Used Fuel Disposition Campaign

Improved Constitutive Relationships for Argillite

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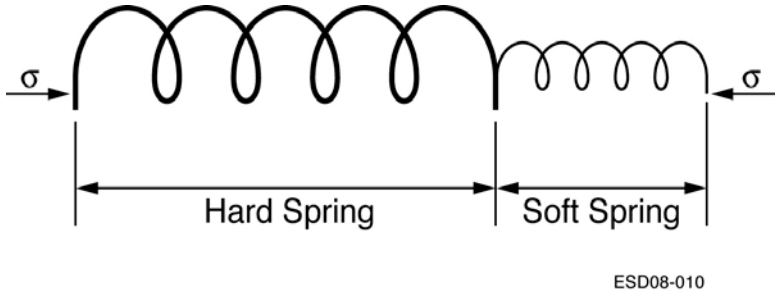
Outline

- **Relationships among permeability, porosity and effective stress for argillite based on the Two-Part Hooke's Model**
  - ✓ The proposed relationship
  - ✓ Evaluation with experimental data
- **Non-Darcian flow and its relevance to clay repository and bentonite buffer**
  - ✓ Development of a modeling approach
  - ✓ The impact of non-Darcian flow on the advection in EDZ

Concept: Two-Part Hooke's Model (TPHM)

A rock body can be divided into two parts: the hard part and soft part (soft part corresponds to a fraction of pore volume subject to a large degree of relative deformation [such as cracks])



Hard Part

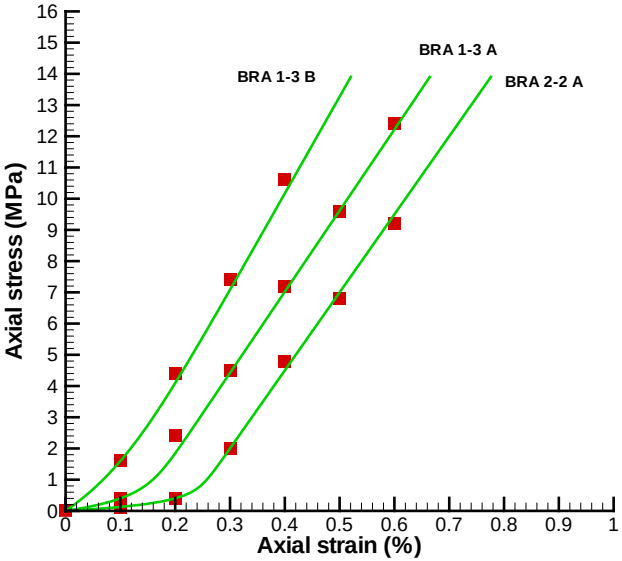
Soft Part

$$-\frac{dV}{V_0} = \gamma_e \frac{d\sigma}{K_e} + \gamma_t \frac{d\sigma}{K_t} \exp\left(-\frac{\sigma}{K_t}\right)$$

$$\gamma_t = \frac{V_{0,t}}{V_0} \qquad \gamma_e = 1 - \gamma_t$$

Stress-Strain Relationship

(Liu et al. 2009)



Data are for Oplinus clay rock (Cokum and Martin, 2007)

Relationships Based TPHM

- **Derived stress-dependent porosity relationship:**

$$\phi = \phi_{e,0}(1 - \mathrm{C}_e\sigma) + \gamma_t \exp\left(-\frac{\sigma}{\mathrm{K}_t}\right)$$

$$\phi_e = \phi_{e,0}(1 - \mathrm{C}_e\sigma) \quad \text{(Hard-part)}$$

$$\phi_t = \gamma_t \exp\left(-\frac{\sigma}{\mathrm{K}_t}\right) \quad \text{(Soft-part)}$$

- **Derived stress-dependent permeability relationship:**

$$\mathrm{k} = \mathrm{k}_{e,0}\exp\left[\beta\left(\phi_e - \phi_{e,0}\right)\right] + \alpha{\phi_t}^{\mathrm{m}}$$

$$\mathrm{k}_e = \mathrm{k}_{e,0}\exp\left[-\beta \mathrm{C}_e \phi_{e,0}\sigma\right]$$

$$\mathrm{k}_t = \alpha{\phi_t}^{\mathrm{m}} = \alpha\left[\gamma_t \exp\left(-\frac{\sigma}{\mathrm{K}_t}\right)\right]^{\mathrm{m}}$$

It is assumed the soft part, which is more deformable under stress, corresponding to those slot like voids (micro-cracks). If this is true, the soft part permeability and porosity under stress should have a relationship similar with the well known “cubic law” for fracture permeability. **The exponent m value should be around 3.**

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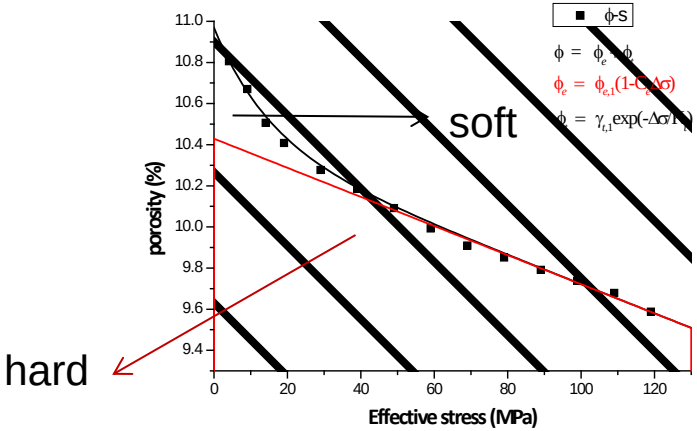
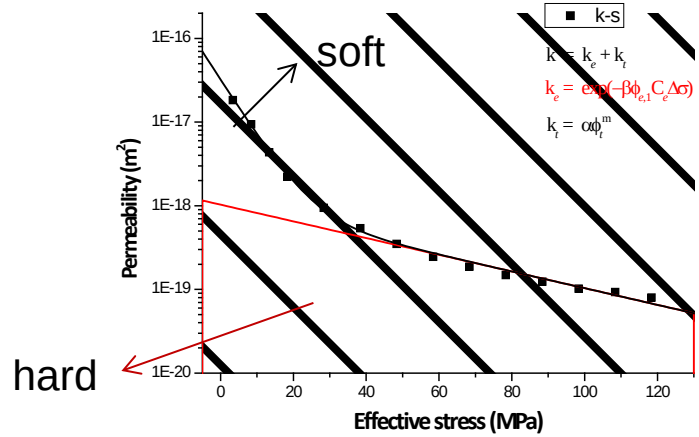
Evaluation of the Derived Relationships

Data sets: intact siltstone cores drilled from 900-1235 m in Taiwan Chelungpu fault (Dong et al. 2010).





Sample	$\phi_{e,1}$ (%)	C_e (MPa^{-1})	K_t (MPa)	$k_{e,1}$ (m^2)	β	m
R287_sec1	10.40	6.81×10^{-4}	14.81	9.54×10^{-19}	3.25	2.34
R351_sec2	8.75	6.97×10^{-4}	8.09	2.54×10^{-19}	2.24	3.03
R390_sec3	10.64	8.11×10^{-4}	8.74	3.66×10^{-17}	3.30	2.04

$$\phi = \phi_{e,1}(1 - C_e\Delta\sigma) + \gamma_{t,1}\exp\left(-\frac{\Delta\sigma}{K_t}\right)$$

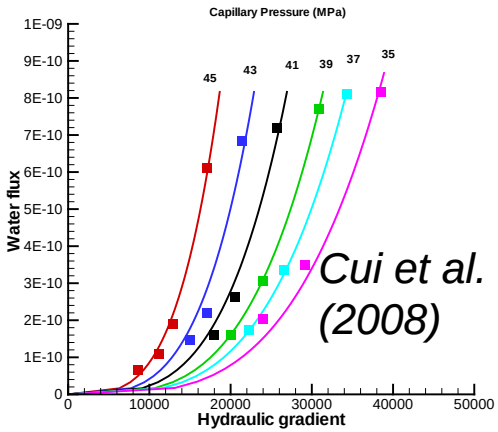
$$k = k_{e,1}\exp\left[-\beta C_e \phi_{e,1}\Delta\sigma\right] + \alpha\phi_t{}^{m}$$

Summary and Implication for Argillite Repository

- A stress-dependent porosity and permeability relationships has been proposed based on TPHM and evaluated with experimental data
- Such relationships should facilitate the calculation of the permeability changes in the clay rock after excavation
- Under low effective stress, slight increase in porosity results in significant increase in permeability, which call attention to the permeability changes in the rock matrix in EDZ
- In the future, such relationships will be implemented in the simulator for better calculation of the hydraulic-mechanical coupling.

Non-Darcian Flow:
Background and Proposed model

- Non-Darcian flow is evidenced in laboratory experiments and nanoscale flow simulation.
- Excavation Damaged Zone (EDZ) is a critical (advection) feature impacting repository performance.
- Water flow from host rock to EBS is critical for buffer to function (swelling).



Cui et al. (2008)

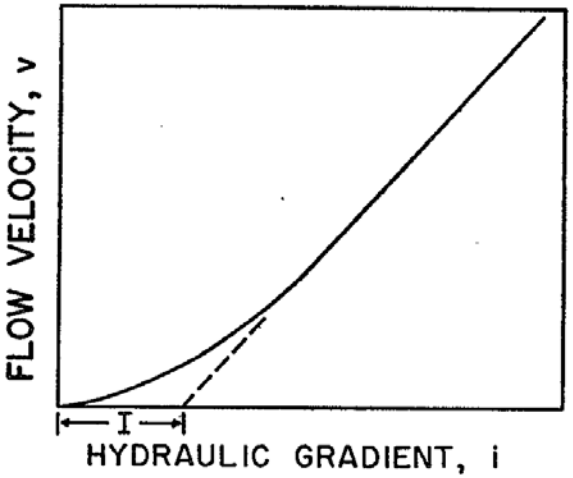
Threshold gradient model $q = K(i - I)$

Swartzendruber (1961): $q = K[i - I(1 - e^{-i/I})]$

Proposed model (Liu and Birkholzer, 2013) :

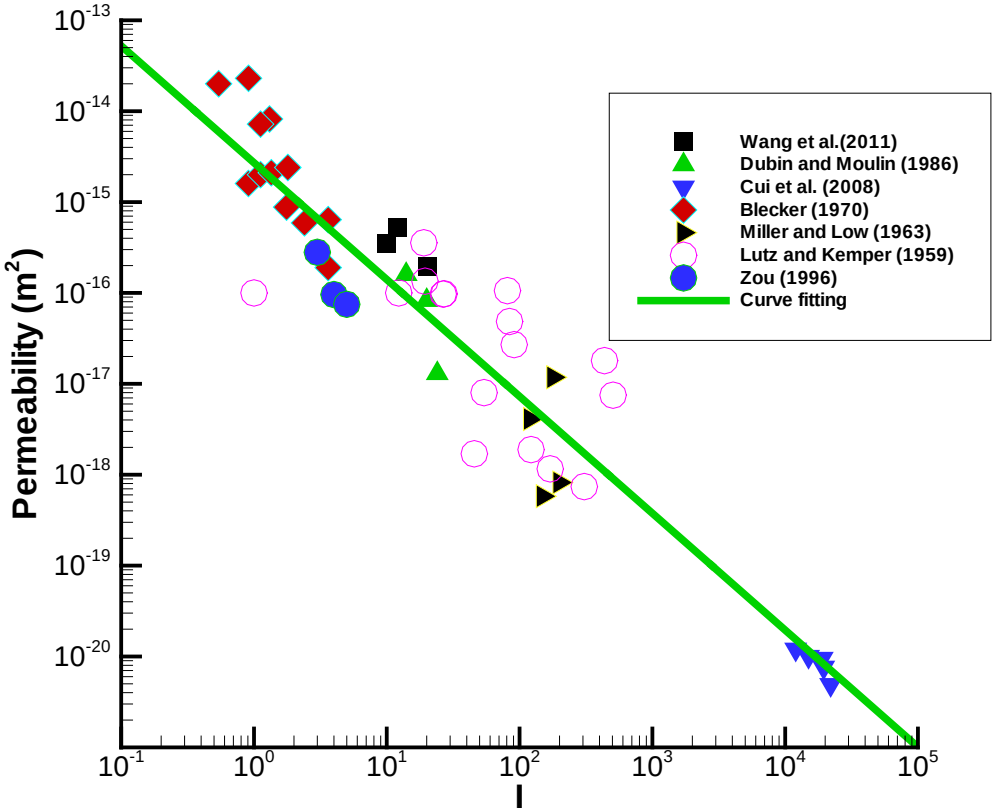
$$q = K[i - \frac{I}{\gamma(\frac{1}{\alpha})}\gamma(\frac{1}{\alpha}, \left(\frac{i}{I*}\right)^{\alpha})]$$

$$I = \frac{I*}{\alpha}\gamma\left(\frac{1}{\alpha}\right) \qquad \gamma(a,x) = \int_0^x t^{a-1}e^{-t}dt \qquad \gamma(a) = \int_0^\infty t^{a-1}e^{-t}dt$$



Non-Darcian Flow:
Proposed Model

Relationship between permeability and threshold hydraulic gradient



$$I = Ak^{B}$$

A= 4.0 E12 and B =-0.78

Liu and Birkholzer, 2013

The degree of non-Darcian flow behavior can be characterized by permeability (k) (or pore size) and threshold gradient (I), respectively.

Non-Darcian Flow:
Recent Development

Three-Dimensional and Anisotropic Cases

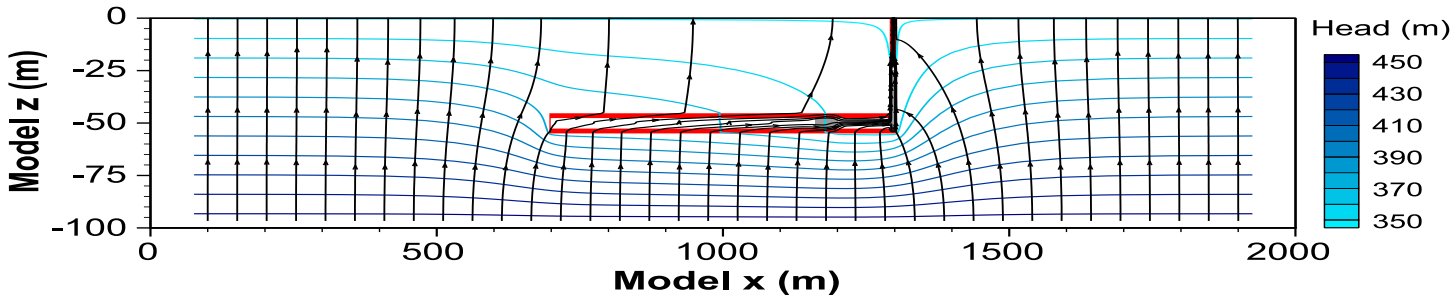
- *Extension of the new flux-gradient relationship to multi-dimensions.*

$$\boldsymbol{q} = -\boldsymbol{K}[i - \frac{I}{\gamma(\frac{1}{\alpha})}\gamma(\frac{1}{\alpha}, \left(\frac{i}{I*}\right)^{\alpha})]\boldsymbol{n}_i$$

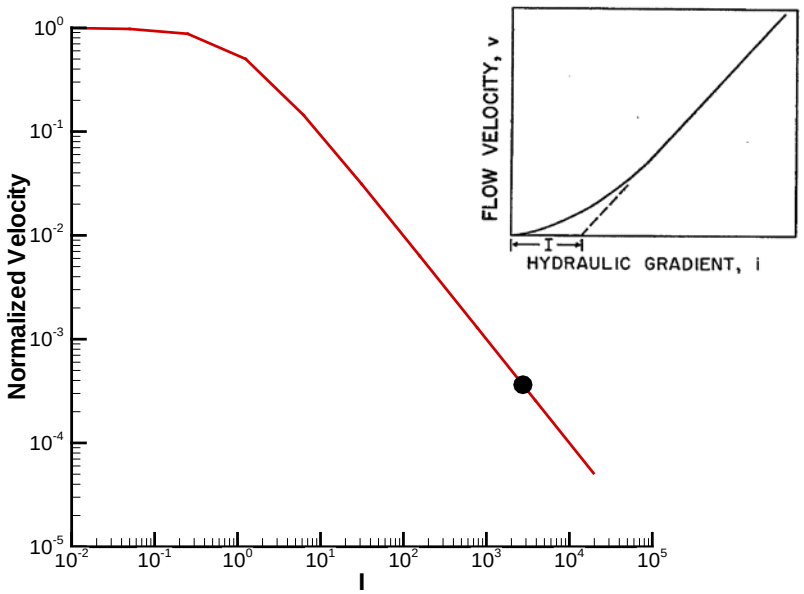
$$I = \frac{\sqrt{(I_x i_x)^2 + (I_y i_y)^2 + (I_z i_z)^2}}{\sqrt{(i_x)^2 + (i_y)^2 + (i_z)^2}}$$

- *The developed relationships can be applied to both saturated and unsaturated conditions.*

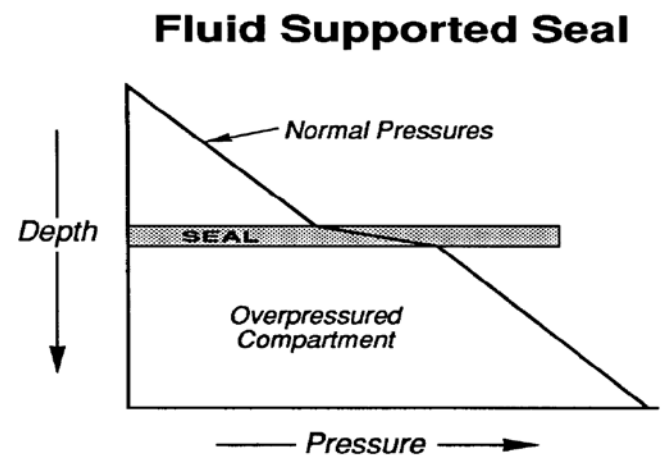
Non-Darcian Flow:
Impact on Advection with EDZ



*Bianchi et al. (2013) found that for a given ambient hydraulic gradient, the upward water flow below the tunnel is intercepted by the high-permeability EDZ and advection indeed becomes important within the EDZ. However, n*on-Darcian flow eliminates advection within EDZ even when its permeability is infinite.



The result is consistent with “pressure seal” studies in the petroleum literature (Deming, 1994)



Non-Darcian Flow:
Conclusions and Future Work

- The existence of non-Darcian flow in clay is supported by data from different sources.
- A systematic modeling approach has been proposed for non-Darcian flow in a clay repository.
- The non-Darcian flow has a significant impact on the performance for a clay repository, especially on the advection in the EDZ and the hydration of EBS.
- Non-Darcian flow could also be very important in salt media, further study is needed.
- In the future, non-Darcian flow could be further tested with long term hydration test of EBS such as FEBEX
- In the future, non-Darcian flow needs to be considered in the PA models