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Modelling of the progressive failure of the sensitive landslide in Saint Monique, Quebec

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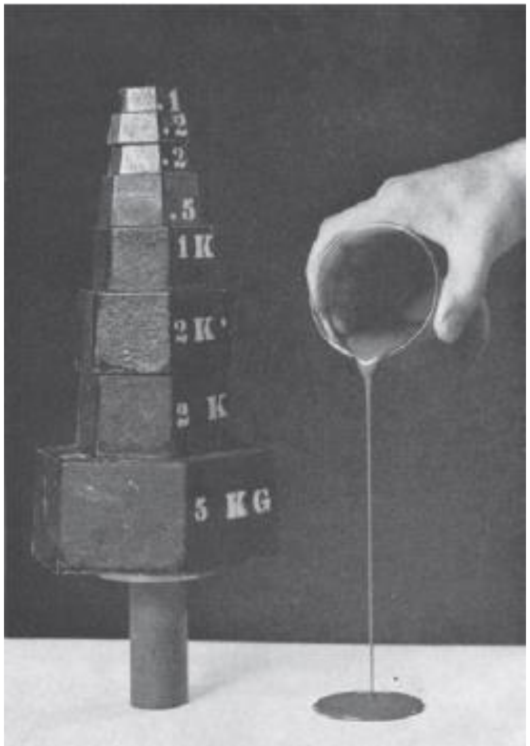
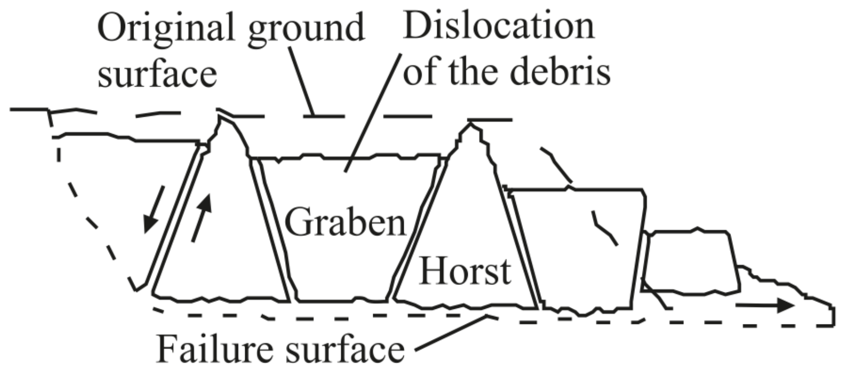
2nd - 4th October 2017 | 28th ALERT Workshop | Aussois, France

Progressive failure of sensitive clays landsides





(after Locat et al. 2017)

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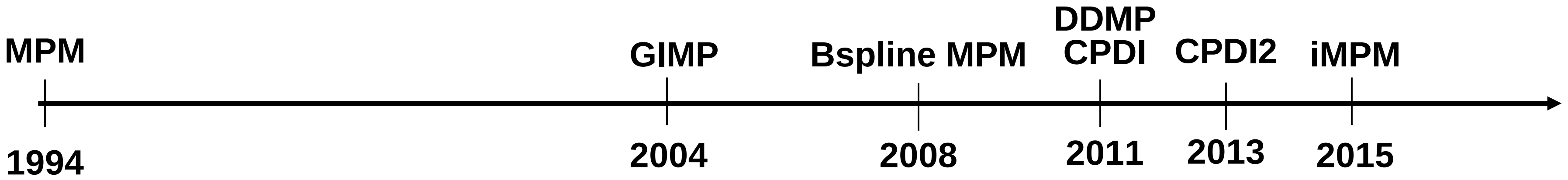
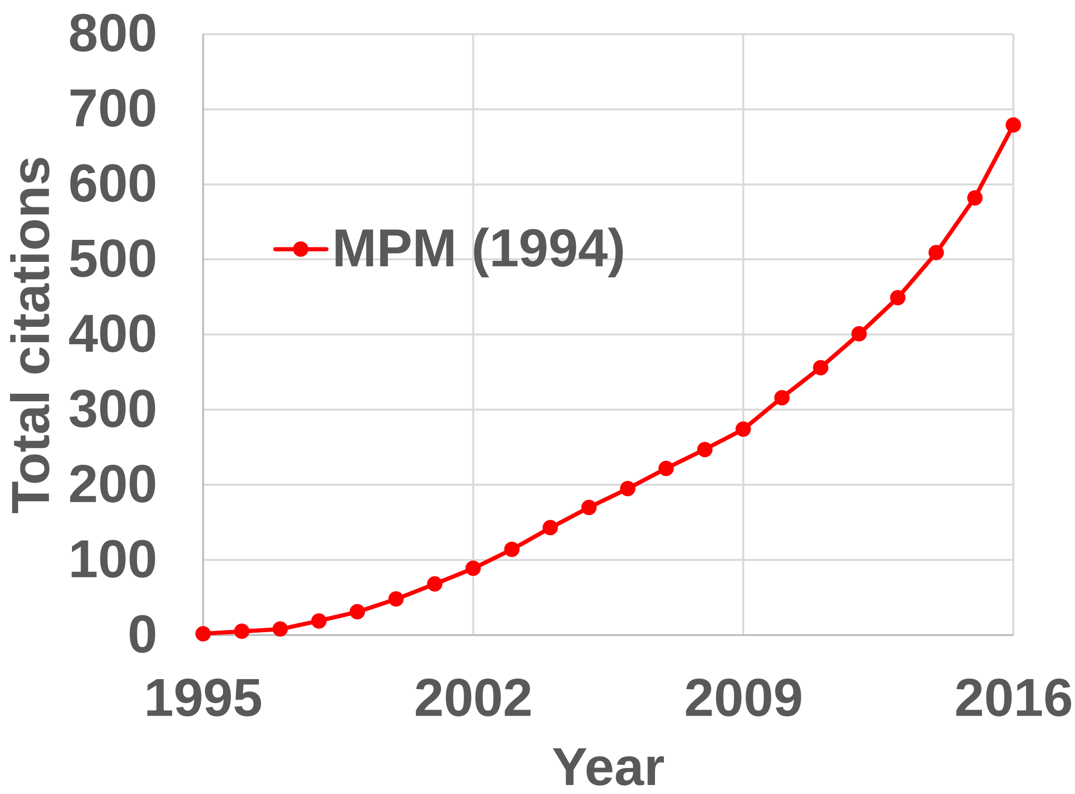
Material Point Method





GIMP: Generalized Interpolation Material Point Method
DDMP: Dual Domain Material Point Method
CPDI: Convected Particle Domain Interpolation
iMPM: improved Material Point Method

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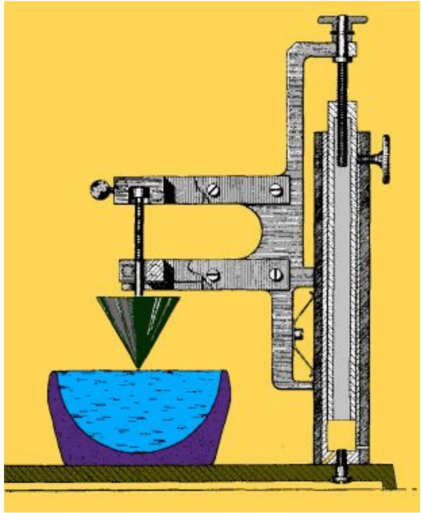
Outline

- Simulation of a progressive failure of a sensitive clay landslide using Generalized Interpolation Material Point Method (GIMP).

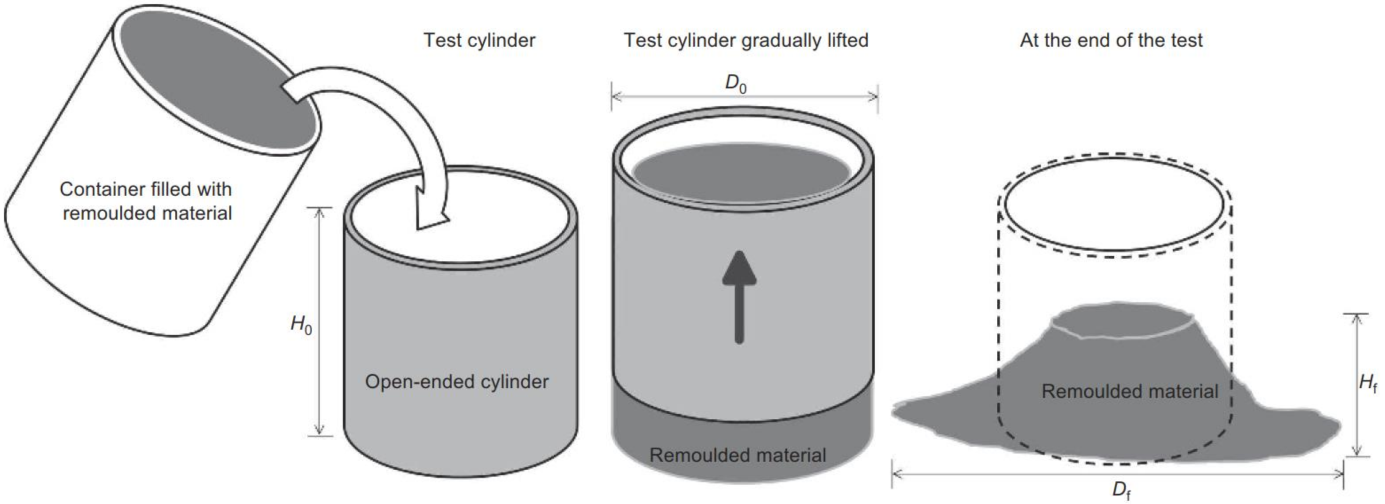
- Using null space filter improved Material Point Method (MPM / GIMP /DDMP) to reduce unphysical oscillations.

Validation

- **fall cone test (kaolin clays)**

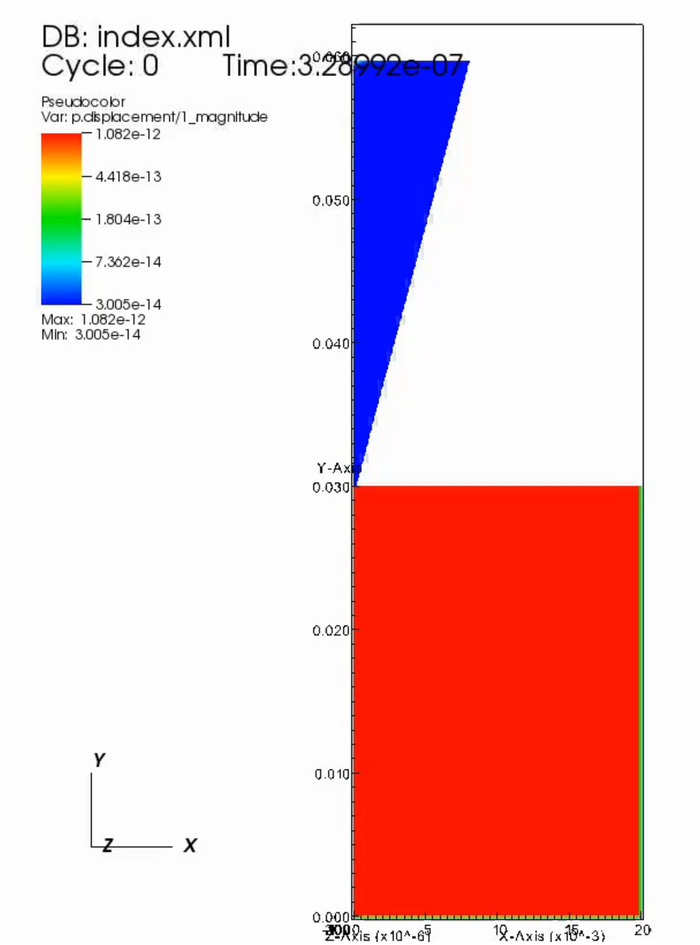


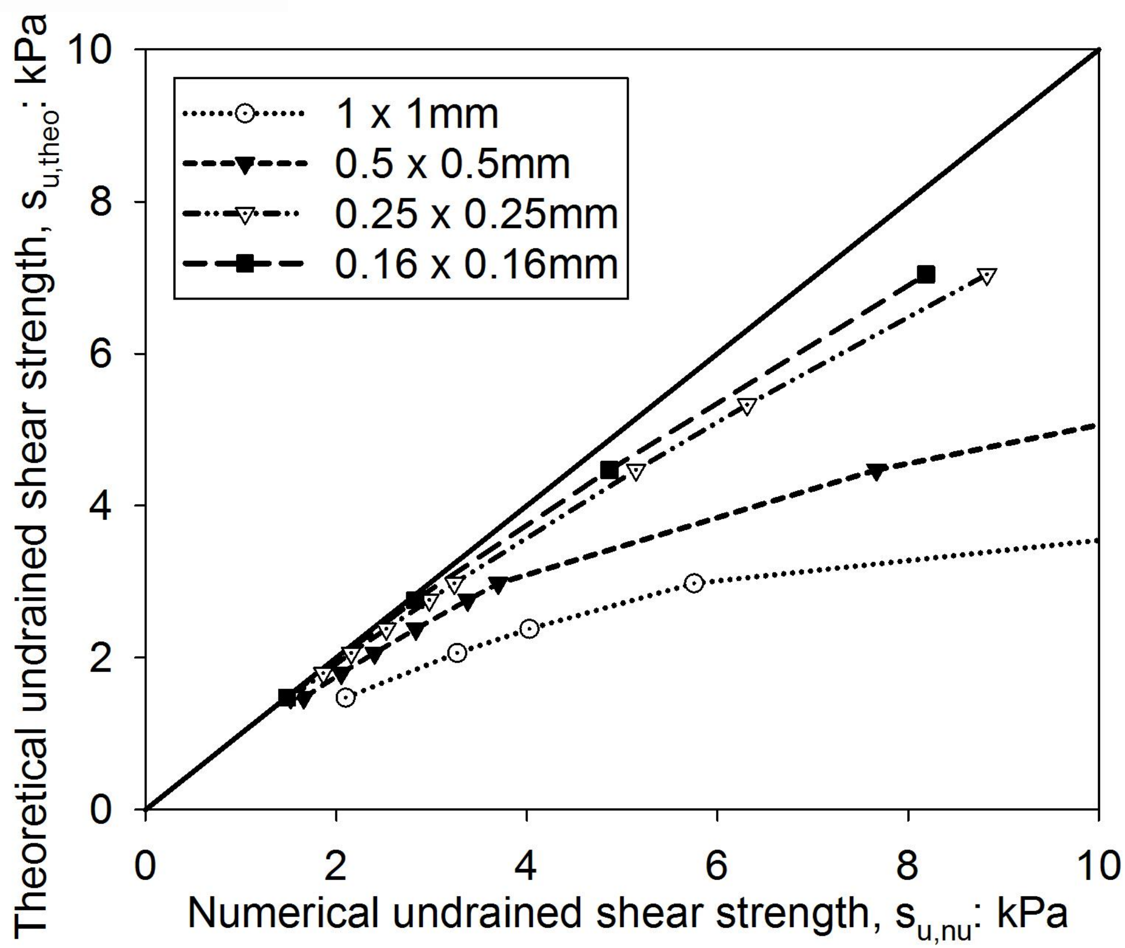
- **quickness test (remoulded sensitive clays)**



First validation: fall cone tests

Numerical vs theoretical solutions (Tran et al. 2017)





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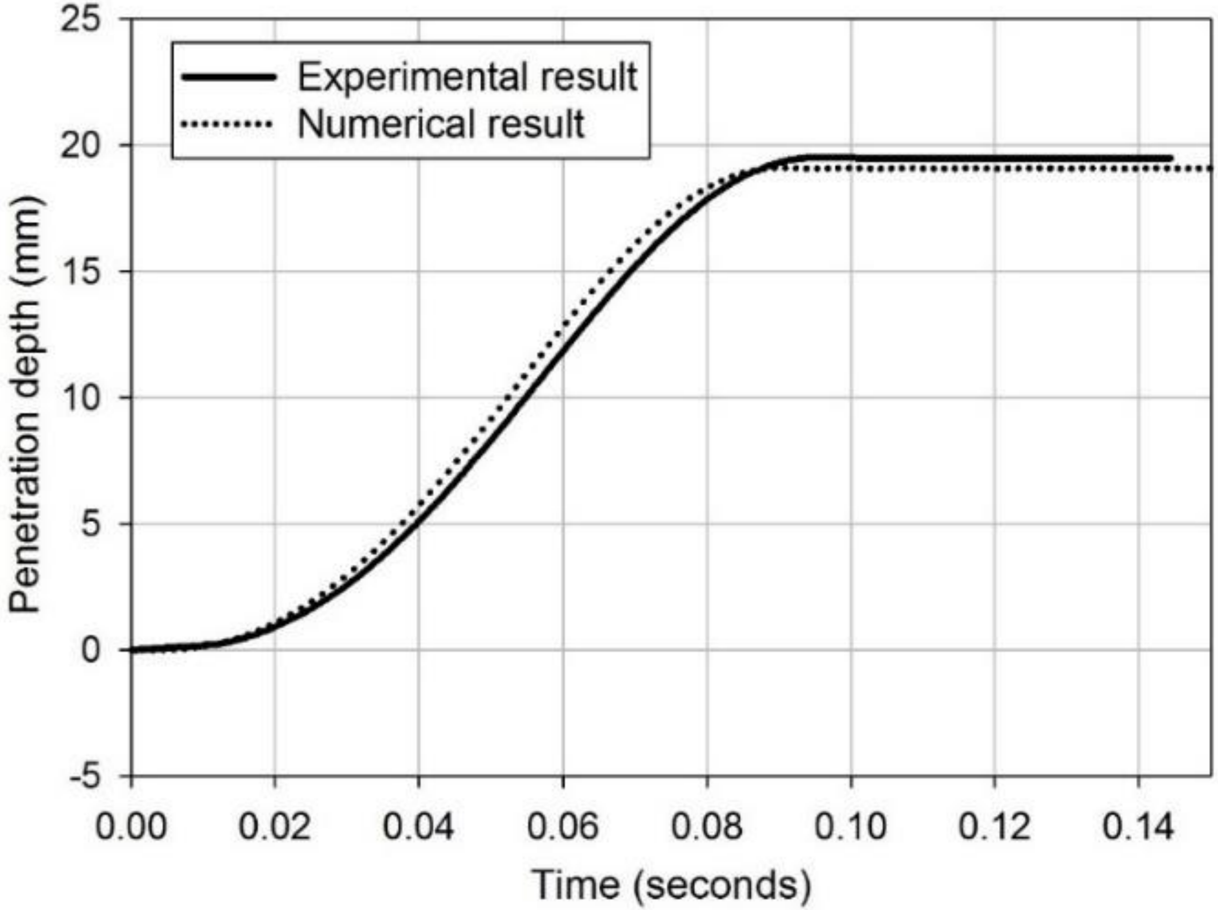
First validation: fall cone tests

Numerical model vs experiment (Tran et al. 2017)



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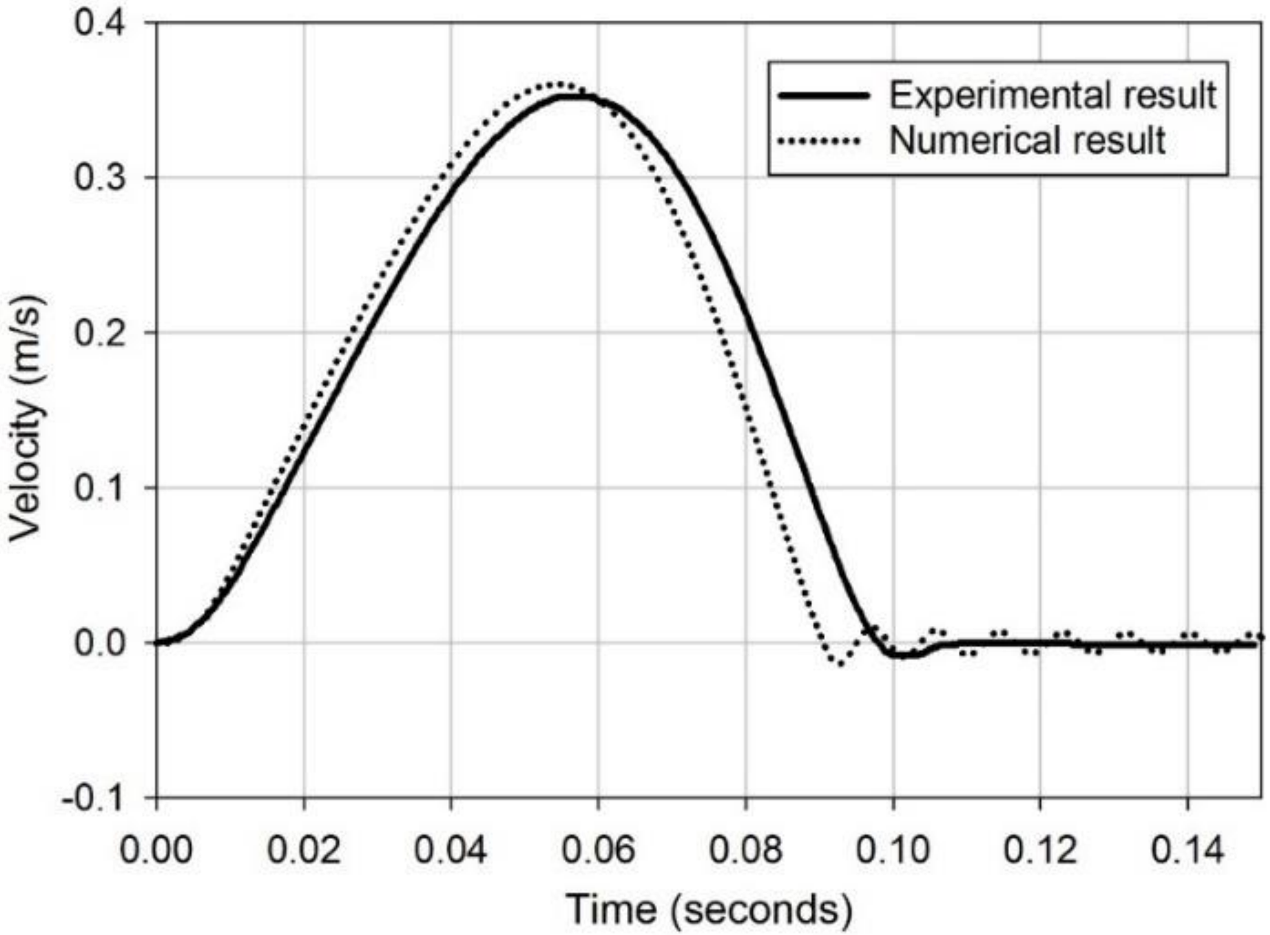
First validation: fall cone tests

Numerical model vs experiment (Tran et al. 2017)



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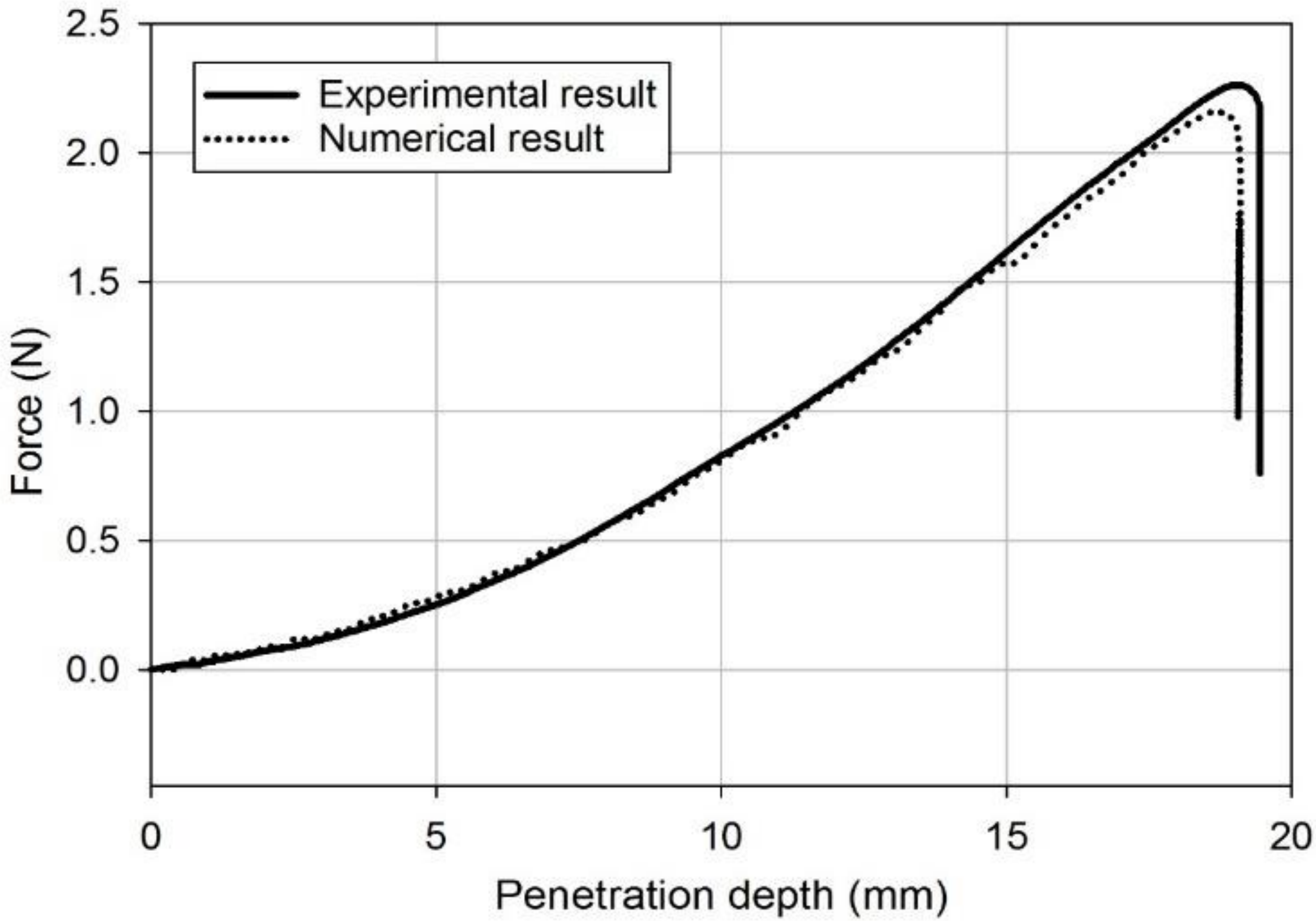
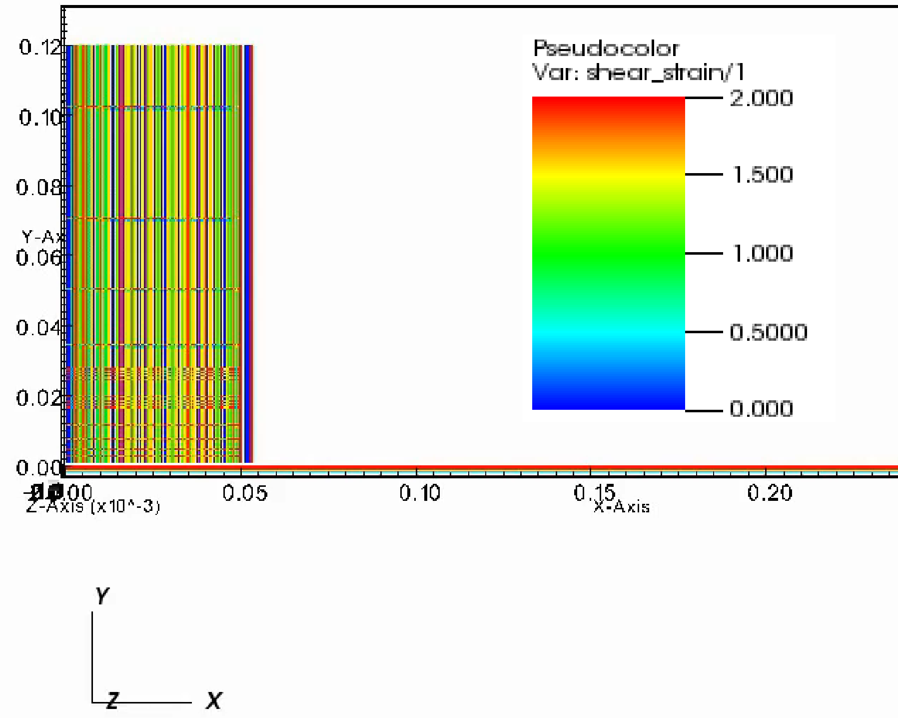
First validation: fall cone tests

Numerical model vs experiment (Tran et al. 2017)



Second validation: quickness tests

Numerical model vs experiment (Tran et al. 2017)



Strain rate parameters for sensitive clays

Oedometer test

$$\frac{\sigma'_p}{\sigma'_{p,ref}} = \left(\frac{\delta\varepsilon}{\delta\varepsilon_{ref}}\right)^{\alpha}$$

Triaxial test

$$\frac{s_u}{s_{u,ref}} = 1 + \mu * \log\left(\frac{\delta\varepsilon}{\delta\varepsilon_{ref}}\right)$$

Direct Shear test

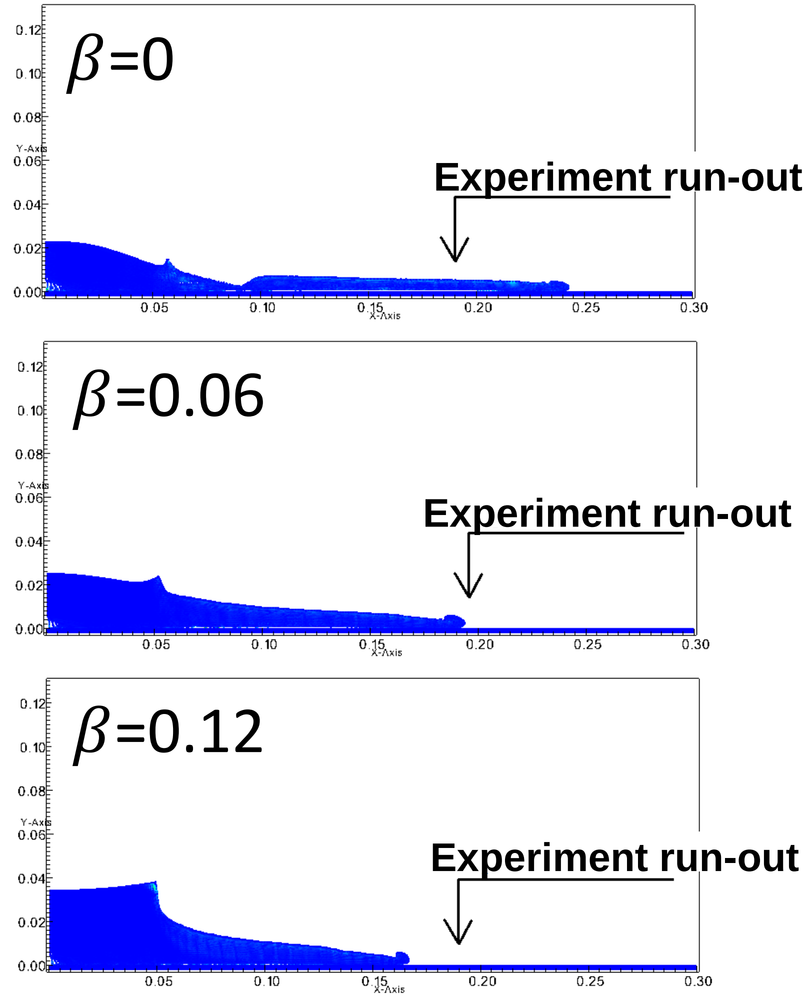
$$\frac{s_u}{s_{u,ref}} = \left(\frac{\delta\gamma}{\delta\gamma_{ref}}\right)^{\beta}$$

Soil type	α	μ	β	Reference
Sensitive clays	0.025-0.1	-	0.025-0.1	(Mesri and Godlewski 1977)
Finnish sensitive clay	0.073	-	0.073	(Länsivaara 1999)
Eberg sensitive clay	0.052	-	0.052	(Länsivaara 1999)
Vanttila sensitive clay	0.045	-	0.045	(Yin, et al. 2011)
Pernio sensitive clay	0.033-0.043	-	0.033-0.043	(Mataic 2016)
Natural soft clays	-	0.09-0.2	0.035-0.065	(Graham et al. 1983)
Canadian sensitive clays	-	0.07-0.14	0.03-0.05	(Lefebvre and LeBoeuf 1987)
Clays	-	0.1	0.035	(Leroueil and Marques 1996)

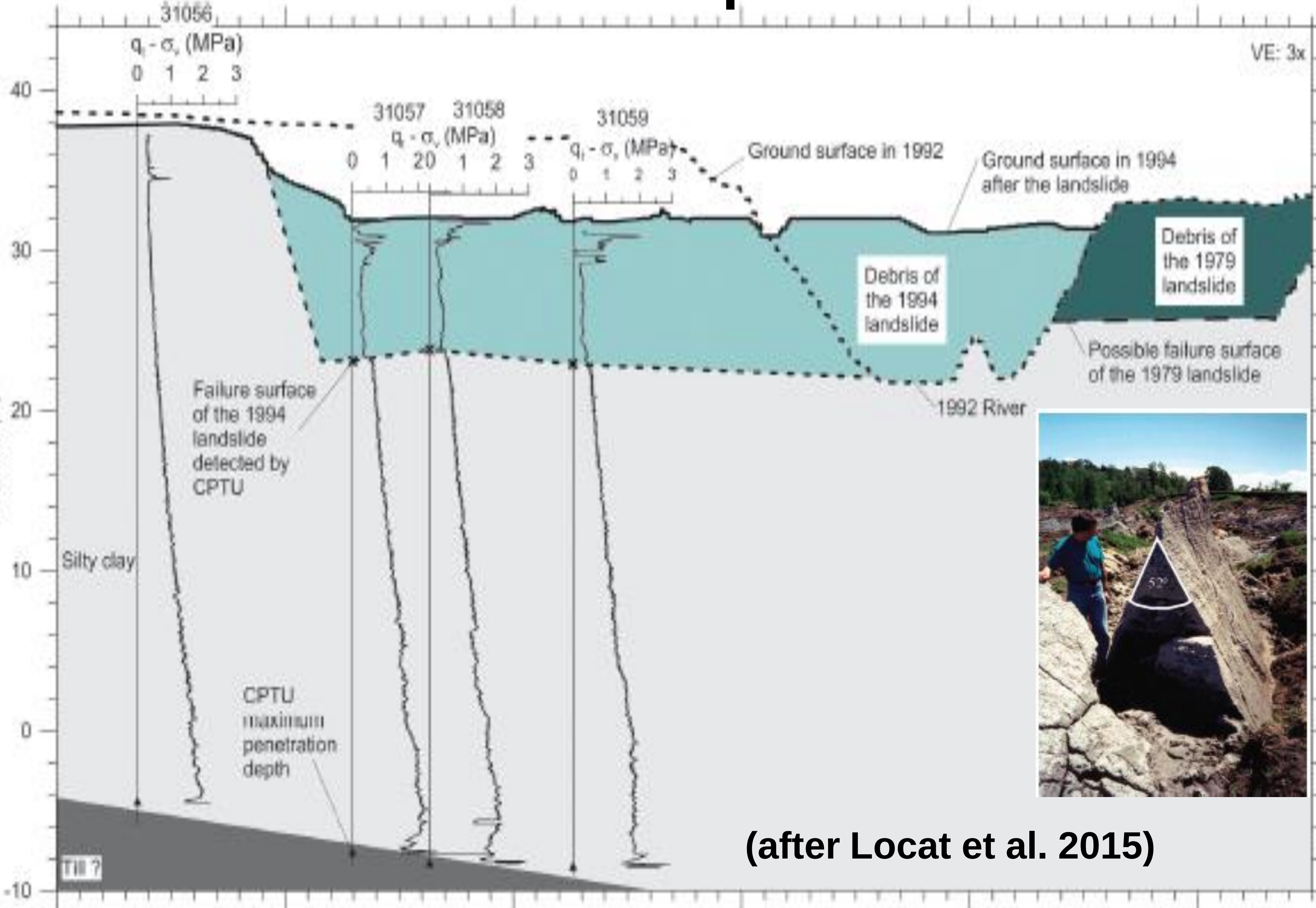
Strain rate effects on run-out distance

Quickness test experiment
Olsøy remoulded clay
Sur = 0.2 kPa
(Tran et al. 2017)

$$s_u = s_{u,ref}\left(\frac{\delta\gamma}{\delta\gamma_{ref}}\right)^{\beta}$$

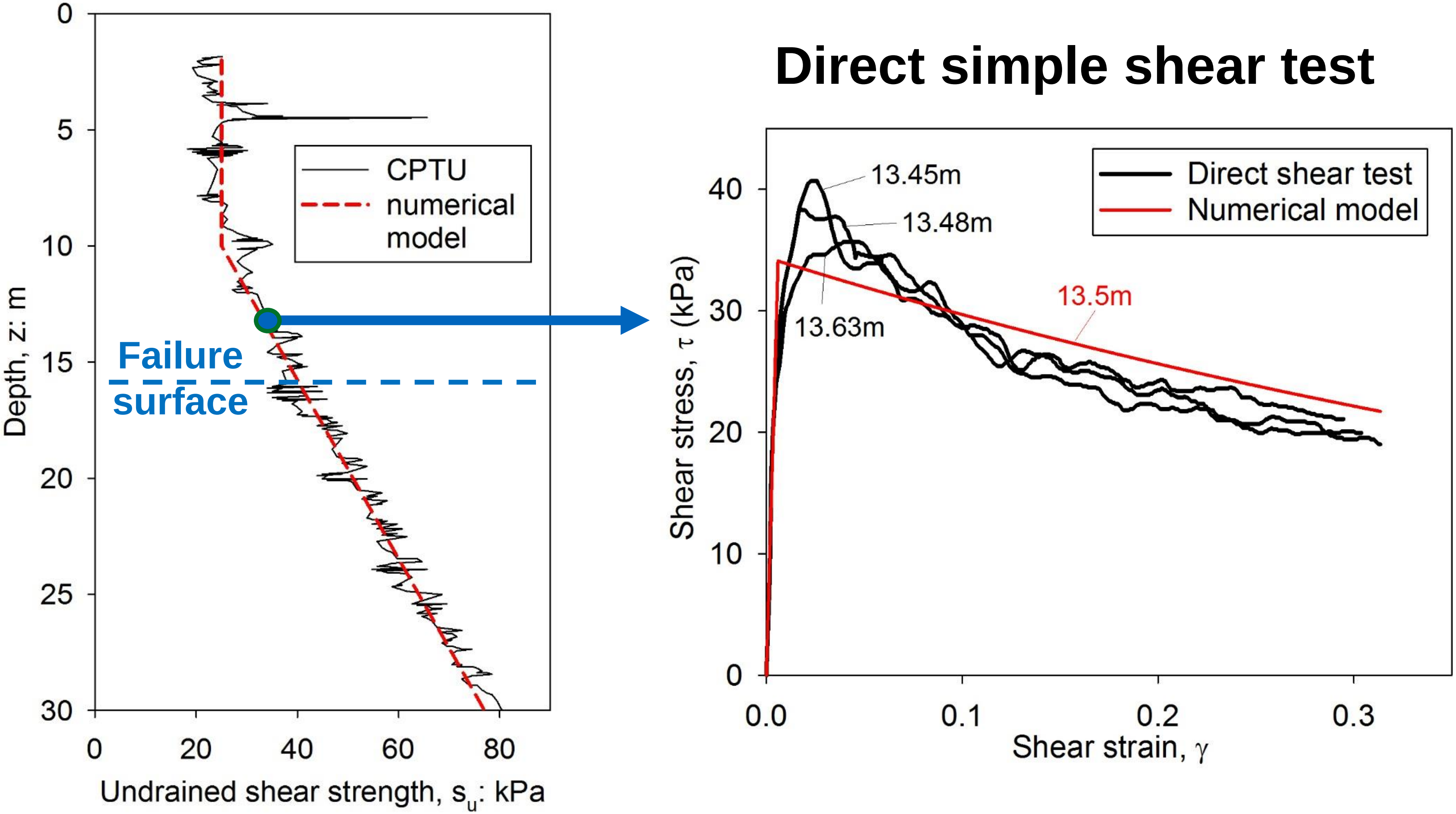


1994 Saint Monique landslide

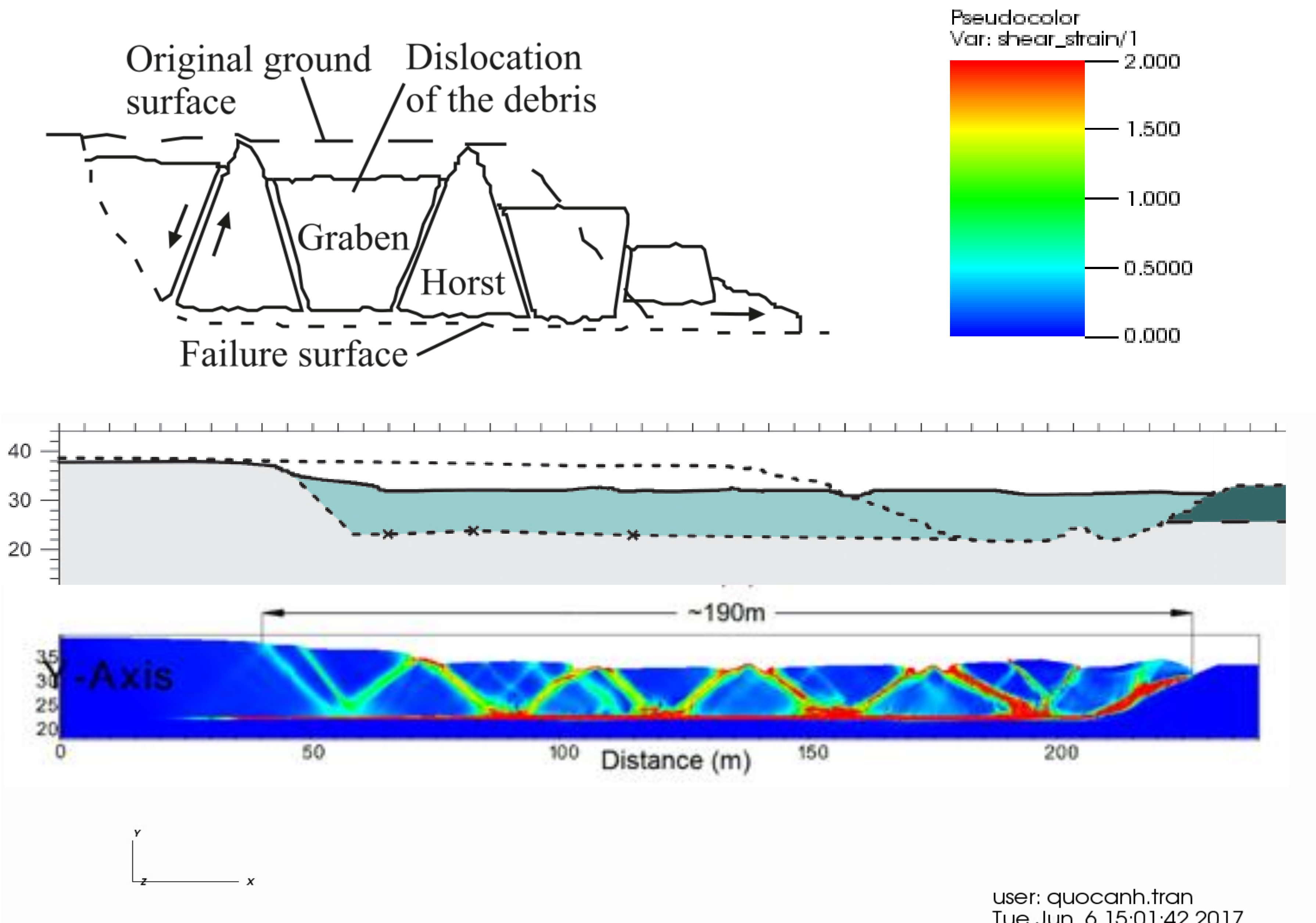


(after Locat et al. 2015)

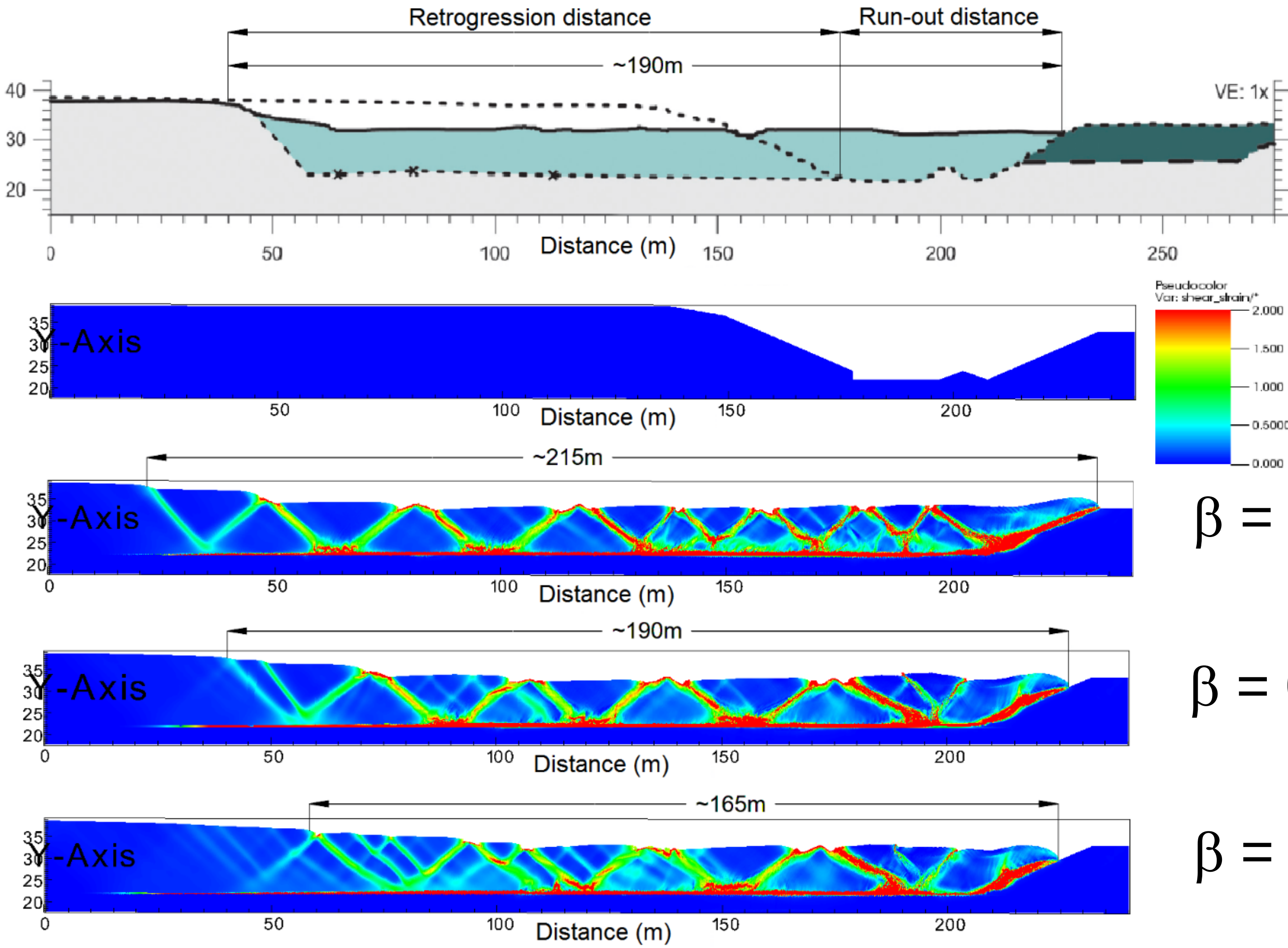
Parameter calibration



Numerical simulations



Strain rate effects on travel distance



On-site
L ≈ 190m

β = 0; L ≈ 215m

β = 0.06; L ≈ 190m

β = 0.12; L ≈ 165m

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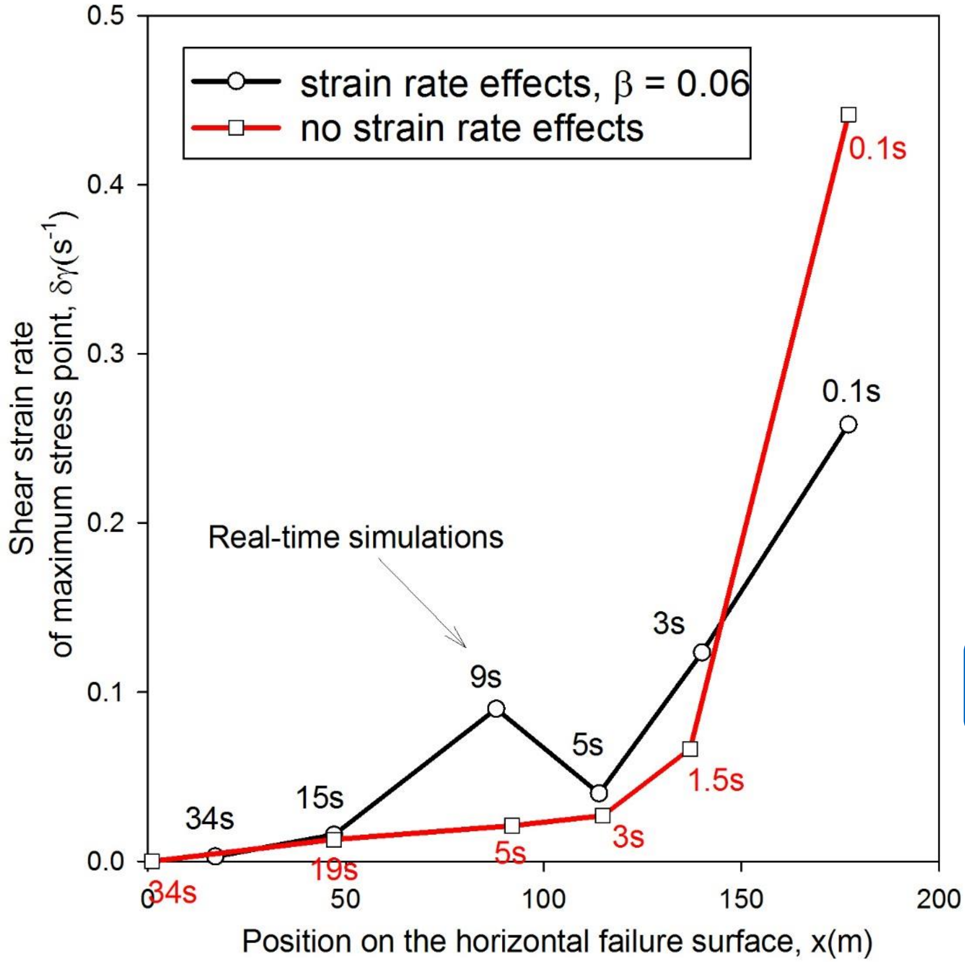
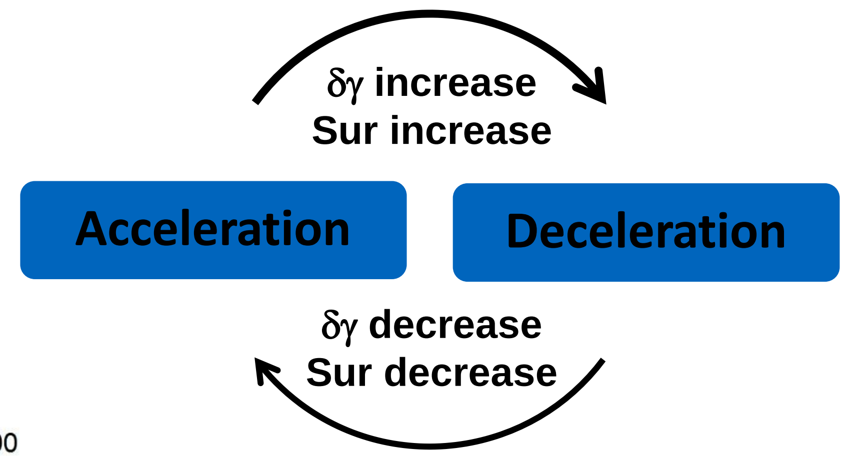
Strain rate effects on dynamic motion



Strain rate effects induce a cycle of acceleration-deceleration movement



Advantages and limitations of MPM

+ Advantage of MPM / GIMP / DDMP /…

Continuum framework

Large-deformation, dynamic simulation

- Limitation of MPM / GIMP / DDMP /…

Concerns about the accuracy and the stability of the solution

Outline

- Simulation of a progressive failure of a sensitive clay landslide using Generalized Interpolation Material Point Method (GIMP).

- Using null space filter improved Material Point Method (MPM / GIMP /DDMP) to reduce unphysical oscillations.

What is the null space?

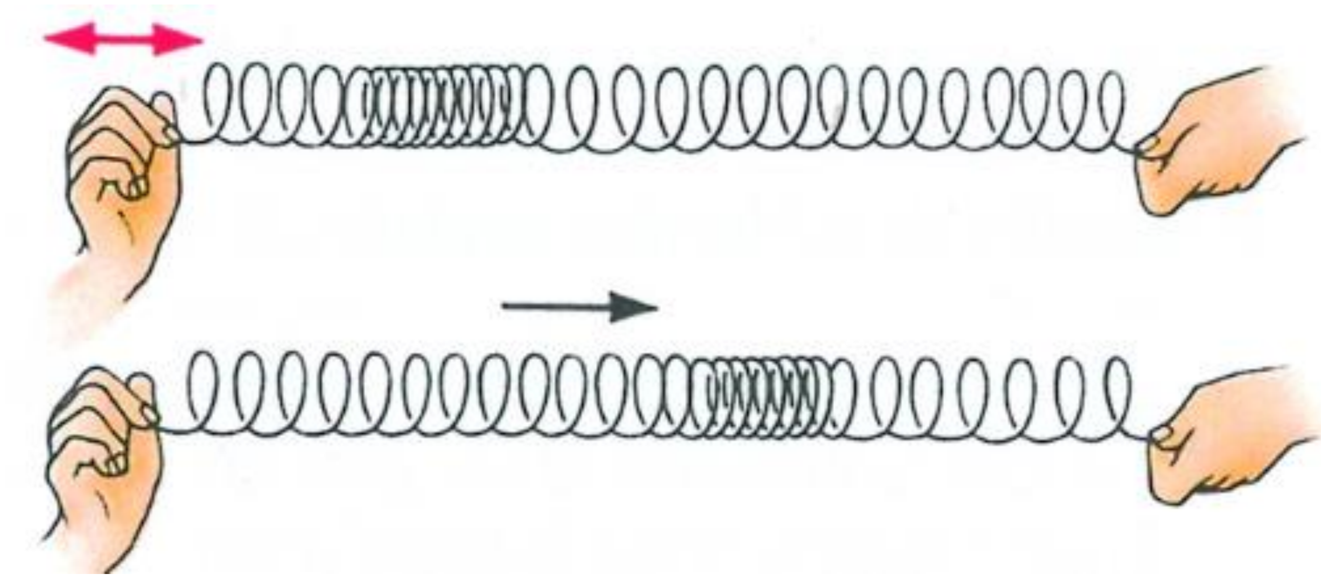
- Definition in linear algebra

The null space of a matrix (A), written null(A), is the set of vectors x that satisfy A.x = 0 ($x \neq 0$)

If A has a nontrivial null space, A is a rank deficient mapping

If A does not have a null space, A is a full rank mapping

Numerical example: 1D elastic vibration



E = 0.04Pa

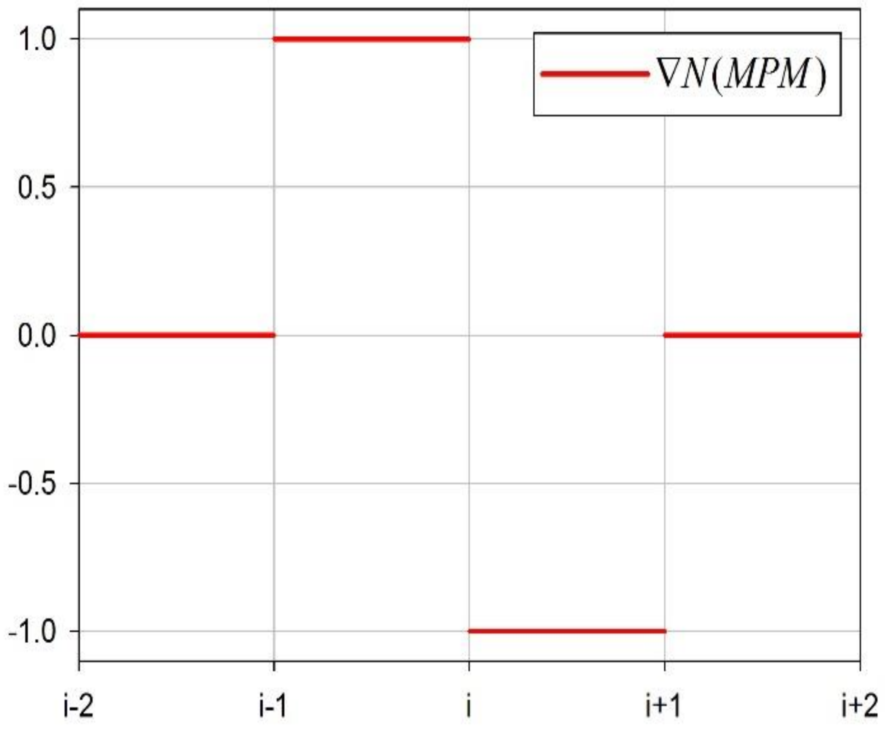
L = 4m

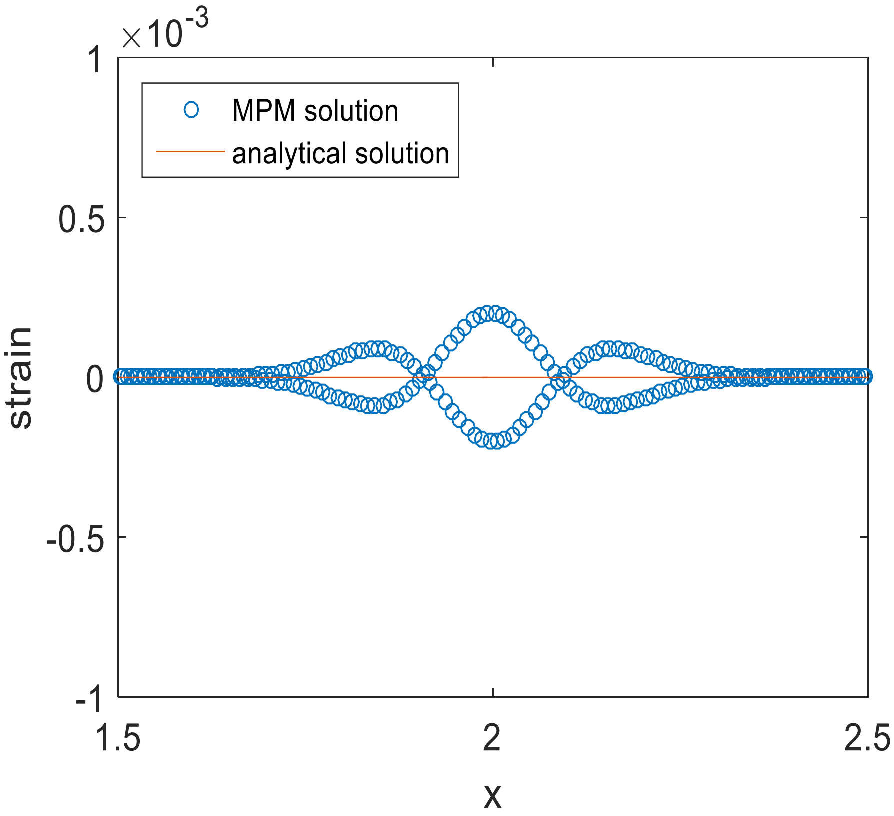
Initial condition: $\varepsilon^{o}(x, t = 0) = -0.12e^{-60x^2}$

Analytical solution:

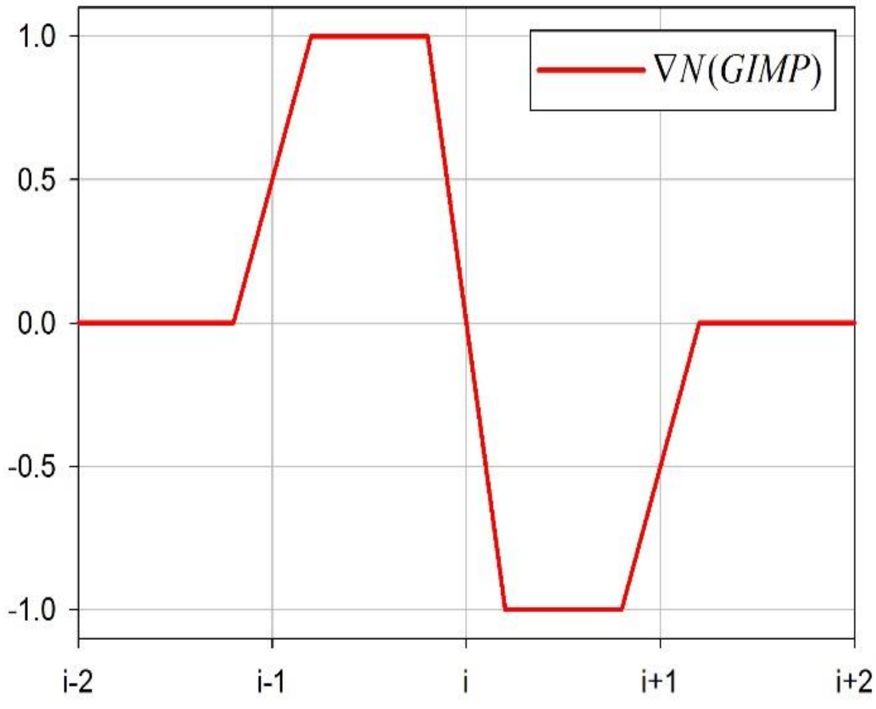
$$\varepsilon^{t}(x, t) = 0.0005\left(e^{-60(x-0.01t)^2} + e^{-60(x+0.01t)^2}\right)$$

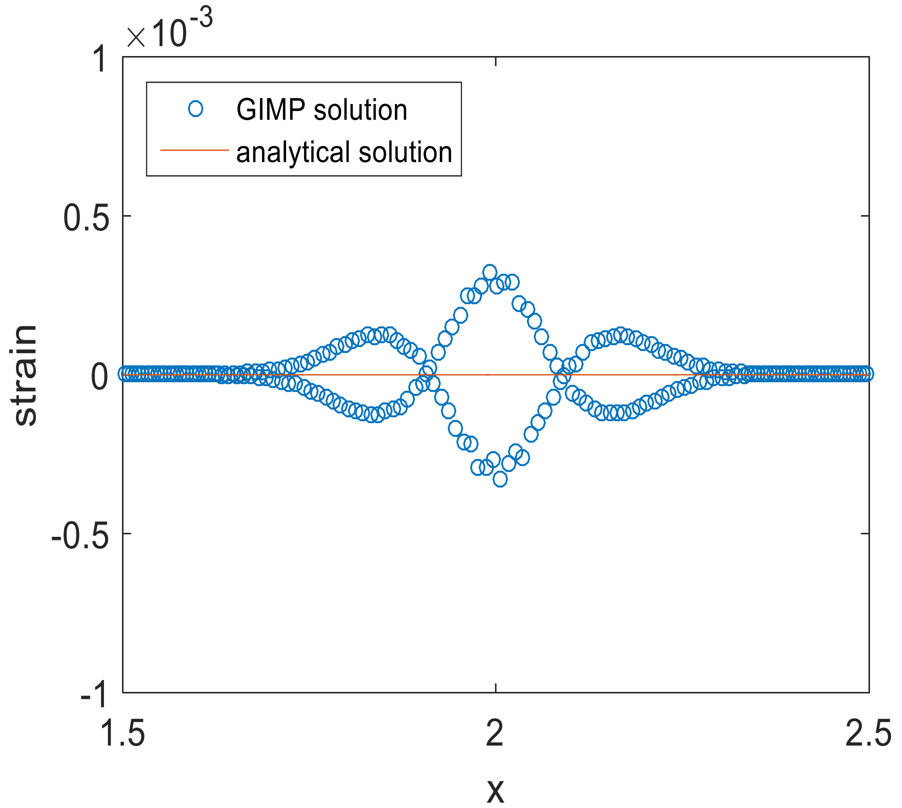
MPM (1994) numerical results



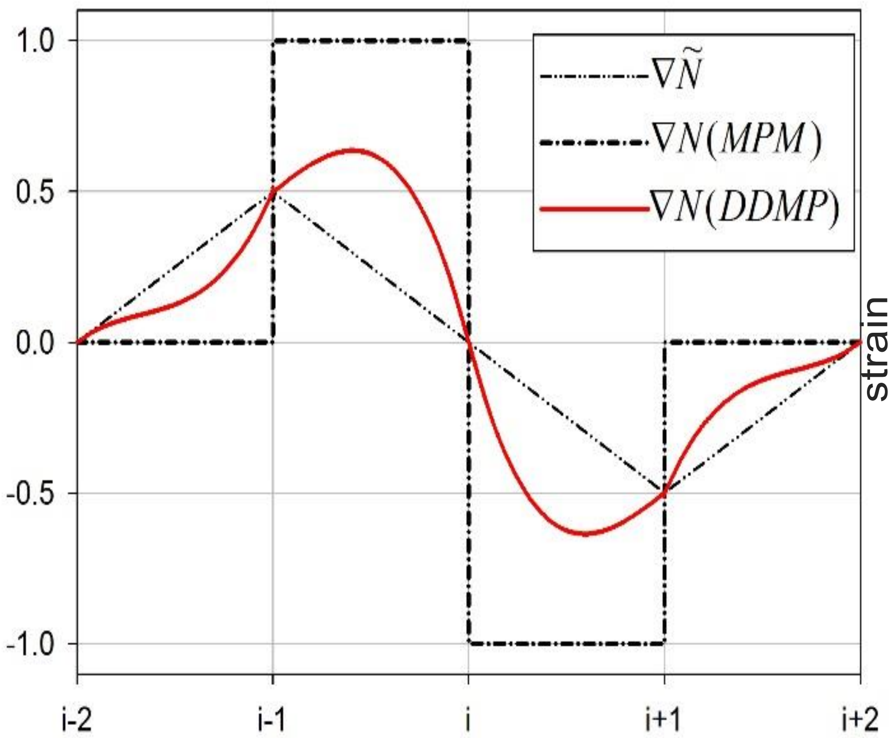


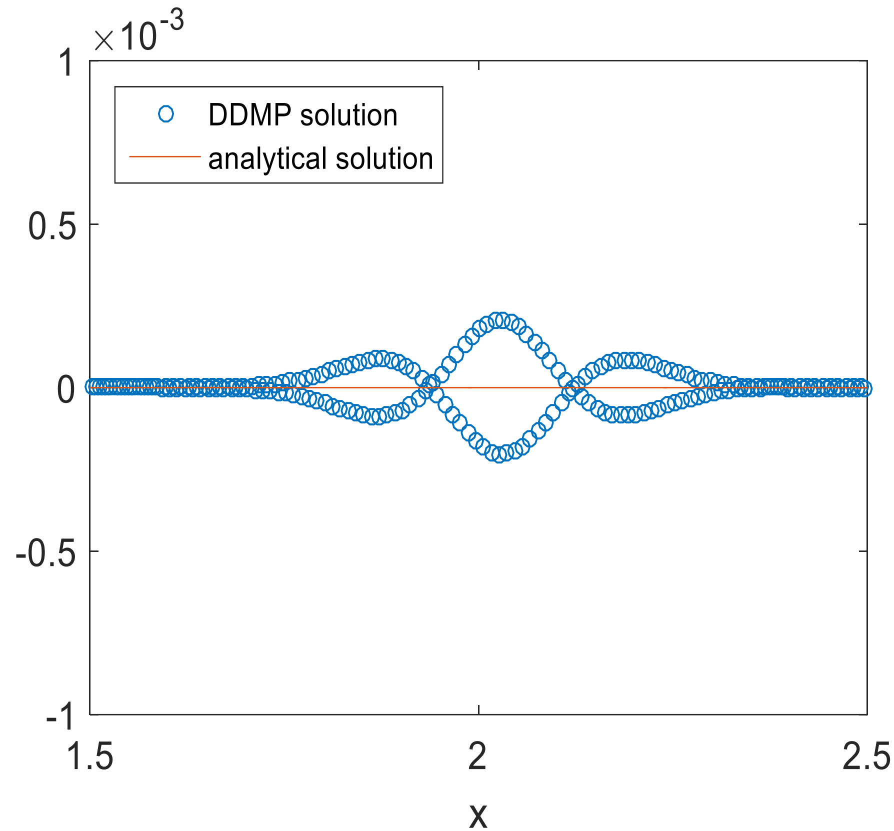
GIMP (2004) numerical results



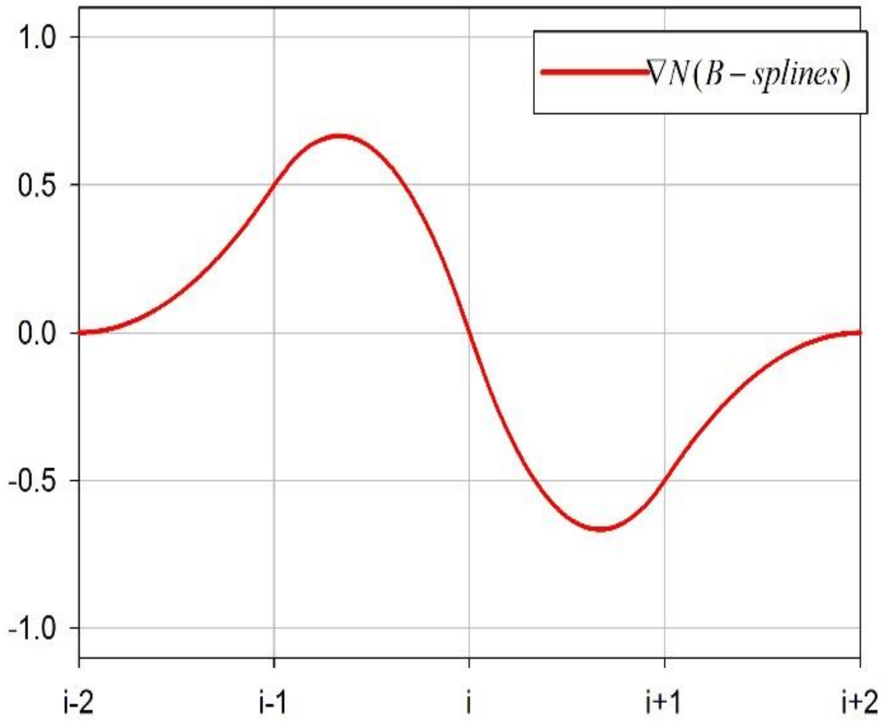


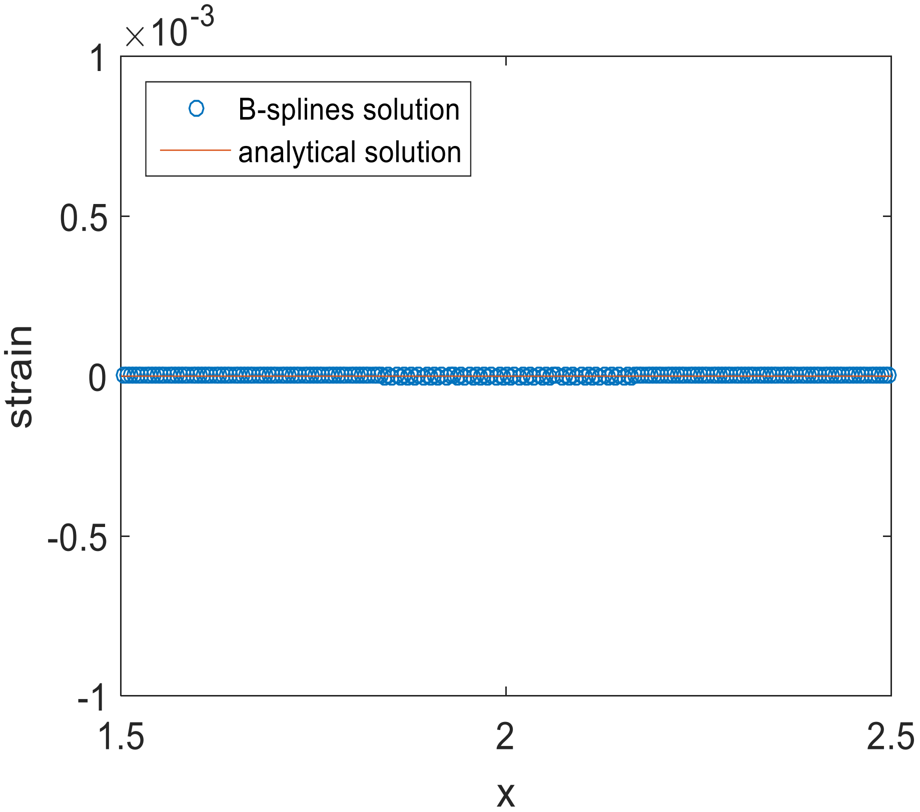
DDMP (2011) numerical results





Spline MPM (2008) numerical results





Summary

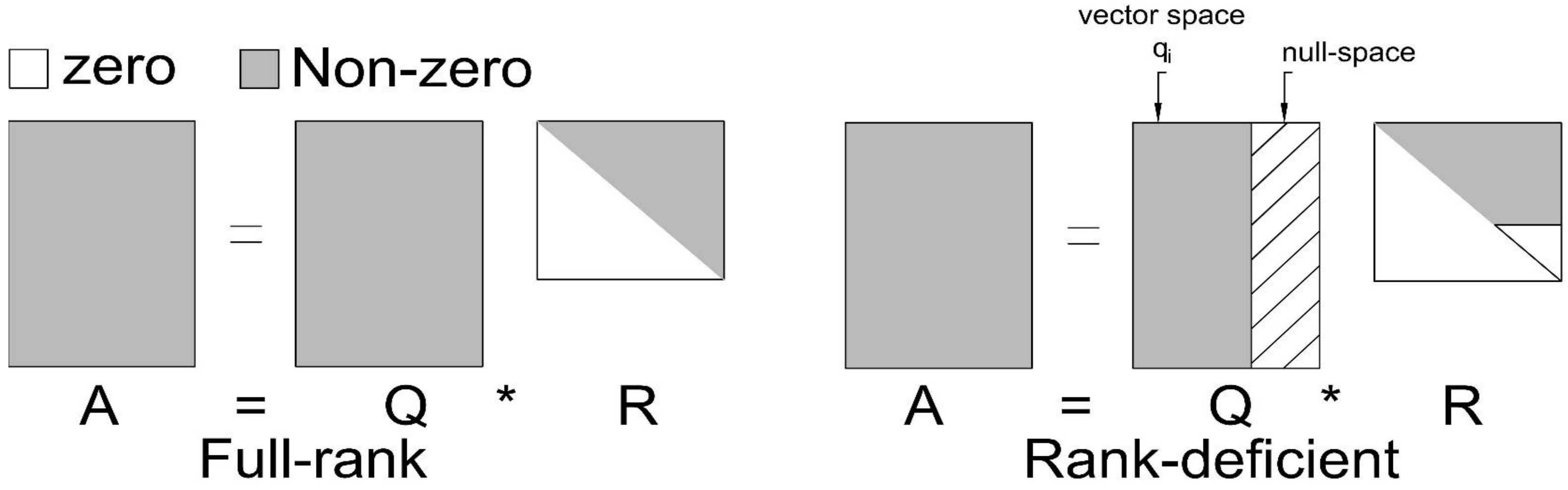
- Stress mappings in MPM, DDMP, GIMP is a rank deficient mapping which generate the null space noise in 1D vibration problem

- B-spline function can reduce the noise of null space as null(∇N^T)=0

- If $N_p > N_n$, null(∇N) > 0, therefore, it is necessary to consider a null space filter to eliminate the noise due to the null space.

A null space filter using QR method

Step 1: Identify the vector space q and null space



Step 2: Projection of the solution into vector space

$$\mathbf{v}_\mathbf{p}^* = \mathrm{Proj}_\mathrm{Q}(\mathbf{v}_\mathbf{p}) = \sum_{i=1}^{r} (\boldsymbol{q}_i^T \mathbf{v}_\mathbf{p}) \boldsymbol{q}_i$$

Dual Domain Material Point Method enhanced with a null space filter (iDDMP)

$$\boldsymbol{v}_i^L$$

$$\Delta\varepsilon_{p,1} = tr\left[\sum_{i=1}^{N_n}\left(\nabla N_i(\boldsymbol{x}_p)\boldsymbol{v}_i^L\right)\right]$$

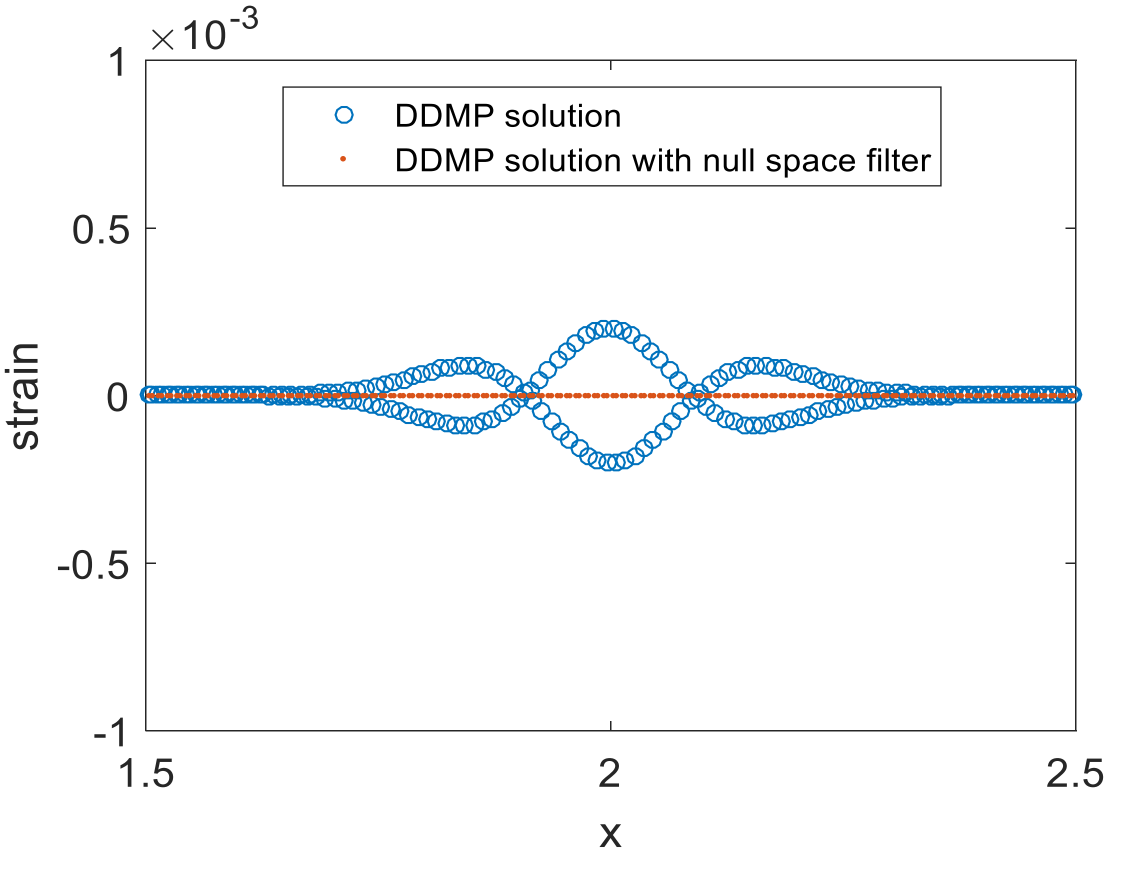
$$\Delta\varepsilon_j = \frac{1}{V_j}\sum_{i=1}^{N_n}\boldsymbol{v}_i^L \int N_j \nabla N_i dv$$

$$\Delta\varepsilon_{p,1}^{*} = \Delta\varepsilon_{p,1} - \Delta\varepsilon_{p,1}^{null}$$

$$\Delta\varepsilon_{p,2} = \sum_{i=1}^{N_n} N_i(\boldsymbol{x}_p)\Delta\varepsilon_j$$

$$\Delta\varepsilon_p = \alpha.\Delta\varepsilon_{p,1}^{*} + (1-\alpha)\Delta\varepsilon_{p,2}$$

Application of null space filter to DDMP



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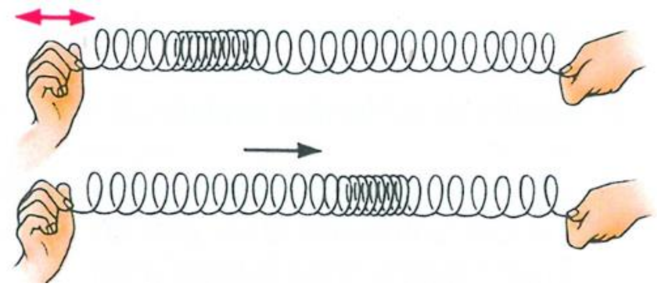
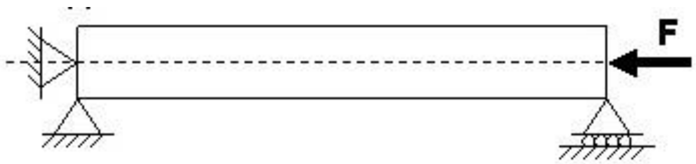
Numerical example for iDDMP

- 1D vibration propagation

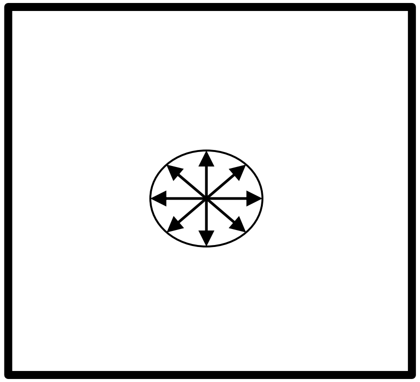


- Tension force impact

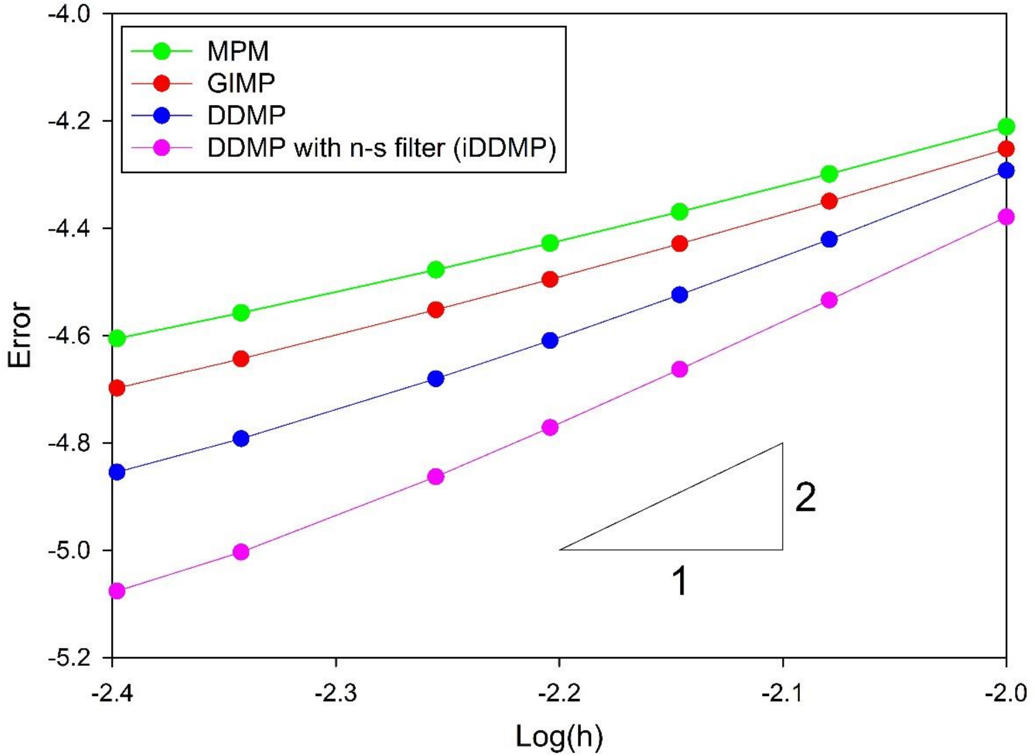


- Gaussian explosion

$$F(t) = \begin{cases} -2\pi^2 f_0^2 (t - t_0)\, e^{-\pi^2 f_0^2 (t-t_0)^2} & \text{if } t \leq 2t_0 \\ 0 & \text{if } t > 2t_0 \end{cases}$$



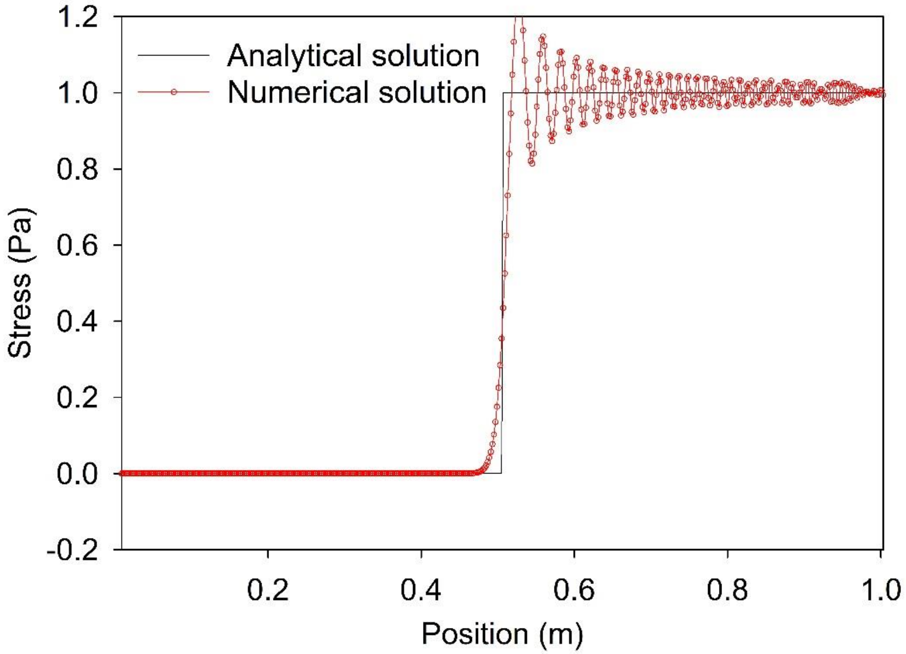
Convergence rate of iDDMP in 1D vibration propagation



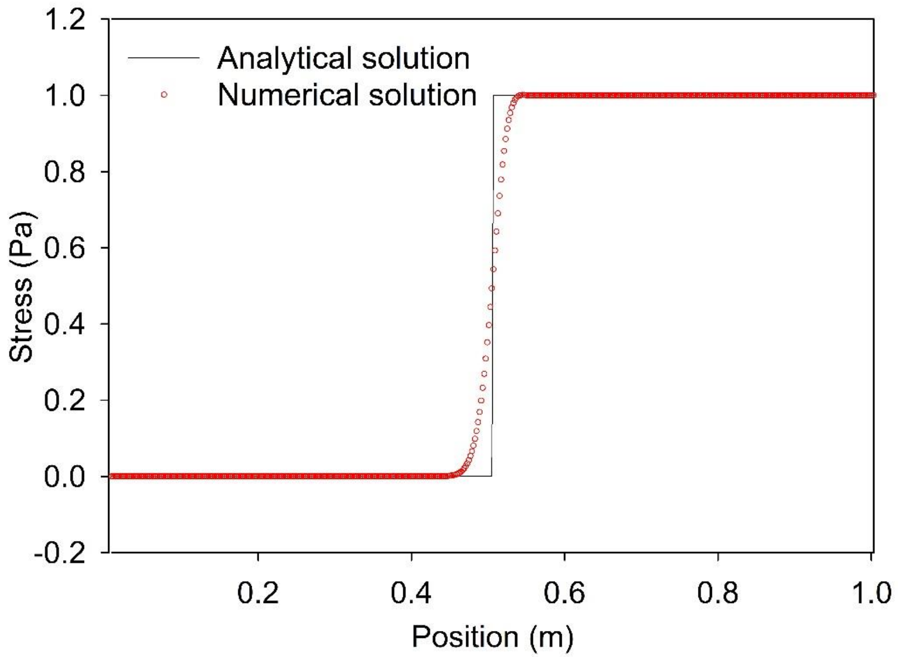
- Cell size h is limited to prevent the cell crossing errors

$$\text{error} = \sqrt{\frac{\sum_{N_p} \| \mathbf{u}_{\text{exact}}(\mathbf{x}_p, t) - \mathbf{u}_{\text{app}}(\mathbf{x}_p, t) \|^2}{N_p}}$$

Pressure oscillation in tension impact

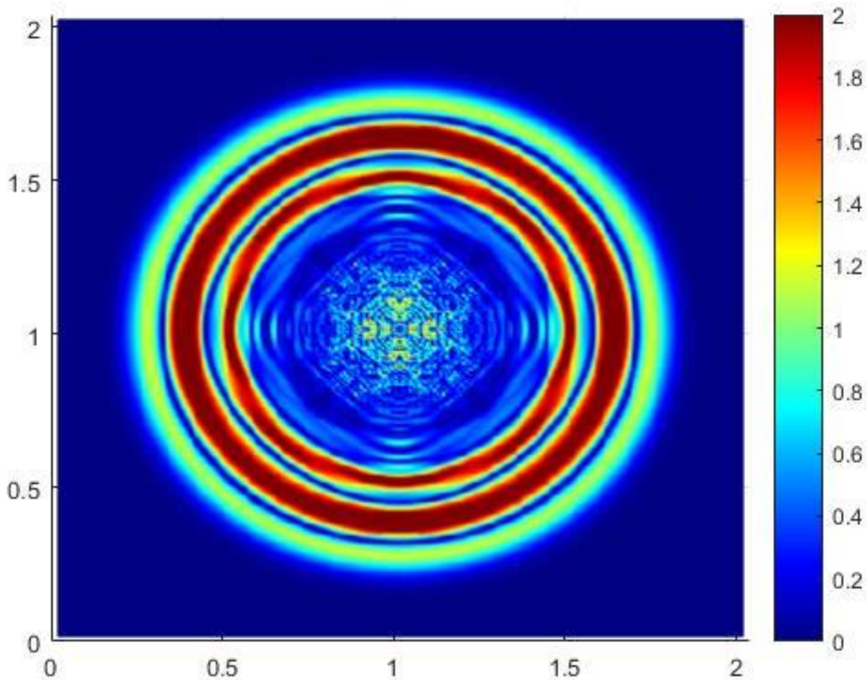


DDMP

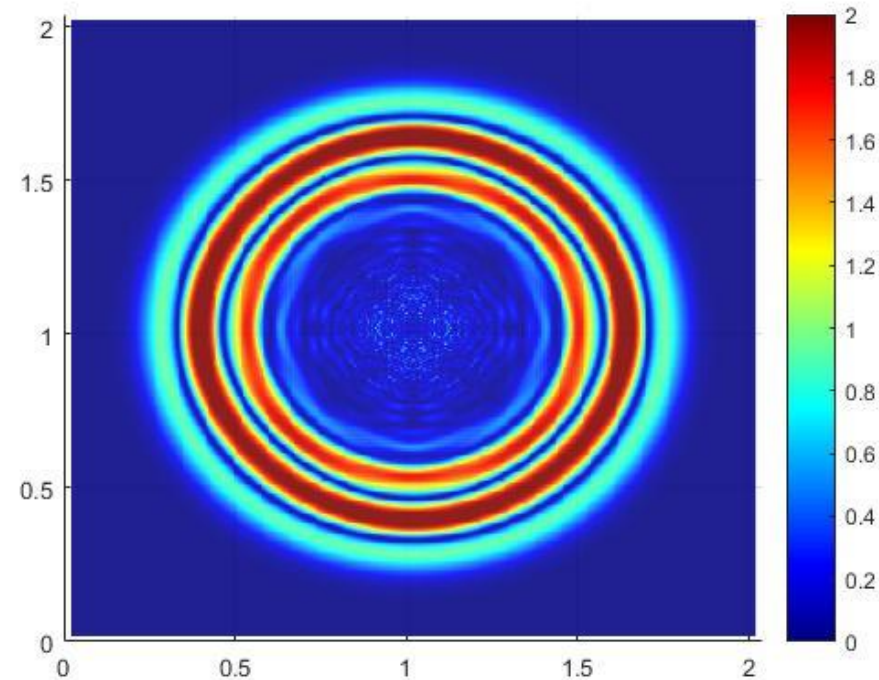


iDDMP

Gaussian explosion

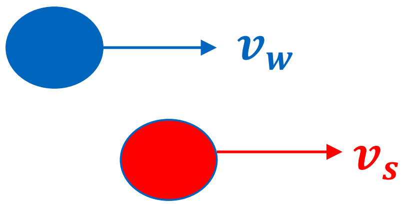


MPM



MPM with null space filter

Hydro coupled formulation



- Effective stress concept:

$$\sigma = \sigma' - \mathbf{p_w}$$

- Momentum balance for water:

$$n\rho_w \boldsymbol{a_w} = -n p_w + n\rho_w \boldsymbol{b_w} - \boldsymbol{f_d}$$

- Darcy law:

$$\boldsymbol{f_d} = \frac{n^2 \rho_w g}{k}(\boldsymbol{v_w} - \boldsymbol{v_s})$$

- Momentum balance for solid:

$$(1-n)\rho_s \boldsymbol{a_s} = \nabla . \sigma' - (1-n)p_w + (1-n)\rho_s \boldsymbol{b_s} + \boldsymbol{f_d}$$

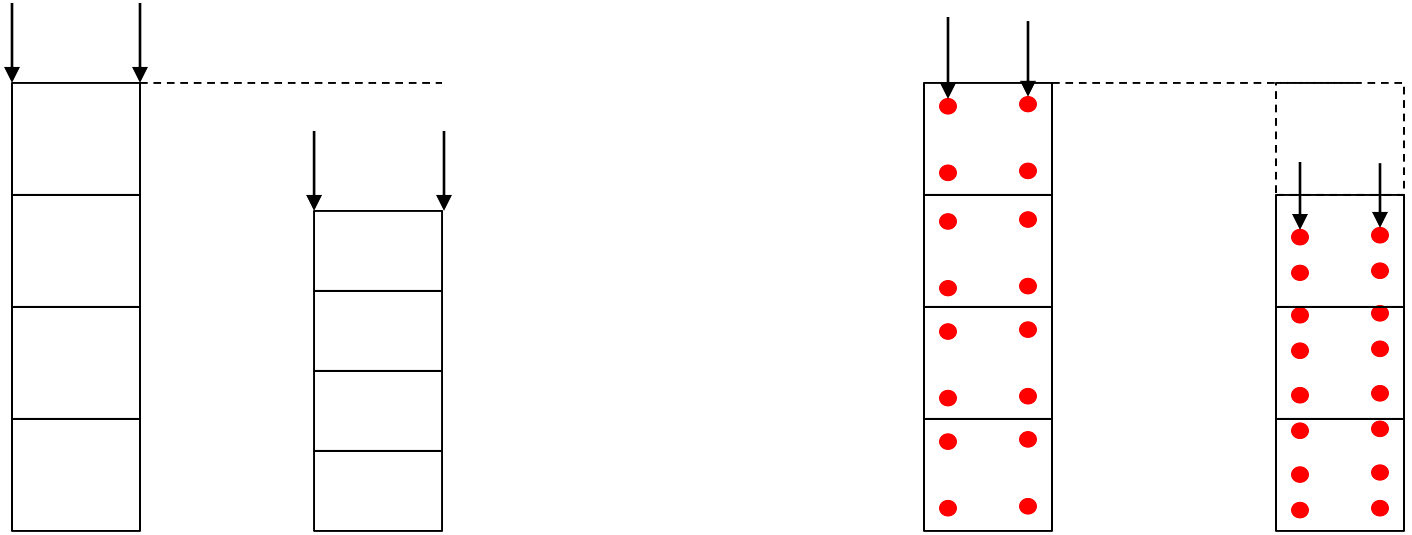
- Mass conservation:

$$\frac{\mathrm{d}p_w}{\mathrm{d}t} = -\frac{K_w}{n}[n\nabla . \boldsymbol{v_w} + (1-n)\nabla . \boldsymbol{v_s}]$$

Numerical example

- Large strain gravity loading (g = 1500 m/s2)
- Large strain consolidation loading (~20% of engineering strain) compared with analytical model (Xie and Leo 2004)

De-rank null space in quasi static large deformation



Compression FEM **Compression MPM**

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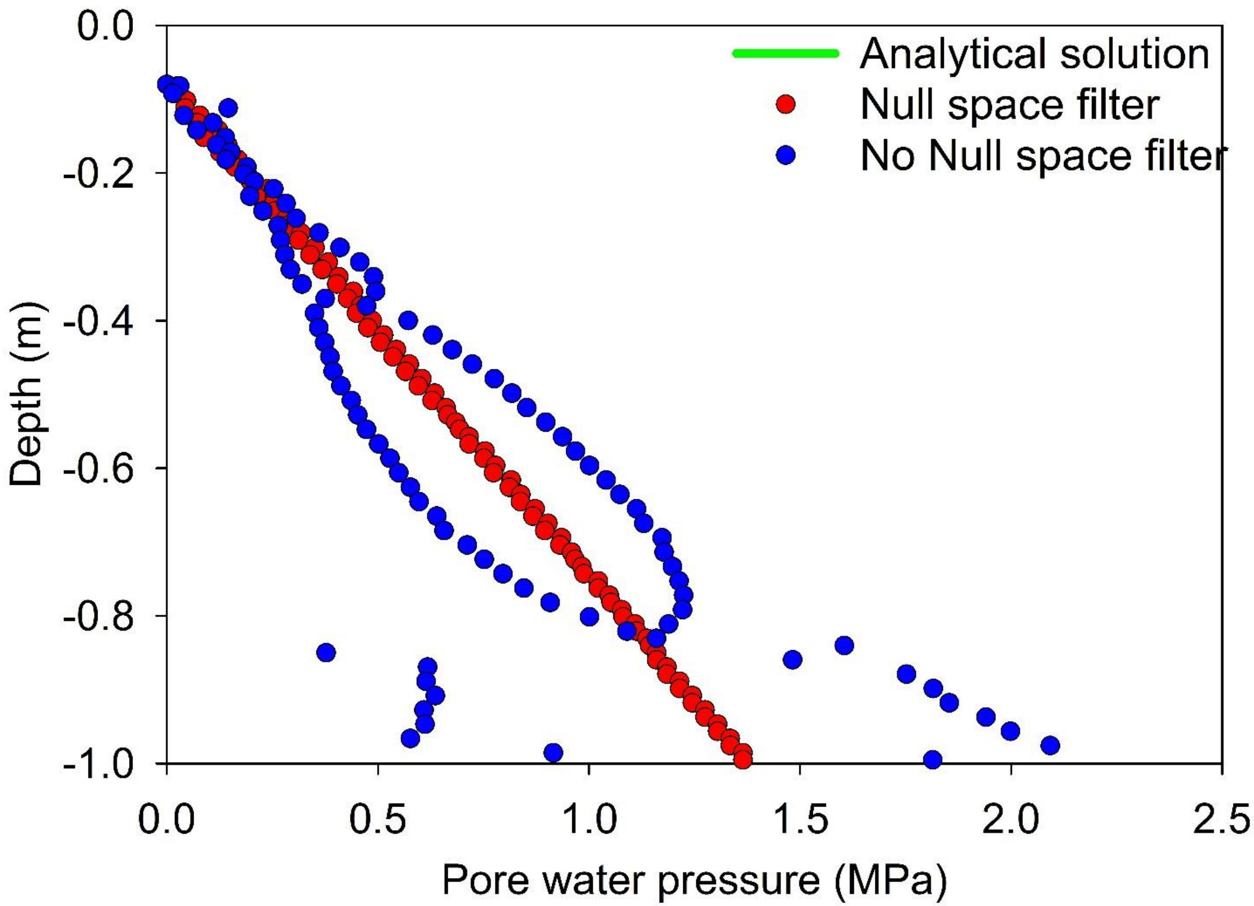
Numerical example: large strain gravity loading using DDMP



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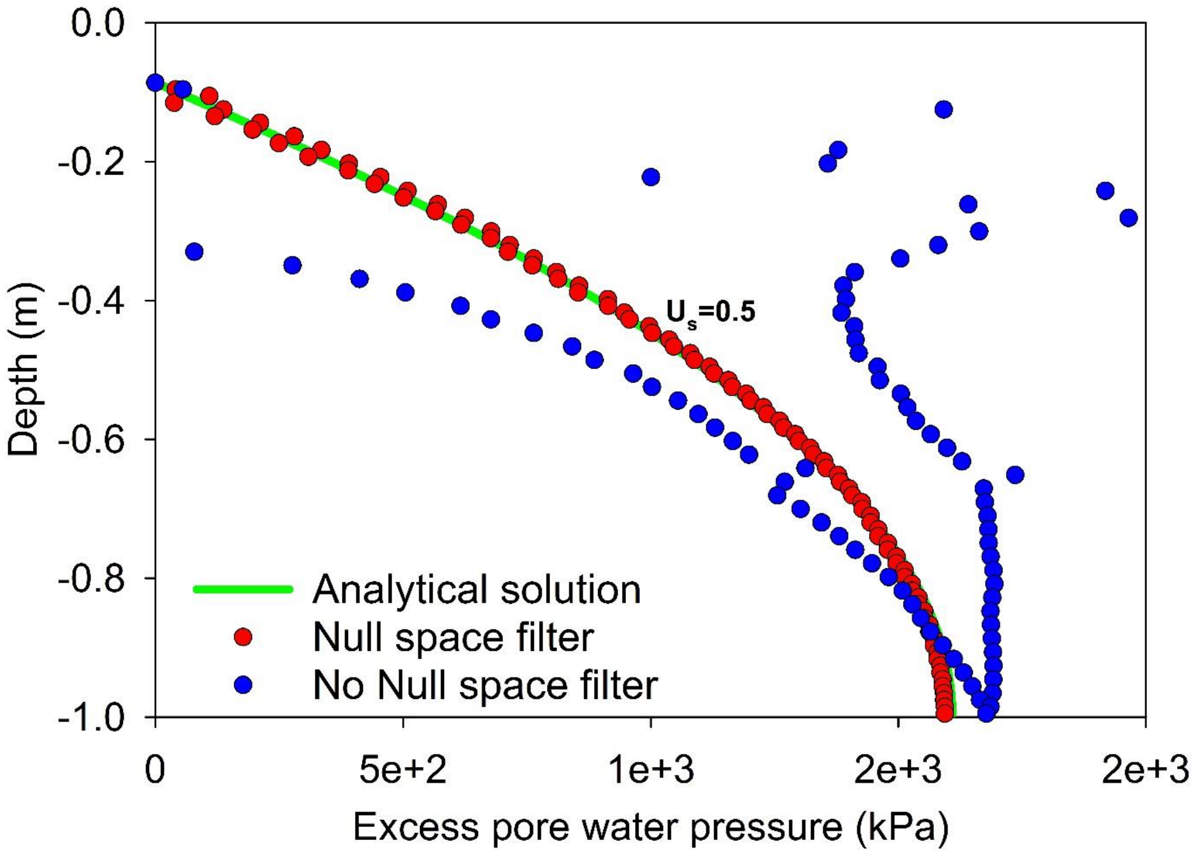
Numerical example: large strain consolidation



$$u = \frac{1}{m_{vl}} \ln\left(1 + (\exp(m_{vl} q) - 1) \sum_{m=1} \frac{2}{(m-0.5)\pi} \sin\left(\frac{(m-0.5)\pi z}{H}\right) \exp(-((m-0.5)\pi)^2 T_v)\right)$$

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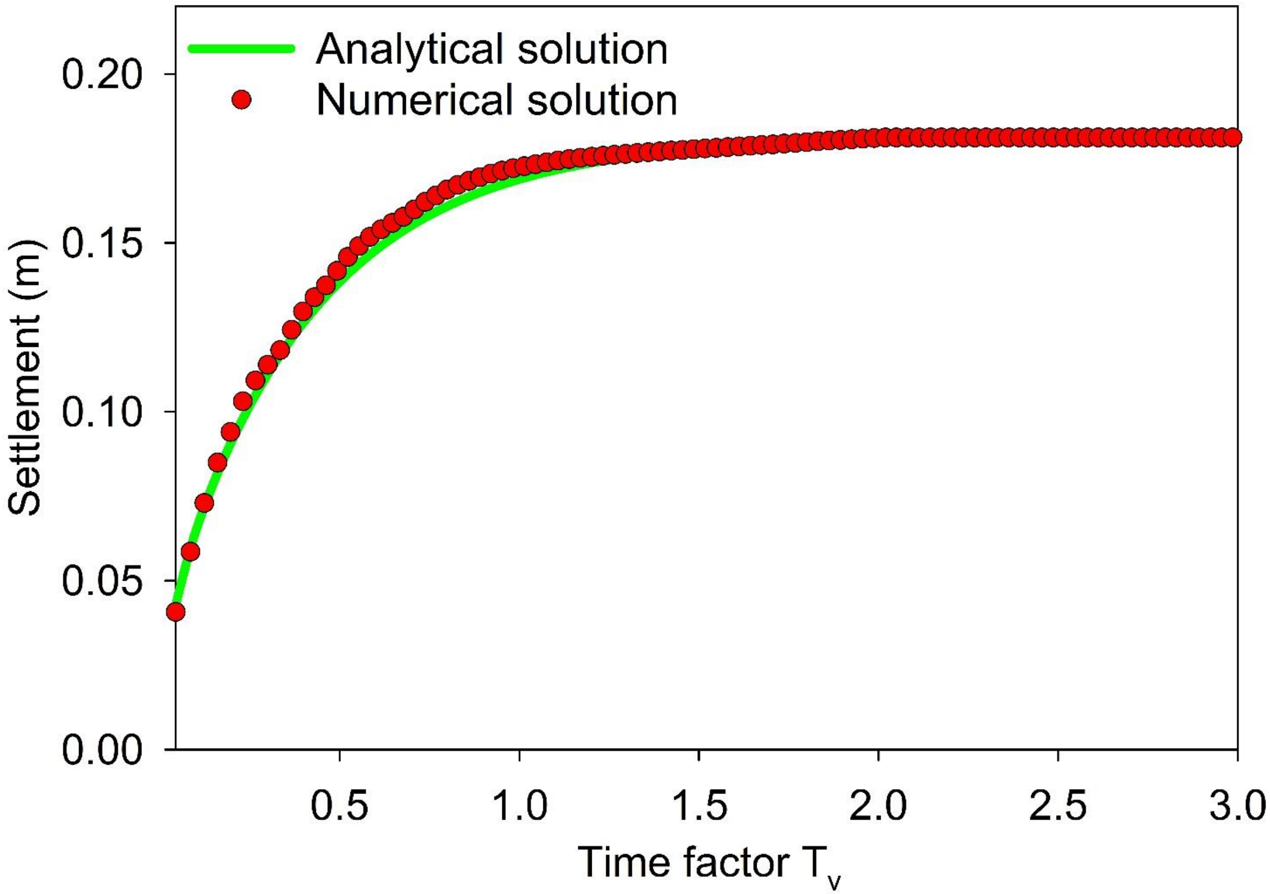
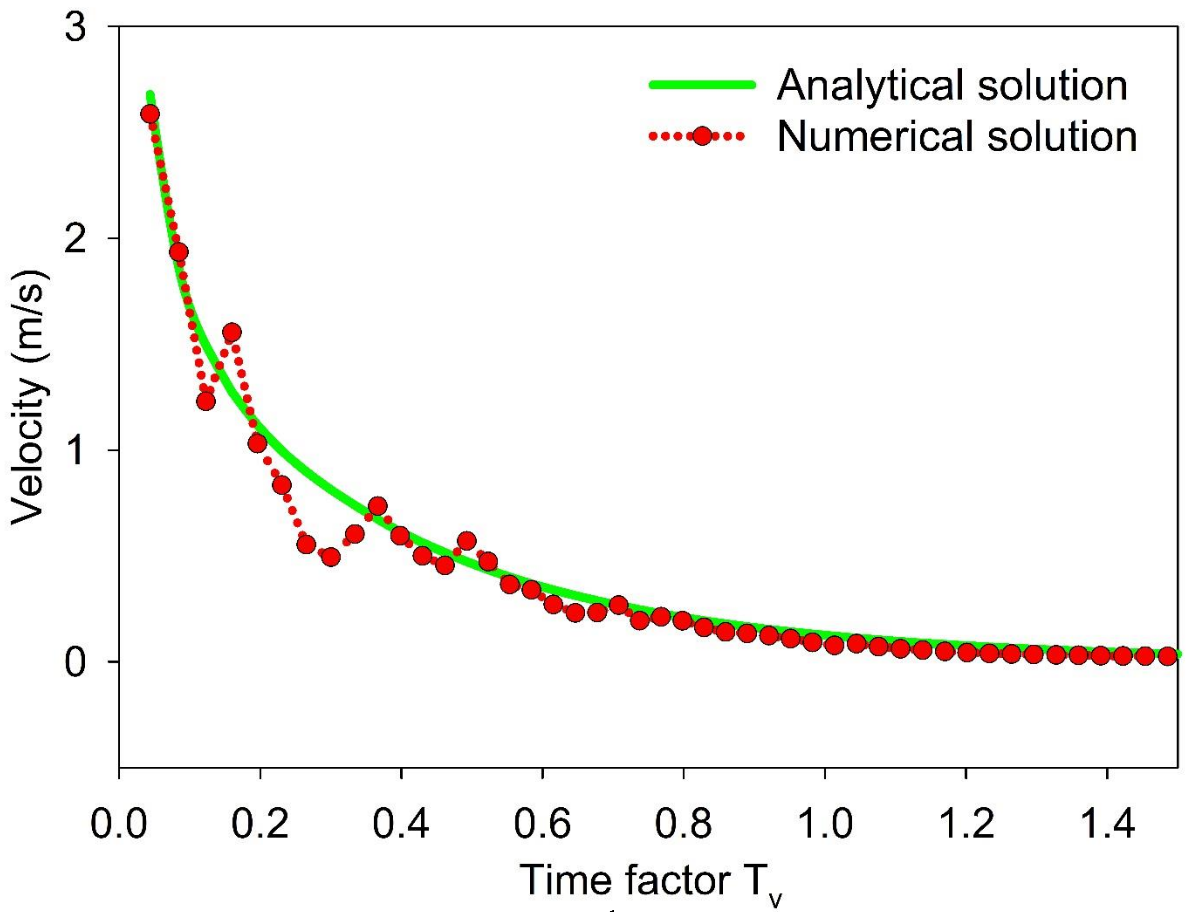
Numerical example: large strain consolidation



$$S_t = \mathrm{H}(1-\exp(-\mathrm{m_{vl}}q))\left(1-\sum_{\mathrm{m}=1}\frac{2}{((\mathrm{m}-0.5)\pi)^2}\exp\left(-((\mathrm{m}-0.5)\pi)^2\mathrm{T_v}\right)\right)\mathrm{c}$$

Numerical example: large strain consolidation



$$v_s = \frac{2c_v}{H}(1 - \exp(-m_{vl}q)) \sum_{m=1} \cos\left(\frac{((m-0.5)\pi)z}{H}\right) \exp\left(-((m-0.5)\pi)^2 T_v\right)$$

Future work

- More and more validations

- Consideration of seepage failure

- Advanced constitutive model (anisotropy, destructuration)