



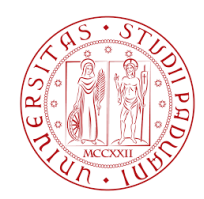
UNIVERSITÀ  
DEGLI STUDI  
DI PADOVA



AGI  
Associazione  
Geotecnica  
Italiana

# Material Point Method per la simulazione di problemi geotecnici a grandi spostamenti. Uno strumento per avanzare lo stato della pratica?

Francesca Ceccato



# Sommario

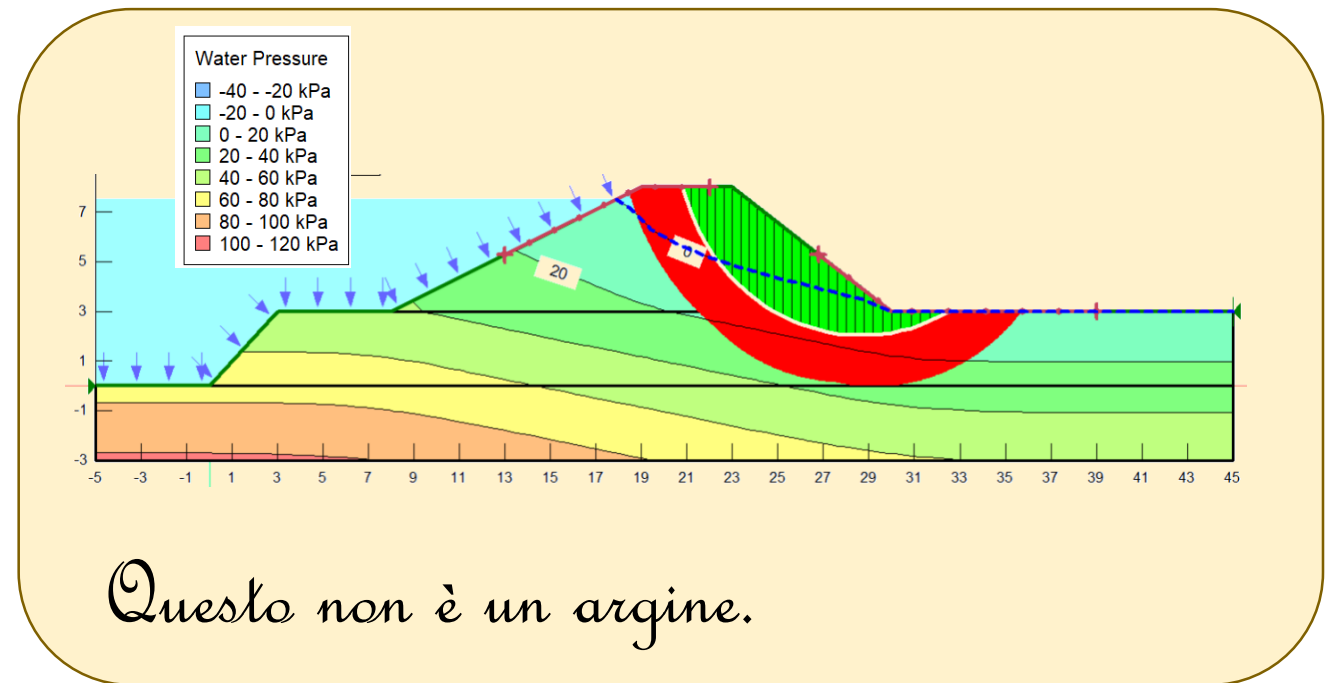
- Introduzione
  - Modellazione numerica in geotecnica
  - Concetti base del Material Point Method
- Applicazioni:
  - Collasso di un rilevato arginale
  - Collasso di un pendio innescato da pioggia
  - Ancoraggi
  - Gallerie

# Cos'è un modello geotecnico?

- **Rappresentazione** matematica e computazionale del terreno e delle strutture geotecniche



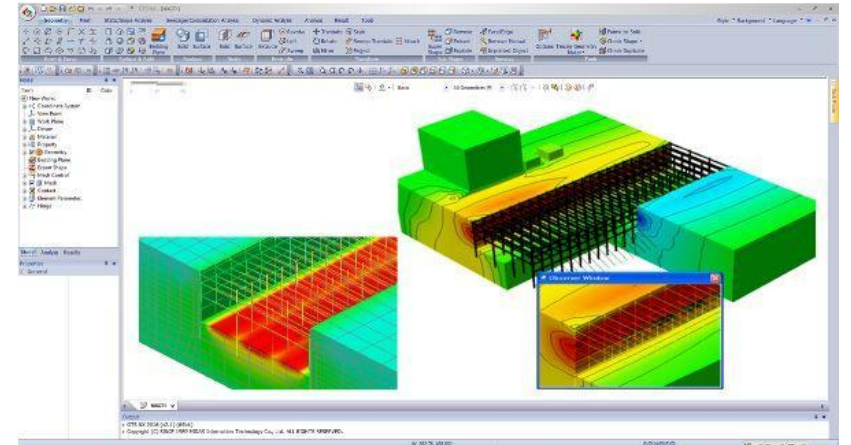
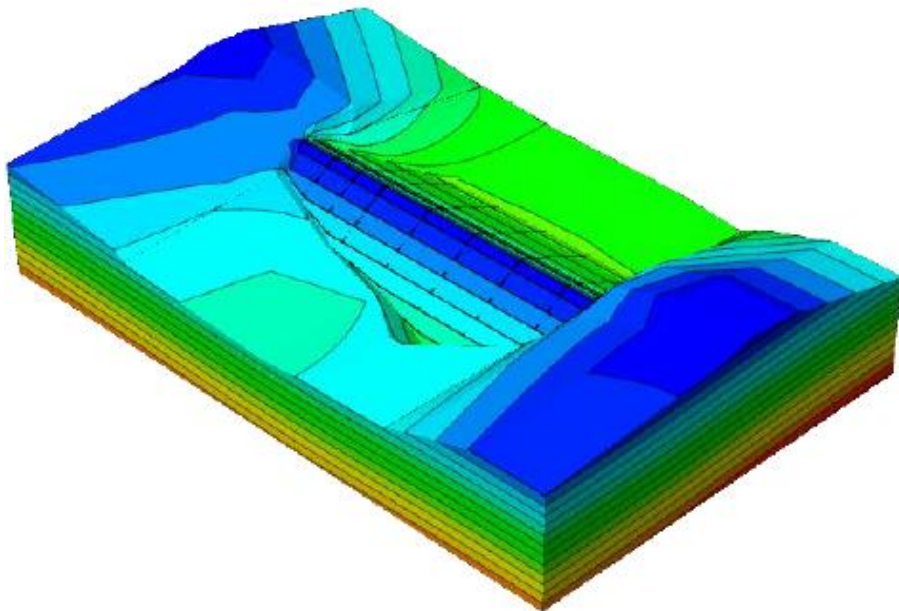
Magritte (1929)

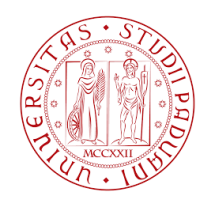


Questo non è un argine.

# A cosa serve la modellazione numerica?

- **Studiare** il comportamento del terreno e delle opere geotecniche in diverse condizioni di carico.
- **Supporto** alla progettazione delle opere e alla valutazione e mitigazione del rischio geotecnico (frana, sisma...)

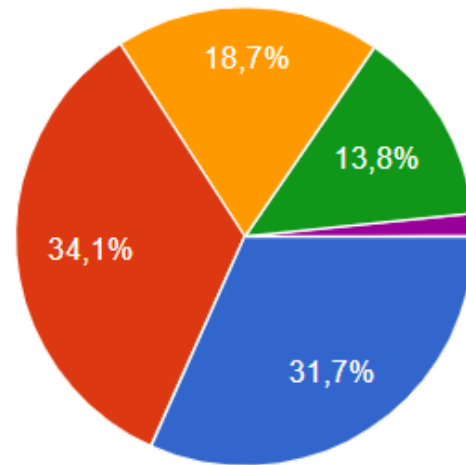




# Stato dell'uso della modellazione numerica

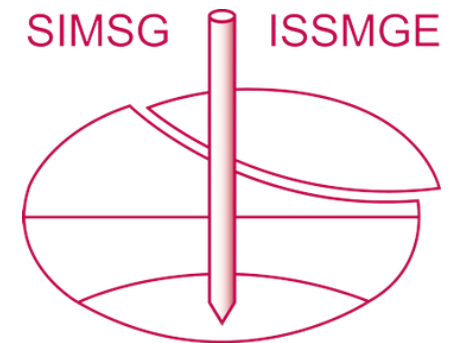
How often do you use numerical methods in your work?

123 risposte

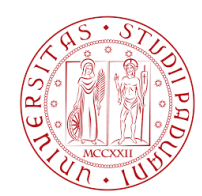


65.8%

- every day
- at least once a week, but not every day
- at least once a month, but not every week
- less than once a month
- never



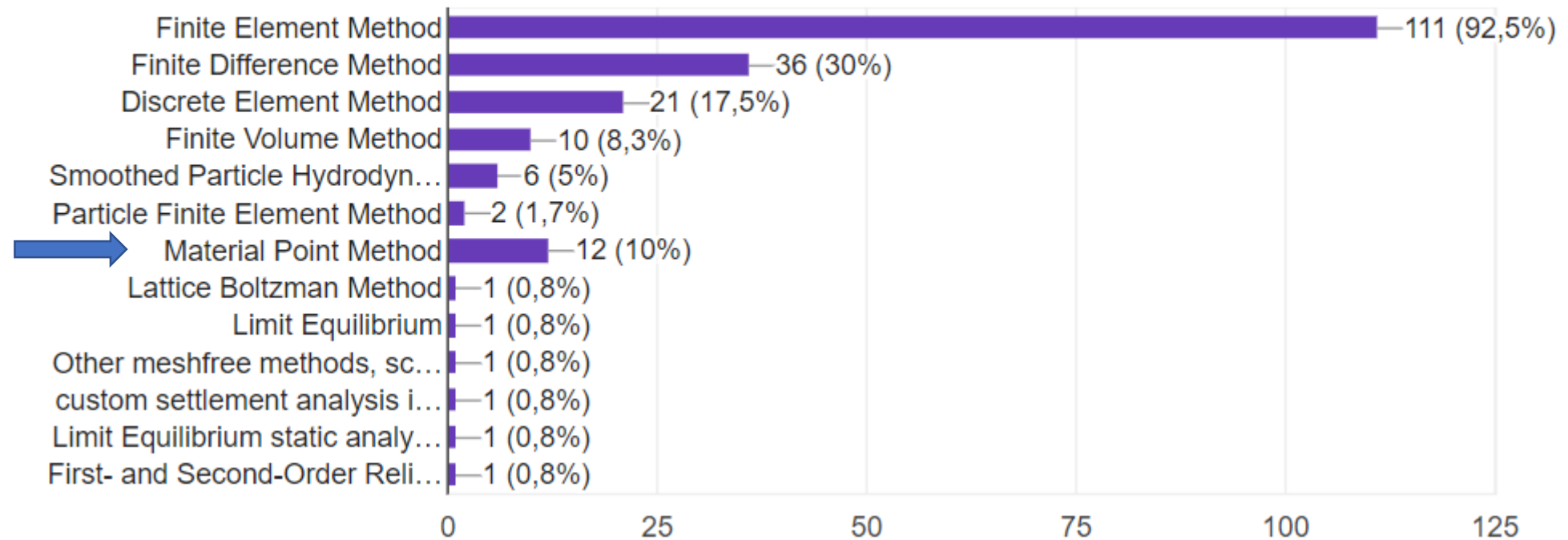
Risultati sondaggio effettuato da TC103 - *numerical methods* (gennaio-febbraio 2022)



# Stato dell'uso della modellazione numerica

What numerical method do you use?

120 risposte



Risultati sondaggio effettuato da TC103 (gennaio-febbraio 2022)

# Problemi a grandi spostamenti

installazione, impatto



argini, dighe, frane



erosione, liquefazione

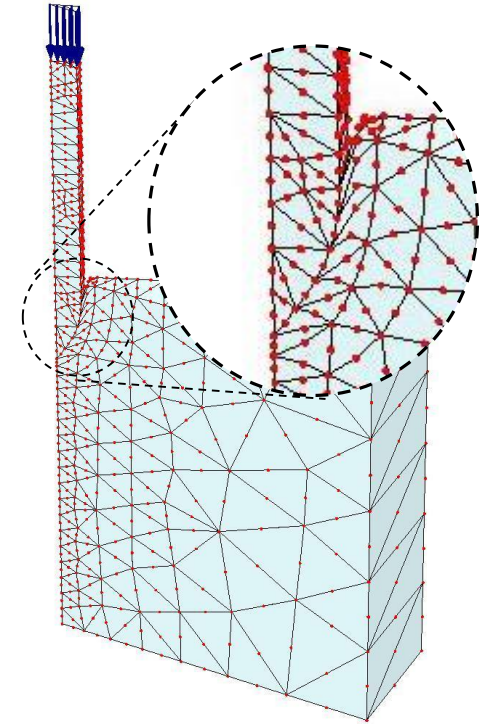
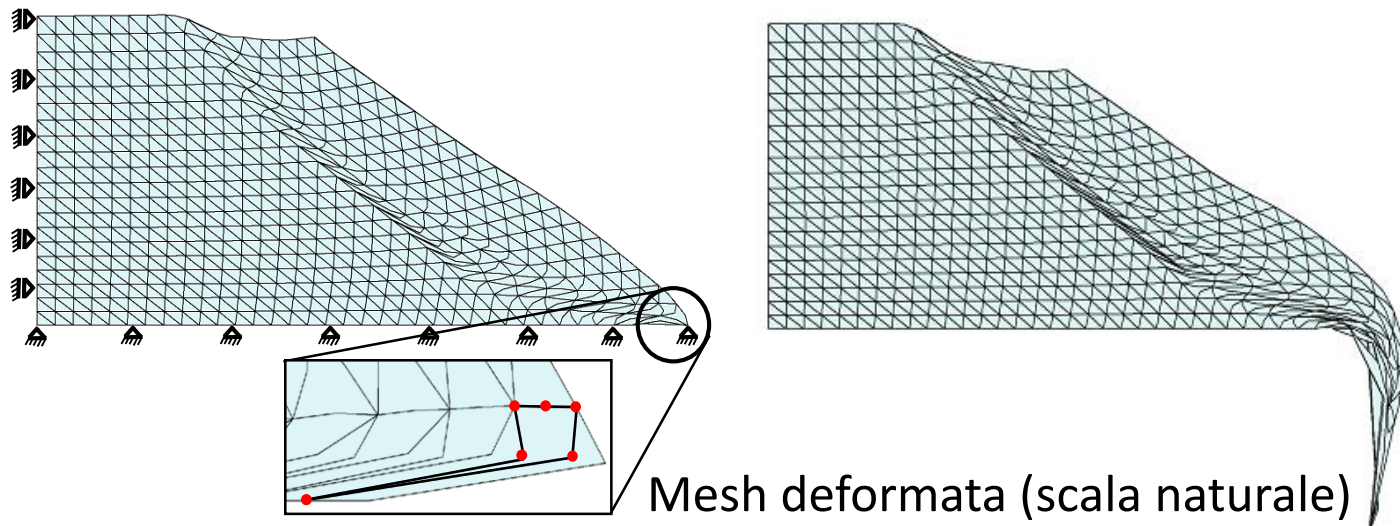


Stabilità degli scavi

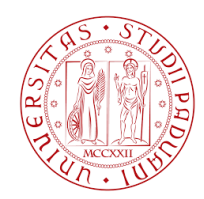


# Simulazione di problemi a grandi spostamenti

UL-FEM non è adatto a simulare grandi deformazioni/spostamenti per problemi di convergenza legati alla deformazione degli elementi



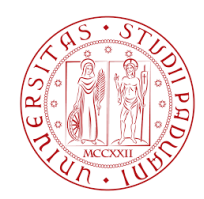




# Metodi alternativi

Tra i metodi basati sul continuo, possono simulare grandi spostamenti:

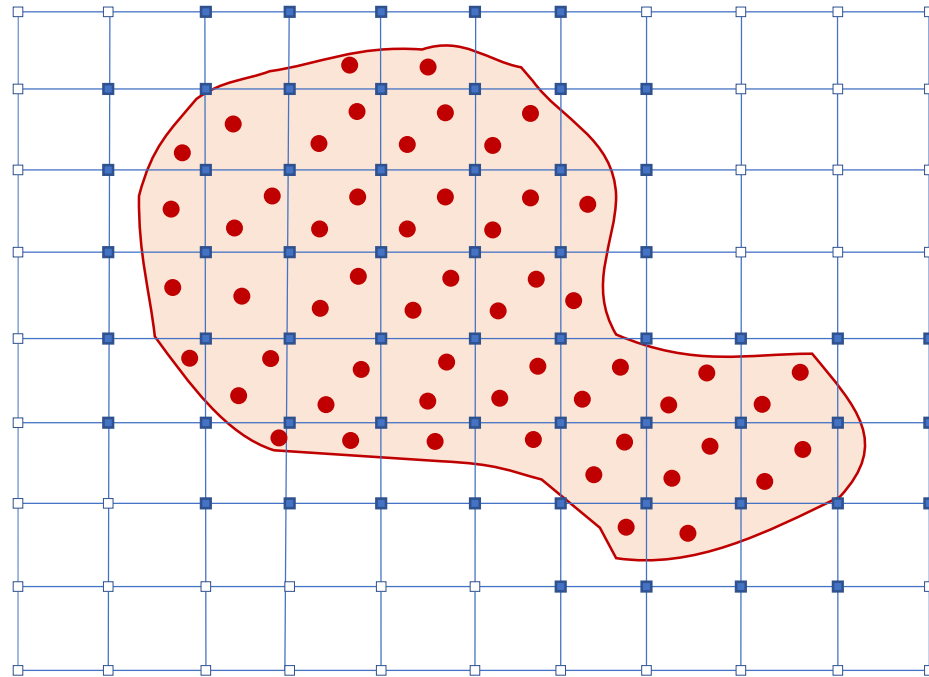
- Arbitrary Lagrangian-Eulerian (ALE) methods
- Coupled Eulerian Lagrangian Method (CEL)
- Smoothed Particle Hydrodynamics (SPH)
- Particle Finite Element Method (PFEM)
- **Material Point Method (MPM)**



# MPM: concetti base

L'MPM utilizza due livelli di discretizzazione:

1. Il corpo è discretizzato da una nuvola di **punti materiali** (MP) che tracciano tutte le proprietà del continuo, ad esempio massa, velocità, accelerazione, sollecitazioni e parametri materiali.
2. Una **mesh** di sfondo copre l'intero spazio in cui ci si aspetta che il corpo si muova.



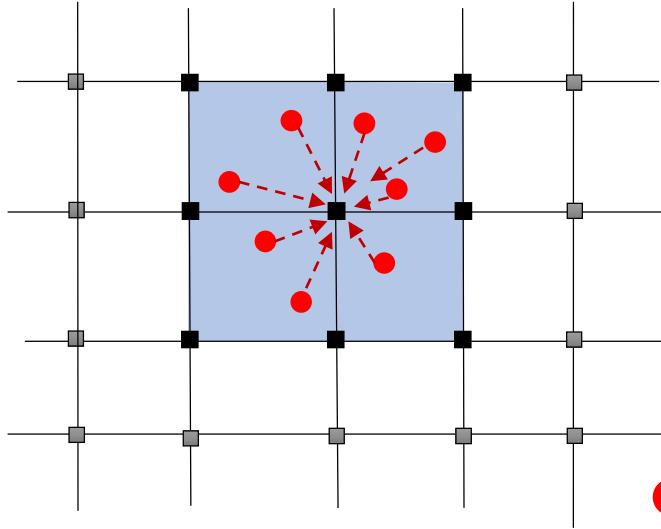
● MP

■ Active node

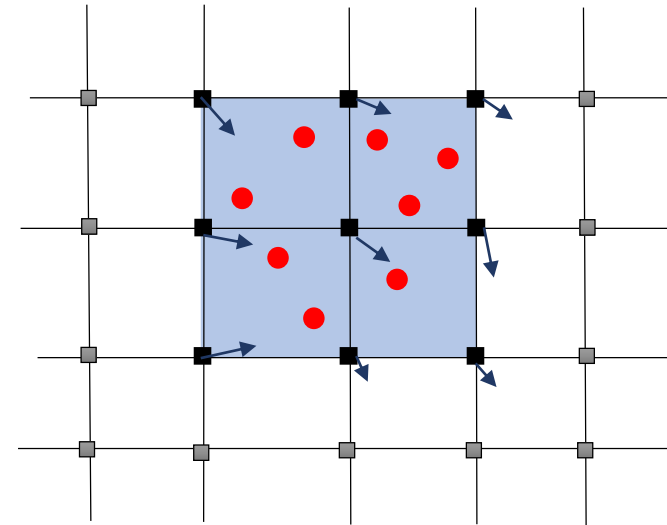
□ Non-Active node

# MPM: concetti base

1.

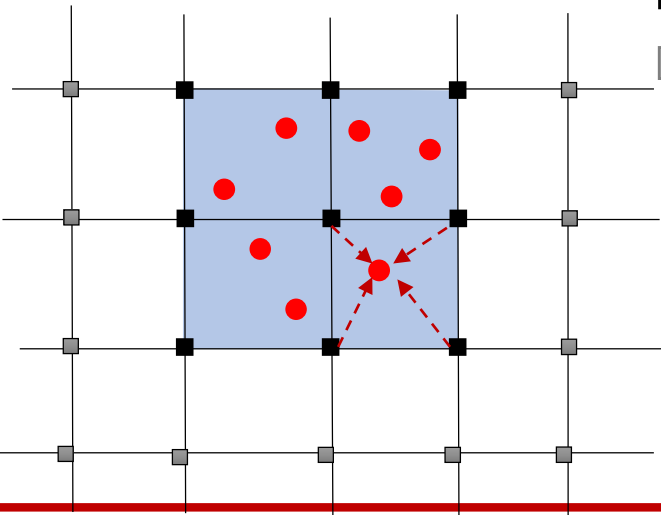


2.

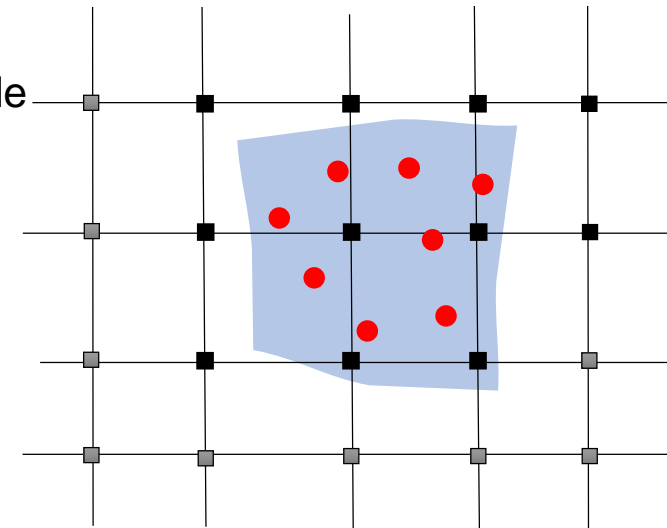


- Material Point
- Active node
- Non-active node

3.



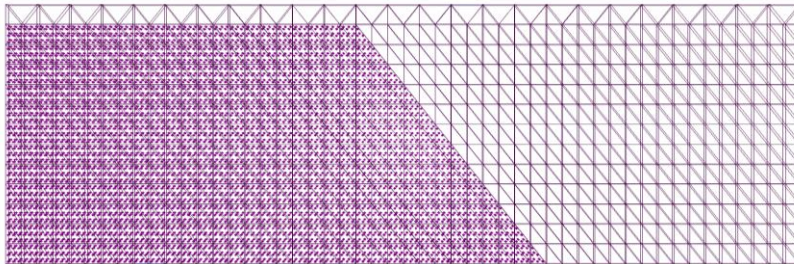
4.



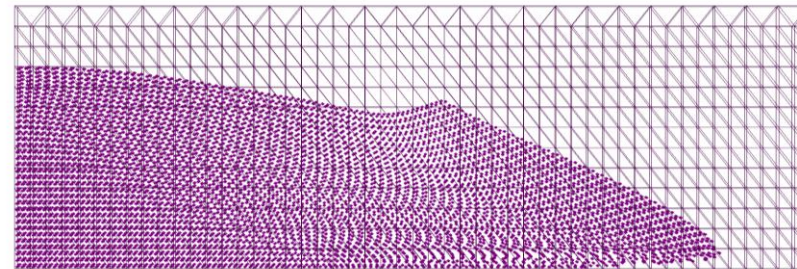
# MPM: concetti base

Grandi spostamenti vengono simulati da MP che si muovono attraverso la mesh

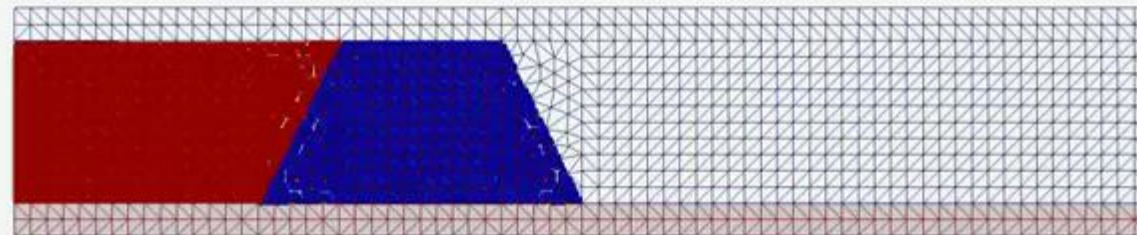
Initial position of material points



Final position of material points



Example: dam failure

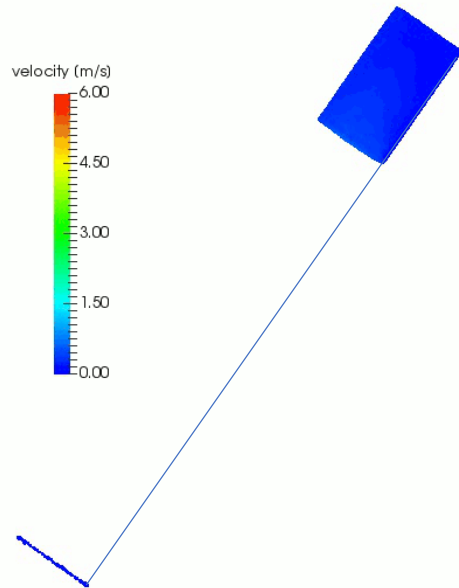


time: 0.00 (s)



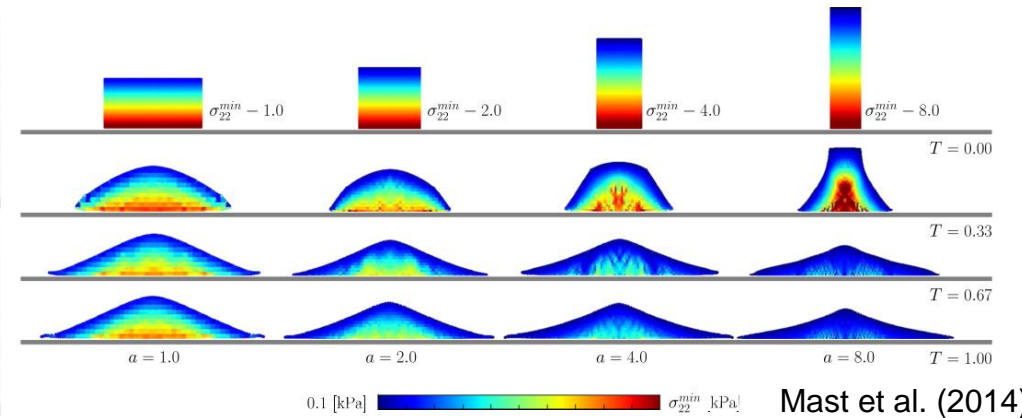
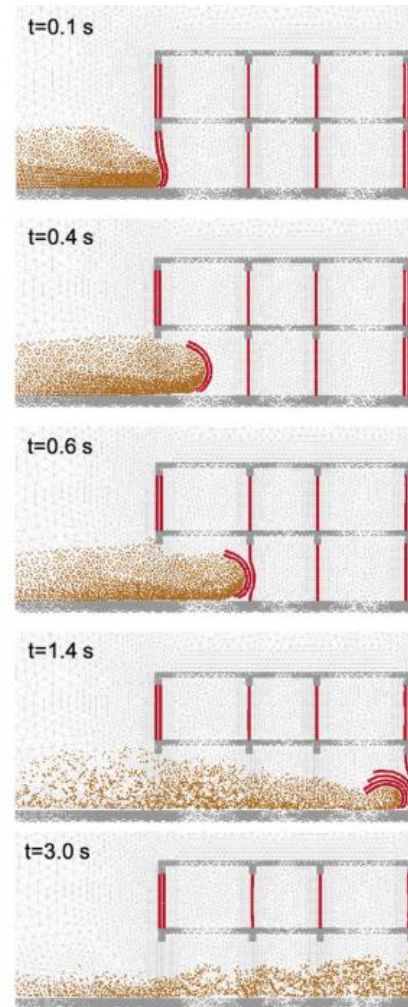
# Applicazioni

- **Flussi glarulari:** column collapse (Mast et al. 2014, Fern et al. 2016, Ceccato et al. 2020...), flussi su piani inclinati, impatto su strutture (Cuomo et al 2021)...

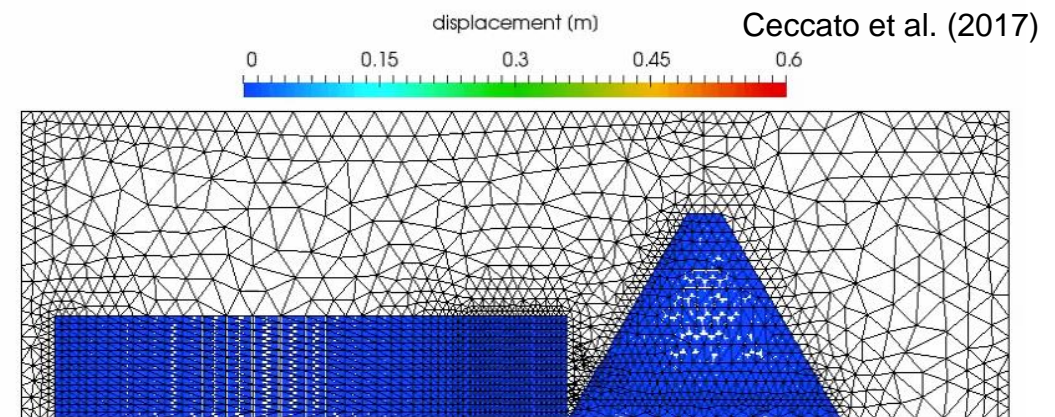


Ceccato et al. (2016)

Cuomo et al. (2021)



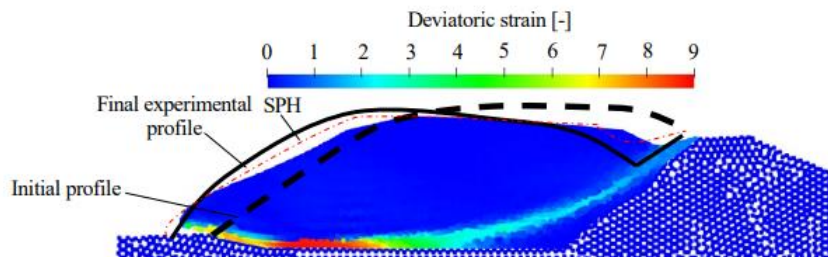
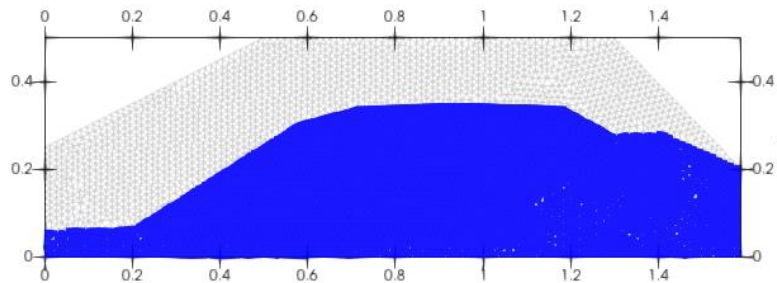
Mast et al. (2014)



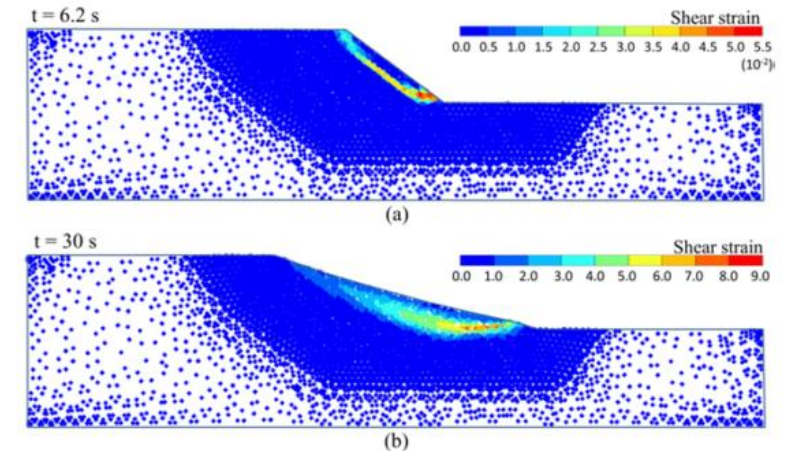
Ceccato et al. (2017)

# Applicazioni

- **Slope stability: frane indotte da sisma** (Alsardi et al. 2021), o pioggia (Cuomo et al. 2021, Girardi et al. 2022), **progressive failure** (Alonso and Zabala 2011, Yerro et al. 2014, Conte et al. 2019, 2020), **instabilità di argini e dighe** (Bandara and Soga 2015, Ceccato et al. 2020, Girardi et al. 2021)...



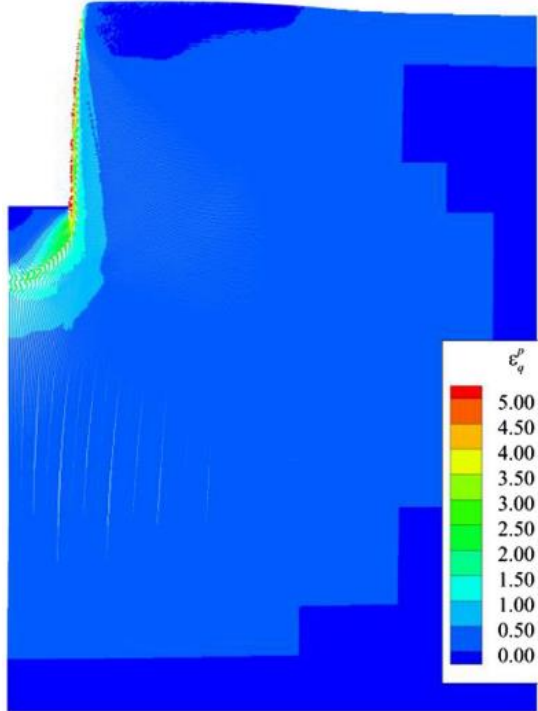
Alsardi, et al. (2021);  
Alsardi and Yerro (2020)



Yerro et al. (2014)

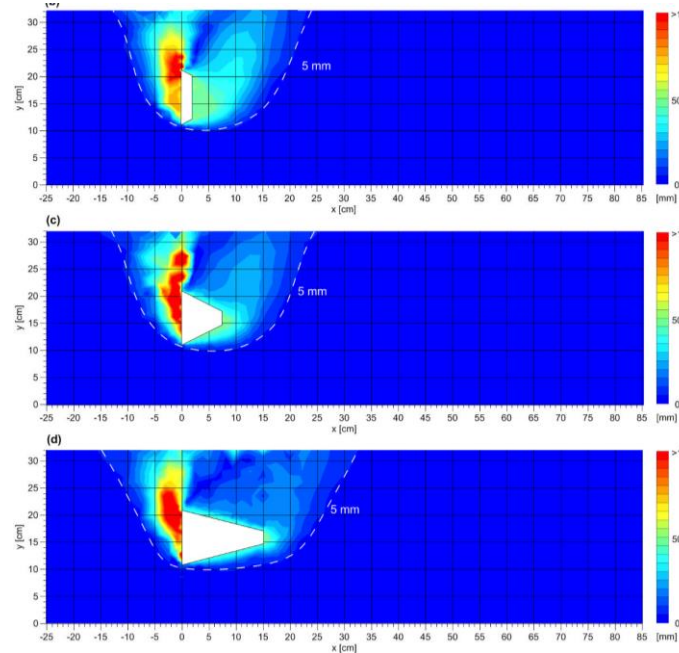
Introduzione/movimento di strutture nel terreno: Fondazioni superficiali (Woo and Salgado 2018), installazione di pali (Nuygen et al. 2014), CPT/CPTU (Beuth and Vermeer 2013, Ceccato et al. 2016), pullout ancore (Ceccato et al. 2018), installazione di ancore

shallow foundation



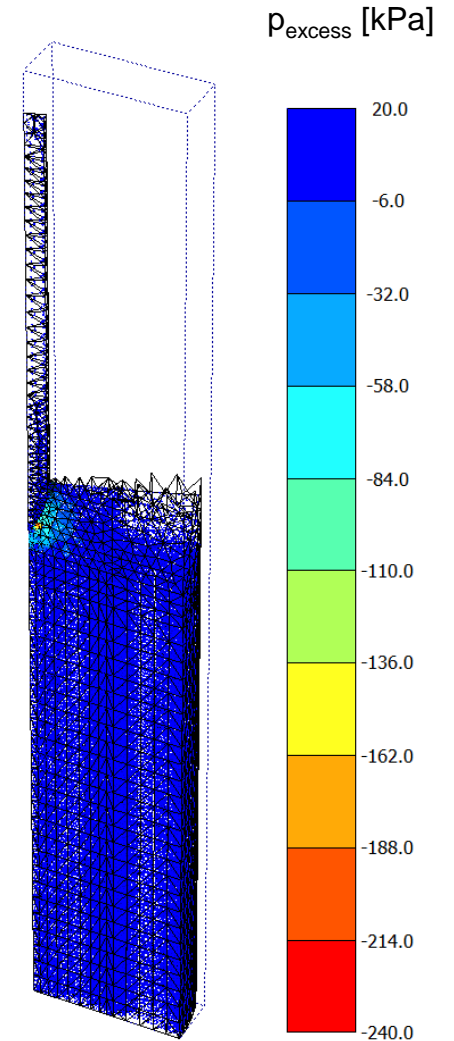
Woo and Salgado (2018)

anchor pullout



Ceccato et al. (2018)

CPT/CPTU penetration

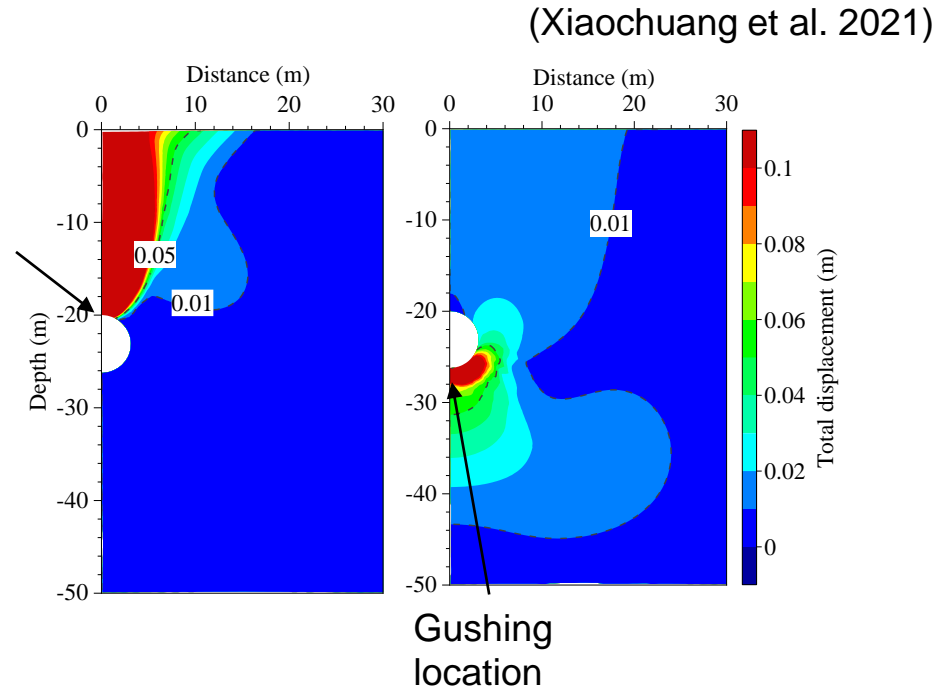


Ceccato et al. (2016)<sup>15</sup>

# Applicazioni

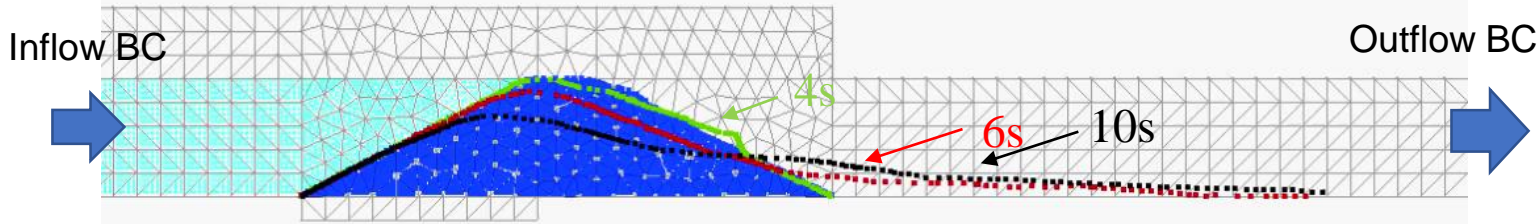
- Problemi erosivi: overflow (*Liang et al. 2020*), suffusion (Yerro et al 2017, Murphy et al 2020), infiltrazioni in opere in sotterraneo (*Xiaochuang et al. 2021*)

Gushing location



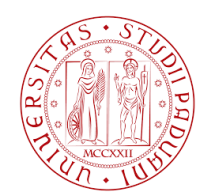
Time: 0.00s

Horizontal displacement



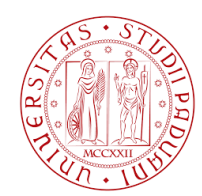
(Zhao & Liang, 2019, Liang et al. 2020)





# Codici attualmente disponibili

- **AMPLE** <https://wmcoombs.github.io/download/> (W. Coombs, C. Augarde, Duram, UK)
- **CB-Geo MPM** [github.com/cb-geo/mpm](https://github.com/cb-geo/mpm) (K. Soga, K. Kumar, Cambridge & UBC Berkeley)
- **SIMPA**: the MPM implementation at TU Delft (P. Vardon)
- **MPM in KRATOS** Multiphysics [github.com/KratosMultiphysics/Kratos/wiki](https://github.com/KratosMultiphysics/Kratos/wiki)
- **NairnMPM/OSParticulas** (and NairnFEA) by prof. John Nairn (Wood Science & Engineering, OSU, Corvallis, OR)
- **Uintah** MPM software [www.uintah.utah.edu](http://www.uintah.utah.edu) (Utah, US)
- **MPM3D**, <http://comdyn.hy.tsinghua.edu.cn/english/mpm3d> (Prof. X: Zhang, Tsinghua University, China)
- **Karamelo** (Deakin University & Monash University, Australia)
- Many others...



# Anura3D research community

Anura3D ([www.anura3d.com](http://www.anura3d.com)):

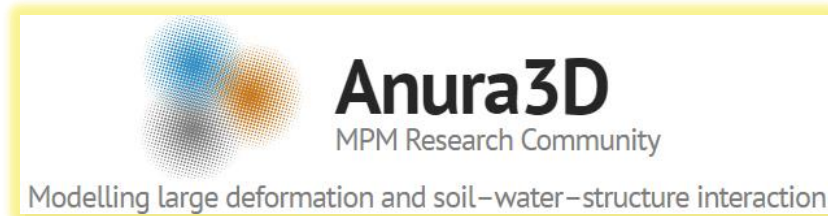
- Open source ([https://github.com/Anura3D/Anura3D\\_OpenSource/tree/main/src](https://github.com/Anura3D/Anura3D_OpenSource/tree/main/src))
- Focus su interazione fluido-terreno-struttura
- Grande Gruppo di sviluppatori&utilizzatori



Deltares



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BARCELONATECH



# Applicazioni: collasso arginale per sollevamento al piede

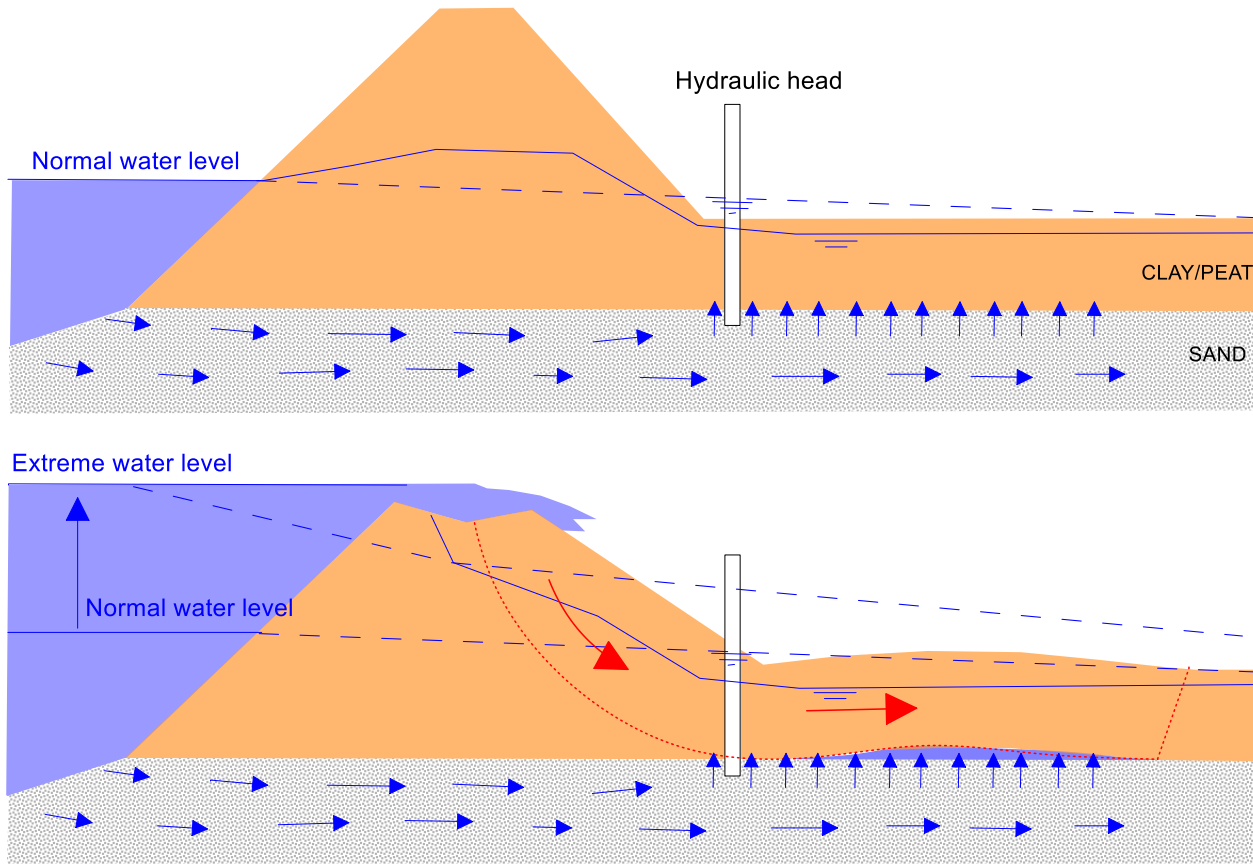


Veronica Girardi, Francesca Ceccato, Alex Rohe, Paolo Simonini, Fabio Gabrieli

Girardi, V. *et al.* (2022) 'Failure of levees induced by toe uplift: Investigation of post-failure behavior using material point method', *Journal of Rock Mechanics and Geotechnical Engineering*. doi:10.1016/j.jrmge.2022.07.015.

# Sollevamento al piede (uplift)

## Come fare la valutazione della sicurezza?



Adapted from Van (2005)

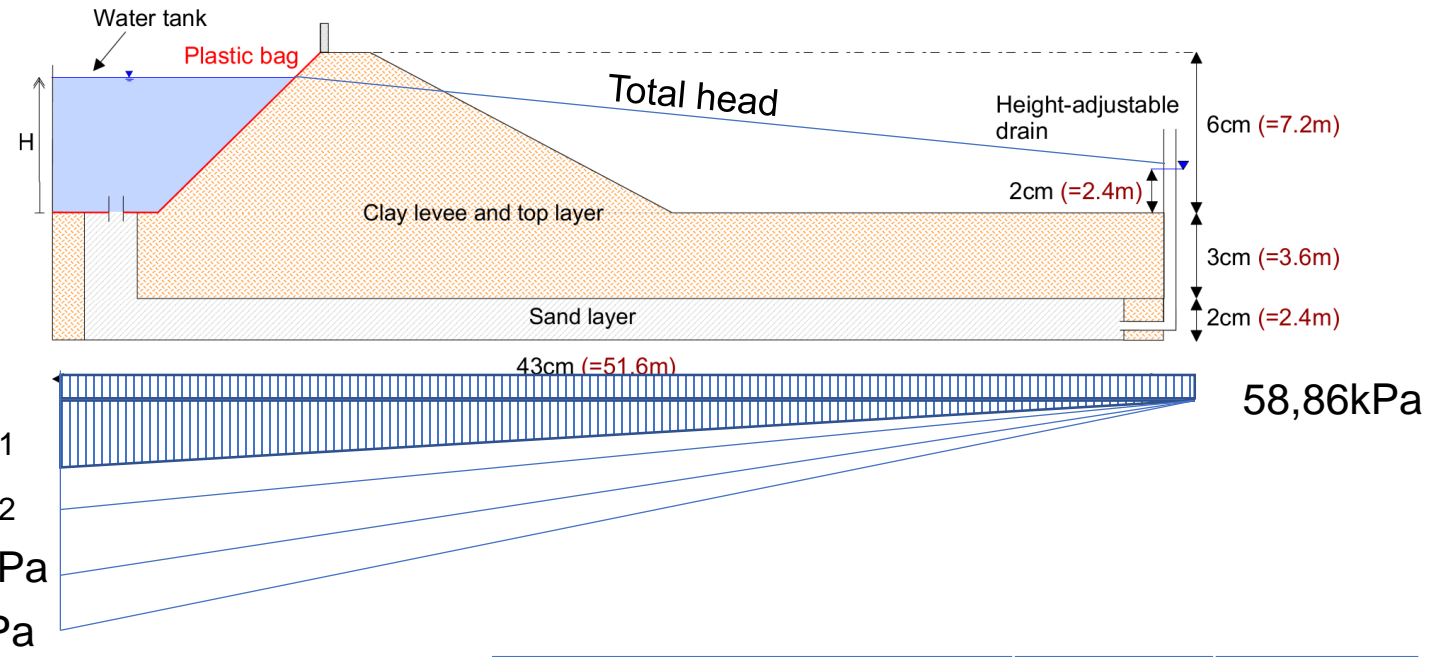
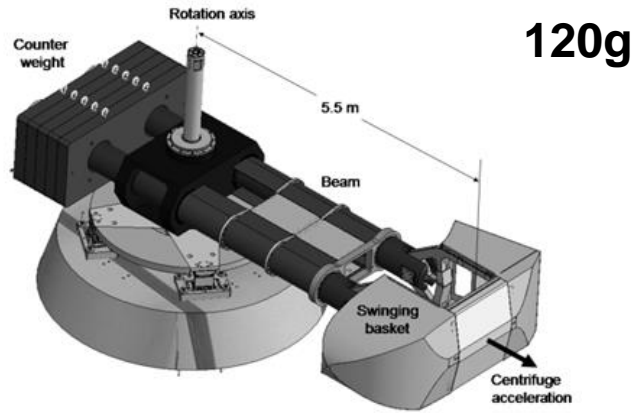
Stato della pratica: valutazione  
fattore di sicurezza (FS)

1. Metodo analitico:  $\sigma > u$
2. Equilibrio limite (LEM)
3. Elementi Finiti (FEM)

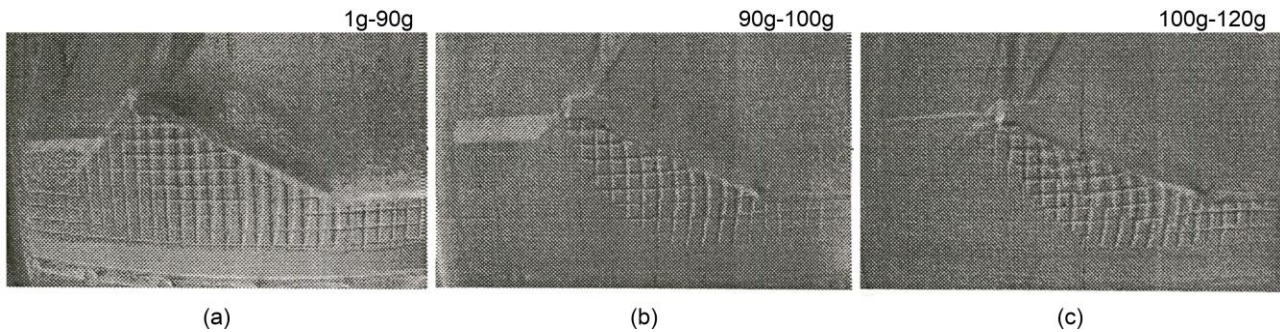
*Spostamenti?*



# Esperimento in centrifuga



Allersma and Rohe (2003)



	Argilla	Sabbia
Peso di volume, $\gamma$ , kN/m <sup>3</sup>	20,4	20
Angolo d'attrito [°]	22	37
Coesione [kPa]	10	0
Conducibilità idraulica [m/s]	$7,4 \cdot 10^{-9}$	$7,4 \cdot 10^{-3}$

# Modello analitico

- $FS = \sigma / u$
- Uplift inizia già prima della fase 3:

$$\sigma = \gamma z = 20,4 * 3,6 = 73,44kPa$$

$$u_{toe,3} = 75,68kPa > 73,44kPa (FS=0,97)$$

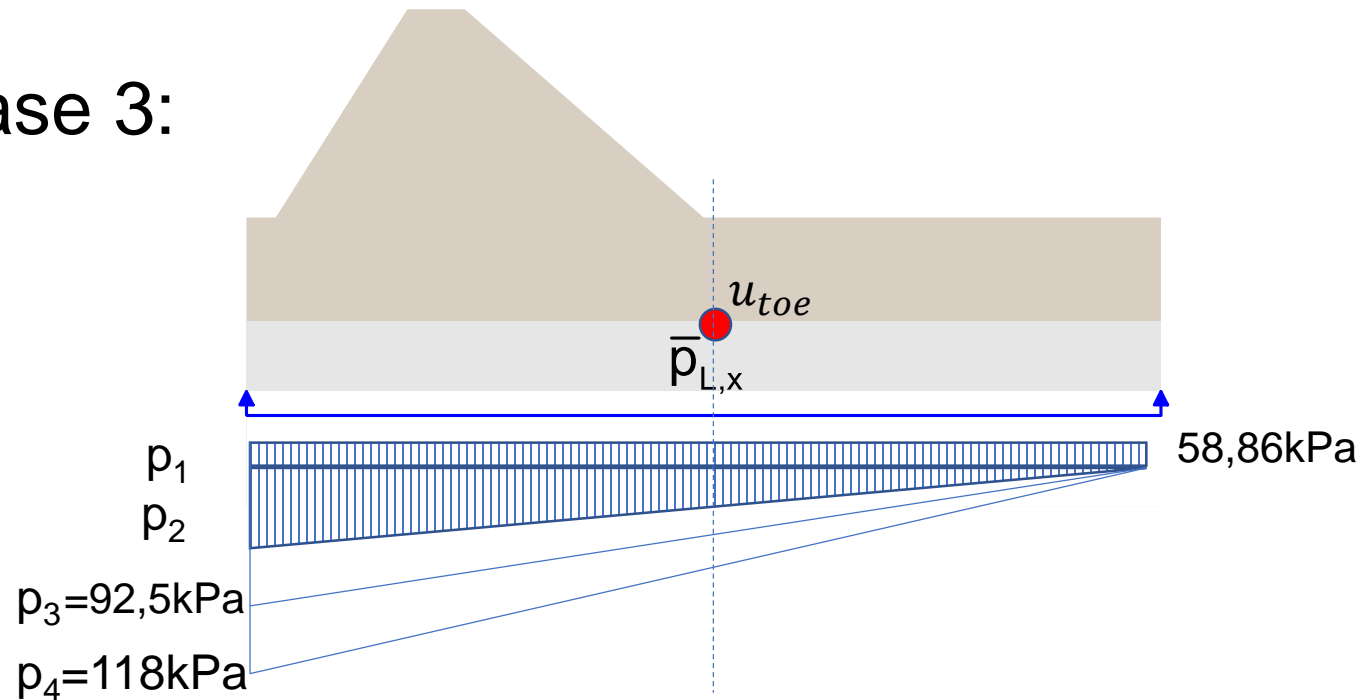
$$u_{toe,4} = 88,43kPa (FS = 0,830)$$

## Vantaggi:

- Analisi molto molto veloci e semplici (utili per analisi probabilistiche o parametriche)

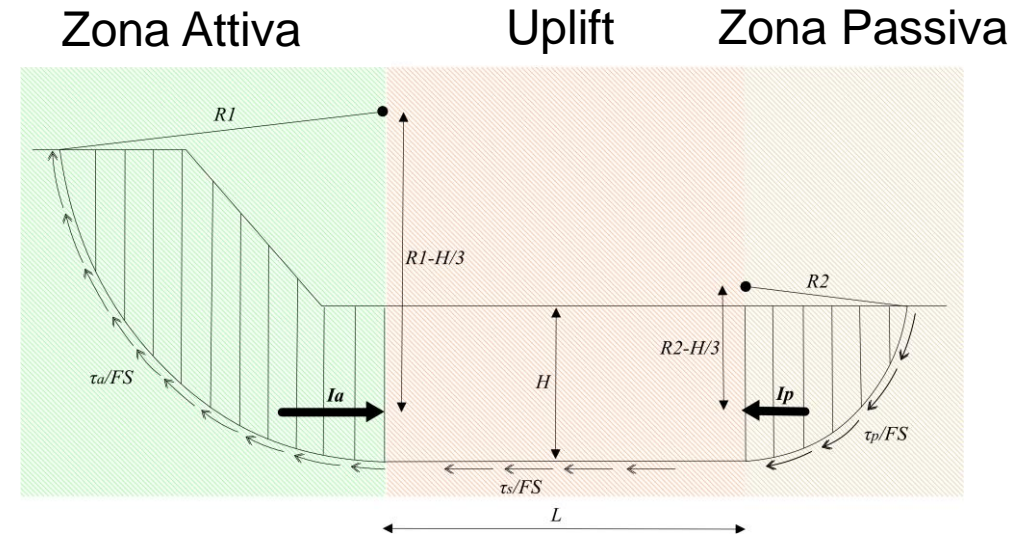
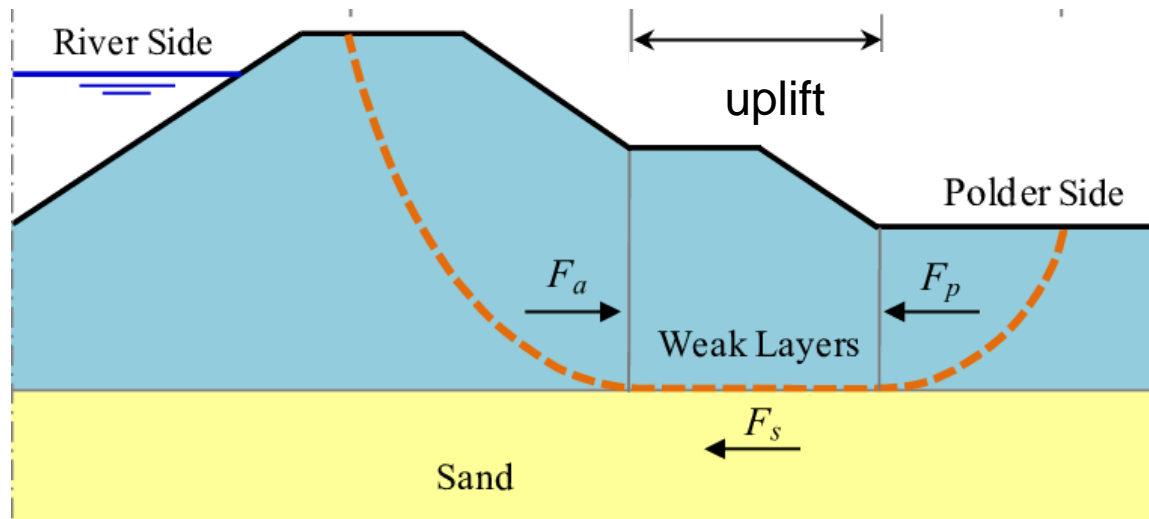
## Svantaggi:

- Solo equilibrio verticale
- I risultati potrebbero non essere realistici
- Nessuna informazione sugli spostamenti

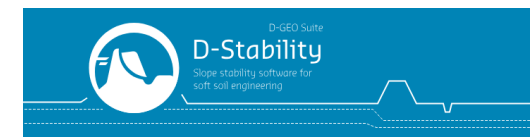


# Modello all'equilibrio limite

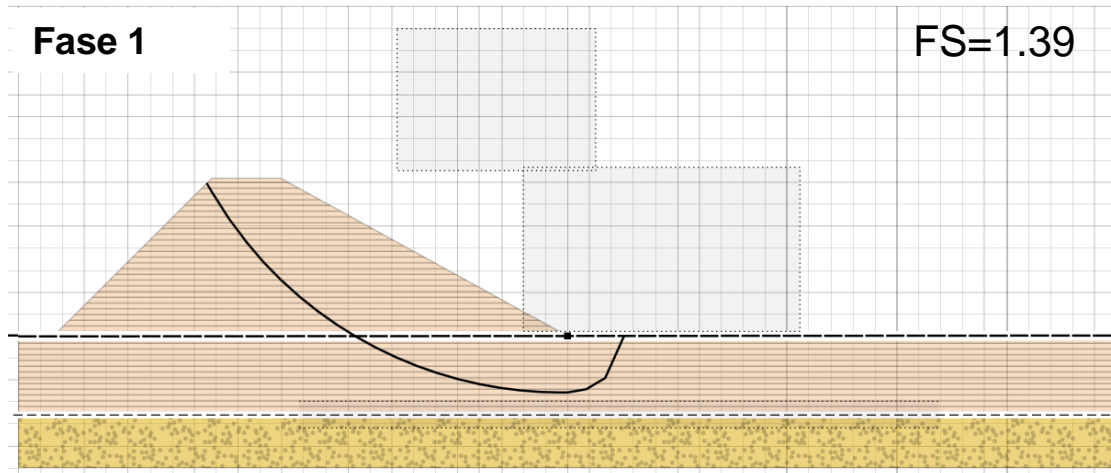
## Metodo di Van (variante del metodo dei conci)



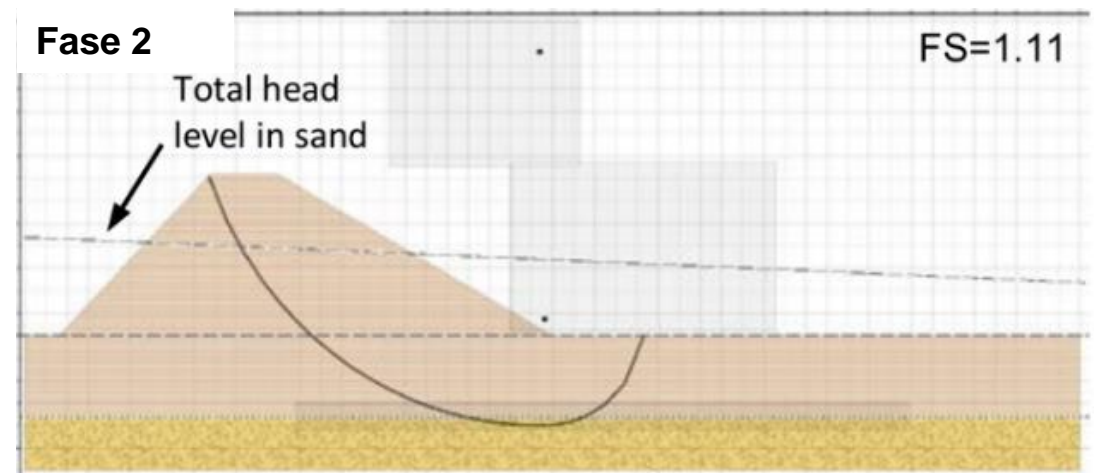
	Argilla	Sabbia
Peso di volume, $\gamma$ , kN/m <sup>3</sup>	20,4	20
Angolo d'attrito [°]	22	37
Coesione [kPa]	10	0



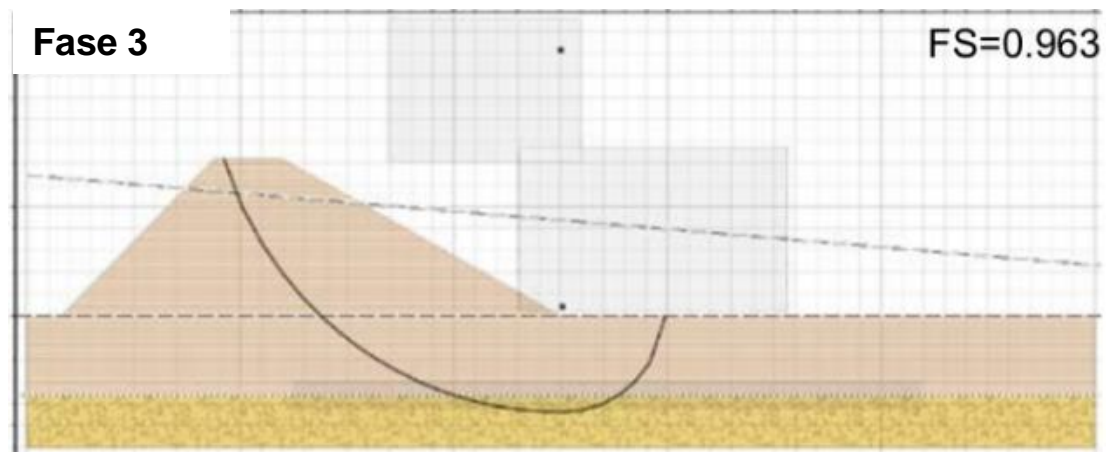
# Risultati metodo di Van



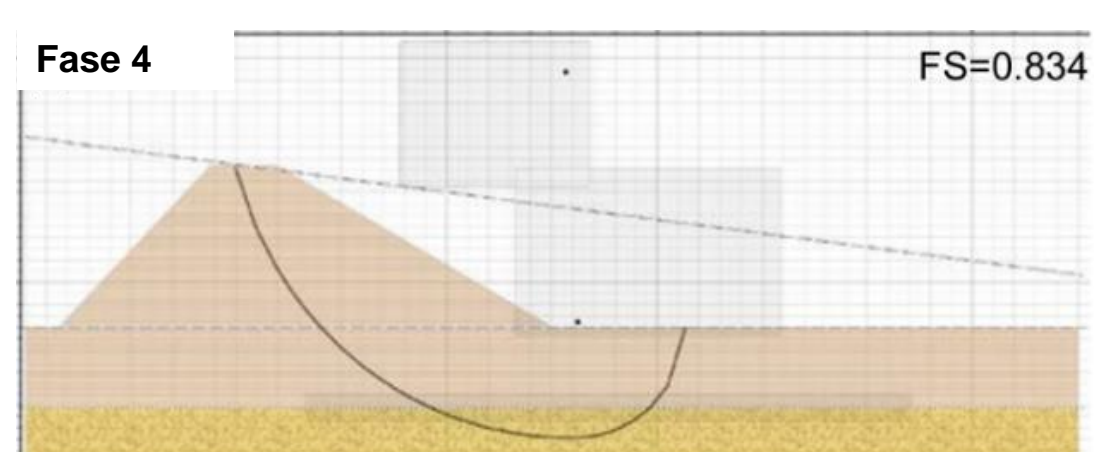
FS>1 argine stabile



FS>1 argine stabile

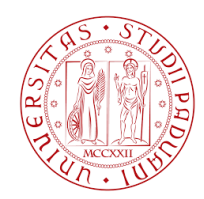


FS<1 argine instabile (inizio rottura)



FS<<Argine instabile (collasso)





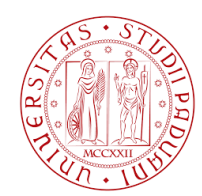
# Considerazioni

## Vantaggi:

- Analisi molto veloci e semplici (utili per analisi probabilistiche o parametriche)
- Sono necessari solo i parametri di resistenza
- Nessun problema di convergenza

## Svantaggi:

- Superficie di rottura ipotizzata a priori
- Nessuna informazione sugli spostamenti



# Modello FEM (stress-seepage)

Filtrazione

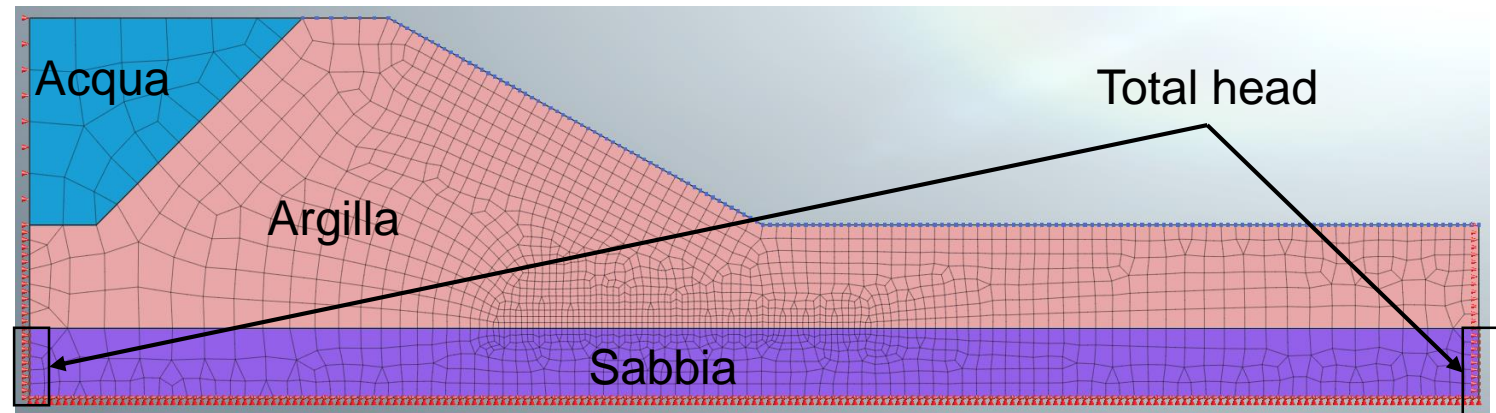


Tensioni e  
deformazioni

FS può essere calcolato con SRM  
(phi-c-reduction)



	Argilla	Sabbia
Peso di volume, $\gamma$ , kN/m <sup>3</sup>	20,4	20
Angolo d'attrito [°]	22	37
Coesione [kPa]	10	0
Modulo Elastico [MPa]	5,5	55
Coefficiente di Poisson [-]	0,15	0,33
Conducibilità idraulica [m/s]	$7,4 \cdot 10^{-9}$	$7,4 \cdot 10^{-3}$



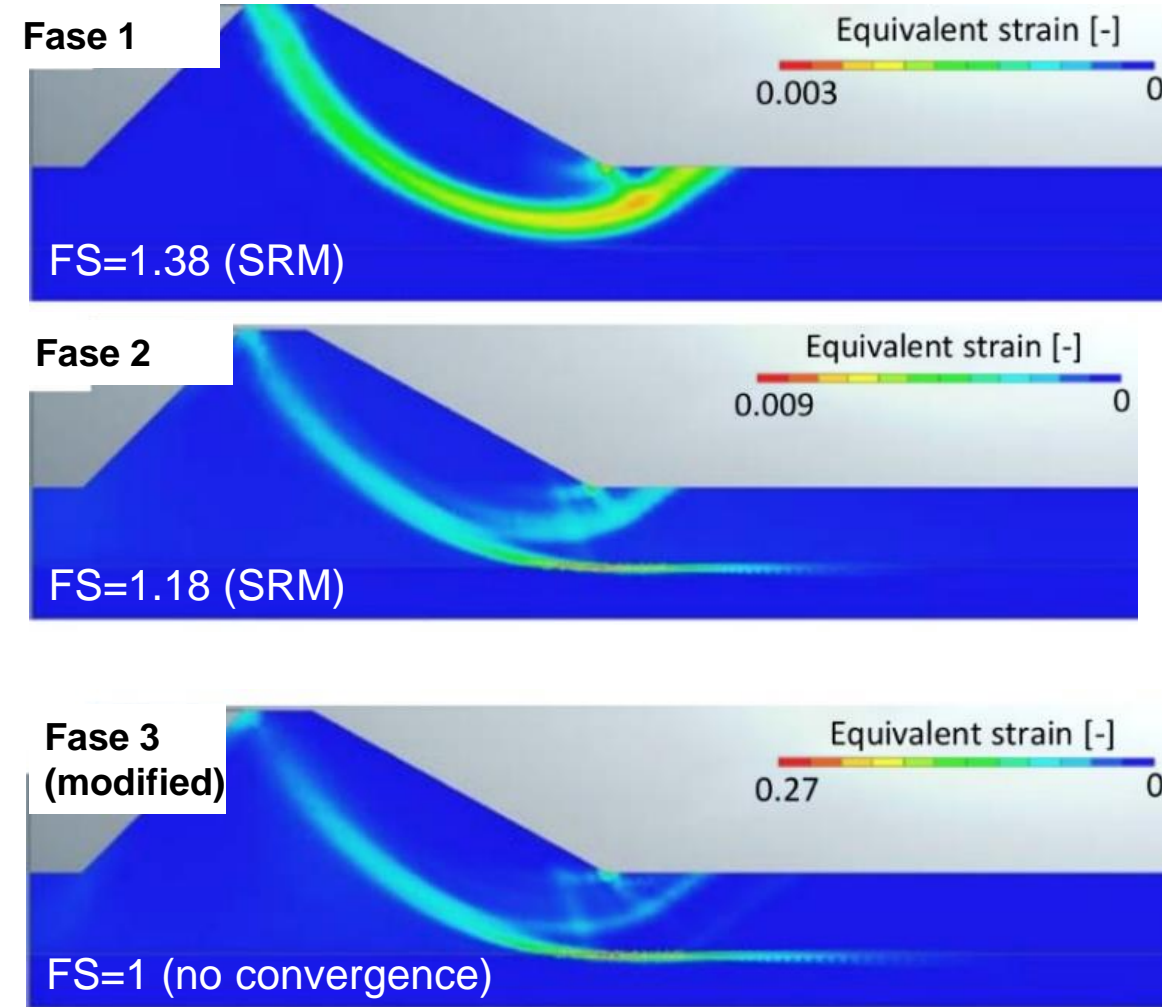
# Risultati modello FEM (stress-seepage)

## Vantaggi:

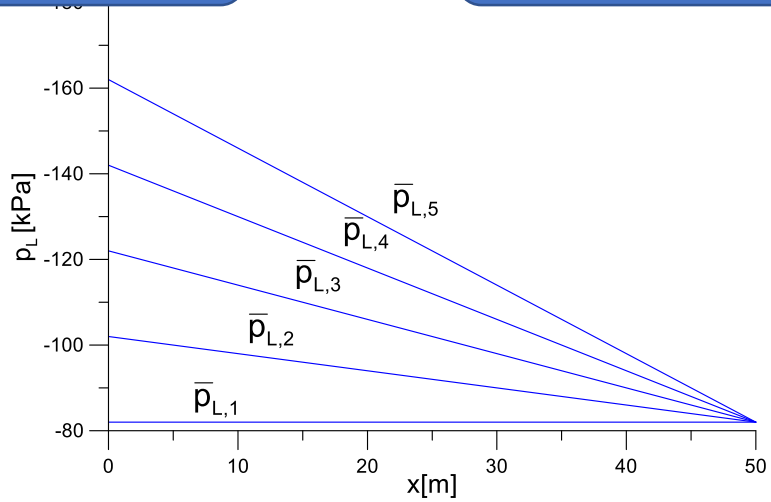
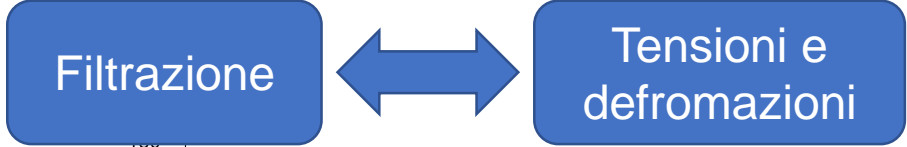
- La superficie di rottura è il risultato del calcolo
- Lo spostamento può essere calcolato solo per piccole deformazioni
- Costo computazionale medio

## Svantaggi:

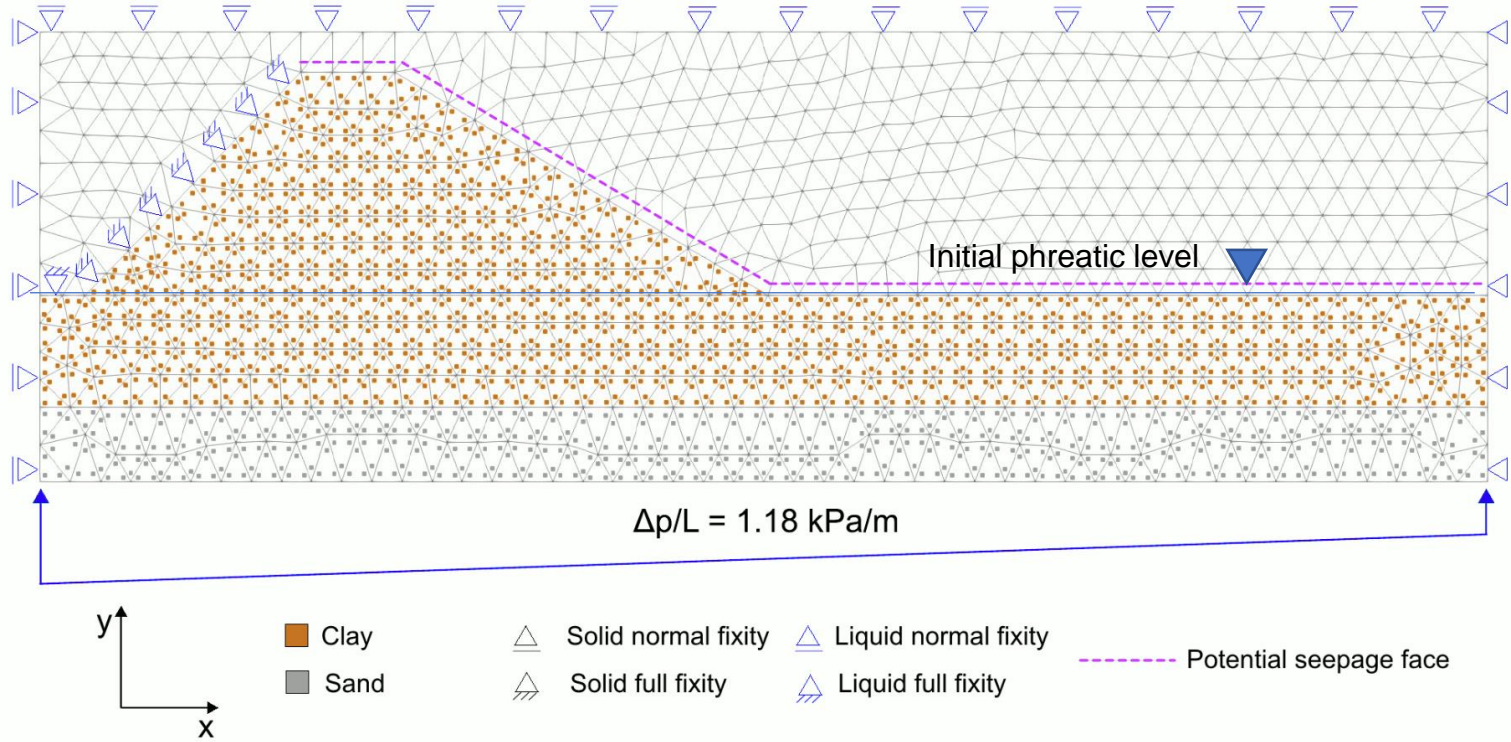
- Richiede più parametri
- Problemi di convergenza (nessuna soluzione per  $FS < 1,1$ )



# Modello MPM (two-phase fully coupled)



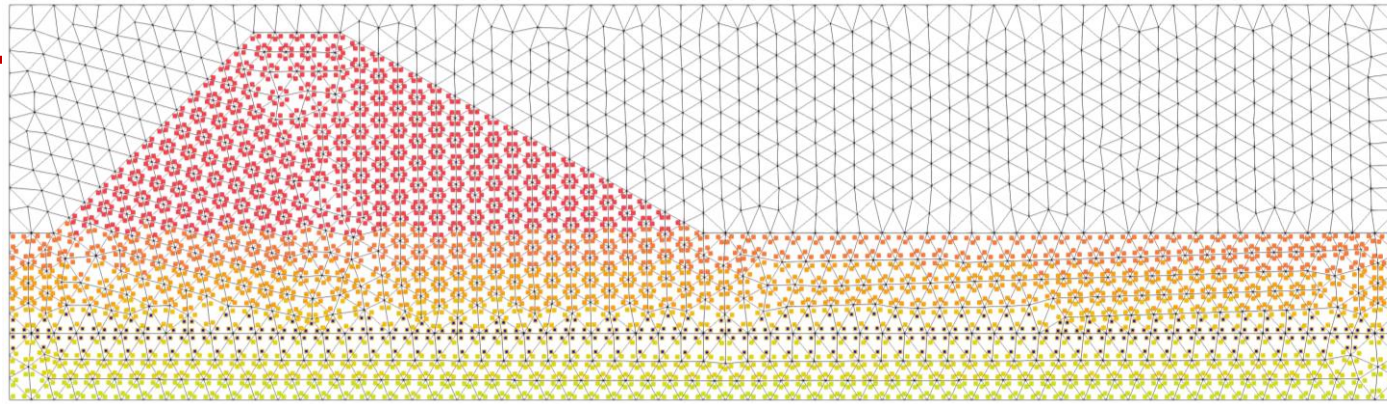
	Argilla	Sabbia
Peso di volume, $\gamma$ , kN/m <sup>3</sup>	20,4	20
Angolo d'attrito [°]	22	37
Coesione [kPa]	10	0
Modulo Elastico [MPa]	5,5	55
Coefficiente di Poisson [-]	0,15	0,33
Conducibilità idraulica [m/s]	$7,4 \cdot 10^{-5}$	$7,4 \cdot 10^{-3}$



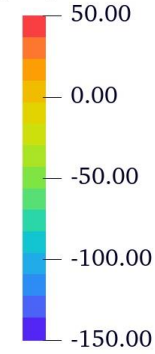


# Risultati modello MPM

Pressione  
dell'acqua



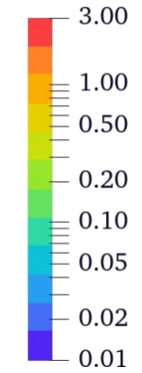
Liquid pressure [kPa]



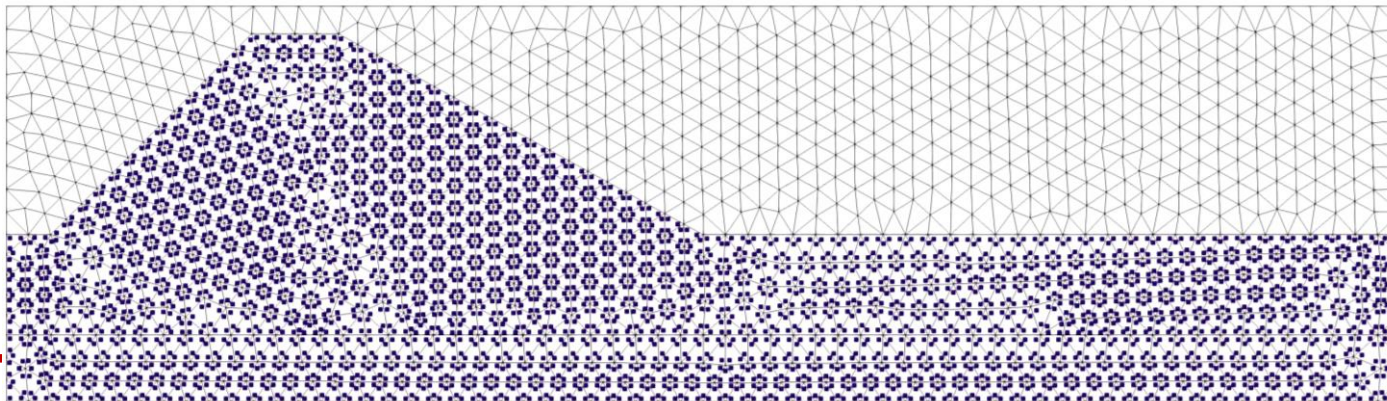
Spostamenti



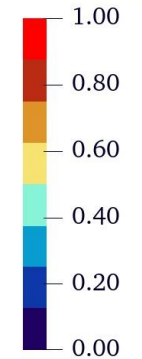
Norm solid displacement [m]



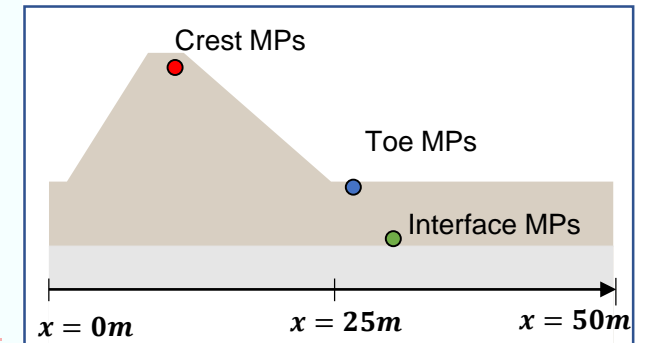
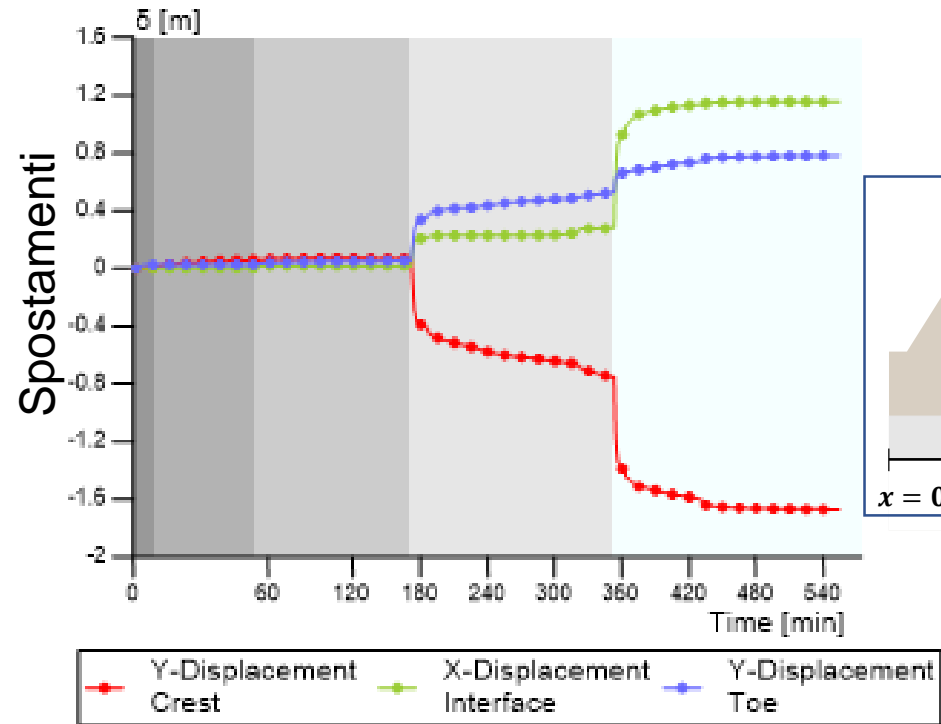
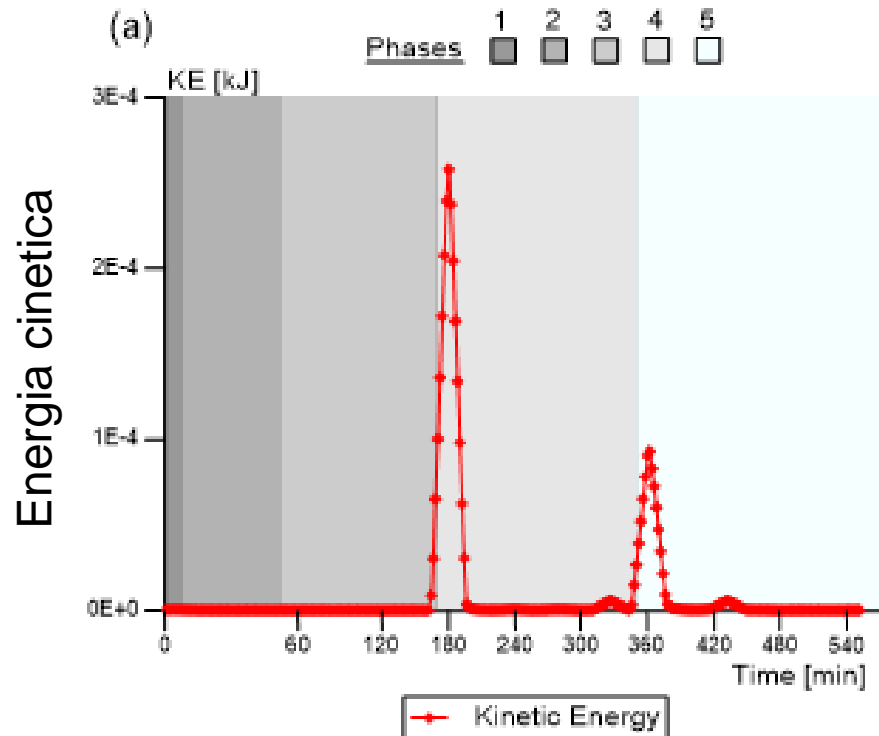
Deformazione  
deviatorica



Deviatoric strain solid



# Risultati modello MPM



# Risultati modello MPM

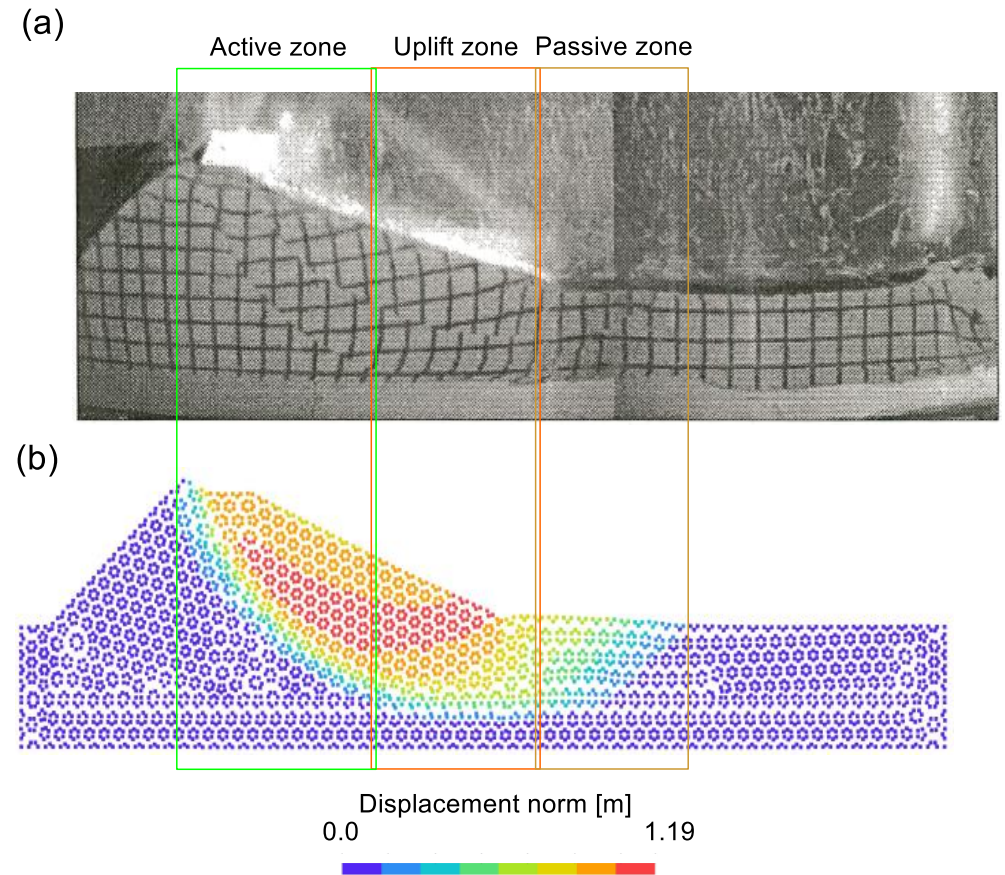
## Vantaggi:

- La superficie di rottura è il risultato del calcolo
- Lo spostamento può essere calcolato anche per grandi deformazioni
- Si può visualizzare tutta l'evoluzione del processo deformativo

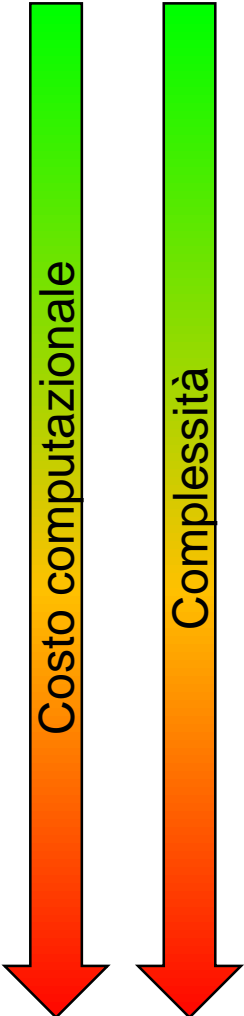
## Svantaggi:

- Costi computazionali elevati

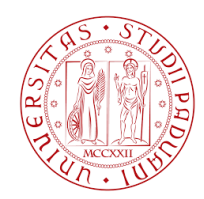
## Fase 4



# Osservazioni

- 
- Metodi analitici e all'equilibrio limite:
    - sono molto semplici e rapidi da utilizzare,
    - richiedono pochi parametri,
    - possono fornire anche  $FS \ll 1$  (qualsiasi condizione di carico è simulabile)
    - non danno informazioni sugli spostamenti
  - Metodo degli elementi finiti:
    - Un po' più complesso e computazionalmente costoso
    - servono più parametri (ad es. modulo elastico, permeabilità ecc)
    - Non può simulare condizioni  $FS=1$  (problemi di convergenza)
    - Ottimo per piccoli spostamenti
  - Material Point Method:
    - Può simulare l'intera evoluzione del collasso, anche grandi spostamenti
    - Computazionalmente più costoso (specialmente nella fase di innesco)





# Applicazioni: collasso di un pendio indotto da pioggia

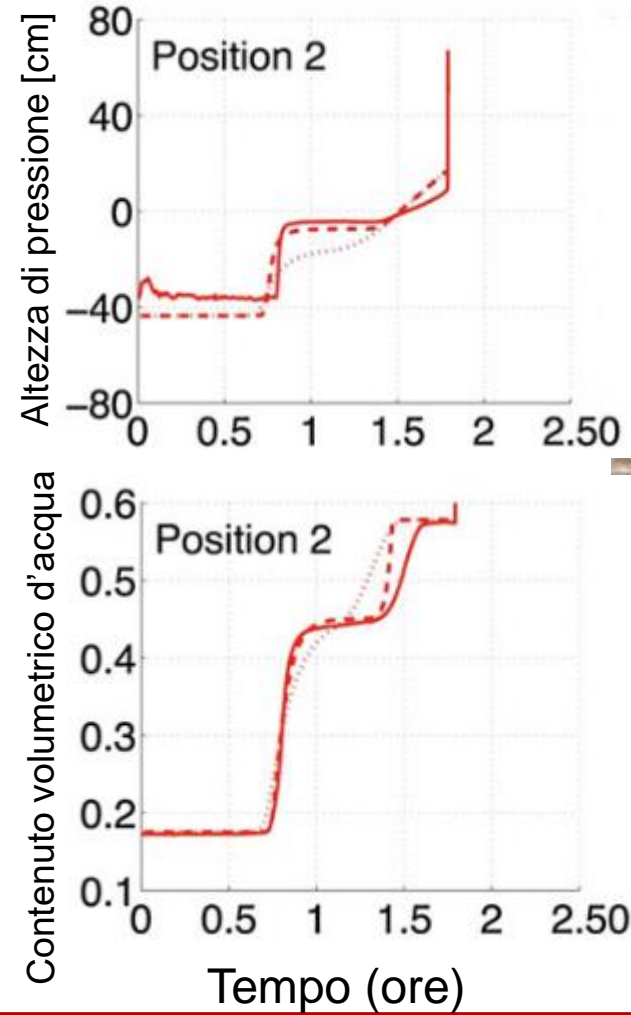
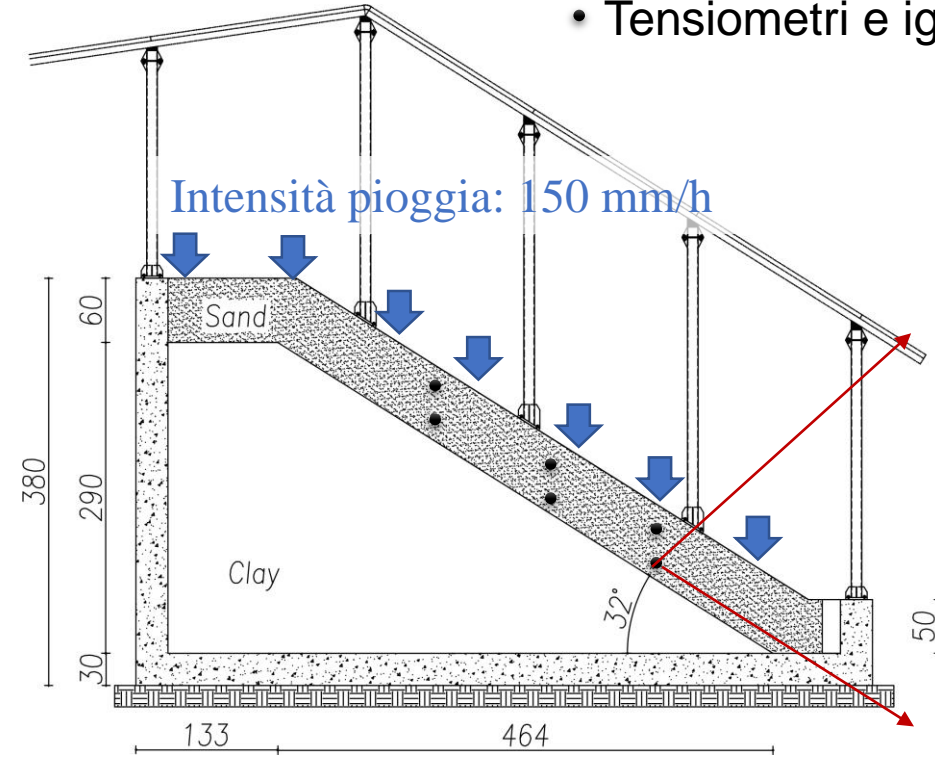


Meng Lu, Francesca Ceccato, Lorenzo Brezzi, Matteo Camporese, Davide Vallisari

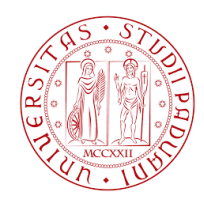
Ceccato, F. *et al.* (2023) 'Simulation of rainfall-induced landslides from small to large displacements with an efficient sequential use of FEM and MPM', in *CNRIG*, Palermo, 5-7 Luglio 2023

# Modello fisico

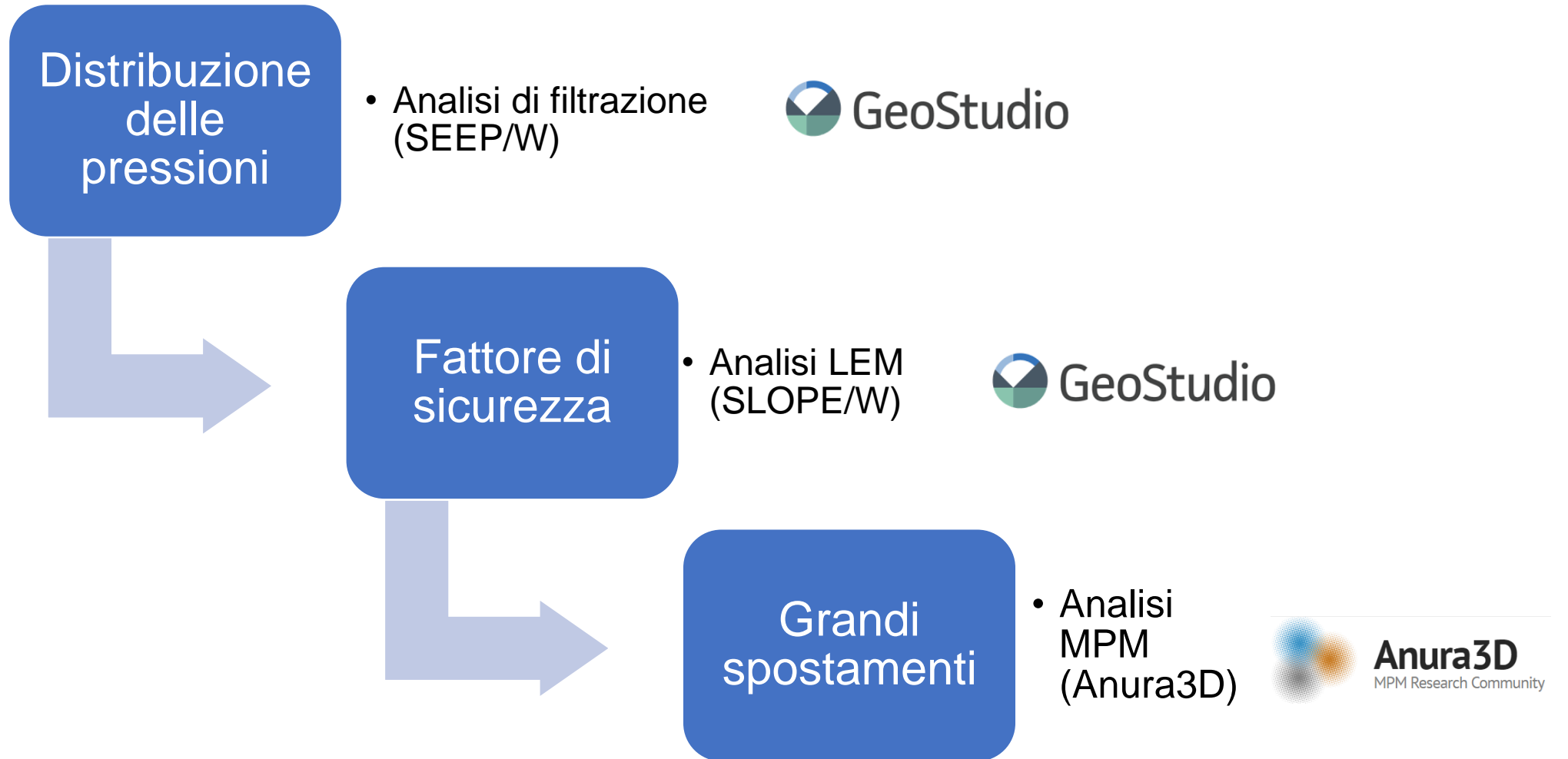
- Tensimetri e igrometri

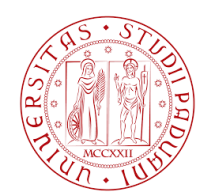


(Lora et al. 2016)

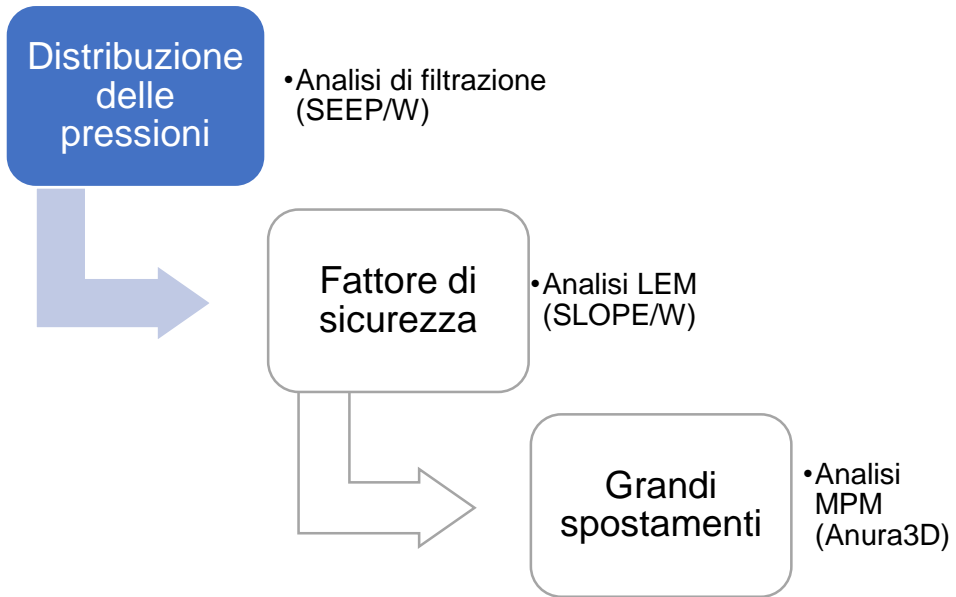


# Strategia di simulazione





# Analisi di filtrazione

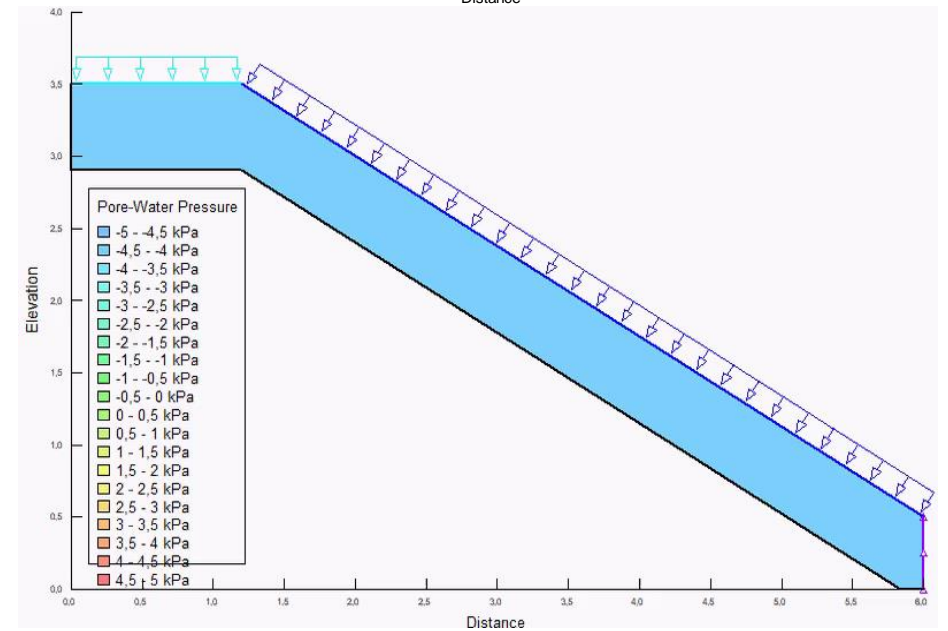
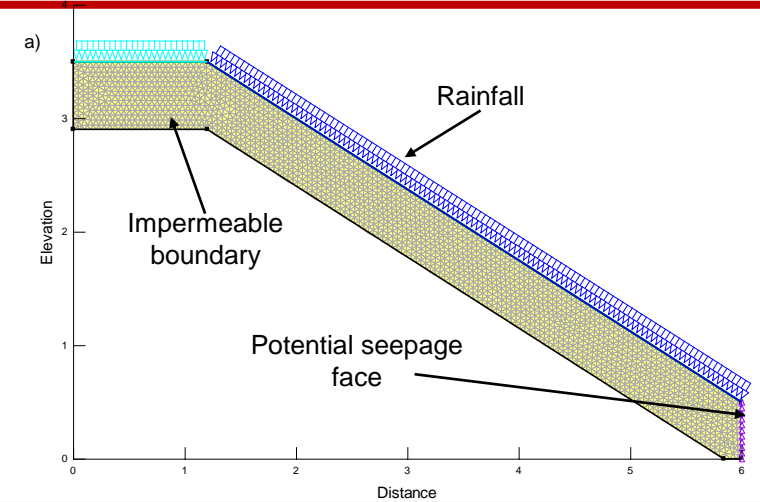


Comportamento parzialmente saturo del terreno:  
modello di Van Genuchten.

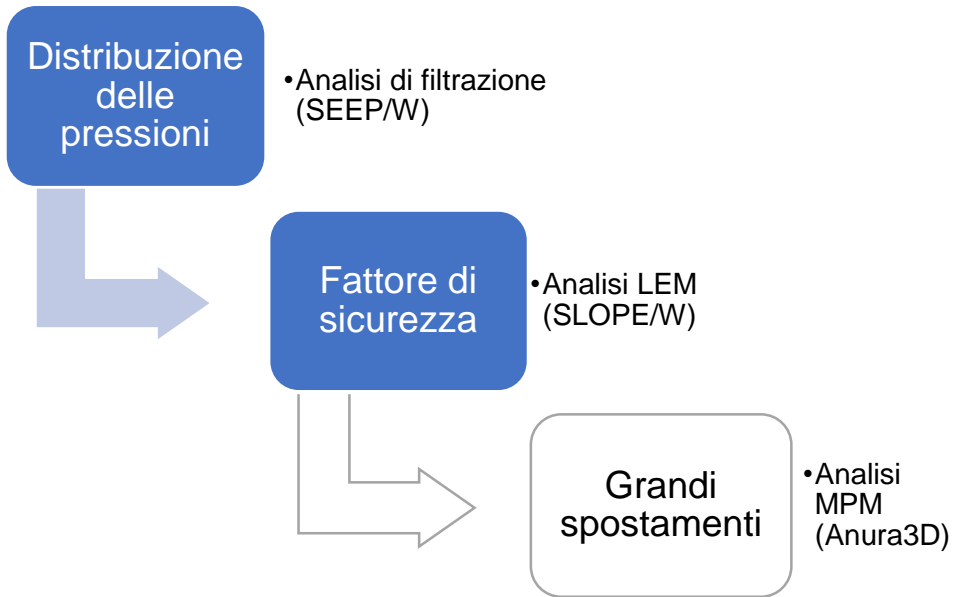
$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + \left(\frac{s}{a}\right)^\lambda\right)^m}$$

$$\frac{k}{k_{sat}} = \frac{\left(1 - \left(\frac{s}{a}\right)^{\lambda-1} \left(1 + \left(\frac{s}{a}\right)^\lambda\right)^{-m}\right)^2}{\left(1 + \left(\frac{s}{a}\right)^\lambda\right)^{\frac{m}{2}}}$$

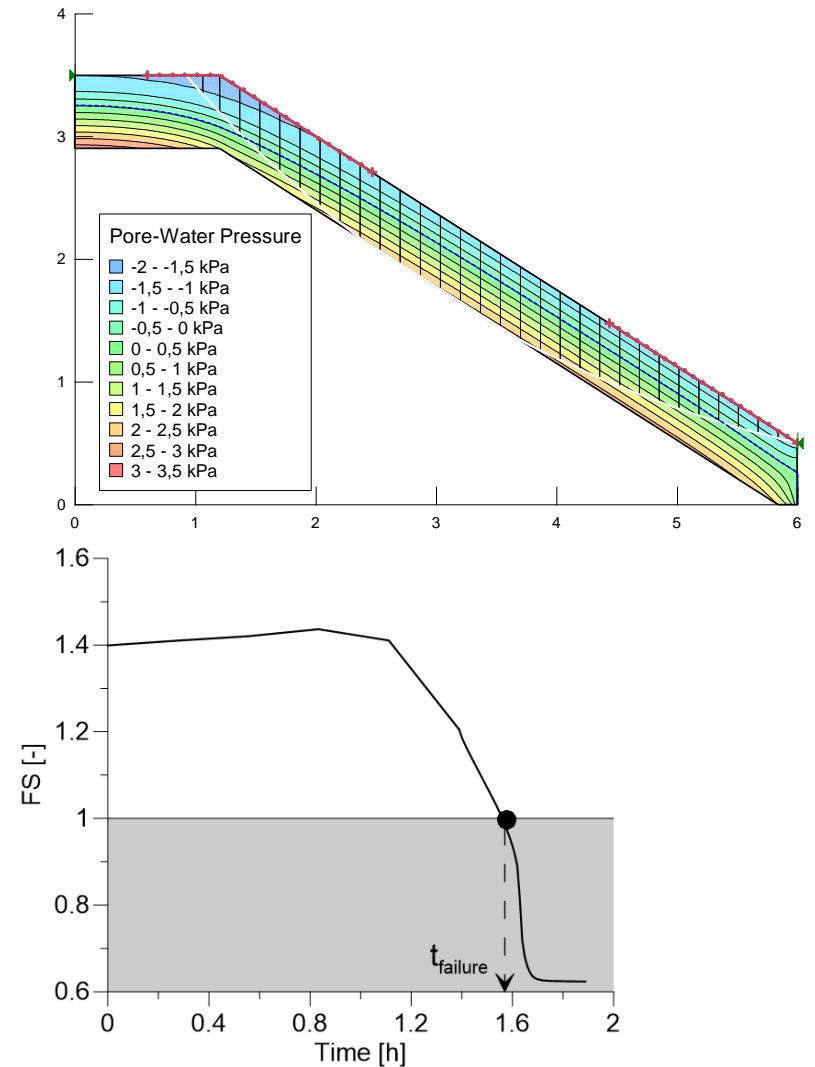
a	1.97 kPa
$\lambda$	2.73
$\theta_{sat}$	0.58
$\theta_{res}$	0.05
$k_{sat}$	$2.047 \cdot 10^{-4}$ m/s



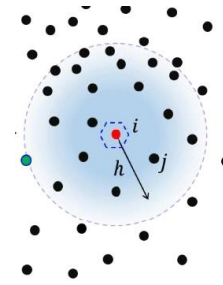
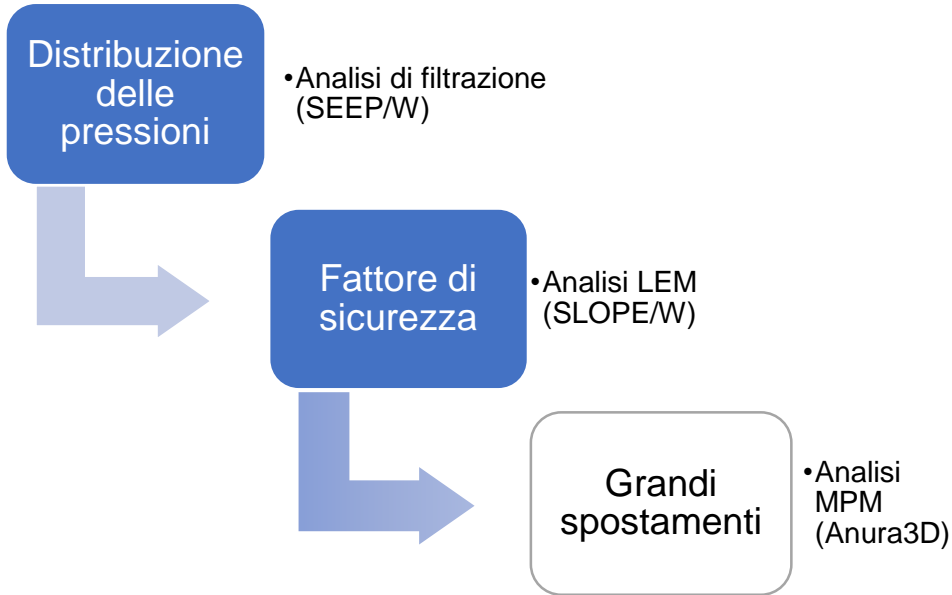
# Analisi di stabilità



$\varphi$	$33^\circ$
$n$	0.58
$\rho_s$	$2718 \text{ kg/m}^3$
$\rho_L$	$1000 \text{ kg/m}^3$

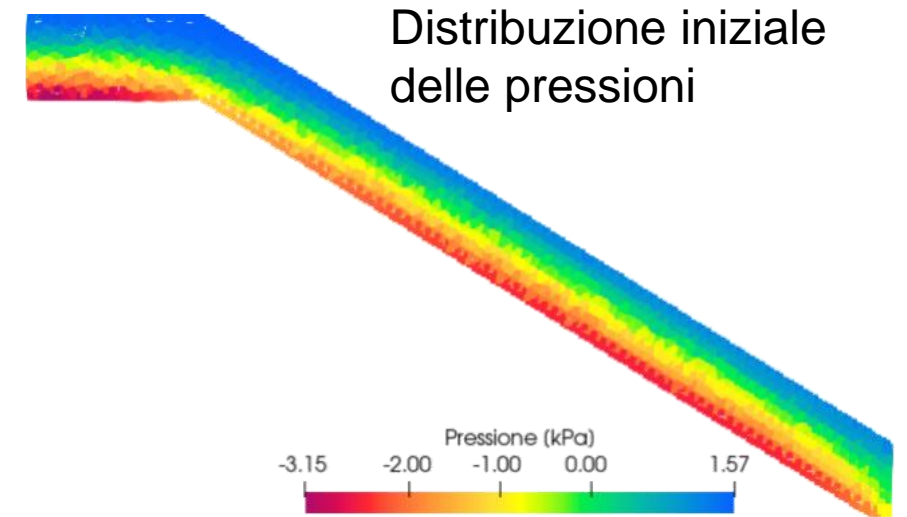


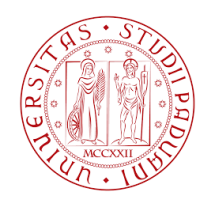
# Inizializzazione analisi MPM



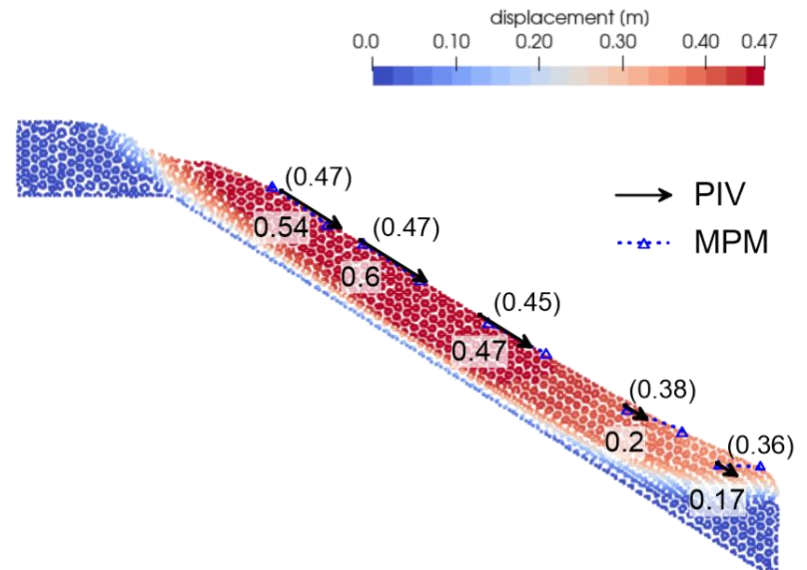
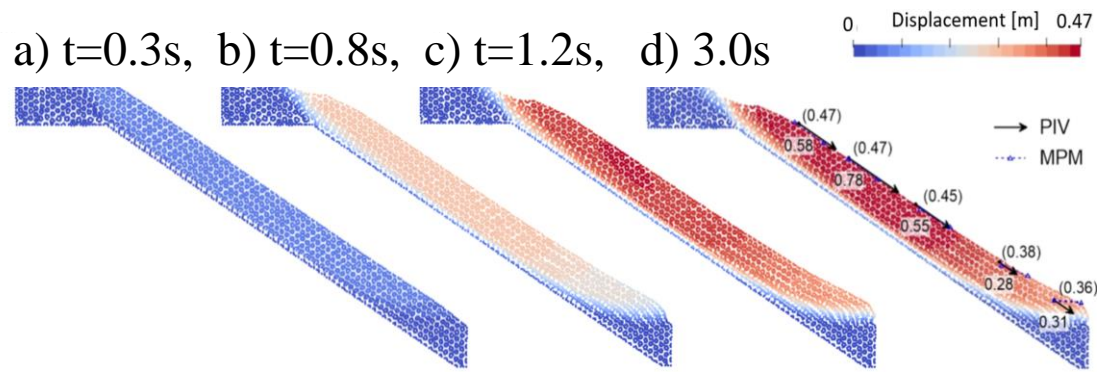
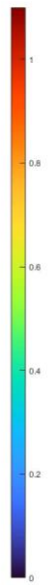
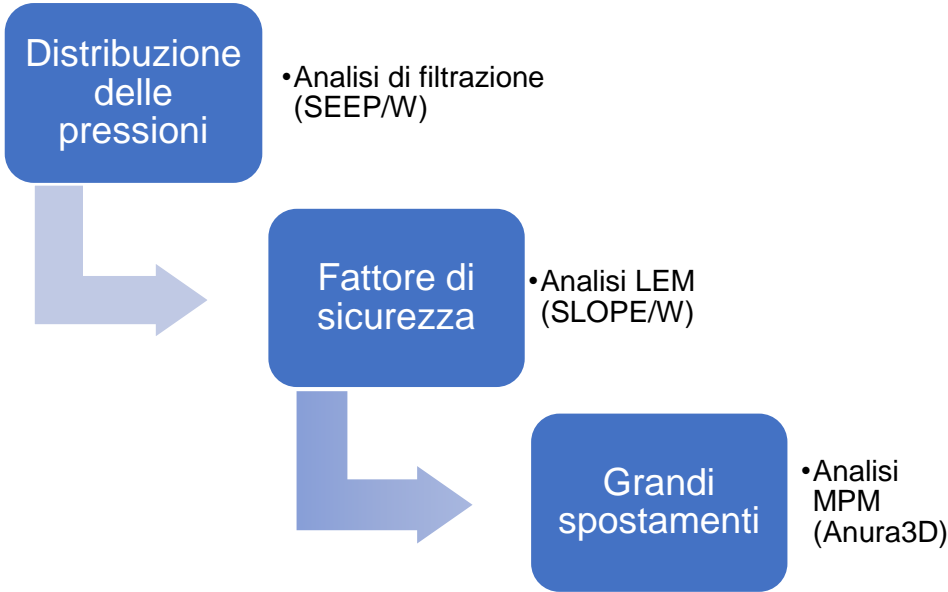
$$f(\mathbf{x}_i) = \sum_{j=1}^N \frac{m_j}{\rho_j} f(\mathbf{x}_j) W(\mathbf{x}_i - \mathbf{x}_j, h)$$

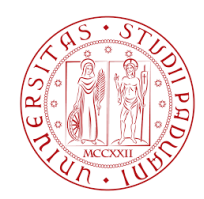
$W$ : Kernel function  $i=MP$   
 $h$ =Smoothing length  $j=FEM\ node$





# Inizializzazione analisi MPM





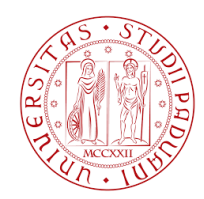
# Osservazioni

- Metodi «tradizionali» (FEM, LEM...) possono essere usati congiuntamente all'MPM per ottimizzare il costo computazionale
- MPM può essere di supporto per stimare gli spostamenti post-collasso

*NTC2018. Cap 6.3.4 VERIFICHE DI SICUREZZA (pendii naturali)*

*[...] L'adeguatezza del margine di sicurezza ritenuto accettabile dal progettista deve comunque essere giustificata sulla base del livello di conoscenze raggiunto, dell'affidabilità dei dati disponibili e del modello di calcolo adottato in relazione alla complessità geologica e geotecnica, nonché sulla base delle conseguenze di un'eventuale frana.*





# Applicazioni: piastre di ancoraggio



Francesca Ceccato



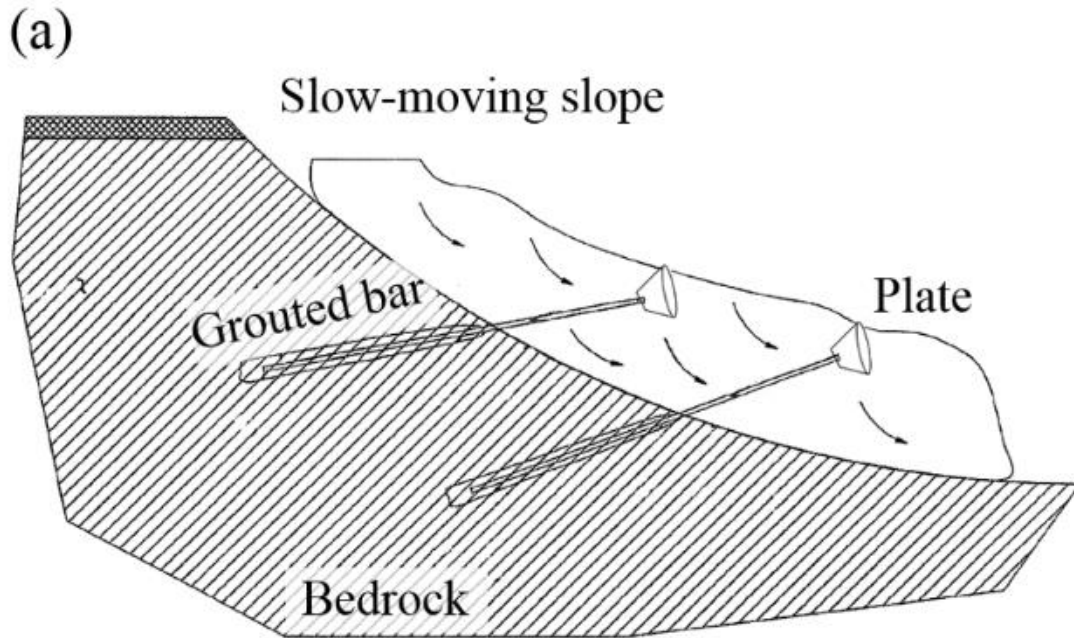
Alberto Bisson



Simonetta Cola

Ceccato, F., Bisson, A. and Cola, S. (2017) 'Large displacement numerical study of 3D plate anchors Large displacement numerical study of 3D plate anchors', *European Journal of Environmental and Civil Engineering*. doi:10.1080/19648189.2017.1408498.

# Anchor pullout



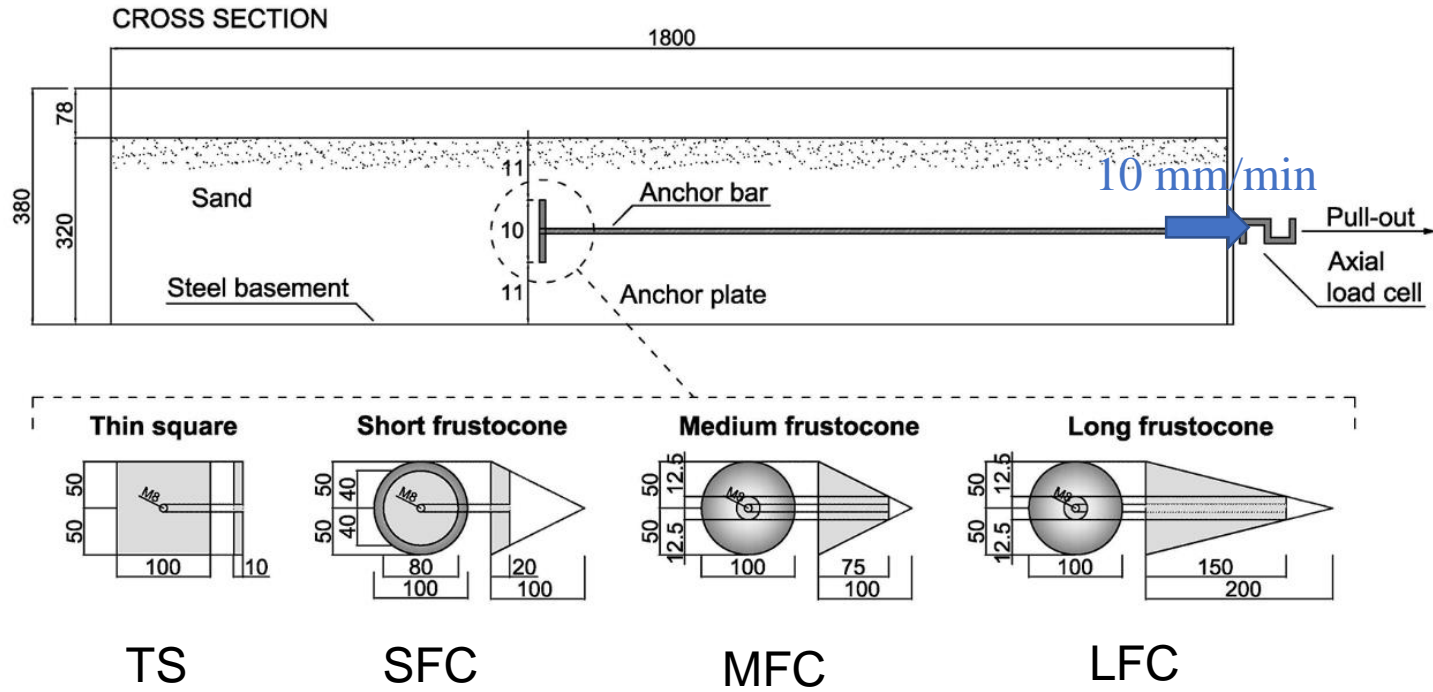
(b)



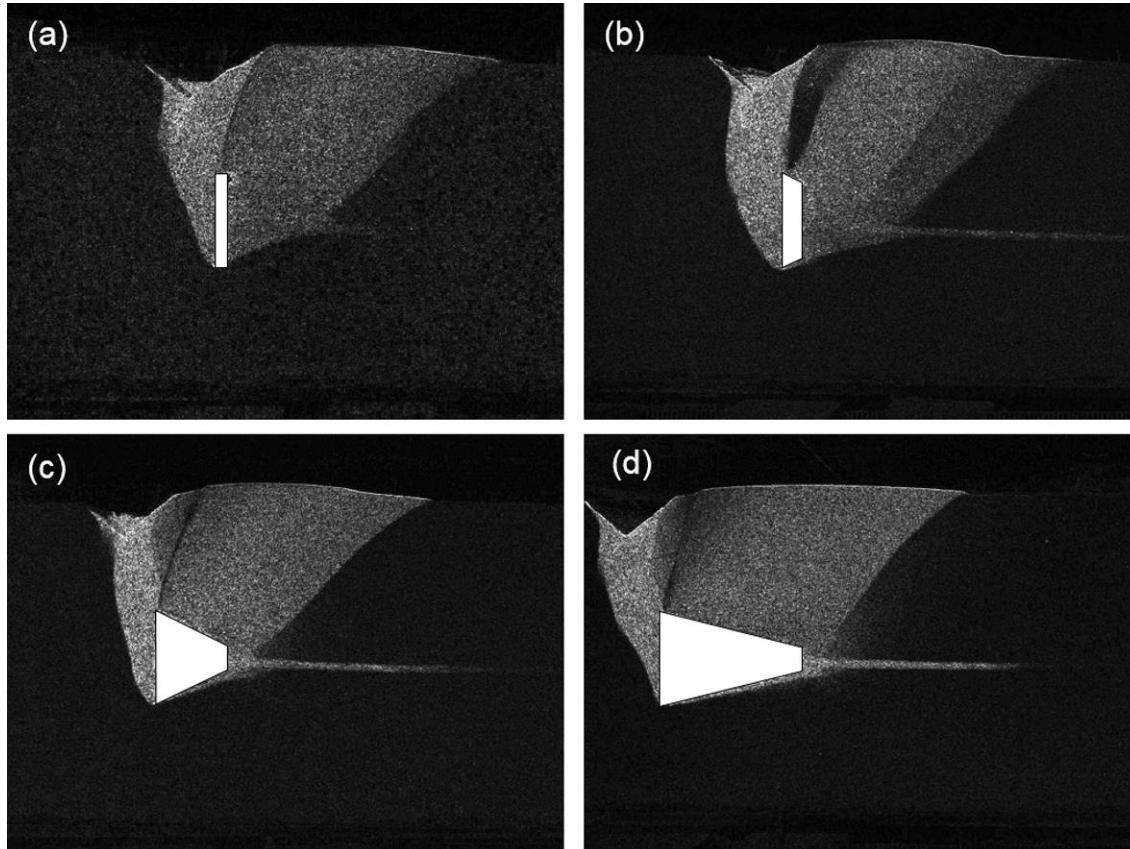
Qual è la forma migliore?  
Qual è l'interasse ottimale?



# Risultati sperimentali



# Risultati sperimentali



Terreno mobilitato a 50mm.

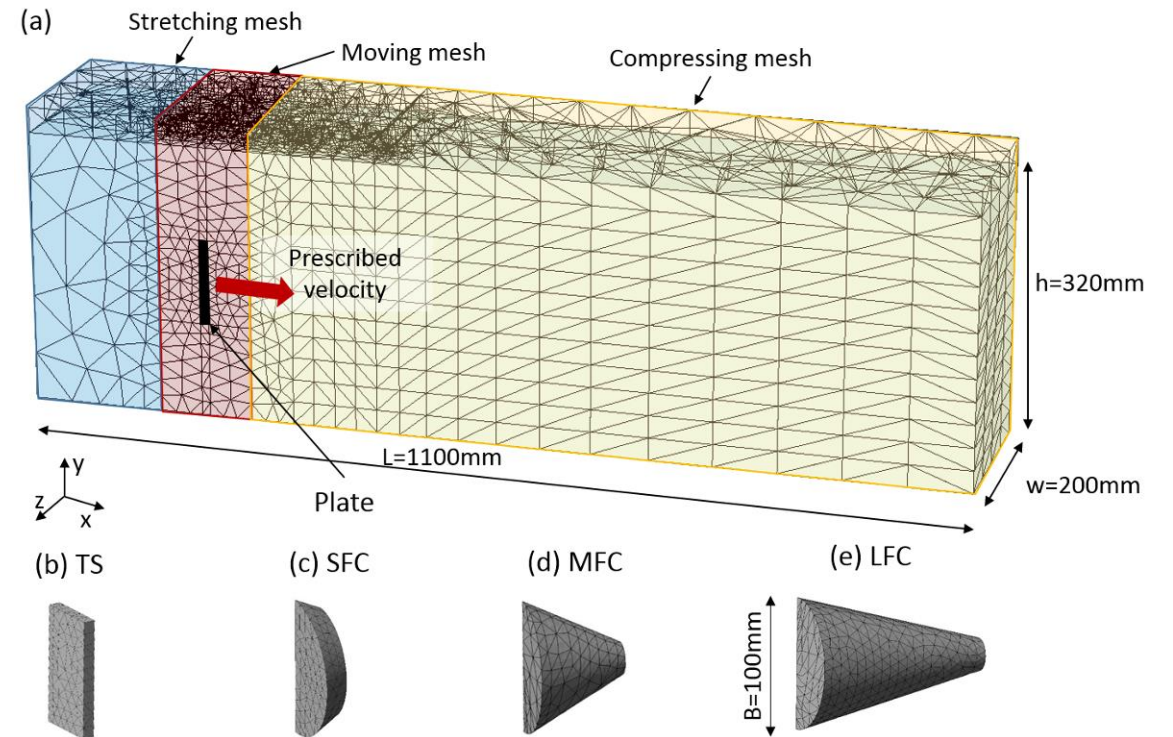
Le zone più chiare indicano porzioni di terreno con spostamenti più elevati.

		Resistenza ultima a grandi spostamenti
	Forma	$q_{exp}$ [kPa]
a	TS	47.4
b	SFC	54.3
c	MFC	66.2
d	LFC	71.8

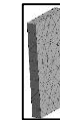
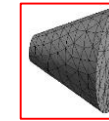
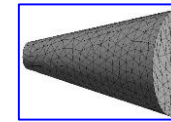
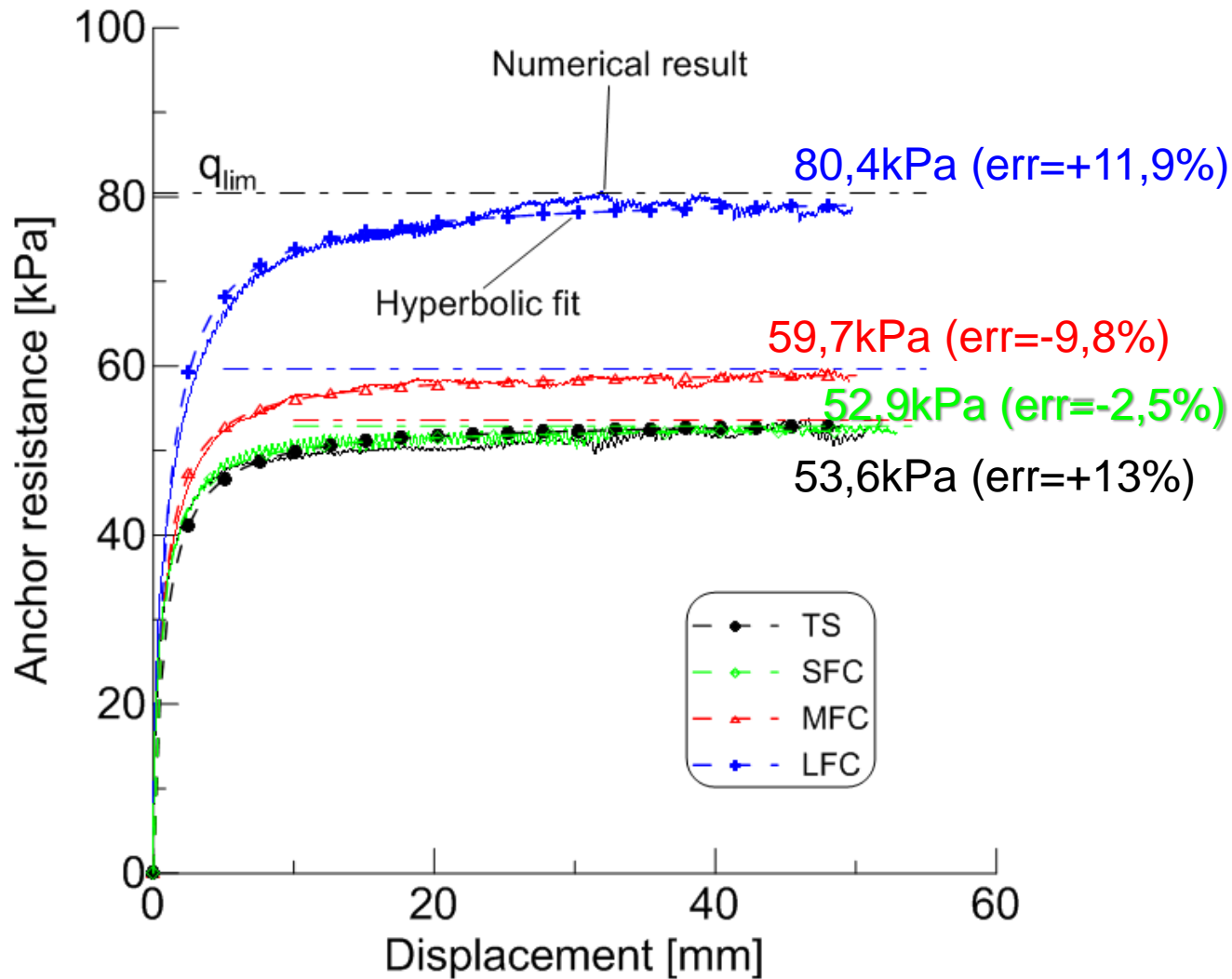
# Modello MPM

- Materiale secco
- Geometria 3D, elementi tetraedrici
- Contatto attritivo ancora-terreno ( $\mu = \tan(\phi)$ )
- Velocità costante dell'ancora ( $v = 20 \text{ mm/s} > 0,17 \text{ mm/s}$ )
- Moving mesh

Parameter	Symbol	Value
Young modulus [MPa]	$E$	12
Poisson ratio [-]	$\nu$	0.2
Solid grain density [ $\text{kg/m}^3$ ]	$\rho_s$	2650
Cohesion [kPa]	$c$	0
Friction angle [°]	$\phi$	35.5
Dilatancy angle [°]	$\psi$	0
Earth pressure coefficient	$K_0$	0.426
Porosity	$n$	0.4



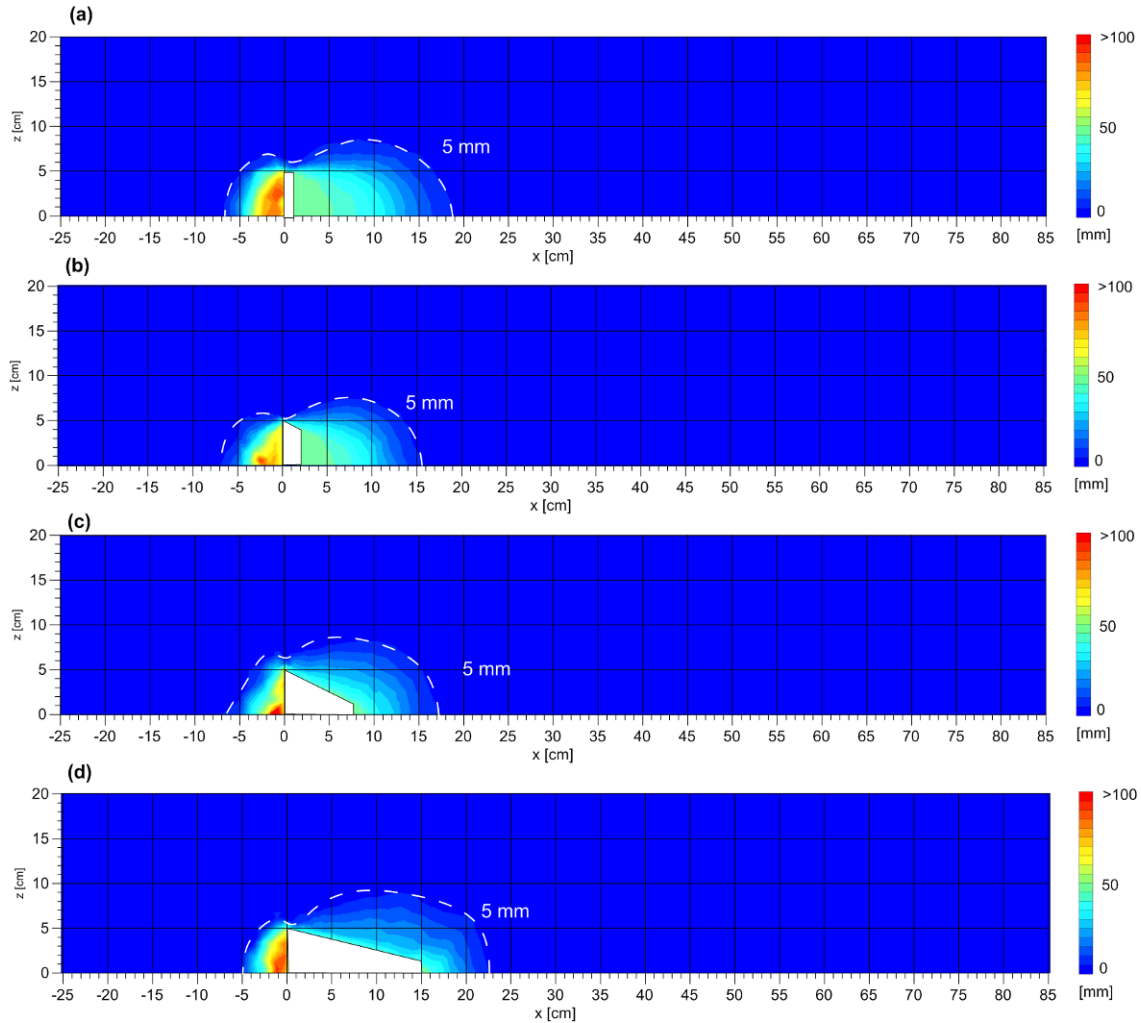
# Risultati numerici



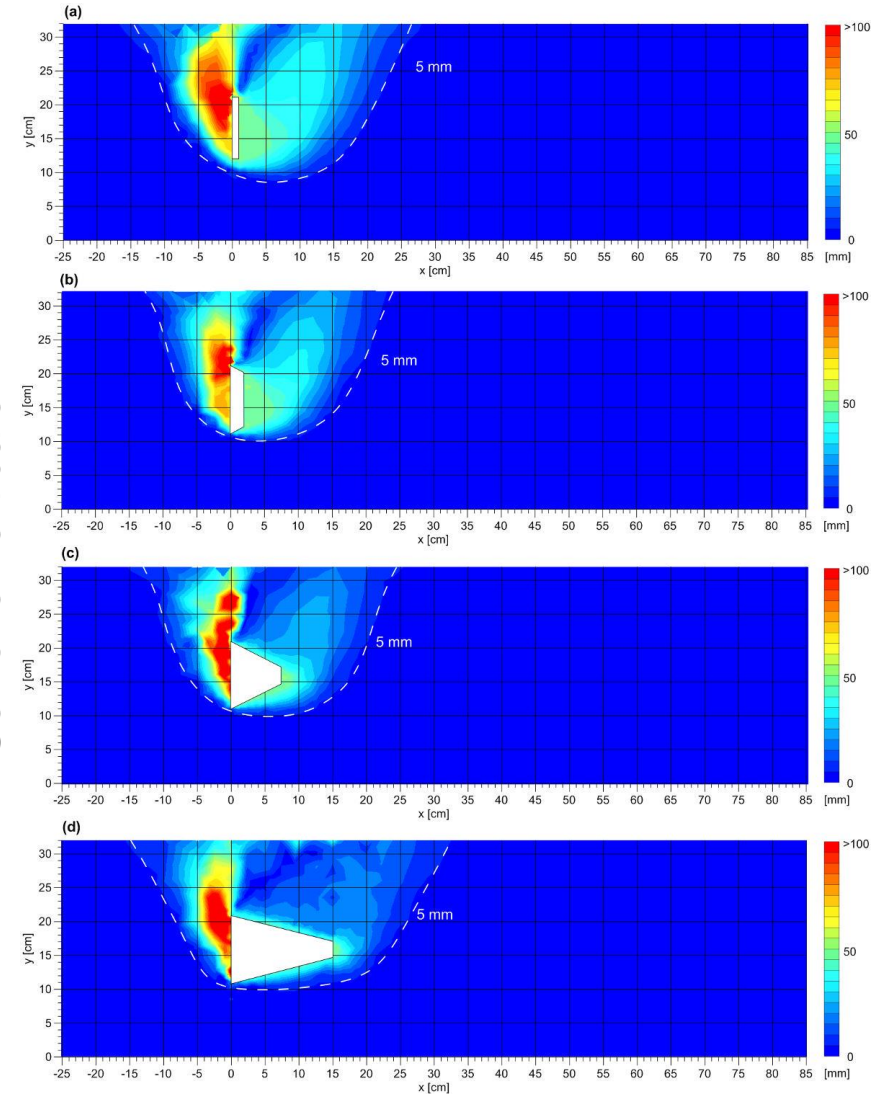
# Risultati numerici

Contour spostamenti del terreno per uno spostamento dell'ancora di 50mm

Sezione orizzontale

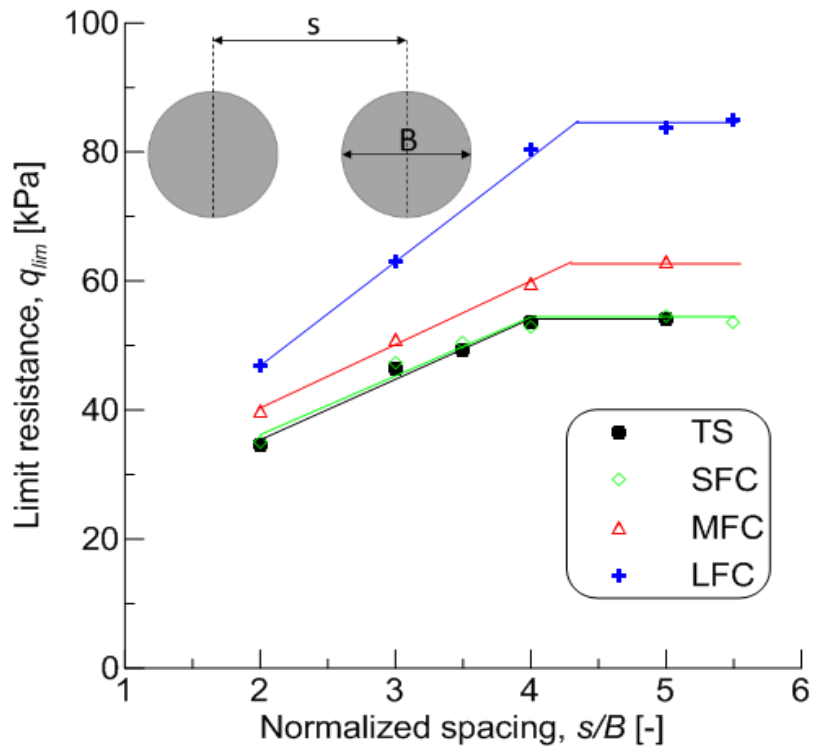


Sezione verticale

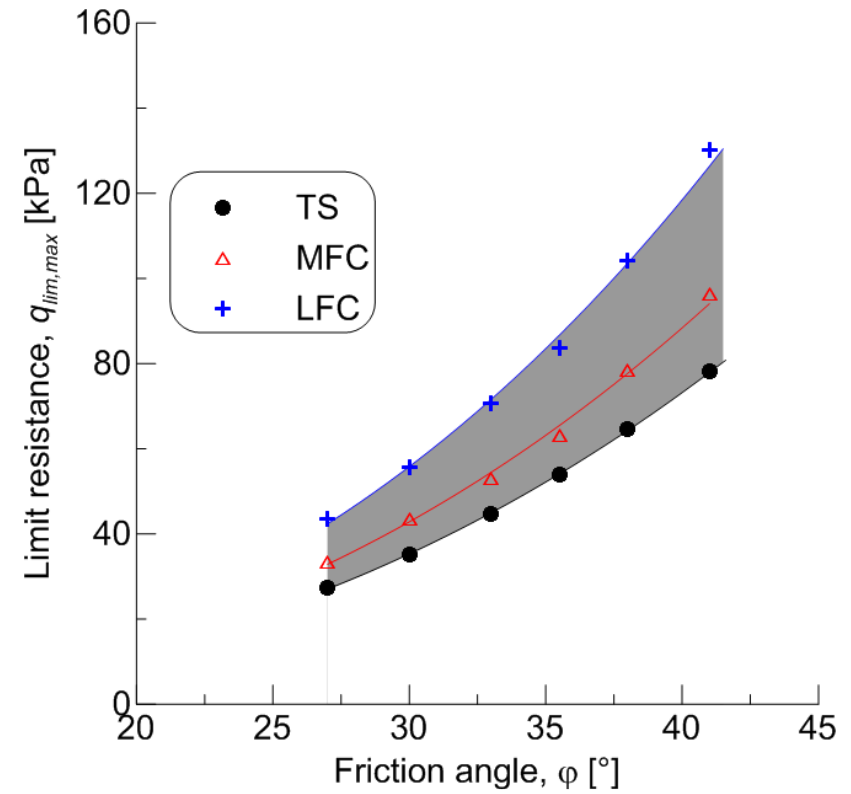


# Analisi parametriche

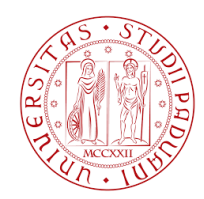
Ottimizzazione dell'interasse.



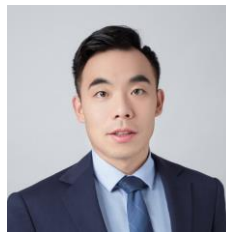
Effetto dell'angolo d'attrito





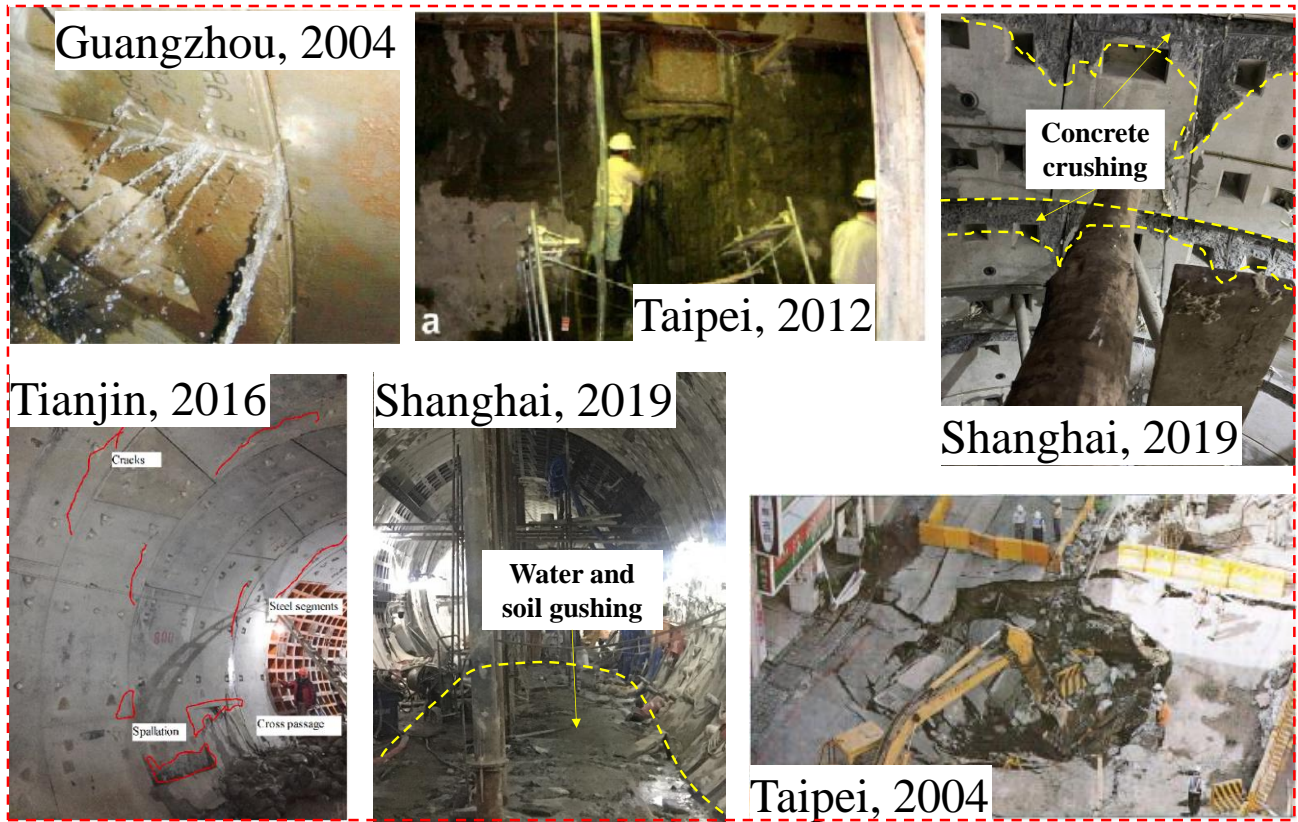
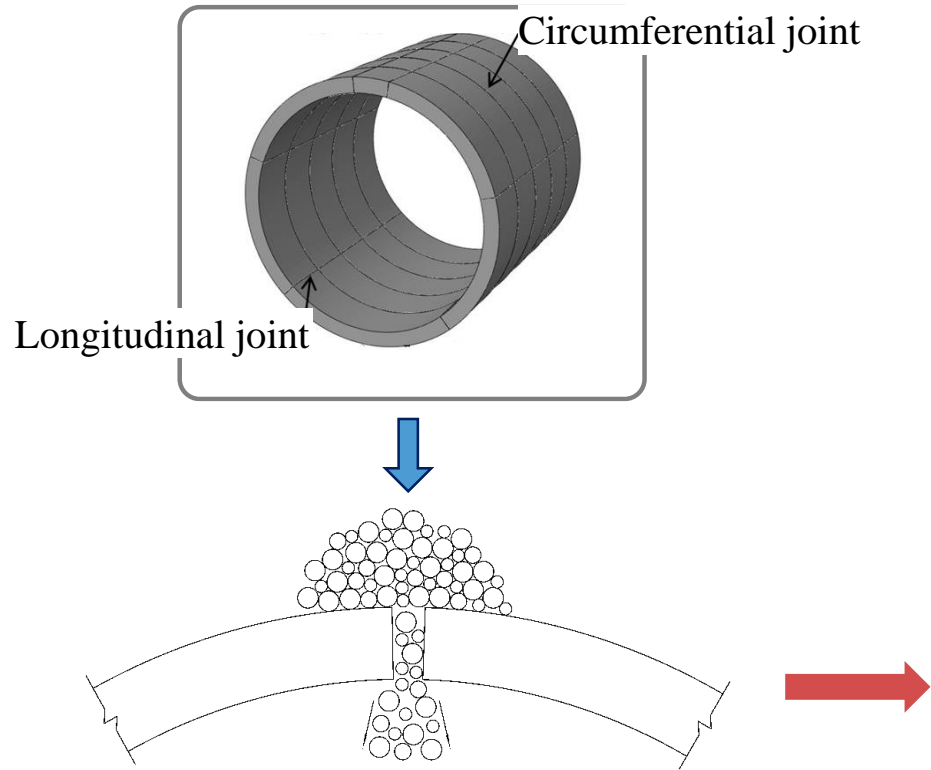


# Applicazioni: danni in galleria



Xie Xiaochuang, Francesca Ceccato, Mingliang Zhou, Dong-Mei Zhang

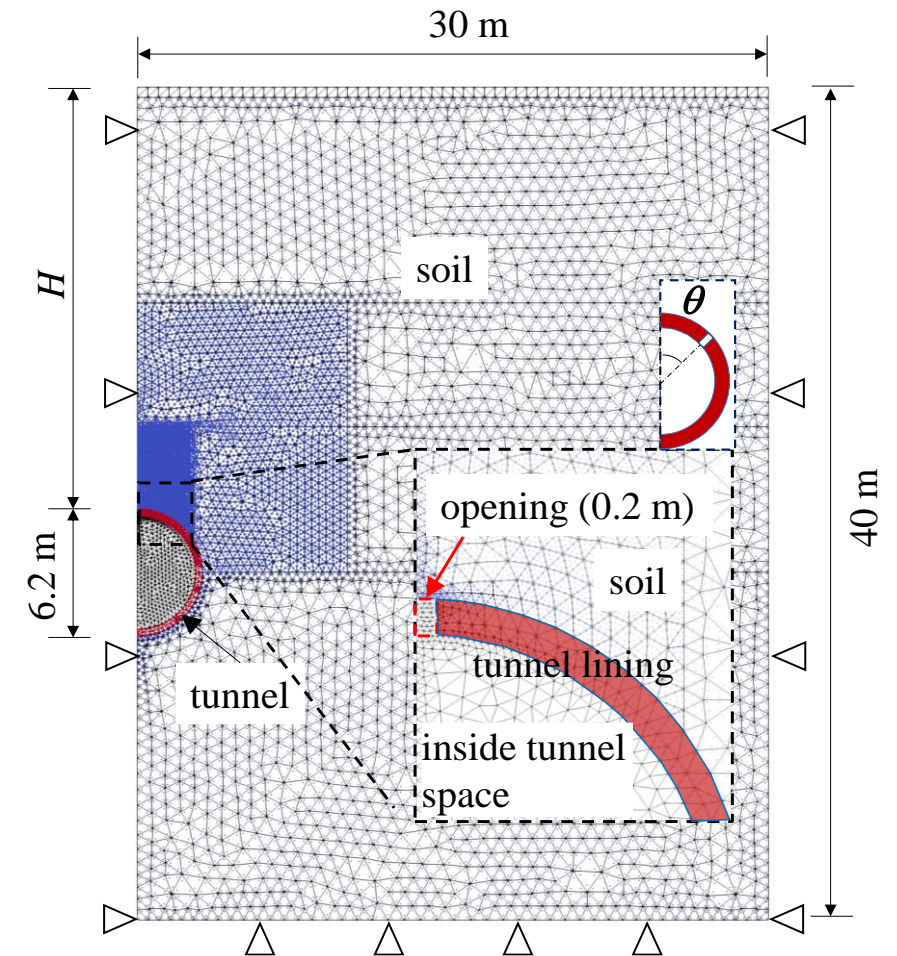
# Motivazioni



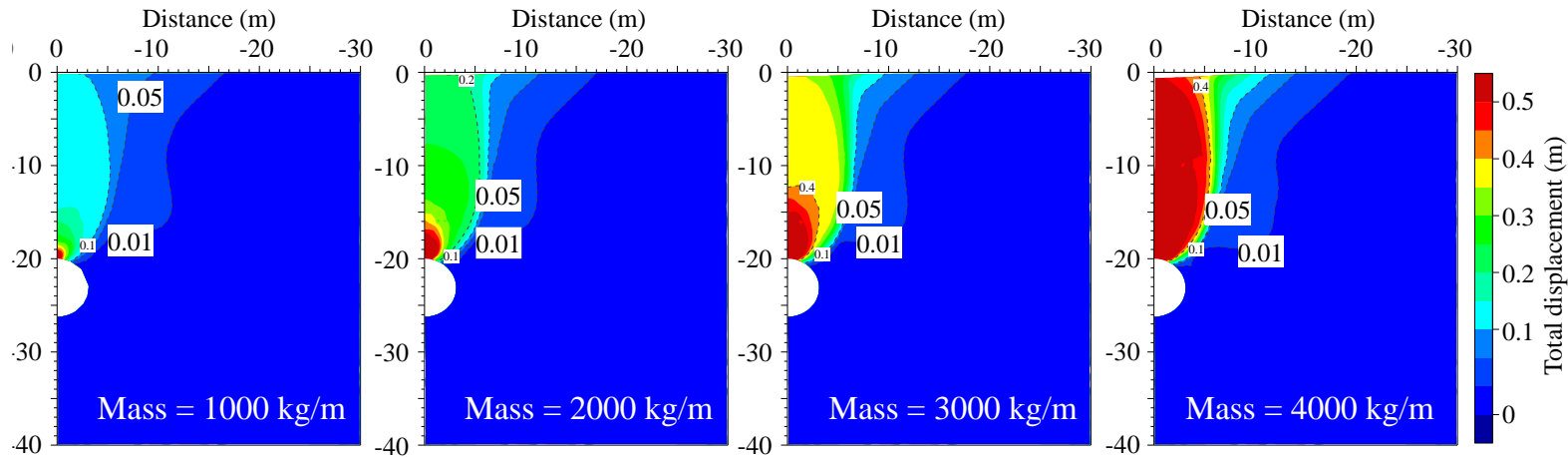
# Modello numerico

- 2D stato piano (elementi triangolari)
- Materiale saturo (*two-phase formulation*)
- Contatto terreno-struttura

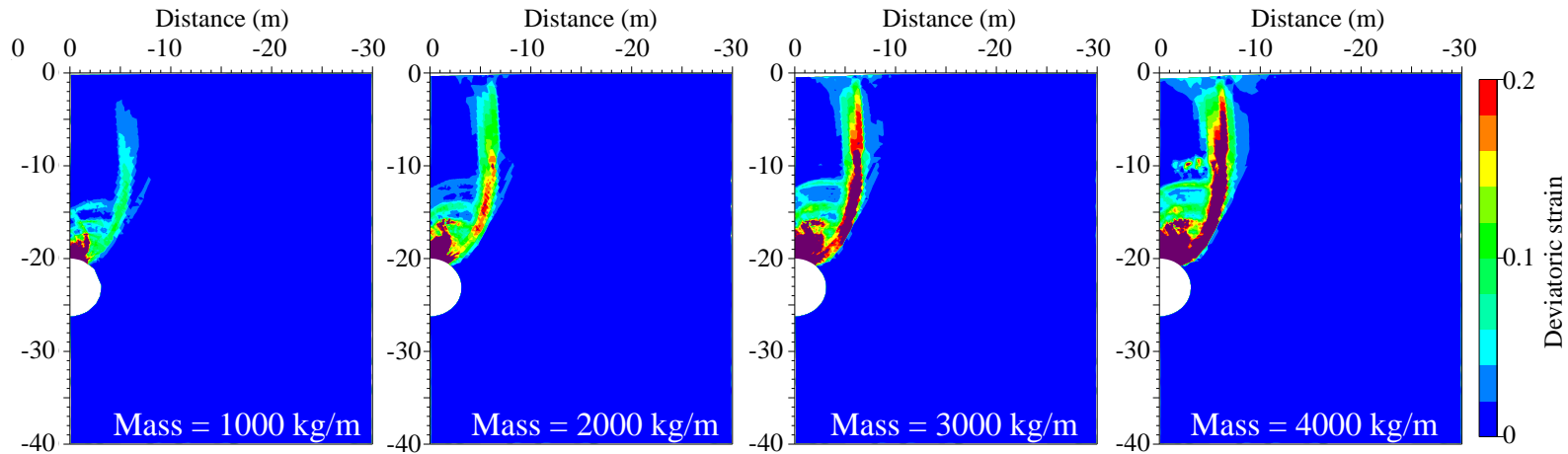
Cohesion, $c$	0	kPa
Friction angle, $f$	35	°
Young's modulus, $E$	40000	kPa
Density of grains, $\rho_s$	2650	kg/m <sup>3</sup>
Poisson ratio, $\nu$	0.3	--
Porosity, $n$	0.45	--
Intrinsic permeability, $k$	$1 \times 10^{-10}$	m <sup>2</sup>
Water density, $\rho_w$	1000	kg/m <sup>3</sup>
Water bulk modulus, $K_w$	80000	kPa
Water viscosity, $\mu$	$1.002 \times 10^{-6}$	kPa·s

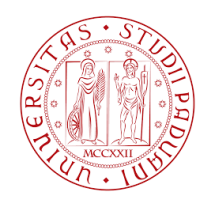


# Evoluzione degli spostamenti e deformazioni



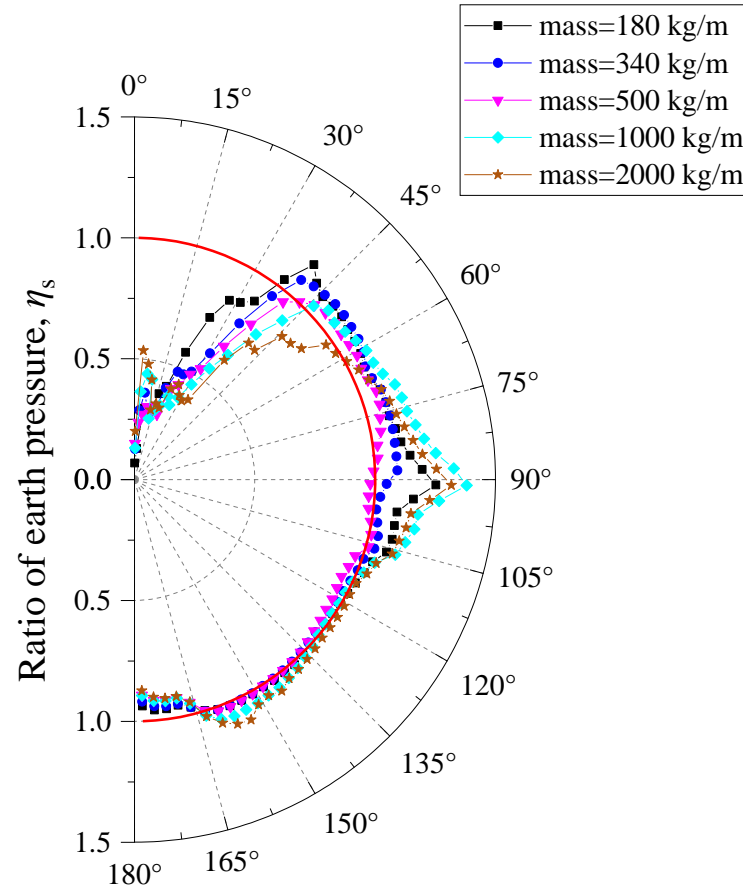
- Flow zone ( $> 0.05$  m)
- Disturbed zone ( $0.01$  m ~  $0.05$  m)
- Stationary zone ( $< 0.01$  m)



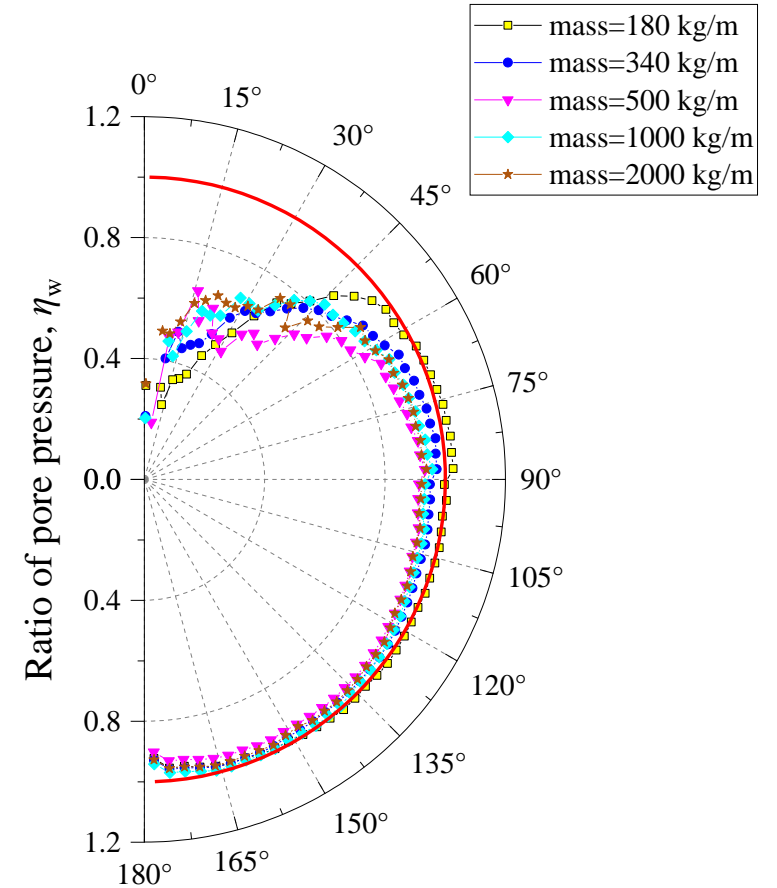


# Evoluzione delle pressioni sul rivestimento

$$\eta = \frac{p_t}{p_0}$$

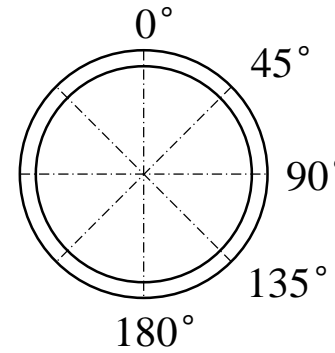
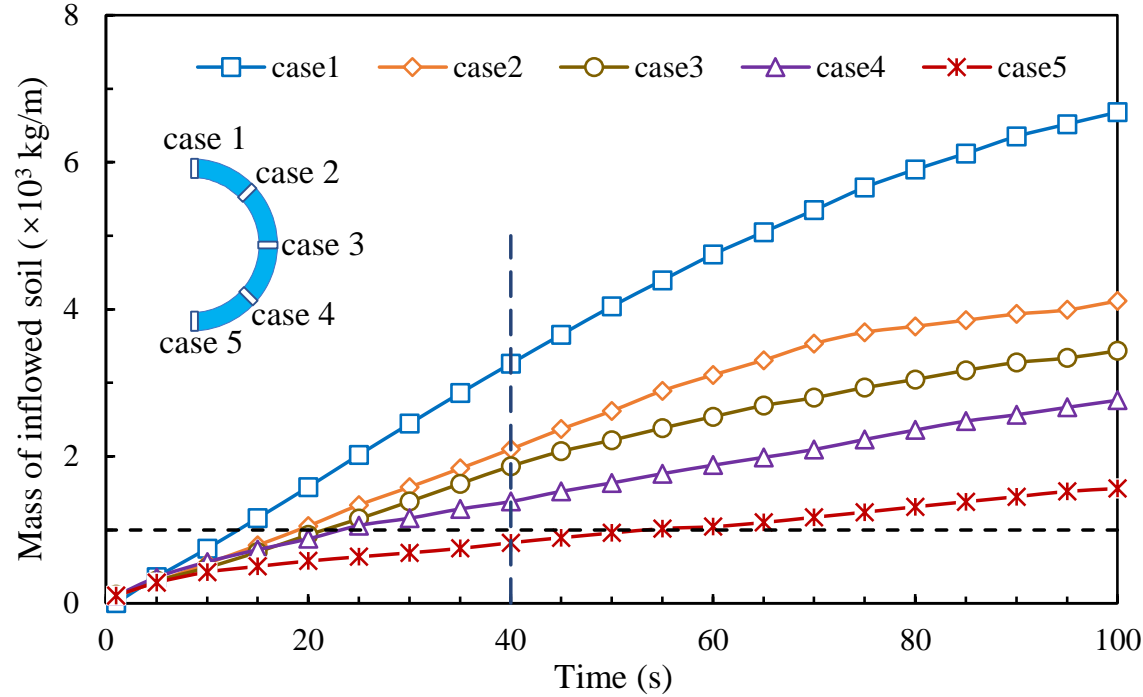


Spinta del terreno



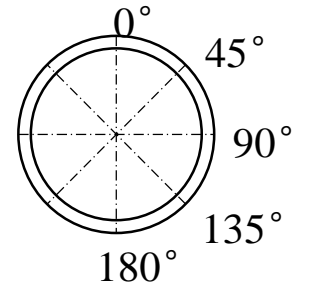
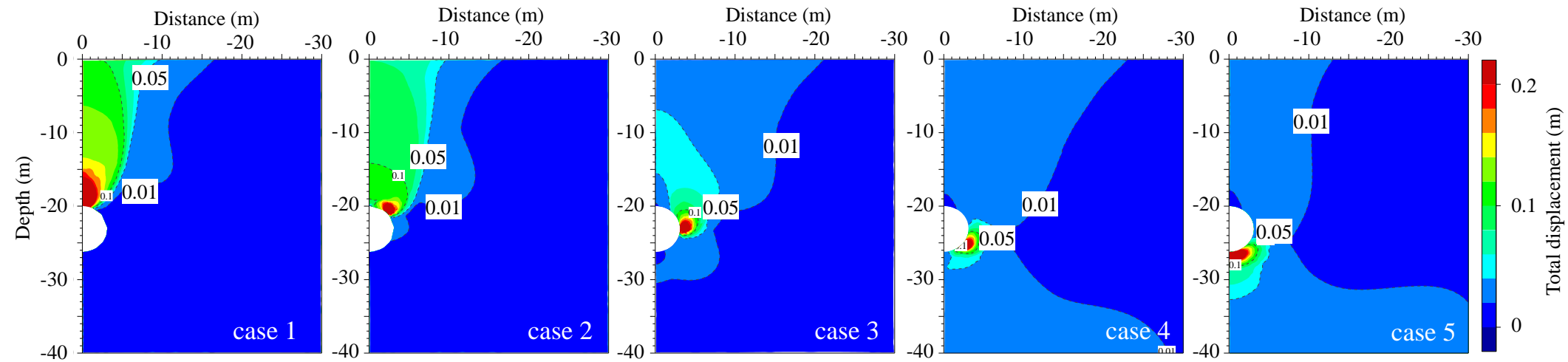
Spinta dell'acqua

# Effetto della posizione del difetto

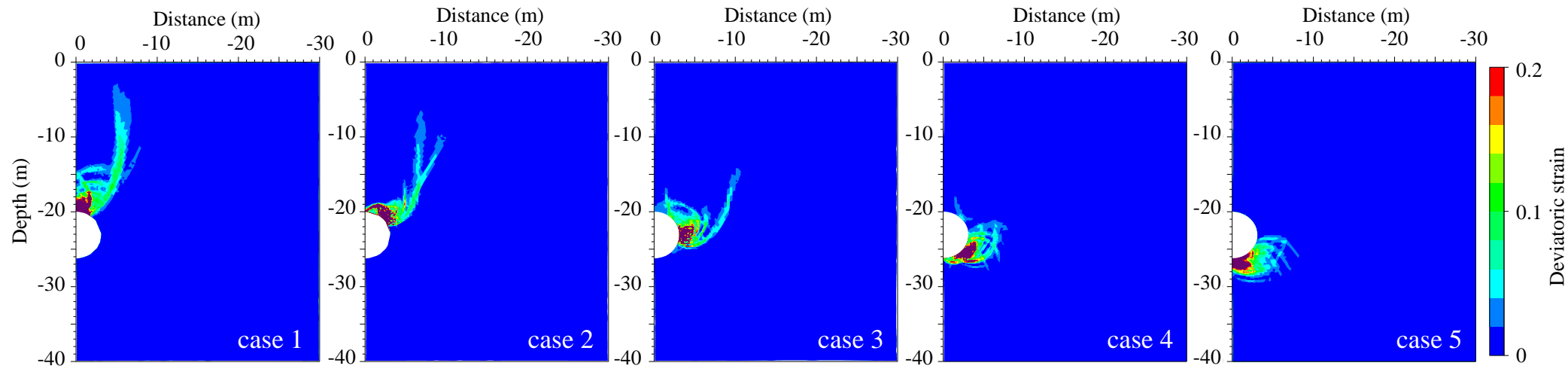


- ✓ case 1 - 0°
- ✓ case 2 - 45°
- ✓ case 3 - 90°
- ✓ case 4 - 135°
- ✓ case 5 - 180°

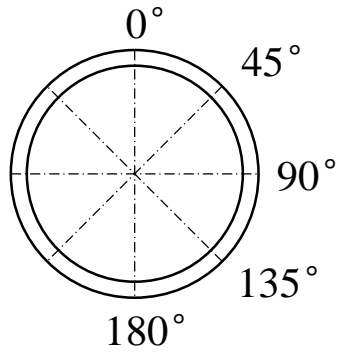
# Spostamenti e deformazioni



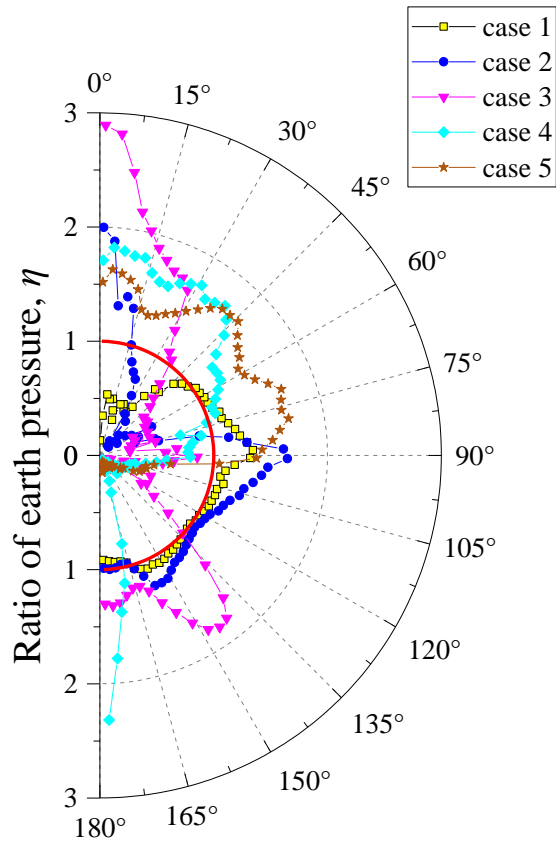
- ✓ case 1 - 0°
- ✓ case 2 - 45°
- ✓ case 3 - 90°
- ✓ case 4 - 135°
- ✓ case 5 - 180°



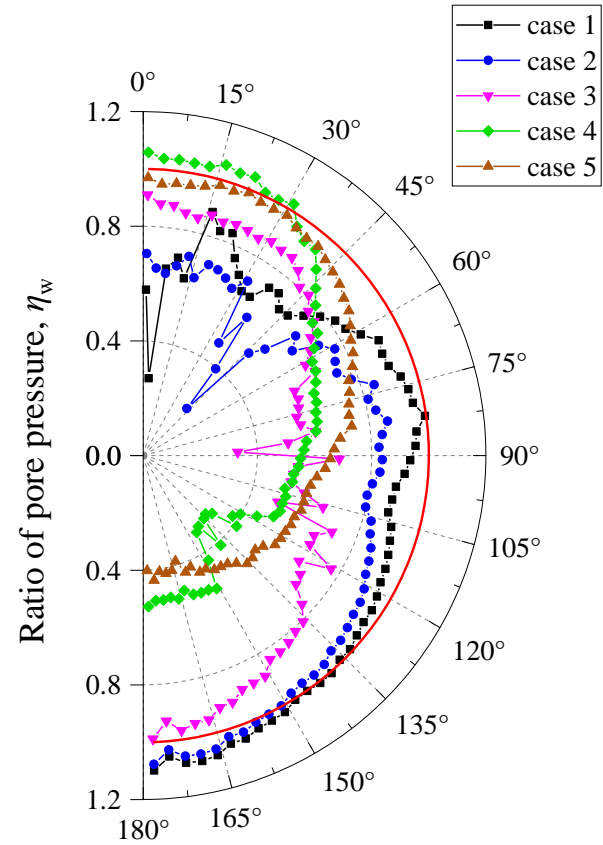
# Pressioni sul rivestimento



- ✓ case 1 - 0°
- ✓ case 2 - 45°
- ✓ case 3 - 90°
- ✓ case 4 - 135°
- ✓ case 5 - 180°

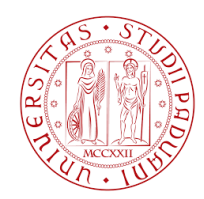


Spinta del terreno



Spinta dell'acqua





# Conclusioni

- MPM è un metodo di discretizzazione adatto per simulare problemi a grandi spostamenti
- Può essere applicato a molti problemi geotecnici
- MPM può essere utilizzato con altri metodi (FEM, LEM...) per avanzare la comprensione di problemi geotecnici
- Attualmente è utilizzato principalmente per progetti di ricerca, ma ha il potenziale di far avanzare lo stato dell'arte e lo stato della pratica nell'ingegneria geotecnica