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Analytical solution of a pressure transmission experiment

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Analytical solutions are derived for a pressure transmission experiment of a saturated charged compressible porous medium. The governing equations describe infinitesimal deformations of charged porous media saturated with a mono-valent ionic solution. From the governing equations a coupled diffusion equation in state space notation is derived for the electro-chemical potentials, which is decoupled introducing a set of normal parameters, being a linear combination of the eigenvectors of the diffusivity matrix. The magnitude of the eigenvalues of the diffusivity matrix correspond to the time scales for Darcy flow, diffusion of ionic constituents and diffusion of electrical potential.

1 Introduction

Shales exhibit swelling and shrinkage behavior induced by changes in external salt concentration. Swelling and shrinkage results from the interaction between the fixed charges on the solid and ions present in the fluid. Donnan-osmosis, electro-osmosis, streaming potentials and streaming currents, (Mitchell 1993) are observed phenomena. Swelling of shales is of major concern for petroleum engineering during active drilling, (Heidug and Wong 1996), (van Oort 1997). (Sherwood 1993), (Ekbote and Abousleiman 2005) developed a chemomechanical model of shale. This model extends Biot's theory to include the diffusion-convection of salt within the deforming shale. (Heidug and Wong 1996) use a thermodynamic framework to build a chemomechanical constitutive model of hydration in water absorbing rocks. The aforementioned rock model show significant analogy to biomechanical models of cartilaginous tissues. (Lai et al. 1991) derived a small deformation triphasic formulation for soft charged hydrated tissues, considering all constituents incompressible. (Huyghe and Janssen 1997) extended the chemo-electro-mechanical model to finite deformation behavior of a porous medium consisting of an electrically charged solid, liquid, cations and anions. This model has been implemented in a finite element formulation and is verified experimentally on one dimensional transient behavior of annulus fibrous tissue by (Frijns et al. 1997). The solution procedure has been verified using an analytical solution of confined swelling and compression by (van Meerveld et al. 2003). While these biomechanical models in-

clude diffusion-convection of salts like the rock models, they differ essentially from the models of (Sherwood 1993; Heidug and Wong 1996) in that they include an electrical potential to explicitly model the ionisation of the material and the ensuing phenomena of Donnan-osmosis, electro-osmosis, streaming currents, diffusion currents, streaming potentials and diffusion potentials. For this reason, (Molenaar et al. 1998) recasted the model of (Huyghe and Janssen 1997) to include compressibility being an important feature of shales. A thorough verification of FEM-implementations of the models, require adequate analytical solutions of transient problems. At present these analytical solutions are available only for the incompressible case. In this paper the governing equations of the compressible quadriphasic model are presented shortly for the case of infinitesimal deformation of a mixture. These equations are decoupled following (Biot 1956). Analytical solutions are presented for the pressure-transmission experiment under conditions of near electroneutrality.

2 Theory

In this section the governing equations, as derived by (Molenaar et al. 1998), are given in the special case of infinitesimal quadriphasic mechanics of compressible charged porous media. Specific constitutive material behavior is considered and corresponding relations for the osmotic pressure and electrical potential at equilibrium are given. Finally the governing equations are reduced for a 1-dimensional configuration and decoupled.

2.1 Governing and balance equations

We consider a porous solid saturated with a monovalent ionic solution. The current volume fraction of the solid is ϕ^s , the current volume fraction of the ionic solution is ϕ^f . The corresponding initial volume fractions are ϕ_0^s, ϕ_0^f . The solution is a molecular mixture of water (w), a cation (+) and an anion (-). The partial densities of water, cations and anions are in the current state ρ^w, ρ^+ and ρ^- , and the in the initial state ρ_0^w, ρ_0^+ and ρ_0^- . The unstrained volume change ζ^β of constituent $\beta = w, +, -$ is :

$$\zeta^\beta = \frac{\rho^\beta - \rho_0^\beta}{\rho_i^\beta} \quad (1)$$

in which ρ_i^β is an intrinsic reference density such that

$$\sum_{\beta=w,+, -} \frac{\rho_0^\beta}{\rho_i^\beta} = \phi_0^f. \quad (2)$$

The momentum balance, neglecting inertia, reads:

$$\nabla \cdot \boldsymbol{\sigma} = 0, \quad (3)$$

with $\boldsymbol{\sigma}$ the Cauchy stress tensor. Mass balance of constituent α requires:

$$\frac{\partial \zeta^\beta}{\partial t} + \nabla \cdot (\mathbf{v}^{\beta s}) = 0, \quad (4)$$

with ζ^β the unstrained volume fraction of constituent β and $\mathbf{v}^{\beta s}$ the unstrained volume flux of constituent β with respect to the solid. In this paper α denotes all constituents, i.e. electrically charged solid (s), water (w), cations (+) and anions (-) ; β, γ cover all constituents except the charged solid matrix. The mixture is assumed to be fully saturated giving the following relation for the saturation condition:

$$\alpha \nabla \cdot \mathbf{v}^s + \frac{1}{M} \frac{\partial p}{\partial t} - \sum_{\beta=w,+, -} \frac{\partial \zeta^\beta}{\partial t} = 0, \quad (5)$$

in which $\mathbf{v}^s$ is the solid velocity, α and M are the Biot coefficients. A negligible departure from electroneutrality is considered for mathematical reasons. This results in the following expression for the electroneutrality condition :

$$\sum_{\beta=w,+, -} F \frac{z^\beta}{V^\beta} \frac{\partial \zeta^\beta}{\partial t} = \varepsilon \frac{\partial \xi}{\partial t}, \quad (6)$$

with F, ε, z^β and V^β Faraday's constant, capacitance, the valence and molar volume of constituent β respectively.

2.2 Constitutive behavior

The fluxes obey a coupled form of Darcy's, Fick's and Ohm's law:

$$\mathbf{v}^{\beta s} = - \sum_{\gamma=w,+, -} \mathbf{K}^{\beta\gamma} \nabla \mu^\gamma \quad \text{for } \beta = w, +, -, \quad (7)$$

with $\mathbf{K}^{\beta\gamma}$ a positive definite symmetric permeability matrix. In relationship (7) the electro-chemical potentials, μ^β are defined as:

$$\mu^\beta = \frac{\partial W}{\partial \zeta^\beta} + \frac{F z^\beta}{V^\beta} \xi, \quad (8)$$

with ξ and W the electrical potential and the energy function respectively. The stress appearing in the momentum balance (3) is the partial derivative of the energy function W with respect to the infinitesimal strain tensor $\epsilon = 1/2(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$, with $\mathbf{u}$ the displacement vector of the solid :

$$\boldsymbol{\sigma} = \frac{\partial W}{\partial \epsilon} \quad (9)$$

The energy function is the sum of the poroelastic strain energy and a mixing energy:

$$\begin{aligned} W = & -\alpha M \text{tr} \epsilon \sum_{\beta=w,+, -} \zeta^\beta + \frac{1}{2} M \left(\sum_{\beta=w,+, -} \zeta^\beta \right)^2 + \\ & \frac{1}{2} \left(2\nu \frac{G}{1-2\nu} + \alpha^2 M \right) \text{tr}^2 \epsilon + G \epsilon : \epsilon + \\ & + \sum_{\beta=w,+, -} \mu_0^\beta \zeta^\beta - RT \Gamma \left(\frac{\zeta^+}{V^+} + \frac{\zeta^-}{V^-} \right) \ln \zeta^w + \\ & + RT \frac{\zeta^+}{V^+} \left(\ln \frac{\zeta^+}{V^+} - 1 \right) + RT \frac{\zeta^-}{V^-} \left(\ln \frac{\zeta^-}{V^-} - 1 \right) \end{aligned} \quad (10)$$

The form (10) of W assumes linear isotropic elasticity and Donnan osmosis as the swelling mechanism of the shale. G is the shear modulus, ν is Poisson's ratio, K_f is the volumetric modulus of the solution, μ_0^β is the reference potential of constituent β , R is gas constant, T the absolute temperature and Γ the osmotic coefficient. Given this expression for the energy function, the electrochemical potentials (8) take the form:

$$\begin{aligned} \mu^w = & \mu_0^w - \alpha M \text{tr} \epsilon + M \sum_{\beta=w,+, -} \zeta^\beta \\ & - RT \Gamma \left(\frac{\zeta^+}{V^+ \zeta^w} + \frac{\zeta^-}{V^- \zeta^w} \right) \end{aligned} \quad (11)$$

Figure 1: Experimental setup

$$\begin{aligned} \mu^+ &= \mu_0^+ - \alpha M tr \epsilon + M \sum_{\beta=w,+, -} \zeta^\beta \\ &+ \frac{RT}{V^+} \ln \frac{\zeta^+}{V^+ (\zeta^w)^\Gamma} + \frac{F}{V^+} \xi \end{aligned} \quad (12)$$

$$\begin{aligned} \mu^- &= \mu_0^- - \alpha M tr \epsilon + M \sum_{\beta=w,+, -} \zeta^\beta \\ &+ \frac{RT}{V^-} \ln \frac{\zeta^-}{V^- (\zeta^w)^\Gamma} - \frac{F}{V^-} \xi \end{aligned} \quad (13)$$

3 The pressure transmission test

Fig. 1 illustrates the experimental setup considered. The shale sample is placed in a sleeve. Upstream, $z = 0$, the sample is in contact with a solution of sodium chloride at a given pressure p_z . Downstream, $z = L$, the shale is resting ($u_z = 0$) on a closed reservoir filled with sodium chloride solution. The outer surface of the sleeve is subject to a pressure p_r . The volume of the closed reservoir is assumed infinitely small compared to the size of the shale sample. The momentum balance (3) is written in the axysymmetric case:

$$\frac{\partial \sigma_{rr}}{\partial r} + \frac{\partial \sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} = 0 \quad (14)$$

$$\frac{\partial \sigma_{\theta\theta}}{\partial \theta} = 0 \quad (15)$$

$$\frac{\partial \sigma_{rz}}{\partial r} + \frac{\partial \sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r} = 0 \quad (16)$$

If we neglect the shear stresses, we find for the pressure transmission test:

$$tr \boldsymbol{\sigma} = -2p_r - p_z \quad (17)$$

throughout the sample and for all times after application of the load. Substituting eq. (17) into eqs. (11-13) yields:

$$\frac{\partial}{\partial t} (\mu^\beta - \frac{F z^\beta}{V^\beta} \xi) = \sum_{\gamma=w,+, -} (\mathbf{W}^{\beta\gamma} + \Theta) \frac{\partial \zeta^\gamma}{\partial t}, \quad \beta = w, +, - \quad (18)$$

in which

$$\Theta = \frac{3\alpha^2 M^2}{\frac{2G(1+\nu)}{1-2\nu} + 3\alpha^2 M} \quad (19)$$

or,

$$\frac{\partial \zeta^\beta}{\partial t} = \sum_{\gamma=w,+, -} \mathbf{C}^{\beta\gamma} \frac{\partial \mu^\gamma - \frac{z^\gamma F \xi}{V^\gamma}}{\partial t}, \quad (20)$$

in which $\mathbf{C}^{\beta\gamma} = (\frac{\partial^2 W}{\partial \zeta^\beta \partial \zeta^\gamma} + \Theta)^{-1}$. We substitute eq. (20) in the electroneutrality condition (6):

$$\sum_{\gamma, \beta=w,+, -} F \frac{z^\beta}{V^\beta} \mathbf{C}^{\beta\gamma} \frac{\partial \mu^\gamma - \frac{z^\gamma F \xi}{V^\gamma}}{\partial t} = \epsilon \frac{\partial \xi}{\partial t}, \quad (21)$$

Substitution of the frictional equation (7) into the mass balance equation (4) yields :

$$\frac{\partial \zeta^\beta}{\partial t} - \sum_{\gamma=w,+, -} \mathbf{K}^{\beta\gamma} \frac{\partial^2 \mu^\gamma}{\partial z^2} = 0 \quad \text{for } \beta = w, +, -, \quad (22)$$

Equation (21) is transformed into :

$$\left(\sum_{\beta, \gamma} \mathbf{C}^{\beta\gamma} \frac{F^2 z^\beta z^\gamma}{V^\beta V^\gamma} + \epsilon \right) \frac{\partial \xi}{\partial t} = \mathbf{Q} \cdot \frac{\partial}{\partial t} [\mu^w \quad \mu^+ \quad \mu^-]^T, \quad (23)$$

with:

$$\mathbf{Q} = \left[\sum_{\beta} F \frac{z^\beta}{V^\beta} \mathbf{C}^{\beta w} \quad \sum_{\beta} F \frac{z^\beta}{V^\beta} \mathbf{C}^{\beta +} \quad \sum_{\beta} F \frac{z^\beta}{V^\beta} \mathbf{C}^{\beta -} \right] \quad (24)$$

Substitution of equations (23) and (11-13) into (22) gives the diffusion equation:

$$\mathbf{E} \frac{\partial}{\partial t} [\mu^w \quad \mu^+ \quad \mu^-]^T = \mathbf{K} \frac{\partial^2}{\partial z^2} [\mu^w \quad \mu^+ \quad \mu^-]^T \quad (25)$$

with,

$$\mathbf{E} = \mathbf{C} - \mathbf{Q}^T \left(\sum_{\beta, \gamma} \mathbf{C}^{\beta\gamma} \frac{F^2 z^\beta z^\gamma}{V^\beta V^\gamma} + \epsilon \right)^{-1} \cdot \mathbf{Q} \quad (26)$$

4 The boundary and initial conditions

A change in the external concentration is considered along the upstream surface of the sample. The electrochemical potentials for the sodium chloride solution in the upstream reservoir are equal to:

$$\begin{aligned} \mu_e^w &= p_z - RT (c_e^+ + c_e^-), \\ \mu_e^+ &= p_z + \frac{RT}{V^+} \ln c_e^+, \\ \mu_e^- &= p_z + \frac{RT}{V^-} \ln c_e^-, \end{aligned} \quad (27)$$

with c_e^+ and c_e^- the external concentration of cations and anions respectively. The change in boundary conditions at the upstream reservoir ($z = 0$) and at the lower reservoir ($z = L$) corresponding with a step-wise change in salt concentration in the upper reservoir is :

$$\begin{aligned}\Delta\mu^w(0, t) &= -RT (\Delta c_e^+ + \Delta c_e^-), \\ \frac{\partial \Delta\mu^f}{\partial z}(L, t) &= 0 \\ \Delta\mu^+(0, t) &= \frac{RT}{\bar{V}^+} \ln \frac{c_e^+(t_0^+)}{c_e^+(t_0^-)}, \\ \frac{\partial \Delta\mu^+}{\partial z}(L, t) &= 0, \\ \Delta\mu^-(0, t) &= \frac{RT}{\bar{V}^-} \ln \frac{c_e^-(t_0^+)}{c_e^-(t_0^-)}, \\ \frac{\partial \Delta\mu^-}{\partial z}(L, t) &= 0, \\ \sigma(0, t) &= -p_z, \\ u_z(L, t) &= 0\end{aligned}\quad (28)$$

with Δc_e^+ , Δc_e^- the change in upstream concentration of cations and anions and t_0^- and t_0^+ time just before and after t_0 when chemical loading is applied. The change in the external concentration is considered sufficiently small such that $\mathbf{C}$ and $\mathbf{K}$ are considered constant in time.

Since inhomogeneous boundary conditions on μ^β are present at $z = 0$ together with homogeneous initial conditions a new variable is introduced as,

$$\kappa_i(z, t) = \eta_i(z, t) - \eta_i(0, t), \quad (29)$$

giving a set of homogeneous boundary conditions and inhomogeneous initial conditions. Utilizing the method of separation of variables a relation for the electro-chemical potentials is obtained, with $\mu_0^\beta = \mu^\beta(0, t)$:

$$\begin{bmatrix} \Delta\mu^w \\ \Delta\mu^+ \\ \Delta\mu^- \end{bmatrix} = [\mathbf{I} - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin\left(\frac{2n+1}{2} \frac{\pi}{L} z\right)] \cdot \begin{bmatrix} \mu_0^f \\ \mu_0^+ \\ \mu_0^- \end{bmatrix}. \quad (30)$$

with $\mathbf{R}_n$ a diagonal matrix with on its diagonal elements:

$$\mathbf{R}_n^{ii} = \exp\left(\left(\frac{2n+1}{2}\pi\right)^2 \frac{\lambda^i(t-t_0)}{L^2}\right). \quad (31)$$

and $\mathbf{M}$ the matrix transforming the normal variables η_i to the original variables μ^w, μ^+, μ^- . The pressure in the shale and in the reservoirs is given as a function of the electrochemical potentials :

$$\Delta p = \Delta\mu^w + \Gamma RT \Delta \Xi \quad (32)$$

with

$$\Xi = \sqrt{(c^{cf})^2 + 4 * n_f^{2*(\Phi_i-1)} * e^{\frac{\bar{V}^+(\mu^+-p) + \bar{V}^-(\mu^+-p)}{RT}}} \quad (33)$$

The ionic volumes are given by:

$$\zeta^\beta = \frac{\bar{V}^\beta}{2} (z^\beta c^{fc} + \Xi), \quad \beta = +, - \quad (34)$$

while the electrical potential is

$$\xi = \frac{RT \ln \frac{\zeta^- \bar{V}^+}{\zeta^+ \bar{V}^-} + \bar{V}^+(\mu^+ - p) - \bar{V}^-(\mu^- - p)}{2F} \quad (35)$$

The fixed charge density c^{cf} , closely related to the cation exchange capacity $CEC = \frac{\phi_0^f c^{fc}}{\phi_0^s}$, is its local value in the shale, while it is zero in the reservoir. The pressure, the ionic concentrations and the electrical potential exhibits a jump at the shale boundary. In particular, the pressure in the downstream reservoir is given by

$$p = \mu^w + 2RT e^{\frac{\bar{V}^+(\mu^+-p) + \bar{V}^-(\mu^+-p)}{2RT}} \quad (36)$$

The permeability matrix $\mathbf{K}^{\beta\gamma}$ is the inverse of a frictional matrix :

$$\mathbf{K}^{\beta\gamma} = \zeta^\beta \zeta^\gamma (\mathbf{B}^{\beta\gamma})^{-1} \quad (37)$$

which in turn depends on the hydraulic permeability K , the ion diffusion coefficients D^+ and D^- , and the formation factor f :

$$\begin{aligned}\mathbf{B}^{ww} &= \phi_f^2 \mathbf{K}^{-1} - (1-f) \mathbf{B}^{+w} - (1-f) \mathbf{B}^{-w}, \\ \mathbf{B}^{++} &= -\frac{\mathbf{B}^{+w}}{1-f}, \\ \mathbf{B}^{--} &= -\frac{\mathbf{B}^{-w}}{1-f}, \\ \mathbf{B}^{+w} &= -\frac{RT \zeta^+}{\bar{V}^+} \mathbf{D}^{+-1}, \\ \mathbf{B}^{-w} &= -\frac{RT \zeta^-}{\bar{V}^-} \mathbf{D}^{-1}, \\ \mathbf{B}^{+-} &= \mathbf{0},\end{aligned}\quad (38)$$

$$(39)$$

5 Results

For the material parameters considered the three eigenvalues equal:

$$2.6 \cdot 10^8 \text{ mm}^2/\text{s}, 0.003 \text{ mm}^2/\text{s}, 1.7 \cdot 10^{-4} \text{ mm}^2/\text{s}. \quad (40)$$

Figure 2: Downstream pressure at $z = L$.

The upstream salt concentration is increased with a small amount from $c_e^+ = c_e^- = 1.000 \text{ mol/l}$ to $c_e^+ = c_e^- = 1.001 \text{ mol/l}$, with boundary condition given in relation (28). At the upstream boundary, $z = 0$, the computation typically shows no change of pressure or electrochemical potentials because of the prescribed boundary conditions. The pressure, the electrical potential and the concentrations, however, do not take their values in the upstream reservoir. There is a jump of these quantities across the boundary of the sample. At the downstream end of the sample, the axial displacement, the pore pressure, the downstream pressure (fig. 2), the chemical potential, the electrochemical potentials, the electrical potential (all show a dual reponse indicating at least two time constants in the system: one in the order of 50-100 hours, the other in the order of 1000 hours. In addition many variables change instantaneously after application of the load.

6 Discussion

The analytical solutions are presented for electrochemomechanical analysis of the pressure

transmission experiment. The literature clearly relates osmotic pressures in shales with ionisation of the clay platelets. Unlike previous models of pressure transmission, which associate the osmosis of the shale with a chemical phenomenon (Sherwood 1993; Detournay et al. 2005), this model introduces the ionisation as the source of the osmotic forces observed. Hence, the experimental parameters needed are closer to the physics of the system. The cation exchange capacity of the shale stand therefore as a key input parameter that governs the osmotic swelling and shrinking. Standard techniques are available to measure the cation exchange capacity. At the output side of the model, the electrical potential is computed that is a measurable quantity as well, and provides a sensitive check for the correct description of the ionic diffusion-convection in the shale. An important spin-off of the inclusion of the ionisation of the shale into the system of equations is that phenomena of electro-osmosis, electrophoresis, streaming potentials and streaming currents are included as well. These phenomena are well-documented and have potential technological applications in high specific surface soils (Yeung and Mitchell 1993). The electrochemo-mechanical model discussed here extends the model developed by (Yeung and Mitchell 1993) to include deformation of the shale.

The linearised equations are reduced to three diffusion equations. To each of these equations one diffusion coefficient is associated (eq. 40). Each of these three eigenvalues is associated with a specific time constant equal to the size of the sample squared divided by the eigenvalue. Physically, one can identify the three eigenvalues as the electric potential diffusion coefficient, the pressure diffusion coefficient and the ionic diffusion coefficient (van Meerveld et al. 2003). The first coefficient is infinite if strict electro-neutrality is handled. Because we included some capacitance ϵ into the system, its value is large but finite. (van Meerveld et al. 2003) showed that the capacitance does not affect the macroscopic behavior, provided its order of magnitude is sufficiently low. All output values (fig. 2) show a dual reponse indicating at least two time constants in the system: one in the order of 50-100 hours, the other in the order of 1000 hours. In fact they are associated with the second eigenvalue ($\frac{L^2}{\lambda_2} \approx 70h$) and the third eigenvalue of eq. 40 ($\frac{L^2}{\lambda_3} \approx 1300h$). The initial decrease of the downstream pressure and its subsequent recovery is consistent with experimental observations (van Oort 1997).

The discontinuous jumps of the concentrations across the interfaces between the sample and the reservoir are at odds with earlier models of pressure transmission (Sherwood 1993), (Detournay et al. 2005), but in agreement with elementary electrochemistry.

The sharp reduction of the shale pore pressure, following a contact with an environment of low chemical potential, has been observed repeatedly in the field (Neuzil 2000). The importance of electrical potential gradients relative to concentration gradients and pressure gradients is related to the ratio between the fixed charge density over the salt concentration with which the shale is in contact. The upstream salt concentrations in pressure transmission experiments in water based muds is usually chosen according to water based mud concentration in the field, typically in the range of several moles per liter. The fixed charge density is usually in the order of a few tenths of mole per liter. This results in a fairly low contribution from electrical phenomena. In the field however, many shale formations have a relatively low salt concentrations, in other words they are equilibrium with a low salt concentration in the order of magnitude of their own fixed charge density, which is a order of magnitude lower than the typical mud concentration. An unusually complete description of a shale formation is given in (Marine and Fritz 1981). They describe a illite rich shale from a Triassic sediment with a porosity of 0.035. They found a osmotic pressure of 1.3 MPa for a total dissolved solute concentration of 15 g/l against an external concentration of 1 to 2 g/l. These high osmotic pressures can be explained using a fixed charge density of the order of 0.5 moleq/l, while the value of 15 g/l may at most correspond to a corresponding equilibrium external salt concentration of the order of a few tenths of mole per liter. This shows a ratio of fixed charge density over salt concentration in the order of one in a virgin formation. This indicates that electrical effects plays a mayor role in the virgin field, as well as away from the borehole. Electro-osmotic permeability has been shown to depend minimally on the pore size, while hydraulic permeability decreases many orders of magnitude as pore size decreases, (Casagrande 1952). The electro-osmotic permeability of fine sand is in the order of $0.410^{-8} m^2/Vs$ and for clays in the order of $0.510^{-8} m^2/Vs$. The corresponding hydraulic permeabilities are $10^{-9} m^4/Ns$ and $10^{-15} m^4/Ns$. Shale having a sub micron pore size is at the extreme lower end of the spectrum and should therefore be very sensitive to electrical potential gradients.

REFERENCES

- Biot, M. A. (1956). General solutions of the equations of elasticity and consolidation. *Journal of Applied Mechanics* 78, 91–96.
- Casagrande, L. (1952). Electro-osmotic stabilization of soils. *Journal of the Boston Society of Civil Engineers* 20, 1–20.
- Detournay, E., J. Sarout, and J. Caurel (2005). Chemoporoelastic parameter identification of a reactive shale. In J. Huyghe, P. Raats, and S. Cowin (Eds.), *Physicochemical and Electromechanical Interactions in Porous Media*, pp. 1–2. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Ekbote, S. and Y. Abousleiman (2005). Incorporating chemical effects in a porothermoelastic formulation and application to inclined boreholes. In J. Huyghe, P. Raats, and S. Cowin (Eds.), *Physicochemical and Electromechanical Interactions in Porous Media*, pp. 1–2. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- Frijns, A., J. Huyghe, and J. Janssen (1997). A validation of the quadriphasic mixture theory for intervertebral disc tissue. *Int. J. Eng. Sci.* 35, 1419–1429.
- Heidug, W. and S.-W. Wong (1996). Hydration swelling of water-absorbing rocks: a constitutive model. *Int. J. Num. Anal. Meth. Geomechanics* 20, 403–430.
- Huyghe, J. M. and J. D. Janssen (1997). Quadriphasic mechanics of swelling incompressible porous media. *Int. J. Eng. Sci.* 35, 793–802.
- Lai, W. M., J. S. Hou, and V. C. Mow (1991, Aug). A triphasic theory for the swelling and deformation behaviors of articular cartilage. *J Biomech Eng* 113, 245–258.
- Marine, I. and S. Fritz (1981). Osmotic model to explain anomalous hydraulic heads. *Water Resources Research* 17, 73–82.
- Mitchell, J. (1993). *Fundamentals of soil behavior* (2 ed.). New York, United States: John Wiley & Sons, Inc.
- Molenaar, M., J. Huyghe, and P. Van den Bogert (1998). Constitutive modeling of charged porous media. In *SPE paper 47332, SPE/ISRM EUROCK'98, Trondheim*, pp. 127–132.
- Neuzil, C. E. (2000). Osmotic generation of 'anomalous' fluid pressures in geological environments. *Nature* 403, 145–150.
- Sherwood, J. (1993). Biot poroelasticity of a chemically active shale. *Proc. Res. Soc. Lond. A* 440, 365–377.
- van Meerveld, J., M. M. Molenaar, J. M. Huyghe, and F. T. P. Baaijens (2003). Analytical solution of compression, free swelling and electrical loading of saturated charged porous media. *Transport in porous media* 50, 111–126.
- van Oort, E. (1997). Physico-chemical stabilization of shales. In *SPE International Symposium*

on Oilfield Chemistry, Houston, Texas, United States, pp. paper 37263.

Yeung, A. T. and J. K. Mitchell (1993). Coupled fluid, electrical and chemical flows in soil. *Géotechnique 1*, 121–134.