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# Land-subsidence relative to Pore-pressure and Effective Stress (Case study: Khorramabad Plain, southwestern Iran)

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**ABSTRACT**

Phenomena of land subsidence, increasing the effective stress ($\sigma_1$) of the body of aquifer sediments have not consolidated. Because the weight of the upper overburden aquifer sediments by the solid and the fluid contained in the pore space to be tolerated when the fluid pressure caused by drop in the water table the decrease in the effective stress increased this results in soil compaction and evidence of subsidence in the area, Such as tensile cracks, crack growth in civil structures tube wells in plain. The last few years Bagstrsh, Land subsidence caused major problems for the agriculture and can be civil structures near these gaps. In line with the international studies in this research area as a pilot scheme studied Khorramabad. In general it can be stated that decline in groundwater levels in Khorramabad plain area, increasing the effective stress in the alluvial plain water depths ranging from plain and prevent to avoid potential supply normal rainfall factors accretion phenomena Khorramabad plain island subsidence. Near the underground water, Thickness of clay and fine materials, the presence of active faults Khorramabad anticline and humanitarian intervention mechanisms developed in this area, because increased incidence of subsidence phenomenon in the area that will be output by the model is consistent with the content.

## 1. Introduction

The intrinsic and internal reaction of an object to the force exerted on the unit surface of that body is called stress. The effective stress is the force transmitted per unit area by the soil skeleton. In soil mass, effective stress controls volume and resistance changes. Larger effective stress causes compaction and conversions of soil into a denser and smaller volume (Budhu, 2010). There are three types of stresses in aquifer layers with the following symbols:

- Total stress as $\delta$,
- Effective stress as $\sigma$,
- Pore-water processor as $u$.

The concept of effective load stress was first introduced by Terzaghi (1925) continued Terzaghi's work and proposed an effective stress relation by adapting the total stress relationship as follows (Terzaghi et al., 1996).

$$\delta = \sigma' + u \tag{1}$$

$$\sigma' = \delta - u = \left[H\gamma_w + (H_A - H)\gamma_{sat}\right] - H_A \cdot \gamma_w \tag{2}$$

Effective stress (σ’), has created in the solid particles of an object (soil or rock) that are transferred to each other in front of the solid particles and the pore pressure between the grains and the force exerted by the force of inter-granular water on the soil and rock particles which encloses water. If pressure is applied to the water in either direction, it will expand in the same proportion in the other direction. Therefore, the hydrostatic pressure for water is 1. But it is for rocks and soils it is always less than 1.

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As the groundwater level in alluvial aquifers decreases, the pore pressure between the soil particles decreases were this increases the effective stress in the discrete layers and ultimately leads to the yield of the soil skeleton and subsidence. This can be explained with the diagram in Fig. 1. The total stress (δ) and the effective stress (σ') before shear under hydrostatic pressure at a certain point S are isotropically all-encompassed, so the point S at the beginning of the stress path at the beginning of the stress change phase is on the horizontal axis of the effective stress. In other words, at the beginning of the cutting stage, the sample is subjected to the effective stress $K_{pan}$ and the total stress $K_{pa}$. Fig. 1 shows the two environments of changes in stress parameters in both drained and non-drained environments. In non-drained environments, with the onset of shear changes, the axial stress $\delta$ increases and reaches level $A$. At this point the sample has reached the yield stress. As the shear changes continue, the axial stress decreases. Finally, in very large deformations, the axial strain of 35% of the sample strength is stabilized at $T$ surface stress. The total stress in the drained environment is one of the influential factors in the discussion of regional subsidence, when it proceeds from position $S$ in the direction of the red line and submits at the location of line $F$ at the level of total stress (δ); After the yield of the skeleton, the effective stress decreases and from the time of the yield point of the $F$ line onwards, the total stress path on the same path (red line) goes through the return process to stop in the direction of the $T$ level. Now it is assumed that the shear stress changes in the drained environment increase; The changes in the path of the $FB$ line go forward and surrender at the stress level $B$. Point $A$ and $F$ are the instantaneous subsidence stage and consolidation meeting, respectively, and point $B$ completes the consolidation stage, which together lead to subsidence. The slope of the orange line, called the critical state line or the M-line, is related to the friction arms in the soil.

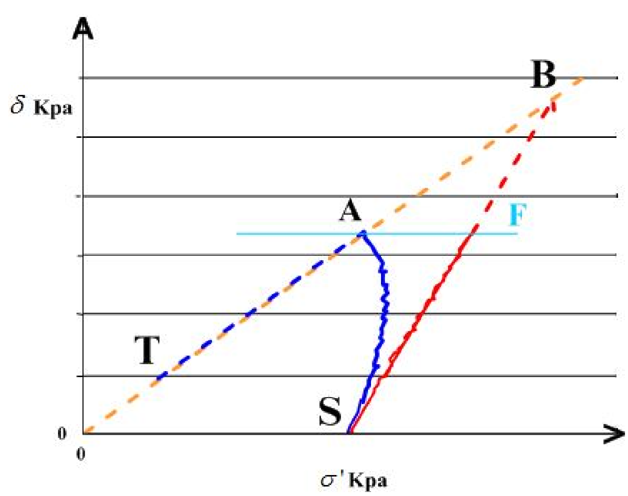


**Figure 1.** Diagram of the effect of stress changes in compacted soils (Reddish and Whittaker, 1989)

It is necessary to remember; if we assume the total stress as a unit, the soil resistance is determined to be effective, which is negatively related to the pore pressure.

## 2. Material and Methods

In Khorramabad plain, more than 120 points were harvested for 25 days in order to measure the potential of land subsidence; the result of these perceptions is the recording of information and evaluation of evidence indicating the susceptibility of land subsidence in the Khorramabad plain. Study of damages, changes and deformations around wells in the region, such as the growth of well wall pipes, tensile cracks, destruction of walls of houses and buildings around wells, and the relationship between the joints in plain structures and gaps Occurrences at the surface are the length of fissures in the plain, which are objective evidence of subsidence in an alluvial aquifer.

### 2.1. Land subsidence

Landslides at the plain level can occur due to declining groundwater levels. This type of subsidence is mainly done in unconsolidated to semi-solidified sediments (Aquitard) which is adjacent to sand layers. In this operation, a nontecoverable compaction is created in the aquifer. However, this operation is time consuming and occurs slowly and as a result, water is drained from the fine layer due to the drop in hydraulic pressure. In such conditions, an inelastic density occurs in the soil due to the increase of effective stress (application of stresses more than the stresses previously tolerated) and the arrangement of soil grains is disturbed and the new arrangement reduces the volume and vertical thickness of the layer and finally subsides. This phenomenon is presented in Fig. 2. It should be noted that the return of very low densities of about 1 to 5% in soil layers is possible if the water level returns. Increase in hydrostatic pressure according to the simple law of attraction according to the Eq. 3.

$$\sigma_e = \sigma_T - P \tag{3}$$

where $\sigma_e$ is the effective stress, $\sigma_T$ is the total stress and P is the water pressure. Reducing the pore water pressure increases the effective stress (Fig. 3).

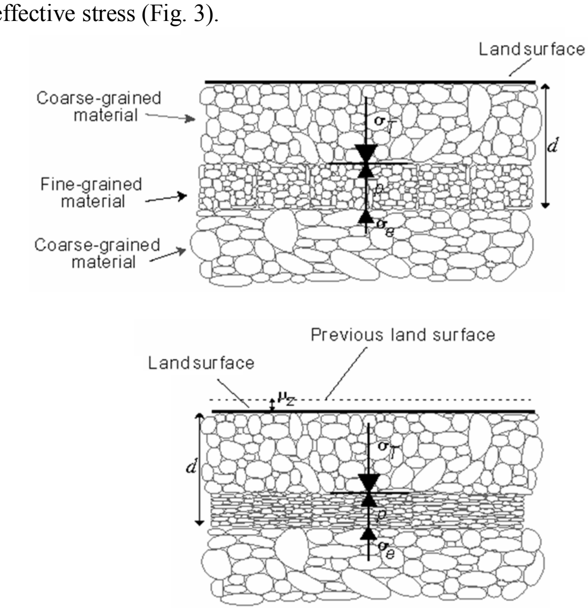


**Figure 2.** Reduction of the volume of the fine-grained layer and its thinning due to drainage (Reddish and Whittaker, 1989)

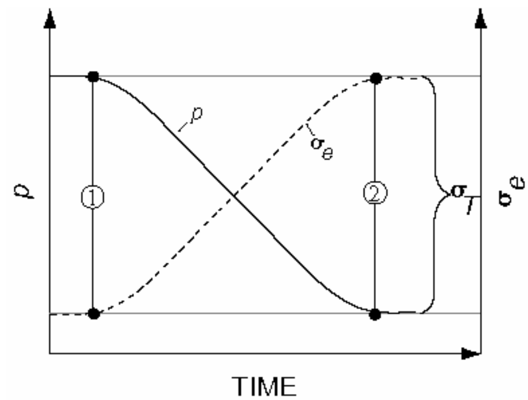


**Figure 3.** Relationship between total and effective stress (Reddish and Whittaker, 1989)

Reducing the pore water pressure due to the decrease of groundwater level increases the effective stress and increases the effective stress causes water to drain from the existing clay and silty soils and finally the aquifer density and subsidence. Since soil compaction causes the earth's surface to drop, from the engineering point of view, this phenomenon is subsidence. In general, the regional meeting occurs at any point due to the sum of the Anio meeting and the consolidation meeting at any point (Budhu, 2010). Improper abstraction of water from groundwater aquifers, which leads to a decrease in aquifer water level, reduces the pore pressure and, consequently, increases the effective stress in the aquifers, which leads to compaction of non-compacted layers and sediments. This phenomenon causes the ground surface to settle suddenly (in sandy aquifers) or gradually (in clay aquifers). This can potentially cause problems such as cracks and crevices in the ground, destruction of buildings and the growth of well pipes, changing the slope of rivers and roads, falling wells, changing the slope of the ground and increasing flooding in the region (David and Pyne, 1995).

The settling phenomenon usually does not occur immediately with the outflow of fluid, but occurs over a longer period of time (Scott, 1979). The amount of subsidence for each ten meters of water level drop varies between 1 and 50 cm, the amplitude of these changes depends on the thickness and compressibility of the layers, loading time, degree and type of stress (Lofgren, 1968). Numerous reports of landslides, especially in arid and low-rainfall areas, have been reported from around the world (Hua et al., 1993). Meetings in Tokyo and Osaka have been reported to be 20 cm per year in Salo and 50 cm per year in Nyagata. Khorramabad plain is one of the plains that has decreased interstitial pore-pressure and increased effective stress due to improper exploitation and digging of illegal wells, and falling groundwater level, which has led to aquifer reservoir deficit; Following the changes that have taken place, the dried up aquifer has been confronted with the category of land subsidence. In Khorramabad plain, with an annual average decrease of 52 cm during the last 15 years (from the interpretation of information of excavated piezometers in the plain) can be considered as the main reason for the increase in effective stress. In such conditions due to increased effective stress (applying more stresses than Previously tolerated) inelastic compaction has occurred in the soil and the arrangement of soil grains has been disturbed and the new arrangement has reduced the overall volume and thickness of the layer and finally the subsidence.

### 2.2. Pore Pressure and Effective Stress

Pore pressure conditions in a soil profile depend on the hydraulic conductivity of the materials, drainage length, and water balance between infiltration and drainage in the different layers. Although reduction of pore pressure due to groundwater drawdown is a transient process, this study is limited to study the steady state conditions at the end of the process. If detailed measurements of pore pressure (u) are not present, estimations are made by assuming a linear dependency between the open and the confined layers (Zeitoun and Wakshal, 2013) Since a clay layer has a very low hydraulic conductivity, hydrostatic conditions between the open and the confined aquifer cannot be assumed. In the case study, pressure heads in the confined aquifer are obtained from an interpolation of average levels from 300 groundwater observation wells. Since observations of heads in the open aquifer are few, groundwater levels in this layer are assumed to correspond to the top of the clay layer. Assuming higher groundwater heads (closer to ground surface) in the open aquifer would result in greater pore-pressure, $u$ and lower effective vertical stress, $\sigma'_0$ (Berntson, 1983). Such assumptions thus result in a higher overconsolidation ratio (OCR) and a greater pre-consolidation margin ($\sigma'_v$-$\sigma'_0$), which means that the critical plastic phase in stage 2 is less likely to occur. Therefore, the given assumption is conservative since it results in greater subsidence magnitudes than the assumption of a higher groundwater head in the open layer. Based on these conditions, the pore pressure varies according to a straight line between the pressure at the bottom and the top of the clay layer which is presented in Fig. 4b (Jonas et al., 2017).

The deformation of a saturated granular medium containing water within its voids is governed by the effective stress ($\sigma'_0$). Here, the effective stress ($\sigma'_0$), i.e., the intergranular load distribution, is the total stress, $\sigma$ minus the pore pressure, $u$ (Fig. 4c). When a groundwater drawdown occurs in the confined aquifer, the pore pressure is reduced (Fig. 4d), which also results in a new effective (vertical) stress (Fig. 4e). In the case study, pore pressure reductions and changes in effective stress corresponding to 0.5, 1, and 2 m of groundwater drawdown in the confined aquifer are calculated at each grid point. As $\sigma$, $u$ and $\sigma'_0$ are simulated at each of the vertical grid points and at every 0.1 - m interval.

### 2.3. Study area and Geological setting

The Khorramabad plain is 144 km$^2$ due to the extension of the zonal-plain plateau in the middle of the mountain range. Area of Khorramabad in zone 39 with geographical features X: 250442 and Y: 3701991 has occurred (Fig. 5). The study area is located in the folded and driven Zagros pre-land belt and below the Lorestan area (Sarkarinejad and Ghanbarian, 2014) in the Zagros pre-land belt. The belt is divided into two domains with SW and NE trends (Agard et al., 2011). These two domains include:

- The folded Zagros pre-arid belt to the Persian Gulf has continued in relatively regular hundreds of kilometers

(Falcon, 1974; Sepehr and Cosgrove, 2004; Mouthereau et al., 2006), and also includes several main hidden faults (Berberian, 1995; Leturmy et al., 2010),

- High Zagros (HZ), this territory has a higher altitude than the folded belt.

Dashtaz road is connected to Khorramabad-Borujerd asphalt road, Khorramabad-Poldakhtar, Khorramabad-Chegni and Khorramabad-Noorabad to the center of the neighboring cities. The plain to be studied is part of the construction unit, which is the oldest and the heaviest unit in this limited area is related to the short period; the Khorramabad plain is covered with Quaternary alluvium. Quaternary alluvial sediments are susceptible to abrasion. These mountain structures are not tolerated, so their layers are horizontal and straightforward. Sediments in four rounds are most often seen in the area of the entrances or cores due to the erosion of the elevations at the base of the valleys (Fig. 6). Completed geophysical studies of wells drilled in Khorramabad plain alluvium show that the constituent layers of Khorramabad plain are composed of a high percentage of silt and clay with inclusion-sand, which is formed by loss of pore water due to weakened structure due to weak skeletal structure (Berberian, 1995).

## 3. Results and Discussions

### 3.1. Hydraulic condition

The number of wells removed from the aquifer of Khorramabad plain is about 500 wells. It is hoped that the aquifer will be emptied by wells. 7 rings arrived; in fact, the reason for the decrease in the number of these piezometers is that they are blinded due to the inability to withstand the particles that make up the alluvium around the wells. During a period of 15 years (1375-1391), the groundwater level drop in Khorramabad plain has an increasing trend and the average annual drop is calculated to be 0.52 meters. During these few years, the minimum and maximum aquifer drop in different parts of the plain between 7 to 20 Meters has dropped. Figure 5 shows the correlation diagram of the annual drop of each piezometer with the annual rainfall recorded in the Khorramabad plain (Figs. 7 to 9).

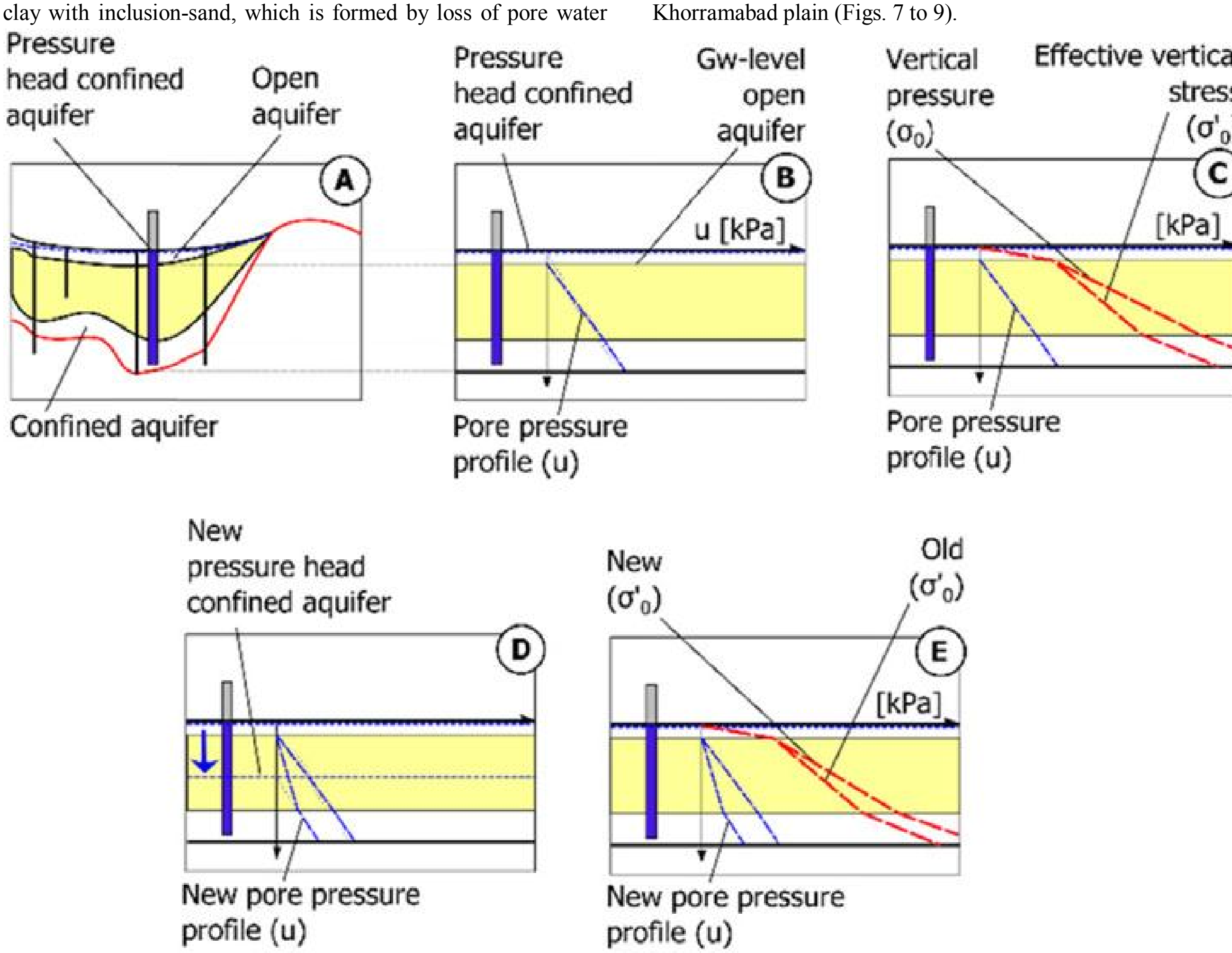


**Figure 4.** The simulation sequence in plains for open/confined aquifer: (a) pressure head, (b) pore-pressure, (c) effective vertical stress, (d) new-pressure head, (e) effective stress (Jonas et al., 2017).

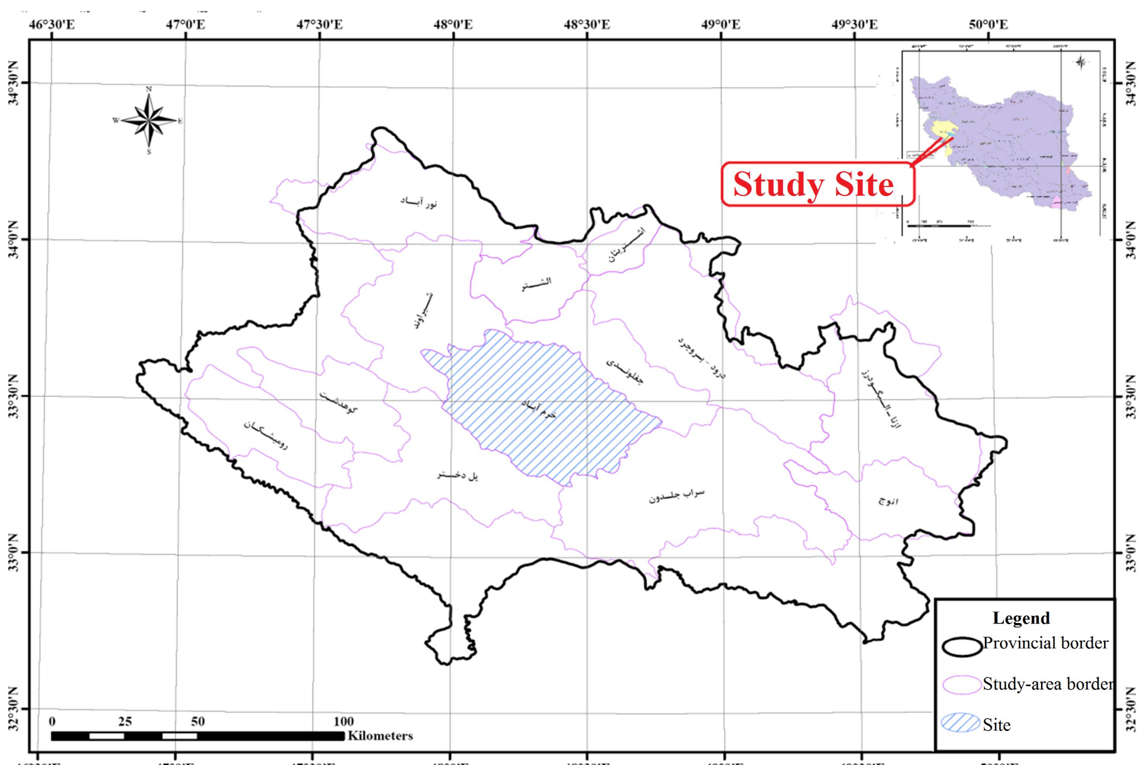


**Figure 5.** Location map of the study area in Lorestan province and Iran

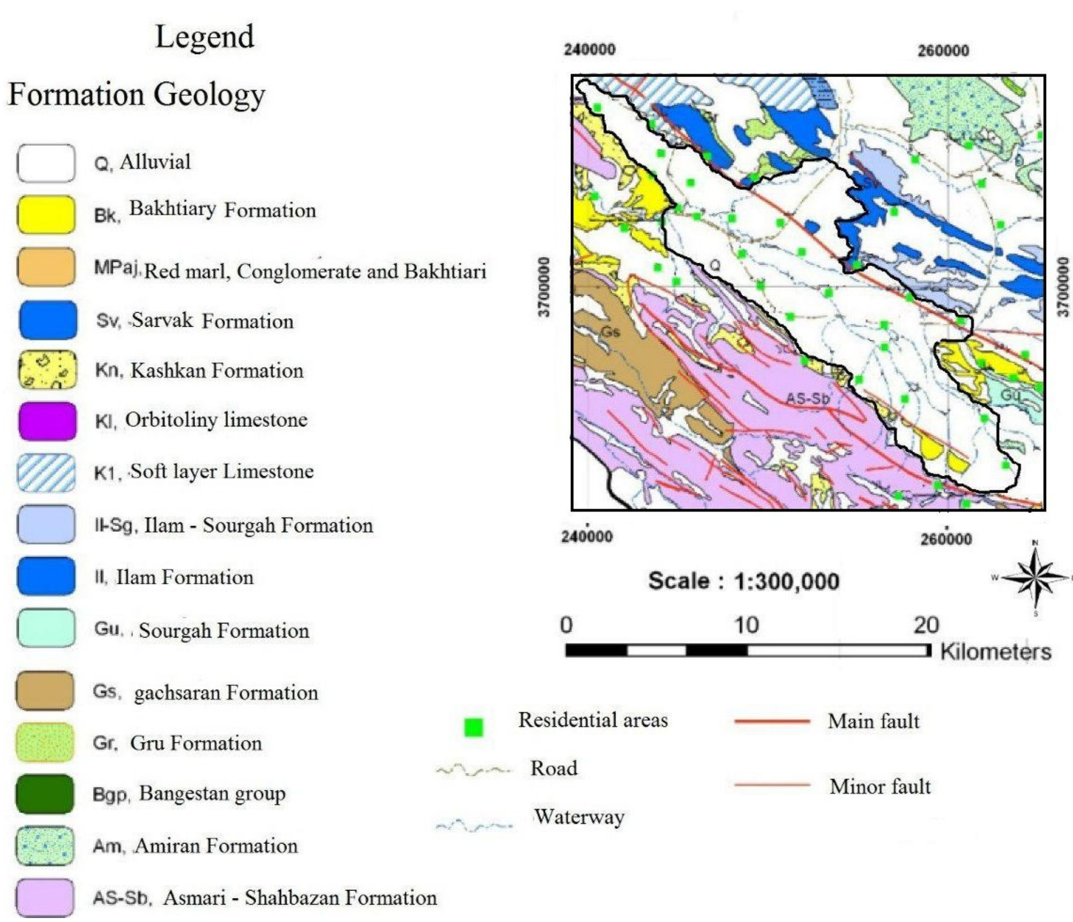


**Figure 6.** Geological map with separation of rock units

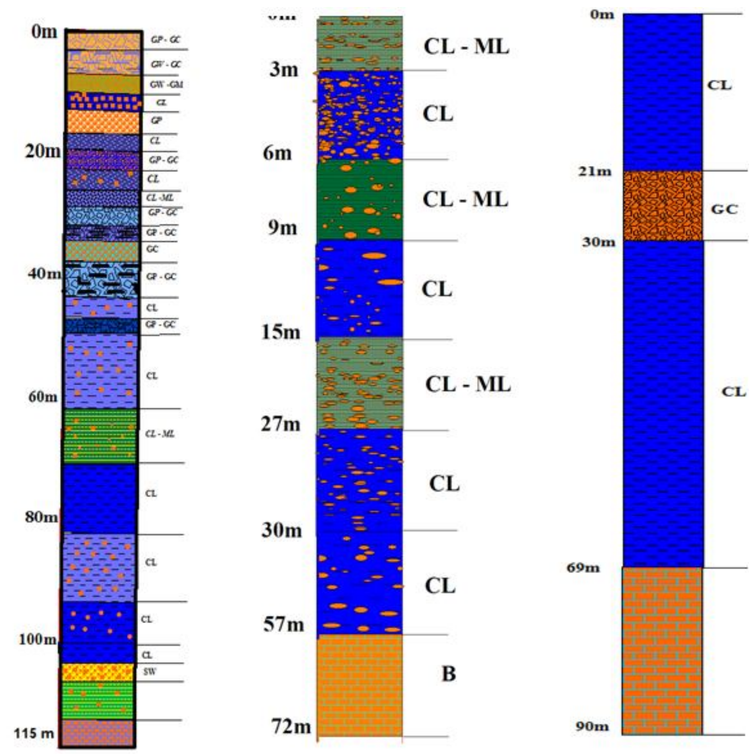


**Figure 7.** Drilling log of alluvial wells of Khorramabad plain aquifer

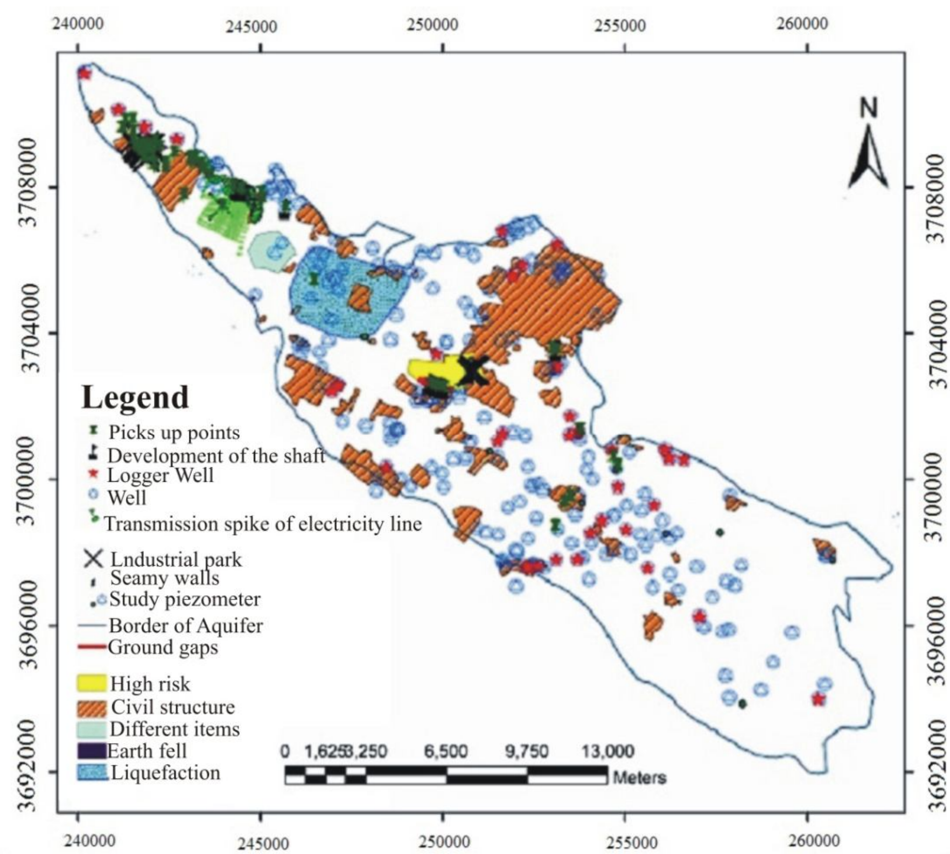


**Figure 8.** Evidence taken under different headings indicates the susceptibility of land subsidence to Khorramabad plain

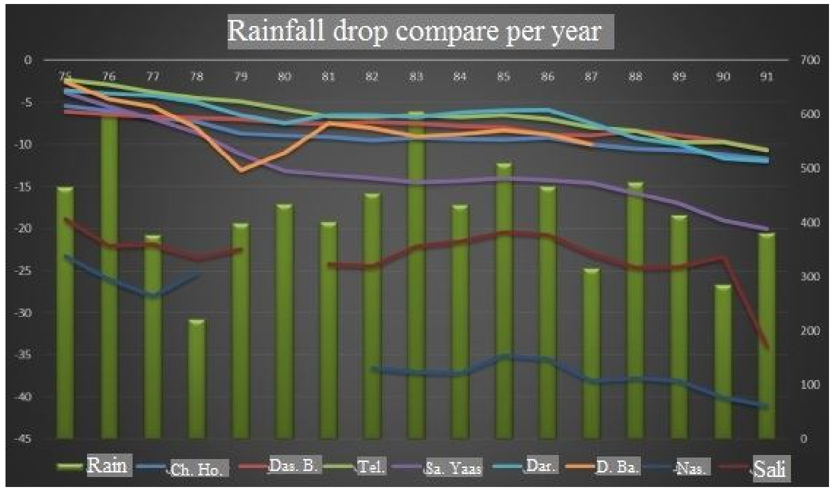


**Figure 9.** Graph of the plain unit hydrograph according to the annual rainfall rate per pizometer in relation to the annual rainfall rate of 15 years

### 3.2. Aquifer pore pressure changes

The main reason for the decrease in pore pressure and the increase in effective stress in the aquifer is the study of changes in the subsurface depth of the aquifer as a proof of the potential for sedimentation in the floodplain. The changes in the pore pressure of the aquifer, the strength of the structure of the aquifer and the particle size of the alluvium in the western half increase with the least to the eastern half and the most with the effective stress affecting the subsidence at any point in this direction (Fig. 10).

Assuming that the cubic element of the particles forming the alluvium on side contains 8 spheres with diameter d (a = 2d) in this case the volume of empty space (total porosity) which is based on the pore pressure between the particle grains which is negatively related to aquifer drop as the following Eq.:

$$\frac{a^3}{d^3} = 8; \quad V_s = \frac{a^3}{d^3} \times \frac{\pi d^3}{6} = \frac{\pi a^3}{6} = 0.523a^3 \tag{4}$$

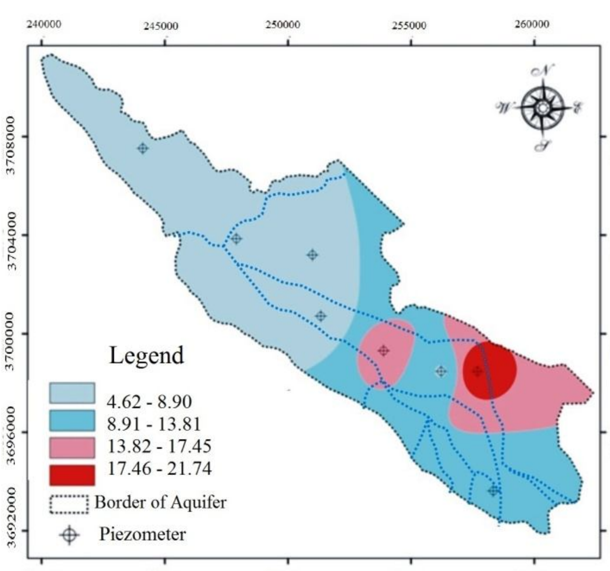


**Figure 10.** Weighting map of changes in the pore pressure of the plain aquifer

In fine-grained particles, in the most optimistic case, the subsidence cultivar with iromoboeder grain arrangement has a porosity percentage of less than 26%, and in the most pessimistic conditions, with the arrangement between eicobic grains, it has a weight percentage of more than 48% for land subsidence (Fig. 11).

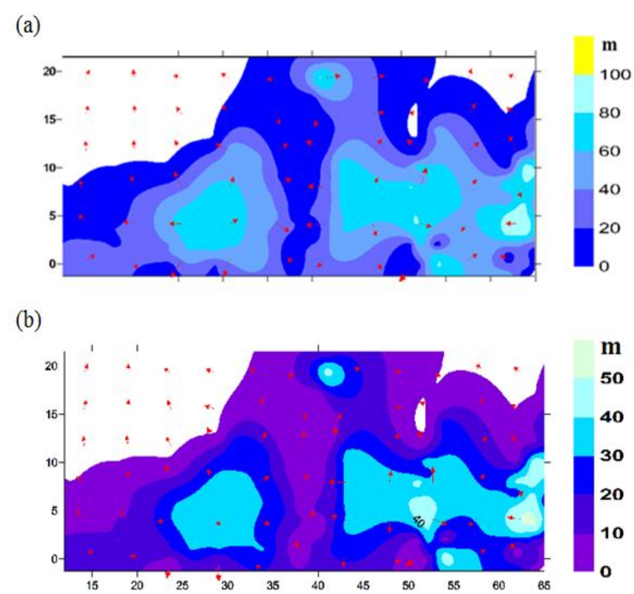


**Figure 11.** Estimation of porosity in plain aquifer: (a) 48% porosity, (b) 26% porosity

### 3.3. Evidence of Khorramabad Dashtasht land meeting

Khorramabad plain is one of the plains that has been affected by the subsurface of the subterranean surface which can be classified as:

- Occurrence of cracks in the surface of the surface of more than 600 meters in the production area with high overlap,
- Destroying agricultural lands and creating a long gap in the ground,


**Figure 12.** Evidence of subsidence due to increased effective stress of the drainage layers of the plain

- Update of the pavilion on the walls of buildings and civil structures such as industrial towns and roads,
- Curvature of the transmission poles of the power cable in the center of gravity in the shape of L,
- Degradation, tube growth and tube growth in harvested wells,
- Growth of tubules in existing wells.

## 4. Conclusion

Land subsidence is observed in parts of this plain due to exploitation, surface and groundwater level drop. Creation of longitudinal tensile gaps in the center and western half of Khorramabad plain and occurrence of elevation in agricultural lands in this region and destruction of residential and civil structures as a result of falling groundwater level and reduction of hydrostatic pressure in an environment with low electrical resistance and It is a fine-grained layer. The most important reason for subsidence and cracking of the earth is its natural reaction against over-exploitation of groundwater resources and increase of effective aquifer stress due to reduction of aquifer pore pressure. This phenomenon depends on several factors, including the characteristics and conditions of the exploitation area, which is sometimes quite complex. In the Khorramabad plain, in the eastern half of the plain, the maximum drop is 21 meters and in the western half of the plain with a minimum of 7 meters during 15 years. Removal has caused land subsidence in this area. In order to prevent the groundwater level from falling, which leads to an increase in effective stress and the occurrence of regional subsidence in the plain; changing the management of water abstraction from aquifers is a requirement and the use of appropriate cultivation patterns is essential. Another way to prevent this is to use the artificial aquifer feeding policy with rainfall in the plain, which flows out of the plain as a runoff.

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## References

Agard P., Omradi J., Jolivet L., Whitechurch H., Vrielynck B., Spakman W., Monie P., Meyer B., Wortel R., 2011. Zagros orogeny: a subduction-dominated process. *Geology Magazine*, 148(5-6): 692-725.

Berberian M., 1995. Master blind thrust fault hidden under the Zagros folds: Active basement tectonics and surface morphotectonics. *Tectonophys*, 241: 143-224.

Berntson J.A., 1983. *Pore Pressure Variations in Clay Soil in the Gothenburg Region (Portrycksvariationer i leror i Göteborgsregionen)*. Linköping, Swedish Geotechnical Institute, Sweden 289 p.

Budhu M., 2010. *Soil Mechanics and Foundations (3rd Edition)*. Wiley, 780 p.

David R., Pyne G., 1995. *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery*. CRC Press, 400 p.

Falcon N., 1974. *Southern Iran: Zagros Mountains*. In: Mesozoic-Cenozoic Orogenic Belts: Data for orogenic studies. Geological Society of London, Special Publication, 4: 199-211.

Hua Z., Tiezhu L., Xinhong L., 1993. Economic benefit risk assessment of land subsidence in Shanhai. *Environmental Geology*, 21: 208-211.

Jonas S., Haaf E., Norberg T., Alén C., Karlsson M., Rosén L., 2017. Risk Mapping of Groundwater-Drawdown-Induced Land Subsidence in Heterogeneous Soils on Large Areas. *Risk Analysis*, 39(1): 105-124.

Leturmy P., Molinaro M., de lamotte, F.D., 2010. *Structure, timing and morphological signature of hidden reverse basement faults in the Fars Arc of the Zagros (Iran)*. Book Chapter, doi: https://doi.org/10.1144/SP330.7.

Lofgren B.N., 1968. Analysis of stress causing land subsidence. *United States Geological Survey (USGS) proceedings*, Paper 600-B: 219-225.

Mouthereau F., Lacombe O., Meyer B., 2006. The Zagros folded belt (Fars, Iran): constraints from topography and critical wedge modeling. *Geophysical Journal International*, 165: 336-356.

Reddish D.J., Whittaker B.N., 1989. *Subsidence: Occurrence, Prediction and Control*. Elsevier Science, 528 p.

Sarkarinejad K., Ghanbarian M.A., 2014. The Zagros hinterland fold-and thrust belt in-sequence thrusting. *Journal of Asian Earth Sciences*, 85: 66-79.

Scott R.F., 1979. Subsidence-a review in evaluation and prediction of subsidence. In: *Proceedings of the International Conference on Evaluation and Prediction of Subsidence (Engineering Foundation Conference)*, Florida, USA, December 1979.

Sepehr M., Cosgrove J.W., 2004. Structural framework of the Zagros Fold-Thrust Belt, Iran. *Marine and Petroleum Geology*, 21: 829-843.

Terzaghi K., 1925. Principles of Soil Mechanics I—Phenomena of Cohesion of Clays. *Engineering News-Record*, 95(19): 742-746.

Terzaghi K., Peck R.B., Mesri G., 1996. *Soil Mechanics in Engineering practice (3rd Edition)*. John Willy & Sons, 540 p.

Zeitoun D.G., Wakshal E., 2013. *Fundamentals of the Consolidation Theory for Soils*. Book Chapter, doi: https://doi.org/10.1007/978-94-007-5506-2_4.