Modeling Swelling and Swelling Pressure
in Expansive Clays and Clay-Sand Mixtures

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Outline

- Purpose of modeling expansive clays
- Constitutive model
- Material parameters for a bentonite-sand mixture
- Numerically simulated oedometer free-swell test
  - Calculated deformation and pressure
  - Effects on void ratio (input to hydrology model)
  - Using measured strain to characterize swelling behavior
- Summary

Expansive Clays and Clay-Sand Mixtures

- Likely material for buffers, backfill, or seal in designs for geologic disposal of nuclear waste in deep saturated zones
- Constructed unsaturated but expected to re-saturate during and after thermal period
- May swell as moisture content increases
  - Swelling is expected to reduce flow and transport
  - High swelling pressure could damage design components
  - Low swelling pressure could favor flowing water reaching the waste package and degradation of design components
- Constitutive model needed to evaluate mechanical behavior and provide input to hydrologic modeling

Constitutive Model Features

- Defines response to external and internal loads
  - External loads from gravity or applied load
  - Internal loads
    - Temperature change (not included in analysis discussed in this presentation)
    - Suction
    - Physico-chemical swelling or shrinkage as moisture content changes
- Incorporates suction effects on strength and stiffness
- Parameters based on well-established laboratory testing
  - Moisture retention characteristic curve
  - Oedometer compression curves
  - Oedometer free-swell curve

Approach to Constitutive Modeling: General Stress-Strain Relationships

- Strain increments are additive and separable

$$\Delta e = \Delta e^{E} + \Delta e^{P} + \Delta e^{\mathrm{Th}} + \Delta e^{\mathrm{CW}}$$

$\Delta e =$ Total strain increment (system equilibrium)
$\Delta e^{E} =$ Elastic strain increment (elasticity theory)
$\Delta e^{P} =$ Plastic strain increment (plasticity theory)
$\Delta e^{\mathrm{Th}} =$ Thermal strain increment
$\Delta e^{\mathrm{CW}} =$ Physico-chemical swelling strain increment

- Incremental stress-strain relationships based on elasticity

$$\{\Delta\sigma\} = [\mathrm{C}]\left(\{\Delta e\} - \{\Delta e^{\mathrm{Th}}\} - \{\Delta e^{\mathrm{CW}}\} - \{\Delta e^{P}\}\right)$$

$\Delta\sigma =$ Effective stress increment
$[\mathrm{C}] =$ Elastic stiffness matrix (Pressure-dependent bulk modulus)

Approach to Constitutive Modeling: General Stress-Strain Relationships cont'd

- Plastic strain based on plasticity theory

- Physico-chemical-swelling strain
  - Free swelling (function of moisture content change)
  - Moisture content gradient
  - Mechanical boundary conditions

- Thermal strain
  - Free thermal expansion (function of temperature change)
  - Temperature gradient
  - Mechanical boundary conditions
  - Thermal effects are not included in the swelling analysis described in this presentation

Bishop Parameter (Suction Stress)

Suction stress ← Bishop parameter ← Effective Saturation

$\{\sigma\} = \{\sigma^T\} - p_s\{\mathbf{I}\}$

$\sigma =$ Effective stress

$\sigma^T =$ Total stress

$p_s = -(u_a - \chi s)$

$=$ Suction pressure

$\chi =$ Bishop parameter

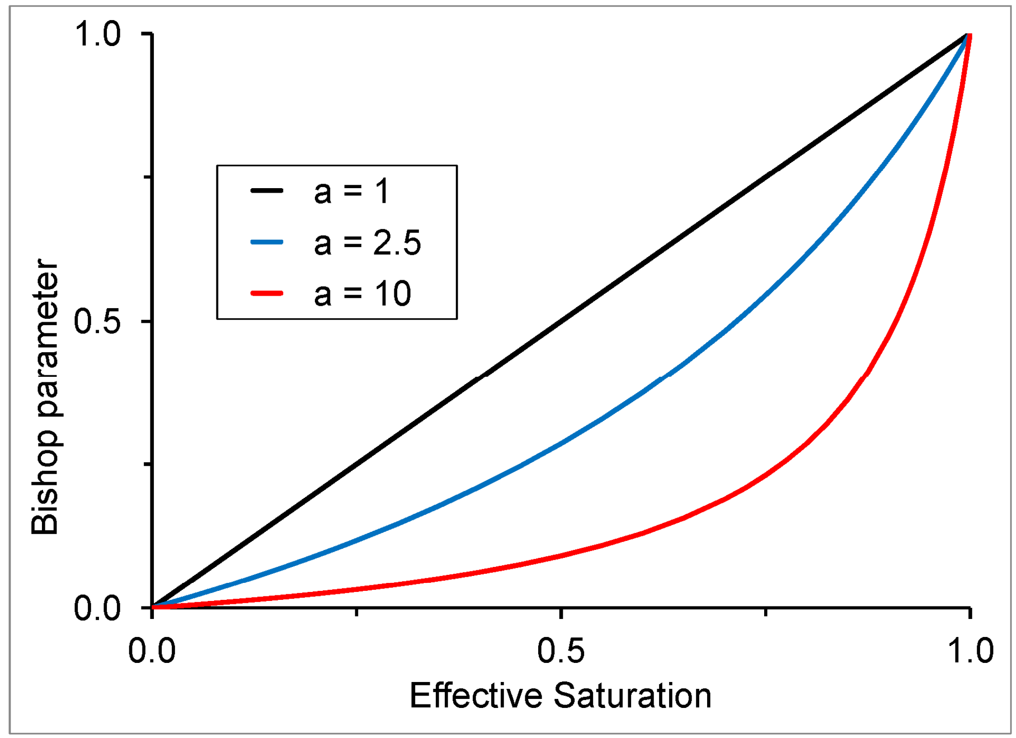
$s =$ Suction; $u_a =$ Air pressure

$$\chi = \frac{S_e}{a_{bs}+(1-a_{bs})S_e}$$

$S_e =$ Effective saturation

$a_{bs} =$ Fitting parameter

S_e based on moisture retention curve



Effective Pressure Due to Suction for a Bentonite-Sand Mixture

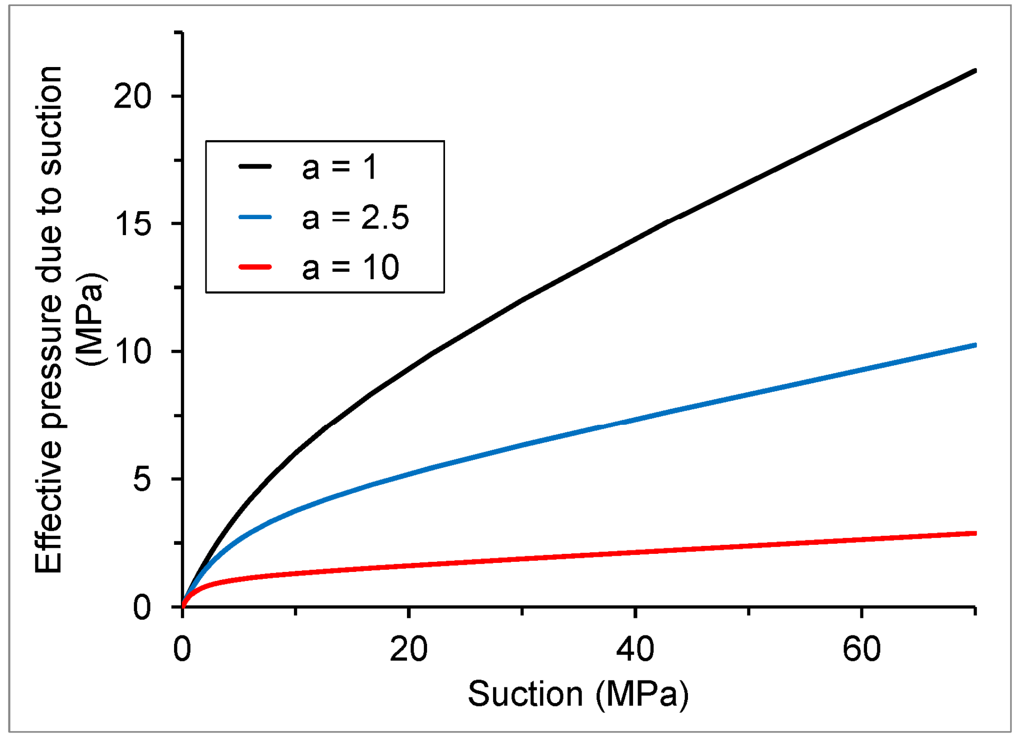
- Bishop parameter evaluated using moisture retention curve

$p_s = \chi s$ (for $u_a = 0$)
= Effective pressure due to suction (s)

$\chi = \chi(S_e, a_{bs})$
Evaluated for a_{bs} =1, 2.5, 10

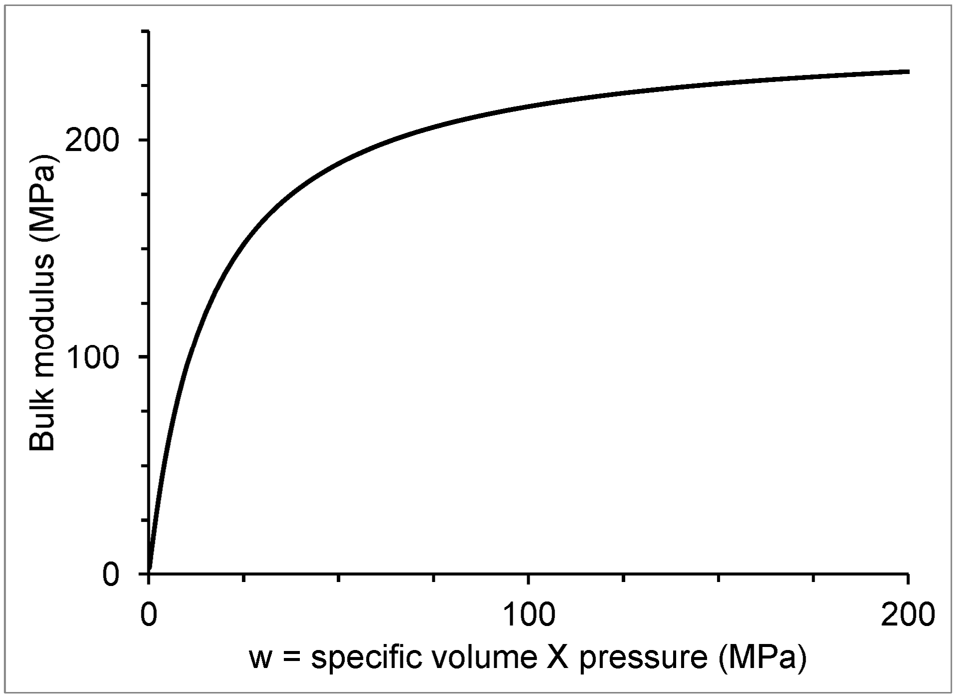
Pre-consolidation pressure

$P_c = P_{c0} + P_{cs}$
$P_{c0} = 0.8$ MPa for $s = 0$
$P_{cs} = p_s$



Oedometer test results and moisture retention data based on J.D. Barnichon (Personal Communication), Head of LR2S Laboratory, Institute for Radiological Protection and Nuclear Safety, France, "DECOVALEX D-2015: description of Task A (SEALEX experiment)," August 2012. jean-dominique.barnichon@irsn.fr

Pressure-Dependent Bulk Modulus, *K*, for a Bentonite-Sand Mixture



- Based on recompression segment of nonlinear specific volume (v) versus effective pressure (p) curve
  - Slope of recompression curve
  - Increases with effective pressure
  - Increases with compaction
  - Reversible

<u>Bulk modulus (K)</u>

$$K = \frac{1}{\kappa_r}\left[w_0 + \frac{w-w_0}{1+b(w-w_0)}\right]$$

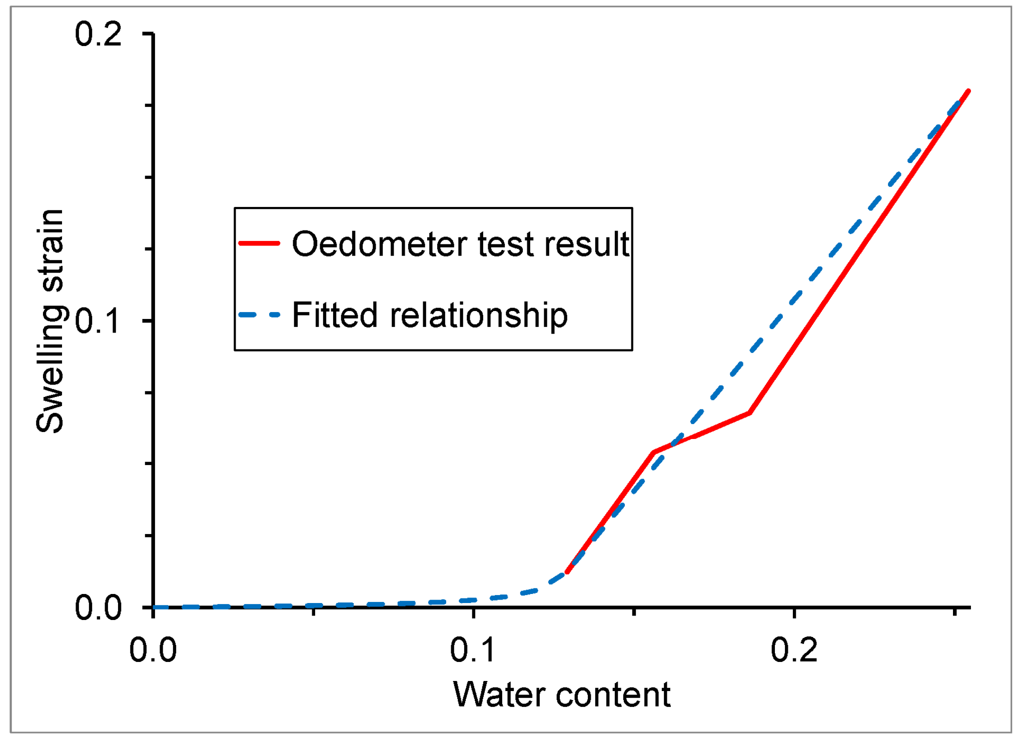
$w = vp;\qquad w_0 = v_0 p_0$

$b = 1/(\kappa_r K_\infty - w_0)$

K_∞ = maximum bulk modulus

Unit Swelling Potential for a Bentonite-Sand Mixture

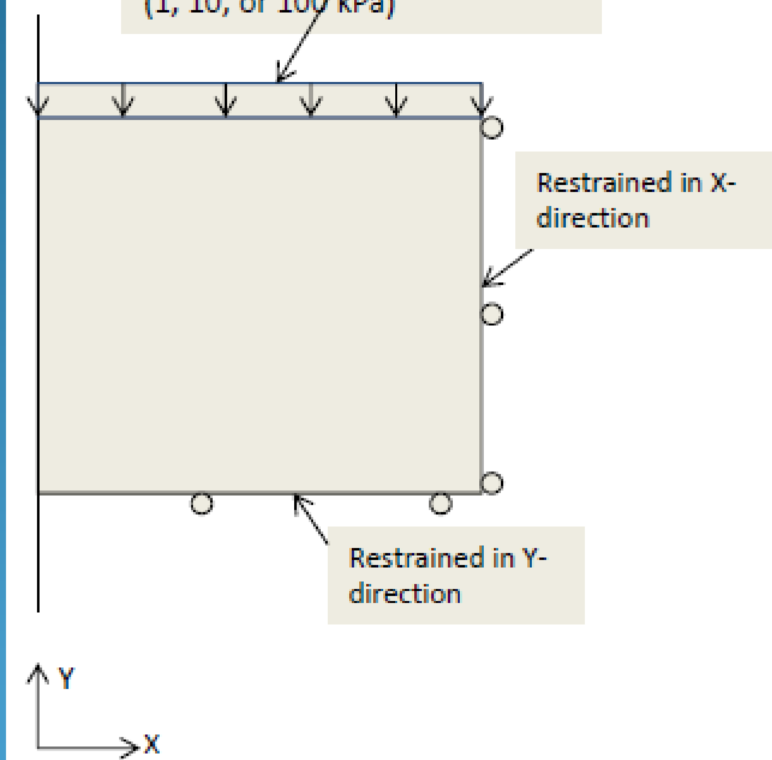
- Equals slope of swelling strain versus water content curve
- Used to define physico-chemical swelling increment in constitutive model



Oedometer test result based on J.D. Barnichon (Personal Communication), Head of LR2S Laboratory, Institute for Radiological Protection and Nuclear Safety, France, “DECOVALEX D-2015: description of Task A (SEALEX experiment),” August 2012. jean-dominique.barnichon@irsn.fr

Numerically Simulated Oedometer Free-Swell Testing

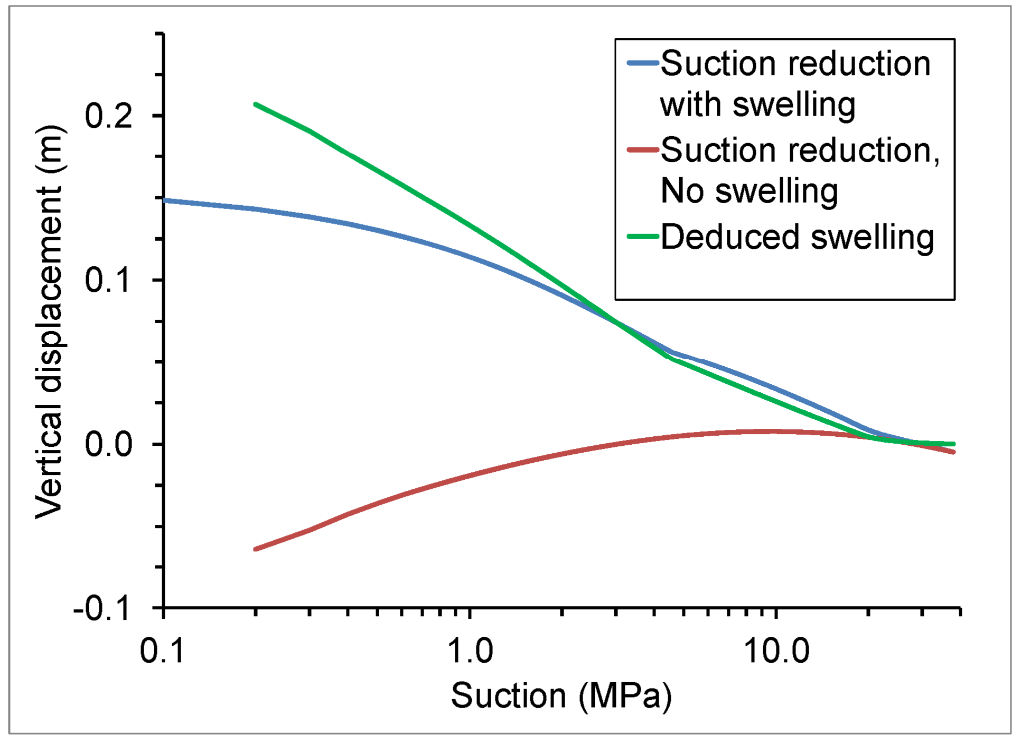
- Axisymmetric model
- Restrained on bottom and sides
- Small surcharge pressure at the top (1, 10, or 100 kPa)
- Suction decreased from 38 MPa to 0.1 MPa in small steps
- Water content calculated from prescribed suction using moisture retention curve
- Mechanical response calculated using FLAC with constitutive model described in this presentation



Axisymmetric Model of a Disk-Shaped Specimen of Bentonite-Sand Mixture

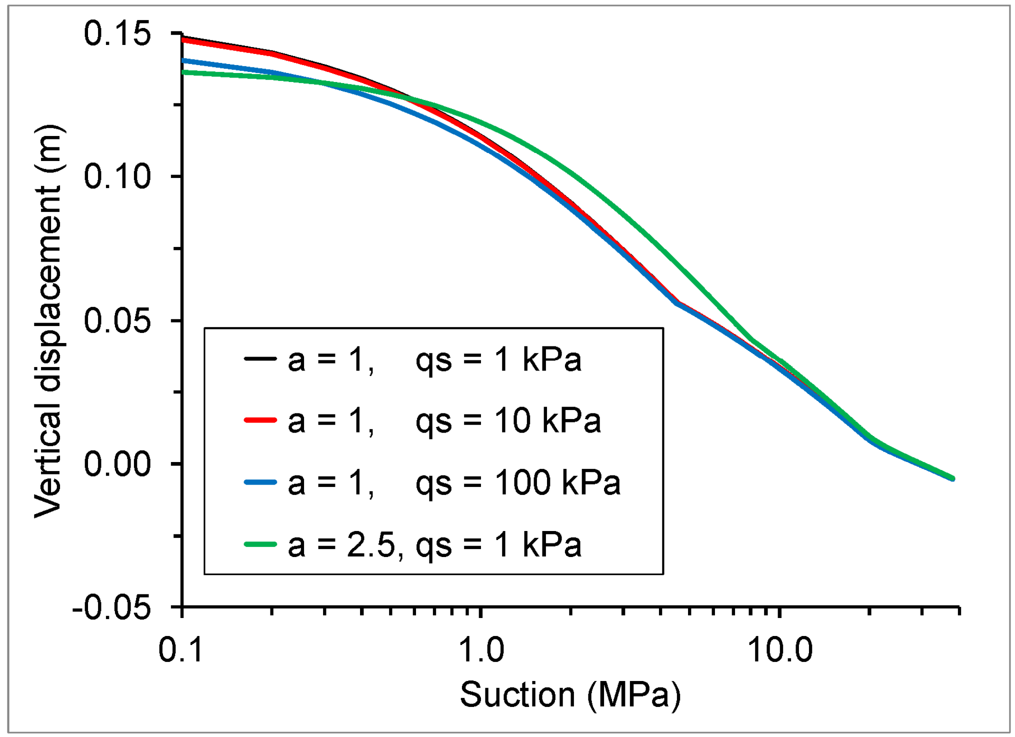
Vertical Displacement
(from Simulated Oedometer Free-Swell Test)

- Deformation due to physico-chemical swelling is dominant
- Other deformation mechanisms could be important
  - Elastic swelling due to decreasing suction
  - Compression due to decreasing elastic stiffness under decreasing pressure



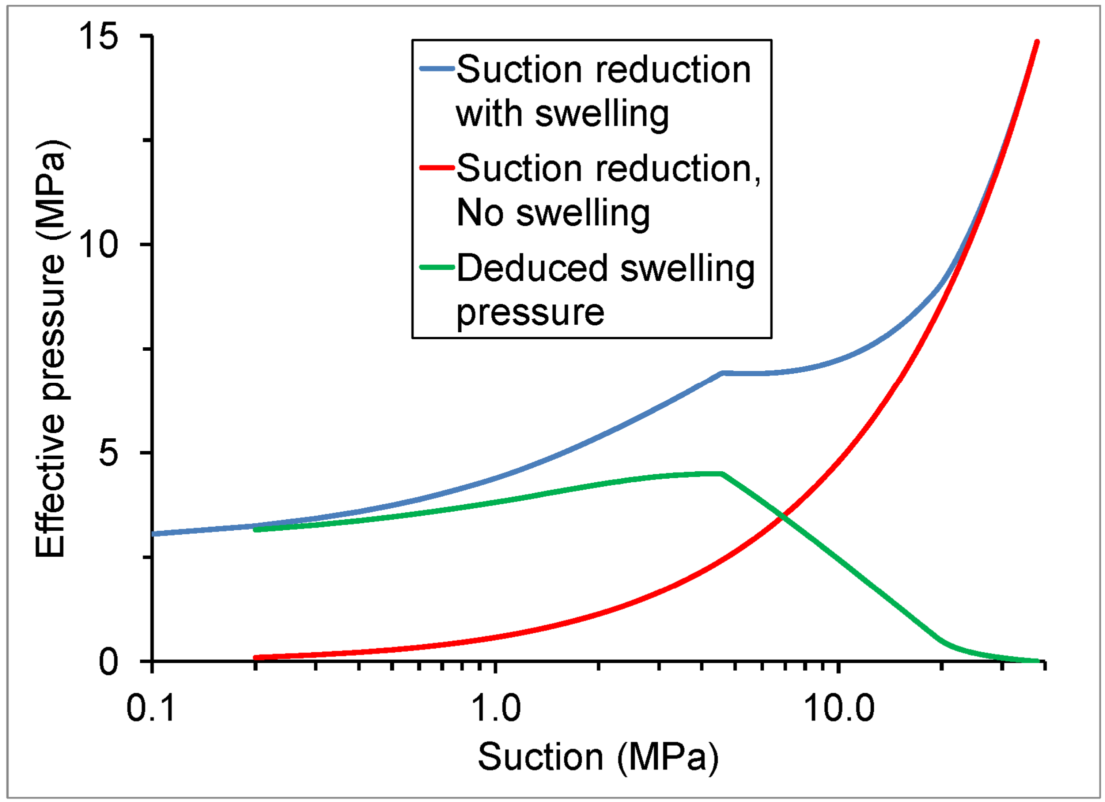
Sensitivity of Vertical Displacement

- Calculated deformation appears insensitive to
  - a_{bs} fitting parameter for suction stress ($a = a_{bs}$)
  - applied surcharge pressure (qs)



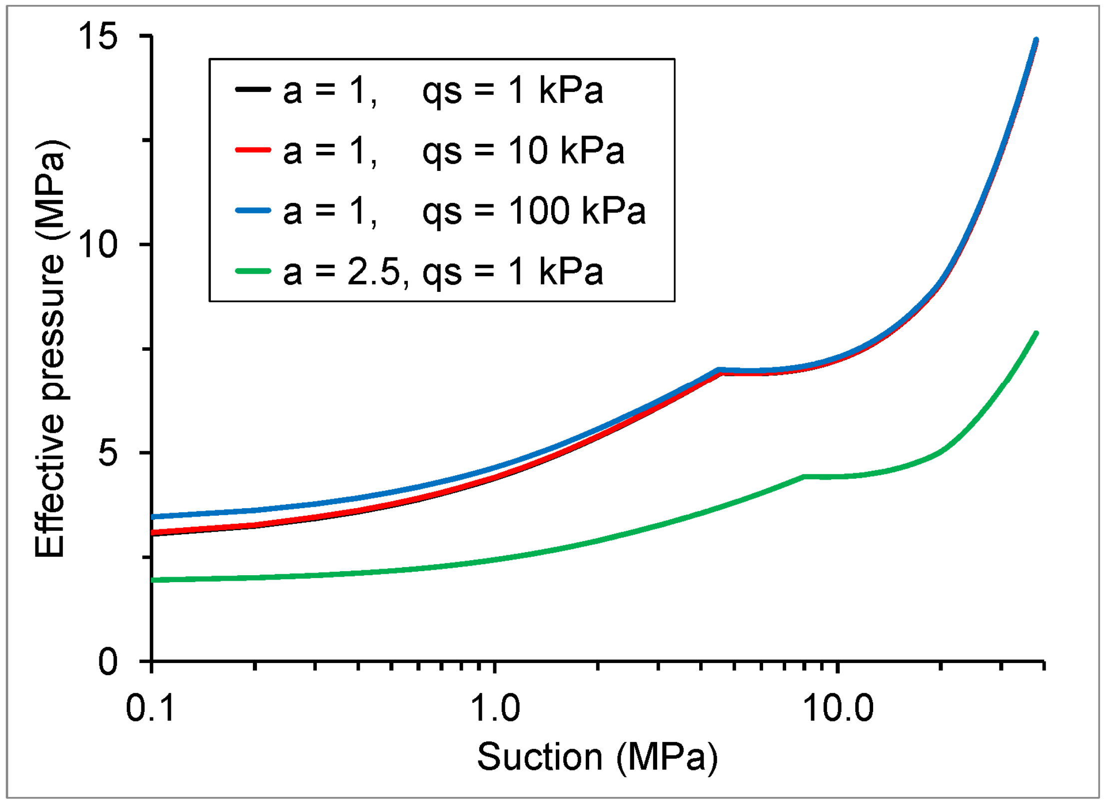
Swelling Pressure
(from Simulated Oedometer Free-Swell Test)

- Swelling pressure depends on several factors
  - Suction history
  - Unit swelling potential
  - Moisture content gradient
  - Boundary restraint



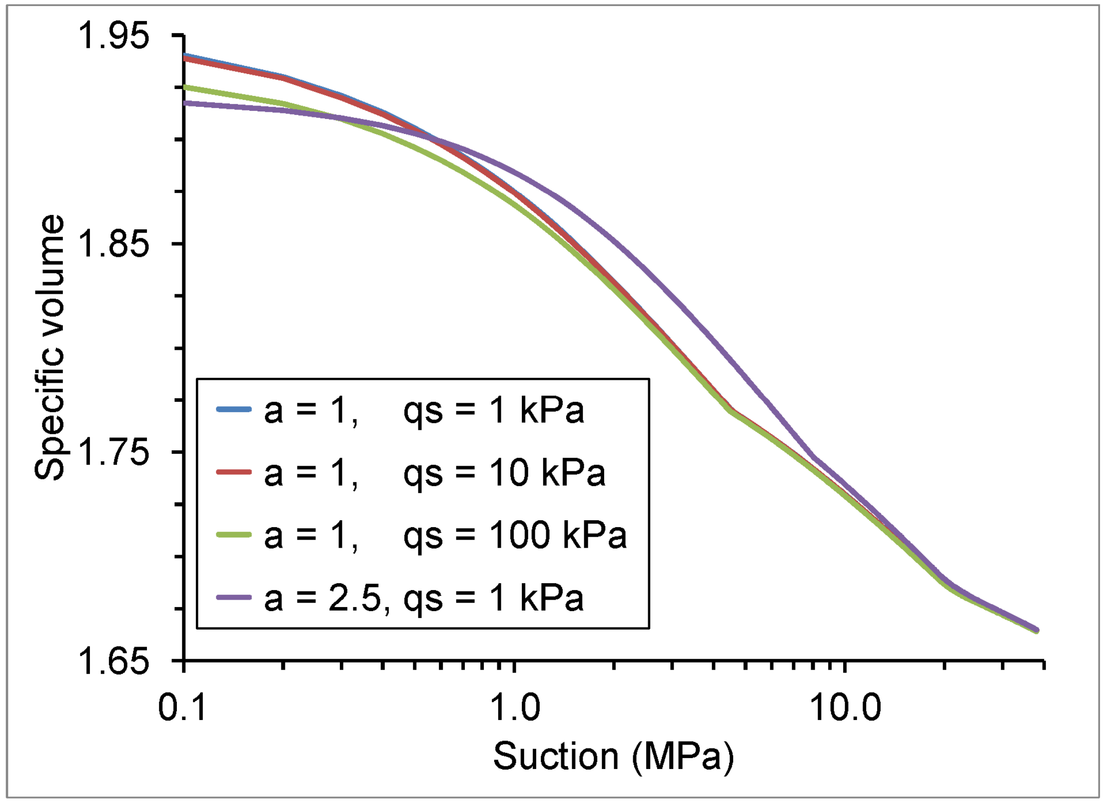
Sensitivity of Swelling Pressure

- Appears sensitive to a_{bs} fitting parameter ($a = a_{bs}$)
- Appears insensitive to the applied surcharge pressure



Specific Volume (and Void Ratio)
(from Simulated Oedometer Free-Swell Test)

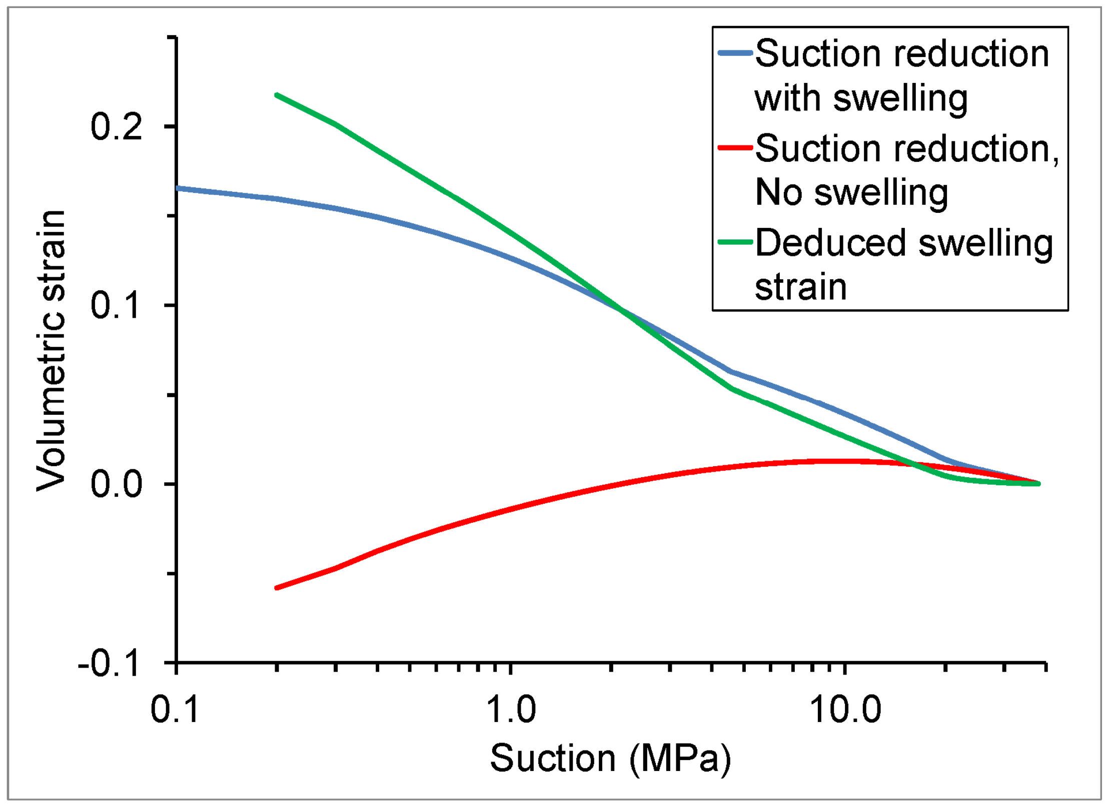
- Appears insensitive to a_{bs} fitting parameter ($a = a_{bs}$)
- Appears insensitive to the applied surcharge pressure



Swelling Strain

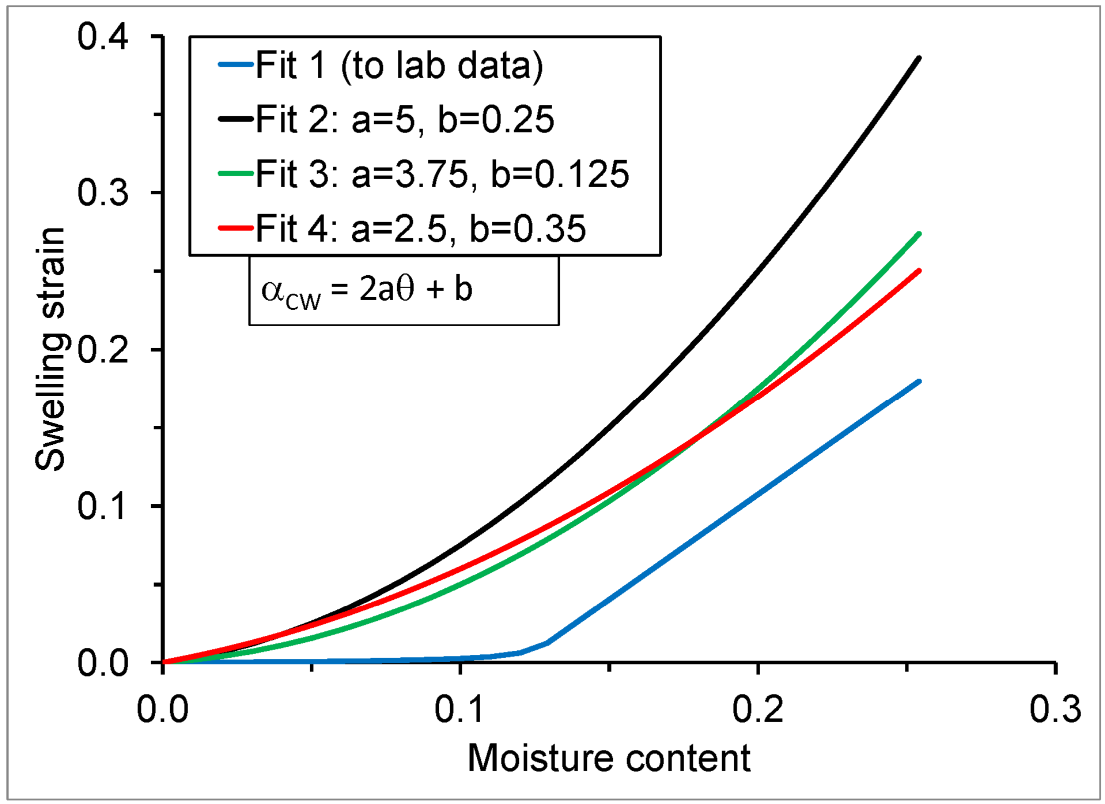
(from Simulated Oedometer Free-Swell Test)

- Calculated strain is smaller than deduced swelling strain
- Therefore, measured strain from oedometer free-swell test is smaller than swelling strain
- Therefore, unit swelling potential based on measured strain may under-estimate swelling behavior



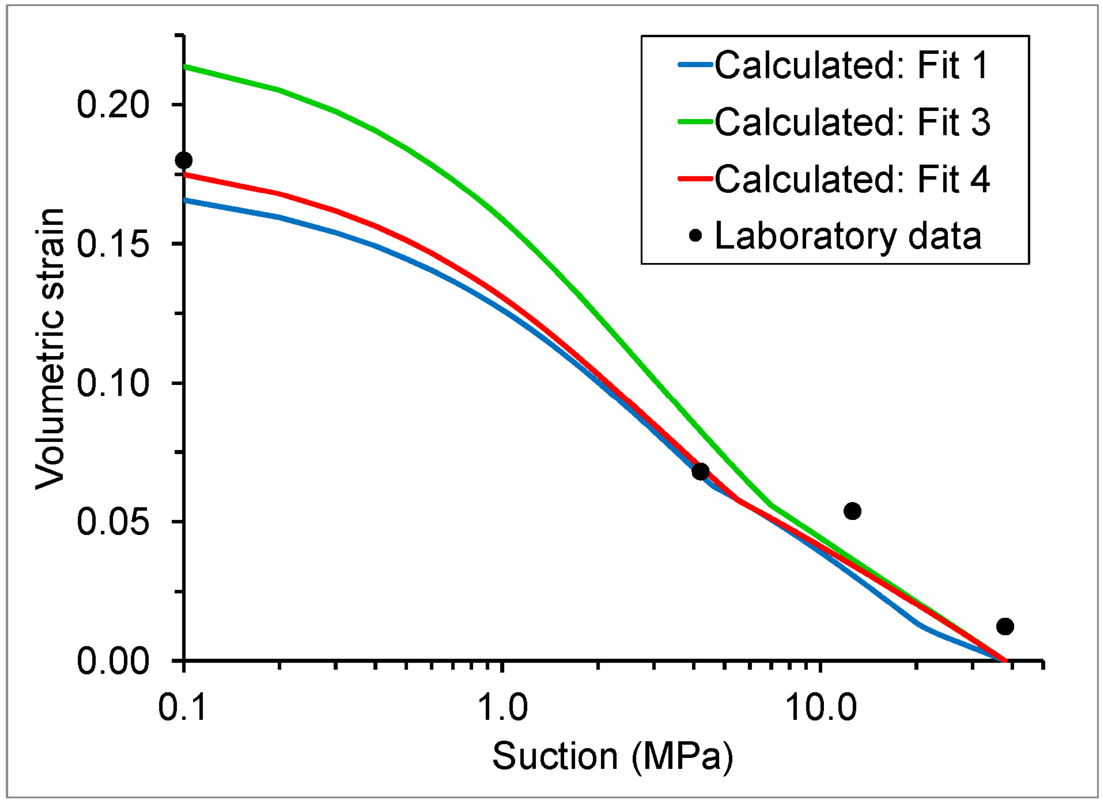
Estimating Unit Swelling Potential From Oedometer Free-Swell Test Results

- Fit 1 assumes swelling strain equals measured strain
- Fits 2, 3, and 4
  - Strain versus moisture content relationships similar to Fit 1
  - Swelling strain greater than measured strain



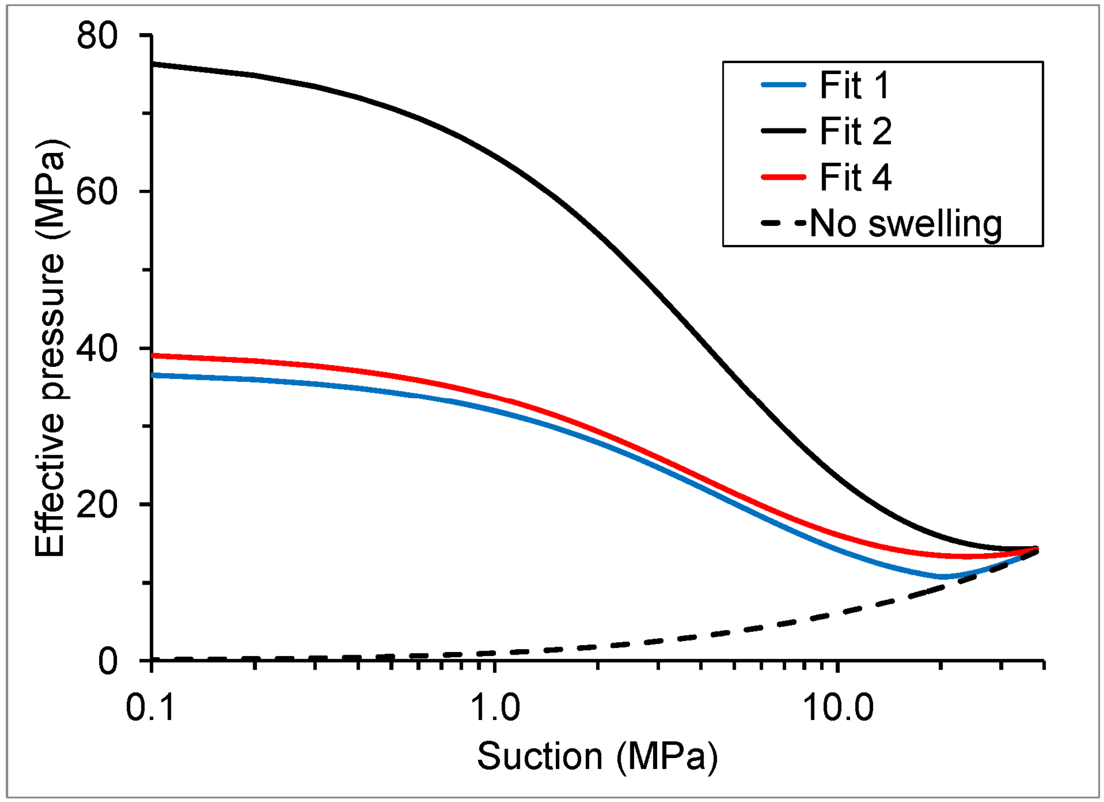
Estimating Unit Swelling Potential: Comparing Measured and Calculated Strains

- Unit swelling potential based on Fits 1 and 4 gives strains closest to measured strain
- Laboratory data includes non-zero strain at the numerical "zero-strain" state



Estimating Unit Swelling Potential: Comparing Calculated Pressure Cases

- Unit swelling potential based on Fits 1 and 4 give essentially the same pressure
- Measured strain may be adequate for calculating unit swelling potential



Summary

- Demonstrated an approach for modeling swelling and swelling pressure

- Approach uses constitutive model for unsaturated clays
  - Suction stress determined using Bishop's modified effective stress principle
  - Incorporates suction effects on mechanical properties
  - Stress-strain relations based on elasto-plasticity

- Described results of numerically simulated oedometer free-swell testing
  - Bentonite-sand mixture specimen
  - Subjected to decreasing suction through water influx
  - Calculated mechanical response
    - Dominated by swelling effects
    - Affected by decreasing bulk modulus (caused by suction decrease)
    - Simulations agree well with laboratory test results
  - Volumetric strain from oedometer free-swell test is adequate to characterize swelling behavior

Acknowledgments

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