Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1334

Modeling geometrical effects on the mechanics of underground gas reservoir

Chen Greenwald-Khudadadi, Shmulik Pinkert
Department of Civil and Environmental Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel, pinkerts@bgu.ac.il

ABSTRACT: Underground gas storage is considered a potential solution for increasing energy efficiency by utilizing natural geological structures characterized by high porosity and permeability. The success of the storage process and the stability of the reservoir depend significantly on the mechanical properties of both the reservoir layer and the overlying caprock. This study examines the impact of caprock geometry on the mechanical stability of the reservoir. As part of the research, a numerical framework was developed in the FLAC3D software, allowing the implementation of diverse geometries and mechanical properties, and the incorporation of advanced constitutive models of the subsurface material. The use of simplified geometries, with a well-defined curvature, enables a schematic investigation of the geometry effect, in the context of reservoir stability during the cyclic gas storage/withdrawal process. The results are interpreted in terms of the interactions between mechanical properties—such as strength, stiffness, and stress regimes—and the geometric characteristics of the layers. In particular, the relationship between the mechanical properties of the reservoir and caprock layers was identified as a critical factor influencing the stability of the system. These findings offer valuable mechanical insights that can be utilized to optimize the design and operation of underground gas reservoirs under diverse operational conditions.

KEYWORDS: Gas reservoir, stability, numerical modeling, caprock geometry.

1 INTRODUCTION

The need for energy storage solutions is growing as part of efforts to improve energy efficiency and reduce carbon footprints (Lebrouhi et al. 2022). In particular, underground gas storage is being considered as a viable option. This type of storage utilizes natural subsurface geological structures, which provide larger storage volumes compared to artificial solutions (Uliasz-Misiak et al. 2024; Saberi Mehr et al. 2024). This process allows for the storage of significant quantities of gas safely and efficiently, with a cyclic monthly/seasonal/annual process of compression and extraction (Sainz-Garcia et al. 2017).

In addition to the reservoir properties (rock/soil) required for gas storage in pores (such as porosity and permeability), the impermeability of the geological layer above the reservoir layer is critical for its existence (Carden and Paterson, 1979; Zhang et al. 2024). The caprock layer prevents gas leakage upward, thereby ensuring that the full stored amount remains within the dedicated reservoir area. Furthermore, this layer must provide mechanical stability during the gas storage and extraction process (Zhu et al. 2022; Wen et al. 2024). Properties such as strength, stiffness and stress regime affect the layer's ability to maintain stability under changing conditions (Zeng et al. 2023). The reservoir stability depends on the relationships between these mechanical properties of the caprock layer and the reservoir layer. Moreover, the geometric structure of the reservoir influences the stress regime within both the caprock and the reservoir rock, such that it can influences the overall stability dramatically (Ghaedi et al. 2024).

Since the storage/extraction process is cyclic, additional mechanical effects related to the cyclic nature of loading may occur, affecting on the overall stability. Generally, cyclic loading can degrade reservoir properties from cycle to cycle and accumulate residual strains. In this way, not only can stability be compromised, but reservoir volume may also decrease over time, potentially reducing its efficiency and economic viability. Additionally, the storage process increases gas pressures in the pores, which reduces the effective stress in the reservoir layer and increases its instability (Zeng et al. 2023; Ramesh Kumar et al. 2023).

The literature discusses reservoir instability in two primary contexts: (1) local instability (Deng et al. 2024), which involves the development of cracks within the caprock layer that can lead to gas leakage, and (2) instability associated with the potential mechanical collapse of the caprock itself. Additional concerns in the literature related to reservoir geometry focus on the potential storage volume of the reservoir. In this work, we focus on the stability of the caprock layer, within the context of industrial gas storage operations.

In anticline-type gas reservoirs, the caprock exhibits a convex geometry that enhances gas storage by trapping energy gases such as hydrogen and methane, which naturally migrate upward. This geometry is also associated with mechanical phenomena such as stress arching (Terzaghi, 1943) which can amplify mechanical responses during engineering operations like gas injection or extraction, beyond the inherent strength properties of the rock mass. This study systematically investigates the interplay between reservoir geometry and elevated pore pressure conditions, and their combined effects on the mechanical stability of underground gas storage systems. The paper identifies and analyzes the fundamental factors necessary for accurately modeling the influence of reservoir geometry, and demonstrates these factors through representative examples of geological gas storage.

2 MODELING PRINCIPLES

A subsurface gas reservoir can be conceptually described as comprising four primary layers: the foundation layer, the reservoir layer, the sealing (caprock) layer, and the overburden. Each of these layers possesses distinct geological and mechanical characteristics, which require different emphases in numerical modeling.

2.1 *Reservoir Geometry*

The geometry of subsurface layers is characterized by parameters such as curvature, inclination, variable thickness, and structural continuity. While natural subsurface geometries are often irregular, numerical models can approximate them using well-defined mathematical functions, which enable easier implementation and systematic analysis.

2.2 *Distinction Between Subsurface Layers*

Transitions between layers may arise from differences in material composition; for instance, between rock types with varying mechanical properties. Other transitions can be as an outcome of differences in phase state, such as between watersaturated and gas-filled zones, even within the same rock type. In both transition cases, these interfaces represent subsurface discontinuities that have critical implications for the development of stress fields and long-term reservoir stability. Accurate modeling of such interfaces requires careful consideration of both the geometrical configuration and the contrasting properties of adjacent layers.

2.3 *Application of Pore Pressure During Injection*

During the operation of an underground reservoir, pore pressure within the reservoir layer gradually increases, affecting the effective stress state within the rock mass. An accurate mechanical analysis of this process requires a numerical model capable of simulating stepwise pressure loading to capture the evolution of stresses and their dependence on the layer geometry. A slow, incremental application of pressure is essential for accuracy, as rapid loading may introduce dynamic effects that do not faithfully represent the actual storage conditions.

2.4 *Boundary Conditions*

Boundary conditions play a crucial role in determining the mechanical response of the reservoir to external loads. Typically, the model's lower boundary is fixed to prevent displacement, while the upper surface is subjected to the weight of the overburden, and the lateral boundaries are constrained to simulate the in-situ earth pressure at rest. In cases where the reservoir geometry is symmetric, the number of numerical elements can be reduced by exploiting this symmetry, provided that the boundaries along the symmetry axis are properly constrained. The influence of boundary conditions becomes even more pronounced in models of irregular geometries—such as domed or inclined structures—where improperly defined boundaries may induce artificial stress concentrations and lead to inaccurate results.

3 NUMERICAL APPLICATION OF GAS RESERVOIR

For the purpose of numerical simulation of a subsurface reservoir, a model was constructed in FLAC3D (Itasca, 2023) consisting of four primary layers: the source rock layer, the reservoir layer, the sealing (caprock) layer, and the overburden layer. Figure 1 illustrates the finite element mesh of a three-dimensional numerical model representing a typical aquifer reservoir. The geometry of the aquifer is idealized using a bell-shaped function that is symmetric along both the X and Y axes but characterized by distinct variances in each direction. To enhance computational efficiency, the model simulates only one-quarter of the total reservoir volume by taking advantage of the geometric symmetry.

In the presented case, the caprock is modeled as a continuous (without cracks) layer of uniform thickness. Its geometry is described using a Gaussian function, which serves as an effective mathematical approximation of a natural structural gas trap, given by:

$$f(x,y) = Ae^{-\left(\frac{x^2}{2B^2}+\frac{y^2}{2C^2}\right)} \tag{1}$$

where the amplitude A represents the maximum height of the dome, while the parameters B and C define the spread in the x and y directions, respectively. This mathematical representation was implemented using the FISH programming language, enabling flexible and systematic parametric studies.

The reservoir and the underlying (source) bedrock are assumed to possess identical mechanical properties; the distinction between them arises from the composition of the fluids saturating the rock pores. While the bedrock may be saturated with a high-density fluid, the reservoir contains a low-density gas. As such, the two layers are visually distinguished in the figure (by red and green colors). Due to the considerable thickness of the overburden layer, reported in the literature to as approximately 1000 m or so (Ghaedi, Andersen, & Gholami, 2024), only a portion of its full thickness was modeled. Equivalent vertical and horizontal loads were applied instead, simulating the removed weight of the layers. Additionally, significant artificial strength was assigned to this layer to ensure that failure would occur within the caprock rather than the overburden.

Fixed constraints were applied along the planes of symmetry due to the quarter-reservoir configuration. The remaining model boundaries were positioned at a sufficient distance from the reservoir and were also assigned fixed boundary conditions to minimize boundary effects on the region of interest.

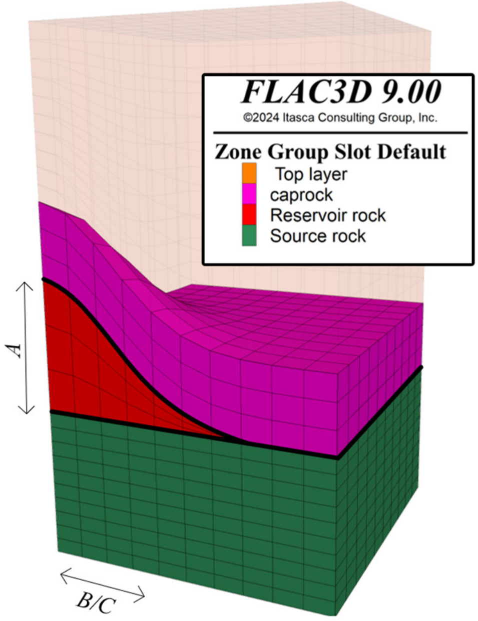

Figure 1. 3D numerical model representing a multi-layered subsurface model. The caprock geometry is defined by a Gaussian profile, simulating a structural trap above the reservoir layer. The model was developed using FLAC3D 9.00.

4 MECHANICAL EFFECTS DURING PORE-PRESSURE LOADING

Applying internal stresses within numerical model elements is a non-trivial task, particularly when dealing with loads that do not arise from the material's self-weight or intrinsic density. In the present model, which simulates a subsurface reservoir subjected to gas pressure within pore spaces, loading was implemented via a hydrostatic pore pressure field without updating the rock density to reflect gas saturation. In computational environments where direct implementation of artificial gas pressure is not supported, manual adjustments must be made. Specifically, the stress field is modified to incorporate the effect of the applied pore pressure on the effective stress field.

Figure 2 presents the vertical stresses distribution under two conditions: (a) the initial state, in which the reservoir is empty and the pore pressure is zero, (b) a filled reservoir, where pore pressure is applied exclusively within the reservoir layer. Although pore pressure is applied solely within the reservoir, a pronounced effect is observed in the surrounding rock layers, particularly in the caprock. This is indicative of the arching effect, in which the internal pressure reduction within the reservoir alters the stress regime and leads to load redistribution toward adjacent layers. This phenomenon highlights the importance of accounting for interactions between the reservoir and its surrounding geological units, in which even localized changes in pore pressure can significantly influence the mechanical response of the entire system.

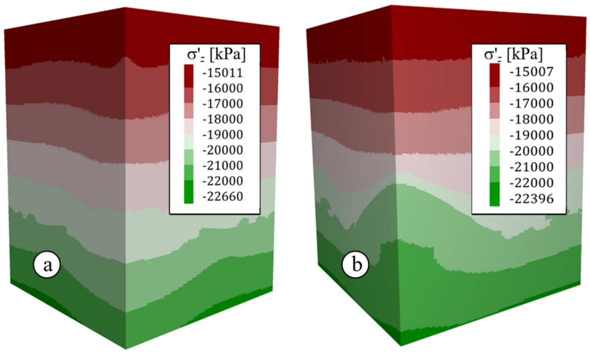

Figure 2. Vertical stress fields (a) at the initial state, without pore pressure loading, and (b) when applying pore pressure at the reservoir rock.

While Figure 2 illustrates the arching effect on a global scale, by presenting changes in vertical stress field in response to increasing pore pressure, Figure 3 offers a more localized and quantified perspective on the development of the phenomenon. This figure demonstrates the influence of reservoir pore pressure on both the magnitude and orientation of the principal stresses at a representative point within the caprock layer. The illustration quantitatively highlights the gradual development of the arching effect as pore pressure rises, reflected by changes in the principal stress values and their directional rotation. Specifically, it can be observed that as pore pressure increases, the orientation of the principal stresses gradually aligns with the geometry of the caprock. Simultaneously, the major principal stress increases while the minor principal stress decreases, resulting in a net increase in deviatoric stress. The examined point (marked by a red dot in the figure) is located at $x = B = 70$ m and approximately 10% of the caprock thickness from the base. This location was chosen due to its proximity to the inflection point of the shape-function describing the caprock geometry, which expected to exhibit significant stress variation. Simultaneously, the selected point lies deep enough within the caprock to minimize the influence of numerical inaccuracies near the layer interfaces, making it a reliable observation point for tracking local principal stress evolution in response to the pore pressure change.

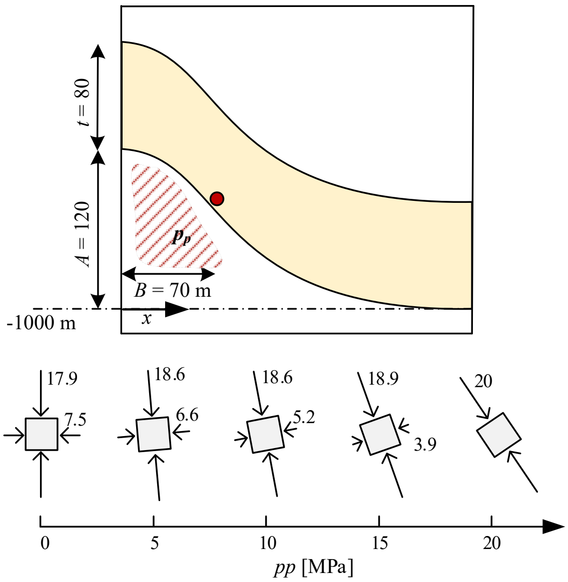

Figure 3. Evolution of principal stress magnitudes and orientations in a representative model element, as a function of pore pressure development within the reservoir.

5 MECHANICAL EFFECT OF THE RESERVOIR GEOMETRY

Since the arching phenomenon described above arises from the mechanical redistribution of stresses within the subsurface, the geometry of the caprock plays a direct role in influencing this mechanical behavior. Figure 4 illustrates the relationship between the caprock geometry and an index that reflects reservoir stability or safety. In this study, the selected index is the Strength-Stress Ratio (SSR), which is implemented in FLAC3D (Itasca, 2023) and serves as an indicator of the proximity of the local stress state to shear failure. The SSR is defined as follows:

$$SSR = \left| \frac{\sigma_1' - \sigma_3}{\sigma_1 - \sigma_3} \right| \leq 10 \qquad (2)$$

where σ_1 and σ_3 are the current effective major and minor principal stresses, respectively, and σ_1' is the value of the major principal stress required to bring the element exactly to the failure envelope (keeping σ_3 constant), according to the Mohr-Coulomb criterion. This ratio functions as a local safety factor, with SSR = 1 indicating failure and higher values representing an increase of safety. Unlike global safety factors, SSR is a purely local indicator defined at the element level.

The graph in Figure 4 presents the SSR behavior for three different reservoir geometries characterized by varying amplitudes (A = 30, 70, and 120 m), while all other geometric parameters remain constant: the spread-deviation values ($B = C$ = 70 m), caprock thickness (t = 100 m), and observation point location (x = 50 m). The simulation results reveal a clear trend: as pore pressure in the reservoir increases, the SSR value decreases, indicating a gradual approach toward failure. However, the rate of this decline is strongly dependent on the reservoir geometry. For higher amplitudes, a steeper drop in SSR is observed, suggesting greater sensitivity of the system to pressure changes. In contrast, for lower amplitudes, the influence of increasing pore pressure on SSR is relatively minor. This phenomenon highlights the strong link between caprock geometry and the mechanical behavior of the reservoir, underscoring the importance of incorporating the reservoir geometry effect into the design and stability assessment of underground gas storage systems.

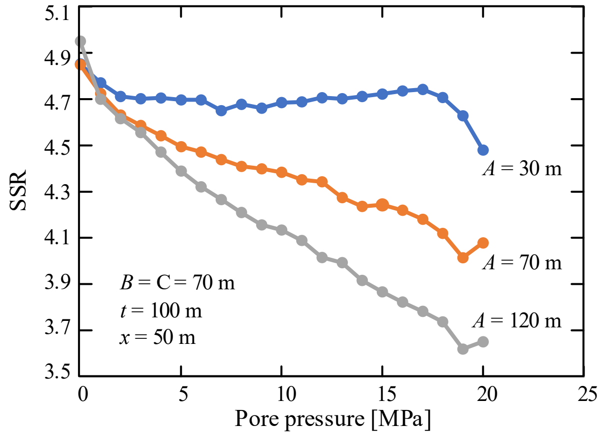

Figure 4. Effect of pore pressure on SSR, depending on the reservoirs' amplitude.

6 DISCUSSION AND CONCLUSIONS

The findings of this study underscore the central role of reservoir structural geometry in shaping the resulting stress field induced by the increase of pore gas pressure. Specifically, the research focuses on the influence of amplitude, A, representing the height of the caprock dome. The results demonstrate that variations in amplitude alone have a significant impact on the intensity of the arching effect: higher amplitudes lead to increased stress concentration within the caprock layer and an accelerated decline in local stability. These observations highlight the direct and substantial contribution of A on the mechanical behavior of the reservoir, even when all other geometric parameters remain constant. This influence is reflected in a steeper decrease in SSR values for high-amplitude reservoirs, indicating greater proximity to failure. In contrast, in reservoirs with low amplitude (i.e., flatter geometries) the stress distribution remains relatively uniform, the arching effect is more moderate, and the impact of pore pressure on SSR is less pronounced.

These insights emphasize that the arching effect links between geometry effects and the mechanical behavior of the reservoir, governing the stress redistribution, both locally and globally, as well as the system's response to pressure changes. Based on the developed methodology, this study also demonstrates the potential of systematic investigation through numerical simulations. The use of flexible programming tools and the integration of built-in parameters, such as the SSR, enable controlled parametric analysis of geometric variables, mechanical properties, and their interactions.

The model developed in this study provides a convenient foundation for extending the research toward additional geometric parameters (other than A) with potential influence on reservoir behavior. One can also expand the model to incorporate other effects, such as non-symmetrical or inclined geometries, nonlinear material behavior, caprock fracturing, etc. Finally, analyzing cyclic scenarios of reservoir filling and depletion, along with models that account for time-dependent changes in rock properties, may offer further insights into the dynamic stability of underground gas reservoirs and their engineering implications.

7 ACKNOWLEDGEMENTS

This research was partially supported by the Israel Ministry of Energy under the Program for Funding Studies in the Energy and Earth Sciences (Contract No. 222-17-004), and by the Ministry of Innovation, Science and Technology through the Binational Research Program (Contract No. 1001573480).

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