Viscous Ubiquitous Joints in Comba User-Defined Model for *FLAC3D/3DEC*

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5th International Itasca Symposium – Vienna, Austria – 20 February 2020

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Context

Creep in rock masses with tight joint sets

Creep behavior governed by joints filled with clay material

Interest to supplement existing constitutive model with viscous behavior - for application to Baihetan site - .

Framework

Comba continuum constitutive model, developed for application to a rock mass with tight joint sets:

- orthotropic elastic behavior
- up to four sets of hardening/softening ubiquitous joints
- Mohr-Coulomb shear failure and brittle tension failure in matrix

Available for *FLAC3D*/*3DEC*

Meng, G., C. Detournay, C. & P. Cundall. Forthcoming. *Formulation and Application of a Constitutive Model for Multi-Jointed Material to Rock Mass Engineering*. International Journal of Geomechanics. DOI:10.1061/(ASCE)GM.1943-5622.0001646.

Project purpose:
Add a creep component to the Comba ubiquitous joints logic.

Challenge

Balance between creep law complexity and computational speed

- Single viscous joint filled with Maxwell/Kelvin isotropic-elastic material
  Relatively easy to implement

- However:
  Difficult to extend logic to:
  - multiple joints
  - anisotropic elasticity
  - plasticity

  Heavy computational load (10 calls to constitutive model per zone in 3D!)

Creep law for Ubiquitous joint

Power law suggested by Malan et al. (1998):

$$\dot{\varepsilon}^{cr} = A\left(\frac{\bar{\tau}}{\bar{\tau}_{\max}}\right)^{n}$$

where:

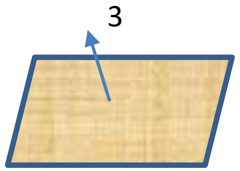
$$\bar{\tau} = \sqrt{\sigma_{13}^2 + \sigma_{23}^2} \qquad \tau_{\max} = c_j - \sigma_{33}\tan\phi_j$$

Creep active for:

σ_{33} compressive & stress/strength ratio above threshold ratio, $S_{\lim}$

2 parameters: A[1/t], n[-]

$\dfrac{\bar{\tau}}{\bar{\tau}_{\max}}$ Stress/strength ratio



Joint plane &
local normal axis

$$\dot{\varepsilon}_{13}^{cr} = \frac{\sigma_{13}}{\bar{\tau}}\dot{\varepsilon}_{cr} \quad , \quad \dot{\varepsilon}_{23}^{cr} = \frac{\sigma_{23}}{\bar{\tau}}\dot{\varepsilon}_{cr}$$

Numerical Implementation

Elasto-plastic stress-strain behavior, already represented in Comba

Joints have normal stiffness and shear stiffness

Total strain increment for the step, sum of elastic, creep and plastic components

Global incremental stress-strain relation (Voigt's vector notation):

$$\{\dot{\sigma}\}_G = \left[\{\dot{\sigma}\}_G^{guess} - \{\dot{\sigma}\}_G^{cr}\right] - \{\dot{\sigma}\}_G^{p}$$

where:

$$\{\dot{\sigma}\}_G^{guess} = C_G \{\dot{\varepsilon}\}_G$$

$$\{\dot{\sigma}\}_G^{cr} = C_G \{\dot{\varepsilon}^{cr}\}_G \Delta t$$

$$\{\dot{\sigma}\}_G^{p} = C_G \{\dot{\varepsilon}^{p}\}_G$$

Local creep contribution from joint i:

$$\{\dot{\sigma}\}_L^{i,cr} = C_L^i \{\dot{\varepsilon}^{cr}\}_L^i \Delta t$$

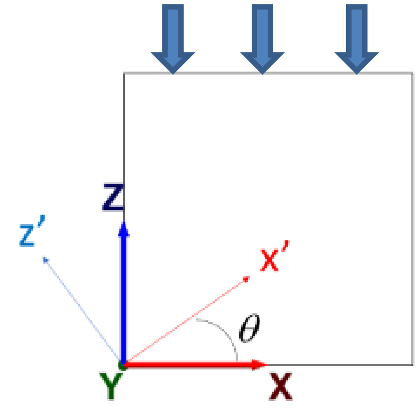
with:

$$\{\dot{\varepsilon}^{cr}\}_L^i = \{0,0,0,0,2\dot{\varepsilon}_{13}^{cr},2\dot{\varepsilon}_{23}^{cr}\}_L^i$$

Creep term subtracted from elastic guess before plastic correction is performed, using documented scheme (Detournay and Cundall, 2016).

Validation by element test

Unconfined visco-elastic load test:



Constant pressure P

⇒ constant creep rate

One active ubiquitous joint

Exact solution:

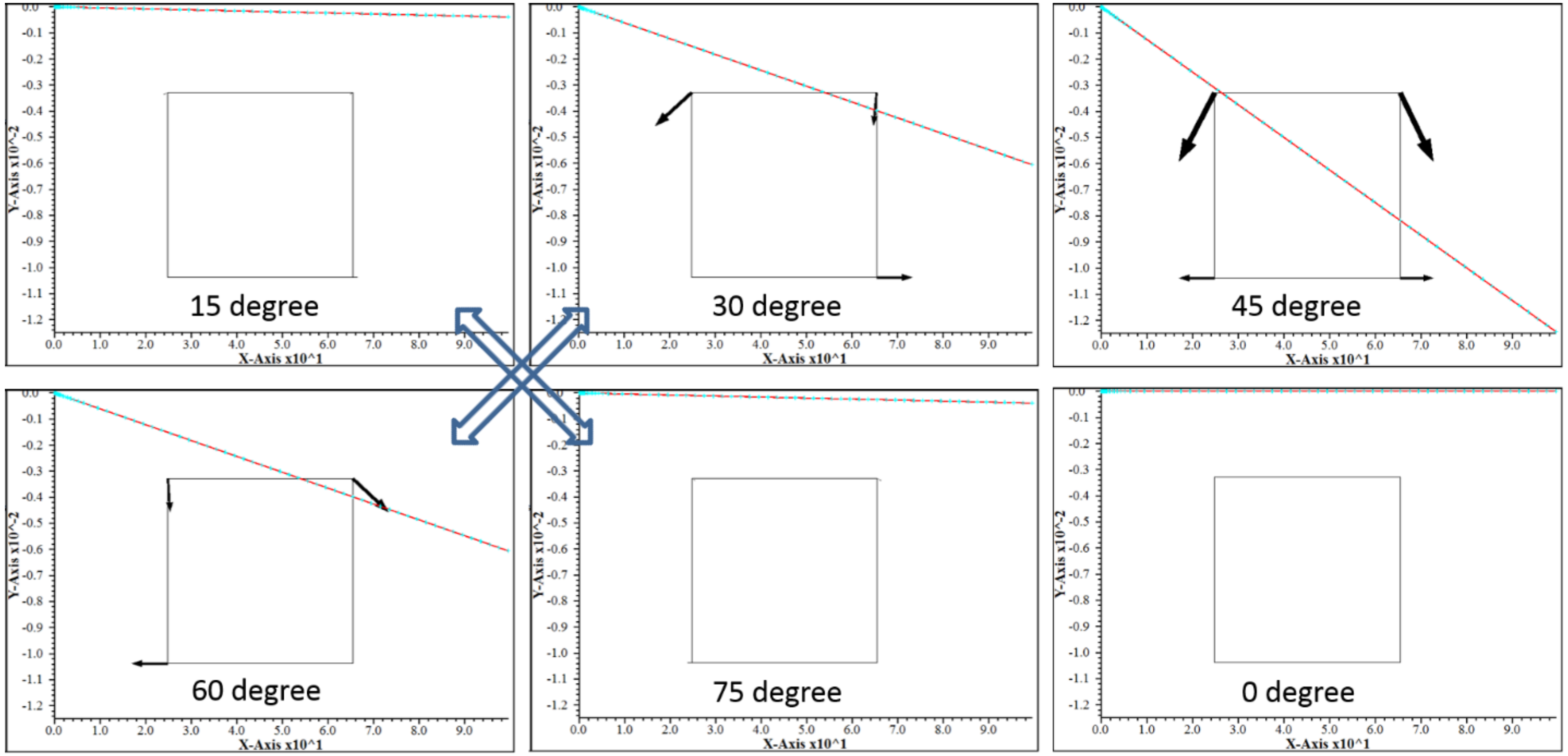
$$\varepsilon_x = -2\varepsilon_{x'z'}^{cr} \sin\theta \cos\theta$$

$$\varepsilon_z = +2\varepsilon_{x'z'}^{cr} \sin\theta \cos\theta$$

$$\varepsilon_{xz} = \varepsilon_{x'z'}^{cr} \left(\cos^2\theta - \sin^2\theta\right)$$

$$\varepsilon_{x'z'}^{cr} = A \cdot t \left[\left(\frac{-P\sin\theta\cos\theta}{c + P\cos^2\theta\tan\phi} \right)^n sign(-P\sin\theta\cos\theta) \right]$$

Element test results



A = 0.002 [1/day]
t = 20 [day]
n = 4

Up to:
At = 0.04

Vertical displacement versus creep time – comparison with exact solution for different joint angles

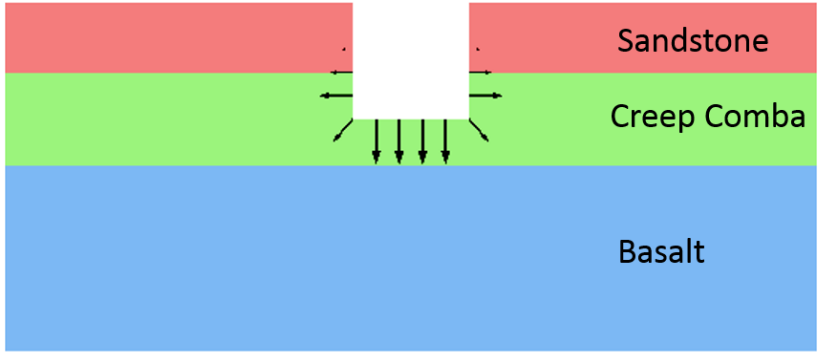
Joint dip angle < 45 degree ⇒ direct shearing
> 45 degree ⇒ complementary shearing
= 45 degree ⇒ both direct and complementary shearing

Element test findings

Joint dip angle < 45 degree	⇒	direct shearing
> 45 degree	⇒	complementary shearing
= 45 degree	⇒	both direct and complementary shearing

Simple valley problem

Two dimensional model, mechanical mode
Three layers
Valley filled instantaneously with impoundment water (Baihetan - generic model)



One set of viscous ubiquitous joints in Comba layer.
Creep induced displacement for different ubiquitous joints angles.

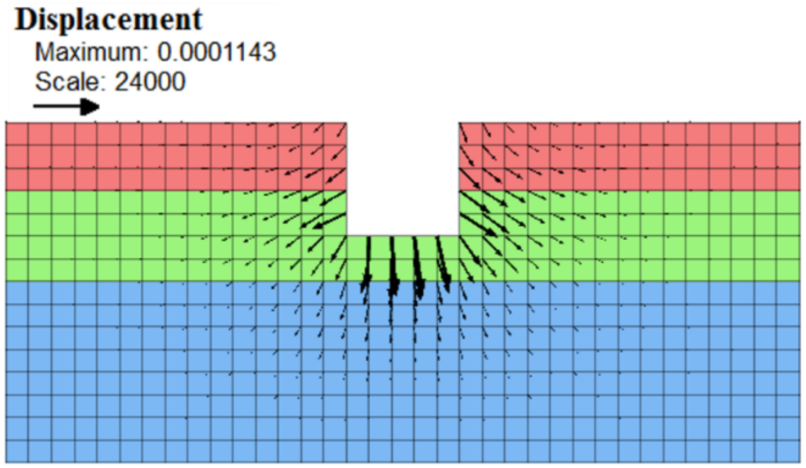
Numerical modelling steps

1. Establish isotropic stress equilibrium for three elastic layers
2. Simulate valley excavation
3. Apply mechanical pressure from standing water, run to equilibrium
4. Allow creep to take place in Comba layer up to A.t = 0.04, with n=4

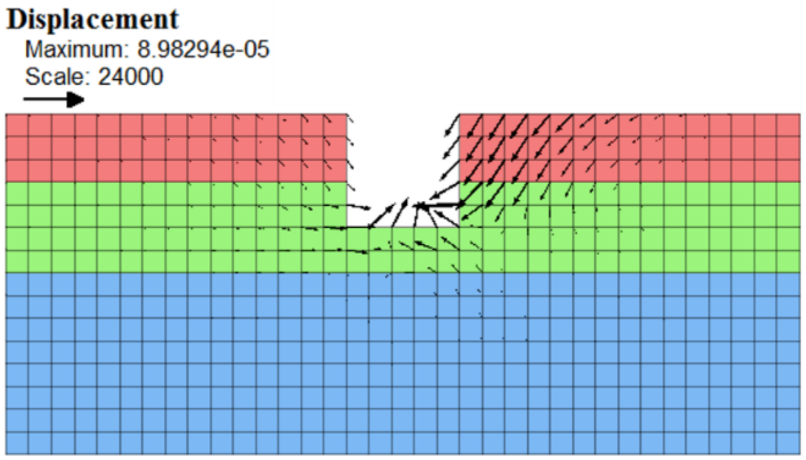
Displacement results - 1

Ubiquitous joint inclination of 30 degree

A.t = 0.04
n = 4



Loading from standing water



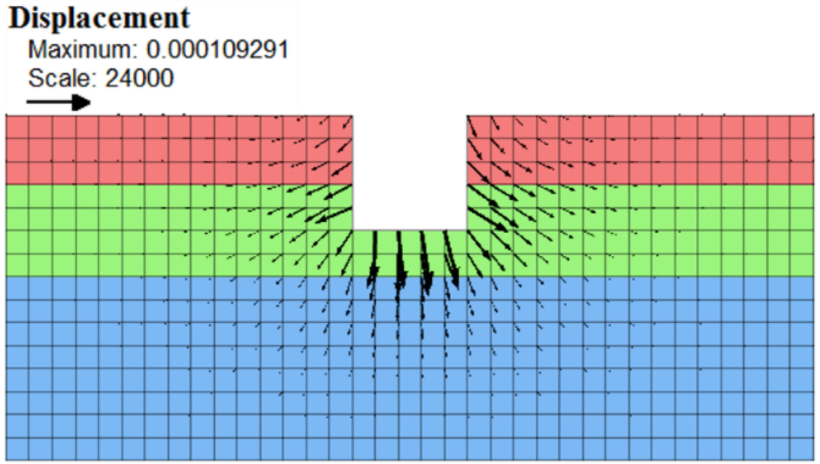
Creep at end of simulation

Displacements induced by water loading only (left) and by creep only (right)

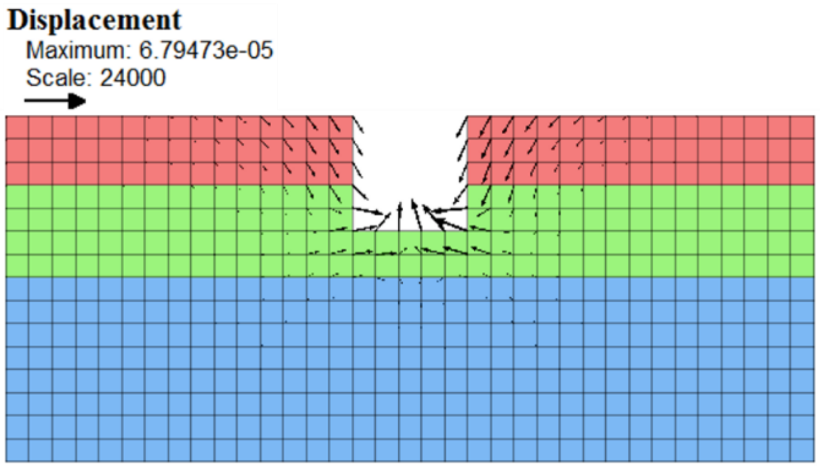
Displacement results - 2

Ubiquitous joint inclination of 45 degree

A.t = 0.04
n = 4



Loading from standing water



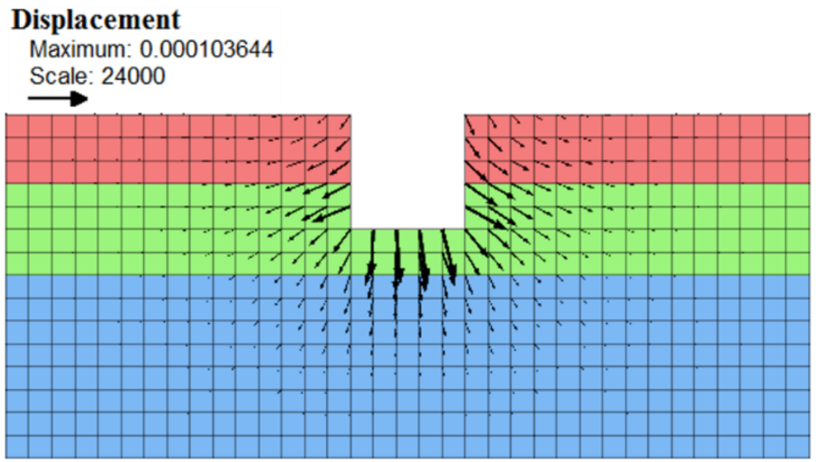
Creep at end of simulation

Displacements induced by water loading only (left) and by creep only (right)

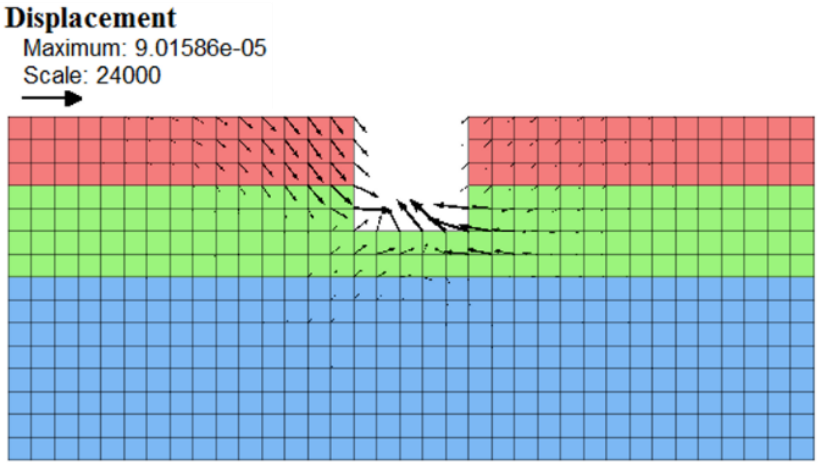
Displacement results - 3

Ubiquitous joint inclination of 60 degree

A.t = 0.04
n = 4



Loading from standing water



Creep at end of simulation

Displacements induced by water loading only (left) and by creep only (right)

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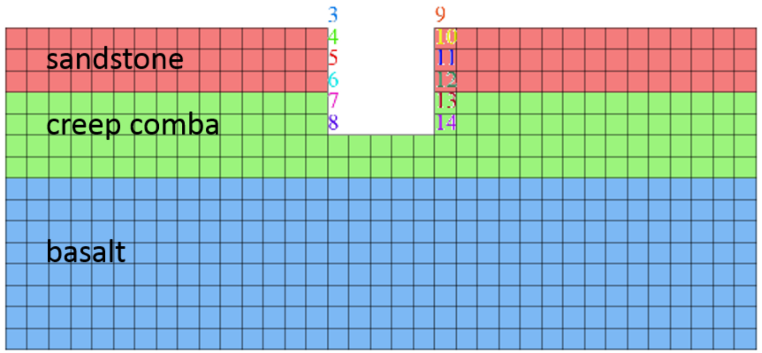
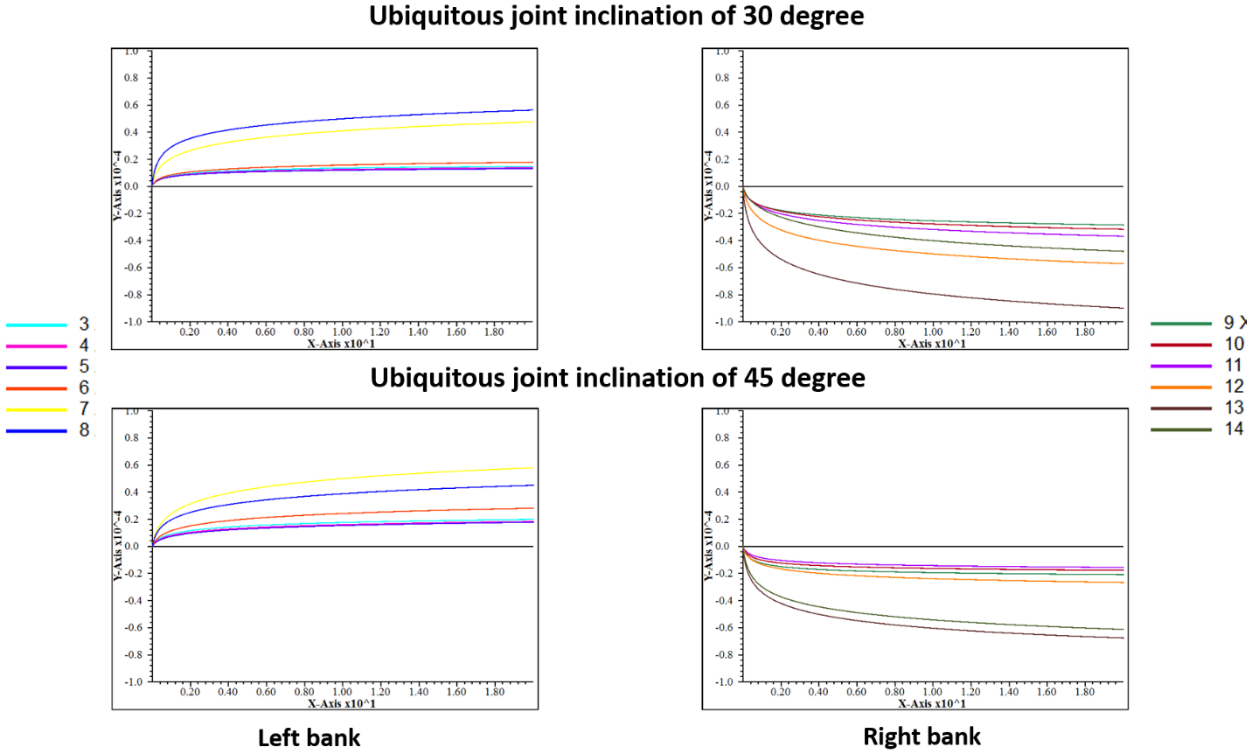
Displacement histories





Horizontal displacements induced by creep vs t - up to A.t = 0.04

Sharp increase in horizontal displacement followed by evolution towards a steady-state of deformation

Conclusions

- Logic for up to four visco-elasto-plastic joints added in Comba model
- Uniaxial load element test results show good match with analytical solution
  direct and complementary shearing modes are exhibited
- Simple valley problem show reasonable and consistent behavior
  - asymmetric displacements from static loading
    caused by joint contributions to overall elastic stiffness matrix
  - creep only exhibited in comba layer, however
    significant creep induced displacements observed in elastic layers above and below
  - direct and complementary shearing modes are exhibited
  - sharp increase followed by steady displacement evolution

Further work:

- Representative creep parameters for different material joints
- More extensive testing , including multiple joints and plasticity

Thank you!