The limitation of this study is that aquifer was assumed as a confined one.

This study first was developed for considering only one well but it would easily extend for groundwater withdrawal in a regional problem similar to assumption which was made in first stage of this study or consider the actual variation of water table level in the field as an input data in finite element analysis.

So in next step we extend the study to predict and also compare of two different aquifers and the related results are given in previous parts and figures of the paper.

Also time dependency of the water table decline around a pumping well can be effected in the model and land subsidence computed as a function of time, distance from the pump station, pumping discharge and other soil physical and mechanical properties of the related soil.

So it will be possible to predict future land subsidence and also the location of probable earth fissures due to different land subsidence by using the model.

Pore water pressure and horizontal displacements at different time and various locations are the other information that can be computed from this study.

References:

[1] Rahmanian, D., Land Subsidence in Kerman due to Pumping of Groundwater, *Mahab Ghods Consulting Company Report*, vol.1,1997, PP. 1-8.

[2] Rahmanian, D., Land Subsidence and Earth Fissures due to Groundwater Withdrawal in Kerman, Journal *of Water*, Vol.6, 1986, PP.1-8.

[3] Toufigh, M. M., and Shafiei, B., Prediction of Future Land Subsidence in Kerman due to Ground Water withdrawal, *5th International Symposium on Land Subsidence*, Netherlands, 1995, PP.245-262.

[4] Toufigh, M. M. and Shafiei, B., Finite Element Consolidation Model for Subsidence Problem Based on Biot's Three Dimensional Theory, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics*, 1996, Vol.33, PP.344A-344A.

[5] Toufigh, M. M. and Q`marsi, k., Single Well Subsidence Modeling Based on Finite Element Formulation, *2nd Canadian Specialty Conference on Computer Application in Geotechnique Proceeding*, 2002, PP.298-303.

[6] Reddy., J.N., *an Introduction to the Finite Element Method*, McGraw-Hill, New York, 1984.

[7] Smith, I. M. and Griffiths, D.V., *Programming the Finite Element*, 2nd ed., John Wiley, 1992.

[8] Najmaei, M., *Engineering Hydrology*, University of Science and Technology of Iran 1990.

[9] Biot, M. A., General Theory of Three-Dimensional Consolidation, *Journal of Applied Physics*, Vol.12, 1941, PP.155-164.

[10] Ziaie. A., Rahnama. M.B., Pridictio of Single Well Land Subsidence due to Ground Water Drainage, *Intrernational Journal of Agricultural Research*, Vol.2(4), 2007, PP349-358.

[11] Sroka. A., Hejmanowski. R., Pridictio of Geometrical Changes on the Surface and in the Rock Mass for Deep Extraction of Solid, Liquid and Gaseous Minerals. *UMM Scientific Bulletins, Environmental Protection Issues Series, Vol.33*, 1991.

[12] Sun. H., Grandstaff. D., R. Shagam., Land subsidence due to groundwater withdrawal: potential damage of subsidence and sea level rise in southern New Jersey, USA, *Environmental Geology*, Vol.37, 1999, PP.290-296.

[13] Wolkersdorfer., Ch., Thiem. G., Ground Water Withdrawal and Land Subsidence in Northeastern Saxony (Germaney), *Mine Water and Environment Association International Mine Water*, 2006.

[14] Papaioannou, A., Plageras, P., Nastos, P. Th. , Grigoriadis D., Dovriki, E., Spanos, Th. S., Koutseris, Paliatsos A.G., Assessment of Soil and Groundwater Quality and Hydrogeological Profile of Drama's Prefecture, North Greece**,** *WSEAS Transactions on Invironment and Development*,Vol. 2, 2006.

[15] Ehret, D., Hannich, D., Schmitt, S., Huber, G., Numerical modelling of site effects - Influences of groundwater level changes, *1st IASME/WSEAS International Conference on Geology and Seismology(GES'07)*, 2007.
[16] Tsang, H., Lam, N., Asten, M., Lo, S. H., Generic Theoretical Formulae for Estimating Site Effects, *1st IASME/WSEAS International Conference on Geology and Seismology (GES'07)*, 2007.