

Tarmat Layer Geo-mechanical Behavior under Producing Oilfield

By

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1. Introduction

Tar-mat zones have been characterized at the base of oil columns in several giant carbonate reservoirs all over the world. These zones form a barrier with almost zero permeability that physically isolates the producing zones and the high pressure aquifer or injection water wells beneath the HC reservoir⁽¹⁾. As a result of this barrier, the reservoir pressure will decrease while production, which will require other means to enhance the pressure of this reservoir. A key parameter on the studies made on this field is the structural behavior of this tarmat layer under varying conditions. Especially the time when the tarmat failure occurs and a fracture happened during the production causing a better communication between the water drive aquifer and the oil reservoir.

Figure 1.1 below shows the tarmat concept.

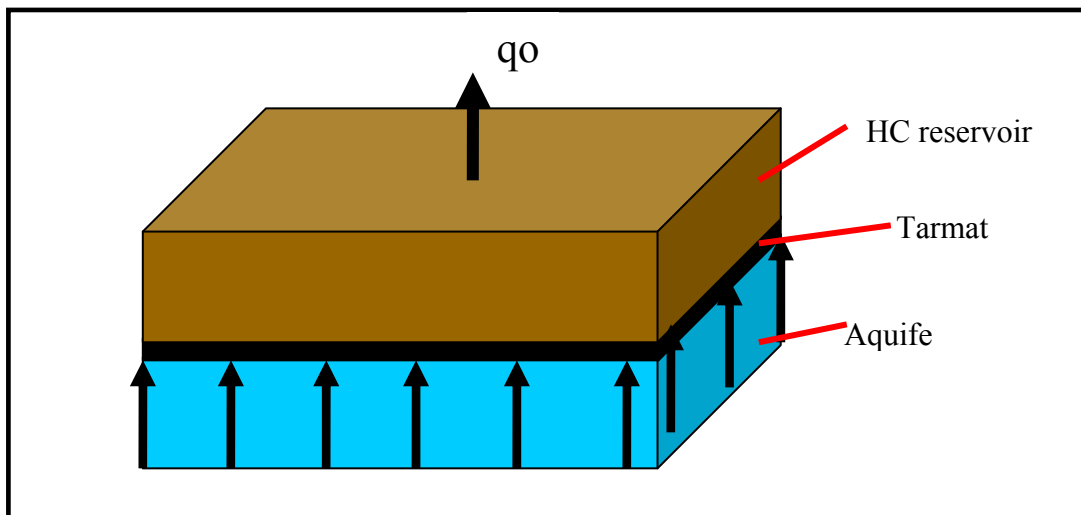


Figure1.1: Tarmat layer in our study occurs between the aquifer and HC layer.

Increasing the pressure difference between the aquifer and the HC reservoir will cause a deformation of the tarmat layer at which it will break and cause a fracture on that layer at some point. Figure 1.2 shows a possible deformation structures on that layer.

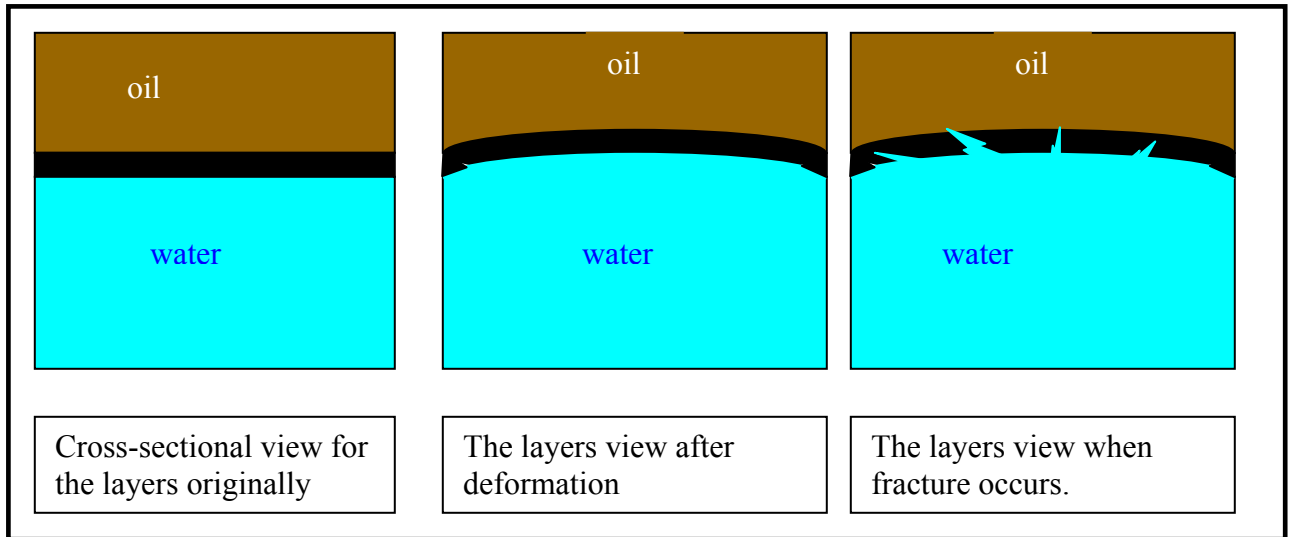


Figure1.2: Tarmat layer deformation process and fracture occurrences.

The fractures in this situation are favorable since they are going to create a connection channels between the isolated layers and in turn give a more supported pressure HC reservoir.

Mechanical behavior in porous media involves mainly two basic elements: fluid flow and rock deformation ⁽²⁾. It is more accurate if both behaviors coupled together in the FEM simulation. Traditionally, the simplistic approach in reservoir simulation estimates the rock deformation using only the pore compressibility which is a function of pore pressure. This will give inadequate results and will lead to wrong predictions. This is why it is important to work with a coupled model where the dependence of flow and deformation on each other can be modeled simultaneously.

2. The physical description and the governing equations:

In its accurate formulation, modeling the dynamic of the middle layer between two active reservoirs requires coupling between fluid pressures and the deformation of the rock system⁽²²⁾. In this study, formulation of fluid flow through porous media for water layer and mechanical behavior of the tarmat layer will be shown, the energy (heat) equation will not be considered.

2.1 The fluid flow equation for water (single phase, incompressible):

$$\frac{\partial}{\partial t} M - Q = -\nabla \cdot q_w \quad (1)$$

$$\text{Where: } M \text{ is the mass per unit volume and } M = \phi \rho_w \quad (2)$$

and Q is the source term.

$$\text{Applying Darcy's law: } q_w = -\rho_w \frac{k}{\mu} (\nabla P - \rho_w g \nabla z) \quad (3)$$

2.2 The mechanical governing equation (equation of motion) is :

$$\nabla \cdot \sigma + \rho_m g = \rho_m \frac{dv}{dt} \quad (4)$$

Where σ is the total stress tensor, ρ_m is the average rock density and v is the solid velocity w.r.t. a fixed system. Equation (4) is in its iterative manner with a stress- strain law. For each time step, the incremental stress and strain is governed by elasto-plastic constitutive laws and in general written as

$$\Delta \sigma' = H(\sigma', \dot{\varepsilon} \Delta t) \quad (5)$$

Where H contains the material functions, $\dot{\varepsilon}$ is the infinitesimal strain-rate tensor and Δt is the time increment.

The infinitesimal strain rate $\dot{\varepsilon}$ and the infinitesimal strain ε are governed by

$$\dot{\varepsilon} = \frac{1}{2} (\nabla v + (\nabla v)^T) \quad \text{and} \quad \varepsilon = \frac{1}{2} (\nabla u + (\nabla u)^T) \quad (6)$$

Where u is the displacement vector

The constitutive laws in (5) work in the effective stress:

$$\sigma' = \sigma + I\alpha P \quad (7)$$

where α is Biot's effective stress parameter, σ' is the effective stress, σ is the total stress and P is the pore pressure⁽¹⁵⁾.

3. COMSOL Formulation:

Generally, for fluid flow system, the pressure distribution can be governed by the Darcy's flow equation. Rock displacements "strains" can be measured from the mechanical governing equation. In this study both were coupled to check the combined effect from fluid flow and strain effect on the pressure distribution, total displacement and permeability changes observed.

The geometry is simplified with 2D plot that contains three layers with the middle layer having a tighter permeability and was linked to the strain effects on both x and y directions as follows ⁽²³⁾:

$$K = \sqrt{K_x * K_y}$$

$$\Rightarrow K = \sqrt{((K_0 * (1 + E_x))^3 * (K_0 * (1 + E_y)))^3}$$

The dimensions of each layer were:

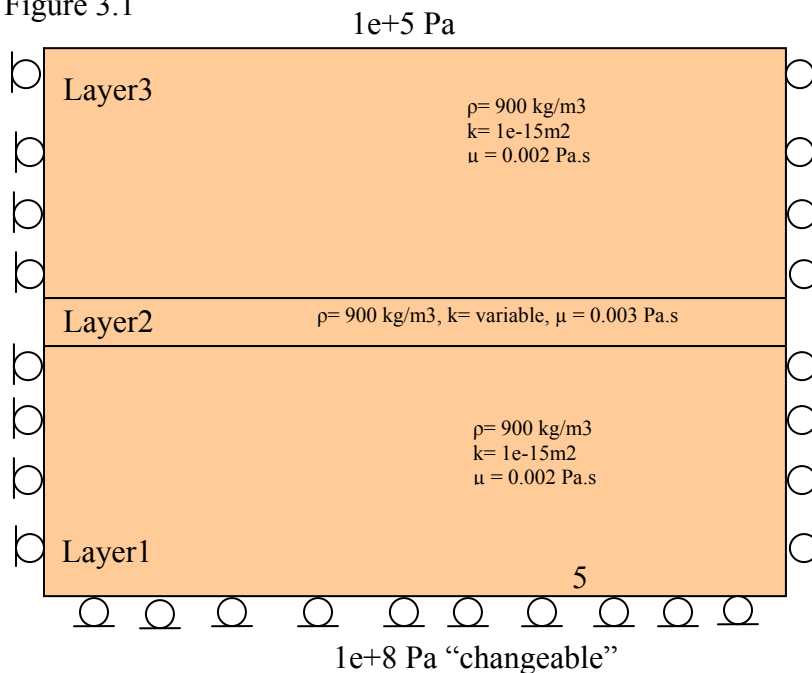
layer	Width	Height	Thickness
1	2000	1000	1
2	2000	100	1
3	2000	1000	1

Nomenclature:

K: permeability
 K_x: x-direction permeability
 K_y: y-direction permeability
 K₀: initial permeability
 E_x: x-direction strain
 E_y: y-direction strain

the figure 3.1 below shows this dimensions in a 2D view with pressure boundaries:

Figure 3.1



4. Numerical Solution

Physical values of the system were set from literatures and simplified as possible. The physical phenomena include:

- Porous flow behavior.
- Plain strain behavior with variable permeability effect.
- A coupling effects between the above mentioned.

With the COMSOL as a graphical user interface it was as follows:

- Structural Mechanics: plain strain
- Chemical Engineering: momentum balance – Darcy's Law.

The pressure distribution captured is as in figure 4.1:

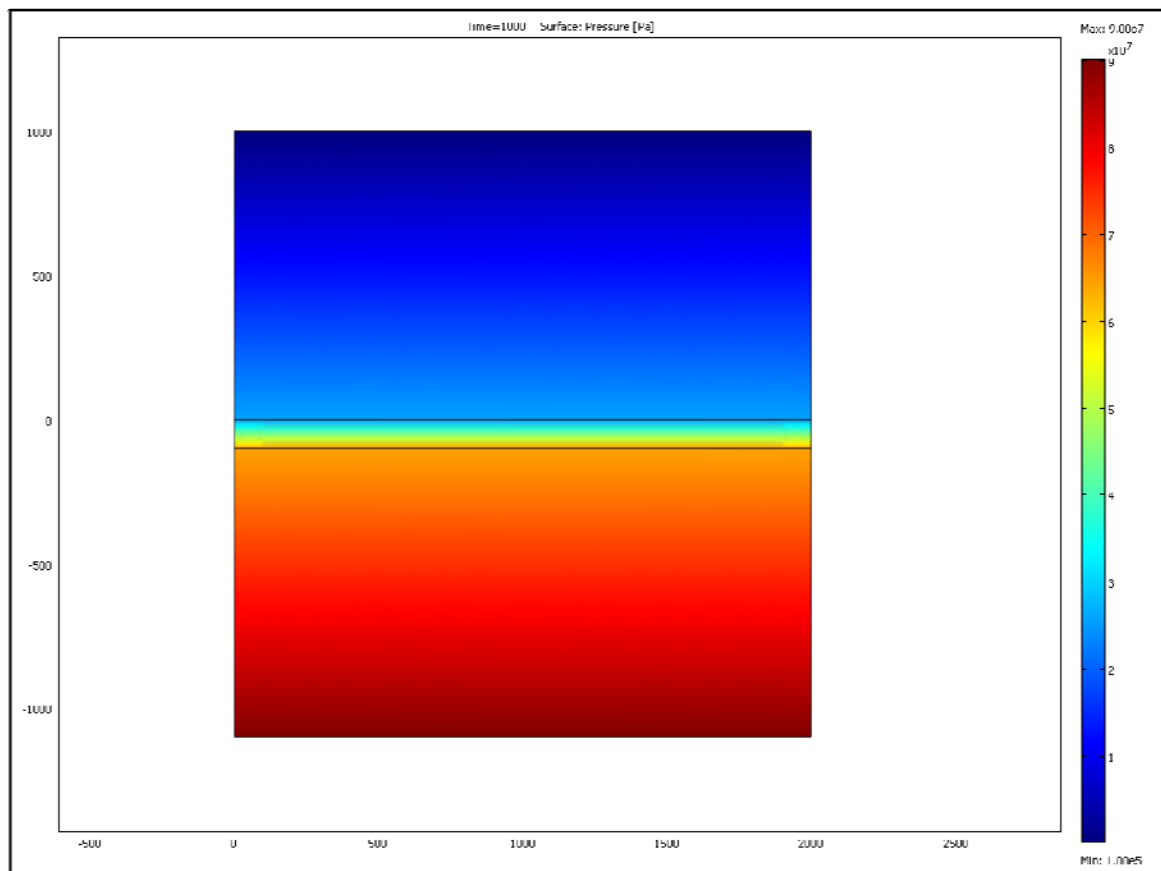


Figure 4.1: The pressure distribution.

We can see that most of the pressure loss occurs in the middle layer because of its lower permeability.

Also, when monitoring the displacement, it shows that the higher displacement change occurs around layer #2 as described in the arrows of the figure 4.2

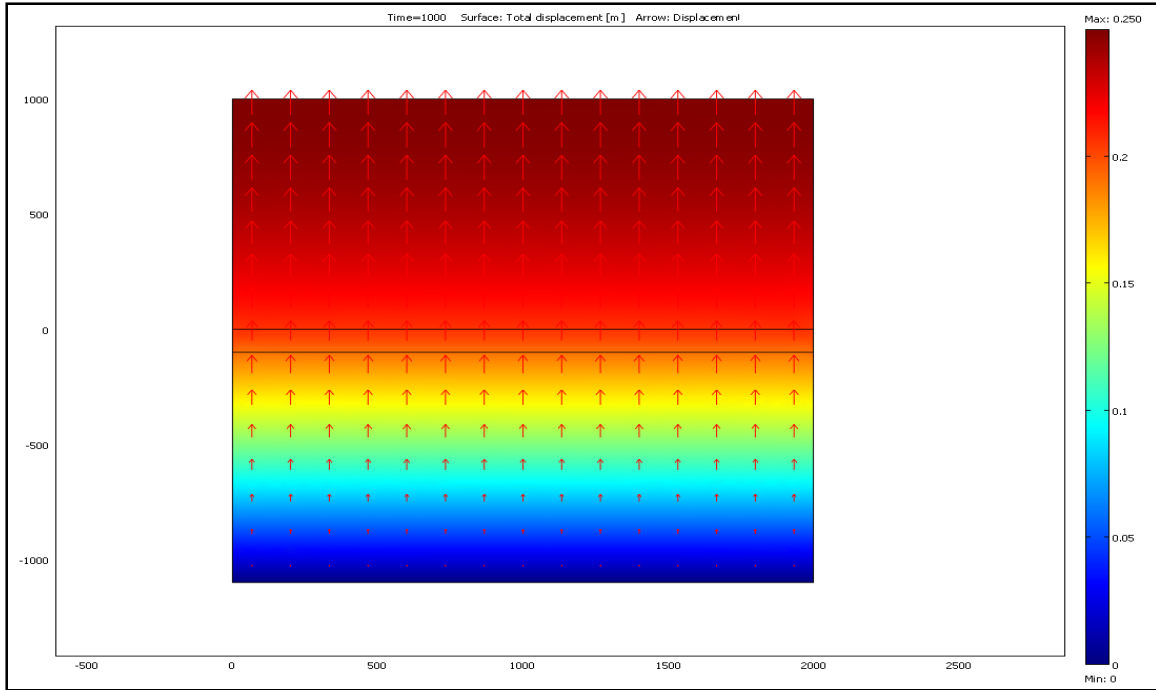


Figure 4.2: The displacement

The permeability change in the middle layer due to strains effects is negligible at these pressure values, however, they change with very small magnitude if the boundary pressure at the bottom layer increased to a very high value ($1e+11$ Pa) as shown in the figure 4.3 (layer1 and 3 were having fixed permeability), the change was small.

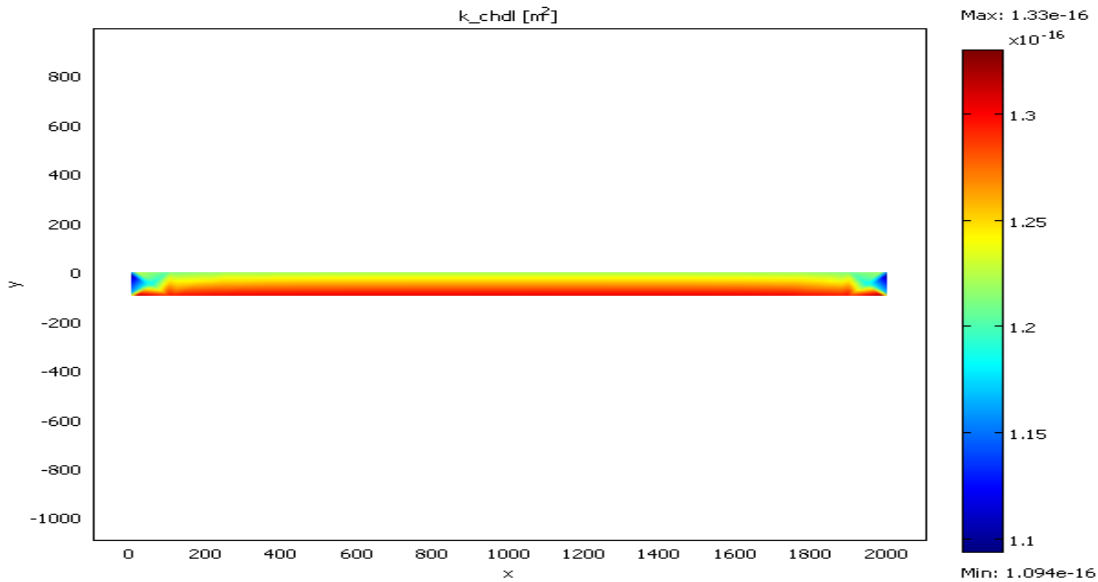


Figure 4.3: Permeability change in the middle layer for high pressure at bottom boundary.

5. Model Validation

To validate the current model, data from Elsworth¹⁷ was used. To indicate the effects of pressure differential-flow across the rock structure, normalized displacement (%) was chosen to be the variable for the validation work. Elsworth presented (Figure 3-a) a distribution of normalized surface displacement at centerline for single and dual porosity systems at various times. In this study, the focus will only be on single porosity system and will monitor the displacement behavior. Also, the time axes will be replaced by increasing pressure differential across the center layer. Figure 3-b shows the calculated displacement with pressure difference from COMSOL. It can then be noted that, the calculated results exhibits similar trend with Elsworth's data. Therefore, the current model provides valid results.

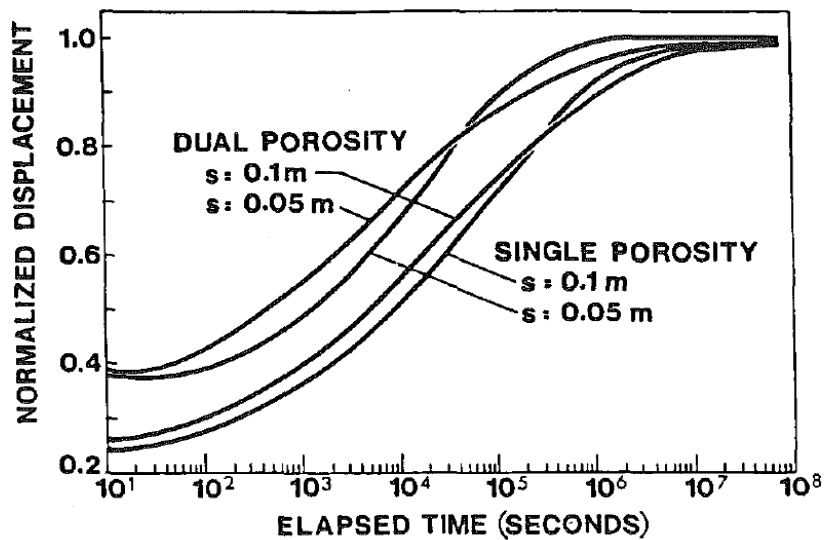


Figure 3-a: Surface displacement response at centerline (from Elsworth)

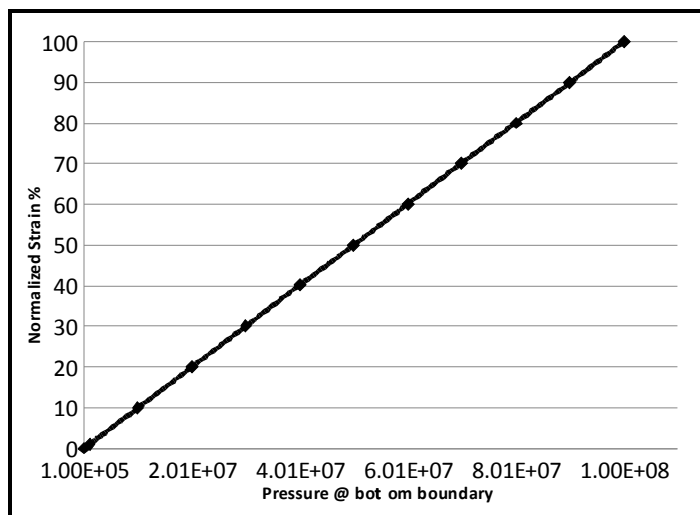


Figure 3-b: COMSOL displacement distribution with changing the pressure difference.

For further validation, it is important to change the mechanical characteristic of the used rock and also include source/sink terms in the surrounding layers for the current model. The model exhibit similar behavior when changing the rock properties but was unstable when introducing the source/sink terms. Thus, at this point, we cannot state that the current model is completely valid. However, we should mention that the model provided at least the expected behavior from the structure under mechanical/flow interaction models.

6. Parametric Study

To analyze the sensitivity of the model, we vary the surrounding layers permeability, porosity as well as the modulus of elasticity of the system. The permeability change had almost no effect on the strains. The porosity change was also not affecting the strains. Comparing the displacement at the center layer for different modulus of elasticity values will yield figure 4.

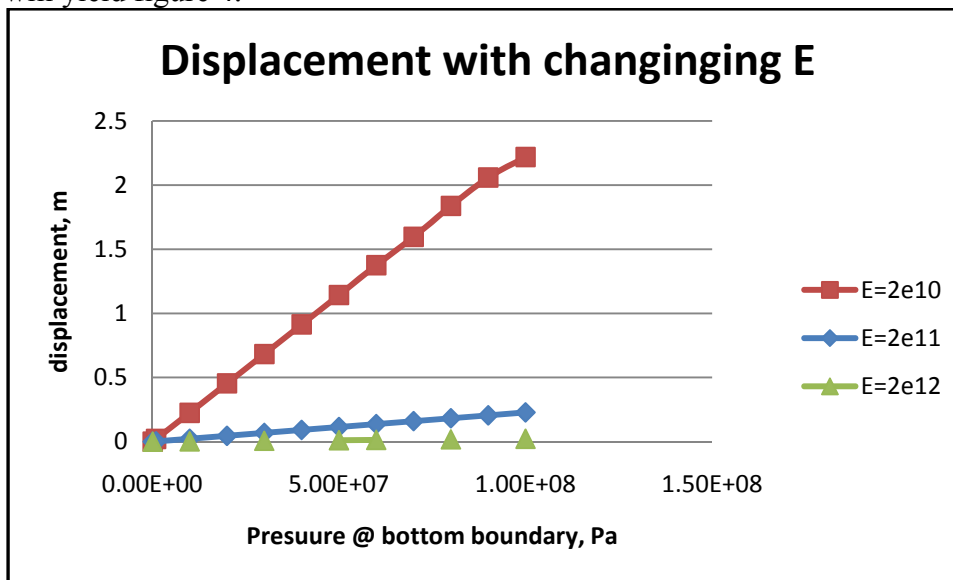


Figure 4: Displacement at center layer vs. pressure at bottom layer for different Modulus.

7. Conclusions

Understanding and prediction of rock structure behavior is a critical issue for petroleum/geological simulation and development of a certain field. The model developed for this study qualitatively described the behavior of the rock displacement due to fluid flow/mechanical interactions as expected. Our results are quite similar to Elsworth¹⁷ work. However, we should emphasis that, most of the physical parameters used in this study, although realistic, were chosen arbitrary. It is important to use specific rock parameter in order to access the stability of the model.

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