# Numerical investigation of swelling soil behavior and its effect on gas well casing internal forces based on unsaturated soil mechanics, case study: Khangiran, Sarakhs

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## ABSTRACT

**The majority of building and infrastructure projects are typically situated on soils that have a greater elevation than the underlying water table. As a consequence, these soils exist in an unsaturated state, resulting in the development of matric suction inside them. The manipulation of soil saturation levels significantly influences its mechanical and hydraulic characteristics. Swelling soils refer to a type of soil that undergoes volumetric expansion as a result of moisture absorption and a subsequent decrease in matric suction. Hence, this matter gives rise to irreversible harm in the realm of infrastructure, transportation networks, and facilities such as oil and gas. This study focuses on the numerical analysis and discussion of the swelling soil surrounding a gas well located within the Khangiran gas refinery. The findings from the numerical simulation demonstrated that, at the critical juncture of the steel pipe within the well structure, the tensile force induced by soil expansion infiltrates the surrounding area. To withstand this force, the design and permissible thickness of the well pipe can be evaluated using two approaches: load coefficients-resistance and allowable resistance. The action is permissible. The findings indicate that the thicknesses obtained are relatively small, thereby suggesting that there is no significant risk associated with soil swelling and the resultant tensile force exerted on the well casing. However, it is important to note that the durability of the well body's steel material over time is crucial in preventing breakage due to soil swelling-induced tension**

## KEYWORDS

**Swelling soil, Unsaturated soil mechanics, Numerical modeling, Khangiran Sarakhs gas zone, Gas well**

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## 1. Introduction

Expansive soils undergo volume changes based on water content, especially swelling types due to clay minerals like smectite, which absorb water [1]. Their behavior in unsaturated states is critical due to potential structural damage. Al-Yaqoub et al. [2] examined loading rates, types, and overburden's effect on soil deformation, noting decreased swelling pressure with more cycles and higher initial moisture. Zhang and Feng [3] found matric suction increases from 100 to 200 kPa raised deviatoric stress in unsaturated clay at higher pressures. Trinh [4] used GeoStudio to model rainfall-induced swelling, affirming reliable predictions with coupled and uncoupled methods. Rajeev and Kodikara [5] used FLAC 3D for soil-pipe interactions in swelling soils, matching experiments. Al-Juari et al. [6] compared swelling pressures in retaining walls, revealing reduced effects with depth. Nadi Yezdi et al. [7] used apparatus to study cement's role in lowering swelling pressure. This research models the volume change behavior of a specific expansive soil under varying matric suctions and confining pressures using GeoStudio. Objectives include assessing the effects of suction and pressure on soil around Khangiran gas wells, the impact of annual rainfall, tensile forces on well casings, and the likelihood of casing failure over time.

## 2. Materials and Methods

### 2.1. Soil Properties

The soil used in this study was collected from the Khangiran operational area of Iran's largest oil industry (Figure 1).

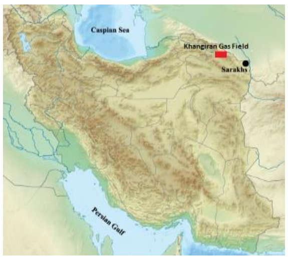


**Figure 1 - Geographical location of the soil of the studied area [7]**

Based on initial tests on the collected soil samples, the soil was classified as CL according to the Unified Soil Classification System (USCS). Additional tests and standards provided further soil specifications, summarized in Table 1. Given the Atterberg limits obtained, the soil's relative swelling potential is moderate based on various criteria. The soil's grain size distribution is shown in Figure 2.

**Table 1. Characteristics of the soil [7]**

| Test | Specification | Result |
|---|---|---|
| Soil Gradation | ASTM D422-63 | Passing percentage of sieve #200 = 91.43% |
| Density of solid grains | ASTM D854 | 2.7 |
| In situ Soil moisture | ASTM D2216-19 | 19% |
| Atterberg limits | ASTM D4318 | PL=23 % , LL=42% |
| Apparent specific gravity | ASTM D1556/1556M | 1.837 |
| Gypsum (%) | ASTM C25-19 | 3.212 |

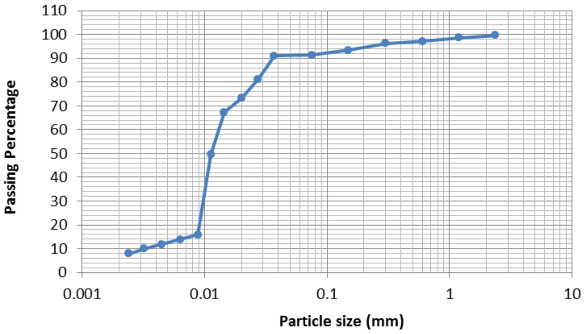


**Figure 2- Particle size distribution of the studied [7]**

The soil-water characteristic curve (SWCC) was determined using unsaturated consolidation, following Nadi Yazdi et al. [7] (Figure 3). The air entry value (AEV) is 49 kPa, with Aubertin et al.'s modified Kovacs method predicting an AEV of 53 kPa, close to the lab result. Figure 3 shows good agreement with curves from three-bar and five-bar pressure plate tests.

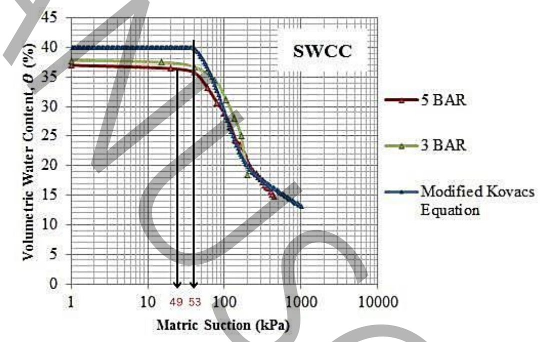
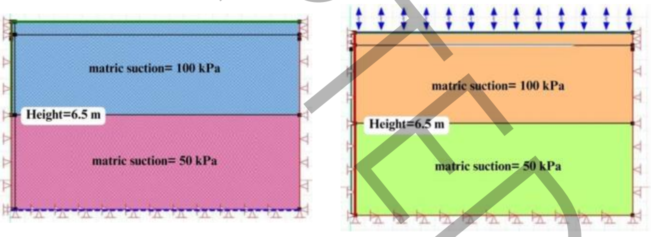


**Figure 3-Soil-water characteristic curve (SWCC) of the studied soil [7]**

### 2.2. Numerical Modeling

Gas well modeling in this region considers a groundwater level 13 meters below ground, influenced by soil suction post-rainfall (100 kPa, down from 130 kPa pre-rain). Modeling excludes saturated depths unaffected by rain-induced swelling. The process involves two stages: analyzing soil stress without the well and simulating well drilling and steel casing placement (Figure 4a). The outer casing is 26 inches in diameter, with the gas well at 7 inches. The steel casing, 1.61 cm thick, is stainless steel with a tensile strength of 655 MPa, exceeding ST37 steel's yield strength of 362 MPa. Rainfall moistens the upper soil, lowering suction. Soil is divided into upper (100 kPa suction) and lower (50 kPa suction) sections for precise calculations. The model spans 5 years, 258 days (50,000 hours), stabilizing water conditions and observing swelling effects. Figure 4b illustrates the final model incorporating climate conditions. Boundaries prevent movement, showing soil swelling-induced height changes without steel casing shear forces.



**(a)** **(b)**

**Figure 4- A view of the built model and soil division, (a) before and (b) after flow analysis**

## 3. Results and Discussion

### 3.1. Soil Effective Elasticity Modulus

The elastic modulus due to pre-rainfall swelling and during gas well construction is calculated using triaxial unsaturated test results. With initial moisture content (*w*) at 19%, volumetric moisture content (*q*) estimated at 29%, corresponding to a soil suction of 100 kPa. Triaxial tests at 100 kPa suction determine the soil's elastic modulus 7 m above ground, while at 6 meters depth, the average suction is 50 kPa. The Hyperbolic model is applied for modulus calculation, revealing that higher soil suction increases modulus, indicating greater stiffness and reduced displacement. The relationship between soil elastic modulus and post-rainfall effective stress is illustrated in Figure 5.

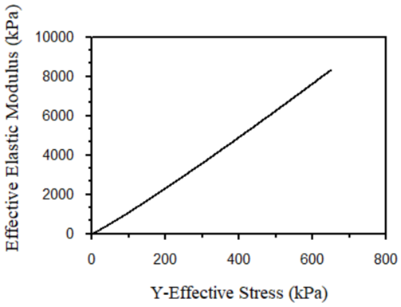


**Figure 5 - Diagram of the effective modulus of elasticity versus the effective vertical stress after flow analysis**

### 3.2. Pore Water Pressure in Soil

After constructing and analyzing the model per the Materials and Methods, a specific point 2 meters deep at the model's center is selected to study pore water pressure and displacements in the soil. Using precipitation data from September 2018 to September 2019. From day 1 to 240 days post-rainfall start, both pressure and suction decrease, reflecting peak soil moisture. Subsequent heat and reduced rainfall until September increase soil dryness, stabilizing pore pressure around 1600 days, indicating stable water flow. Figure 6 confirms water flow effects from a year of rainfall dissipate after about 1600 days, with analysis extended to 2083 days.

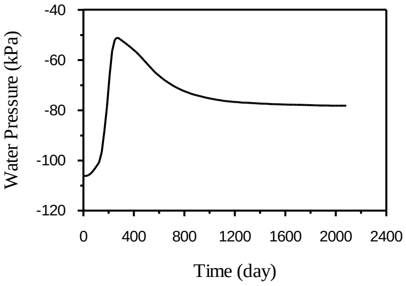
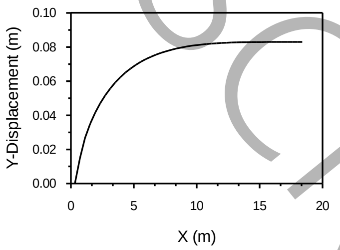


**Figure 6 - Diagram of pore pressure changes over time at the desired point**

### 3.3. Soil Displacements

Significant swelling occurred in the modeled soil after 2083 days of modeling. Approximately 5.8 cm of swelling was observed over 13 meters, constituting 0.70% of the total model. Figure 7(a) shows that vertical displacements stabilize beyond approximately 15 meters horizontally from the casing. Figure 7(b) illustrates vertical displacement over time at a depth of two meters in the model's center. Swelling continues due to water infiltration for up to 1600 days, followed by stabilization, indicating no further swelling.



(a)

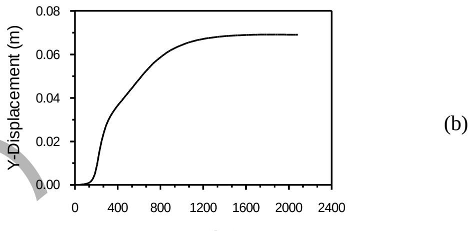


**Figure 7 – (a) vertical displacement diagram along the horizon, (b) vertical displacement diagram over time**

### 3.4. Forces in the Well Steel Body

Figure 8 illustrates axial force distribution in the steel casing after one, two, and three years. Changes in axial force reveal varying soil behavior influenced by suction and shear resistance. Increased soil suction increases stiffness and reduces displacement, lowering axial forces in the top six meters of the casing due to swelling. This reduction contributes to fractures observed in axial force diagrams over time along the casing. After 1600 days, soil water flow stabilizes, halting further swelling and fixing axial forces. The maximum axial force, 163 kN, occurs at the critical point. Current 1.61 cm steel thickness proves adequate against soil-induced tensile stresses, barring extensive corrosion, aligning with prior studies [8-9].

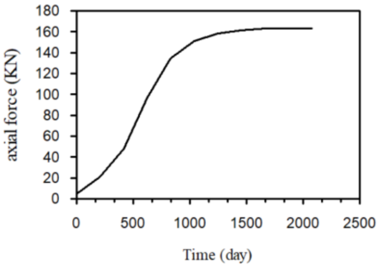


**Figure 8 - Diagram of axial force over time for the critical point in the steel body of the well**

## 4. Conclusions

This study focused on numerical modeling of the soil around a gas well in Khangiran, Sarakhs. The modeling considered the region's climate from late 2018 to mid-2019, determining soil swelling and tensile forces on the steel casing of the well, and identifying the minimum required thickness to withstand these forces. Key findings are summarized below:

- Before rainfall, soil matric suction was 130 kPa. It takes about 3.4 years for rainfall to fully impact soil swelling to a depth of 13 m, with annual swelling of 8.49 cm.
- Swelling is minimal near the well but increases with distance, peaking further away.
- The gas well structure enhances soil stiffness within a 15-meter radius.
- Maximum tensile force of 163 kN occurs at the steel casing's lowest point, 13 m deep, due to swelling-induced forces.

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