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Prediction of Earth Fissures Development in Sirjan

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Abstract: In this study, the relationship between the decrease of the water level of an aquifer, the sinking of the land surface (subsidence) and the generation of earth fissures is investigated. Comparing with the real field data for Sirjan land, the obtained results are confirmed. A decrease in ground water level will causes an increase in effective stresses at clay layers which results the consolidation of lower soil layers. Modeling of this behavior is possible using finite element technique and it baneful to predict the future settlement and the location of potential fissures. It is possible to approximate the model by assuming elastic time dependent behavior due to decrease in water table level. Also a finite element model is established and related to classical soil mechanics consolidation parameters in this study. To finding the water level of an aquifer, WTAQ computer program is used in this study.

Key words: Subsidence, finite element, WTAQ, ground water, consolidation, withdrawal, fissure

INTRODUCTION

In recent decades, ground water withdrawal caused a continuous decrease of groundwater level in so many parts of the world and one of its direct results is earth fissures. Earth fissures occur at the edges of basins, usually parallel to mountain fronts, or above local bedrock highs in the subsurface and typically cut across drainage. Their surface expression range is from less than a yard to several miles long and from less than an inch to tens of feet wide. In some dry areas because of extensive ground water withdrawal, the rate of subsidence increases rapidly. For example, subsidence rate is more than 10 cm year⁻¹ in Sirjan. Extensive ground water pumping for agricultural uses and pistachio farming in this area, beside the semi desert type climate of this part of Kerman Province of Iran land are the causes of this high rate of subsidence. Another example of the notable subsidence rates appears in Bangkok, such as the maximum rate of the land subsidence due to ground water withdrawal in last 35 years is reported as 120 mm year⁻¹ in Bangkok (Phien-wej *et al.*, 2006). When this grate rates of subsidence accrue in the land of two neighboring area with different soil characteristics, for example different soil permeability, the magnitude of land subsidence (that are functions of soil characteristics), differ from each other in these two neighboring areas. Theoretically at the sharing border of them two value of subsidence exist, so an earth fissure should be accrued at this border to let the different parts having their own value of subsidence. In this study, the process subsidence finite element modeling due to ground water decrease and the subsequently generated earth fissures are studied. The obtained results of this study may be used for prediction of probable settlement and also potential fissures of a land.

Fissures change flood patterns, break buried pipes and lines, cause infrastructure to collapse, provide a direct conduit to the groundwater table for contaminants thrown into them and even pose

a life safety hazard. Flooding caused by loss of elevation and changes of topographic gradients are the most costly impacts of land subsidence, but most of these problems can be avoided, corrected or at least mitigated with a comprehensive ground water management program (Sahugillo *et al.*, 2005). Surprisingly, flooding is most severe where land subsides adjacent to water bodies, particularly in coastal regions. This causes either permanent submergence or more frequent flooding. Changes of topographic gradients occur where loss of elevation is not uniform. The most conspicuous examples of coastal subsidence in the United States are in Long Beach, California, the greater Houston, Texas, Metropolitan region and Santa Clara Valley, California (Holzer and Galloway, 2005). Earth fissures also can be detrimental to canals, levees and dams because void space caused by extension during fissure formation creates the potential for catastrophic release of water when fissures intersect these structures.

The results shows that in some parts of Kerman Province such as Sirjan land, subsidence and earth fissures were related only to heavy pumping of the ground water and subsequent continued decline in the water table (Rahmanian, 1997). Later investigations that provide a prediction model in order to simulate the future settlement were continued by Toufigh and Shafeiei (1996). Also a prediction model was suggested in order to simulate the future settlement of a single well under operation based on finite element formulation, determining the water level decline by a computer program (WTAQ) and using a formulation of finite element which was based on Biot's three-dimensional consolidation theory (Biot, 1941). Also an appropriate procedure for evaluating known or suspected subsidence areas is to conduct a geophysical survey tied to well drilling and other subsurface data to determine buried bedrock configuration (Larson, 1984).

Humans have also caused widespread and significant elevation loss by other processes. Collectively, the impacts from these processes rival those from withdrawal of underground fluids. When the groundwater level decrease which is resulted by groundwater withdrawal declines pore-water pressures, inter-granular stress multiplies porous-medium consolidate. To quantify this causality, an elastic-plastic consolidation deformation model was built. Results show the relationship between the stages of surface subsidence and the corresponding periods of groundwater level decrease. Compared with the expansion of the decline cone trough, the expansion of the subsidence area lags behind.

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 (1986, 1997).

Because the greatest amount of compaction of sediments occurs at this interval as the water level declines. Gravity has been the most effective geophysical method in terms of correlation of anomalies with fissure occurrences, particularly where buried topographic highs exist. Convex-upward gravity anomalies can be generally correlated with a buried convex-upward bedrock surface. At sites where geophysical or other data indicate a high risk of fissuring, land survey measurements to monitor horizontal and vertical ground movements can be used to predict possible fissure locations and subsidence patterns (Larson, 1984).

When effective stress exceeds the yield strength of the granular skeleton of the media, the compaction is permanent and irreversible. All aquifer systems deform to some extent in response to water-level change. The seasonal cycle of recharge and discharge from unconsolidated heterogeneous aquifer systems typically causes minor elastic (recoverable) expansion and compression and respective uplift and subsidence (on the order of millimeters to centimeters) of the land surface (Amelung *et al.*, 1999; Hoffmann *et al.*, 2001; Bawden *et al.*, 2001; Lu and Danskin, 2001; Heywood, 1997; Heywood *et al.*, 2002). In confined aquifer systems, the water supplied to a pumping well is initially derived from deformation of the aquifer system, i.e., expansion of water and compression of the granular skeleton or matrix (Jacob, 1940).

In fact, water and matrix compressibility and porosity determine the storability of the aquifers and the interbedded and confining aquitards in the aquifer system. Depending on the magnitude of the pressure change and stress history of the aquitards, either elastic (recoverable) or inelastic (unrecoverable) compaction occurs as groundwater drains from the fine-grained aquitards into the coarser-grained aquifers.

MATERIALS AND METHODS

The developed computer program based on Biot's three-dimensional consolidation theory is used in this study to predict the settlement of Sirjan land, using the computer program (WQAT) for achieving the under ground water table of the related aquifer. At the next step, different conditions of the soil of this area are applied on the model and finally the location of potential fissures of this land is predicted.

Subsurface conditions and surface deformation measured near straight to actuate earth fissures, as well as theoretical considerations, indicate that these ground failures are caused by localized differential compaction. In other words, whenever we have the differential land subsidence, earth fissures will appear. Land subsidence associated with withdrawal of underground fluids from porous granular media is caused by a decrease in the volume of the reservoir system. As fluids are withdrawn from porous media, pore-fluid pressures decrease. Because deformation of porous media is controlled by effective stress the difference between the total stress and pore-fluid pressure a decrease in pore-fluid pressure causes a decrease of pore volume. This phenomenon is known to hydrologists as compaction.

Aquitards both within and bounding the aquifer system is particularly prone to large compaction because of their compressibility. Typically, matrix compressibility (and therefore storability) of aquitards is several orders of magnitude larger than the compressibility of coarser-grained aquifers, which in turn is typically much larger than water compressibility.

Therefore, much of the water from aquifer storage is derived from deformation of the matrix. Accordingly, aquitard storability and drainage control the compaction of these aquifer systems and account for most of the land subsidence that accompanies groundwater development of these aquifer systems.

The effective stress at which deformation in a porous media undergoes the transition from primarily elastic to permanent compaction is known as the preconsolidation stress. This concept was originally proposed by geotechnical engineers to describe the volumetric response of soil to changes of effective stress.

Although, there are no methods of quantifiably predicting the exact probability and exact magnitude of earth fissures, but the locations of potential fissures may be predictable in specific areas if enough information about the subsurface, material properties and groundwater levels are available. However, as long as subsidence continues (even if the groundwater levels should rise and stabilize), fissures will continue to occur and the magnitude of the fissures vary with the depth to groundwater, type of surface material and some other different elements as present amount of groundwater removed, basin depth, volume of runoff from precipitation and human intervention. In an attempt to categorize the probability of future events of fissures, the hazard was analyzed using an analytical method, based on stress-strain theory of the soil elements. This method also takes into account the levels of magnitude/severity, warning time and duration.

The fissures result from horizontal tensile strains produced by bending of the overburden. The strains attain maximum tension at the point of maximum convex-upward curvature in the subsidence profile. By modeling the bending process within a small area in south-central Arizona, it can be estimated that tensile strains at failure ranged approximately from 0.02 to 0.2%. These values agree with strain at failure inferred from average annual strain rates measured across earth fissures at other locations (Jachens and Holzer, 1982).

The complex polygonal network pattern of some fissures suggests that these fissures are caused by a horizontally isotropic tensile stress field. By analogy to desiccation cracks, the probable source of such tension is the large negative capillary stress in the dewatered zone above a declining water table. Such a mechanism was proposed by Neal *et al.* (1968) to explain naturally occurring fissures that form giant polygons on playas. In addition to surface faults, earth fissures large tension cracks are commonly associated with subsidence caused by are commonplace. Much of the eroded material is trans-groundwater withdrawal.

Field studies indicate ported down into the fissure. Because the inferred crack openings the tension is caused by bending of the surface layer resulting are only a few centimeters, this suggests the cracking extends to from localized differential subsidence. The deepest reported open depth is 25 m (Holzer, 2000), although others have studied surface faults, tension cracks open by slow creep cal grounds that the tension is caused by horizontal strains in the (Holzer, 2000). As a result, they may undergo repeated episodes aquifer (Sheng *et al.*, 2003).

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. 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 and it can be determined by WTAQ software. This software shows the water level around a single pumping well using a numerical method in base. More information about this program is given in previous papers of the same author.

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 behavior should be achieved by actual mathematical equations (Reddy, 1984; Smith and Griffiths, 1992). Final governing equation which is expressed and extended in last research of the author is as follow:

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

Where:

- u_e = Excess pore water pressure
- P = Mean total stress
- z and r = Axial and radial directions
- t = Time
- C_r = Coefficient of consolidation in radial direction
- C_z = Coefficient of consolidation in axial direction

Applying the equilibrium equations and stress-strain relations this matrix equation will be achieved:

$$\begin{Bmatrix} q_r \\ q_z \end{Bmatrix} = \frac{1}{\gamma_w} \begin{bmatrix} K_r & 0 \\ 0 & K_z \end{bmatrix} \begin{Bmatrix} \frac{\partial u_e}{\partial r} \\ \frac{\partial u_e}{\partial z} \end{Bmatrix} \quad (2)$$

where, q_r , q_z are volumetric flow rates per unit area into and out of the element and K_r , K_z are coefficient of permeability in radial and axial directions, respectively.

At the other hand for fully saturated soil and incompressible fluid condition, outflow from an element of soil equals the reduction in volume of element. Hence:

$$\frac{K_r}{\gamma_w} \frac{\partial^2 u_e}{\partial r^2} + \frac{K_z}{\gamma_w} \frac{\partial^2 u_e}{\partial z^2} + \frac{d}{dt} \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) = 0 \quad (3)$$

As usual in a displacement method σ are eliminated in terms of u, v so that the final coupled variables are u, v, u_e . In Eq. 3, 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 $\theta = 0.5$ in Crank-Nicolson method and after summarizing and combination of the equations the final equation can be written as follows:

$$\begin{bmatrix} KM & C \\ C^T & -\frac{\Delta t}{2} KP \end{bmatrix} \begin{bmatrix} r_{n+1} \\ u_{n+1} \end{bmatrix} = \begin{bmatrix} -KM & -C \\ C^T & \frac{\Delta t}{2} KP \end{bmatrix} \begin{bmatrix} r_n \\ u_n \end{bmatrix} + \begin{bmatrix} 2F \\ 0 \end{bmatrix} \quad (4)$$

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 (Drever, 2005) 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. 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 (Najmaei, 1990). Solving the Eq. 4, applying the initial conditions (Ziaie and Rahnama, 2007; Franklin Schwartz and Hubao, 2003), the following equation will obtain:

$$\begin{aligned} \bar{h}_D(\gamma, \beta, \sigma, z_{D1}, z_{D2}, p) &= \frac{1}{(z_{D2} - z_{D1})} \int_{z_{D1}}^{z_{D2}} \bar{h}_D(\gamma, \beta, \sigma, z_D, p) dz_D \\ &= \sum_{n=1}^{\infty} \frac{2K_0(x_n) \{ \sin[\varepsilon_n(1 - l_D)] - \sin[\varepsilon_n(1 - l_D)] \} [\sin(\varepsilon_n z_{D2}) - \sin(\varepsilon_n z_{D1})]}{p(l_D - d_D) \varepsilon_n [0.5 \varepsilon_n + 0.25 \sin(2\varepsilon_n)]} \end{aligned} \quad (5)$$

The parameters of Eq. 5 are described in the last research of the same author.

RESULTS AND DISCUSSION

Sirjan Land

Sirjan is a part of Kerman Province, located in Eastern South of Iran. Because of semi desert climate of this region and small amount of rainfall at one side and huge amount of requested water for agricultural uses, especially for pistachio farming, at the other side, water is doing continuously from the under water of this aquifer with an extensive rate. So, the water budget of this basin has been negative for years. This continuous decrease of groundwater level in Sirjan will have some sequences as earth fissures. Passing four main faults (Naibandan, Kuhbanan, Zagros and Sanandaj) from this area and also having the largest number of Qantas in Iran beside of earth fissures due to decrease of ground water level, Sirjan's land is like to a broken shell which need so more care to behave about.

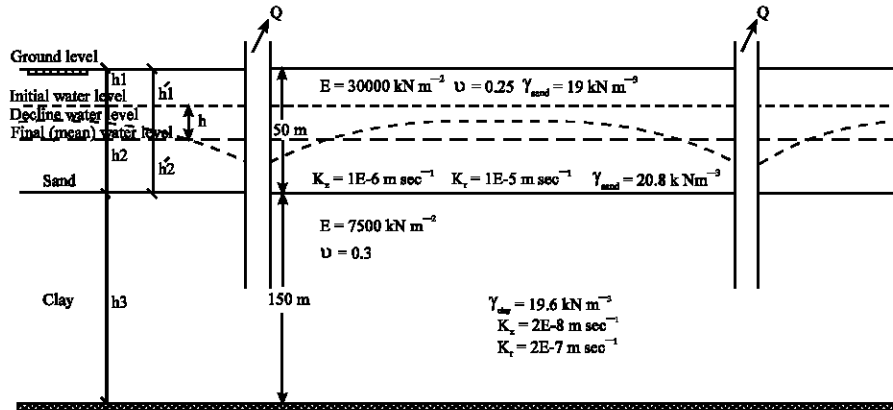


Fig. 1: Declined water level and Sirjan aquifer soil profile

So, knowing about the subsidence rate, also the number, direction and expansion rate of the earth fissures in an area of this land will make a true vision for us to have a true behavior. This study is a powerful tool to distinguish the mentioned important factors for future decisions.

In this research, the amount of the subsidences of different parts of the supposed land are achieved at the first stage of the study and applying the real existing conditions of different parts of the lands, these data are compared. Compare and analyzing of these data at the next stage, will tend to the new findings such as probable locations of earth fissures in Sirjan land.

The density wide, deep gullies; gully widths of 1 to 2 m and depths of 2 to 3 m of fissures vary greatly between areas. In some places only a few. Earth fissure associated with land subsidence caused by pumping of groundwater in Sirjan land, Kerman. Soil and aquifer properties of Sirjan land are shown in Fig. 1.

Variations in the density of failures from area to area are conspicuous and are obviously determined by more than just area differences of water-level decline and compressibility of sediments. For example, the area extent and magnitude of subsidence in the Sirjan land of Kerman Providence is one of the greatest one of any area in Iran and also the ground failure is so. Part of the explanation for these density variations probably lies in differences in the subsurface conditions among the areas. Surface faults and straight to actuate earth fissures are associated with preexisting faults and subsurface zones conducive to localized differential compaction, respectively. Prediction of locations of potential ground failure on the basis of subsurface conditions appears to be feasible. The results of this study shows the location of potential earth fissures in Sirjan land after about 15 years of pumping and the related field data in Sirjan confirm this amount well.

As it said before, because of variable soil properties, such as density, permeability and depth of soil layers in this area, applying the governing equation, different stresses are resulted from the assumed model and naturally different strains will obtain. These different strains will form the earth fissures in this land. The obtained field data from Sirjan land confirm the model and the results of this analyses well. Some pictures of these fissures in Sirjan are shown in Fig. 2-4.

Although, horizontal displacements across fissures during their formation are small, they are sufficient to damage rigid engineered structures. In addition, differential vertical displacements in narrow zones near fissures may affect structures whose operation is sensitive to small tilts. Gullies associated with fissures are commonly large enough to trap and injure livestock and other animals as well as pose a potential hazard to people.

Fissures also serve as conduits for large quantities of water. Consequently, they are potential hazards to water-conveyance structures such as canals. Because of their depth, fissures can also serve



Fig. 2: Earth fissures caused by differential settlement of Sirjan land



Fig. 3: Earth fissures will damage the structures

as conduits or preferential flow paths for contaminants from the surface into shallow aquifers. Finally, fissures can be sinks for a large volume of sediments. Their formation may locally trigger severe erosion and create badlands topography near the fissure.

If water levels recover in an aquifer system that has compacted and then the aquifer is pumped again at similar rates, water-level drawdown will be more rapid than during the first cycle of water-level decline. This allowed water levels in the aquifer system to recover by the time of drought. When heavy pumping resumed during the drought, water levels declined 10-20 times as rapidly as when groundwater was pumped for the first time from the aquifer system.

It should be noted that values of E and other material properties can be varied in depth or other directions. Values of C_1 , C_2 are functions of K , E , v , γ and Δt and was chosen from 30 min to one day



Fig. 4: Earth fissures among the pistachio trees in Sirjan land

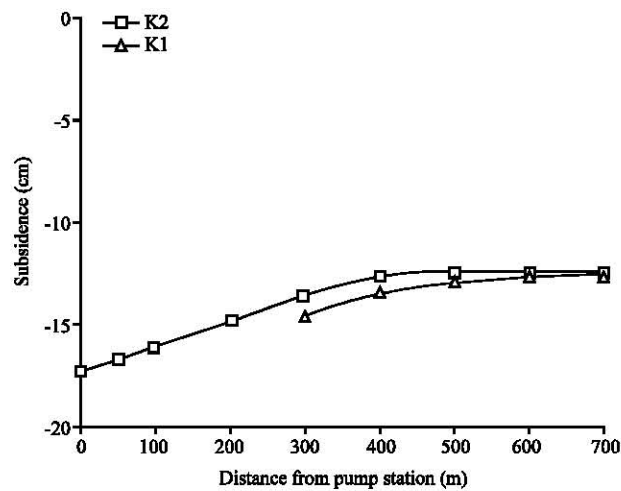


Fig. 5: Differential settlement due to different soil permeability

depend on required accuracy and the problem. A section with height of 200 m and width of 1000 m was discretized to 160 rectangular elements with 189 nodes. 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 field condition under pumping of groundwater through wells.

In this study, different condition of aquifer and also soil profile in Sirjan land (Fig. 1) is considered to apply the model. Figure 5 shows an example of these analysis. Figure 5 shows the subsidence of modeled land due to groundwater withdrawal after four years of pumping with the average rate of 5 L sec^{-1} . As it is shown in Fig. 5, whenever the coefficient of permeability, (K), is variable ($K_1 < K_2$) in different parts of the supposed land, neglecting of other effecting parameters, the amount of obtained subsidence are variable too. In the other words, in case of the smaller K the resulted subsidence will be larger. So, the distance of two graphs is growing and this theoretical distance causes the differential stress and strains and finally the fissure will happen. Also the other mentioned effective parameters, considering their own sharing ratio, act as above.

CONCLUSIONS

Ground failure takes place in most lands of the areas with land subsidence, that caused by ground-water withdrawal. The first failures in each area took place after subsidence began and in those areas that now have large numbers of failures, the number gradually increased as subsidence continued. Thus, in a sense, ground failure may be considered as a secondary, although relatively common, condition caused by ground-water withdrawal from unconsolidated sediments.

The developed computer program based on Biot's three-dimensional consolidation theory gave satisfactory results. First, the proposed method was examined with classical and one dimensional consolidation theory and then extend to more complicated causes which still confirmed field data and using the computer program (WQAT), under ground water table and finally based on that the prediction of future settlement can be obtained. In terms of a stress problem the unknowns are the boundary conditions of our model (boundaries without capacity of consolidation or capacity of deformation that are forming the basin), mechanical properties of the body to deforming (stress-strain behavior of the materials that are filling the basin) and the load of the system (conditions of applied stress). The surveys have shown that if sufficient data on tensile strength and the configuration and compressibility of subsurface materials are available, the finite-element method satisfactorily predicts the approximate magnitude of water-level decline at which fissuring will take place.

In this study, the relationship between the decrease of the water level of an aquifer, the sinking of the surface and the generation of earth fissures is obtained and for Sirjan land and the results compared with the real field data. It is notable that the field data confirm the obtained results, so that some front extension of potential fissures in Sirjan land are obtained with this study's method and the field data shows the positive values of fissure extension at the same locations.

The mentioned relationship is not so obvious because it is very difficult to obtain values of the variables that are interacting in this problem such as the soil strata sequence at any depth of the aquifer system, the mechanical properties of the soil to depths longer than common exploration depths in soil engineering (depths longer than 10 m), the variation of the water level at any point of aquifer etc. Due to these difficulties the behavior of an aquifer system that includes deformations is calculated by means of simplified models.

The limitation of this study is that aquifer was assumed as a confined one. This study first was developed for considering the groundwater withdrawal in a regional problem similar to assumption which the actual variation of water table level in the field as an input data in finite element analysis and then the stress-strain matrix of the different elements of the model can obtained. Finally, the strains are conducting us to predict the probable fissures location in the supposed area.

Finally, we know that numerous problems and potential long-term impacts have arisen due to intensive use of ground water, when a local institution for control and management does not exist. These problems include excessive lowering of ground water levels, ground water storage depletion, land subsidence, impacts to other users, decreased discharge to and effects on base flow of rivers and springs, potential mobilization of contaminants and impacts aquatic ecosystems and as it said before, most of these problems can be avoided, corrected or at least mitigated with a comprehensive groundwater management program.

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