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ORIGINAL ARTICLE

A discussion on analytical and numerical modelling of the land subsidence induced by coal seam gas extraction

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Abstract
Coal seam gas (CSG) is an increasingly important source of natural gas all over the world. Although the influence of conventional oil and gas extraction on surface subsidence has been widely recognized and studied, few studies are carried out on the surface subsidence in coal seam gas fields and its impact on surface infrastructure and the environment. This paper discusses modelling of the surface subsidence associated with coal seam gas production by applying both analytical and numerical methods. By comparison of results from the numerical model and two analytical models, i.e. the disc-shaped reservoir model and the uniaxial compaction model, the analytical solutions cannot describe the complex process of water and gas extraction and have the limitations to predict the surface subsidence, while the numerical model can be better used in prediction of subsidence. After applying the numerical model in numerical analysis, the deformation characteristics of coupled fluid flow, and the effects of permeability change of coal seam, associated overlying and underlying layers, and depressurization rates on surface subsidence are investigated. The results demonstrate that the proposed model can simulate the production of water and gas from coal seams and the associated surface subsidence.

Keywords Subsidence · Coal seam gas production · Depressurization · Coal matrix shrinkage · COMSOL

Introduction

The occurrence of land surface subsidence associated with activities of underground engineering is of great concern due to the potential impacts on infrastructure and environment (Ferronato et al. 2001; Geertsma 1973; Pineda and Shjeng 2014; Schmid et al. 2014). Coal seam gas (CSG), as an unconventional energy source, has attracted increasing interest in coal seam gas extraction in Australia and other countries. In some geological settings, the gas extraction from coal beds may require more extensive depressurisation of the formations containing the coal. This is generally achieved through local and regional groundwater extraction, leading to compaction of the depressurised zones and potentially to subsidence at the surface. This compaction may have consequences for surface infrastructure, water courses and agriculture. There remains a risk in certain hydrogeological conditions such as where water table lowering could occur at or close to the surface within poorly consolidated sediments; or where geological conditions favour differential movement. Hence, it is necessary to assess the land surface subsidence induced by coal seam gas extraction (Asadi et al. 2005; Connell 2009; Freij-youb 2012).

Coal seam gas is a natural gas comprised of about 97% methane, which is extracted from the relatively shallow coal beds located at 300–1000 m depth (Pineda and Shjeng 2014). The vast majority of gas (90–98% of all gas) within coal seams is adsorbed to the coal matrix. Gas can be desorbed from the coal and become mobile after the pore pressure, e.g. water pressure in reservoir is reduced to below the

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desorption pressure. Land subsidence due to fluid (groundwater and gas) extraction incurs when the pore pressures in geologic unit decrease (Du and Olson 2001; Gambolati et al. 2001). Gas extraction involves the extraction of groundwater to facilitate depressurisation (reducing groundwater levels with consequent lowering of groundwater pressure) of the target coal seam. This depressurisation can cause compaction of the targeted coal measure in the vicinity of the well and any similarly affected aquifers above or below the coal seam. This can, in turn, lead to settlement at the ground surface. In addition, when gas is extracted from coal seam formation, the effect of gas desorption-induced shrinkage may result in additional compaction of the coal seams that causes the subsidence of land surface.

Compared with the conventional gas production, mining or civil engineering activities, the subsidence caused by coal seam gas extraction is even more complicated due to the special interrelationship between different phases (gas, liquid and solid) within coal seams (Chamani and Rasouli 2011). The main problem for predicting subsidence lies in the fact that the hydro-mechanical behaviour of each layer in geological profile is different and their hydraulic connection to the coal seams are not well understood. Under ideal conditions, if the hydro-mechanical behaviour of each layer can be acquired and the fluid flow in the coal is assumed as a single phase, it would be possible to predict the subsidence by the analytical method such as Geerstma's nucleus model and uniaxial compact model (Fjær et al. 2008; Geertsma 1973; Taherynia et al. 2013). However, in reality, subsidence is difficult to predict using the analytical methods due to the complex response of pore pressure of the entire geological profile to the gas extraction. The magnitude of subsidence mainly depends on the depth and thickness of coal seam reservoir, and the properties of geological units overlying the compacting geological units. Numerical simulations for gas flow, mass transport and coupled gas–solid effect in coal seams have been widely applied (Basu et al. 1988; Wang and Peng 2014; Zhu et al. 2007). Subsidence associated with coal seam gas extraction can be predicted using numerical models to calculate the amount of depressurization of various geological units and then to estimate the compaction due to both changes in groundwater pressure and degassing of the coal seam.

The objective of this paper is to discuss modelling of the land subsidence associated with CSG production by analytical and numerical methods. The analytical method is based on the disc-shaped reservoir model and the uniaxial compaction model, whereas the numerical method is based on a coupled multi-phase fluid flow-geomechanical model to simulate water and gas production from coal seams using the commercial software package COMSOL. After simulation analysis with this coupled model, the gas/water flow, and deformation characteristics in geologic units are modelled during the processes of dewatering and gas production, and the effects of depressurization rate and permeability change in geologic units on subsidence are investigated.

Analytical models of subsidence associated with CSG production

For CSG production, two analytical models for predicting land subsidence are presented: the disc-shaped reservoir model and the uniaxial compaction model.

Disc-shaped reservoir model

The surface subsidence associated with gas extraction in a disc-shaped reservoir (as shown in Fig. 1) can be calculated by the analytical solutions in the half space (Geertsma 1973). After the necessary mathematical manipulations, the simple formulation for surface subsidence S and radial displacement u_r can be obtained as follows:

$$\begin{cases} S(r,0) = -2C_{\mathrm{m}}(1-\mu)\alpha\Delta p_f H_{\mathrm{coal}} A(\rho,\eta) \\ u_r(r,0) = 2C_{\mathrm{m}}(1-\mu)\alpha\Delta p_f H_{\mathrm{coal}} B(\rho,\eta), \end{cases} \quad (1)$$

where C_m is the compressibility coefficient of reservoir, μ is the Poisson's ratio, r is the radial distance from vertical axis through the nucleus, α is the Biot coefficient, Δp_f is the changed value of reservoir pressure, $A(\rho,\eta)$ and $B(\rho,\eta)$ are the functions of the dimensionless ratios $\rho = r/R$ and $\eta = D/R$ (Fjær et al. 2008), R is the radius of disc-shaped reservoir, D is the summation of overlying layers, and H_{coal} is the thickness of the reservoir.

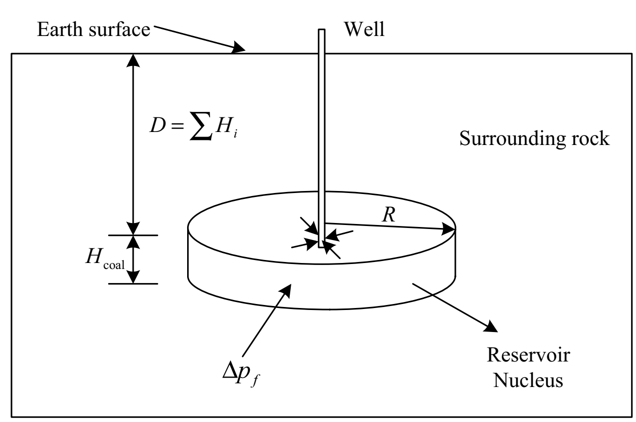

Fig. 1 Reservoir configuration

Uniaxial compaction model

Assuming that the mechanical behaviour of the rock layer can be described as a linear pore elasticity, the strain and stress of the target coal seam formation can be expressed by Hooke's law.

The rock layer is assumed to have settlement only in vertical direction and no lateral strain, resulting in only uniaxial deformation. The settlement of the target coal seam formation is defined as:

$$S_{\text{coal}} = C_m H_{\text{coal}} \alpha \Delta p_f, \tag{2}$$

where H_{coal} is the thickness of coal seam formation.

Land subsidence due to CSG extraction also results from the indirect compaction of overlying and underlying geological units that are hydraulically connected to the coal seams. Thus, the subsidence associated with the decrease of pore pressure is defined as:

$$S = S_{\text{coal}} + S_{\text{indirect}} = \sum_{i=1}^{N} C_{m(i)} H_{(i)} \alpha_{(i)} \Delta p_{f(i)}, \tag{3}$$

where S_{indirect} is the indirect compaction resulting from overlying and underlying geological units hydraulically connected to the target coal seam, and N is the total number of formations including the coal seam, overlying and underlying layers.

The groundwater in the coal seams must be pumped from a well to decrease the water pressure in the surrounding coal. As the water pressure is decreased below the critical desorption pressure, methane desorbs. The methane first dissolves in water. Because methane solubility in water is limited, the recovery efficiency of the dissolved methane is not very high. Efficiency is increased when the water pressure in the coal is decreased sufficiently for methane to exist largely as a free gas phase and to migrate to the production well. This migration involves the movement of both water and gas from the micropores in the coal matrix and coal cleats.

During the course of gas extraction, the desorption-induced strain can be determined by the following relationship (Wu et al. 2010; Zhang et al. 2008):

$$\varepsilon_{\text{ds},t} = \frac{\varepsilon_{\max} p_g}{P_L + p_g} - \frac{\varepsilon_{\max} p_0}{P_L + p_0}, \tag{4}$$

where $\varepsilon_{\text{ds},t}$ is the desorption-induced strain at current pore pressure after a given time t, p_0 is the initial pore pressure in the target coal seam formation, p_g is the gas pressure, $\varepsilon_{\max}$ is the maximum strain at infinite pore pressure and P_L is Langmuir pressure constant.

The desorption-induced compaction, S_{ds}, for a coal seam with thickness H, can be defined as:

$$S_{ds} = \frac{\varepsilon_{\max} P_L}{\left(P_L + p_g\right)\left(P_L + p_0\right)} \Delta p_f H, \tag{5}$$

where $\Delta p_f = p_g - p_0$ is the pressure change.

Therefore, the ultimate compaction in the geological profile can be calculated as follows:

$$S_{\max} = \sum_{i=1}^{n} C_{m(i)} H_{(i)} \alpha_{(i)} \Delta p_{f(i)} + \frac{\varepsilon_{\max} P_L}{\left(P_{\text{L}} + p_{\text{g}}\right)\left(P_{\text{L}} + p_0\right)} \Delta p_f H. \tag{6}$$

Coupled fluid flow-geomechanical model

The numerical model is developed based on the following assumptions: (1) coal seam formation and other layers are assumed to be isotropic and elastic continuum, (2) deformation is much smaller than the length scale, (3) the rate of water or gas flow through the layers can be described by Darcy's law, and (4) gas within the coal seam is ideal and its viscosity is constant under isothermal conditions.

In consideration of the desorption-induced strain and pore pressure effect, the constitutive relation for the coal seam is defined as (Fjær et al. 2008):

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K} p_f \delta_{ij} + \frac{\varepsilon_{ds}}{3}\delta_{ij}, \tag{7}$$

where G is the shear modulus, K is the bulk modulus of rock, ε_{ij} is the component of total strain, σ_{ij} is the component of total stress, α is the Biot coefficient, p_f is the reservoir pressure, and ε_{ds} is the desorption-induced strain.

The equilibrium equation can be written as:

$$G u_{i,kk} + \frac{G}{1 - 2\mu} u_{k,ki} - \alpha p_{f,i} - K \varepsilon_{\text{ds},i} + f_i = 0, \tag{8}$$

where u_i is the component of displacement and f_i is the component of body force.

Equation (8) is the governing equation for coal seam deformation, where the ε_{ds} can be calculated from Eq. (5) and the p_f can be solved from the two-phase flow equations discussed as follows:

$$p_f = p_{nw} s_{nw} + p_w s_w, \tag{9}$$

where p_{nw} and s_{nw} are the pressure and saturation for the non-wetting fluid, respectively, and p_w and s_w are the pressure and saturation for the wetting fluid, respectively.

Two-phase flow of water and gas occurs in the case that the pore pressure in the coal seams is lower than the desorption pressure. After large depressurisation, gas desorbs from the coal seams and the two-phase flow is developed near the extraction well. The water transport in the coal seam can be described by the mass conservation equation (Comsol 2013):

$$\frac{\partial(\phi\rho_w s_w)}{\partial t} + \nabla \cdot \left(-\frac{kk_{rw}}{u_w}\rho_w(\nabla p_w + \rho_w g\nabla Y)\right) = f_w, \quad (10)$$

where ϕ is the porosity of coal seam, ρ_w is the water density, s_w is the water saturation, k is the absolute permeability of coal seam, k_{rw} is the relative permeability of water, u_w is the water viscosity, p_w is the pore pressure of water, g is the gravitational acceleration, Y is the coordinate of vertical elevation, and f_w is the source of water.

The mass conservation equation of gas can be defined as (Comsol 2013; Wang and Peng 2014):

$$\frac{\partial m}{\partial t} + \nabla \cdot \left(-\frac{kk_{rnw}}{u_{nw}}\rho_{nw}(\nabla p_{nw} + \rho_{nw} g\nabla Y)\right) = f_{nw}, \quad (11)$$

where k_{rnw} is the relative permeability of gas, u_{nw} is the gas viscosity, ρ_{nw} is gas density, p_{nw} is the current gas pressure, f_{nw} is the source of gas, and m is the gas content in coal seam including free-phase gas and absorbed gas, which can be defined as:

$$m = \phi\rho_{nw}s_{nw} + \rho_{ga}\rho_c\frac{V_L p^*}{P_L + p^*}, \quad (12)$$

where s_{nw} is the gas saturation, ρ_{ga} is the gas density at standard condition, ρ_c is the coal density, V_L is the Langmuir volume constant, $p^* = s_{nw}p_{nw}$ is the partial gas pressure, and P_L is Langmuir pressure constant.

The gas density can be described by the gas pressure according to the state equation:

$$\begin{cases} \rho_{nw} = \dfrac{M_g}{RT}p_{nw} = \beta p_{nw} \\ \rho_{ga} = \beta p_a, \end{cases} \quad (13)$$

where M_g is the molecular mass of the gas, R is the universal gas constant, T is the absolute gas temperature, and p_a is the atmosphere pressure.

Therefore, the mass conservation equations of water and gas can be simplified as follows:

$$\begin{cases} \dfrac{\partial(\phi s_w)}{\partial t} + \nabla \cdot \left(-\dfrac{kk_{rw}}{u_w}(\nabla p_w + \rho_w g\nabla Y)\right) = \dfrac{f'_w}{\rho_w} = f_w \\ \dfrac{\partial}{\partial t}\left(\phi s_{nw}p_{nw} + p_a\rho_c\dfrac{V_L p^*}{P_L + p^*}\right) + \nabla \cdot \left(-\dfrac{kk_{rnw}}{u_{nw}}p_{nw}(\nabla p_{nw} + \rho_{nw} g\nabla Y)\right) = \dfrac{f'_{nw}}{\beta} = f_{nw}. \end{cases} \quad (14)$$

The van Genuchten–Mualem model is used to build the relative permeability model (Chen et al. 2013; Comsol 2013), which can be expressed as:

$$\begin{cases} k_{rw} = s_w^L\left[1 - \left(1 - s_w^{\frac{1}{m}}\right)^m\right]^2 \\ k_{rnw} = (1 - s_w)^L\left(1 - s_w^{\frac{1}{m}}\right)^{2m}, \end{cases} \quad (15)$$

where L and m are the parameters of van Genuchten–Mualem model.

The capillary pressure p_c is defined as:

$$p_c = p_{nw} - p_w = p_d\left(s_w^{-\frac{1}{m}} - 1\right)^{1/n}, \quad (16)$$

where p_d is the entry capillary pressure and n is model parameter.

By introducing the change of the capillary pressure with saturation in Eq. (14), the final form of two-phase flow can be defined as:

$$\begin{cases} -\phi C_p\dfrac{\partial p_w}{\partial t} + \nabla \cdot \left(-\dfrac{kk_{rw}}{u_w}(\nabla p_w + \rho_w g\nabla Y)\right) = -\phi C_p\dfrac{\partial p_{nw}}{\partial t} + f_w \\ \phi'(s_{nw} - p_{nw}C_p)\dfrac{\partial p_{nw}}{\partial t} + \nabla \cdot \left(-\dfrac{kk_{rnw}}{u_{nw}}p_{nw}(\nabla p_{nw} + \rho_{nw} g\nabla Y)\right) = -\phi' p_{nw}C_p\dfrac{\partial p_w}{\partial t} + f_{nw}, \end{cases} \quad (17)$$

where ϕ' is the desorption modified porosity, $\phi' = \phi + p_a\rho_c\frac{V_L P_L}{(P_L + p^*)^2}$.

The permeability and porosity of coal seam is pressure dependent, which can be described as (Zhang et al. 2008):

$$\begin{cases} \phi = \dfrac{1}{1+S}\left[(1 + S_0)\phi_0 + \alpha(S - S_0)\right] \\ k = k_0\left(\dfrac{\phi}{\phi_0}\right)^3, \end{cases} \quad (18)$$

where $S = \varepsilon_v + \left(\frac{p_f}{K_s}\right) - \varepsilon_{ds}$, $S_0 = \left(\frac{p_0}{K_s}\right) - \frac{\varepsilon \max p_0}{p_0 + P_L}$, ε_v is the volumetric strain, K_s is the bulk modulus of coal grains, and k_0 and ϕ_0 are the initial permeability and porosity at initial pressure p_0, respectively.

Assuming that water saturation s_w is equal to 1.0, Eq. (10) is also suitable for the overlying and underlying layers of the coal seam formation.

Comparison with the typical analytical models

To investigate the numerical method, two simple comparisons of subsidence induced by gas extraction and desorption-induced deformation by degassing are presented, with results of analytical models including the disc-shaped reservoir model and the uniaxial compaction model.

Subsidence induced by gas extraction

In this example, an axial symmetric model is simulated with a well screen positioned near the axial line. Among the strata, there is a coal seam bearing formation confined by two impermeable layers. The coal bearing formation may include (potentially numerous) coal seams interbedded with sedimentary units. In this study, the coal bearing formation is assumed to be combined into an amalgamated geological unit. The two impermeable layers are assumed to be horizontally layered units underlying and overlying the coal-bearing formation, respectively (see Fig. 2a). The left end of the model is set as a fluid outlet for production well, and the flow condition of the right end is the same with the left end for one-dimensional condition. In terms of mechanical boundary conditions, the left, right and bottom ends of the model are constrained in normal directions, and the top of the model is set free but applied with an overburden pressure.

As we know, surface subsidence results from two parts: (a) direct compact of coal seam formation, and (b) indirect compact of underlying and overlying strata. The compaction effect will be incurred once the pore pressure in the entire profile is modified. Because Geerstma's model cannot be used in the condition that the surrounding rock of the target reservoir is permeable, there is definitely no pore pressure in the strata underlying and overlying the CSG bearing formation. To compare the subsidence results of three models, in this example, we just focus on the change of pore pressure in the CSG bearing formation. At the initial stage, the pore pressure along the depth is a diagonal line via a zero pressure at the top surface (the groundwater table is flush with the top surface). At the final stage, due to the cause of gas extraction, the pore pressures in the whole CSG formation are decreased by a water head of 315 m (as shown in Fig. 2b, and the water head 315 m is commonly adopted in Australia (Australian 2014)). Although it is an extreme state for the decrease of water head 315 m in the whole CSG formation, it still can be used in comparison of subsidence analysis induced by gas extraction in consideration of the impermeable surrounding rock in Geerstma's model and one-dimensional state in uniaxial compaction model. The properties of coal bearing formation are listed in Table 1.

One of the major controls of subsidence is the ratio D/R of the target reservoir (D and R are the depth and radius of reservoir, respectively, as mentioned in Sect. "Disc-shaped reservoir model"). Figure 3 shows the maximum vertical

Table 1 The properties of coal bearing formation (Australian 2014)

Name	Value
Coefficient of volume compressibility/MPa^{-1}	5.38×10^{-5}
Permeability/m^2	1.19×10^{-15}
Porosity	0.13
Young's modulus (GPa)	16.73
Poisson's ratio	0.2
Biot coefficient	1
Density of coal/kg m^{-3}	1.65×10^{3}

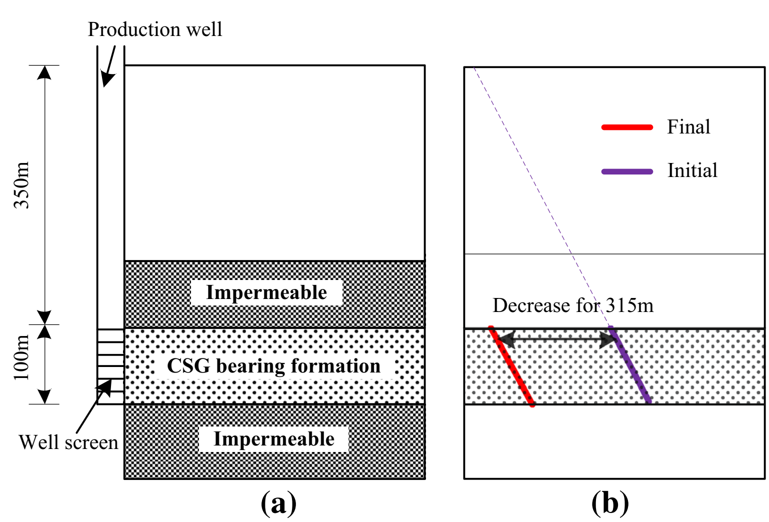

Fig. 2 Schematic diagram of **a** ground profile and **b** groundwater head change in initial and final conditions in coal bearing formation

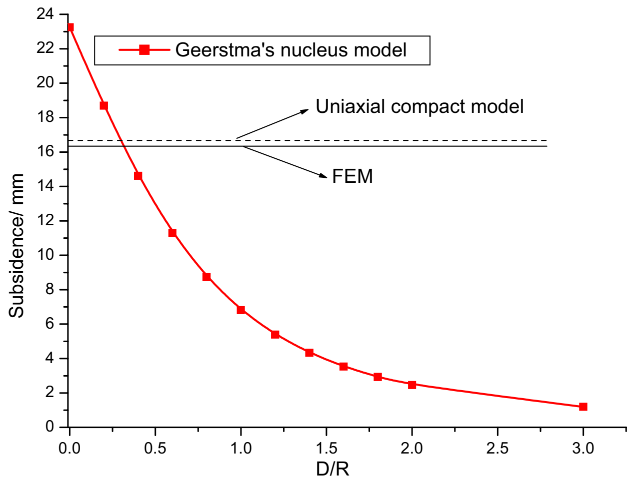

Fig. 3 Subsidence comparison of three models for different *D*/*R* ratios (Geertsma 1973)

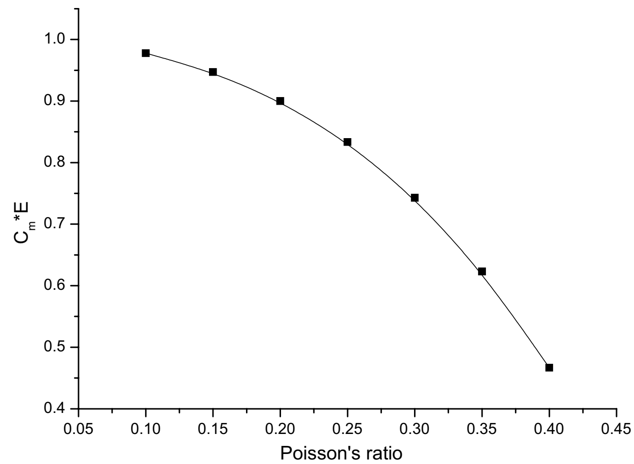

Fig. 4 Sensitivity of C_m to Poisson's ratio when the Young's modulus is fixed

subsidence with the variation of the ratio D/R for the three models the coupled numerical model, the uniaxial compact model (Fjær et al. 2008), and the Geerstma's model (Geertsma 1973). One can see that for the extreme state of decreasing the water head 315 m in the whole CSG formation, the results of the uniaxial model are marginally larger than those of the numerical results, and they are both nearly constant. Minor difference between the results by the uniaxial model and finite element method (FEM) is produced because of element scale and convergence accuracy of numeric model. However, the results of the Geerstma's model is not constant, but decreases obviously with the increase of D/R. Due to the same conditions for the well screen (as near field) and the right boundary (as far field), the results demonstrated that it is feasible for the uniaxial model and the coupled model, and is not feasible for the Geerstma's model to calculate subsidence of coal seam extraction in one-dimensional condition (Geertsma 1973). Considering that the conventional oil and gas traps are different with the coal seam reservoir, there are more restricted conditions for the Geerstma's model used in the coal seam extraction, such as the shape, impermeable surrounding rock, and the radius of the target reservoir (Geertsma 1973).

The compressibility coefficient C_m is related to the Young's modulus E and Poisson's ratioμ, which is defined as:

$$C_m = \frac{(1+\mu)(1-2\mu)}{E(1-\mu)}. \tag{19}$$

For a fixed value of Young's modulus, C_m is changed with different Poisson's ratio. Figure 4 shows the values of calculated C_m vary by less than 30% for Poisson's ratios between 0.1 and 0.3. FEM results also show that the stiffer the coal bearing formation, the lesser the amount of subsidence will be, which is consistent with the results from Eq. 3. This indicates that good knowledge of the mechanical propertied of coal is important when subsidence is studied.

A group of numerical simulation is conducted to simulate subsidence with the same compressibility coefficient of coal bearing formation C_m and different Biot coefficient α. From Table 2, one can see that the Young's modulus and Poisson's ratio with the same value of C_m do not affect the subsidence results. The Biot coefficient affects the subsidence results obviously and the subsidence of CSG bearing formation decreases linearly with the decreasing of Biot coefficient.

Desorption-induced deformation by degassing

The same geometrical model as Fig. 2 is applied to calculate the desorption-induced deformation of coal seam formation. The sorption properties of coal seam formation are shown in Table 3.

Figure 5 shows the results of the desorption-induced strain with depth for the uniaxial model and the coupled numerical model. One can see that the desorption-induced strains for the uniaxial model are consistent in trend with the numerical results. For comparison, at the top of the coal bearing formation, the maximum strain difference between the analytical and numerical coupled models is 0.19×10^{-4}, with the relative error of 2.47%; the deformations for the numerical model and the analytical model are 70.10 mm (as shown in Fig. 6) and 68.42 mm (derived from Eq. 5), respectively, and the corresponding error is about 2.46%. Although the results are very close for the two models, the uniaxial compact model is limited only in an extreme state when

Table 2 Numerical results of subsidence for seven cases with different deformation parameters

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Young's modulus (GPa)	18.17	16.73	13.81	8.67	13.81	13.81	13.81
Poisson's ratio	0.1	0.2	0.3	0.4	0.3	0.3	0.3
Biot coefficient	1	1	1	1	0.4	0.6	0.8
Subsidence of FEM (mm)	16.40	16.40	16.40	16.40	6.65	9.97	13.20

Table 3 Coal bed sorption properties used in computation (Australian 2014; Chen et al. 2013)

Parameter	Value	Physical meanings
P_L	4.3 Mpa	Langmuir pressure of CH_4 in coal
$\varepsilon_{\max}$	0.0078	Langmuir strain at infinite pore pressure
V_L	15 m^3/t	Langmuir capacity of coal for CH_4
K_s	27.88 Gpa	Bulk modulus of coal grains
s_{w0}	99.99%	Initial water saturation in coal seam
μ_g	1.84×10^{-5} Pa s	Methane dynamic viscosity
ρ_{ga}	0.717 kg/m^3	Density of methane at standard condition
L	0.50	Genuchten–Mualem model parameter
m	0.65	Genuchten–Mualem model parameter
n	2.80	Genuchten–Mualem model parameter

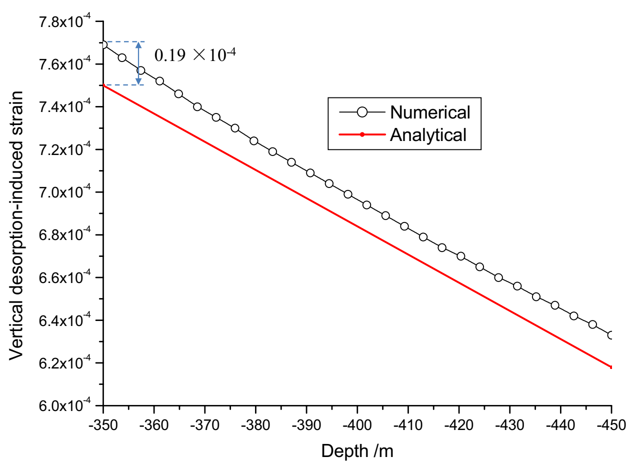

Fig. 5 Desorption-induced strain comparison between analytical and numerical model

the value of decreased water head is the same in the whole CSG formation (one-dimensional condition), and ignores the lateral extent of coal seam formation (three-dimensional condition), thus it may overestimate the subsidence.

From the above two comparisons, it concludes that the coupled model can be better used in analysis of subsidence of coal seam gas extraction without the limitation of one-dimensional condition, geometry of coal seam reservoir and so on.

Parametric study

In this analysis, the numerical model is applied to study the characteristics of subsidence and possible influence factors in CSG extraction.

Modelling approach

To conduct an analysis of subsidence in coal seam, an axisymmetric conceptual model is established with a well spacing of 800 m [it is a common distance in coal seam gas well fields (Australian 2014)]. From the top to the bottom of the model, the strata are alluvium, sedimentary unit 1, sedimentary unit 2, sedimentary unit 3, coal seam, sedimentary unit 4 and sedimentary unit 5, respectively, as shown in Fig. 7. The coal bearing formation is located at a depth of 350–450 m (correspondingly the thickness is 100 m).

The production is achieved by depressurising the coal seam which leads to desorption of the methane according to Langmuir relations. To predict the compaction induced by changes of both groundwater pressure and degassing of coal seams, we assume that dewatering has lowered the groundwater head level to 35 m above the CSG bearing formation, which is the typical degree of dewatering required for CSG production (Australian 2014). At the wellbore wall corresponding to the coal seam locations, a drawdown pressure is applied to deplete the coal seam and invoke the methane desorption. Otherwise the wellbore wall is considered impermeable. We keep the dewatering for 10 days, and then fix it to keep degassing. The methane is assumed to be desorbed and diffused from the coal matrix immediately, and controlled mainly by gas Darcy flow rather than by its diffusion in the matrix (Seidle and Arri 1990; Freij-youb 2012).

The geomechanical properties of the coal seam have been assigned in Tables 1 and 3, and the properties of the other layers are listed in Table 4. To study the possible influence factors associated with the permeability of geological layers, the permeability is assumed as constant during the course of CSG extraction.

The stress field of the model is lithostatic and pore pressure is hydrostatic. The left end of the coal seam formation is set as a fluid outlet for production well. On the right end of the model (radial boundary), which is 400 m from the left end, no flow condition is imposed by considering of the well spacing with 800 m. The pressure on the top is specified as

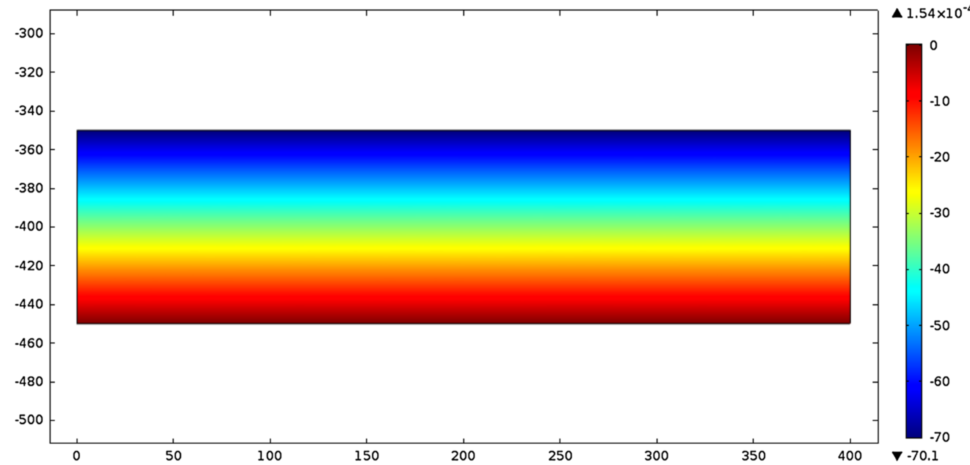

Fig. 6 Deformation contour of numerical simulation

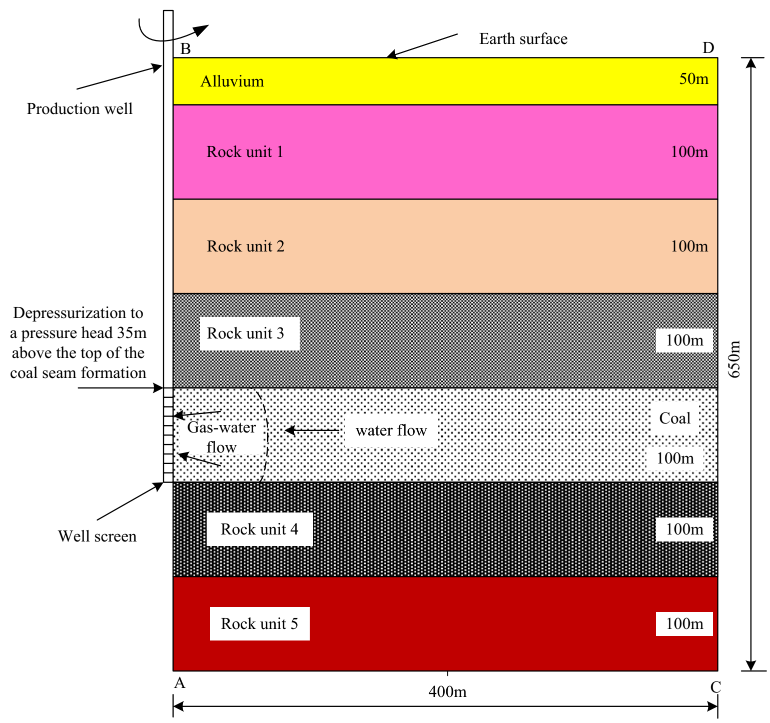

Fig. 7 Conceptual model for subsidence prediction in CSG production

Table 4 General model parameters of different layers (Australian 2014)

Layer	Young's modulus (Gpa)	Poisson's ratio	Density (kg/m^3)	Permeability ($\times 10^{-15}$ m^2)	Porosity	Biot's coefficient
Alluvium (saturated)	0.2	0.3	2100	1.19	0.2	1
Rock unit 1	8	0.25	2100	1.19	0.2	1
Rock unit 2	14	0.25	2140	0.356	0.16	1
Rock unit 3	20	0.25	2140	0.119	0.16	1
Rock unit 4	28	0.25	2140	0.119	0.16	1
Rock unit 5	32	0.25	2200	0.119	0.16	1

0 MPa. In addition, the other end of the model is considered impermeable. For mechanical boundary conditions, the left, right and the bottom ends are normal constrained, and the top is free.

The coupled fluid flow-geomechanical model is implemented in software COMSOL to estimate the deformation and pore pressure evolution of sedimentary layers induced by water and gas extraction.

Deformation characteristics of coupled fluid flow

Figure 8 shows the pore pressure distribution with depth for the left and right edge of the model for different time. Due to the dewatering and water and gas flow from the well screen, the pore pressure near to the well drops more quickly than that of the right edge (far field) in 1000 days. However, with the growth of time, the pore pressure near the right edge decreases clearly, especially in the coal seam formation. After 4000 days, the pore pressures in the underlying layer are almost the same for the well (AB) and the right edge (CD). Because of the effect of methane desorption, there is still obvious difference in the target coal seam formation in 4000 days.

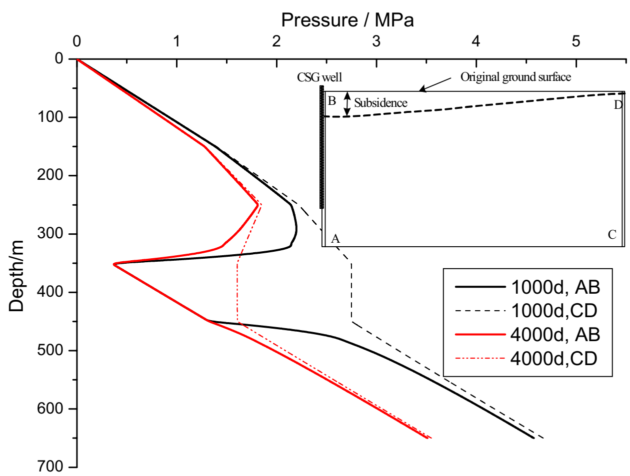

Fig. 8 Comparison of pore pressure distribution between the left and right edge of the model for different time

Coal seam gas-related subsidence is induced by compression due to ground water and gas extraction from the well, thus it is natural that the subsidence near the well is greater than that near the far field (Fig. 9). Because the far right edge of the model represents an impermeable symmetry line between the two production wells spaced at 800 m, there is no remarkable subsidence difference between the vicinity of well and far field with the radius 400 m (see Fig. 9a, b).

The strains include desorption strain and mechanical stain due to the methane desorption effect and the change of effective (mechanical) stress, respectively. Five locations are monitored: 1, 5, 15, 30 and 60 m radial distance from the production well, and curves of sorption strain and volume strain for different locations are presented (see Fig. 10a, b). The desorption strain and mechanical stain increase abruptly in the early stage of dewatering and then slowly increase with time. From the comparisons of rising slopes in the early stage, the contribution of this desorption strain to subsidence is significant.

Influence of coal seam permeability

One of the most uncertain parameters in the subsidence model is the permeability of coal seam formation. It may change during the course of gas extraction due to change in effective stress and coal shrinkage. Increase in

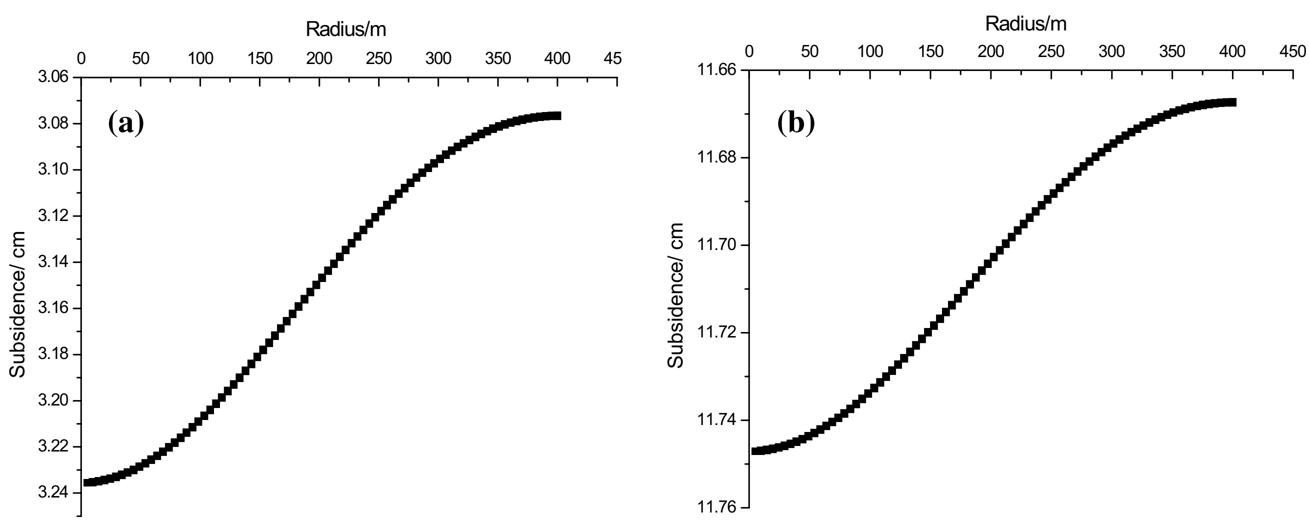

Fig. 9 Ground subsidence change with different time: **a** 500 days and **b** 4000 days

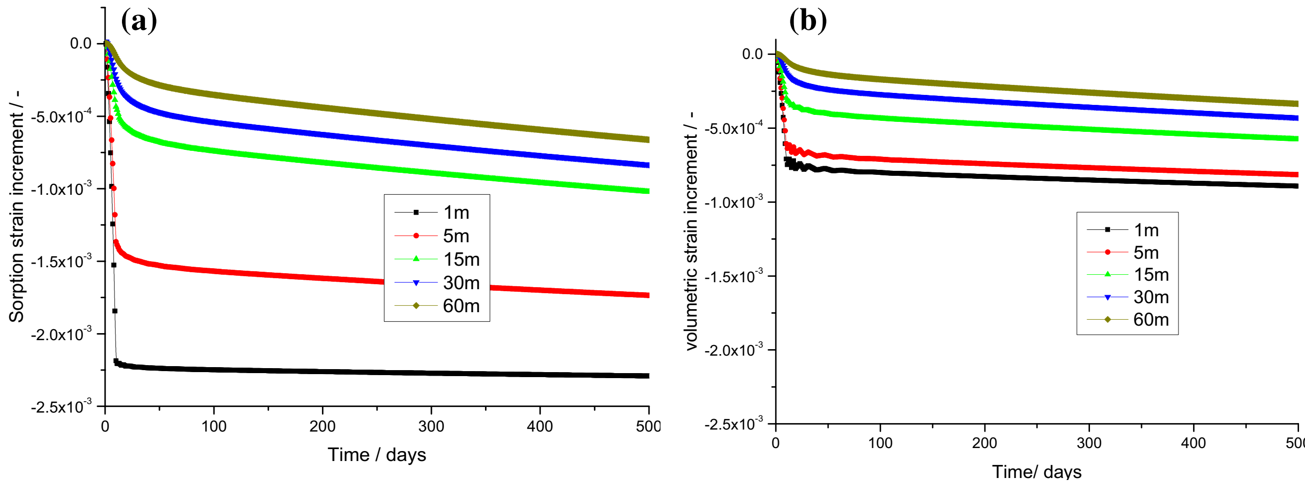

Fig. 10 Strain evolution in the coal seam formation with time for different distances from production well: **a** sorption strain; and **b** mechanical volume strain

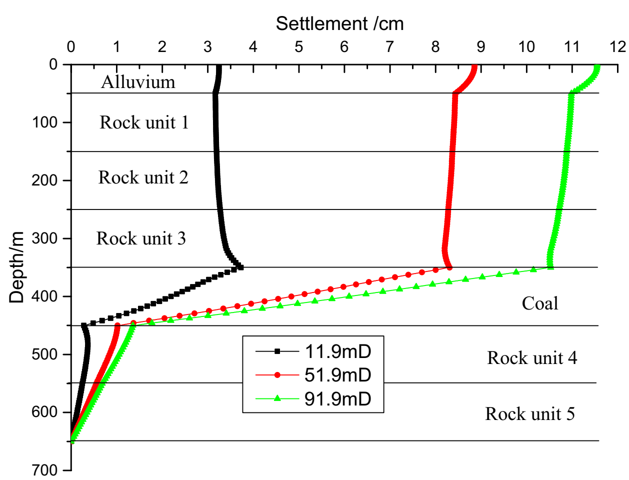

Fig. 11 Settlement curves in the vicinity of the well vs. depth after 500 days of gas extraction for different permeability of coal seam formation

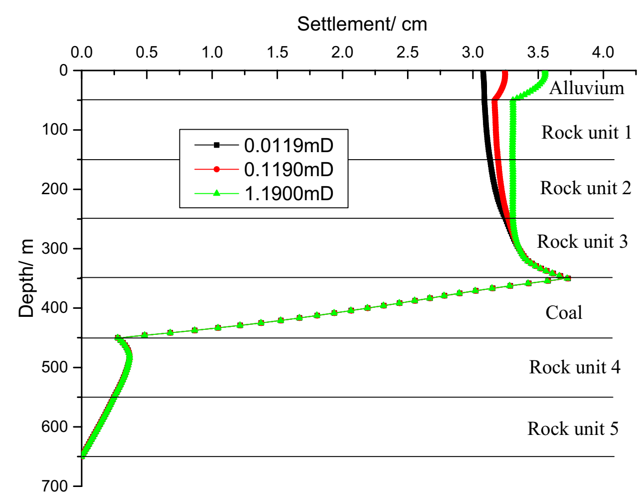

Fig. 12 Settlement curves in the vicinity of the well vs. depth after 500 days of gas extraction for different permeability of overlying layer

the effective stress will induce a decrease in permeability whilst coal shrinkage will cause an increase in permeability. Accordingly, the coal seam permeability can definitely impact the surface subsidence. Figure 11 presents the settlement in the vicinity of the well vs. depth with different permeabilities of coal seam formation, obtained after 500 days of gas extraction. It is worth noting that the higher the permeability of coal seam formation, the larger the subsidence induced by gas extraction. The maximum subsidence is around 3.2 cm for the coal seam permeability of 11.9 mD, while the maximum subsidence is approximately 11.5 cm when the permeability of coal seam is 91.9 mD after 500 days of gas extraction. Therefore, the land subsidence is sensitive to the permeability change of the target coal seam. It can be seen that the settlement of rocks overlying confined coal seam gradually increases with time in short-term depressurizing; meanwhile, heave appears in underlying rock of coal seam formation, which is "rock-arch effect" that is influenced by the abrupt pressure change and the difference of permeability between overlying layer and coal seam formation. When the coal seam permeability is 11.9 mD, the depressurizing effect of overlying layers is not obvious with small deformation and the settlement mainly occurs in target coal seam formation, which shows obvious "rock-arch effect" due to a larger pore pressure gradient between the overlying layer and coal seam. With the increase of coal seam permeability, the pore pressure becomes smaller in the target coal seam formation and overlying layers in a specified time, and the settlement mainly occurs in coal seam and overlying layers. Because the deformation is obvious in overlying layers, "rock-arch effect" is not obvious between coal seam formation and overlying layer.

Influence of permeability of overlying and underlying layer

Figure 12 provides the settlement in the vicinity of the well vs. depth for different permeability of overlying layer, obtained after 500 days of gas extraction. The permeability of the confining clay layer (overlying layer relative to the target coal seam formation) varies two orders of magnitude

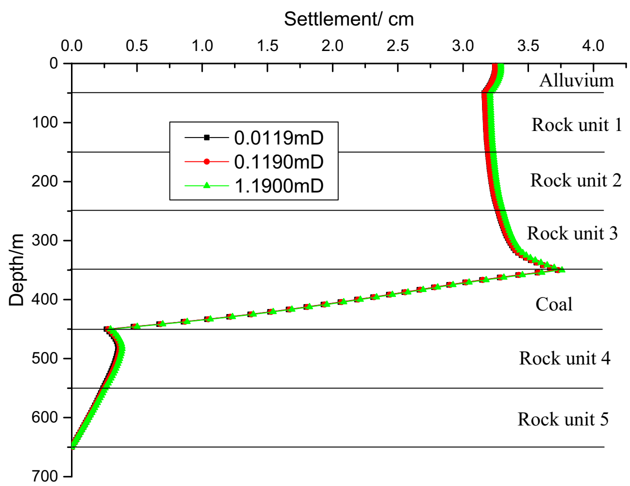

Fig. 13 Settlement curves in the vicinity of the well vs. depth after 500 days of gas extraction for different permeability of underlying layer

between 0.01 and 1 mD. As the same as the change rule in the coal seam, the larger the permeability of overlying layer, the larger the subsidence induced. However, the maximum subsidence ranged only from 3.1 to 3.6 cm relative to the permeabilities of two orders of magnitude.

Figure 13 shows the settlement in the vicinity of the well vs. depth with different permeabilities of underlying layer, obtained after 500 days of gas extraction. It is worth noting that the subsidence is not sensitive to the permeability change of underlying layer within two orders of magnitude.

Discussion

According to the above analysis, the coal seam gas extraction-induced subsidence mainly depends on the four key parameters: (1) the mechanical properties of coal seam and overlying layers, (2) the poro-elastic coefficient of geological units hydraulically connected to the target coal seam, (3) the pore pressure change of geological units and (4) the shrinkage effect associated with desorption of coal by depressurization. This indicates the importance of having a prior knowledge of the geology of the field to have a good estimate of subsdence. The land subsidence caused by the gas extraction is a transient problem. This means, the deformation, the pore pressure, an the flux are all dependent on time. The desorption-induced compaction and the mechanical compaction mainly depend on the pore pressure change, which can also be seen from Eq. 5. Taking well operational conditions as example, the influence of pore pressure change is investigated. In particular, three different depressurization rates are analyzed, i.e. the bottomhole pressure head decreased by 315 m in (a) 10 days (fast depressurization), (b) 100 days (intermediate depressurization) and (c) 300 days

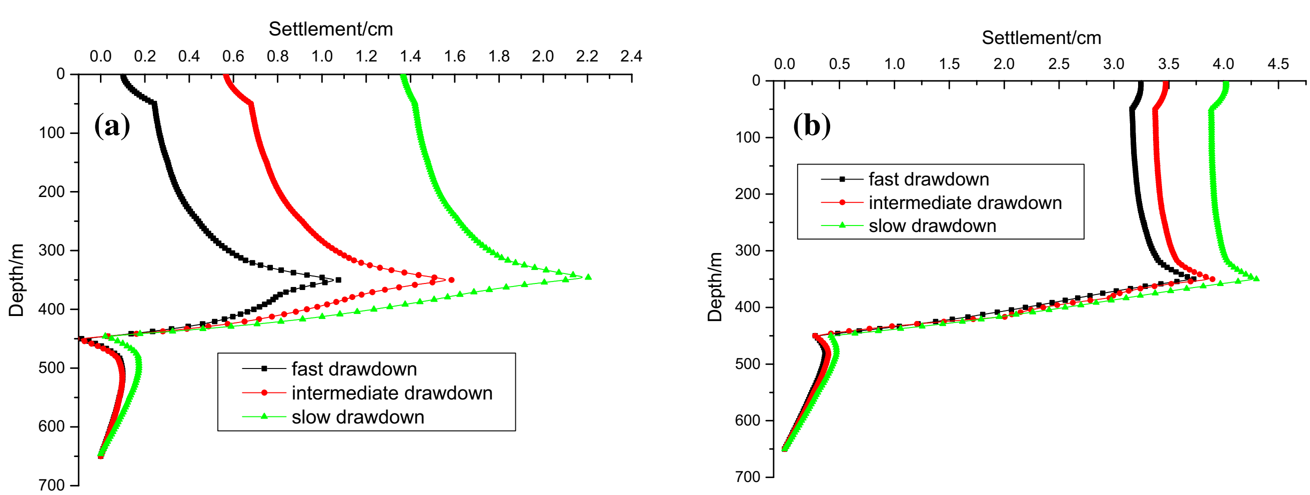

Fig. 14 Settlement curves in the vicinity of the well vs. depth with different dewatering operational conditions: **a** after dewatering and **b** 500 days of gas extraction

(slow depressurization). All the other model input parameters remain the same.

Figure 14 gives the settlement in the vicinity of the well vs. depth with different dewatering operational conditions, obtained (a) after bottomhole pressure head decreased by 315 m and (b) 500 days of production. It can be seen that the settlements of different layers are sensitive to the manner how fast the bottomhole pressure is reduced. Afer a long-term production, the settlement becomes less sensitive to the way how the bottomhole pressure was decreased.

The causes of subsidence are pressure depletion and rock deformation during dewatering process and gas production vs. time. Permeability of different geological units impacts the pressure depletion rate. To study the possible influence associated with the permeability of coal seam formation, overlying and underlying layer, two orders of magnitude change are considered in this sensitivity analysis in Sects. "Influence of coal seam permeability" and "Influence of permeability of overlying and underlying layer". The result demonstrates the importance of having a good understanding about the permeability change in coal seam and overlying layer during gas/water production with time. Therefore, predicting changes in permeability and porosity of coal reservoir and overburden is a fundamental problem in the estimation of subsidence by gas extraction.

For comparing analytic solutions, the applied model for the geomaterials is simplified as elastic and isotropic media in this work. Compared to other gas reservoirs, coal bed methane is a fractured medium and contains significant amount of fissure systems as dual-pore media. To predict subsidence, the porosity and permeability related to pressure/stress are indispensable for coal seam formation and overlying layers. Due to lack of experimental data currently, the developed model still stays in the poro-elastic stage. This, however, is questionable for the residual land subsidence, which is generally unrecoverable deformation and should be considered as plastic deformation.

Conclusions

The land subsidence induced by coal seam gas extraction was mainly investigated using a type of numerical method in this paper. Some conclusions can be made.

For analytical models, the Geerstma's model (representative of disc-shaped reservoir model) disregards the permeability of confining layer of coal seam and is subject to more restricted conditions such as the geometry of coal seam reservoir. So it may underestimate the real subsidence induced by coal seam gas extraction; the uniaxial compact model is limited in one-dimensional condition, ignoring the lateral extent of coal seam formation, thus it may overestimate the potential pressure distribution and cannot reflect the realistic production.

The numerical model is capable of describing the transport properties of coal seam, including water flow, gas flow and desorption, and rock deformation. Due to the methane desorption effect and the change of effective (mechanical) stress during dewatering and gas production process, the mechanical stain and desorption strain increase abruptly in the early stage of dewatering and then slowly increase with time, while the contribution of the desorption strain to subsidence is significant.

The pressure depletion and rock deformation of associated geologic units are the main causes by coal seam gas extraction. The pore pressure depletion rate is controlled by well operational condition and permeability change of different geological units. Through numerical analysis, subsidence is influenced by not only permeability change of coal seam but also that of overlying and underlying layers. Above all, permeability of coal seam is a key factor that affects the land subsidence induced by coal seam gas extraction.

The mechanism of land subsidence is complicated, depending on many physical properties of the coal seam and other layers. Compared to other layers, coal seam is a naturally fractured dual-porosity medium, consisting of micro-porous matrix and cleats. The permeability and porosity of coal seam is extremely stress or pressure sensitive and its unrecoverable deformation should be taken into account. Further research will be carried out in future.

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Compliance with ethical standards

Conflict of interest No conflict of interest exists regarding the publication of this paper.

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