

Geomechanical Behavior of Gas Hydrate-Bearing Reservoir During Gas Production*

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Abstract

Deformation of gas hydrate-bearing reservoir may pose a risk of geohazard. While recent advancement in laboratory experiments has provided insights into geomechanical behavior of gas hydrate-bearing sediments in a phase-stable condition, its behavior under non-uniformly evolving multi-physics conditions, happening during gas production, is more complex and requires rigorous investigation. For example, deformation of gas hydrate-bearing sediments may be enhanced by the change in hydrate-dependent sediment permeability as it alters pore pressure field and by non-uniform hydrate dissociation as dissociating sediments release their stresses, which need to be carried by the neighboring sediments. Therefore, it is crucial for accurate deformation prediction to adopt a soil model that captures the behavior of gas hydrate-bearing sediments and comprehensively model the complex process during gas production. This study provides the importance of capturing volumetric deformation and hydrate dissociation-induced stress relaxation through simulations of 30-day gas production from homogeneous gas hydrate-bearing reservoir via depressurization. It is found that, for accurate prediction of reservoir deformation, a soil model needs to consider volumetric yielding. In addition, as volumetric deformation affects sediment permeability, gas production is also affected by volumetric deformation. These findings demonstrate that geomechanical modeling plays a key role not only for predicting potential geohazard but also for an estimate of gas production.

Introduction

Deformation of gas hydrate-bearing reservoir may pose a risk for geohazard. There are mainly two causes for deformation of gas hydrate-bearing sediments during depressurization-driven gas production: (a) the increase in the effective stress caused by depressurization; and (b) the reduction in sediments' stiffness and strength caused by hydrate dissociation. Depressurization can be viewed as isotropic consolidation and soil exhibits a change in the volumetric response from elastic to plastic, termed volumetric yielding, as shown in [Figure 1a](#), where p is the mean

total stress, p' is the mean effective stress and P_w is the pore water pressure. Therefore, volumetric yielding plays a key role for development of deformation.

The solid hydrates in pores are known to contribute to interlocking of host soils, leading to hydrate-bearing soils being stiffer, stronger and more dilatant than its host soils (e.g. Hyodo et al., 2013). This implies that both hydrates and host soils carry the load but upon hydrate dissociation, the effective stress carried by the solid hydrates is released under constant strain, the process known as stress relaxation. The effective stress recovery to the original value therefore results in additional deformation. This hydrate dissociation induced deformation is illustrated in Figure 1b. These two deformation mechanisms in gas hydrate-bearing reservoir could occur simultaneously in a highly coupled manner during gas production. For example, volumetric yielding may slower hydrate dissociation due to permeability reduction caused by pore volume reduction. Another example is hydrate dissociation enhances volumetric yielding as depressurization propagates faster due to increases the sediment permeability. Therefore, it is crucial for accurate deformation prediction to adopt a soil model that captures the behavior of gas hydrate-bearing sediments and comprehensively model the complex coupled process during gas production.

To demonstrate the importance of model's capability to capture volumetric yielding, hydrate dissociation and also their coupled behavior, this study shows difference in the deformation development under different conditions including with/without volumetric yielding, with/without hydrate dissociation and with/without hydrates in pores. The analyses are conducted using the thermo-hydro-mechanical simulator for gas hydrate-bearing reservoir developed by Klar et al. (2013). The detailed description, governing equations and adopted physical parameters, other than presented later in Figure 2 and Figure 3 can be found in the referred paper. Figure 2 shows the considered model reservoir, which is (initially) homogenous gas hydrate-bearing reservoir with hydrate saturation $S_h = 50\%$ (or 0% when zero hydrate is considered) and 5 m production zone. The top of the model boundary is assumed to be located at 1275 m below sea level and 275 m below sea floor. The initial temperature is set to be $11.25\text{ }^\circ\text{C}$ at the top of the model boundary and increases with the gradient of $0.03\text{ }^\circ\text{C/m}$. This leads to hydrate phase equilibrium pressure $P_{eq} \approx 10\text{ MPa}$ near the production zone. The initial porosity is 0.4 and the initial intrinsic permeability is $|K| = 10^{-12}\text{ m}^2$ and the effective permeability follows a simple power law, given by $K_h = K(1-S_h)^5$ (Masuda et al., 2015). The intrinsic permeability value changes according to the porosity. The well boundary is mechanically fixed in the radial direction, open for fluid flow in the production zone but impermeable above and below the production zone. No thermal flow is allowed at the well boundary. The top, bottom and farfield boundaries all have constant pore water pressure, temperature and effective stress (except the bottom boundary being mechanically fixed in the vertical direction).

For the hydrate-bearing soil behavior, this study adopts the drained triaxial test data conducted by Yoneda et al. (2015b, 2017). The tests were carried out using the pressured-core samples recovered from offshore Nankai Trough, Japan. The coring, subsampling and testing were conducted their state-of-the-art system called TACTT (Yoneda et al., 2015a) and thus the results can be deemed most representative of the natural hydrate-bearing soil behavior under triaxial shearing. Figure 3 presents the test data and the model fitting done by two different soil models: (a) the methane hydrate critical state model (Uchida et al., 2012) and (b) no volumetric yielding model achieved by the Mohr-Coulomb based hydrate-bearing soil model (Klar et al, 2013). The calibrated parameters are listed next to each figure. It is important to state that the critical state model has volumetric yielding criterion, but the Mohr-Coulomb model does not. Yet, both models can capture the mechanical behavior under triaxial shearing condition. This is because the soil does not yield in volume under triaxial shear. When considering

depressurization-induced behavior, the difference may become significant, which will be highlighted later in this study. The following simulations adopt the methane hydrate critical state model except when the case is referred to as “No volumetric yielding”.

Figure 4 presents the considered gas hydrate-bearing reservoir responses when subjected to 8 MPa of depressurization, achieved by 2 days, at the elapsed time of 30 days. The depressurization (Figure 4b) induces hydrate dissociation (Figure 4c) and both contribute to the sediments' deformation represented by the scaled arrows (Figure 4a). The stress ratio q/p' (where q is the deviator stress and p' is the mean effective stress) plotted in Figure 4a can be used to indicate the deformation pattern. When the sediments deform in shearing manner, the value of q/p' increases whereas when they deform in volumetric manner the value of q/p' decreases. The initial value of q/p' in this study is 0.75 and thus it is clear that the sediments deform dominantly in volumetric manner. Therefore, it is important to consider not only shearing deformation but also volumetric deformation. In other words, in laboratory experiments, it is important to carry out not only triaxial shear tests but also isotropic consolidation tests to obtain relevant soil model parameters.

Discussion and Results

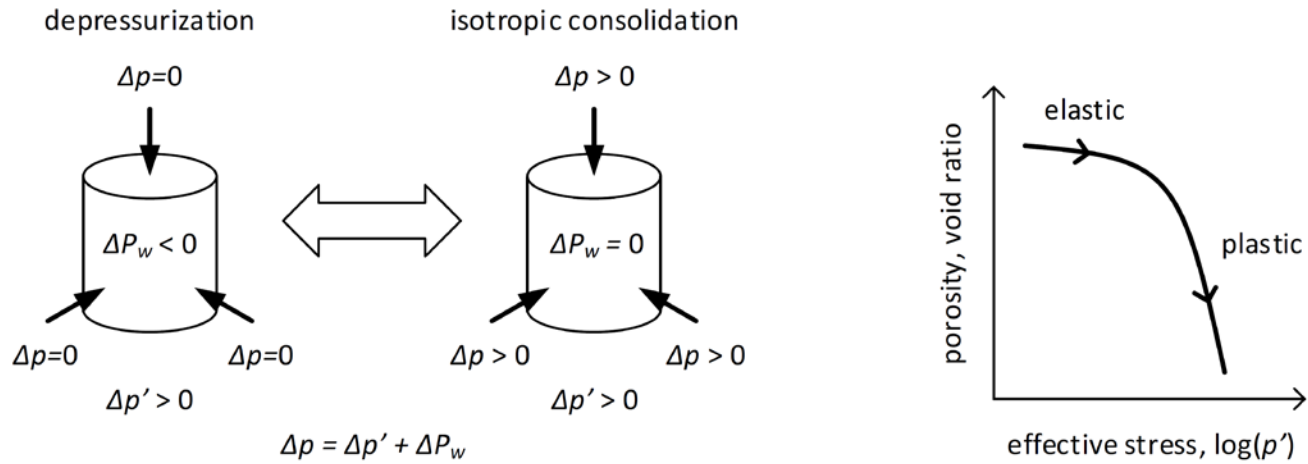
To highlight the importance of volumetric yielding, hydrate dissociation and their coupled behavior, three more different cases are considered in the analyses. The first case utilizes the no volumetric yielding model to highlight the importance of volumetric strain so that it is referred to as “No volumetric yielding”. Secondly, the temperature is set low enough so that no hydrate dissociation occurs. This case highlights the importance of hydrate dissociation and thus is referred to as “No hydrate dissociation”. The third case removes all hydrates from the beginning and is referred to as “Zero hydrate”. The base case shown previously incorporates all the features discussed (volumetric yielding and hydrate dissociation and hydrates) and thus herein referred to as “All included”. Figure 5a presents the developed vertical strain (compression positive) of the production zone against the radial distance from the well for the four cases at $t = 30$ days. As can be seen, “All included” results in the maximum vertical strain, highlighting the importance of incorporation of volumetric yielding, hydrate dissociation and their coupled behavior for accurate deformation prediction.

Comparison between “All included” and “No volumetric yielding” highlights the importance of the volumetric yielding whereas “All included” and “No hydrate dissociation” suggests the importance of hydrate dissociation. It is interesting to note that the vertical strain developed in “Zero hydrate” case is not as great as those “All included” or “No volumetric yielding”. This is because depressurization cannot reduce the pore pressure away from the well when the permeability is spatially constant. Figure 5b shows the average pore water pressure in the production zone for the four cases at $t = 30$ days. In “No hydrate dissociation” and “Zero hydrate” cases, the sediments have homogenous permeability which remains constant, resulting in the same logarithmic pore pressure distribution, defined by the radius (variable) and the four constants which are the radii of the well, the far-field and the pressures at the well and the far-field. In contrast, “All included” and “No volumetric yielding” cases increase their permeability near the well with hydrate dissociation, leading to lower pore water pressure. Thus, it is crucial to incorporate the coupled behavior for accurate deformation prediction. Furthermore, as greater volumetric strain results in lower permeability, leading to less reduction in the pore pressure, “All included” case has higher hydrate saturation (= less hydrate dissociation) than “No volumetric yielding” case as shown in Figure 5c, which presents the average hydrate saturation in the production zone at $t = 30$ days. This clearly demonstrates the importance of incorporating the volumetric yielding also for accurate gas production prediction.

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(a) Isotropic consolidation and volumetric yielding



(b) Hydrate dissociation-induced deformation

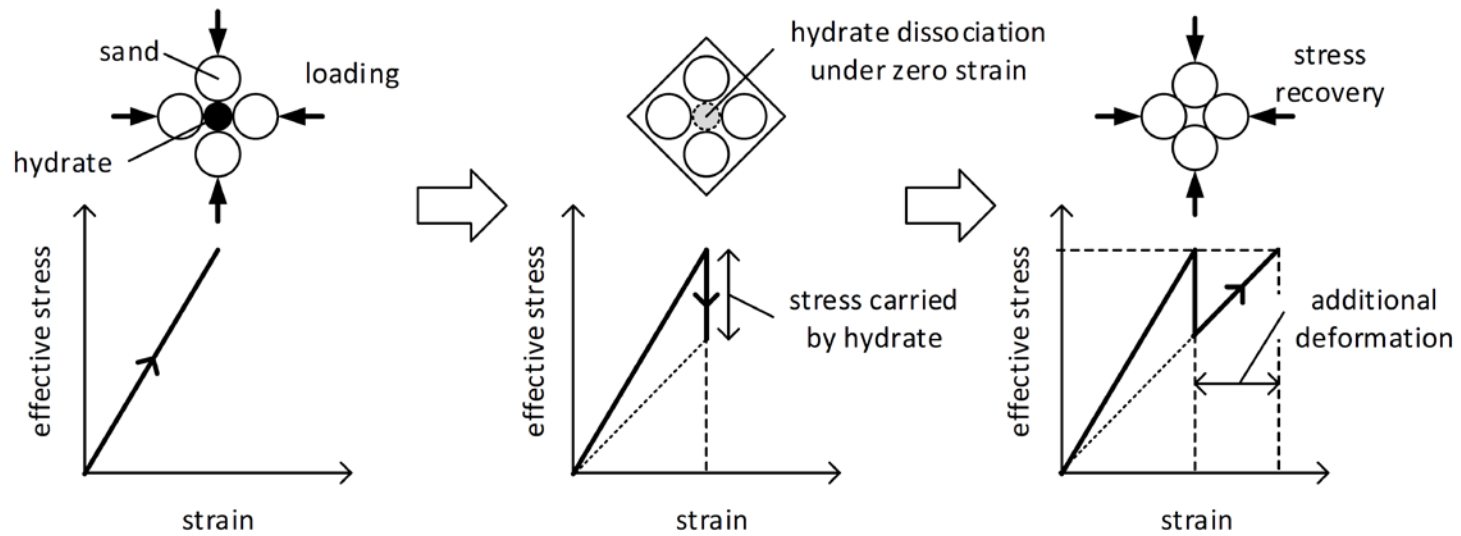


Figure 1. (a) Isotropic consolidation and (b) hydrate dissociation-induced deformation.

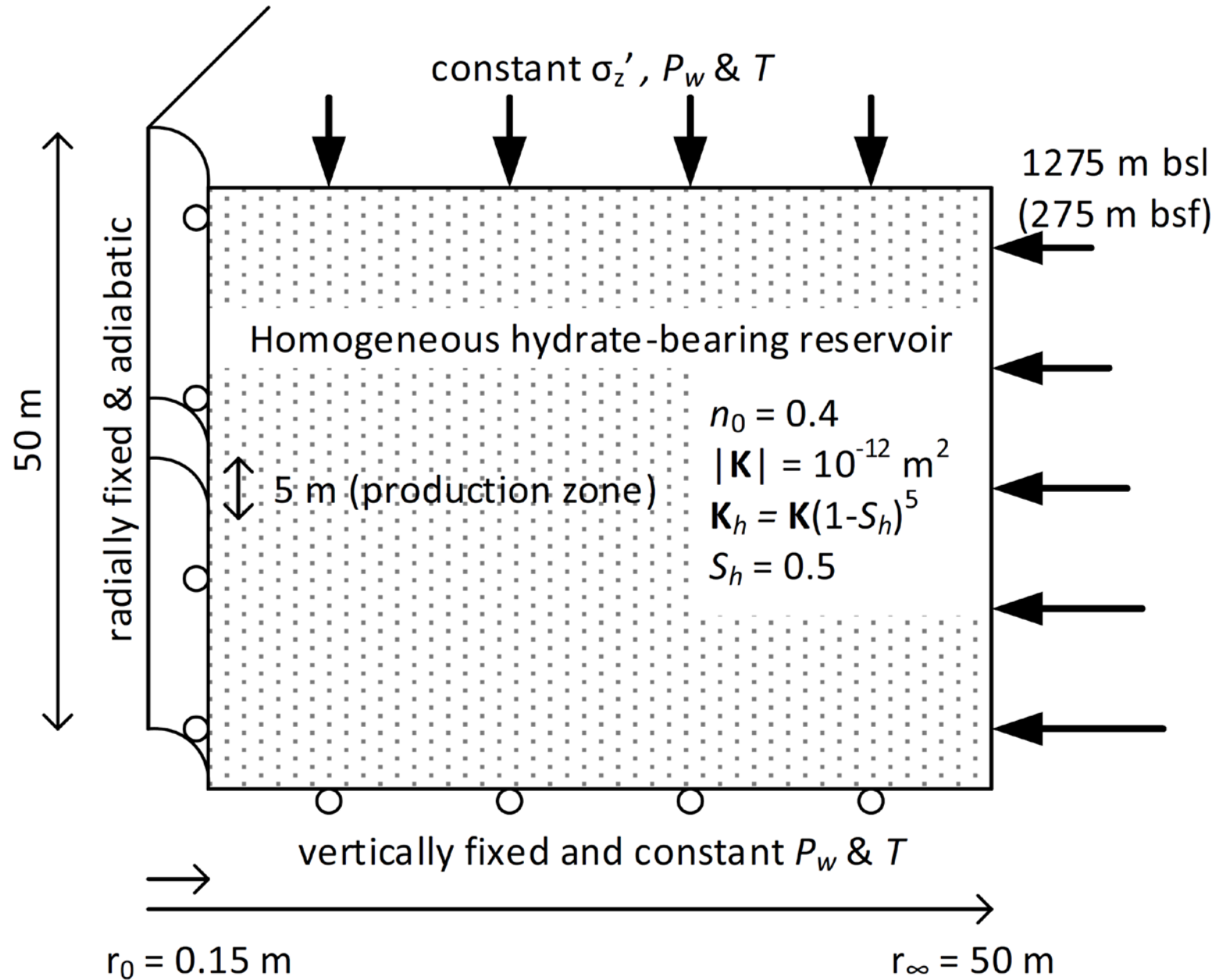
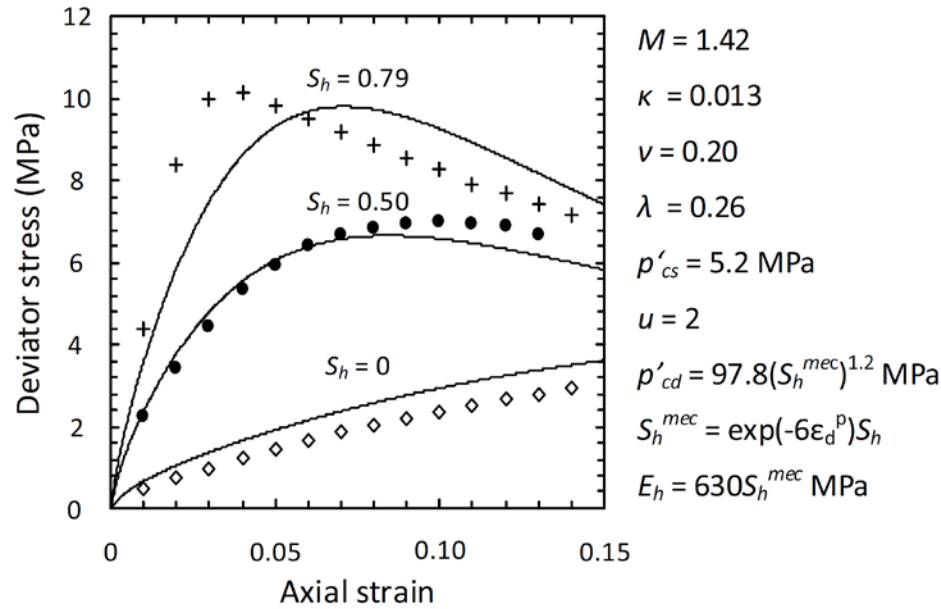
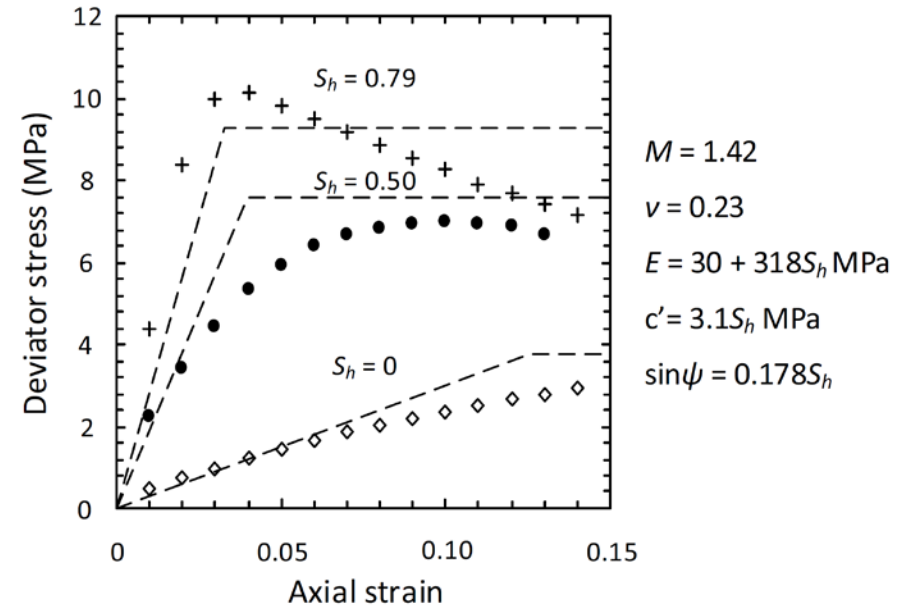


Figure 2. Model geometry, boundary conditions and initial conditions.

(a) Methane hydrate critical state model by Uchida et al. (2012)



(b) No volumetric yielding model (Mohr-Coulomb based methane hydrate soil model by Klar et al., 2013)



— Model fit Markers: Yoneda et al. (2015b, 2017) --- Model fit

Figure 3. Drained triaxial tests by Yoneda et al. (2015b, 2017) and fitting by (a) Methane hydrate critical state model by Uchida et al. (2012) and (b) No volumetric yielding model by Klar et al. (2013).

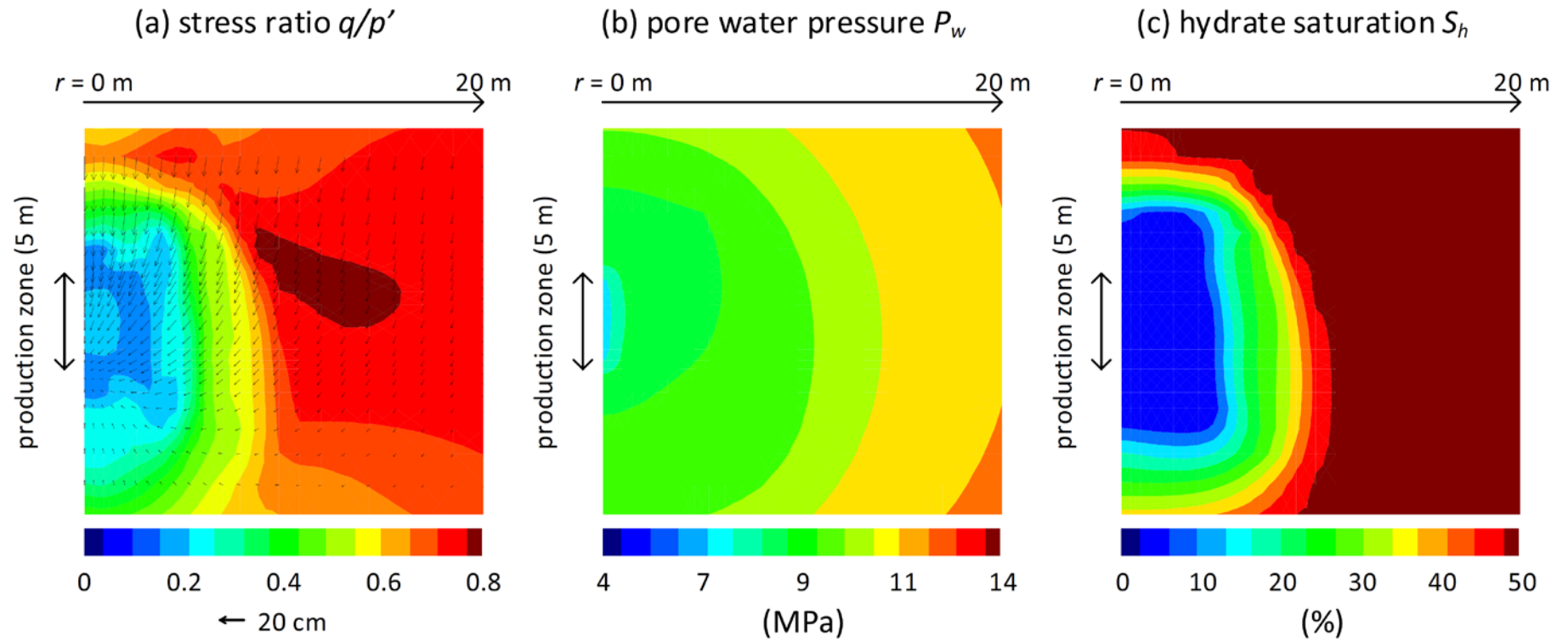


Figure 4. Gas hydrate-bearing reservoir response to depressurization in terms of (a) stress ratio and deformation (scaled arrows); (b) pore water pressure; and (c) hydrate saturation at $t = 30$ days.

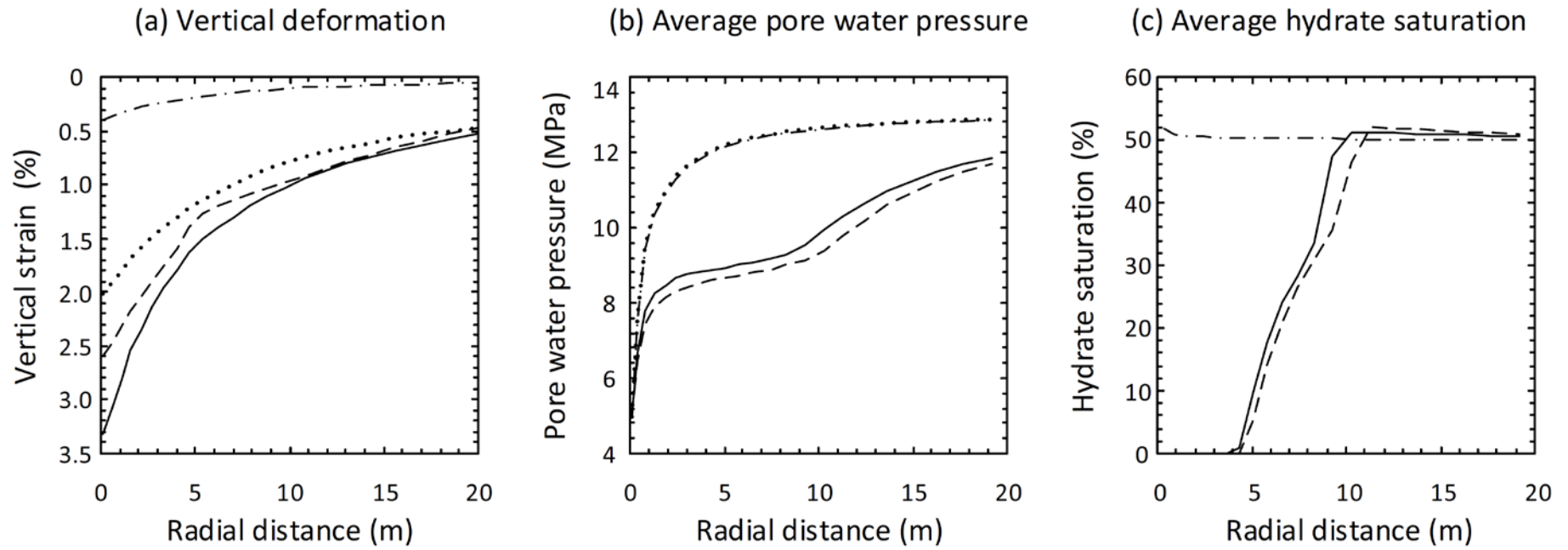


Figure 5. Development of (a) vertical strain of the production zone; (b) averaged pore water pressure in the production; and (c) averaged hydrate saturation in the production zone at $t = 30$ days.