**GAS INTRUSION IN SATURATED BENTONITE – A THERMODYNAMIC APPROACH**

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A thermodynamic description of the response of a saturated bentonite system to changes in external variables has successfully been adopted in several different cases. Examples include correspondence between swelling pressure and water retention properties of unconfined bentonite (Bucher and Müller-Vonmoos, 1989), pressure response due to changes in salt concentration of an external solution (Karnland et al., 2005) and the description of the behavior of confined bentonite below 0°C. In the present work the same thermodynamic framework is used as a starting point for describing gas intrusion in saturated bentonite.

The response to changes in external variables (water pressure, gas pressure, temperature, salinity etc) of a confined bentonite system penetrable to water is a matter of equalization of the chemical potentials of water in the clay and water external to the system. The chemical potential of clay water under isothermal conditions and without added solutes is

\[ \mu_{\text{clay}}(w) = \mu^0 + RT \ln \frac{\text{RH}_{\text{unconf.}}(w)}{w_{\text{sat}}} + P \cdot v_w \]

Where \( \mu^0 \) is a reference chemical potential for bulk water in equilibrium with its vapor pressure at the considered temperature, \( \text{RH}_{\text{unconf.}}(w) \) is a function describing equilibrium relative humidity for the *unconfined* clay with water content. Here the molar volume of clay water is assumed to be equal to the bulk value, \( v_w \), and independent of pressure.

A homogenous, isotropic model of bentonite is presented which is completely defined by the curve \( \text{RH}_{\text{unconf.}}(w) \), and the water content at saturation, \( w_{\text{sat}} \). Total pressure at equilibrium in this model is

\[ P_{\text{TOT}}(P_g, P_l) = \begin{cases} P_s + P_l, & \text{saturated} \\ P_g, & \text{unsaturated} \end{cases} \]

where

\[ P_s = -\frac{RT}{v_w} \ln \text{RH}(w_{\text{sat}}), \]

\( P_g > 0 \) is gas pressure and the chemical potential of external water is

\[ \mu = \mu^0 + P_l \cdot v_w, \]

which defines liquid pressure, \( P_l \), when \( \mu - \mu^0 < 0 \). The criterion for saturation is

\[ P_s > P_g - P_l = s, \]

where \( s \) denotes suction.

It should be noted that the present model is based on thermodynamic equilibrium in a rather strict sense which is not achieved in experiments where the initial state is unsaturated. E.g. the stress build-up in a infiltration test do not follow the equation for total pressure from above. On the other hand, it can be argued based on experimental facts that the model is relevant to adopt when describing gas entry events, where the initial state is a water-saturated system.
The presented theory is exemplified by a modeling of two gas migration experiments using Code_Bright, a 2-phase FEM-code for mass, energy and momentum balance in porous media (CIMNE, 2000). Quantitative agreement with experiment is achieved when adopting a Gas Entry Value (GEV) retention curve, i.e. a constitutive equation relating liquid saturation, , and suction with the property that

\[ S_j(s) = 1 \text{ for all } s \leq P_g. \]

An example of results from such a modeling is presented in Figure 1.

**Figure 1:** Results of modeling of gas migration experiments by Horseman and Harrington, 1997. A breakthrough event occurs around day 7, and the gas inflow is turned off at day 14. The Code_Bright model, based on the presented theory, successfully captures the breakthrough, and the subsequent flow rate and pressure level evolution.

**References**


CIMNE, (2000). CODE_BRIGHT. A 3-D program for thermo-hydro-mechanical analysis in geological media. Departamento de Ingenieria del Terreno; Cartografica y Geofisica, UPC, Barcelona, Spain
