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Simulation of Depletion-induced Surface Subsidence in a Coal Seam

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Abstract

Coalbed methane (CBM) drew increasingly the attention as an unconventional source of natural gas during the last decades, globally and domestically. In spite of the fact that it is one of the main hazardous concerns in coal mining it is one of the most advantageous sources of natural gas especially due to its high purity of methane and quality.

In conventional natural gas reservoirs the pressurized gas is stored in porous space or fracture space but in CBM natural gas molecules mainly is adsorbed to coal matrix. Therefore in contrast to conventional natural gas reservoirs, the gas production of CBM initiates after decreasing the reservoir pressure down to a threshold in order to initiation the desorption process. According to the presence of water in CBMs which creates a remarkable pressure due to hydrostatic head of water the above desorption threshold will be achieved after dewatering process. Dewatering process will lead in decreasing reservoir pressure in one hand which helps the gas desorption but will lead in increasing effective stress which is applied to rock solid skeleton on the other hand. Such an increase in effective stress accounts for rock structure deformation which has a high impact on surface subsidence due to shallow depth of coal seams. Presence of soft formations in dewatered horizon especially coal seams will increase effectively the deformation of the formations, which could potentially result in remarkable subsidence profile.

Studying the depletion induced deformation due to CBM production is the main aim of this study. A three-dimensional finite element program developed will be used to investigate the stress field perturbation and rock structure deformation with emphasize on surface subsidence. In order to cover a wide range of real condition in CBM production a sensitivity analysis is carried out on main parameters including coal seam thickness and deformability properties.

1. Introduction

Since 1990s a revolution emerged with regards to the impact of geomechanical behavior of the reservoir formation or/and its surrounding media (e.g. overburden, sideburden and underburden) when studying producing reservoirs. The main reason for such a need in a reservoir engineering study is the fact that numerous hydrocarbon reservoirs locate in challenging geological environments (Fredrich and Fossum, 2002). Reservoir formations with high porosity and low degree of consolidation (e.g. poorly consolidated sands) or formations of poor geomechanical condition (e.g. weak strength) or formations with proved time-dependent behaviour (such as creeping salt bed and shale) are good instances of these challenging environments. Such miscellany problematic aspects lead into expensive experiences and events during the course of reservoir production including well casing collapse, remarkable change of porosity and permeability of the reservoir formations, reactivation of pre-existing sliding planes such as fractures at different scales, surface movements and subsidence. These and other similar incidences have been repeatedly reported in major hydrocarbon fields all around the globe (e.g. Ekofisk, South Belridge, Groningen, Bolivar Coast, Inglewood, Wilmington and Valhalla) in a wide spectrum of rocks like as highly porous chalk and sandstones with different consolidations and creeping media.

At any point inside a porous formation whose pores filled with pressurized fluids the total stress field partly sustained by the solid skeleton and partly by the fluid pressure. This description is equivalent to the so-called effective stress concept. According to this concept if by any reason the pore pressure changes the portion of the total stress field sustained by the solid skeleton will change simultaneously. As an instance, inside a producing porous reservoir during the depletion phase where the reservoir fluid pressure decreases the solid skeleton experiences more compression. Contrary to this, during the course of injection, when the fluid pressure builds up, the solid skeleton compression inside the reservoir horizon decreases. This indicates the need for simultaneous consideration of fluid flow and rock responses in reservoir geomechanics studies (David & Le Ravalec-Dupin, 2007).

In conventional natural gas reservoirs the pressurized gas is stored in porous space or fracture space but in Coal bed methane (CBM) natural gas molecules is mainly adsorbed to coal matrix. Therefore in contrast to conventional natural gas reservoirs, the gas production of CBM initiates after decreasing the reservoir pressure down to a threshold in order to initiate the desorption process. The production of gas begins once the pressure reduces below this threshold. Dewatering process leads in decreasing reservoir pressure in one hand which helps the gas desorption but results in increasing effective stresses which is applied to rock solid skeleton on the other hand. Such an increase in effective stress causes rock structure deformation which could have a significant impact on surface subsidence due to shallow depths of coal seams deposition. Presence of soft formations in dewatered horizon especially coal seams will increase effectively the deformation of the formations, which could potentially result in remarkable subsidence profile (Connell & Detournay, 2009).

In this paper a 3D finite element (FE) numerical code which was developed by Authors was used to study the changes in the induced stresses and displacements in a complete isotropic elastic media due to reduction in reservoir pressure in a coal seam. The numerical code was used to simulate the production-induced stress and displacement and ground subsidence. It is shown that this three-dimensional model which is extended horizontally behaves similar to a simple one-dimensional model due to the absence of the arching effect. Sensitivity analysis results are shown with respect to the effect of coal seam's Young modulus and thickness as the governing parameters of ground subsidence.

2. Two-phase porous media deformation

The subject of solid skeleton deformation associated with pore fluid motion is of vital importance in many branches of engineering such as soil mechanics (e.g. earthquake and consolidation problems), petroleum engineering (e.g. coupled porous reservoir analysis), and biomechanics (e.g. fluid circulating through bones) (Zienkiewicz and Shiomi, 1984). Such studies concern the interaction between pore fluid and solid skeleton which can be described in its simplest form as effective stress concept where

$$\dot{\sigma}_{ij} = \dot{\sigma}''_{ij} - \alpha \delta_{ij} \dot{p} \tag{1}$$

In this equation $\dot{\sigma}_{ij}$ is the rate of total Cauchy stress tensor, $\dot{\sigma}''_{ij}$ is that part of the rate of total stress tensor which is responsible for all deformation of solid skeleton, δ_{ij} is the Kronecker delta, $\dot{p}$ is the rate of pore fluid pressure, and α is Biot's constant of the porous media which is defined as:

$$\alpha = 1\text{-}\frac{\delta_{ij}D_{ijkl}\delta_{kl}}{3K_s}. \tag{2}$$

where D_{ijkl} is the tangential stiffness matrix of the bulk solid skeleton, and K_s is the average bulk modulus of the solid grains. α is close to unity for soil-like material whereas for rock-like material it may reduce as low as 0.5. When $\alpha = 1.0$, $\dot{\sigma}''_{ij}$ becomes the rate of so-called effective stress tensor which is conventionally referred to in soil mechanics (Zienkiewicz and Shiomi, 1984).

Based upon equation (1) we may introduce the incremental form of this equation as:

$$d\sigma_{ij} = d\sigma''_{ij}\text{-}\alpha\delta_{ij}dp. \tag{3}$$

In addition we may proceed with the matrix notation form of the above equation which is more convenient in finite element discussion as:

$$d\sigma = d\sigma''\text{-}\alpha m dp. \tag{4}$$

Due to the symmetric characteristic of stress and strain tensors, we can use the contract form of stress and strain tensor and then $\boldsymbol{m}$ can be defined as:

$$m^T = (1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0). \tag{5}$$

The problem of equilibrium state of a two-phase porous media consisting of solid skeleton phase and fluid phase that occupies the pores was comprehensively discussed by Zienkiewicz (1982).

Zienkiewicz (1982) comprehensively discussed all possible assumptions and approximates regarding engineering applications. He also showed that the full set of governing equations in drained static condition with slow consolidation (such as production from a reservoir) can be decomposed or decoupled into four major sets of equations. The first equation describes the well-known three-dimensional Darcy flow equation. And the other three equations describe the effective stress concept, the static equilibrium equation, and strain-displacement relationship of a continuum, respectively. Because of the decoupled nature of these equations the first equation can be modeled or solved independently from the other three equations in order to obtain the fluid pressure field. Afterwards, this fluid pressure filed can be accounted for through effective stress concept and three sets of equations describing the structural displacement and stress fields can be solved simultaneously by using an appropriate method. Providing a numerical solution to these three sets of equations simultaneously is a conventional and routine task of standard finite element analysis considering their continuum nature. The only difference with conventional finite element analysis of structures is the role of effective stress rather than total stress.

3. Developed 3D Finite element code

This finite element program was developed based on three-dimensional hexahedron 8-noded isoparametric element. Loading due to body force (e.g. gravity force) throughout the structure domain and prescribed traction on outer boundary of elements (e.g. constant pressure due to overburden on top of the buried model) are mainly supported. However, loading due to nodal point force and or prescribed nodal displacement (by means of penalty method) are also supported for some validation purposes which will not be discussed here. Assemblage strategy is based upon skyline storage method and the solver is based on Gauss elimination method regarding the skyline storage feature of the global stiffness matrix (Bathe, 1996). Besides, for the sake of computational speed all equations related to the fixed degree of freedom (DOF) are removed. This especial feature together helped us to reduce remarkably the required storage memory, computational cost and subsequently run-time duration (Bathe, 1996). The program is developed in incremental form (see equation (16)) because of two main reasons: capability of simulating the successive loading and unloading which is very essential for geomechanical applications and our upcoming aims toward accounting for nonlinear behaviors such as plasticity. However, in this paper we only focus on the linear elasticity. In addition to the main finite element program, we developed two other programs: one for mesh generation (pre-processing) and other for profile extraction of the results (post-processing). All of these programs were written by FORTRAN programming language.

In next subsections at first we introduce the main model characteristics. Then we discuss the results of two sensitivity analysis we carried out on coal seam thickness and Yong's modulus.

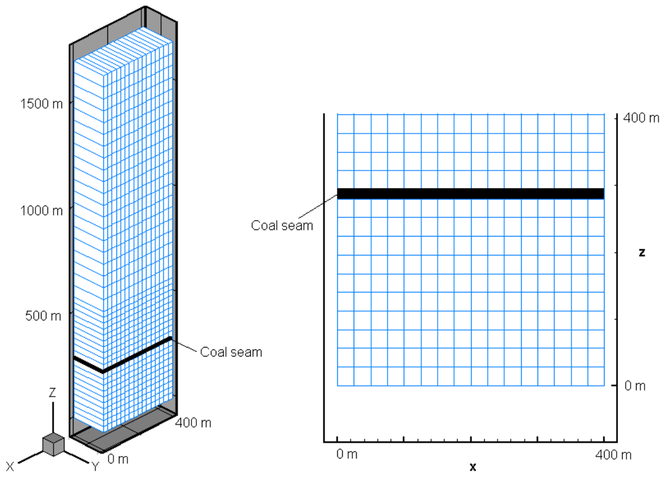
4. A case study in a Coal seam

The main features of this case study are similar to that of reported by Connell & Detournay (2009). Here, we do not carry out the production scenario reported there but investigate the effect of depletion from the coal bed methane reservoir. Table 1 shows the data corresponding to the coal seam reservoir that is studied in this paper.

Table 1: Coal seam reservoir data used for modeling (Connell & Detournay, 2009)

Property	Value
Initial reservoir pressure	4789 KPa
Depth to coal seam	1400 m
Coal seam thickness	14 m
Coal Young's modulus, Poisson's ration, bulk density	2 Gpa, 0.35, 1470 kg/m^3
Other layer Young's modulus, Poisson's ration, bulk density	12 GPa, 0.21, 2450 kg/m^3

The finite element model was extended vertically upward to the surface and 280 m under the coal seam layer whereas laterally it covers 200 m on each side of the center line of the model. The model geometry and finite elements configuration are illustrated in Figure 1. In terms of boundary conditions, all the sidewalls of the model are restrained in normal direction to its corresponding sidewall and the bottom of model is restrained in vertical direction.



3D Model View

2D Section View

Figure 1: Model Geometry.

The first step of loading is due to gravity. The results for vertical and horizontal stresses are depicted in Figure 2 and Figure 3, respectively.

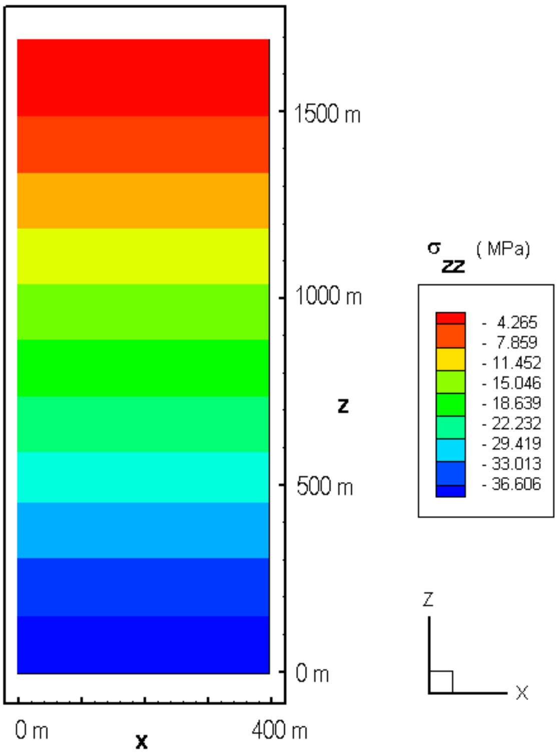


Figure 2: Vertical stress after gravitational consolidation (σ_{zz}).

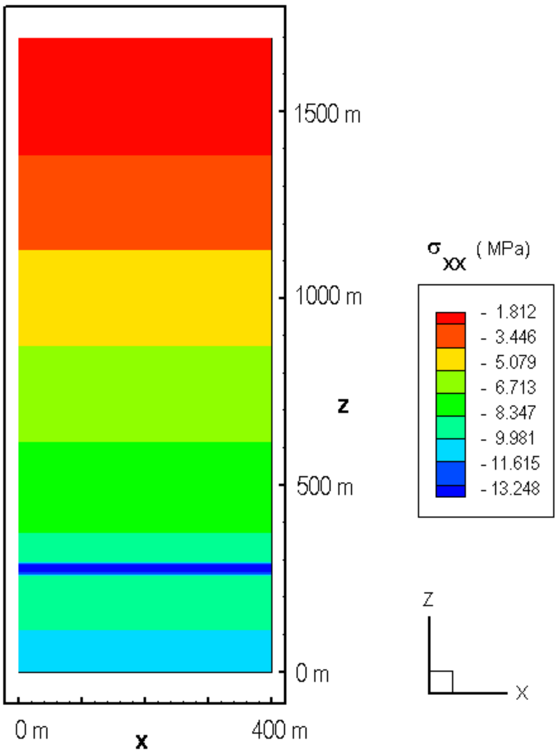


Figure 3: Horizontal stress after gravitational consolidation (σ_{xx}).

The important feature of these results after gravitational consolidation is the increasing ratio of horizontal to vertical stresses inside the coal seam due to a higher Poisson's ratio of the coal comparing to surrounding rocks. In all models this ratio is 0.2658 except inside the coal layer where this ratio is 0.5384. These ratios equal to the elastic stress ratio coefficient, i.e. $\left(\frac{\nu}{1-\nu}\right)$, in both coal and other formations. For coal seam this ratio is:

$$\left(\frac{\nu}{1-\nu}\right) = \left(\frac{0.21}{1-0.21}\right) = 0.2658 \qquad (6)$$

whereas for other layers it is equal to:

$$\left(\frac{\nu}{1-\nu}\right) = \left(\frac{0.35}{1-0.35}\right) = 0.5384 \qquad (7)$$

For coal layer where the amount of Poisson's ratio is different from other part of the model, the increase of horizontal stresses is clearly observed in Figure 3.

In the next step of this study the effects of gravitational consolidation and reservoir pressure was modeled. The reservoir pressure increased up to the initial reservoir pressure and then it was reduced in three unloading steps of 75, 50, and 25 % of the initial value.

Due to the depletion of the reservoir, the subsidence occurs in overburden and especially at the ground surface. In order to highlight the effect of coal seam depletion the effect of gravitational consolidation was discarded and the result of downward movement in overburden is shown in Figure 4.

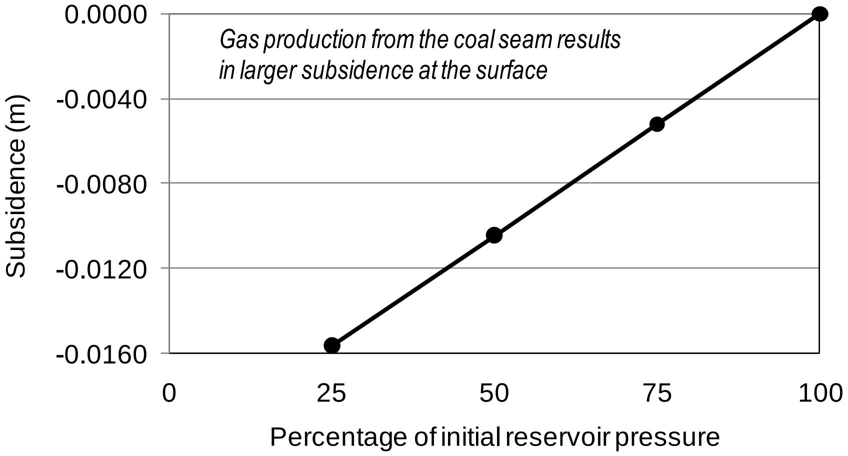


Figure 4: Subsidence at the ground surface due to depletion of coal seam pressure.

The linear nature of subsidence, as is seen from Figure 4, is due to the linear elastic analysis used for this study.

The other interesting point which is to be highlighted is the fact that the amount of depletion-induced downward movement is the same in entire overburden zone from above the coal seam to top of the model. The main reason for such a result is that in the models presented here the coal seam was assumed to have an infinite lateral extension: this results in no arching and sideburden effects and therefore the model behaves unidirectional in vertical direction, similar to the behavior of a column of rock. In addition, due to the assumption of free movements in this model at the top, all the overburden moves similarly as a rigid translation due to production occurs inside the coal seam without any straining and stressing happening. This is again due to discarding the effect of sideburden and assuming a large lateral extension for the coal seam.

The above discussion indicates that in the particular model presented here the characteristics of the overburden rocks have no direct consequences on the production-induced subsidence. However, the properties of the coal seam, in particular the thickness and Young's modulus of the coal, have substantial effects on the amount of subsidence. The results of sensitivity analyses on these two parameters are presented below which demonstrate this effect.

Sensitivity analysis

In Figure 5 the amount of subsidence calculated for three different values of coal seam Young's modulus of 1.5, 2.0, and 2.5 GPa is shown. From this figure it is clearly seen that the stiffer the coal layer, the lesser the amount of subsidence will be. This indicates the importance of having a good knowledge about the mechanical properties of coal when subsidence is to be studied. Performing rock mechanics laboratory tests, such as tri-axial compression tests, could provide valuable information about coal mechanical properties.

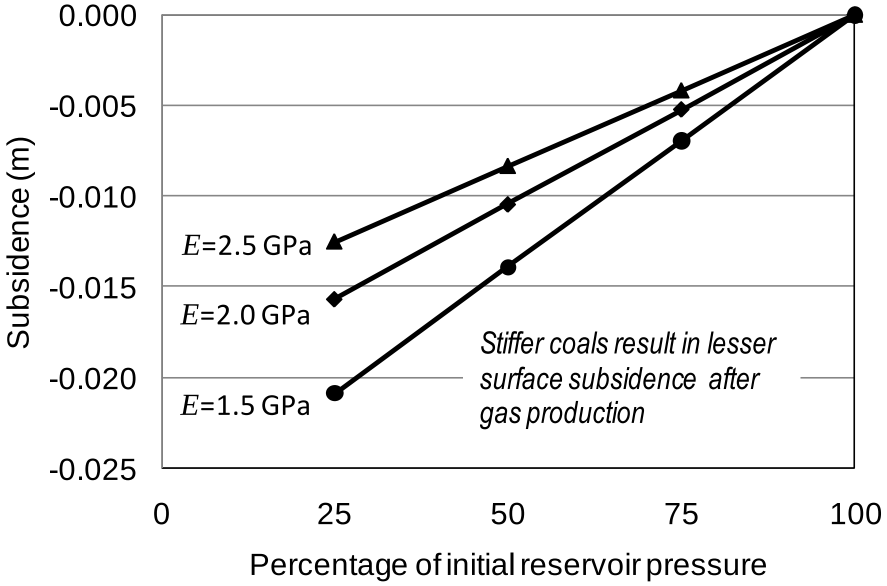


Figure 5: The effect of coal seam's Young modulus on subsidence.

To show the importance of coal thickness on the amount of subsidence three models with different thicknesses of 14, 28, and 42 m for the coal seam were analyzed and the results are presented in Figure 6. From this figure it is observed that the thicker the coal seam, the larger amount of movement and subsidence will be. This also demonstrates the importance of having a prior knowledge of the geology of the field in order to have a good estimation of the coal thickness for subsidence analysis.

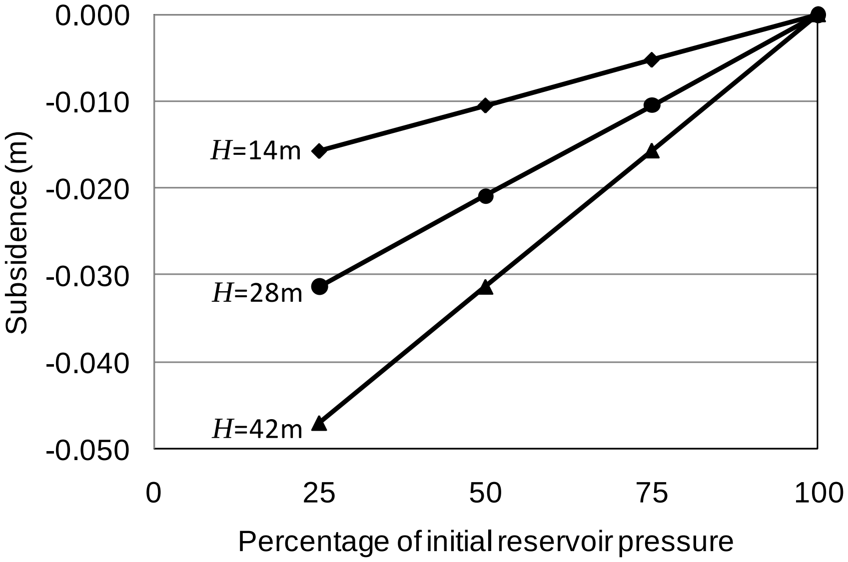


Figure 6: The effect of coal seam thickness on subsidence.

5. Conclusions

In this paper the results of gravitational consolidation and reservoir pressure changes in a horizontal coal bed methane reservoir were presented. A 3D finite element code was used for the simulation purposes. The results indicated that the amount of production-induced subsidence when considered far from the edges of the coal layer and in the absence of side-burden effects is independent of the deformability properties of overburden layers. The overburden rocks showed to behave in a rigid translational manner in this case. On the other hand, the results showed that the amount of production-induced subsidence is dependent strongly on deformability properties (i.e. Young modulus) and the thickness of the coal seam.

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