THM DISCONTINUITIES IN 2D AND 3D

CODE_BRIGHT

2020

Contents

I ESTRATEGIES TO REPRESENT DISCONTINUITIES WITH BBM MODEL

I.1 Discontinuities with mechanical coupling

Programs that solve only water and heat flow and transport, usually use lower dimension elements to calculate flow (i.e. triangles combined with tetrahedral elements). CODE_BRIGHT has specific implementation for segments in 2D and triangles in 3D. This can be used as well in a hydro-mechanical coupled problem also if mechanical deformations of the discontinuity are not significant and therefore its transmissivity will remain constant (for instance for rock fractures with constant transmissivity).

When a discontinuity needs to be represented with its mechanical properties and the geometrical representation is finite, properties have to be calculated taking into account the thickness of the finite zone representing the discontinuity.

The particular case of discontinuities generated by bentonite based materials (contacts with rock and canister and contacts between blocks) requires specific attention as it is desirable that the discontinuity evolves in a way that its properties remain similar to the clay based materials.

I.2 Strength estimation from soil properties

Strength is different in a discontinuity as compared to a soil. If there are direct measurements of cohesion and friction angle of the discontinuity, they can be used directly for interface elements simulated with finite thickness or zero thickness. If these interface properties are not known, they can be reduced accordingly by using a reduction factor *R*. In practice, for geotechnical models, Mohr-Coulomb parameters for discontinuities can be estimated as:

$$c' = c'_{soil} R \quad (1)$$

$$\phi' = \text{atan}(R \tan \phi'_{soil}) \quad (2)$$

Where $R \leq 1$ is a reduction coefficient that represents the different strength of discontinuities.

The correspondence of BBM parameters for cohesion and friction angle is (see Appendix BBM):

$$p_{s_{discontinuity}} = R(p_{s0} + ks)_{soil} \quad (3)$$

$$M_{discontinuity} = RM_{soil} \quad (4)$$

Therefore what has to be done is to reduce BBM parameters (M, p_{s0}, k) by application of a reduction factor *R* in the same way as would be done for Mohr-Coulomb in the case of retaining walls or other geotechnical applications. As plastification is related with stress level it does not matter if a contact or a continuum element is considered.

I.3 Stiffness estimation from discontinuity properties

The question of deformability is different, as it is desirable that deformations do not depend on the thickness of the continuum element with finite thickness considered.

It is assumed that a discontinuity can be characterized by the following relationships:

$$\Delta\sigma_n = k_n \Delta u_n \quad (5)$$
$$\Delta\tau = k_s \Delta u_s \quad (6)$$

With normal and shear stiffness parameters defined with displacements instead of deformations.

From these parameters, the following elastic parameters can be used for a zone of equivalent thickness (t):

$$G_d = k_s t \quad (7)$$
$$K_d = \frac{(1+\nu)}{3(1-\nu)} k_n t \quad (8)$$
$$E_d = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} E_n = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} k_n t \quad (9)$$
$$\nu_d = \frac{E_n - 2G_d}{2E_n - 2G_d} = \frac{k_n - 2k_s}{2k_n - 2k_s} \quad (10)$$

Derivation of these equations is done in an Appendix. This is an interesting option for rock discontinuities which are well characterized by normal and shear stiffness.

I.4 Stiffness estimation from soil properties

If the discontinuity properties (k_n, k_s) are not known, then it is necessary to derive them from soil properties.

Here, 3 alternatives to estimate elastic properties for the discontinuities are proposed:

a) REDUCED SHEAR STIFFNESS AND INCOMPRESSIBILITY: The elastic parameters can be estimated as according to what is proposed in Plaxis:

$$G_d = R^2 G \quad (11)$$
$$\nu_d = 0.45 \quad (12)$$

From which Young and Bulk modulus can be calculated:

$$E_d = 2(1+\nu_d)G_d \quad (13)$$
$$K_d = \frac{2G_d(1+\nu_d)}{3(1-2\nu_d)} \quad (14)$$

This is interesting for soil-concrete interfaces for which volumetric deformation can be neglected (i.e. Poisson Ratio near to 0.5).

b) NON-LINEAR COMPRESSIBILITY AND REDUCED SHEAR STIFFNESS: If interface volumetric stiffness K_d is considered in the same range as the bentonite and shear modulus is assumed constant, the following parameters can be used:

$$K_d = K = \frac{p'(1+e)}{\kappa} \quad (15)$$
$$G_d = R^2 G \quad (16)$$

In addition to modifying shear modulus, it is convenient to remove swelling parameters for the interface ($\kappa_s = 0$).

c) NON-LINEAR COMPRESSIBILITY AND MODIFIED POISSON RATIO: If interface volumetric stiffness K_d is considered in the same range as the bentonite and, Poisson ratio is used to calculate a nonlinear shear modulus $G(K,\nu)$, the following parameters can be used:

$$K_d = K = \frac{p'(1+e)}{\kappa} \tag{17}$$

$$G_d = R^2 G = R^2 \frac{3K(1-2\nu)}{2(1+\nu)} \tag{18}$$

Both, *K* and *G* are non-linear as compressibility of soils depends on effective stress (and Poisson ratio was considered constant). Poisson ratio for the discontinuity can be calculated independently:

$$\nu_d = \frac{3K_d - 2G_d}{2(3K_d + G_d)} = \frac{3K - 2R^2 \frac{3K(1-2\nu)}{2(1+\nu)}}{2\left(3K + R^2 \frac{3K(1-2\nu)}{2(1+\nu)}\right)} = \frac{1+\nu - R^2(1-2\nu)}{2\left(1+\nu+R^2(1-2\nu)\right)} \tag{19}$$

Equations (17), (18) and (19) permit to use BBM model with the same parameters as for the bentonite except for shear modulus *G* or Poisson ratio.

For instance if *R*=0.6 and ν=0.3, it results in a Poisson ratio for the discontinuity equal to 0.4. In addition to modifying Poisson ratio, it is important to remove swelling parameters for the interface ($\kappa_s = 0$).

Alternatives a), b), c) permit to use an interface with finite thickness to model a clay – solid interface.

I.5 Stiffness scaling for different finite thickness elements

Finally, if the thickness changes from laboratory scale to in situ scale, the following relations can be used:

$$K_d^{in\ situ} = K_d^{sample} \frac{t^{sample}}{t^{in\ situ}} \text{ or } \kappa_d^{in\ situ} = \kappa_d^{sample} \frac{t^{in\ situ}}{t^{sample}} \tag{20}$$

$$G_d^{in\ situ} = G_d^{sample} \frac{t^{sample}}{t^{in\ situ}} \tag{21}$$

$$\nu_d^{insitu} = \nu_d^{sample} \tag{22}$$

$$E_d^{in\ situ} = E_d^{sample} \frac{t^{sample}}{t^{in\ situ}} \tag{23}$$

Note that Poisson Ratio (see equation (19) does not depend on the equivalent thickness considered. Note also that, if *G* changes with the finite thickness element to be used, *R* is not going to coincide with *R* used to reduce strength parameters.

I.6 Hydraulic and thermal properties

Both intrinsic permeability and retention curve depend on porosity as indicated in an Appendix. If permeability and retention curve depend on porosity, it is sufficient to consider a larger porosity for the interface in order to increase permeability, reduce air entry value and decrease thermal conductivity. The following options can be used:

- Exponential equation. In the case presented below, increasing porosity of the interface zone by 50% may be sufficient to produce this effect.
- Kozeny equation. It is also a function of porosity but it does not include parameters except a value of permeability for a given porosity.
- For thermal conductivity, the function of porosity available may be a good option.
- Other alternatives can be considered if variation should be larger (cubic law) and more information of the discontinuity is available.

II INTERFACE REPRESENTATION IN 2D. APPLICATION

Description

Four models are presented, two with interface and two without interface. The two models with interface are based, respectively, on BBM with modified properties and on a combination of non-linear elasticity plus Mohr-Coulomb (friction).

The models with interface use the following parameter modification (the following applies to BBM and to non-linear elasticity plus Mohr-Coulomb.

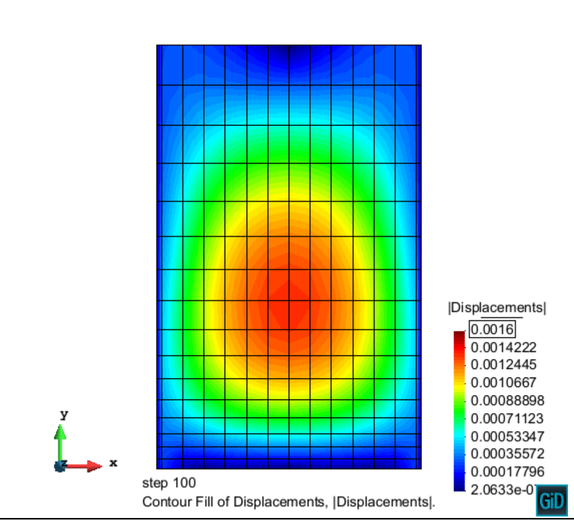
- Friction parameter *M* has been reduced by a factor *R*=0.6
- Poisson ratio has been recalculated to 0.4 instead of 0.3 using the same factor.
- Swelling parameters for the interface are set to 0 (BBM model).
- Porosity has been increased to 0.6 (instead of 0.43) at the interface zone which increases permeability and reduces capillary pressure at the initial conditions.
- Parameters for hydraulic laws are the same as for the buffer.

Compression of the interface element during clay swelling produces a reduction of porosity and leads to permeability in the range of bentonite permeability.

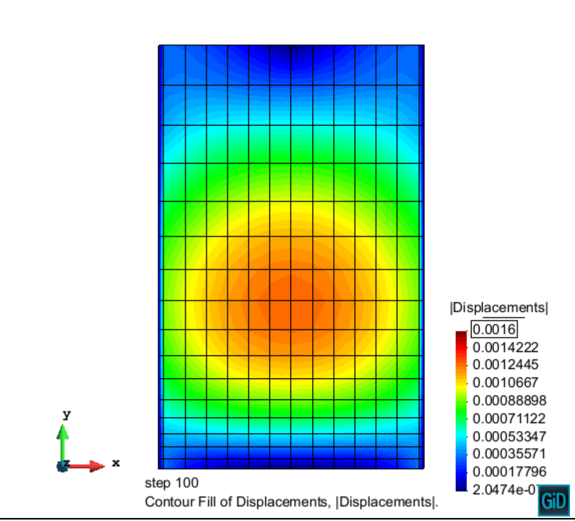
The four models that are presented are:

- Interface with BBM
- Interface with nonlinear elasticity + Mohr Coulomb
- No interface and fixed displacement on boundary all directions
- No interface and fixed displacement on boundary along normal direction

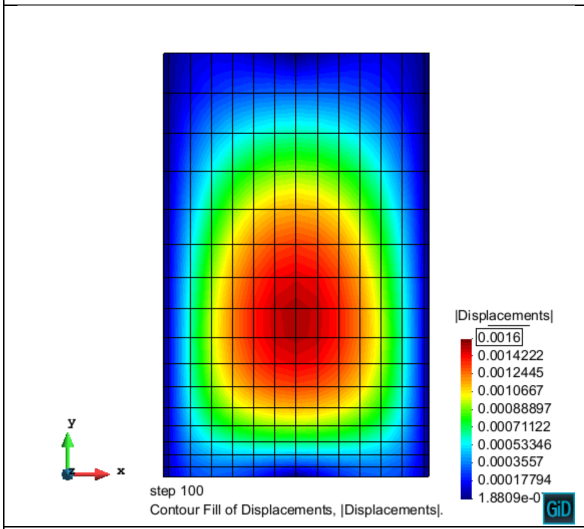
Results



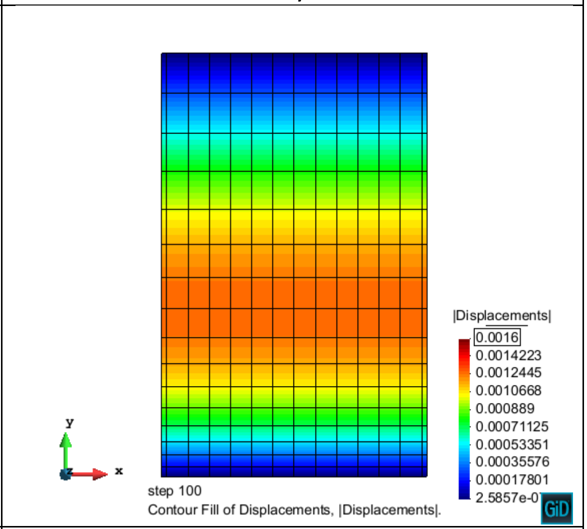
BBM



Non-linear elasticity + Mohr Coulomb

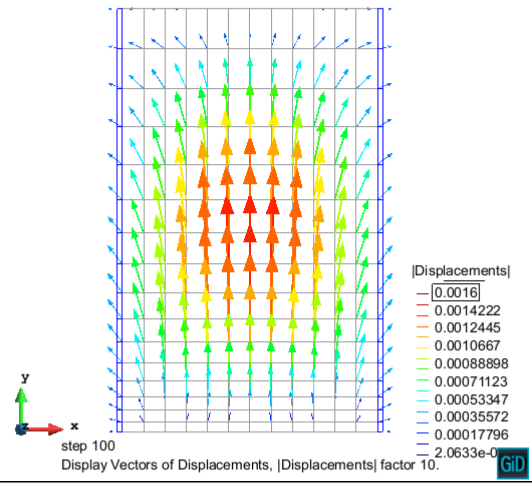


No interface, fixed

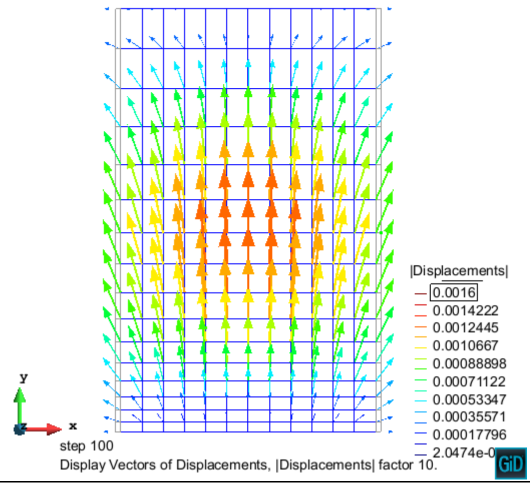


No interface, sliding

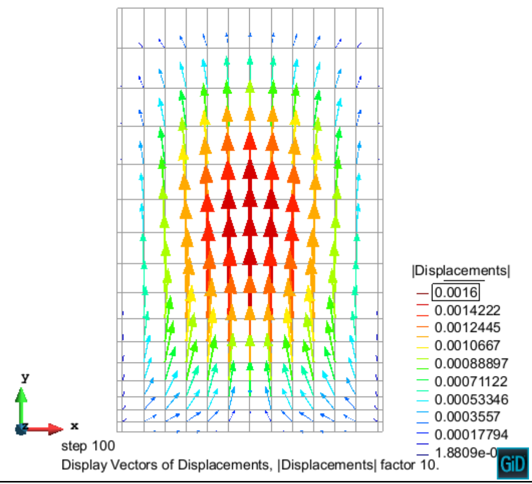
Figure II.1 Displacements at the end of hydration



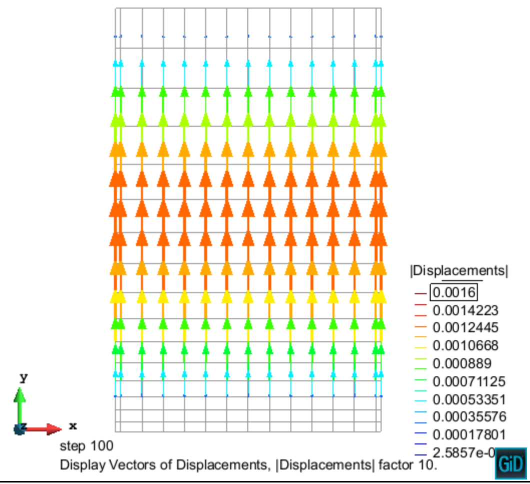
BBM



Non-linear elasticity + Mohr Coulomb

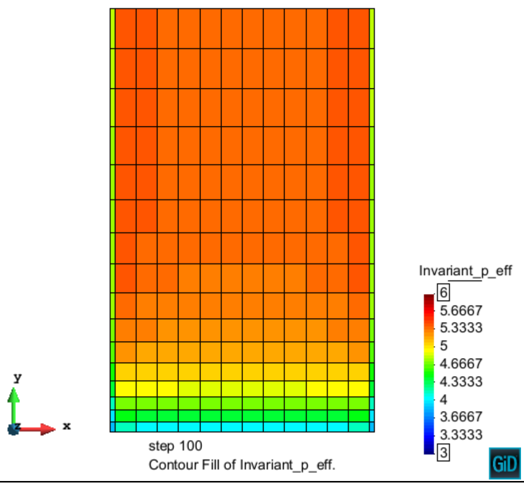


No interface, fixed

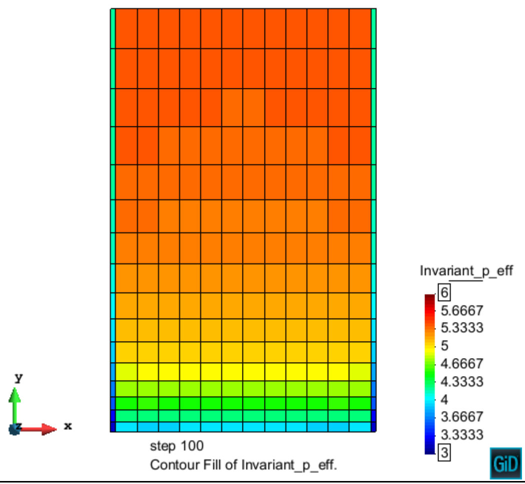


No interface, sliding

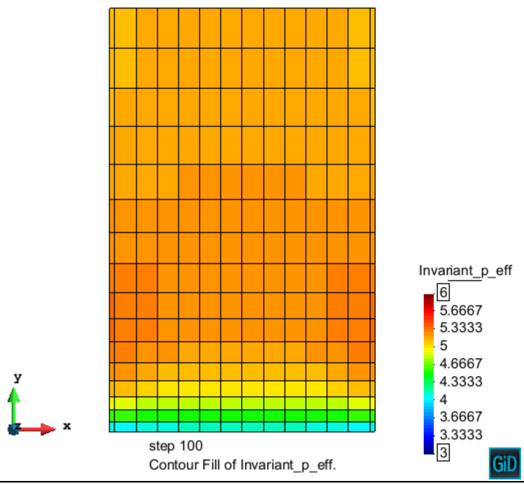
Figure II.2 Displacements at the end of hydration



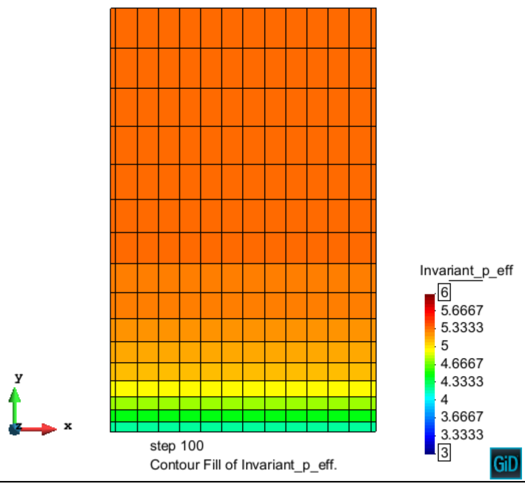
BBM



Non-linear elasticity + Mohr Coulomb



No interface, fixed



No interface, sliding

Figure II.3 Mean effective stress at the end of hydration

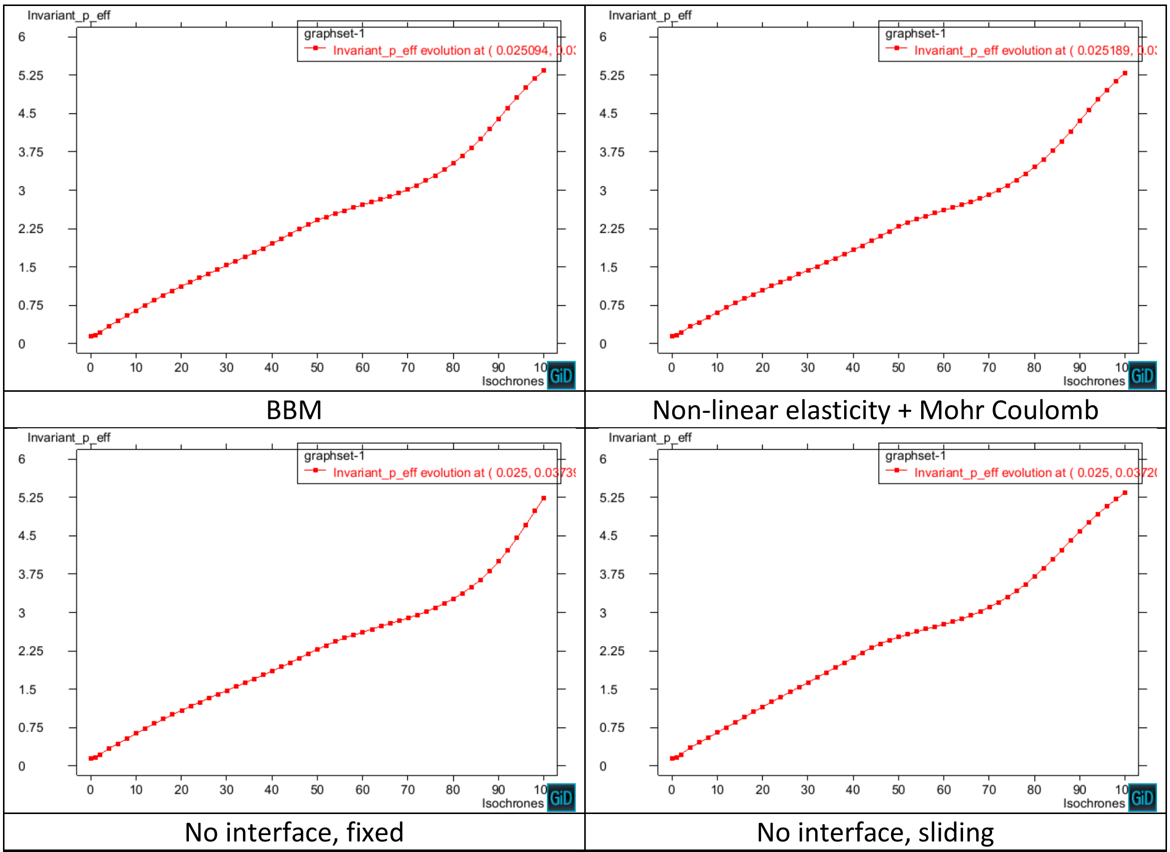
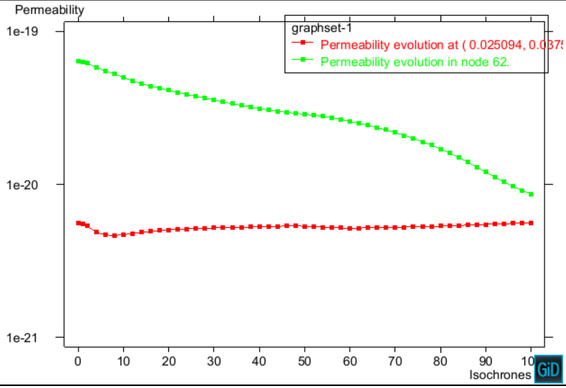
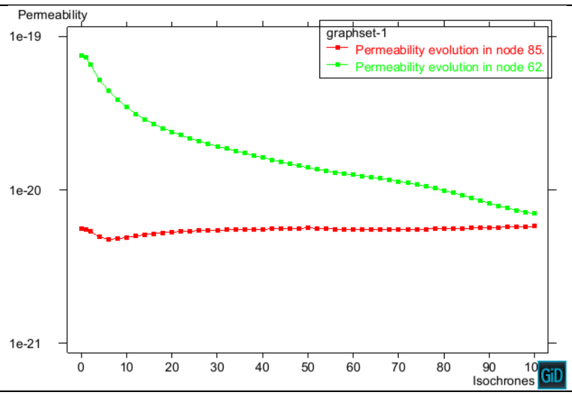


Figure II.4 Mean effective stress evolution at the sample centre



BBM



Non-linear elasticity + Mohr Coulomb

Figure II.5 Permeability evolution at the discontinuity and clay centre

II INTERFACE REPRESENTATION IN 3D. APPLICATION

Description

Three models are presented with interface:

- 2D model with quadrilateral elements
- 3D model with hexahedral elements
- 3D model with tetrahedral elements

The models with interface are based, respectively, on BBM with modified properties.

- Friction parameter *M* has been reduced by a factor *R*=0.6.
- Poisson ratio has been recalculated to 0.4 instead of 0.3 using the same factor.
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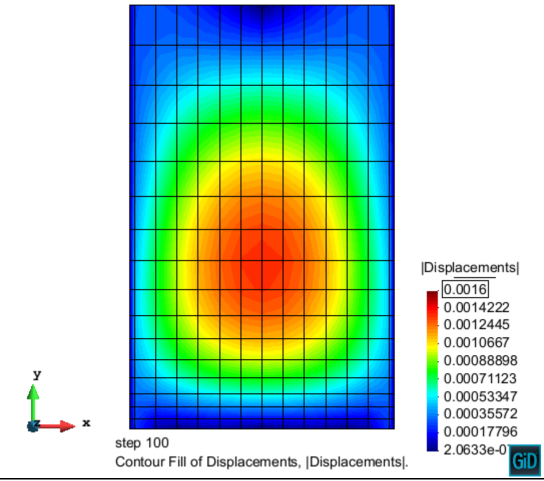
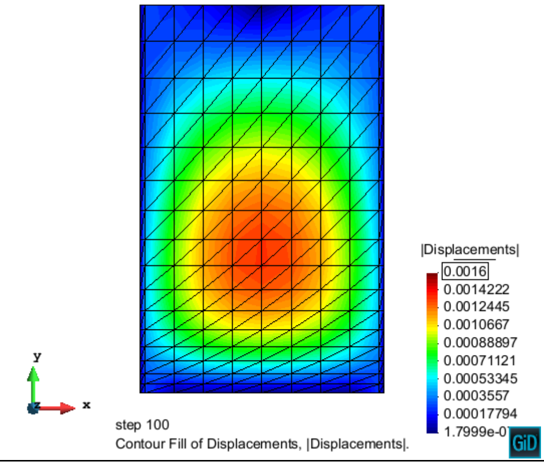
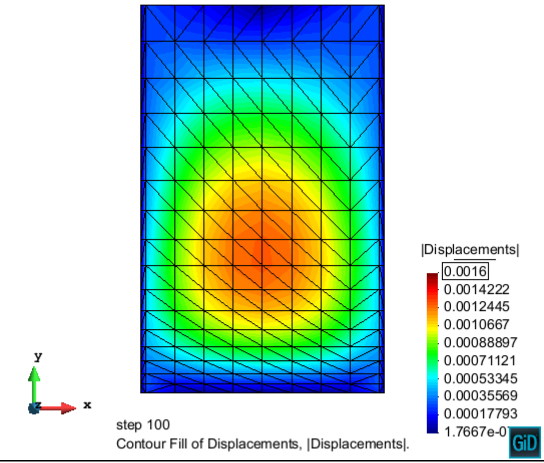


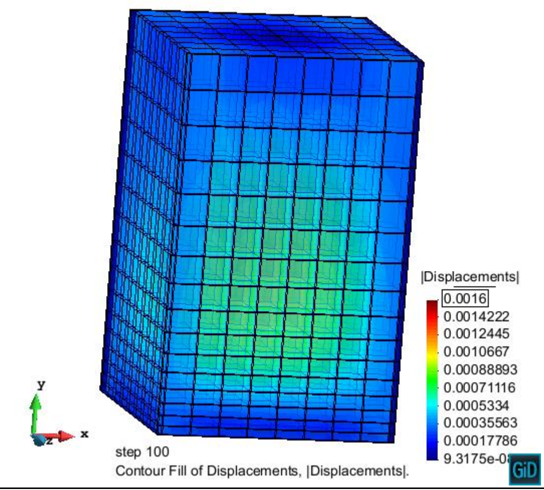
2D cuadrilateral elements



3D hexahedral (cut plane uses triangles)



3D tetrahedral



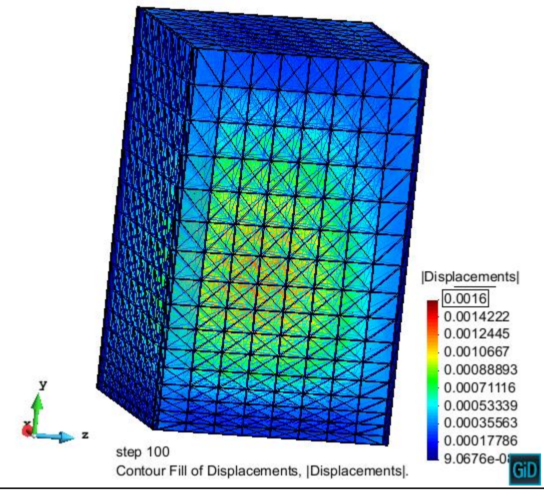
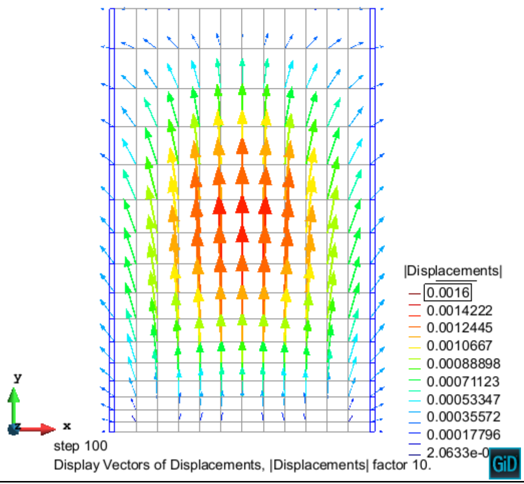
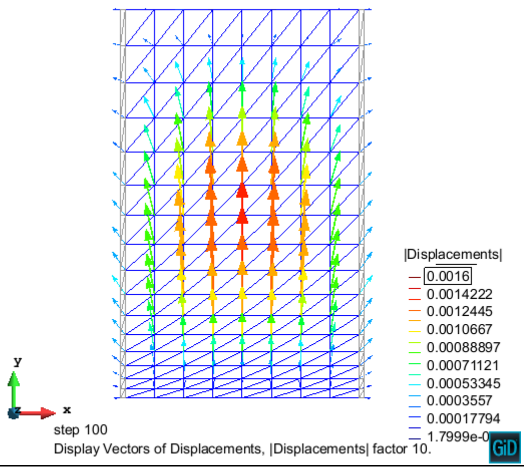


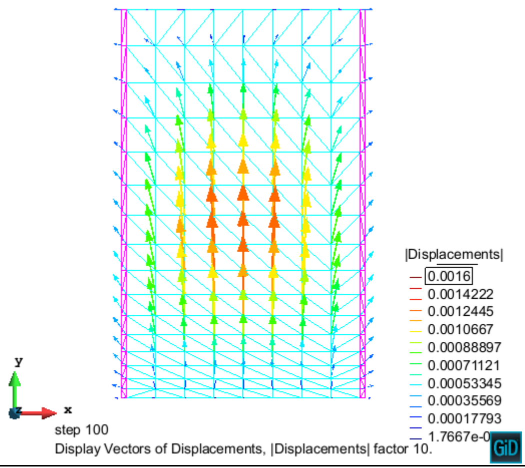
Figure II.1 Displacements at the end of hydration



2D cuadrilateral elements

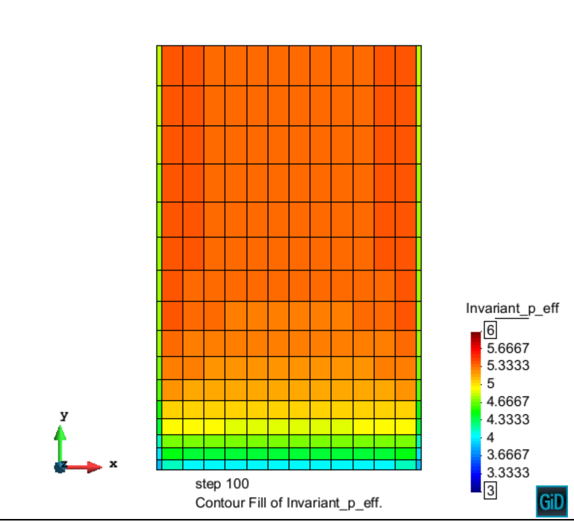


3D hexahedral (cut plane uses triangles)

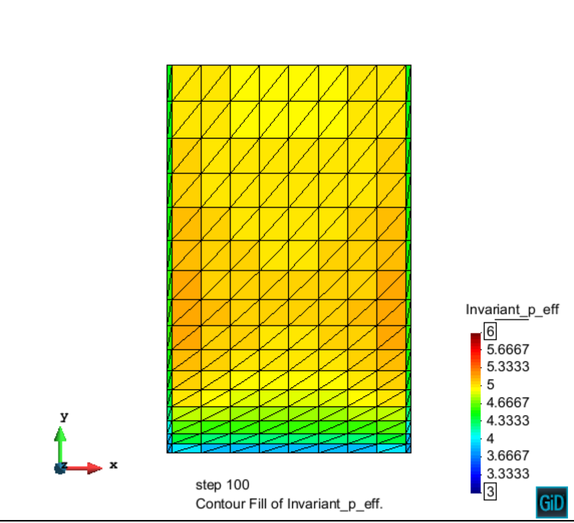


3D tetrahedral

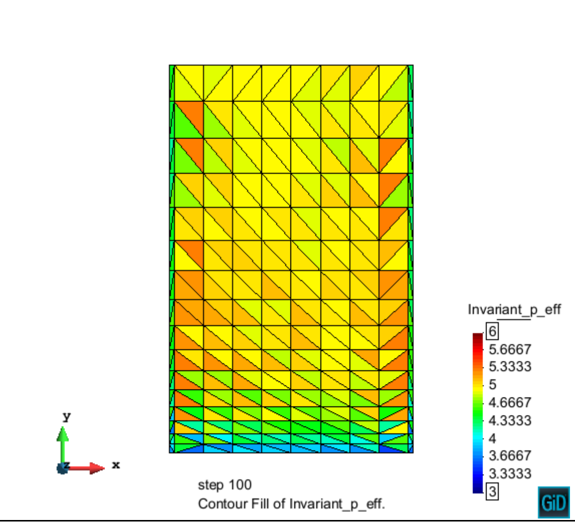
Figure II.2 Displacements at the end of hydration



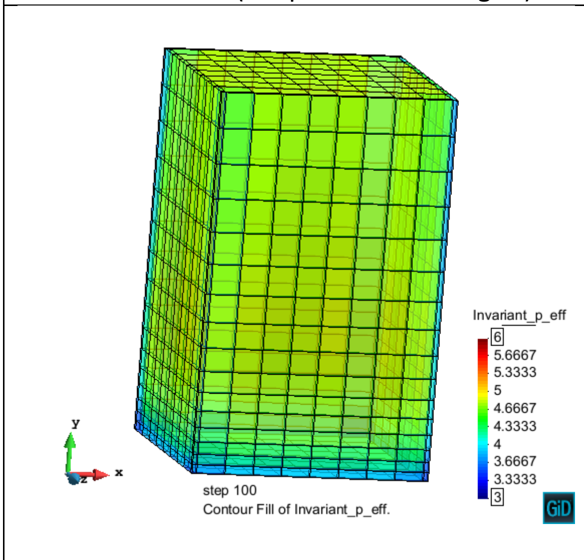
2D cuadrilateral elements



3D hexahedral (cut plane uses triangles)



3D tetrahedral



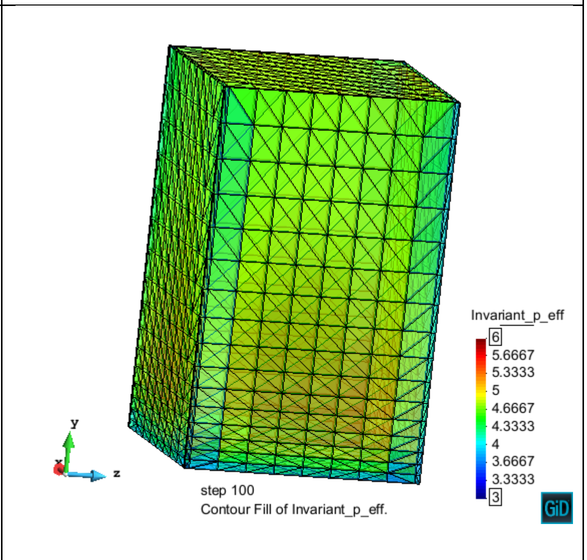
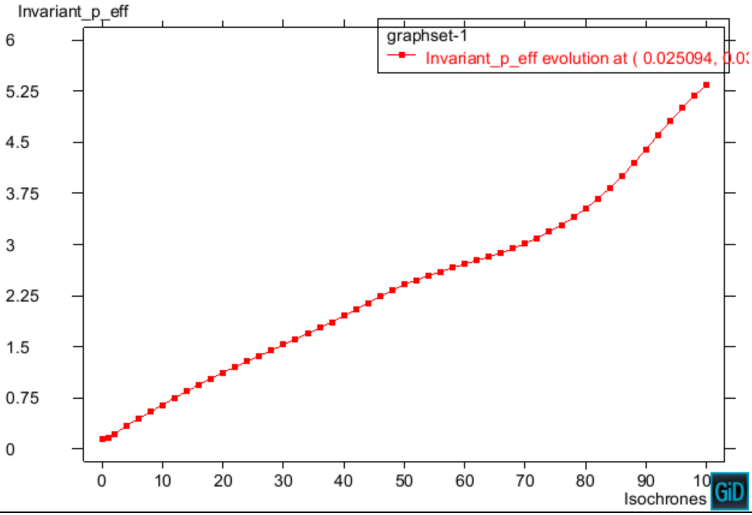
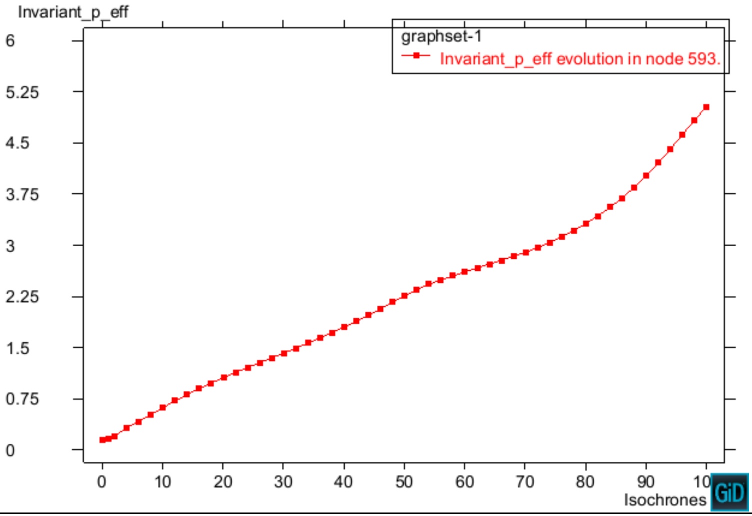


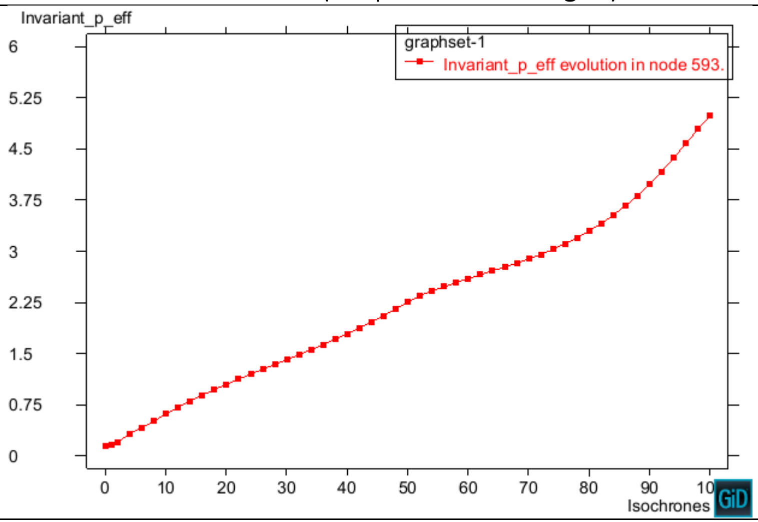
Figure II.3 Mean effective stress at the end of hydration



2D cuadrilateral elements

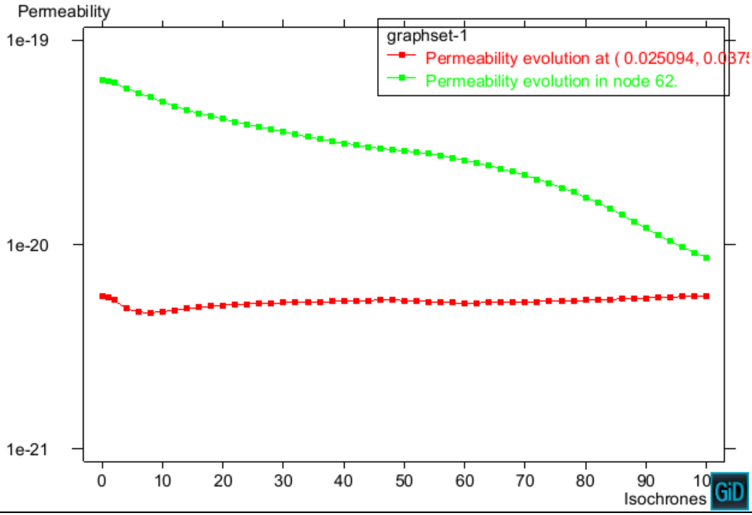


3D hexahedral (cut plane uses triangles)

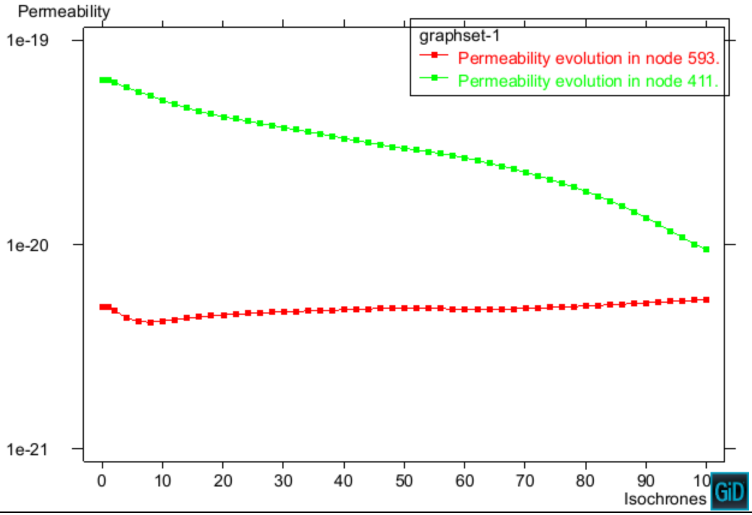


3D tetrahedral

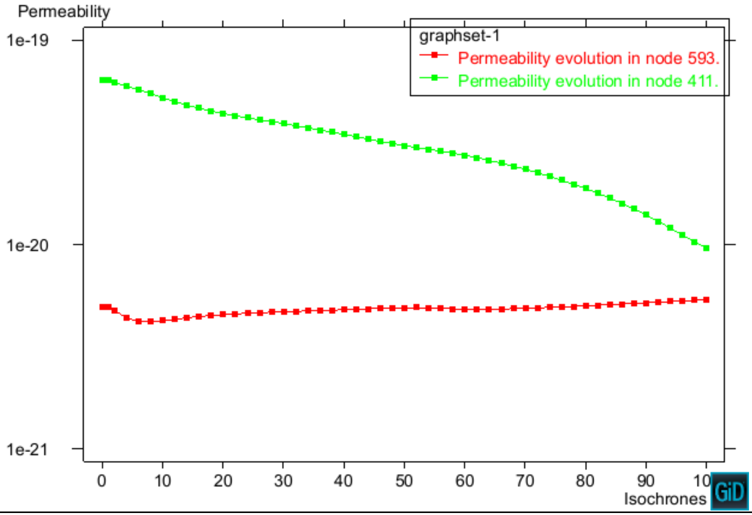
Figure II.4 Mean effective stress evolution at the sample centre



2D cuadrilateral elements



3D hexahedral (cut plane uses triangles)



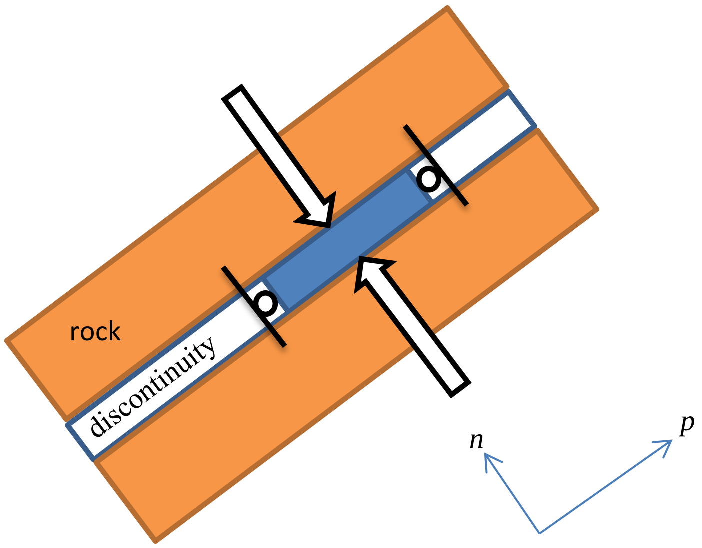
3D tetrahedral

Figure II.5 Permeability evolution at the discontinuity and clay centre

Appendix ELD Elasticity for discontinuities

Elastic properties of a layer of finite thickness under normal and shear deformation

A discontinuity is considered a layer of material that can be characterized by Normal Stiffness or Normal Deformation Modulus (E_n) and Poisson ratio (ν). Normal Stiffness or Deformation Modulus is defined by the ratio between normal stress and normal deformation, assuming that axial deformation only takes place along the normal direction.



The Normal Deformation Modulus can be referred to as Oedometric Modulus by analogy with the vertical deformation of a soil layer.

A Normal Deformation Modulus in a discontinuity of finite thickness without lateral deformation can be derived from elasticity. The following equations represent deformation, normal and parallel to the plane of a fracture (see figure):

$$\varepsilon_n = \frac{\sigma_n}{E} - \frac{\nu}{E}\left(\sigma_p + \sigma_p\right) \tag{ELD.1}$$

$$\varepsilon_p = \frac{\sigma_p}{E} - \frac{\nu}{E}\left(\sigma_n + \sigma_p\right) \tag{ELD.2}$$

Assuming that deformation parallel to the plane of the discontinuity is zero, it follows:

$$\varepsilon_p = \frac{\sigma_p}{E} - \frac{\nu}{E}\left(\sigma_n + \sigma_p\right) = 0 \rightarrow \sigma_p = \frac{\nu}{1-\nu}\sigma_n \tag{ELD.3}$$

This is the same result obtained when a lateral stress has to be calculated in a soil or rock with horizontal surface assuming elastic response and no tectonic effects, i.e. oedometric conditions.

Substitution of (ELD.3) in (ELD.1), results in:

$$\varepsilon_n = \frac{\sigma_n}{E} - \frac{\nu}{E}(\sigma_p + \sigma_p) = \frac{\sigma_n}{E} - \frac{\nu}{E}\left(\frac{2\nu}{1-\nu}\sigma_n\right) = \frac{\sigma_n}{E}\left(1 - \frac{2\nu^2}{1-\nu}\right) = \frac{\sigma_n}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu} \tag{ELD.4}$$

From this equation, a deformation modulus for the normal direction under zero lateral deformation can be easily determined defined as follows ((E_n), Normal Deformation Modulus or Normal Stiffness):

$$\varepsilon_n = \frac{\sigma_n}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu} = \frac{\sigma_n}{E_n} \tag{ELD.5}$$

Finally, elastic modulus and normal modulus can be related:

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)}E_n \tag{ELD.6}$$

Introducing the bulk modulus $K = E/(3(1-2\nu))$ in (ELD.6) it follows:

$$K = \frac{(1+\nu)}{3(1-\nu)}E_n \tag{ELD.7}$$

In addition, the shear modulus, $G = E/(2(1+\nu))$, can be introduced in (ELD.6) resulting in:

$$E_n = \frac{2(1-\nu)}{(1-2\nu)}\frac{E}{2(1+\nu)} = \frac{2(1-\nu)}{(1-2\nu)}G \tag{ELD.8}$$

From this, Poisson ratio can be solved for:

$$(1-2\nu)E_n = 2(1-\nu)G \rightarrow \nu = \frac{E_n - 2G}{2E_n - 2G} \tag{ELD.9}$$

As a summary, it has been shown that a layer of finite thickness under Oedometric deformation can be described by any of the following pairs of elastic parameters:

E_n	E_n	K	E	K
ν	G	G	ν	ν

An example is that, if E_n and G were known, the elastic parameters Young and Poisson would be calculated as:

$$\nu = \frac{E_n - 2G}{2E_n - 2G}; \qquad E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)}E_n \tag{ELD.10}$$

Or inversely, if Young and Poisson are known, then it follows that:

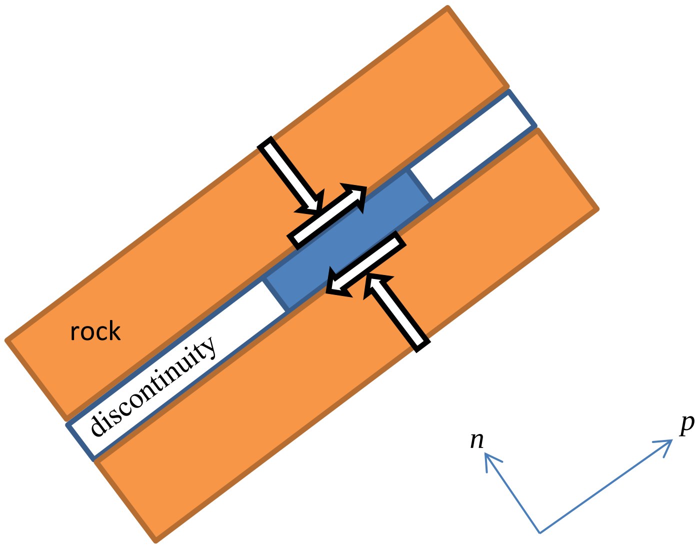
$$E_n = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)}; \qquad G = \frac{E}{2(1+\nu)} \tag{ELD.11}$$

This will be used in what follows to propose equivalent material parameters for discontinuities.

Equivalence of stress strain parameters in a discontinuity when using a finite thickness representation

If a zone of thickness t is used to represent a discontinuity, equivalent parameters are required. The objective is to propose parameters for discontinuities when a finite thickness representation is considered. Form discontinuity parameters (k_n, k_s) and a finite thickness(t), equivalent parameters can be determined. It will be assumed that a

$$\Delta\sigma_n = k_n \Delta u_n \tag{ELD.12}$$
$$\Delta\tau = k_s \Delta u_s \tag{ELD.13}$$



For the case of shear deformation, the following relationship can be written based on a discontinuity having an arbitrary thickness of t:

$$G = k_s t \tag{ELD.14}$$

This can be shown easily because substitution of (ELD.14) in equation (ELD.13) leads to:

$$\Delta\tau = k_s \Delta u_s = \frac{G \Delta u_s}{t} = G \Delta\varepsilon_s \tag{ELD.15}$$

The implication of this is that G can be calculated for a zone of given thickness representing the discontinuity. However, it should be modified if the thickness of the equivalent continuum zone is modified. So, it depends on the thickness.

For the case of normal deformations, the normal deformation modulus can be calculated as:

$$E_n = k_n t \tag{ELD.16}$$

This can be shown easily because substitution of (ELD.16) in equation (ELD.12) leads to:

$$\Delta\sigma_n = k_n \Delta u_n = \frac{E_n \Delta u_n}{t} = E_n \Delta\varepsilon_n \tag{ELD.17}$$

The Normal Deformation modulus E_n can be related to Young's modulus through the following equation (Equation ELD.6):

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} E_n \qquad \text{(ELD.18)}$$

This result can be deduced from elastic equations simply by imposing that deformation is zero in the transversal two directions (see equations AII.1 to AII.5). The parameter E_n can be called oedometric modulus (Plaxis use this name) because it is obtained in the same way. Poisson ratio can be obtained (see equations AII.8, AII.9):

$$\nu = \frac{E_n - 2G}{2E_n - 2G} \qquad \text{(ELD.19)}$$

Finally, if the elastic properties of a discontinuity (k_n, k_s) are known, the following elastic parameters can be used for a zone of equivalent thickness (t):

$$G = k_s t \qquad \text{(ELD.20)}$$

$$\nu = \frac{E_n - 2G}{2E_n - 2G} = \frac{k_n - 2k_s}{2k_n - 2k_s} \qquad \text{(ELD.21)}$$

$$K = \frac{(1+\nu)}{3(1-\nu)} k_n t \qquad \text{(ELD.22)}$$

$$E = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} E_n = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} k_n t \qquad \text{(ELD.23)}$$

Any of the pairs (E, ν), (K, G) or (K, ν) can be used for the equivalent discontinuity. All parameters, except Poisson ratio, depend of the thickness chosen.

Note that for the case of normal stiffness very high $(k_n \gg k_s)$ equation (ELD.21) implies $\nu \to 0.5$ i.e. incompressible material. In this case, the elastic modulus should be calculated using $E = G/(2(1+\nu))$ because AII.23 give indetermination.

Appendix BBM. Equations for BBM and parameters considered in this study

BBM parameters for Buffer

Parameter	Symbol	MX-80
Poisson ratio (-)	ν	0.3
Minimum bulk module (MPa)	K_{min}	10
Reference mean stress (MPa)	p_{ref}	0.01
Parameters for elastic volumetric compressibility against mean net stress change (-)	κ_{i0}	0.09
Parameters for elastic volumetric compressibility against suction change (-)	κ_{s0}	0.09
Parameter for elastic thermal strain ($^{o}C^{-1}$)	α	$9x10^{-4}$
Slope of void ratio – mean net stress curve at zero suction (-)	$\lambda(0)$	0.25
Parameters for the slope void ratio – mean net stress at variable suction (-,MPa^{-1})	r	0.8
	β	0.02
Reference pressure for the P_0 function (MPa)	p^c	0.1
Pre-consolidation mean stress for saturated soil (MPa)	P_o*	2
Critical state line (-)	M	1.07
Tensile strength parameter	k	0.1

Mechanical model for bentonite

The Barcelona Basic Model is usually used to model the thermo-hydro-mechanical (THM) behaviour of several engineered barrier components such as buffer and backfill blocks. This model is implemented in CODE_BRIGHT referred to as thermo-elasto-plastic (TEP) model. The model formulation is described in this subsection.

The effective stress is defined as $\sigma' = \sigma - \max(p_g, p_l)$ (for positive compressions), which is a modification of the usual effective stress considered for saturated soils. The effective mean stress p' is defined as $p' = p - \max(P_g, P_l)$. The mechanical constitutive equation reads:

$$d\boldsymbol{\sigma}' = \mathbf{D}d\boldsymbol{\varepsilon} + \mathbf{h}ds \tag{BBM.1}$$

is derived from $d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p = (\mathbf{D}^e)^{-1}d\boldsymbol{\sigma}' + \alpha\mathbf{I}ds + \Lambda\frac{\partial G}{\partial \boldsymbol{\sigma}'}$ and the volumetric strain is defined as $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$.

Elastic, isotropic and non-isothermal volumetric strains are defined by:

$$d\varepsilon_v^e = \frac{\kappa_i(s)}{1+e}\frac{dp'}{p'} + \frac{\kappa_s(p',s)}{1+e}\frac{ds}{s+0.1} + (\alpha_0 + 2\alpha_2\Delta T)dT \tag{BBM.2}$$

with parameter dependence on suction and stress as follows:

$$\kappa_i(s) = \kappa_{i0}(1 + \alpha_i s) \tag{BBM.3}$$

$$\kappa_s(p',s) = \kappa_{s0}\left(1 + \alpha_{sp}\ln\frac{p'}{p_{ref}}\right)\exp(\alpha_{ss}s) \tag{BBM.4}$$

where *e* is the void ratio, where *p'* is the mean effective stress, *s* is the suction, k_{io} and α_i are parameters for elastic volumetric compressibility against mean stress change, and k_{so}, α_{sp}, p_{ref} and α_{ss} are parameters for elastic volumetric compressibility against suction change. The parameters α_i, α_{sp} and α_{ss} do not belong to the original BBM model and were implemented later in order to be able to deal swelling clays with the BBM model. The model is quite sensitive to these parameters.

The elastic properties are defined using two constants: κ and ν, respectively, elastic compressibility in a natural log scale and Poisson ratio. The effective bulk modulus *K* depend on the mean effective stress p', and the shear modulus is calculated as:

$$K = \frac{1+e}{\kappa}p', \qquad G = \frac{3K(1-2\nu)}{2(1+\nu)} \tag{BBM.5}$$

The yield surface $F = F(\sigma', \varepsilon_v^p, s) = F(p', J, \theta, \varepsilon_v^p, s)$, where ε_v^p is the plastic volumetric strain, depends on stresses and suction and can be expressed using stress invarBBMnts:

Mean effective stress: $p' = \frac{1}{3}(\sigma'_x + \sigma'_x + \sigma'_x) = p - \max(P_g, P_l)$

Deviatoric stress: $J = \sqrt{\frac{1}{2}(\mathbf{s}:\mathbf{s})} \qquad \mathbf{s} = \sigma' - p'\mathbf{I}$

Lode's Angle: $\theta = -\frac{1}{3}\sin^{-1}(1.5\sqrt{3}\det\mathbf{s}/J^3)$

For simplicity, a form of the classical Modified Cam-Clay model is taken as the reference isothermal saturated constitutive law, so the yield surface reads:

$$F = q^2 - M^2(p' + p_s)(p_0 - p') \tag{BBM.6}$$

with M being a critical state line parameter, and p_o is considered to be dependent on suction:

$$p_0 = p^c \left(\frac{p_0^*(T)}{p^c}\right)^{\frac{\lambda(0)-\kappa_{i0}}{\lambda(s)-\kappa_{i0}}} \tag{BBM.7}$$

$$p_0^*(T) = p_0^* + 2(\alpha_1 \Delta T + \alpha_3 \Delta T|\Delta T|)$$

$$\lambda(s) = \lambda(0)[(1-r)\exp(-\beta s) + r] \tag{BBM.8}$$

$$p_s = p_{s0} + ks\exp(-\rho\Delta T) \tag{BBM.9}$$

where p^c is the reference stress; p_0^* is the initial preconsolidation stress for saturated conditions; $\lambda(0)$ is the slope of void ratio in saturated conditions; r defines the maximum soil stiffness; β controls the rate of increase of soil stiffness with suction; α_1 and α_3 are parameters for elastic thermal strain, p_{s0} is the tensile strength in saturated conditions; k takes into account the increase of tensile strength due to suction; and ρ takes into account the decrease of tensile strength due to temperature.

Hardening depends on plastic volumetric strain according to:

$$dp_0^* = \frac{1+e}{\lambda(0) - \kappa_{i0}} p_0^* d\varepsilon_v^p \tag{BBM.10}$$

The plastic potential G is taken as:

$$G = q^2 - \alpha M^2(p' + p_s)(p_0 - p') \tag{BBM.11}$$

where α is a non-associativity parameter.

Hydraulic parameters for MX-80

Equation	Parameter	MX-80
Van Genuchten retention curve	*P* (MPa)	27
	λ (-)	0.45
	a (-) in $P(\phi)$	11
	b (-)in $\lambda(\phi)$	4
	ϕ_0	0.43
Darcy flux	*k* (m^2)	$5.6x10^{-21}$
	b (-) in $k(\phi)$	15
	ϕ_0	0.43
	m (-)	3
Diffusive flux	τ (-)	0.4

The liquid degree of saturation (shortened to degree of saturation in the following) of the porous medium is related to the liquid pore pressure by use of a *retention law*, here exemplified by van Genuchten's retention law (van Genuchten, 1980):

$$S_l(p_l) = \left(1 + \left(\frac{p_g - p_l}{P}\right)^{\frac{1}{1-\lambda}}\right)^{-\lambda} \quad \text{(BBM.12)}$$

with $P = P_0 \frac{\sigma}{\sigma_0}$, P_0 is the air entry value at certain temperature, σ_0 the water surface tension at that temperature and σ the surface tension as function of the temperature,

The parameters *P* and λ were measured for different porosities following the relations:

$$P_0(\phi) = P_0 \exp\big(a(\phi_0 - \phi)\big) \quad \text{(BBM.13)}$$

$$\lambda(\phi) = \lambda \exp\big(b(\phi_0 - \phi)\big) \quad \text{(BBM.14)}$$

For intrinsic permeability:

$$k(\phi) = k_0 \exp\big(b(\phi - \phi_0)\big) \quad \text{(BBM.15)}$$

And relative permeability:

$$k_{rl} = S_l^m \quad \text{(BBM.16)}$$

Appendix SUMMARY-TABLE

Equivalent parameters for discontinuities discretized as thin elements of thickness *t*

Conditions	Equation for elastic parameters	Other
Normal and shear stiffness of the rock are known	$\nu_d = \frac{k_n - 2k_s}{2k_n - 2k_s}$ $E_d = \frac{(1+\nu_d)(1-2\nu_d)}{(1-\nu_d)} k_n t$	Normal and shear stiffness of the rock are defined as: $\Delta\sigma_n = k_n \Delta u_n$ $\Delta\tau = k_s \Delta u_s$ *t* is the element thickness
Shear stiffness of the rock (G) is known and fracture does not deform in volume	$G_d = R^2 G$ $\nu_d = 0.45$ $E_d = 2(1+\nu_d)G_d$	*R* is a parameter for reduction of strength (see below) Bulk modulus can be calculated as well: $K_d = \frac{2G_d(1+\nu_d)}{3(1-2\nu_d)}$
Discontinuity assumed like clay without swelling	$K_d = K = \frac{p'(1+e)}{\kappa}$ $G_d = R^2 G$ Where κ is the elastic compression index in CamClay model	Young and Poisson can be calculated as well: $\nu_d = \frac{3K_d - 2G_d}{2(3K_d + G_d)}$ $E_d = \frac{9K_d G_d}{3K_d + G_d}$
Discontinuity assumed like clay without swelling	$K_d = K = \frac{p'(1+e)}{\kappa}$ $\nu_d = \frac{1+\nu-R^2(1-2\nu)}{2(1+\nu+R^2(1-2\nu))}$	Young and shear modulus can be calculated as: $E_d = 3K_d(1-2\nu_d)$ $G_d = \frac{E_d}{2(1+\nu_d)}$

Conditions	Equation for plastic parameters	
Cohesion and friction angle are known	$c'_d = Rc'_{soil}$ $\phi'_d = \text{atan}(R \tan \phi'_{soil})$	*R* is a reduction factor for strength properties
Slope of critical state and cohesion term are known	$M_d = RM$ $p_{s_d} = R(p_{s0} + ks)$	

In general, the corresponding intrinsic permeability is easy to calculate from transmissivity, if this later is known.

For soils, both intrinsic permeability and retention curve depend on porosity. If permeability and retention curve depend on porosity, it is sufficient to consider a larger porosity for the interface in order to increase permeability and reduce air entry value. The following options can be used:

- Exponential equation. In the case presented here, increasing porosity of the interface zone by 50% may be sufficient to produce this effect.
- Kozeny equation. It is also a function of porosity but it does not include parameters except a value of permeability for a given porosity.

Other alternatives can be considered if variation should be larger (cubic law) and more information of the discontinuity.