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B+TECH

Erosion of bentonite clay caused by groundwater:ESM-application

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Description and Open Questions

• High Pressure Groundwater flowing into deposition hole via intersecting fracture can form a *pipe*

• *Piping* takes place during and after emplacement face before the buffer and backfill are fully functional

• Groundwater flow may carry away even a significant amount of buffer (and backfill)

• What is the maximum mass loss during pre-saturation erosion? How does the buffer and backfill self-heal and what is the level of inhomogenization?

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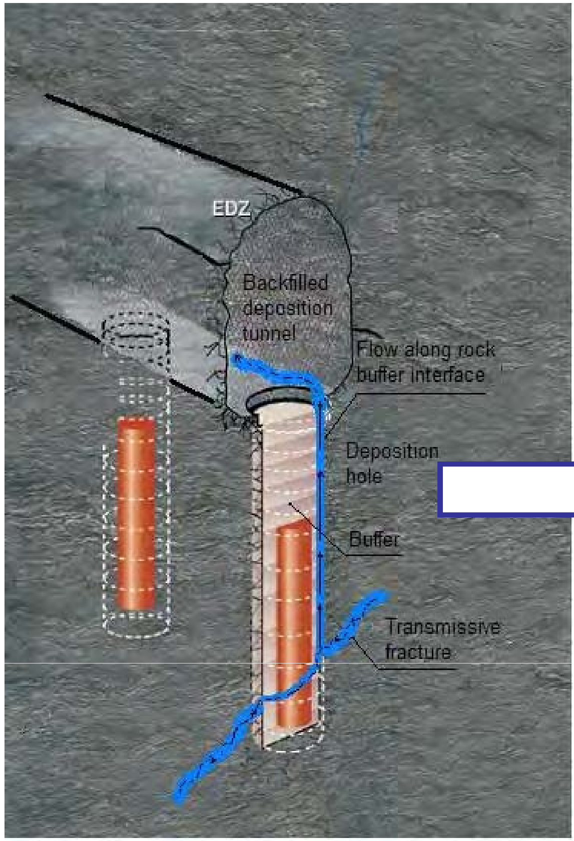
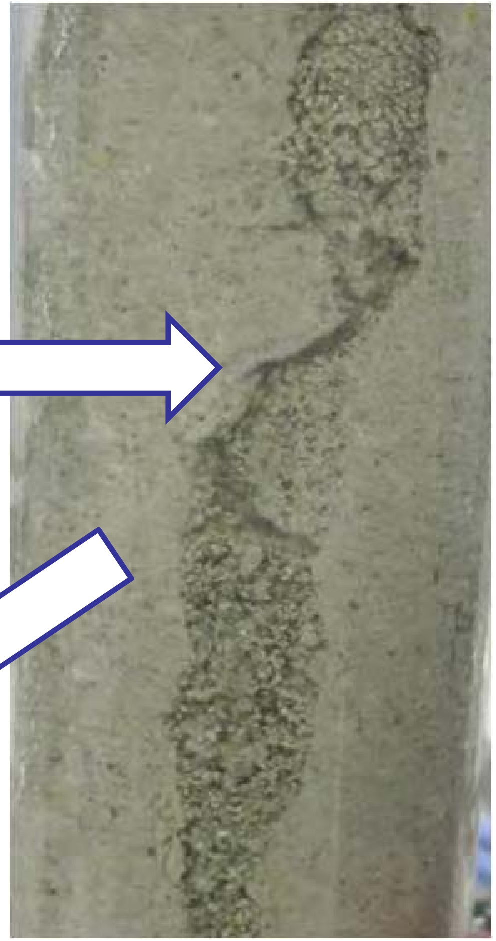
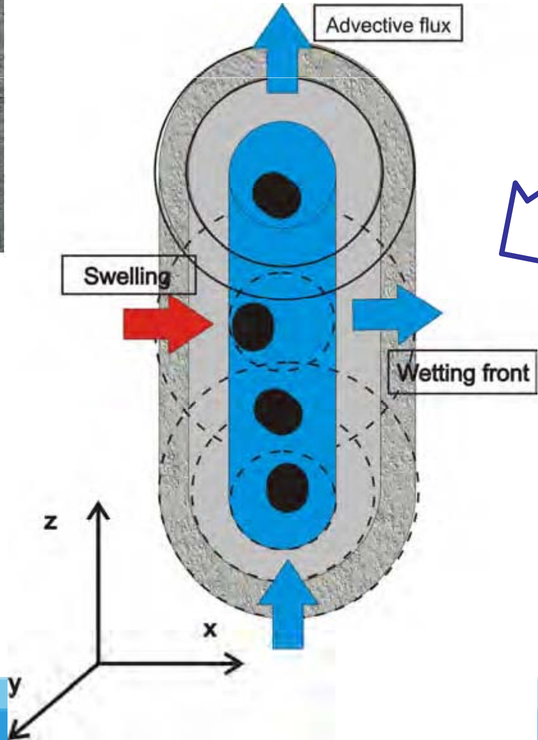

EDZ
Backfilled deposition tunnel
Flow along rock buffer interface
Deposition hole
Buffer
Transmissive fracture




Advective flux
Swelling
Wetting front
z
x
y

Pre-Saturation Erosion Process

Wetting, *Free Swelling* and Transport

- Erosion starts by formation of erosion channel in the buffer by high pressure groundwater, i.e. piping

- In contact with groundwater the buffer first wets and as a consequence *swells freely*

- The swelling bentonite migrates into channel, and simultaneously the flowing groundwater shears off less dense buffer material

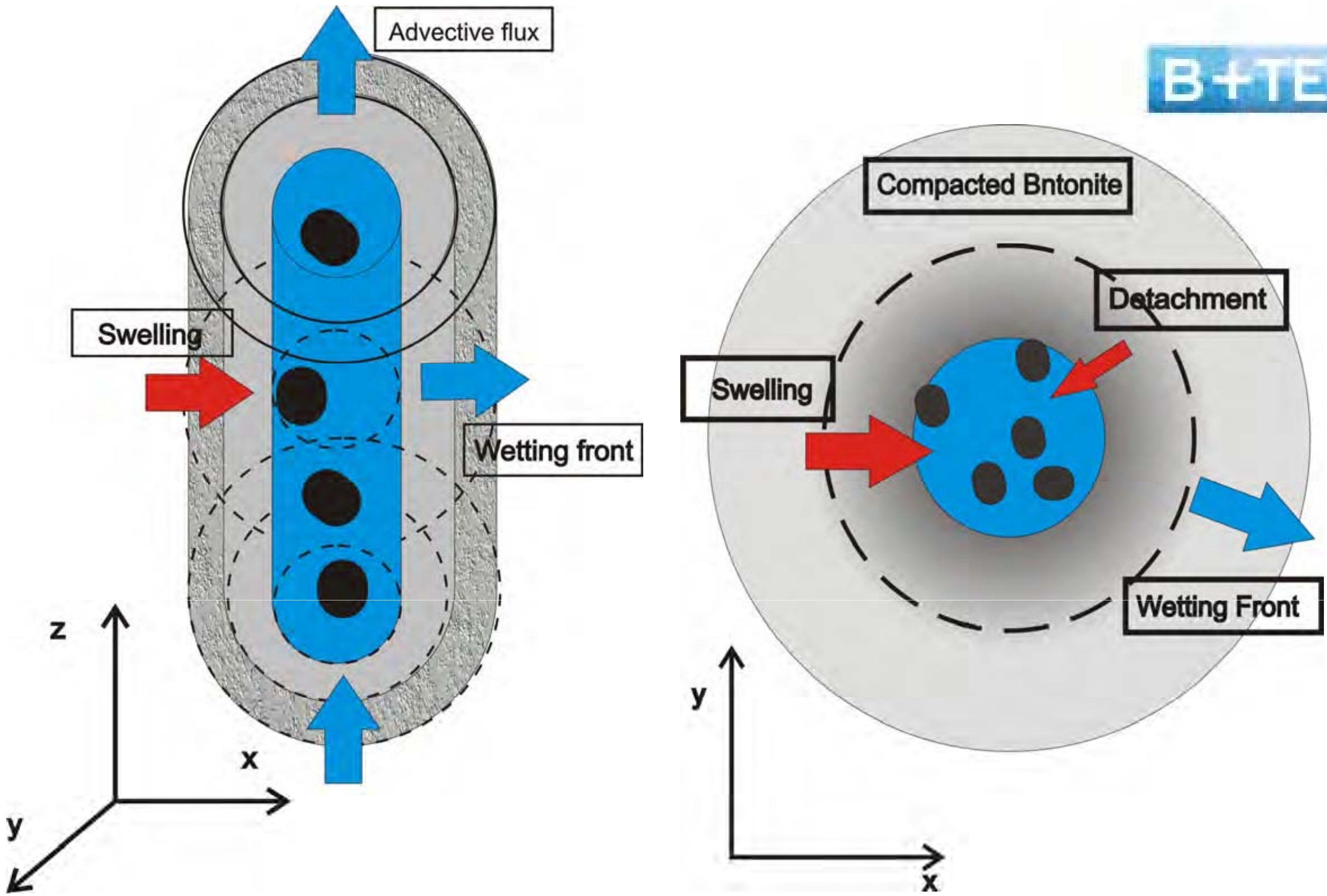


Fig. 2. Schematic representation of the system under study. Cylindrical erosion channel, water is flowing from bottom to top. Swelling is balanced by detaching bentonite particles, that are carried away by the advective flux in vertical direction.

Pre-Saturation Erosion Model

Velocity of groundwater flow in the erosion channel is laminar

$$v(r) \equiv v(\mathrm{r})\mathbf{k} = \frac{\mathrm{Q}}{\pi \mathbf{a}^2}\left(1 - \left[\frac{\mathrm{r}}{\mathrm{a}}\right]^2\right)\mathbf{k}$$

Water infiltration into dry buffer material by *Richard's equation*

$$\frac{\partial \theta}{\partial t} = \nabla \cdot [K \nabla \varphi] - S_r \frac{\partial \phi}{\partial t} \equiv \nabla \cdot [D(\theta)\nabla \theta] - S_r \frac{\partial \phi}{\partial t}$$

Deformation field by *nonlinear stress-strain module* application

$$\frac{1}{2}\left(\boldsymbol{\nabla}^2 \boldsymbol{u} + \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{u})\right) - -\boldsymbol{D}^{-1} f + b \boldsymbol{\nabla} \boldsymbol{\varphi} + \Lambda \frac{\partial \boldsymbol{G}}{\partial \boldsymbol{\sigma}}$$

Concentration of detached particles by *convection diffusion* equation

$$\frac{\partial c}{\partial t} = \nabla \cdot (D_o \nabla c) - \left[\frac{Q}{\pi R_0{}^2}\left(1 - \left[\frac{r}{a}\right]^2\right) - \frac{Mg}{\gamma}\right]\frac{\partial c}{\partial z} + 2\frac{\sigma(t)}{R}$$

Approx 1: Purely Suction Induced Free Swelling

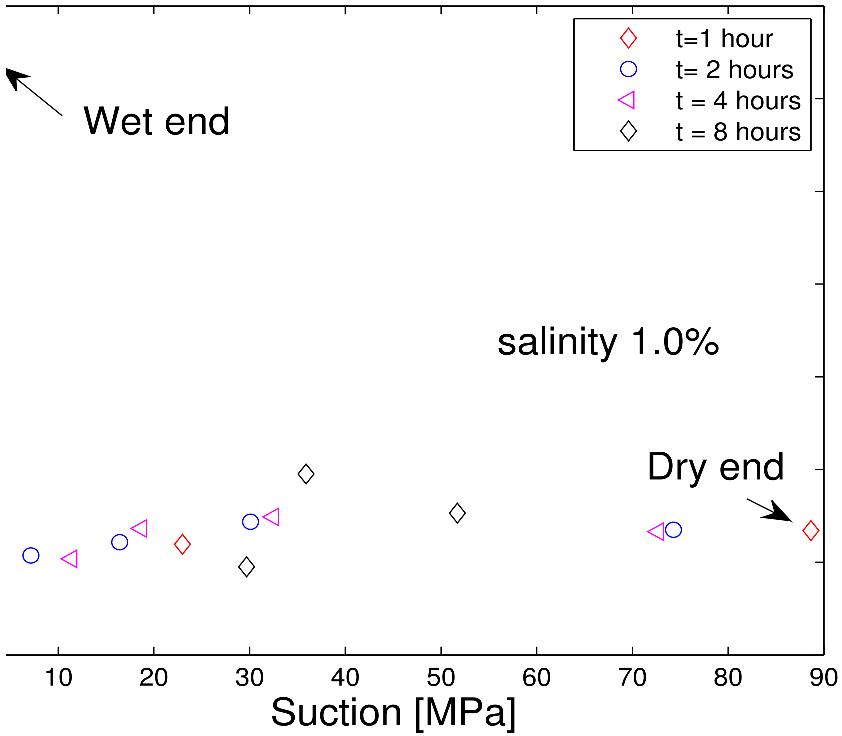
$$\frac{1}{2}\left(\nabla^2 \boldsymbol{u} + \nabla \cdot (\nabla \boldsymbol{u})\right) \cong -\kappa_s \frac{\nabla \varphi}{[-\varphi + p_0]}$$

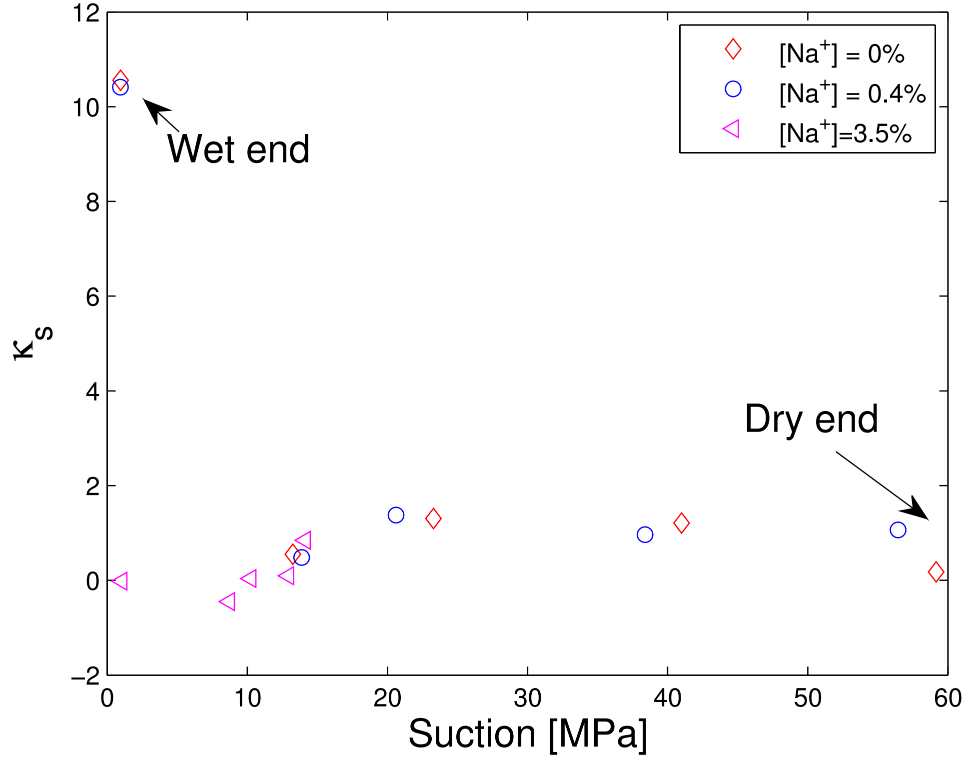
Calculate suction from the given water content θ values by assuming van Genuchten parametrization for *water retention curve*

$$\theta = \left[\frac{1}{1 + (\alpha\varphi)^n}\right]^{1-\frac{1}{n}}$$

One can match the gradient of volumetric strain with the gradient of suction under radially symmetric swelling

$$\nabla^2 \boldsymbol{u} = -\frac{\nabla \rho_{dry}}{\rho_{dry}} \equiv -\kappa_s \frac{\nabla \varphi}{[-\varphi + p_0]}$$





Figs. 10 and 11. Bulk suction calculated based on measured dry density gradient and suction gradient. Suction induced bulk modulus seems to decrease as a function of suction. Salt is 1:1 mixture of NaCl and CaCl.

Approx 2: Fixed radius erosion channel

Preliminary hole erosion results suggest almost a *constant radius* during the test!

By assuming fixed radius erosion, the detachment term just balances the swelling of solid clay. This leads to

$$\sigma(R,t) \equiv D_{dry} \nabla \rho_{dry}\big|_{wet} \cong -\kappa_s K_0 \rho_s \nabla \varphi(R,t)$$

Thus, one has an equation system for two variables, suction and the concentration of clay particles in the channel, where the detachment term is as above.

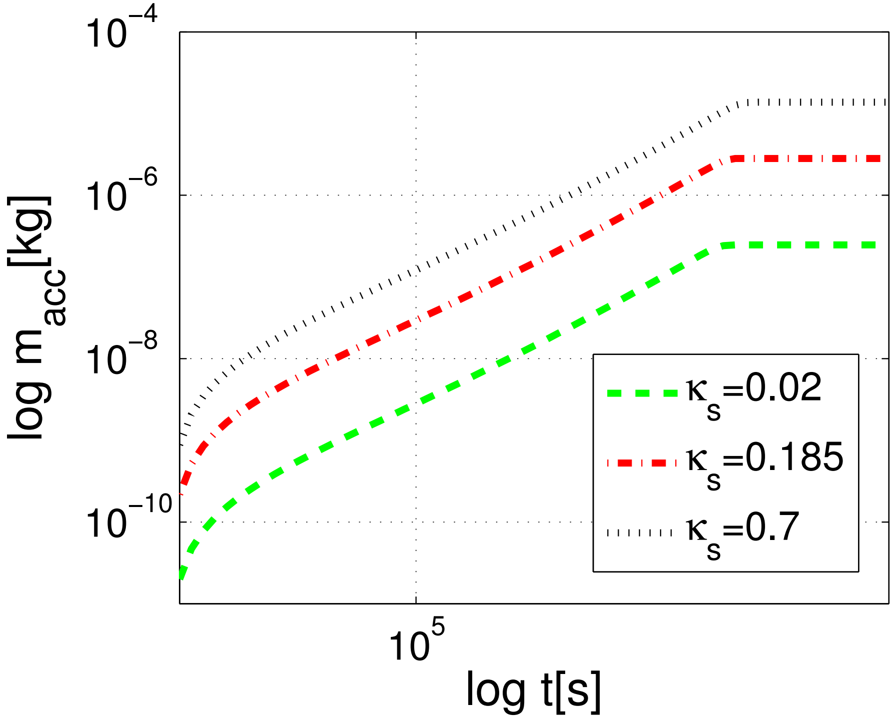
Preliminary simulation results

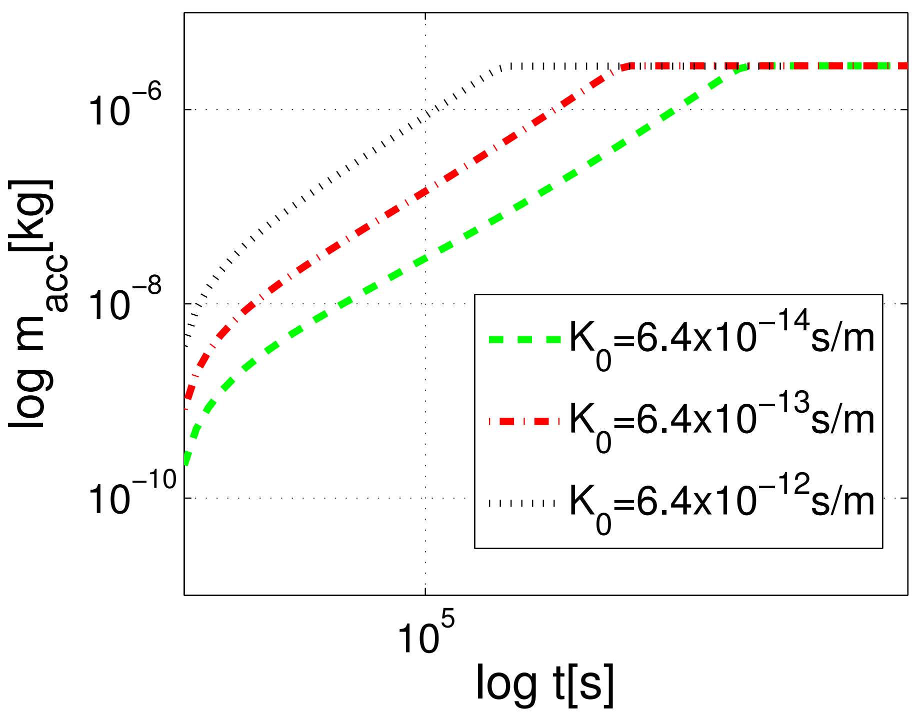
Accumulated mass increases linearly as a function of total amount of flown water, i.e. as a function of time in double logarithmic presentation:

$$m_{acc}(t) = m_0 \left[\frac{t}{t_0}\right]^{\alpha} \equiv m_0 \left[\frac{m_w}{m_{w,0}}\right]^{\alpha}$$

where the exponent α can be estimated from computer simulations as

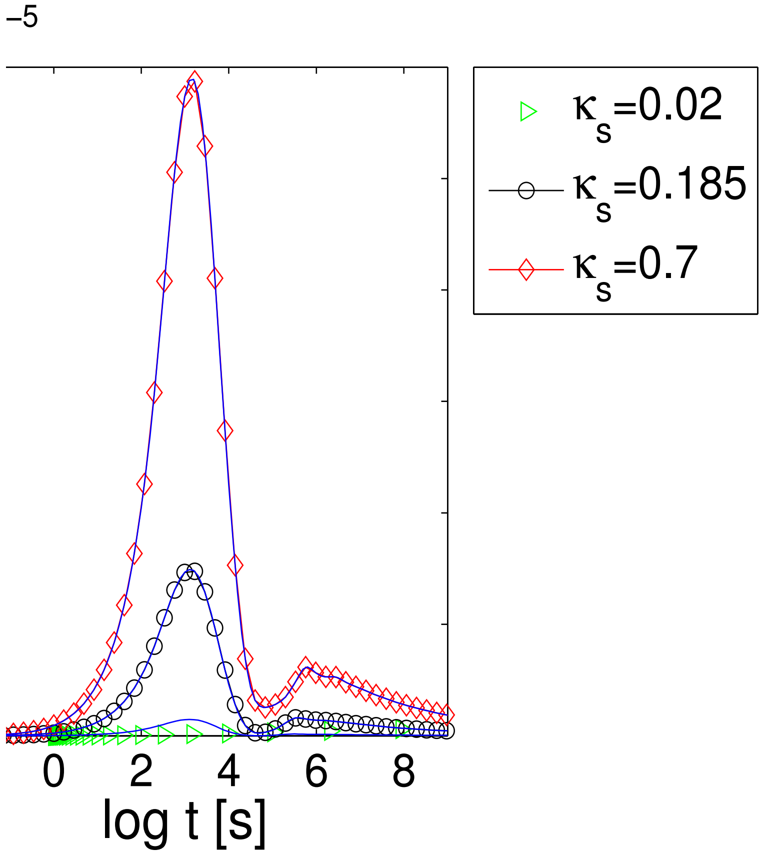
$$\alpha \in (0.7, 1)$$

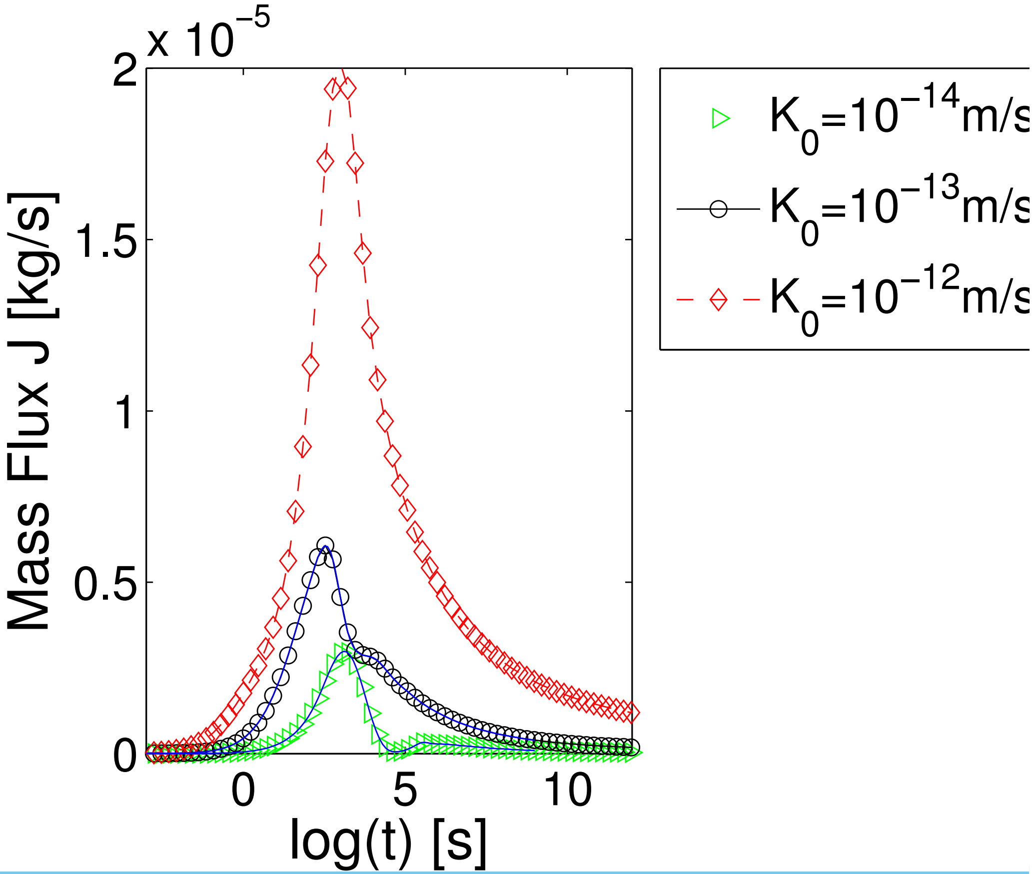




Figs. 12 and 13. Here κ_s is the suction induced bulk modulus determining the free swelling rate, and K_0 is the hydraulic permeability of water, determining the infiltration rate of water into buffer.

Erosion rates as a function of logarithmic time. Erosion rate curve has a steep rise when active erosion starts, which is followed by gradual decrease toward zero.





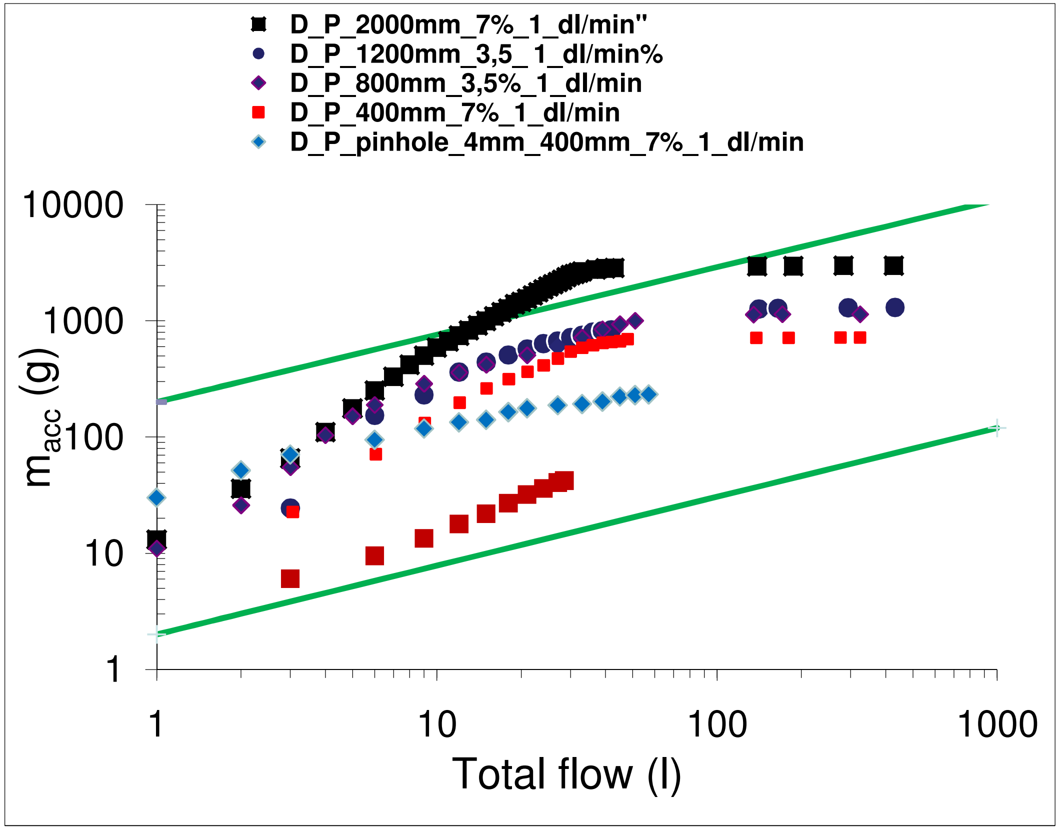


Fig. 3. Summary of the erosion tests in plexiglass tubes of various lengths, varying salinity of effluent, and various flow rates. Green lines represent the model fits of ClayTech, that are exceeded for highest salinity case (black squares)