Coupling thermo-hydro-mechanical-chemical model for methane hydrate bearing sediments with COMSOL

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引言： As shown in Fig.1, there are many geotechnical problems during gas production from hydrate layer. To solve theses problems, we need to build numerical coupling thermo-hydro-mechanical-chemical models for methane hydrate bearing sediments(MHBS). However, most of current models are based on finite differential method (FDM) or finite volume method (FVM). Few models for MHBS based on finite element method (FEM) and Galerkin variation principle are published. We use COMSOL Multiphysis® to simulate the mutiphysics behavior of MHBS during the gas production. The model is built upon the PDE interface and structure mechanical module. Good matching can be obtained with this model.

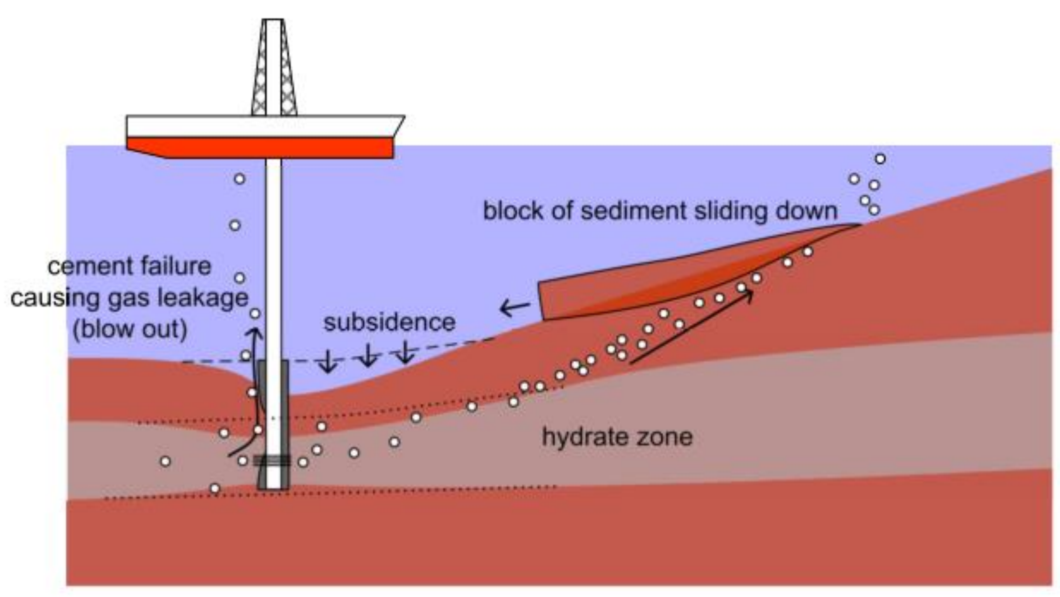

图 1. 开采引起的环境问题

计算方法： In this model, the governing equations include:

① flow equation for solving out pore pressure Pw and Pg:

$$\frac{dp_w}{dt}=\frac{B_w}{n_w}\left(\partial_x(k_w\partial_x p_w)+\partial_y(k_w\partial_y p_w)+\frac{M_wN_hR_h}{\rho_w}-\left(n\frac{ds_w}{dt}+s_w(1-n)\frac{d\varepsilon_v}{dt}-n_w\beta_w\frac{dT}{dt}\right)\right)$$

$$\frac{dp_g}{dt}=\frac{B_g}{n_g}\left(\partial_x(k_g\partial_x p_g)+\partial_y(k_g\partial_x p_g)+\frac{M_gR_h}{\rho_g}-\left(n\frac{ds_g}{dt}+s_g(1-n)\frac{d\varepsilon_v}{dt}-n_g\beta_g\frac{dT}{dt}\right)\right)$$

② heat equation for solving out temperature T：

$$c_T\frac{dT}{dt}=\partial_x(k_T\,\partial_x T)+\partial_y(k_T\,\partial_y T)+\rho_w c_{wT}k_w(\partial_x p_w\partial_x T+\partial_y p_w\partial_y T)+\rho_g c_{gT}k_g(\partial_x p_g\partial_x T+\partial_y p_g\partial_y T)-\Delta HR_h$$

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③dissociation equation for solving out hydrate saturation Sh：

$$\frac{ds_h}{dt}=-\frac{M_wN_hR_h+M_gR_h}{n\rho_h}-\frac{s_h(1-n)}{n}\frac{d\varepsilon_v}{dt}+s_h\beta_h\frac{dT}{dt}$$

④equilibrium equation for solving σ and ε：

$$\nabla\cdot\left(\boldsymbol{\sigma}'-\frac{s_gp_g+s_wp_w}{1-s_h}\boldsymbol{\delta}\right)+\boldsymbol{f}=\mathbf{0}$$

$$\boldsymbol{\sigma}'=\boldsymbol{E}:\boldsymbol{\varepsilon}$$

Fig.2 shows the coupling relationship between different physical fields. Flow equations and heat equation are built on PDE interface. The mechanical module is used to simulate the deformation of MHBS influenced by other physical fields. A new feature called external material model in COMSOL 5.2 is utilized to build an advanced critical state constitutive model for MHBS.

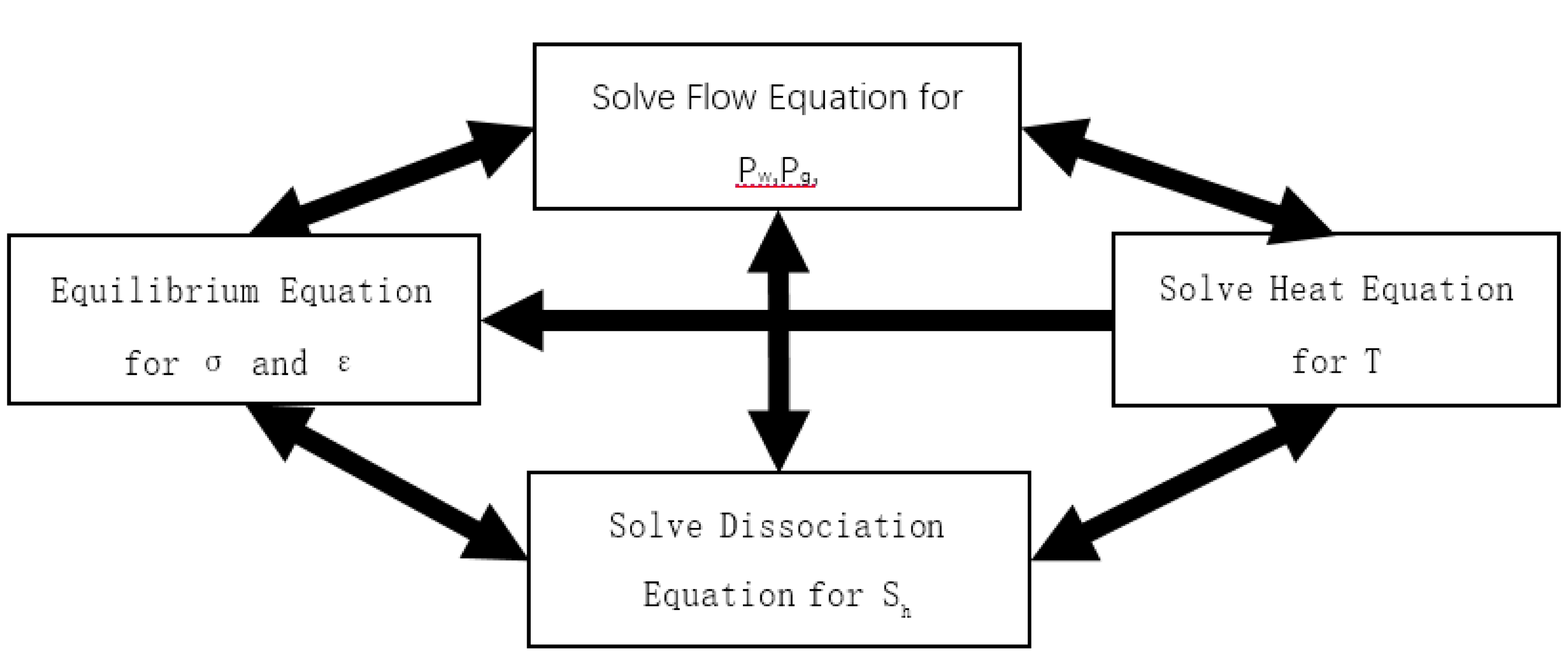

图 2. 不同物理场之间的耦合关系

结果： We compare the results with many different methods including CMG STARTS, HydrateResSim, MH21 HYDRES, STOMP-HYD, and TOUGH-FX/HYDRATE to verify the model and simulate the influence of plasticity, heat boundary condition and hydrate saturation distribution on the layer.

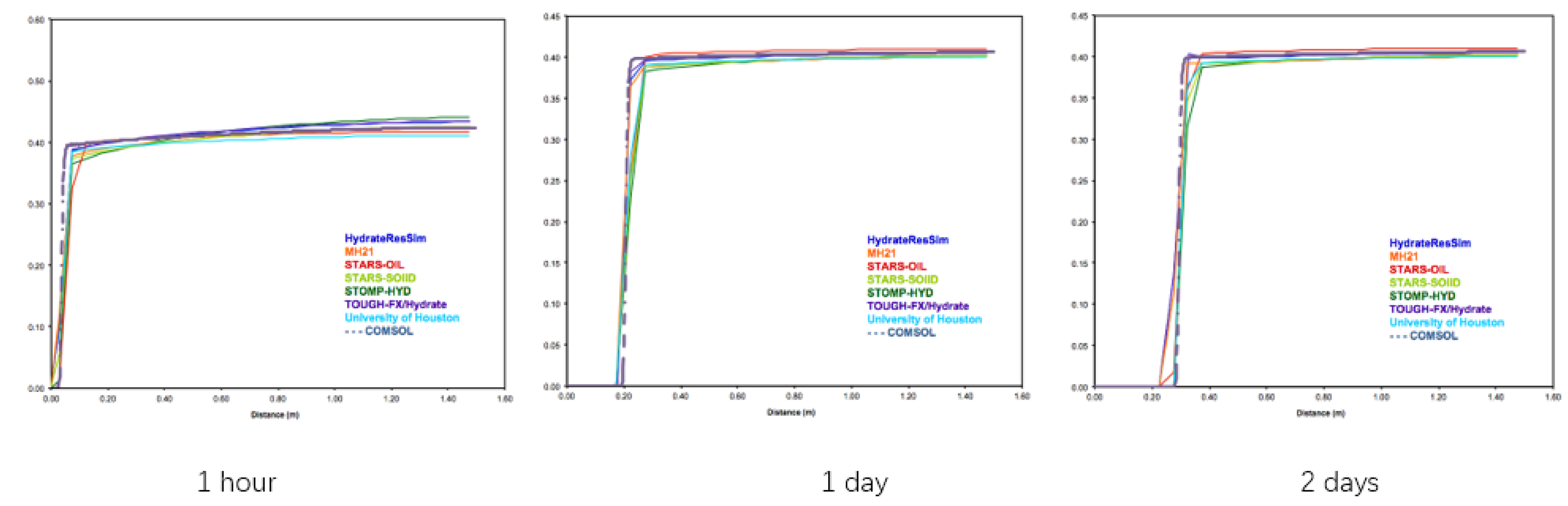

图 3. 水合物饱和度不同方法间的比较

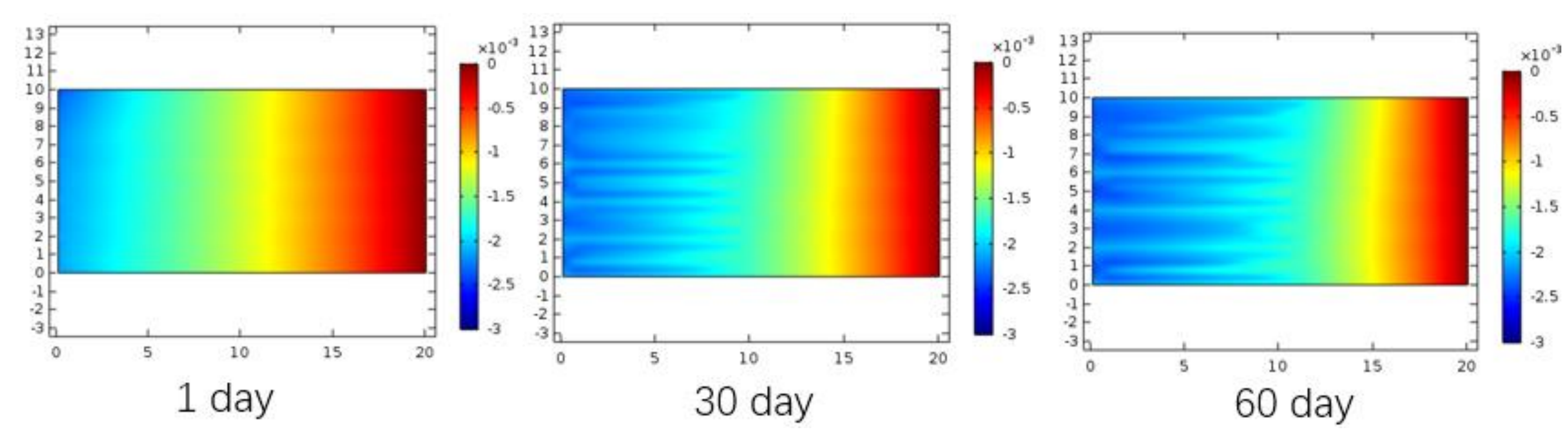

图 4. 水合物饱和度分布对气体开采中体变的影响

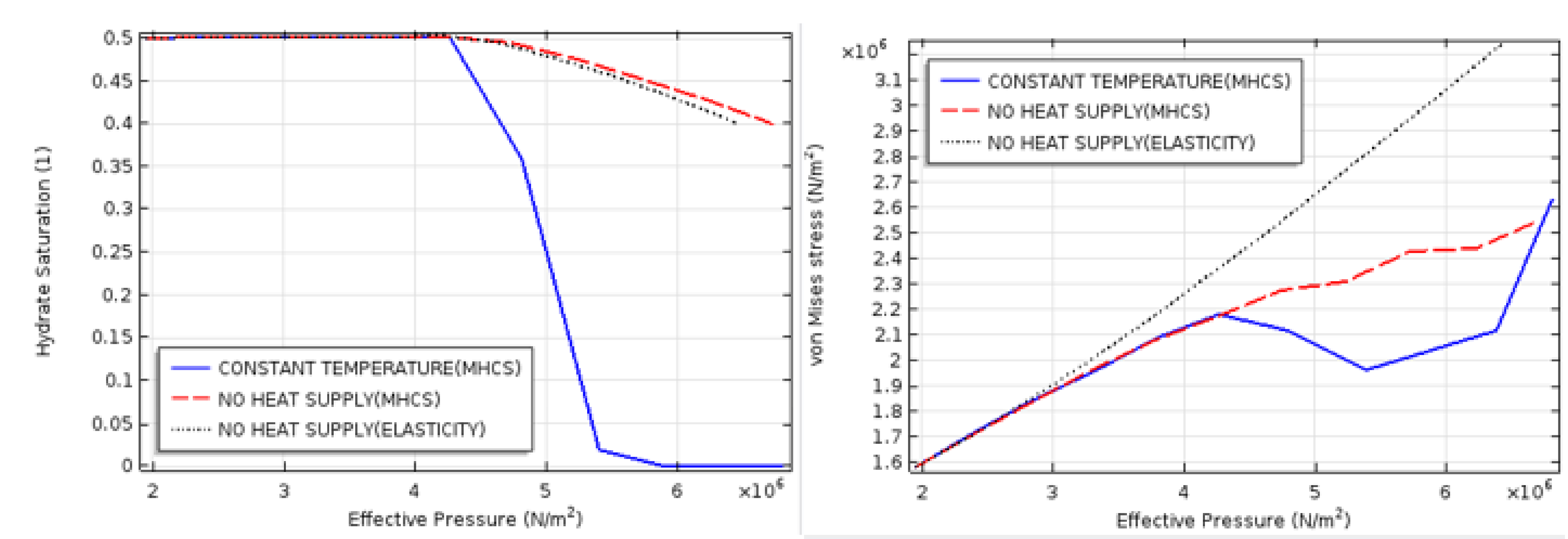

图 5. 塑性与热边界条件对气体开采中体变的影响

结论： COMSOL can be well applied to build the multiphysics model for MHBS. Through the comparison with other software, the results calculated by COMSOL are well verified. The MHCS model can be successful to be embedded into the software by the external material module. The calculated results indicate that the inelastic behavior of MHBS has great impact on the coupling simulation. Dilatancy makes volumetric contraction less. The greater diffusion coefficient in the MHCS case makes dissociation faster. So, it is necessary to build user defined inelastic constitutive model in the coupling model..

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