



PROJET RITA / PROGETTO RITA
Réponse Impacts Tempête Alex / Risposta Impatti Tempesta Alex

CONFERENCE FINALE / CONFERENZA FINALE

Evaluation de la performance des barrages poids soumis à des crues extrêmes
Valutazione delle prestazioni delle dighe a gravità in condizioni di piena estrema

EHSAN BADAKSHAN, GUILLAUME VEYLON, LAURENT PEYRAS
Avec la participation de / Con la partecipazione di PAOLO ROPELE

Aoste, 25.05.2023

Introduction

Introduzione

Actions appliquées aux ouvrages pendant une tempête

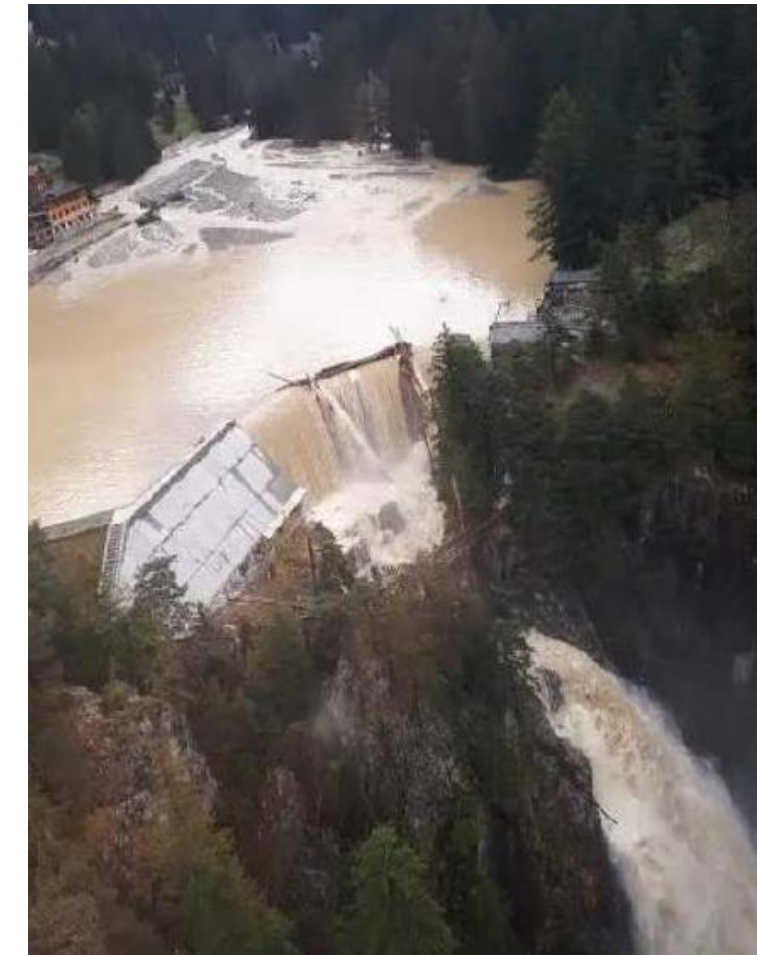
Azioni applicate alle strutture durante una tempesta



*Surverse par-dessus le barrage
due à une crue
Straripamento della diga a causa
di un'inondazione*



Vague induite par un glissement de terrain
dans la retenue
Onda indotta dalla frana nel bacino



Impact des embâcles
*impatto degli oggetti
galleggianti*

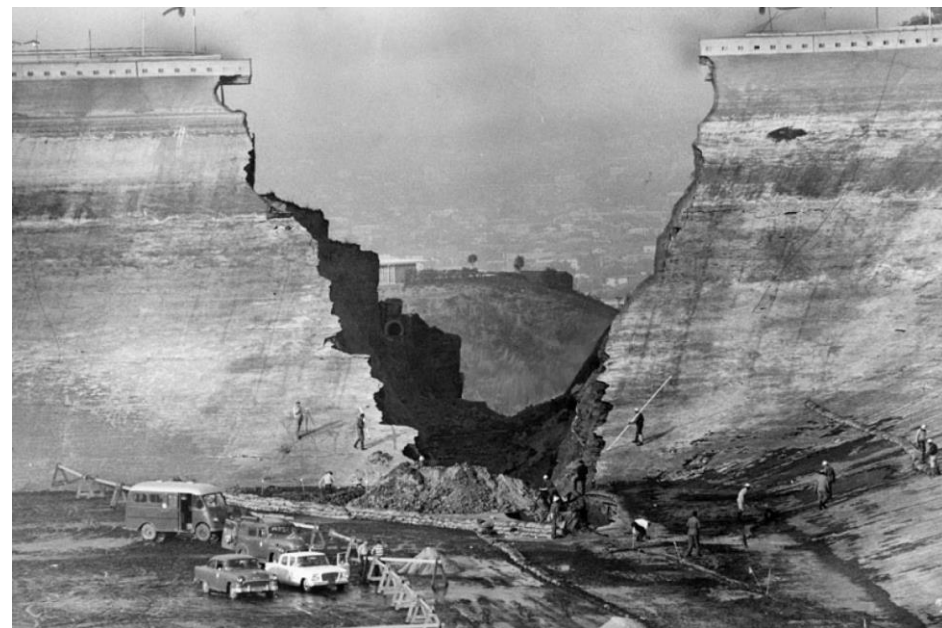


Chutes de blocs rocheux
Caduta di massi

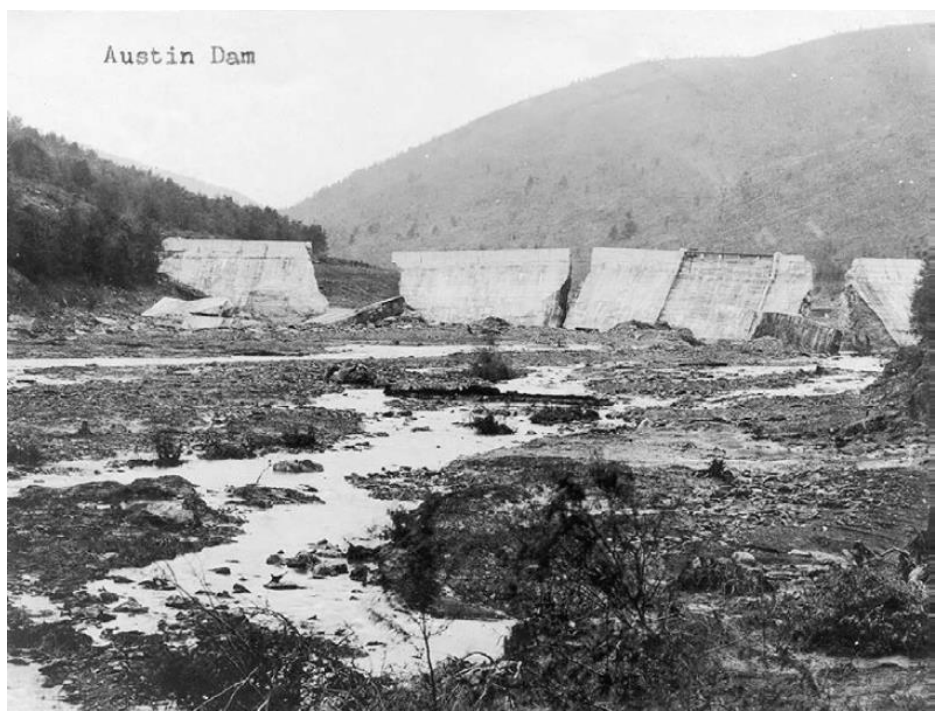
Exemples de ruptures de barrages-poids en crue *Esempi di cedimenti di dighe a gravità durante un'alluvione*



Rupture du barrage du Bouzey (1895)
Cedimento della diga de Bouzey (1895)



Rupture du barrage de Baldwin Hills (1963)
Cedimento della diga de Baldwin Hills (1963)



Rupture du barrage de Austin (1911)
Cedimento della diga de Austin (1911)

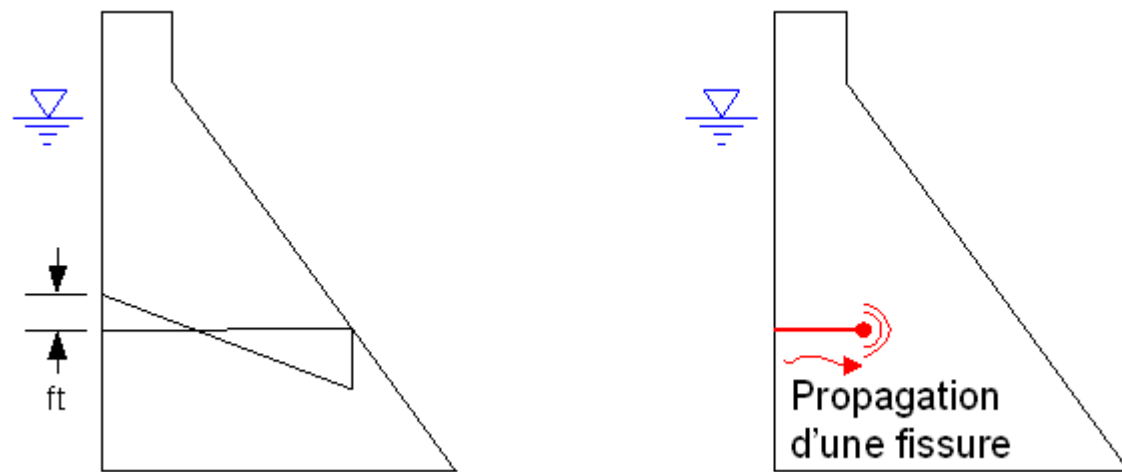


Rupture du barrage de Dunlap Lake (2019)
Cedimento della diga del lago Dunlap (2019)



Question scientifique *Problema scientifico*

Modèle idéalisé utilisé pour la justification des barrages poids
Modello idealizzato utilizzato per la giustificazione delle dighe a gravità



Modèle simplifié ? *Modello semplificato ?*



Ruptures observées et résultats issues de modèles numériques
Interruzioni osservate e risultati da modelli numerici

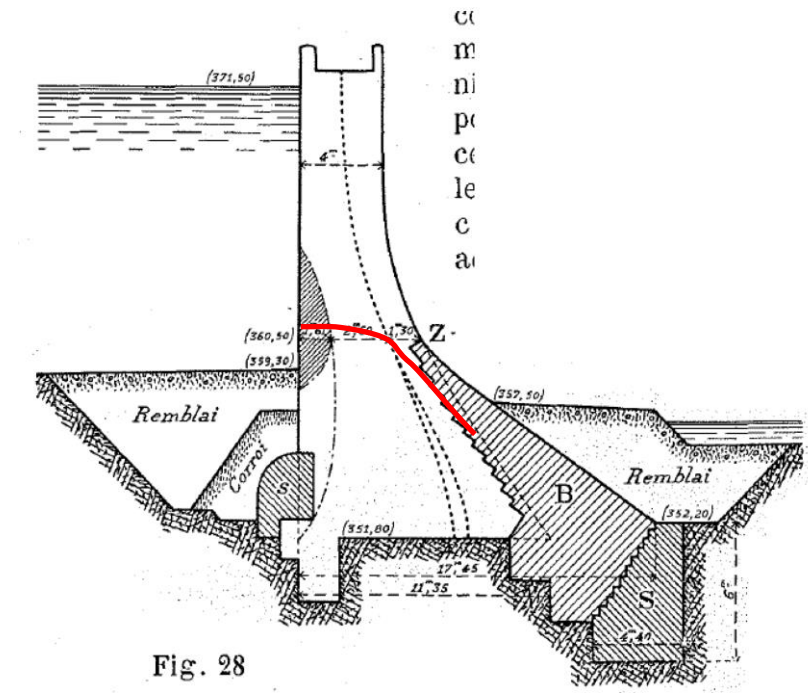
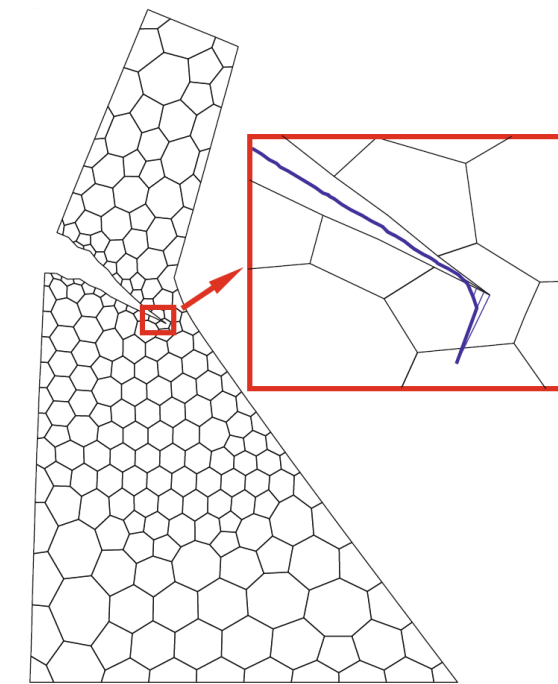
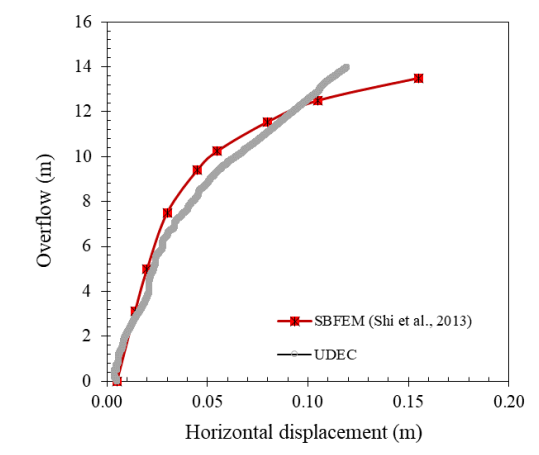
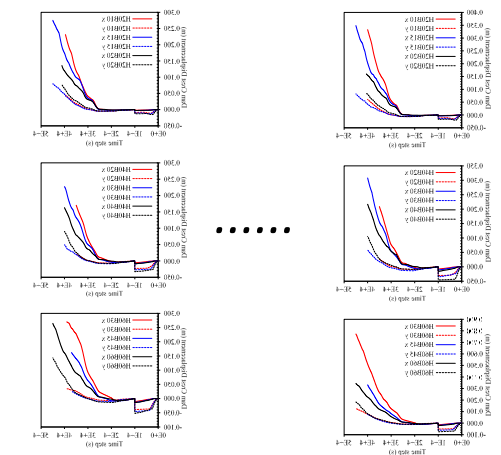
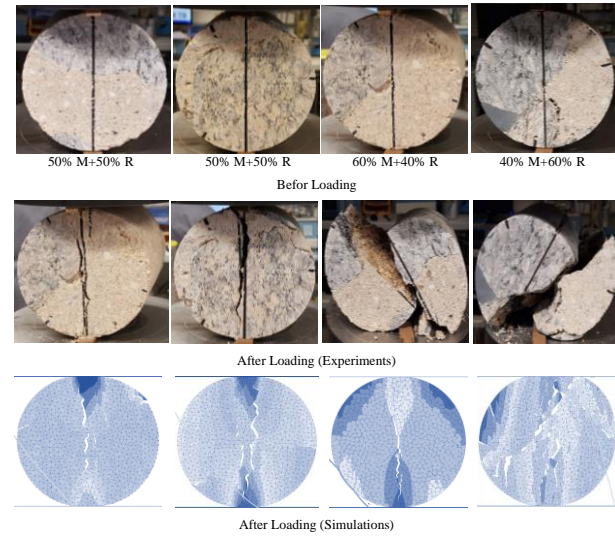


Fig. 28



Démarche générale du projet

Approccio generale al progetto



Analyse bibliographique
Revisione della letteratura

Choix de la méthode UDEC (GBM-DEM)
Scelta del metodo UDEC (GBM-DEM)

Validation sur des essais en laboratoire
Convalida su test di laboratorio

Analyse des résultats et établissement du modèle de fissuration
Analisi dei risultati e definizione del modello di cracking

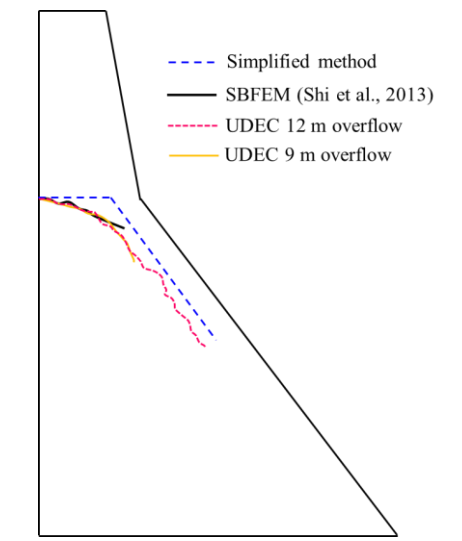
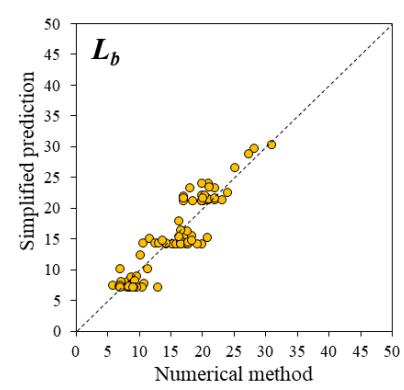
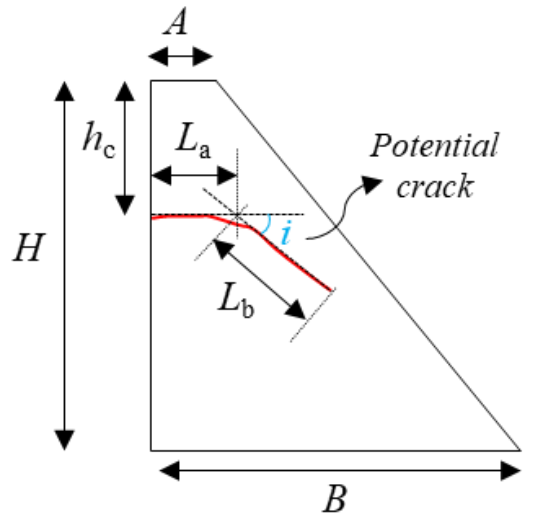
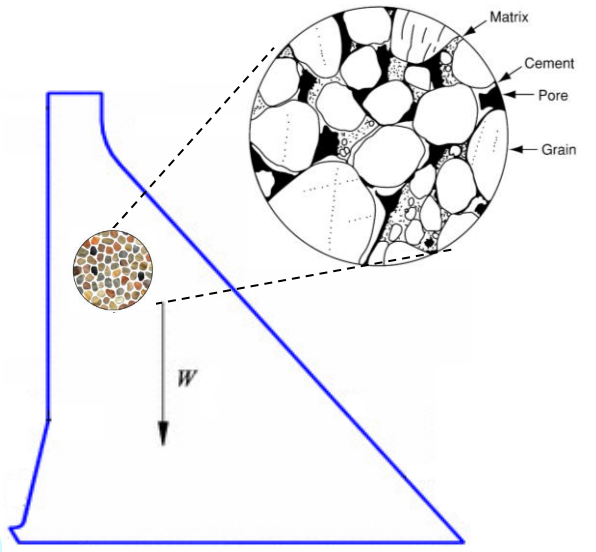
Constitution de la base de données de résultats de calculs (81)
Costituzione della banca dati dei risultati di calcolo (81)

Post-traitement des résultats pour établir des équations simplifiées
Post-elaborazione dei risultati per stabilire equazioni semplificate

Vérification du modèle sur un cas d'étude
Verifica del modello su un caso di studio reale

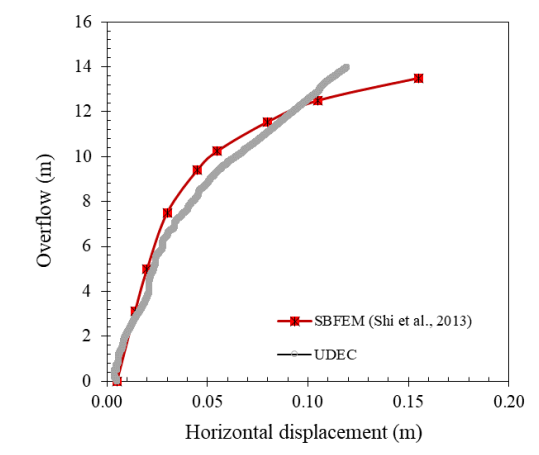
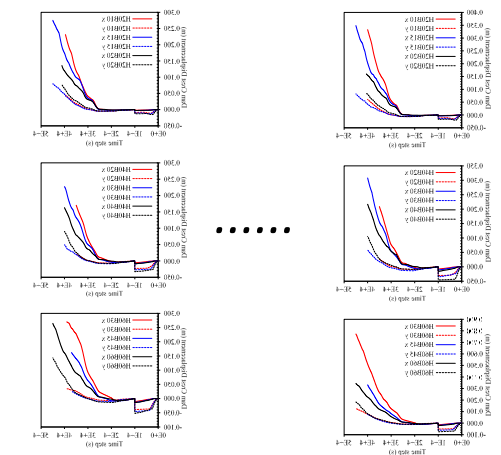
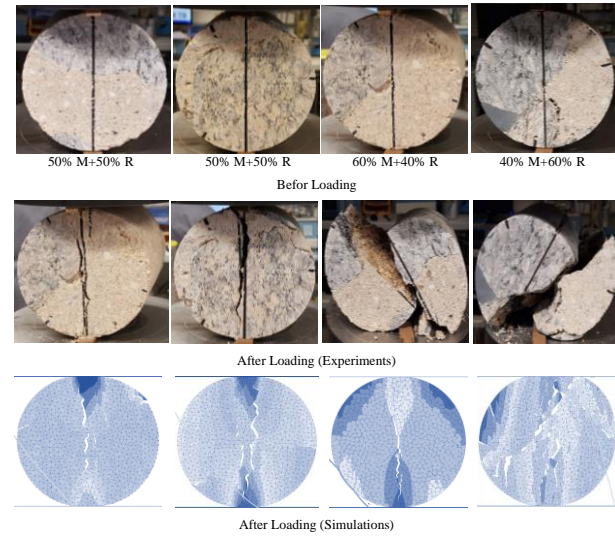
Validation sur une étude de cas
Convalida su un caso di studio

Validation croisée du modèle
Convalida del modello



Démarche générale du projet

Approccio generale al progetto



Analyse bibliographique
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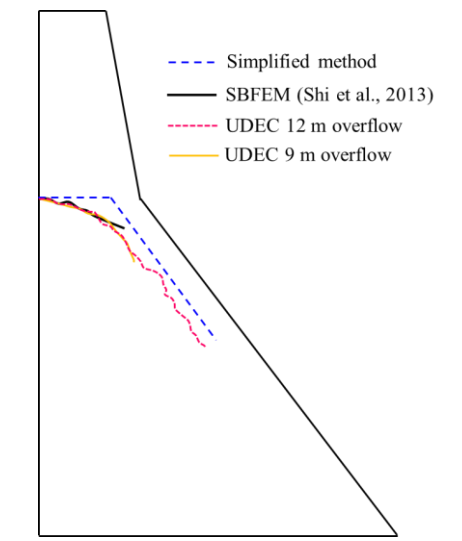
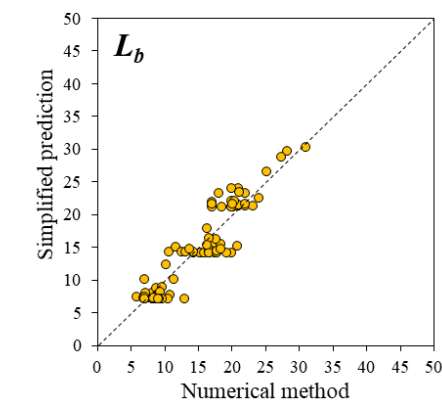
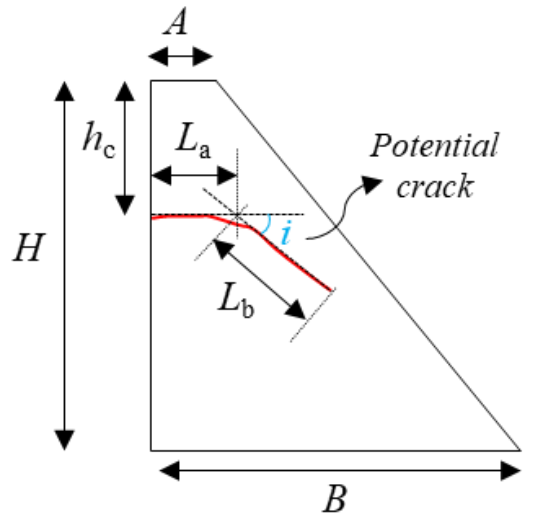
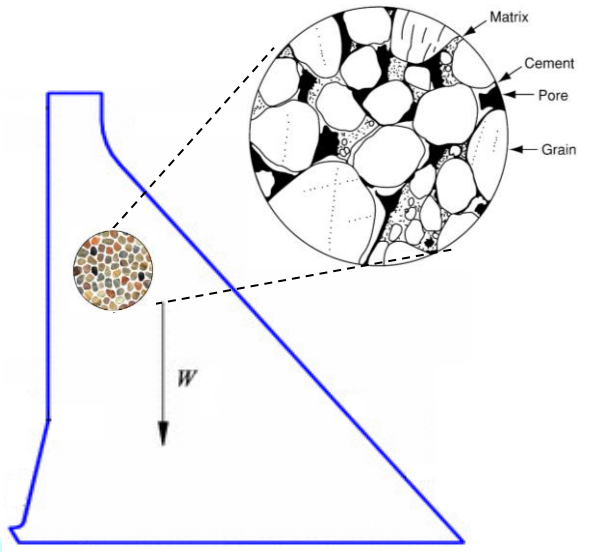
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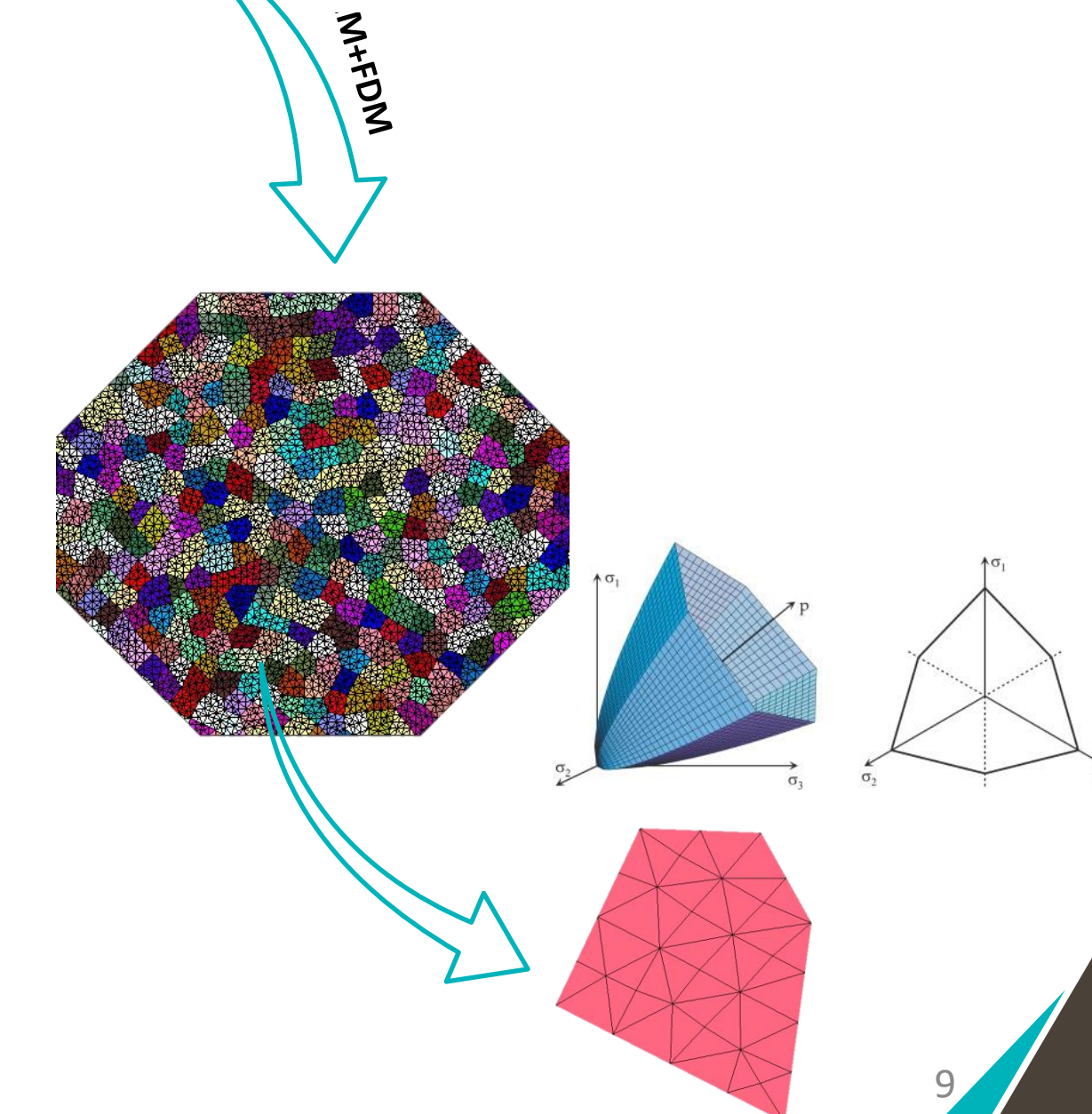
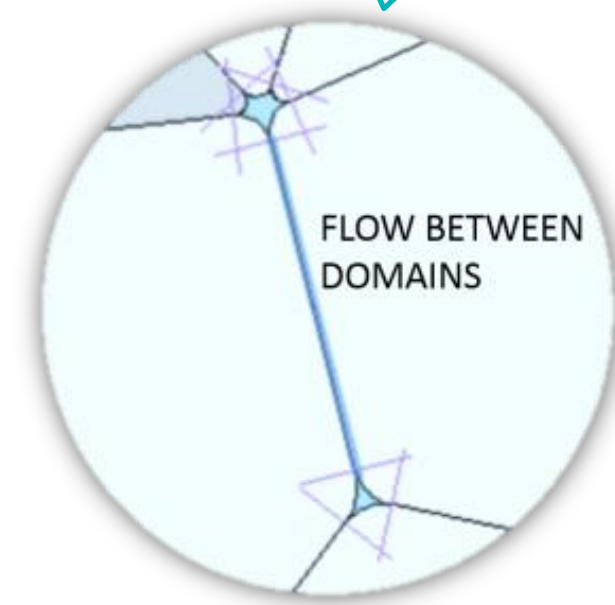
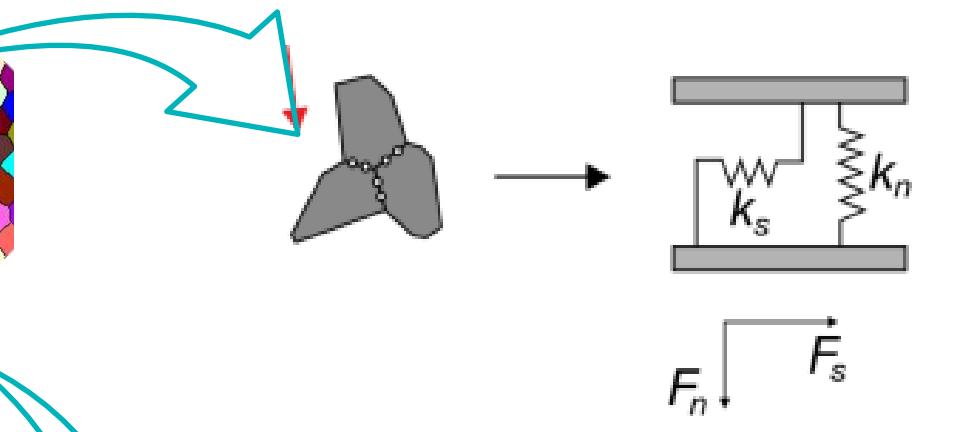
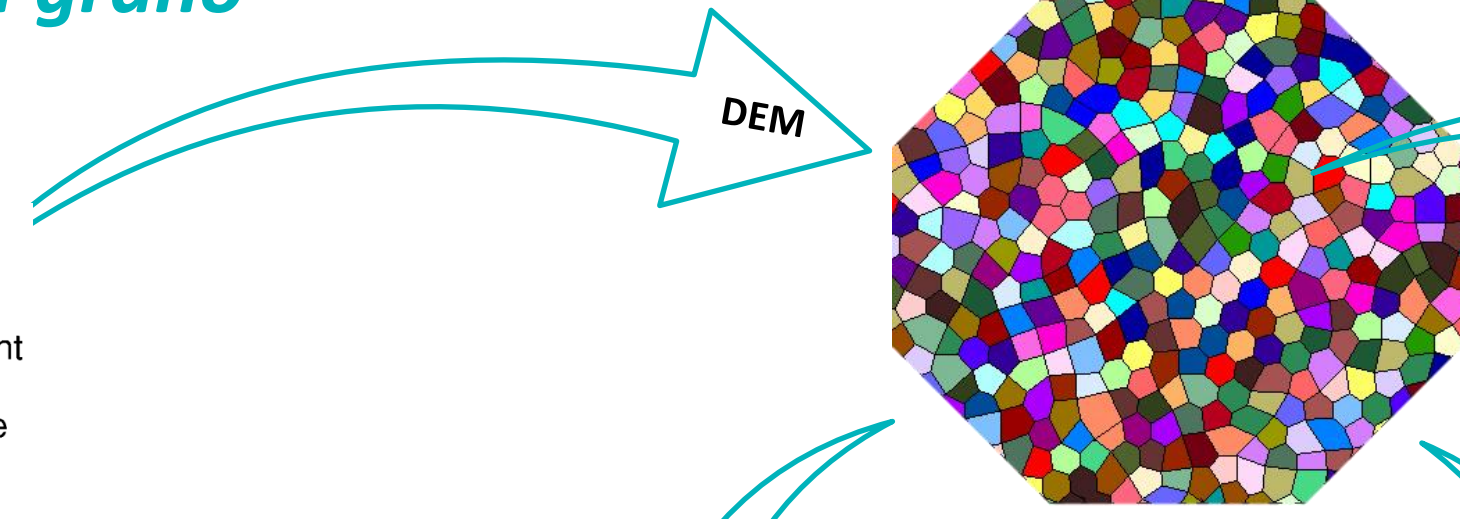
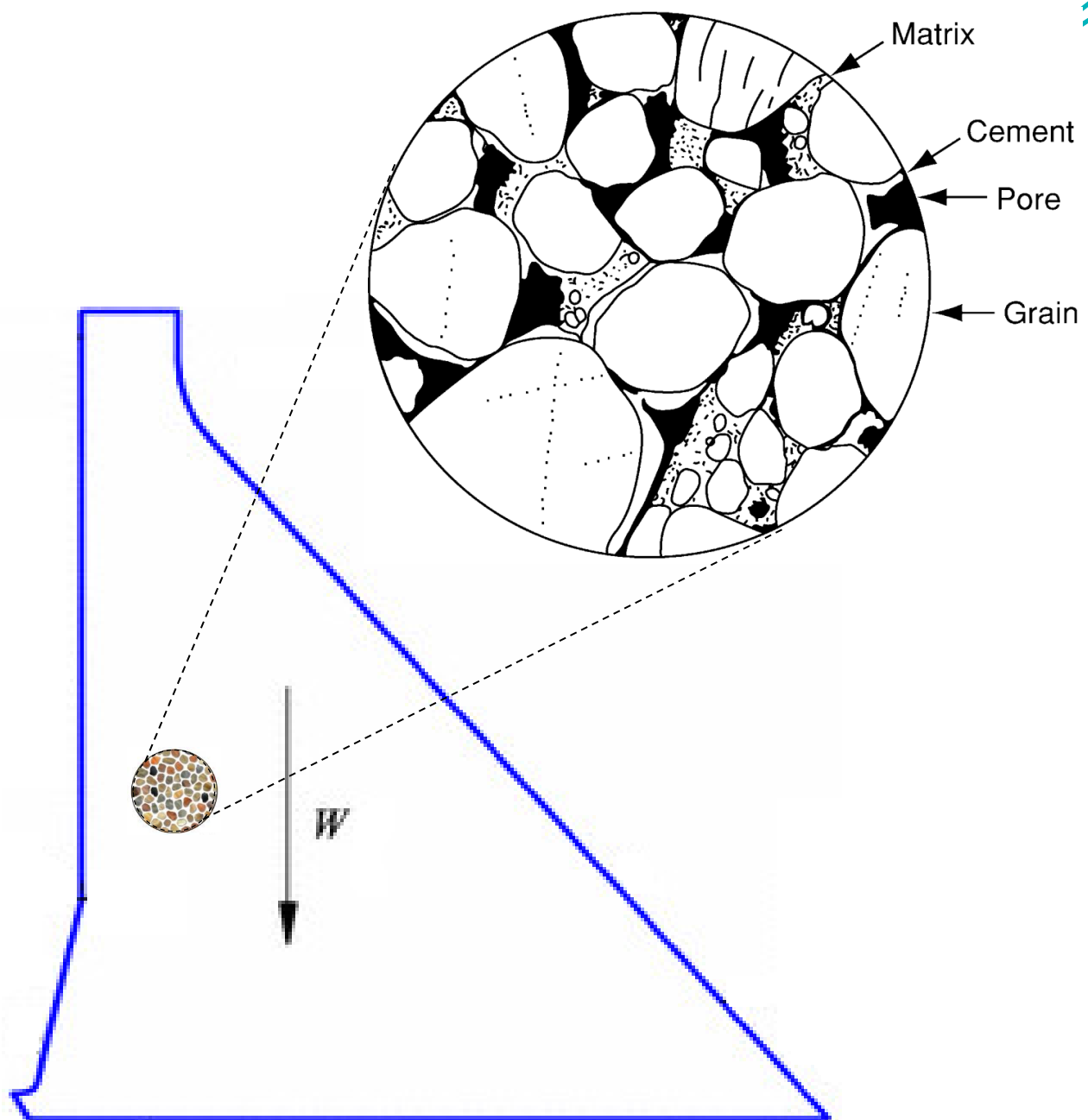
Validation sur une étude de cas
Convalida su un caso di studio

Validation du modèle
Convalida del modello



Méthodologie
Methodologia

Modélisation à base d'éléments grains Modellazione basata su elementi grano



 **UDEDEC™** VERSION 7.0
Distinct-Element Modeling of
Jointed and Blocky Material in 2D

Model validation and the case study
Validazione del modello e studio di caso



Le barrage de Gabiet

La diga de Gabiet

Construction / *Costruzione* : 1919-1923

Remplissage / *Riempimento* : 1938

Bassin versant / *Spartiacque* : 3 km²

Volume de la retenue / *Volume del serbatoio*: 4 170 000 m³

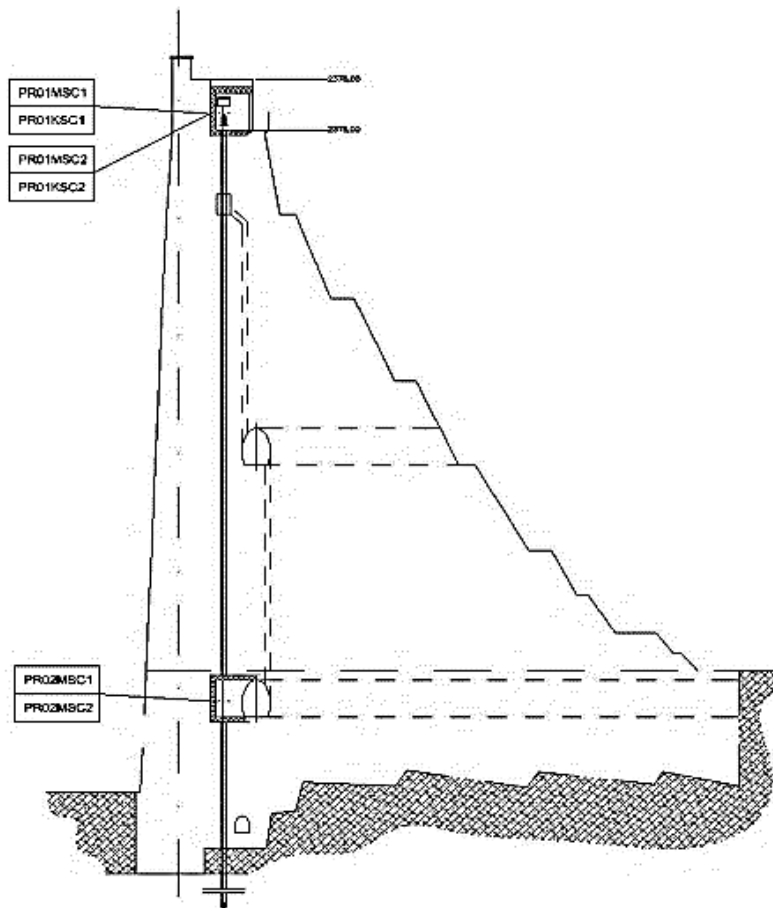
Type de structure / *Tipo strutturale* : barrage poids en maçonnerie / diga a gravità in muratura

Hauteur / *Altezza* : 46 m

Longueur en crête / *Lunghezza della cresta* : 212 m

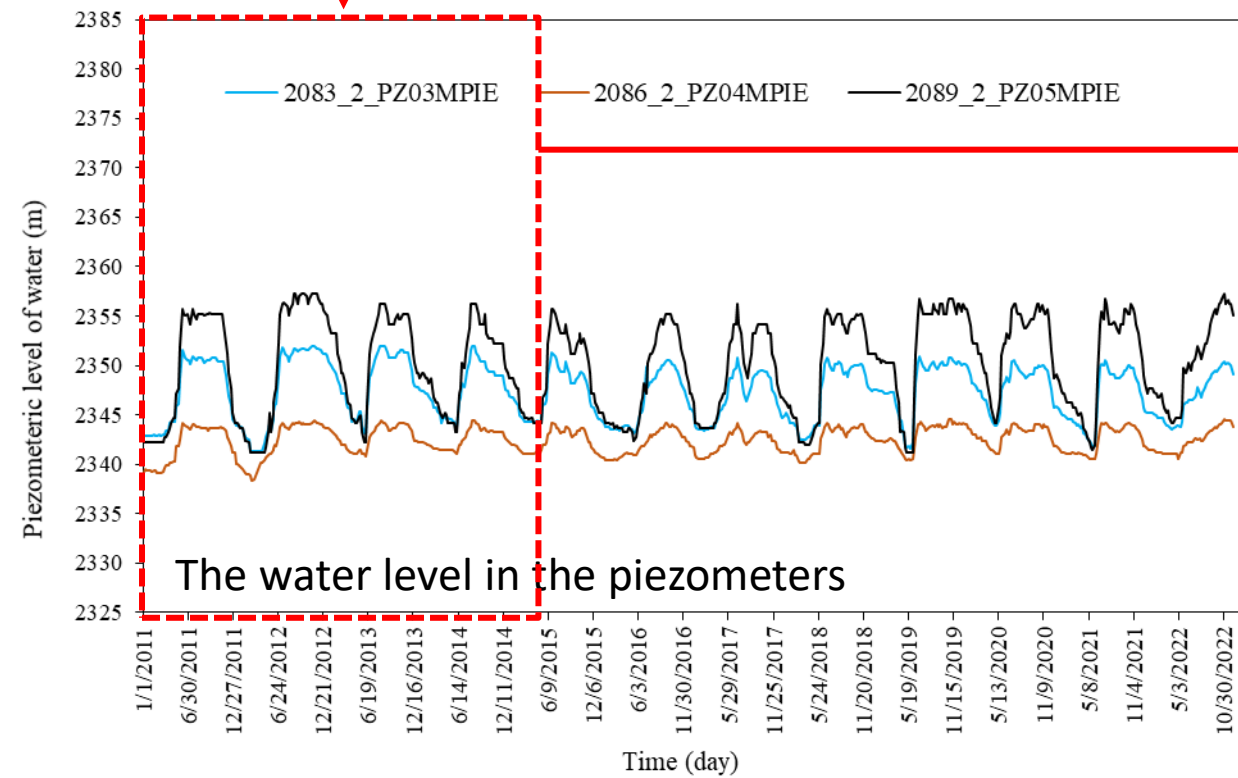
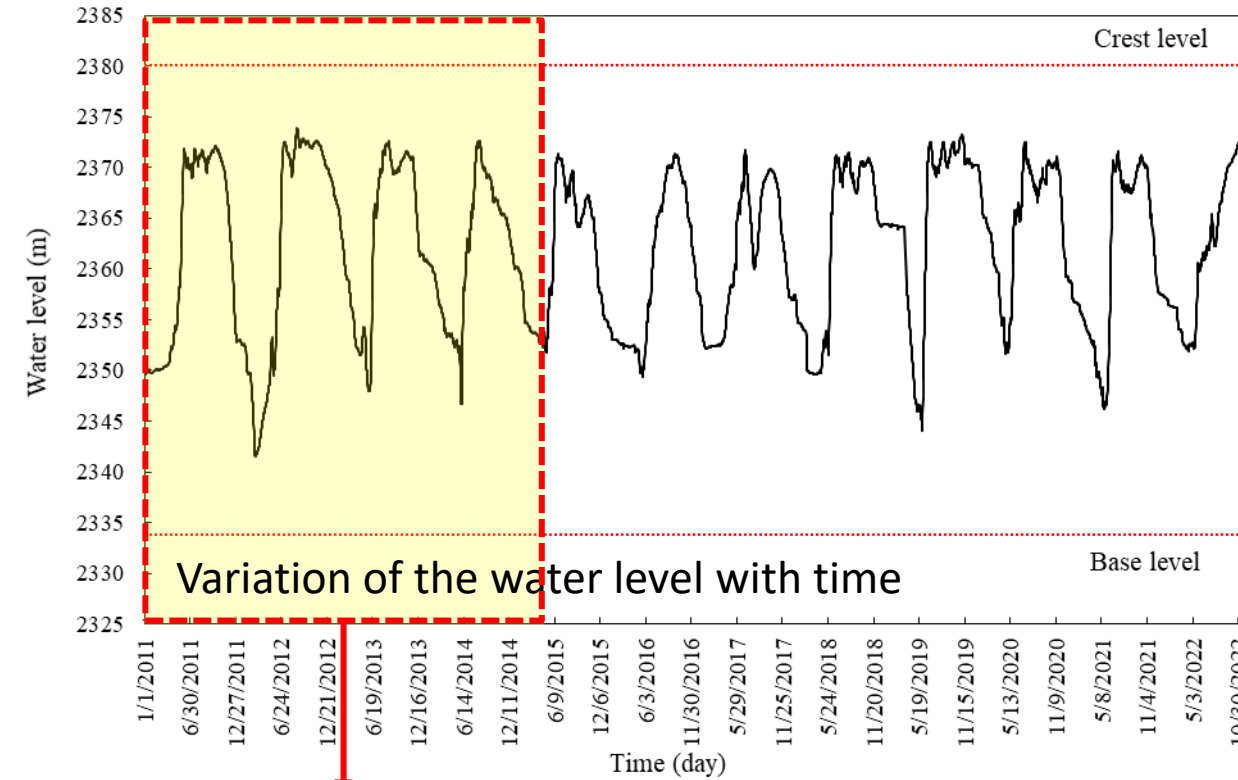
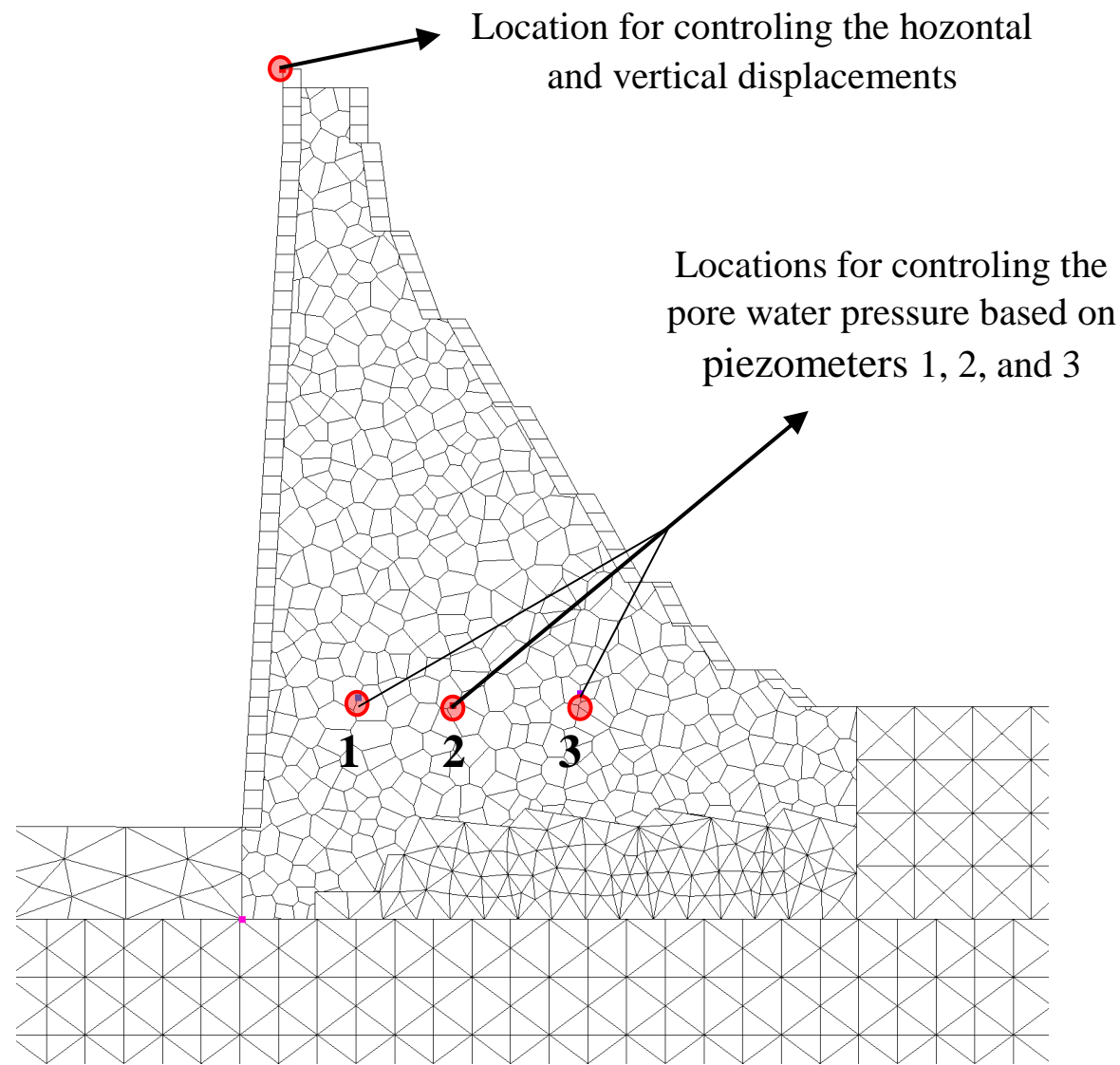
Largeur à la base / *Larghezza della base* : 33 m

Largeur en crête / *Larghezza della cresta* : 4,30 m

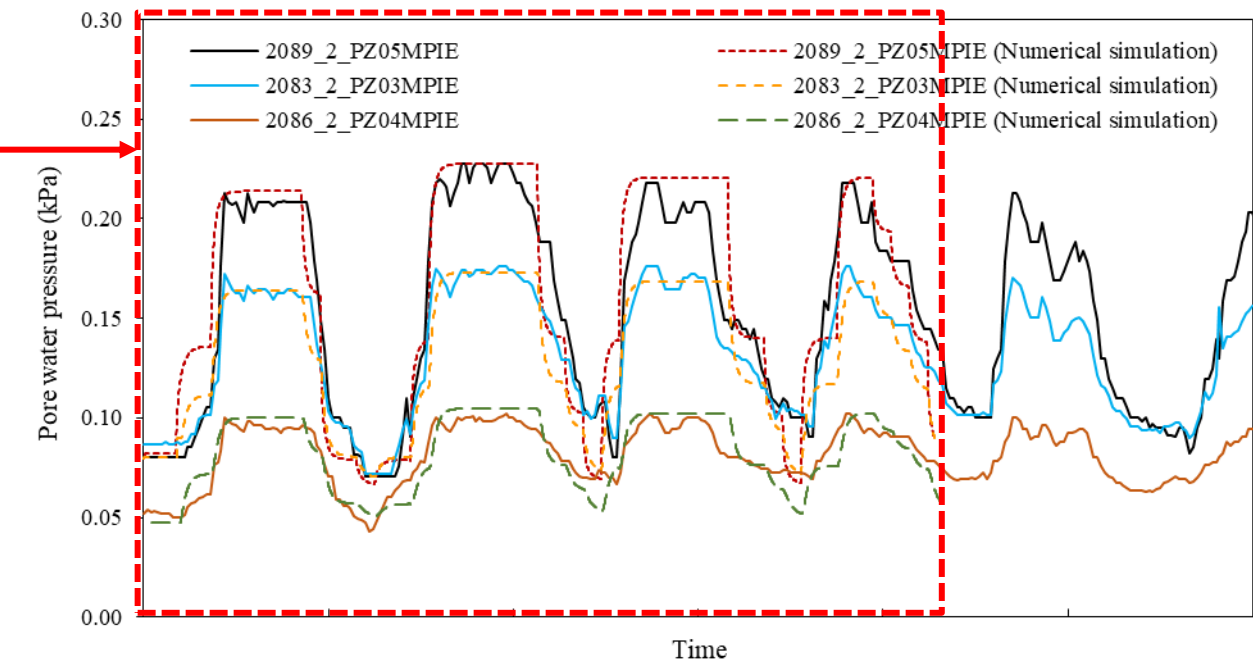




Validation du modèle Convalida del modello



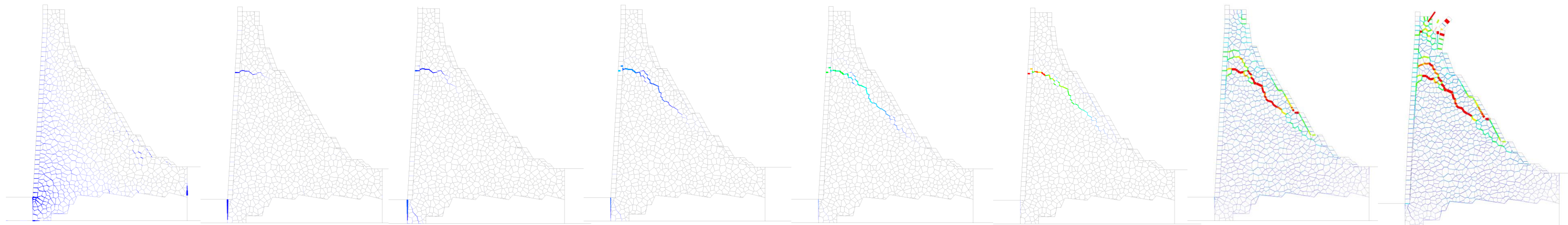
Durée considérée pour la verification du modèle
La durata considerata ai fini della verifica



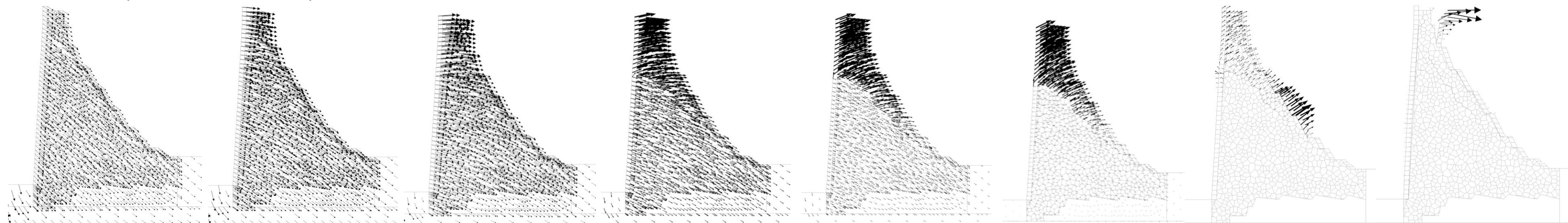


Réponse du barrage en crue / Risposta della diga in piena

Ouverture des joints / Apertura contatti



Vecteurs déplacement / Vettori di spostamento



4 m over flow

6 m over flow

8 m over flow

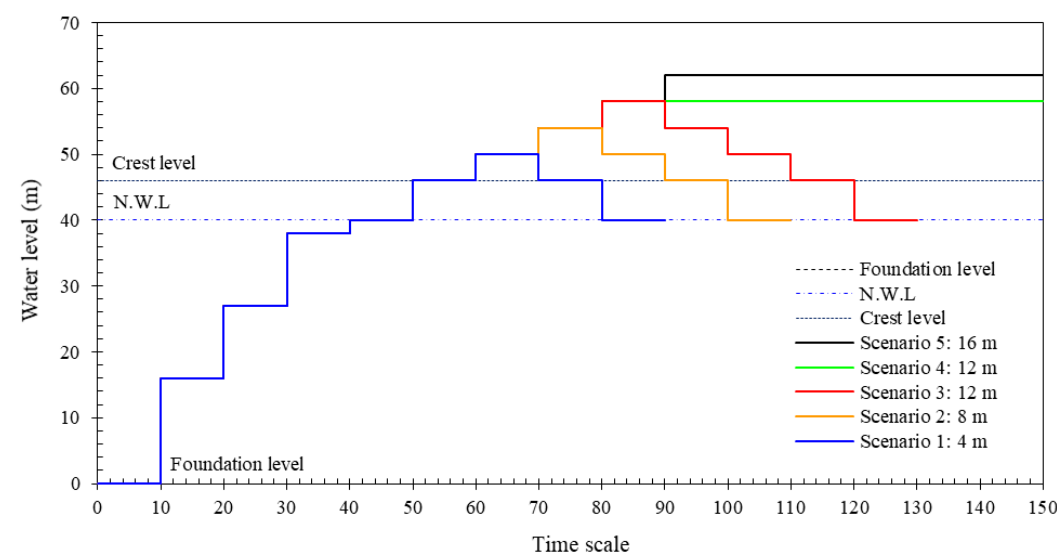
10 m over flow

12 m over flow

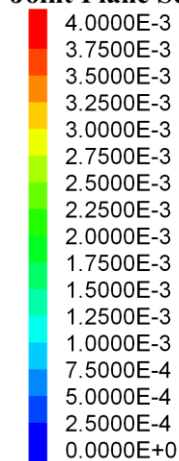
N.W.L

12 m overflow long period

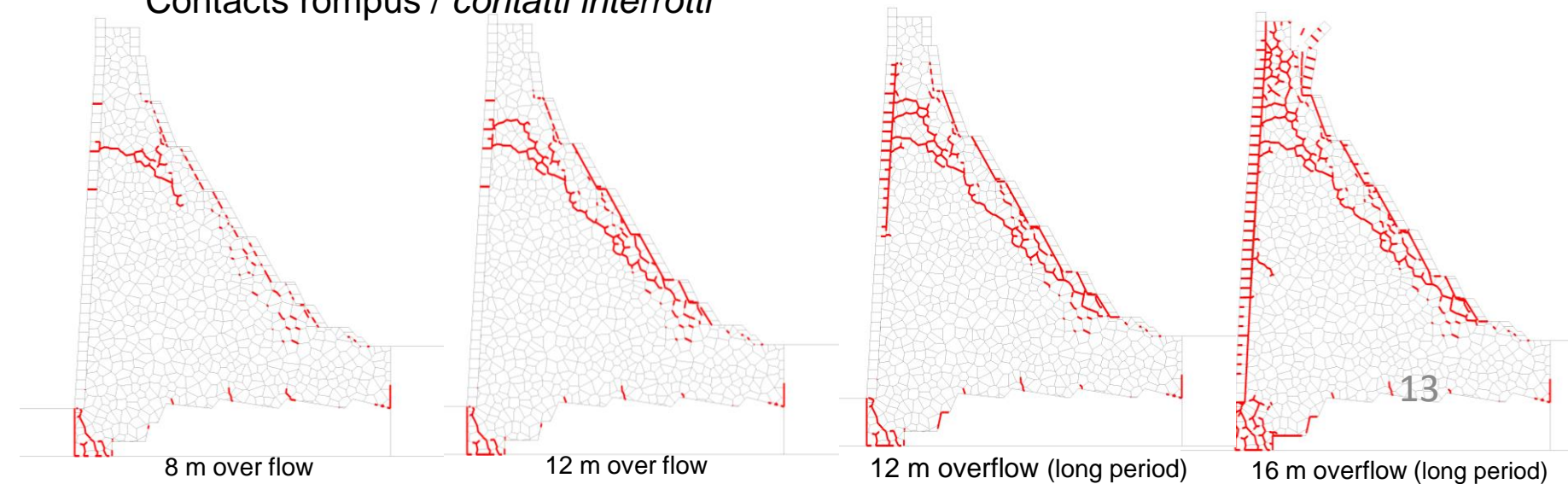
16 m overflow long period



Joint Plane Separation



Contacts rompus / contatti interrotti



8 m over flow

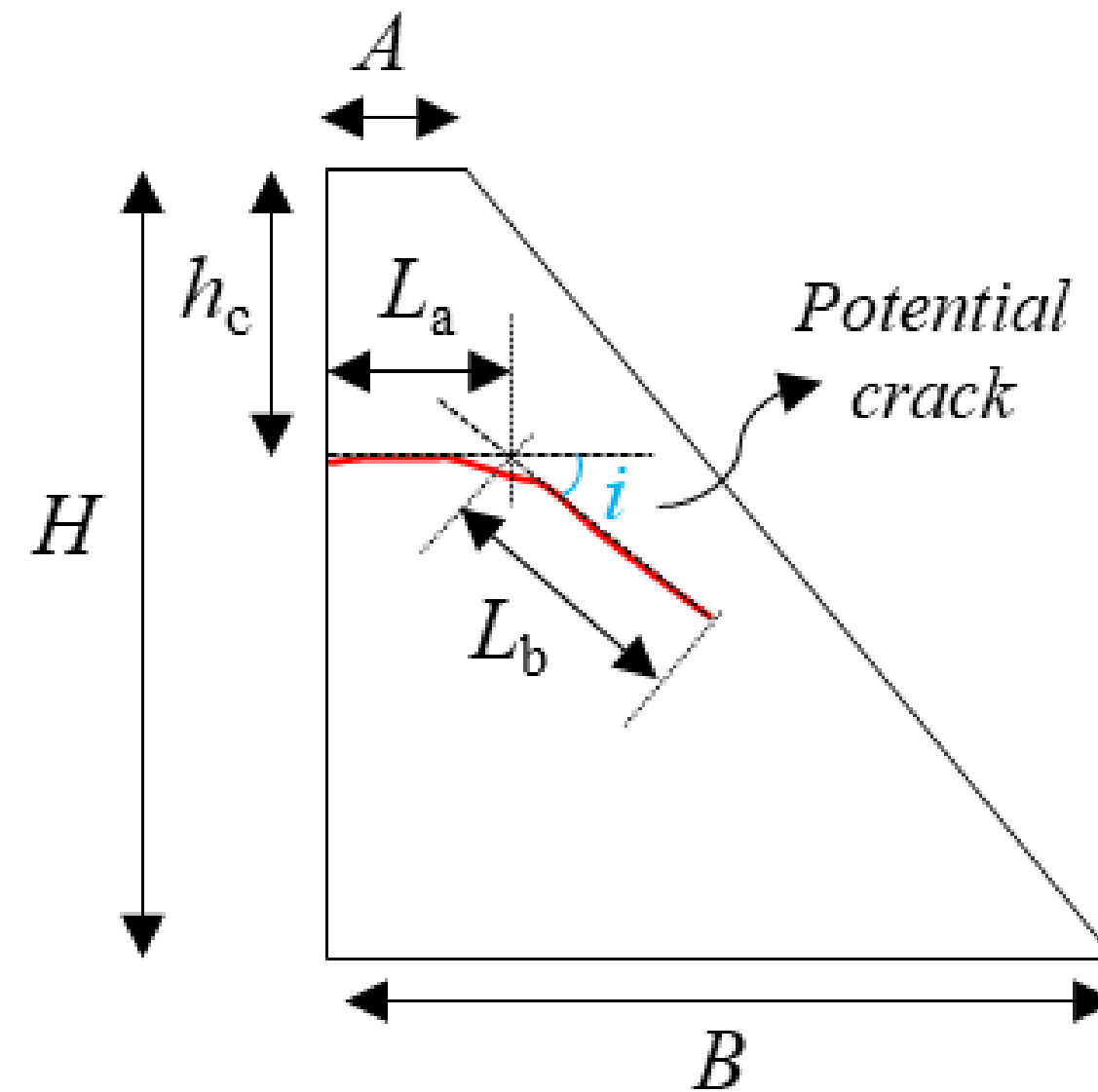
12 m over flow

12 m overflow (long period)

16 m overflow (long period)

Modèle de fissuration

Modello di fessurazione



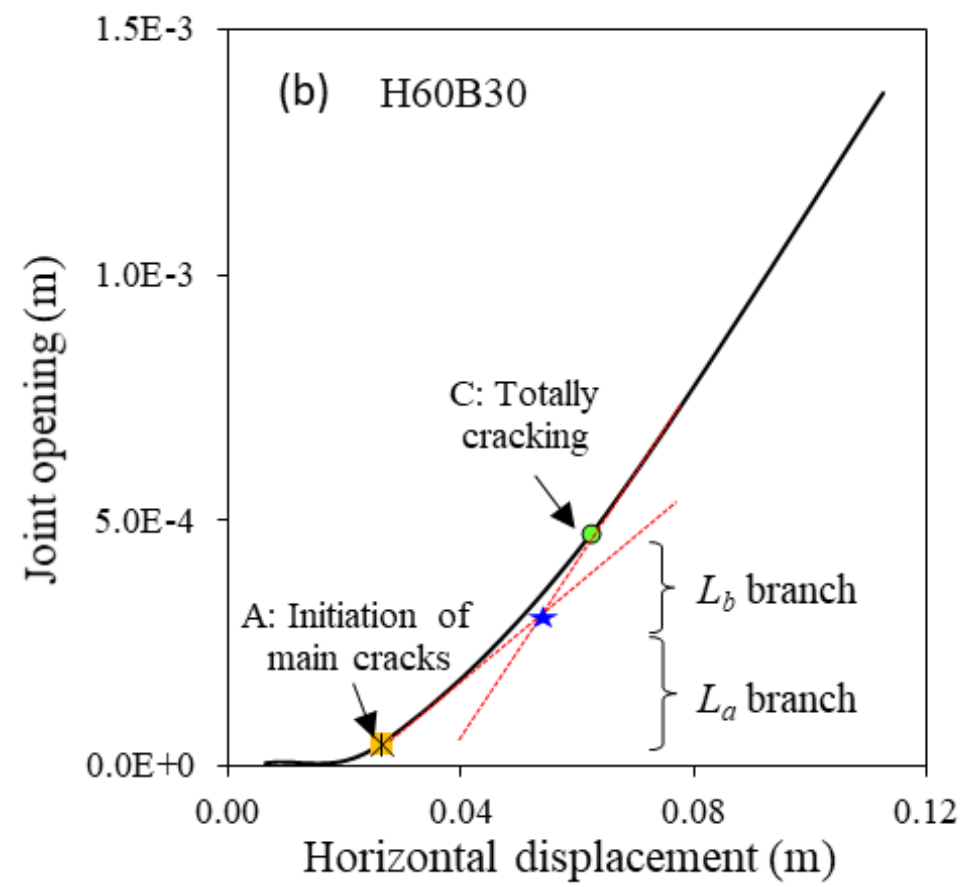
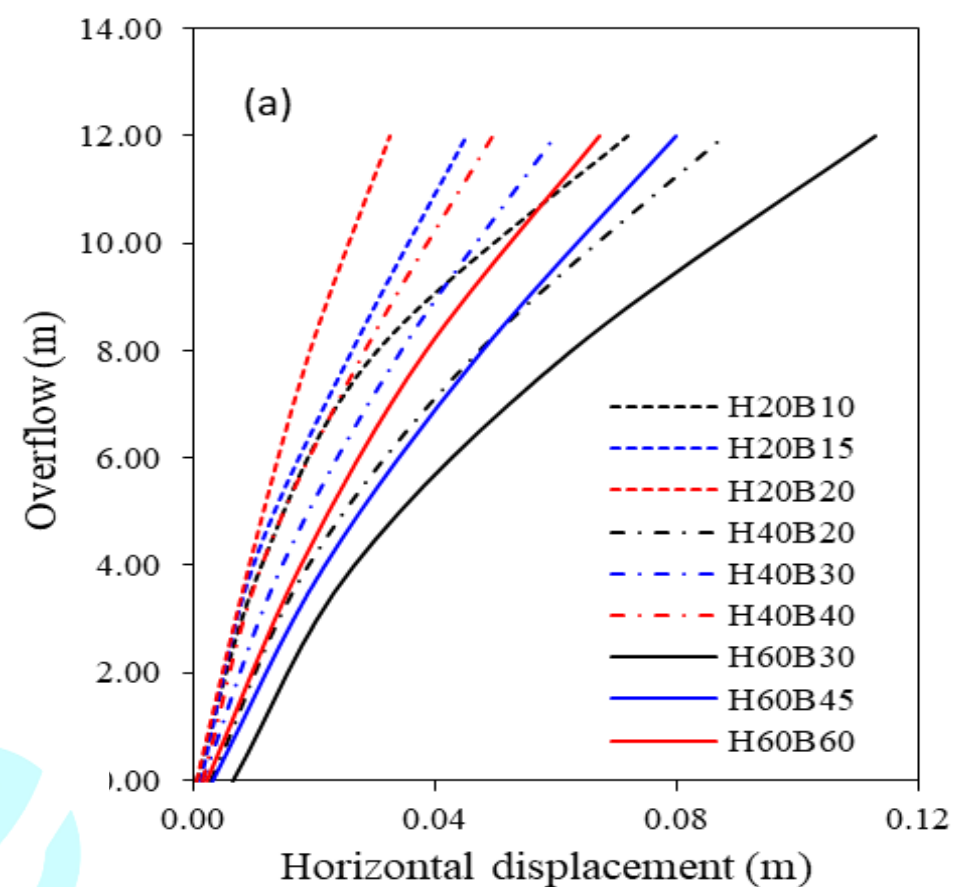
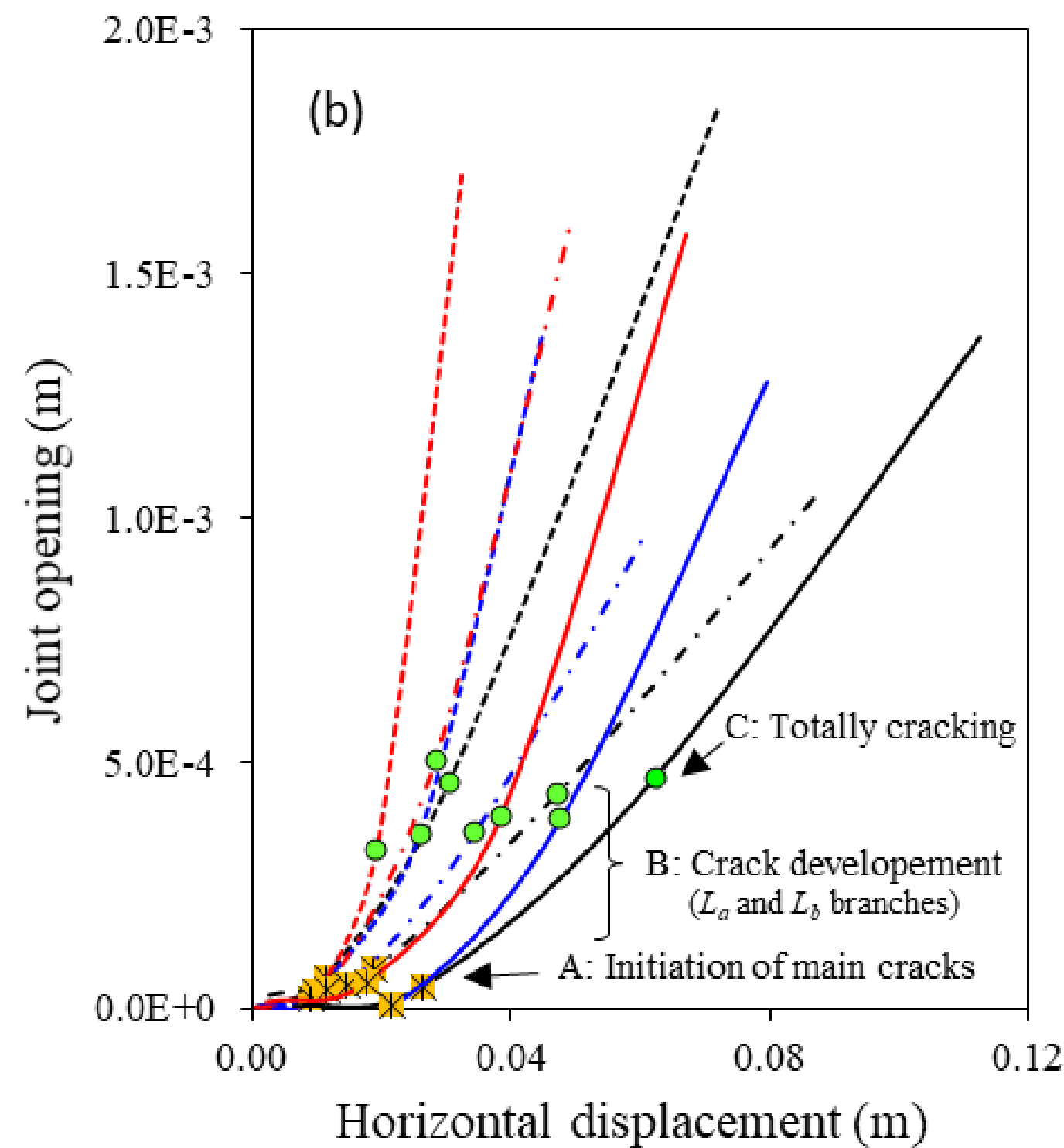
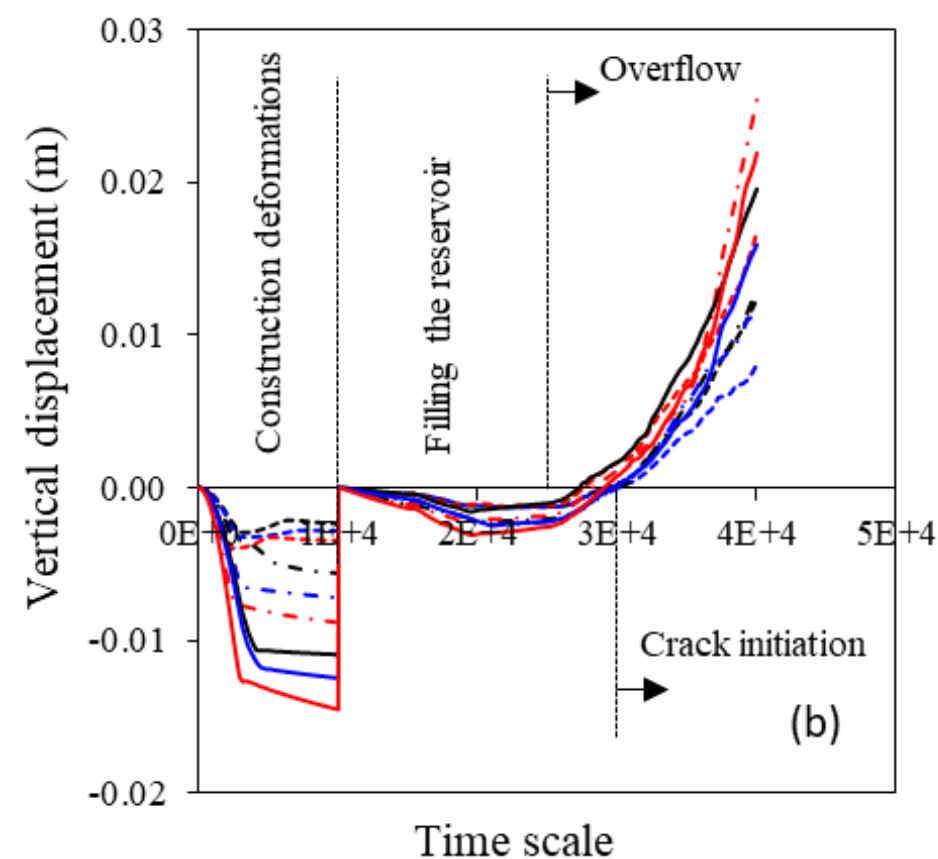
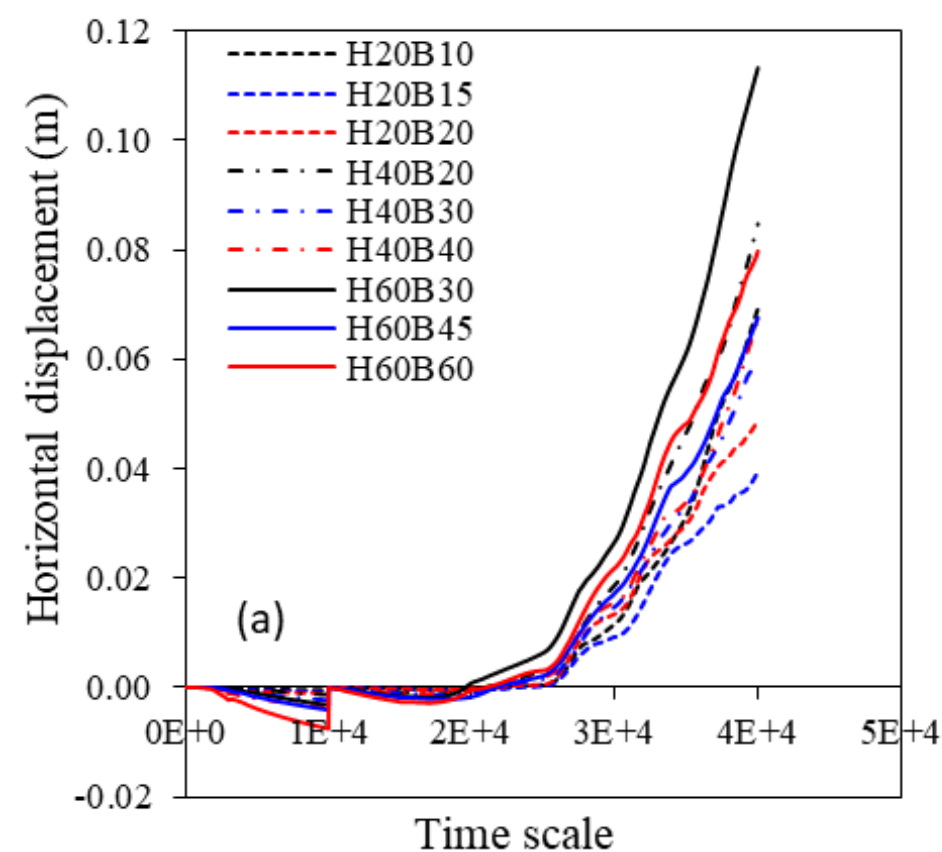
La vue schématique de la technique de la double tangente pour modélisation de la trajectoire de la fissure à l'intérieur du corps du barrage

La vista schematica della tecnica della doppia tangente per modellare la traiettoria della fessura all'interno del corpo diga

L_a L_b h_c i



Modèle de fissuration Modello di fessurazione


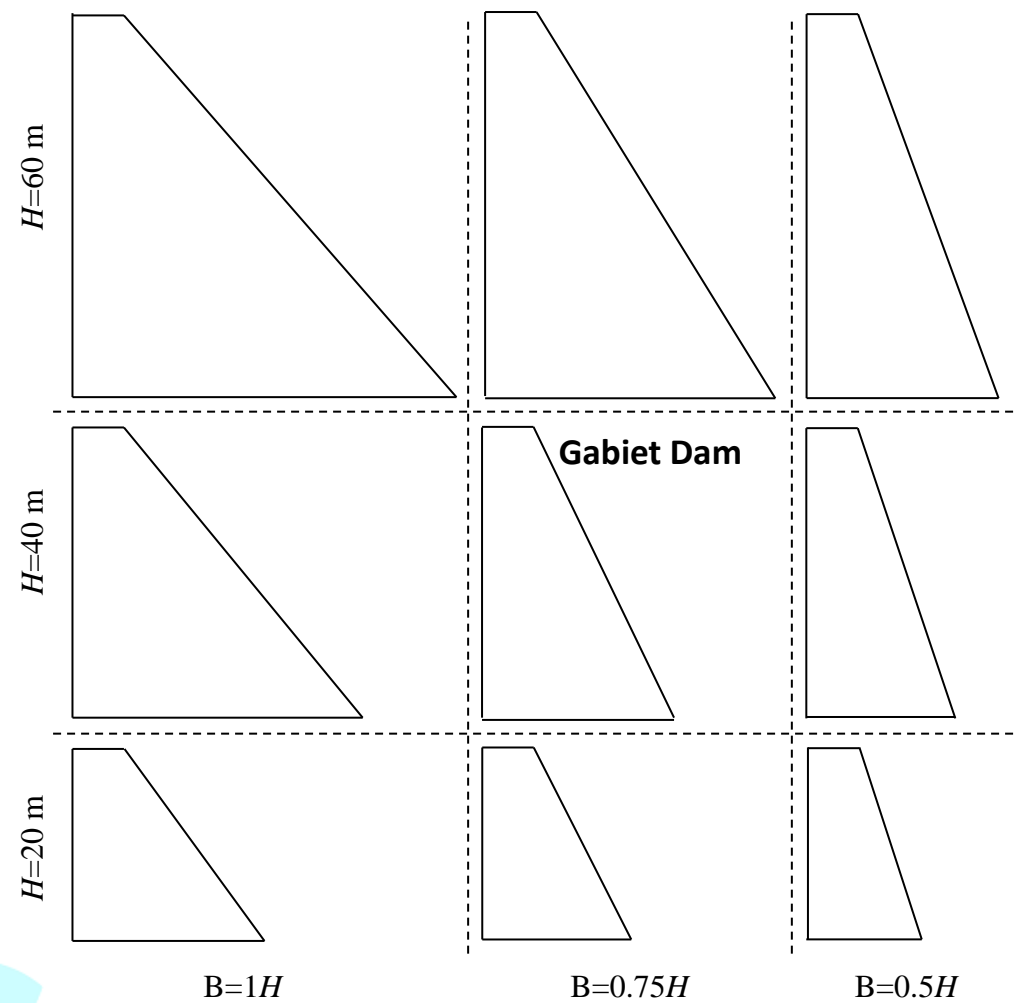
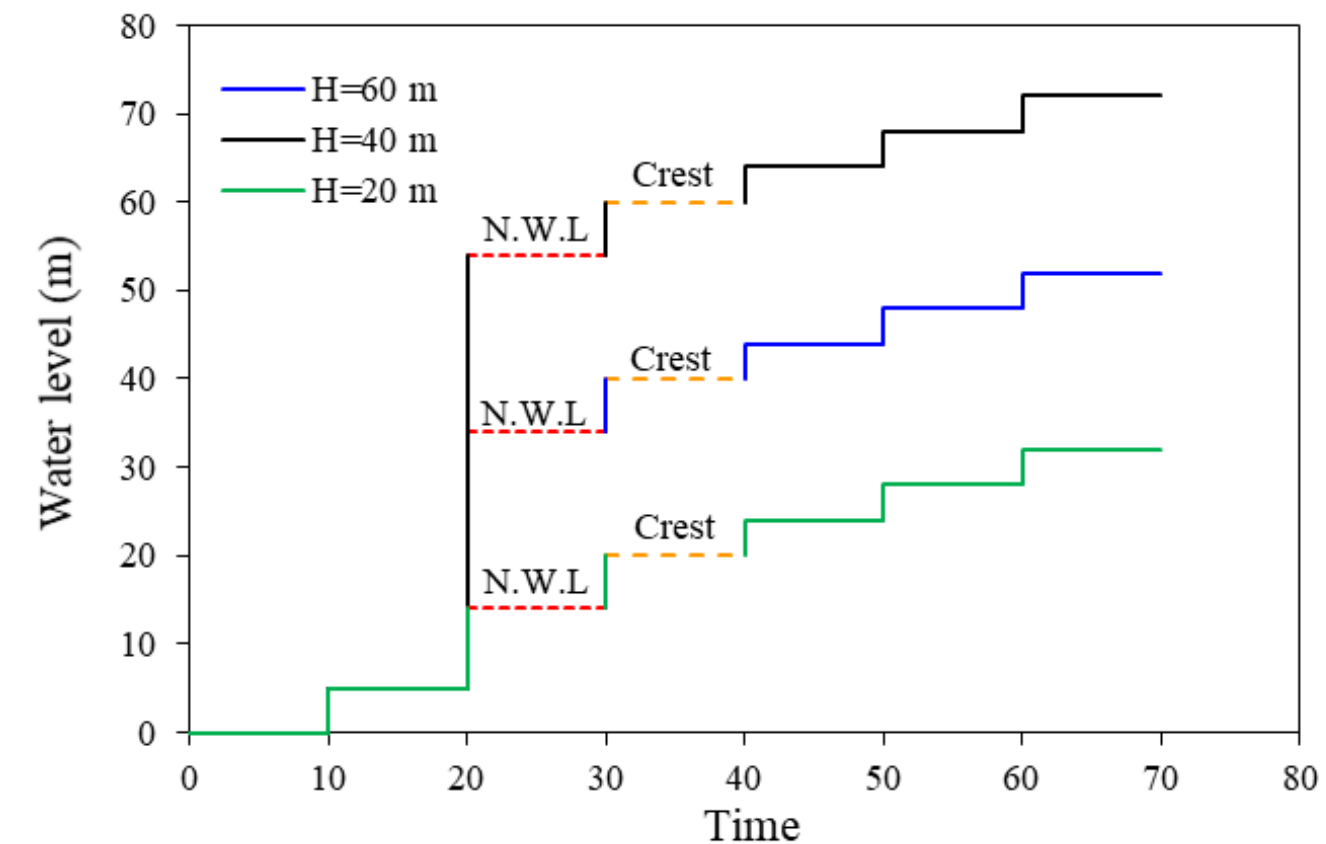


Etude paramétrique
Studio parametrico

Parametric study

Propriétés géométriques et géotechniques
Proprietà geometriche e geotecniche

Type	Parameters	Values
Geometry	Height (H)	20, 40, and 60 m
	Base width (B)	$0.5H$, $0.75H$, and $1H$
	Crest width	6 m
Geotechnical	Cohesive joint strength (c')	$0.5c'$, $1c'$, and $1.5c'$
	Contact friction angle (ϕ')	$0.5\phi'$, $1\phi'$, and $1.5\phi'$
	Permeability of joints (k_{void})	$0.5k_{void}$, $1k_{void}$, and $1.5k_{void}$
	Tensile strengths (τ)	0.5τ , 1τ , and 1.5τ

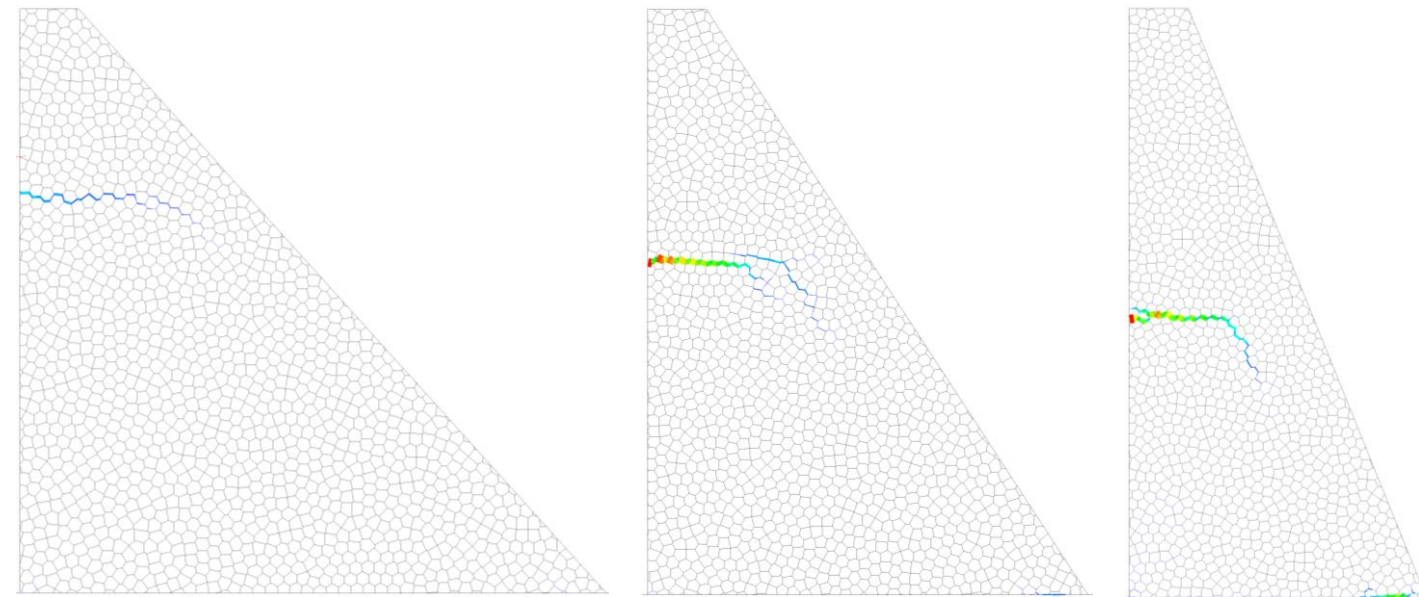
 81 models
Configurations des barrages simulés
Configurazioni delle dighe simulateÉtapes d'élévation du niveau d'eau
Gradini di aumento del livello dell'acqua

Modèle de base Modello base



Ouverture des joints pour 8 m de surverse / Apertura contatti per 8 m di straripamento

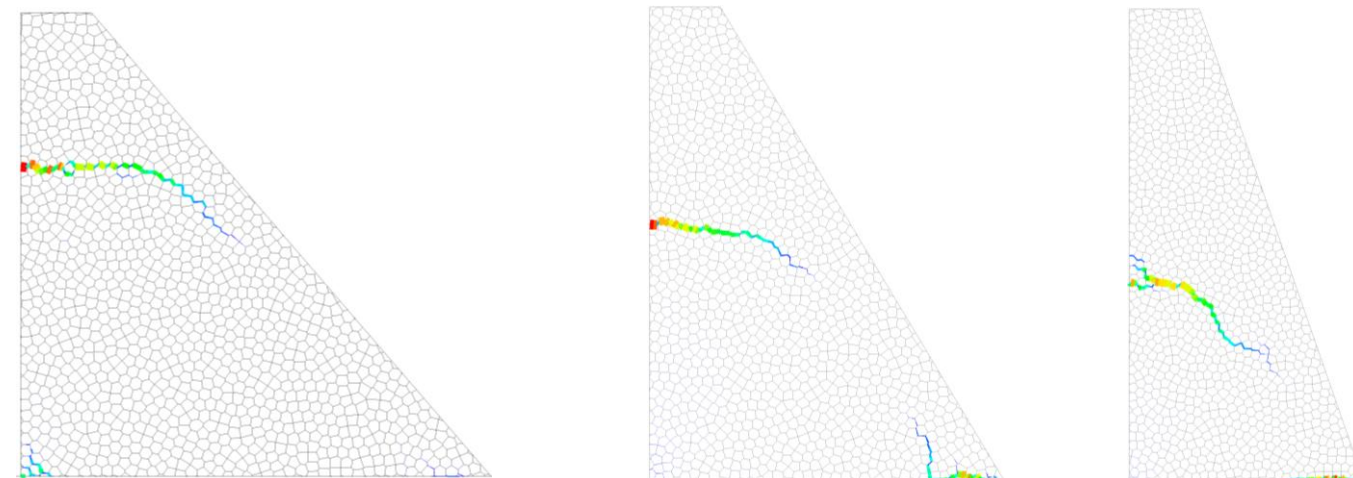
12 m de surverse / 12 m di straripamento



H60B60

H60B45

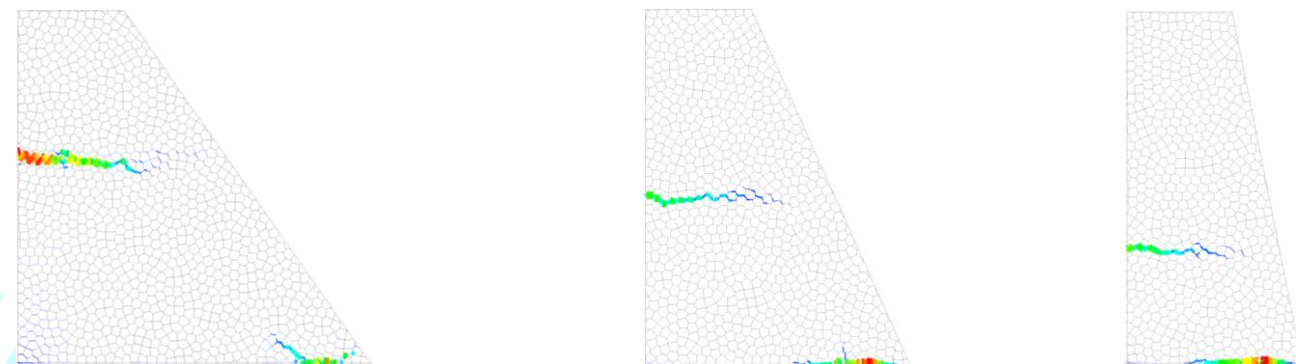
H60B30



H40B40

H40B30

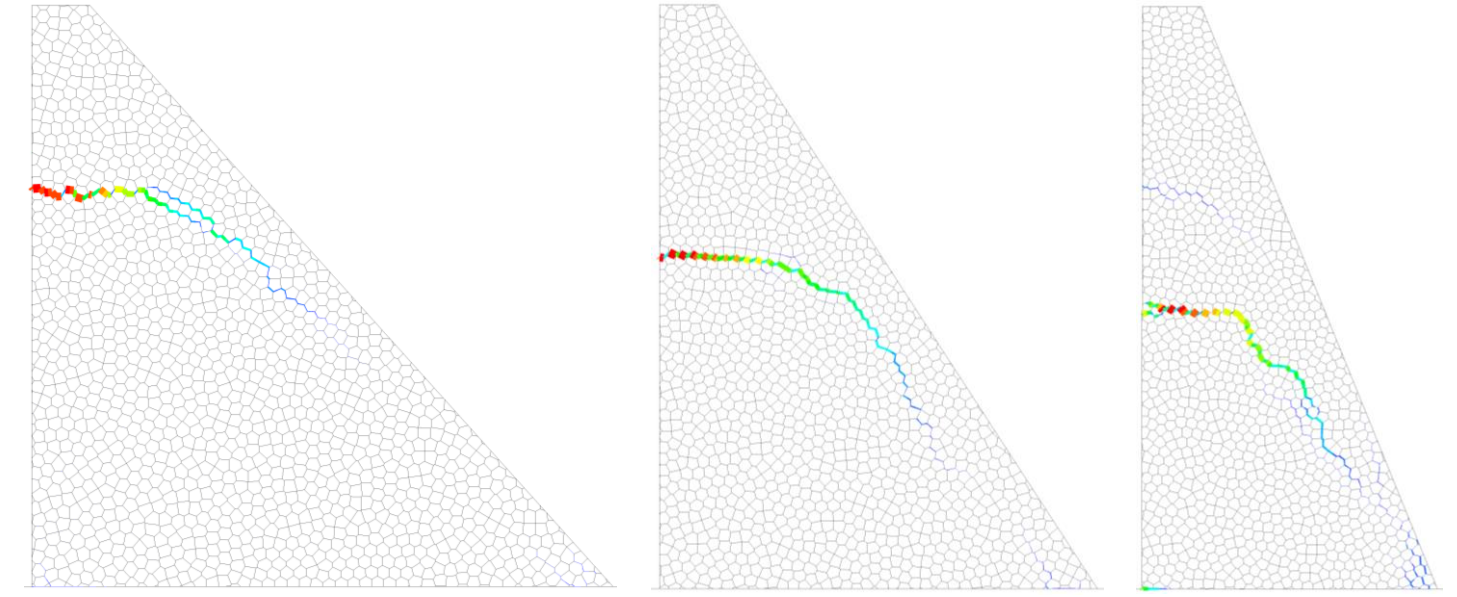
H40B20



H20B20

H20B15

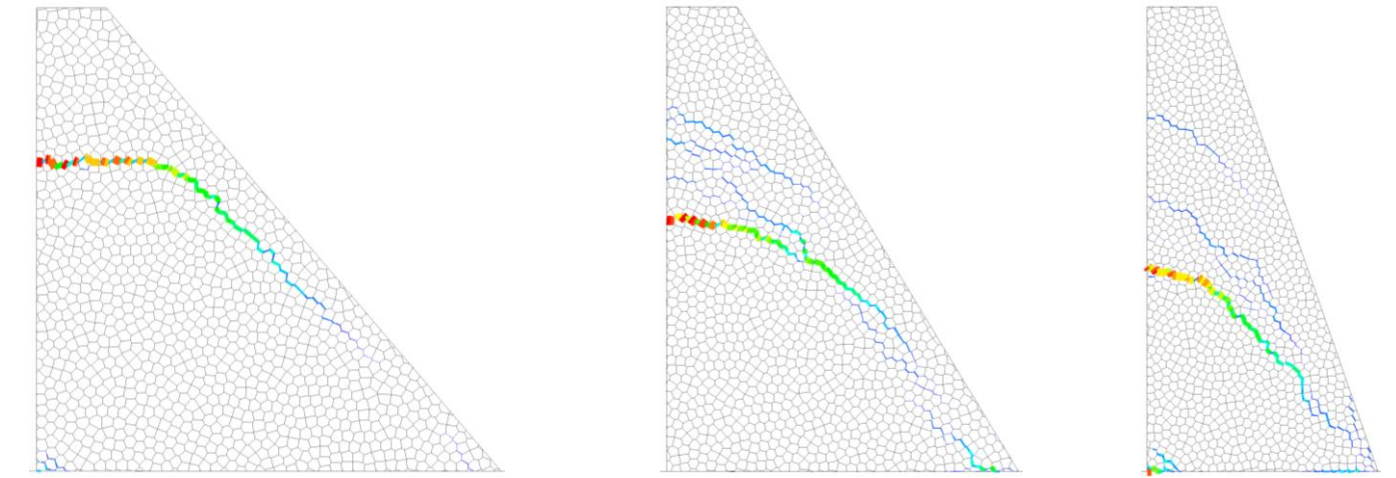
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H60B60

H60B45

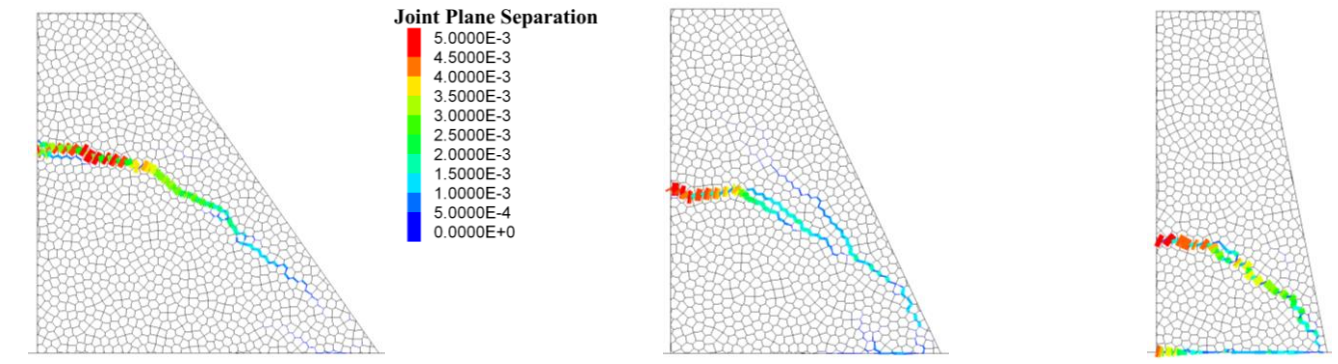
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H40B40

H40B30

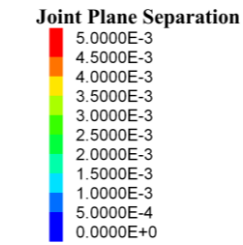
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H20B20

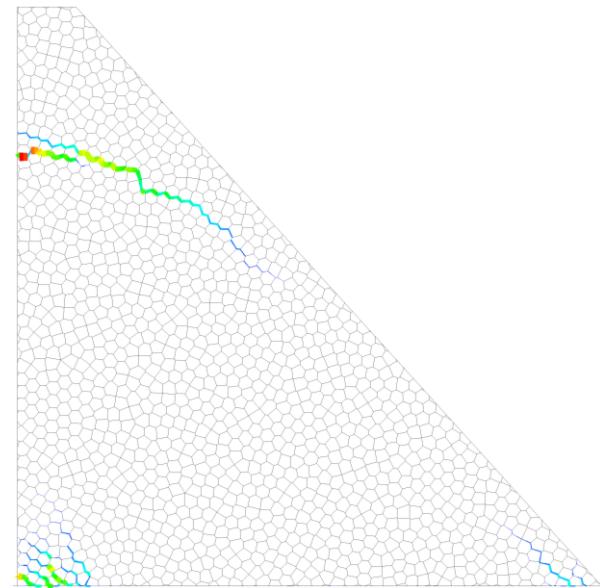
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H20B10

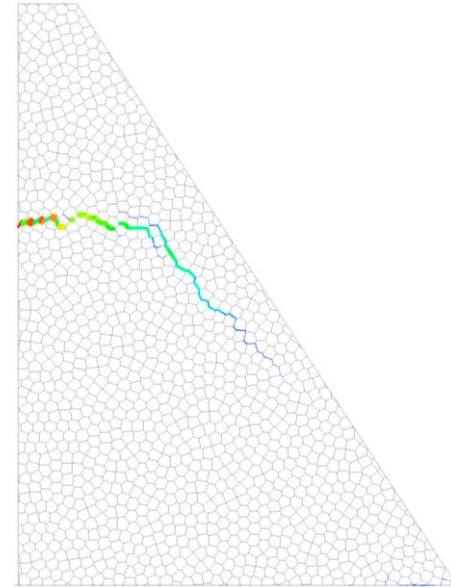


Avec majoration de la résistance à la traction (1.5τ)
 Con maggiore resistenze alla trazione (1.5τ)

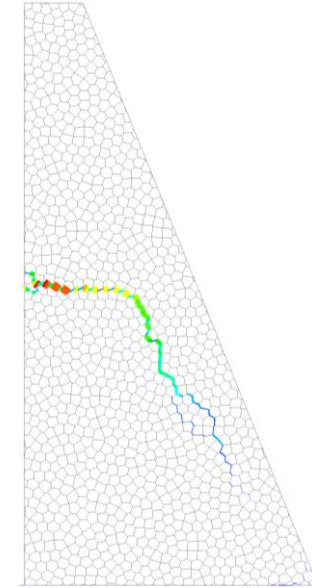
Avec minoration de la résistance à la traction (0.5τ)
 Con resistenza alla trazione ridotta (0.5τ)



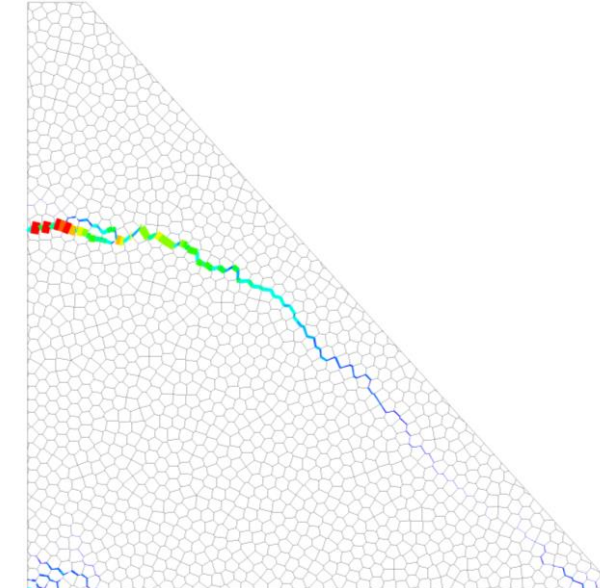
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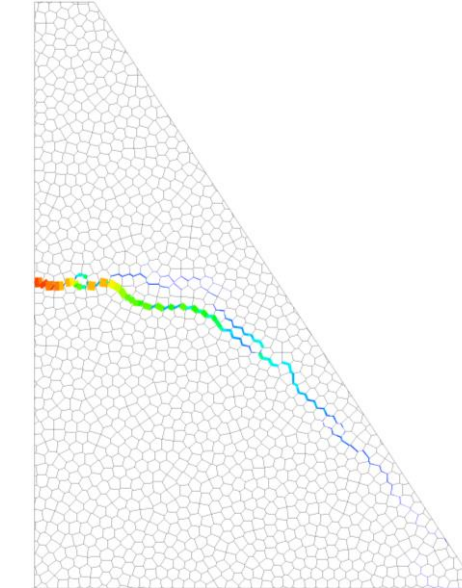
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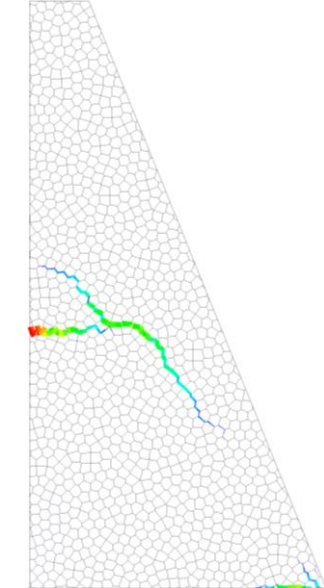
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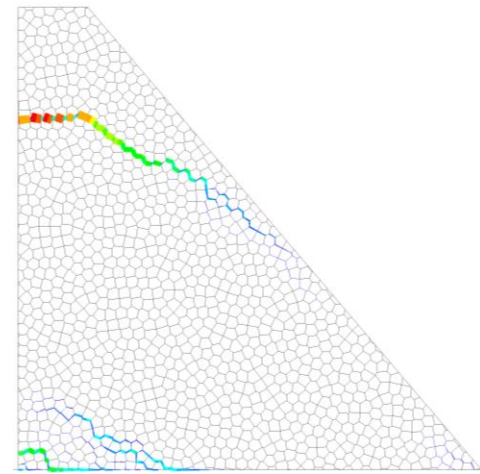
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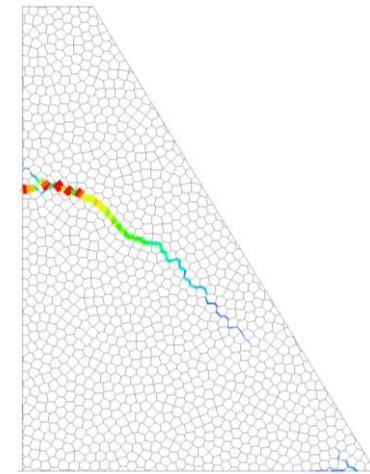
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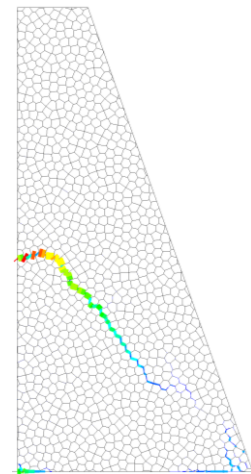
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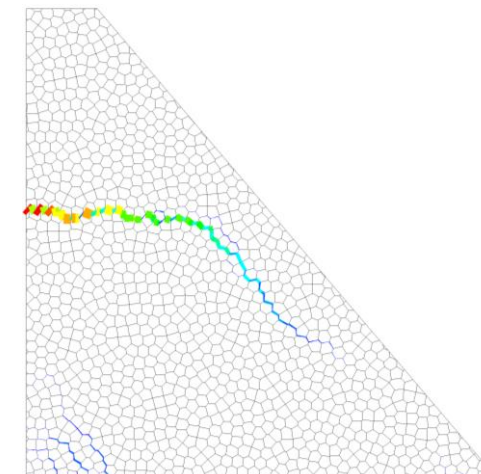
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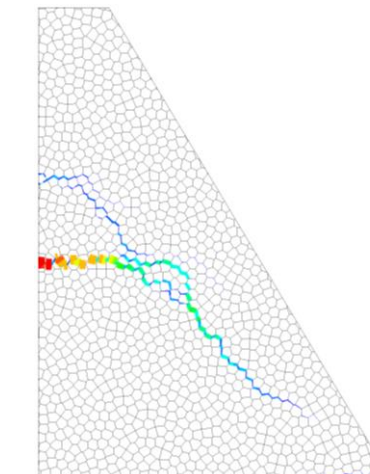
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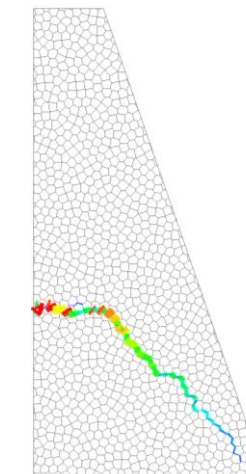
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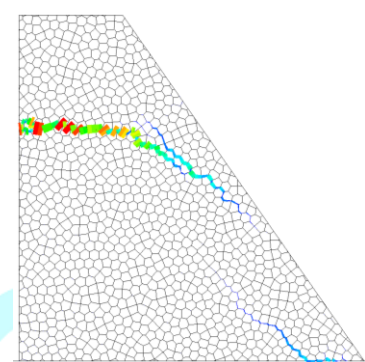
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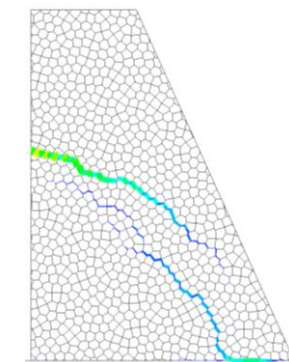
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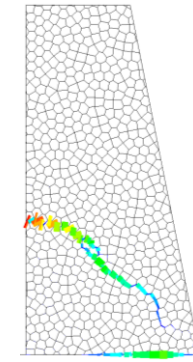
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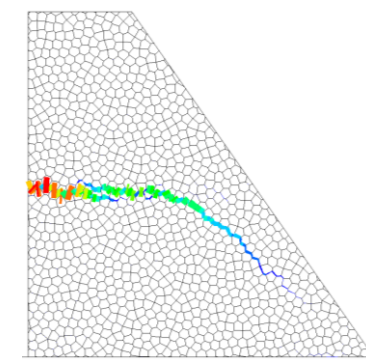
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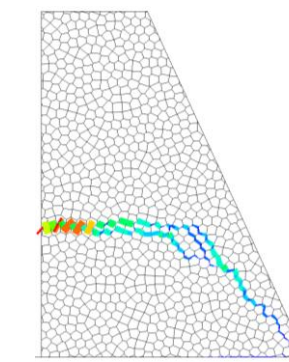
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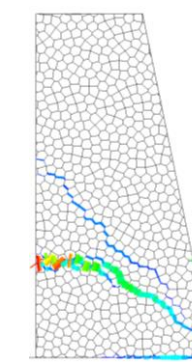
H20B10



H20B20



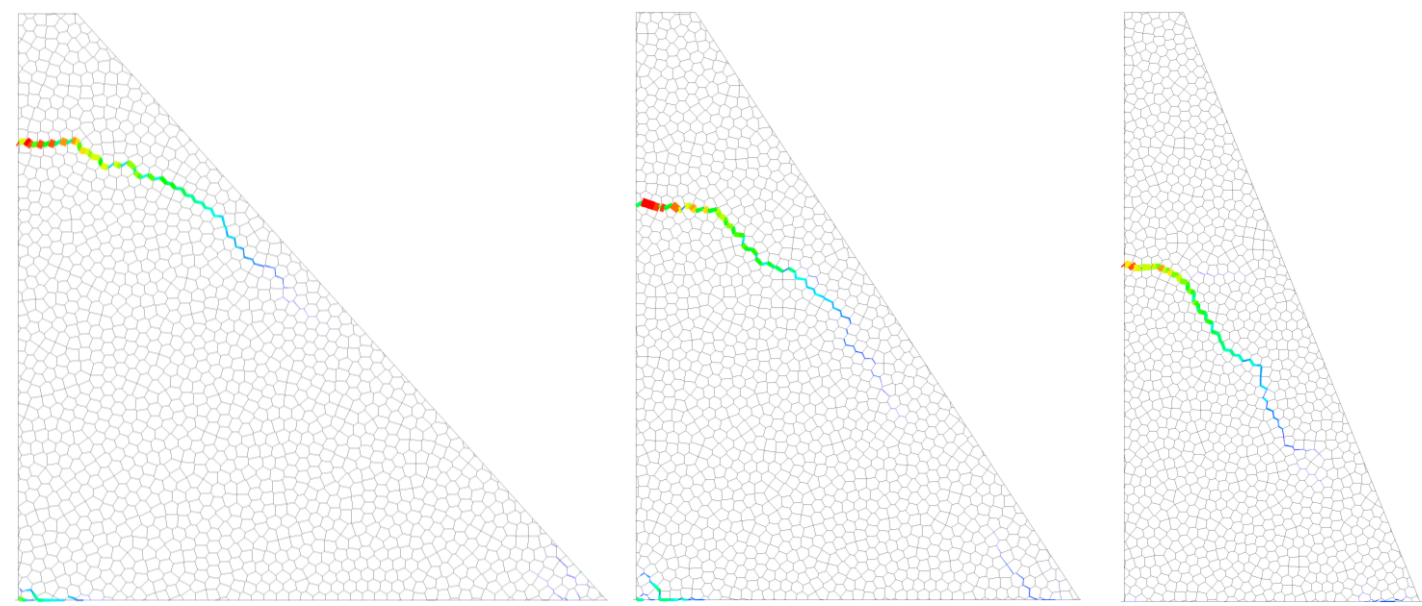
H20B15



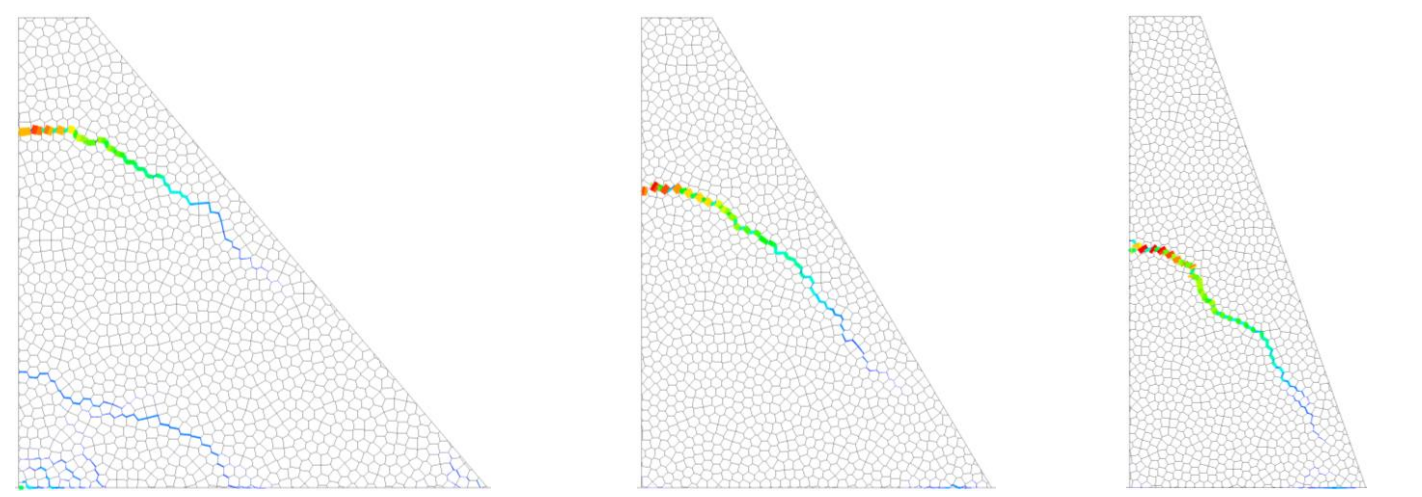
H20B10

Avec majoration de la cohésion (1.5c)
Con maggiore coesione (1.5c)

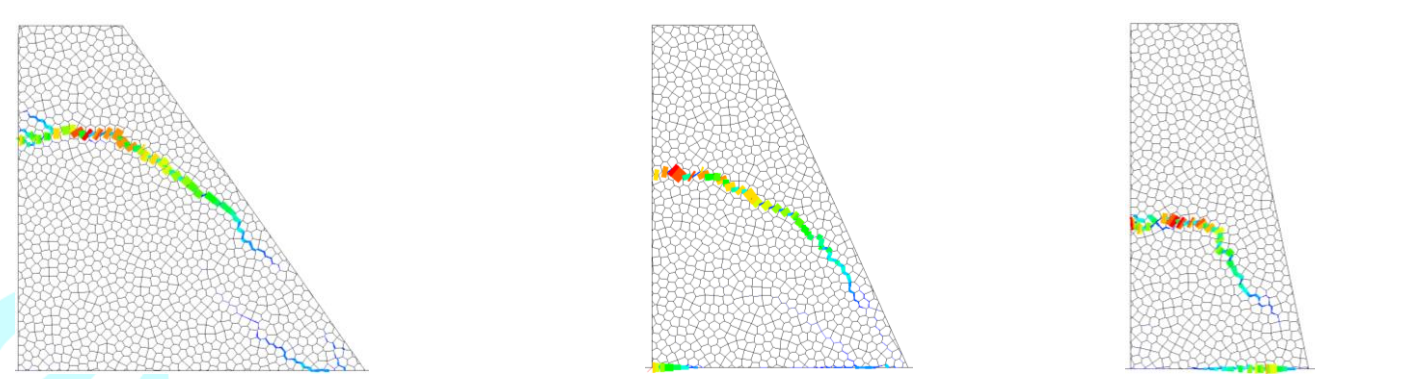
Avec minoration de la cohésion (0.5c)
Con minore coesione (0.5c)



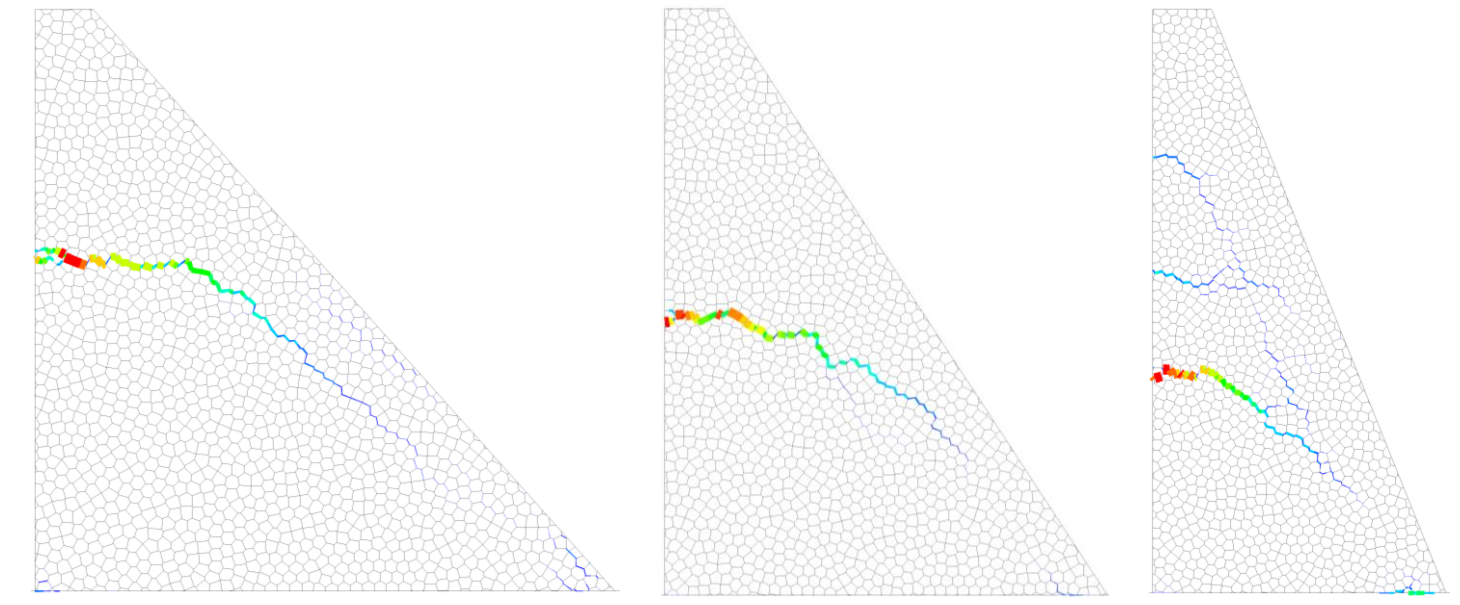
H60B60 H60B45 H60B30



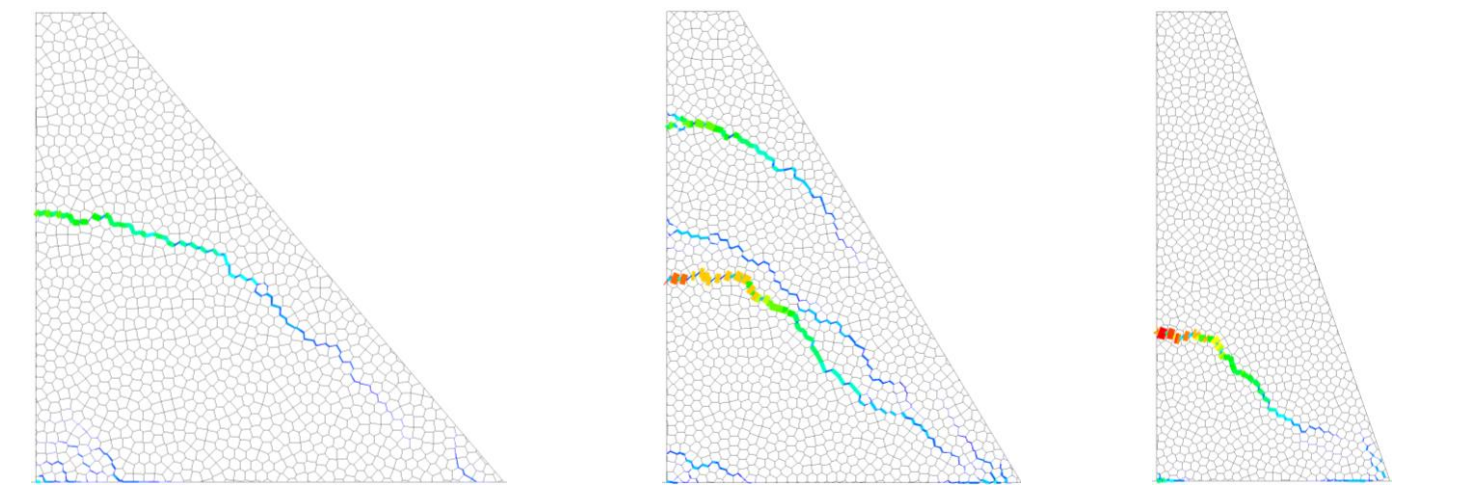
H40B40 H40B30 H40B20



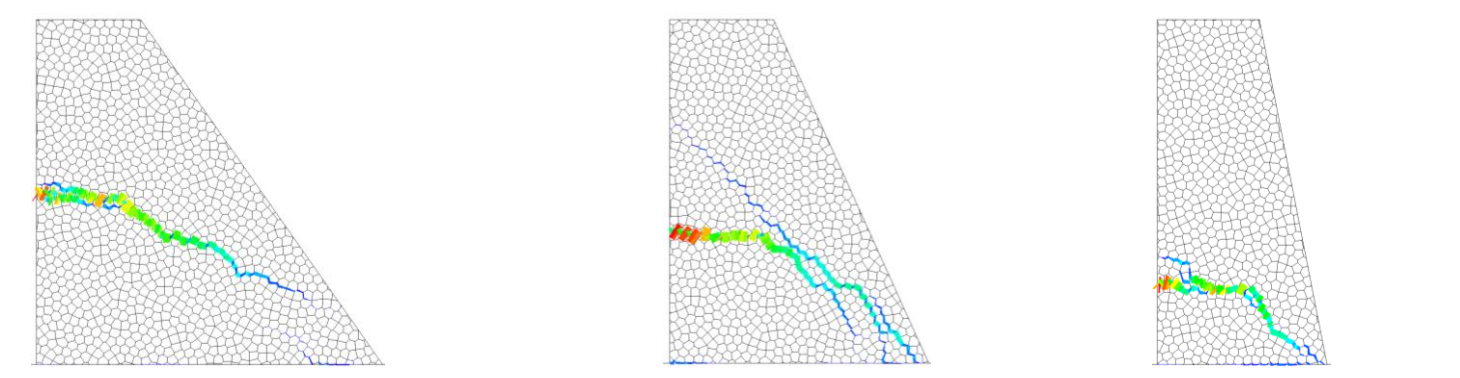
H20B20 H20B15 H20B10



H60B60 H60B45 H60B30



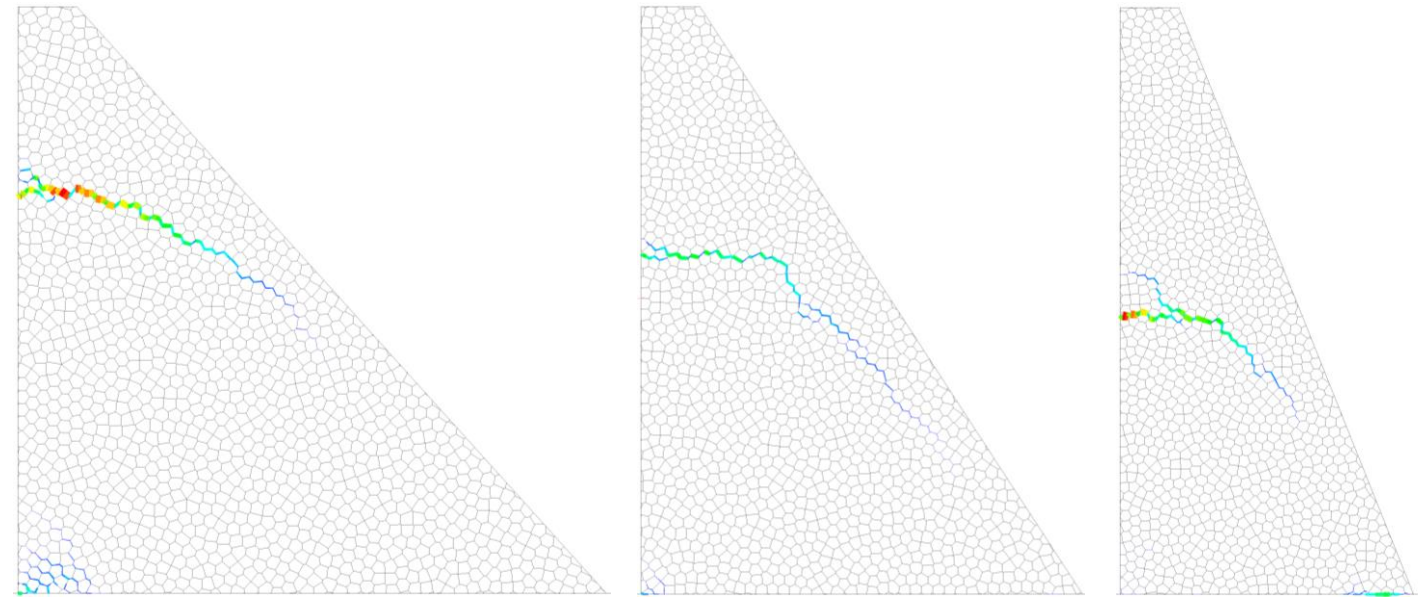
H40B40 H40B30 H40B20



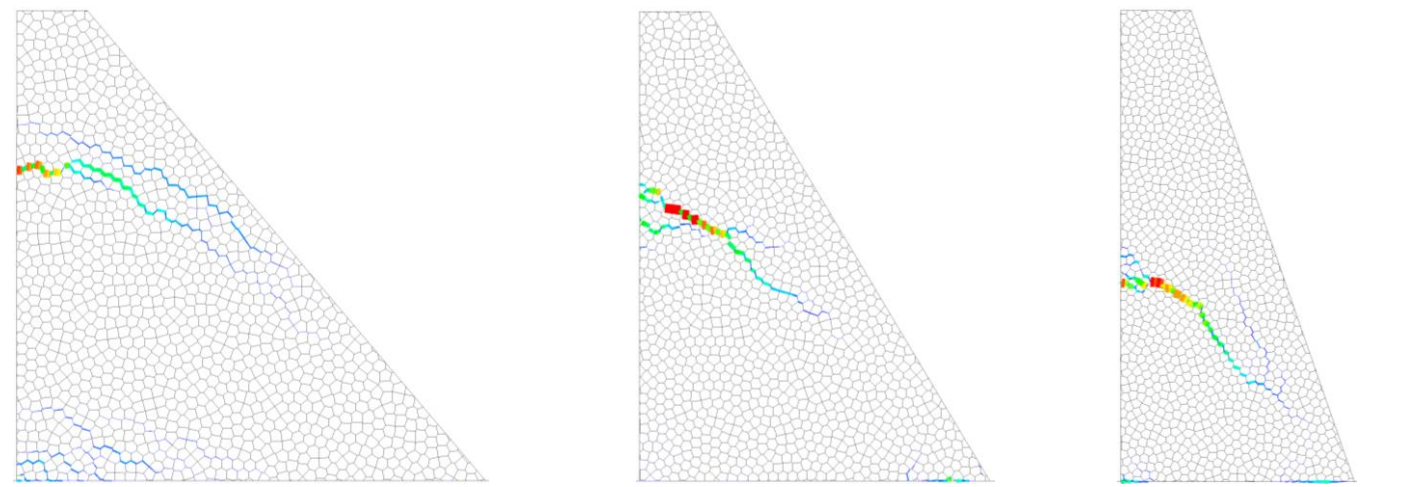
H20B20 H20B15 H20B10

Avec majoration de l'angle de frottement (1.5φ)
Con maggiore angolo di attrito (1.5φ)

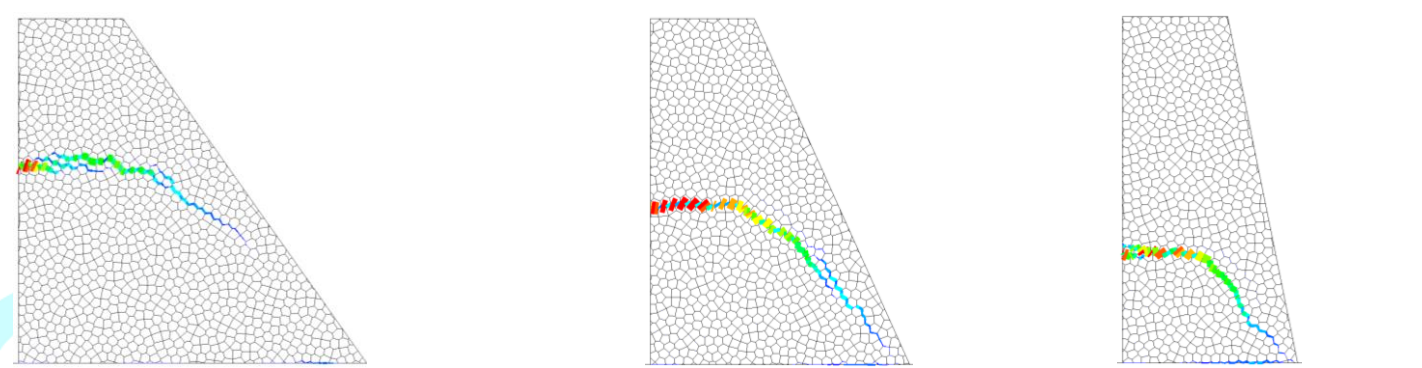
Avec minoration de l'angle de frottement (0.5φ)
Con angolo di attrito ridotto (0.5φ)



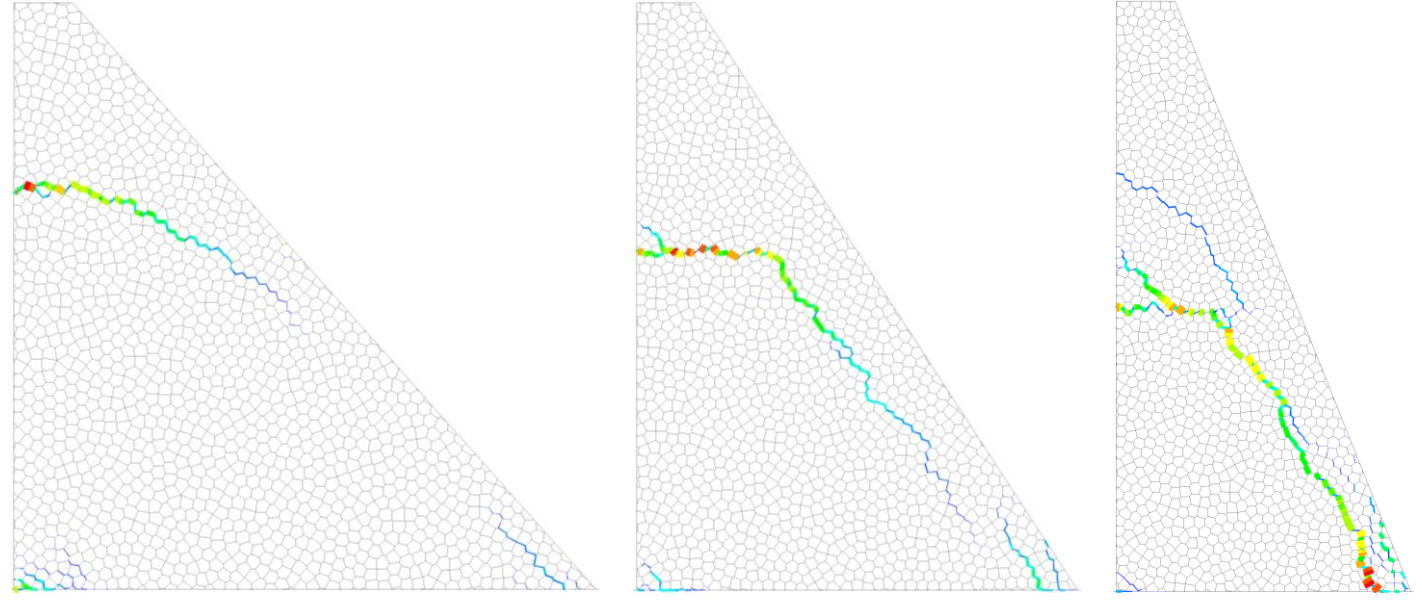
H60B60 H60B45 H60B30



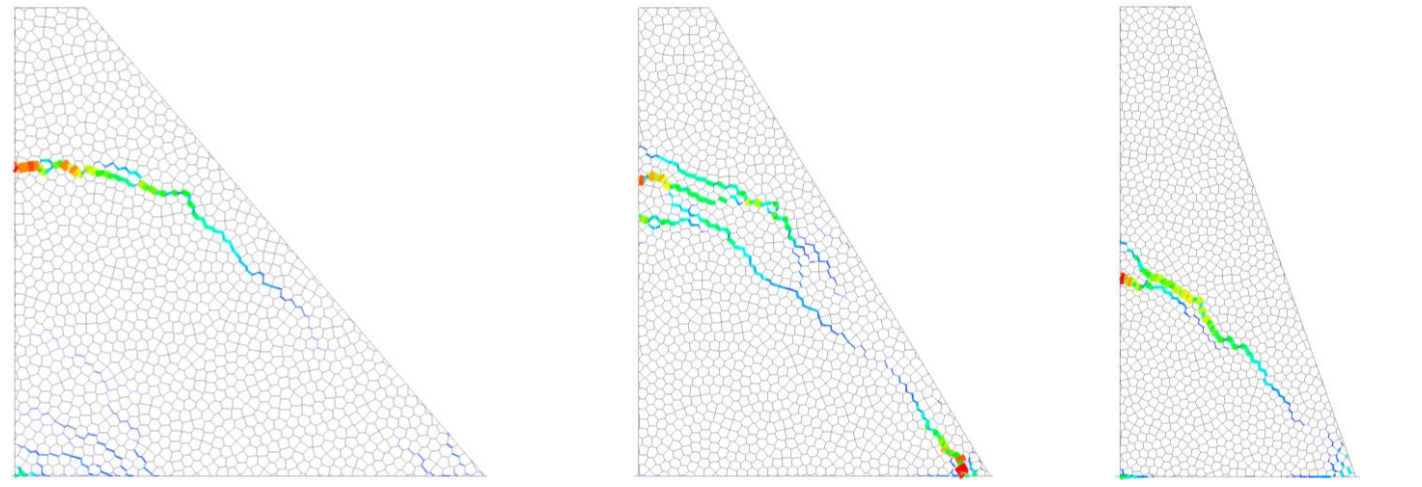
H40B40 H40B30 H40B20



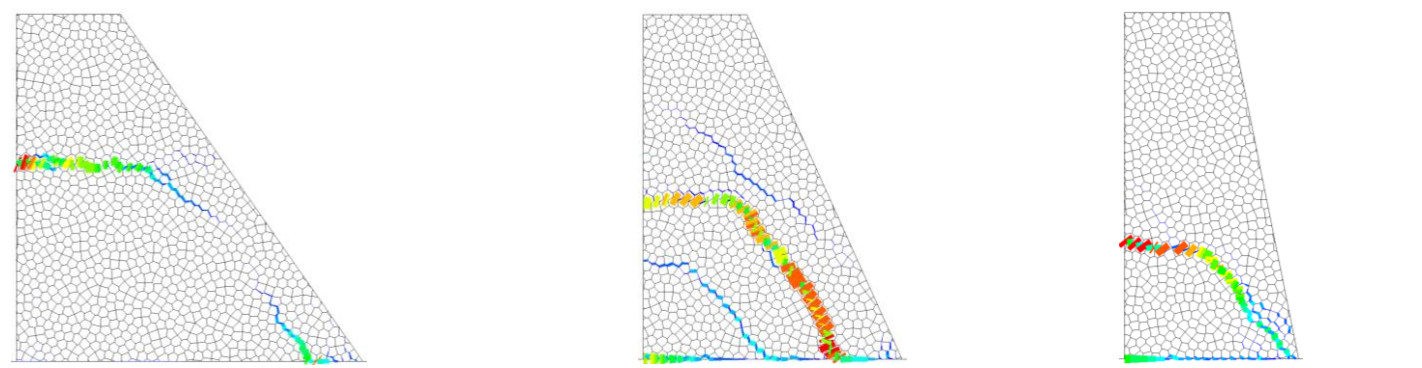
H20B20 H20B15 H20B10



H60B60 H60B45 H60B30



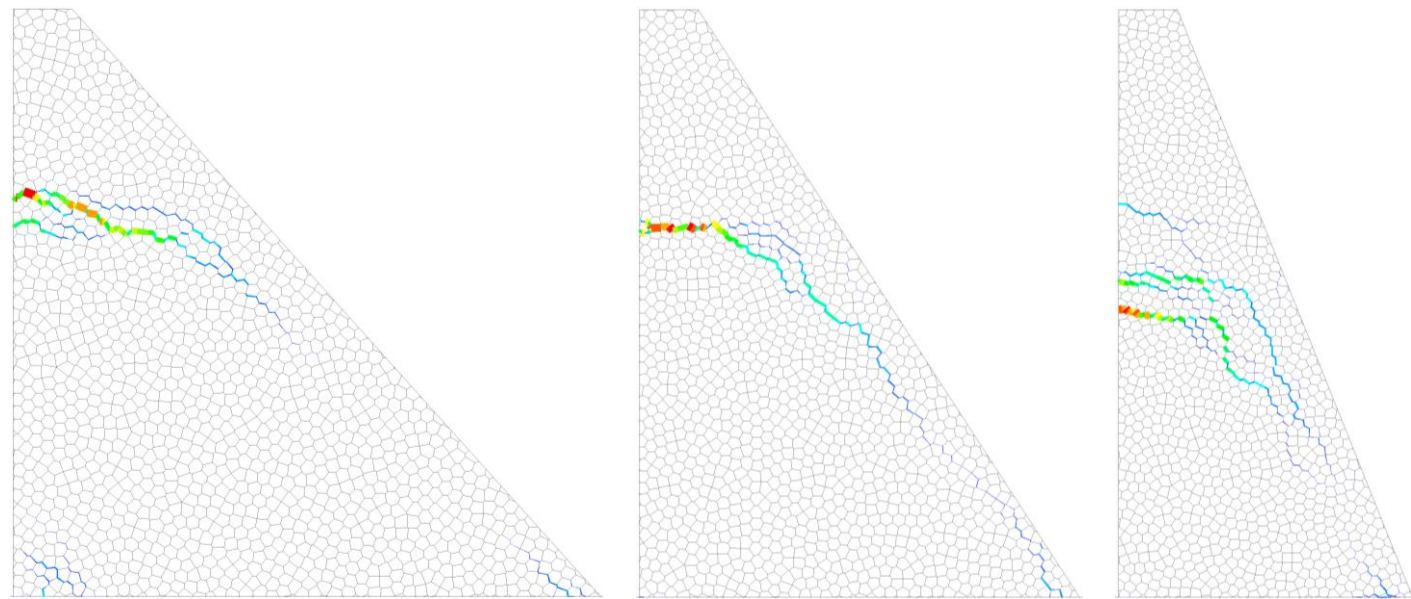
H40B40 H40B30 H40B20



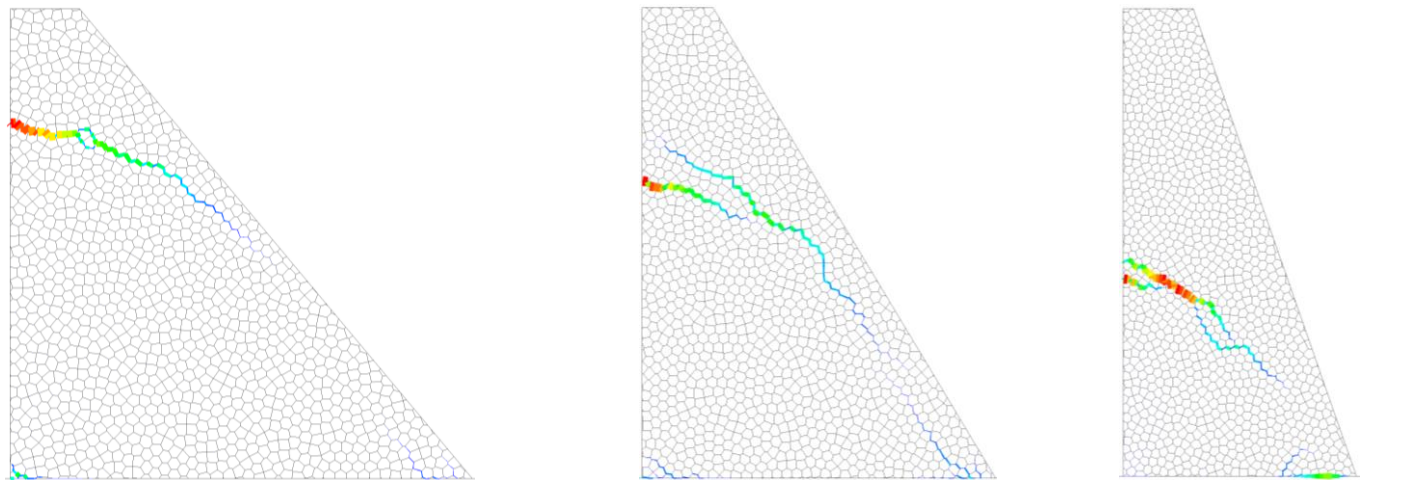
H20B20 H20B15 H20B10

Avec majoration de la perméabilité (1.5k)
Con maggiore de la permeabilità (1.5k)

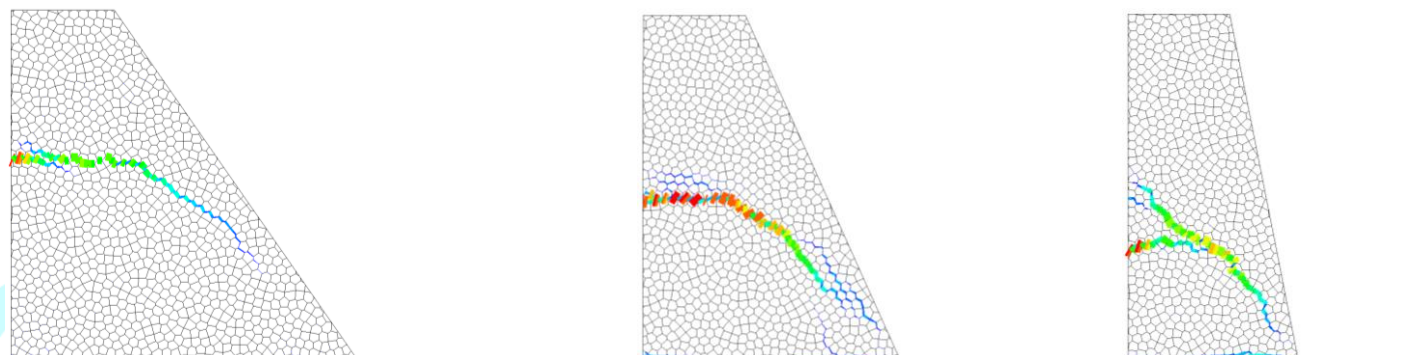
Avec minoration de la perméabilité (0.5k)
Con la permeabilità ridotta (0.5k)



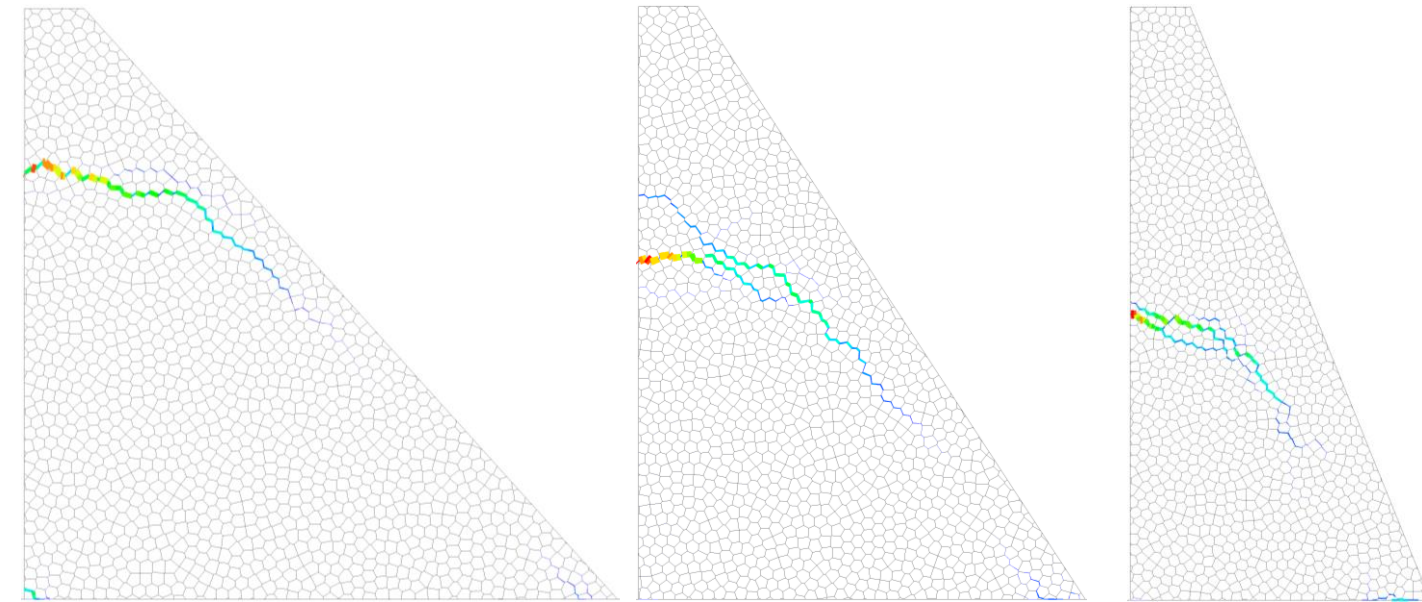
H60B60 H60B45 H60B30



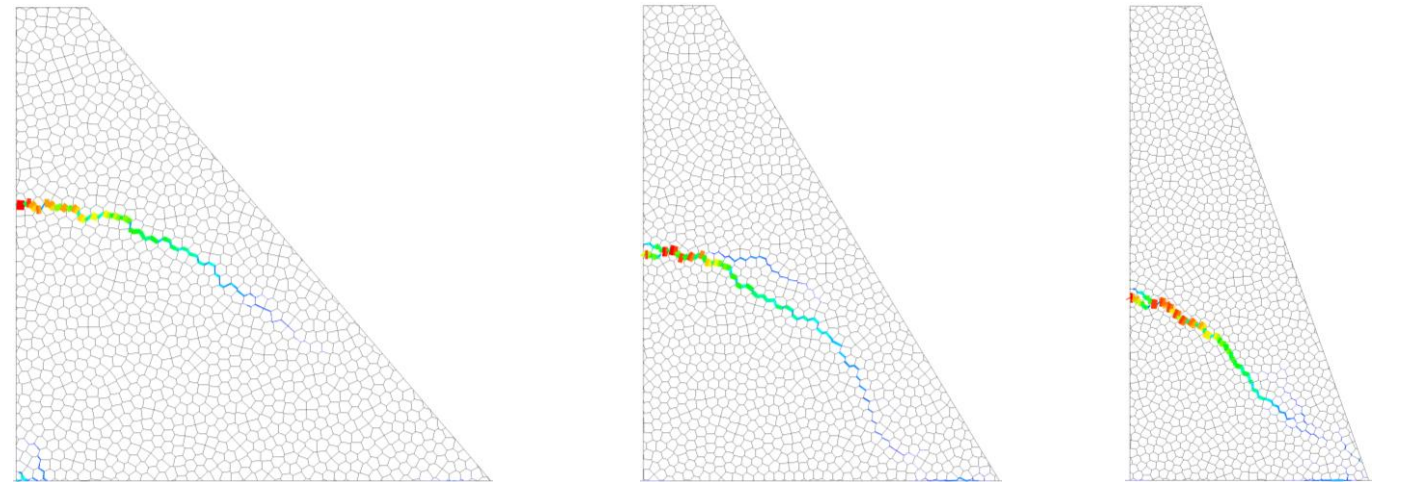
H40B40 H40B30 H40B20



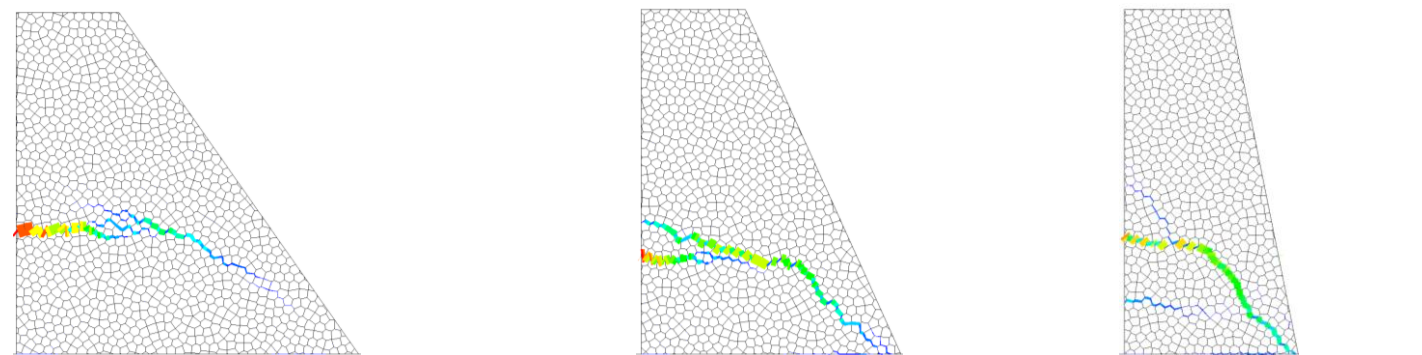
H20B20 H20B15 H20B10



H60B60 H60B45 H60B30



H60B60 H60B45 H60B30

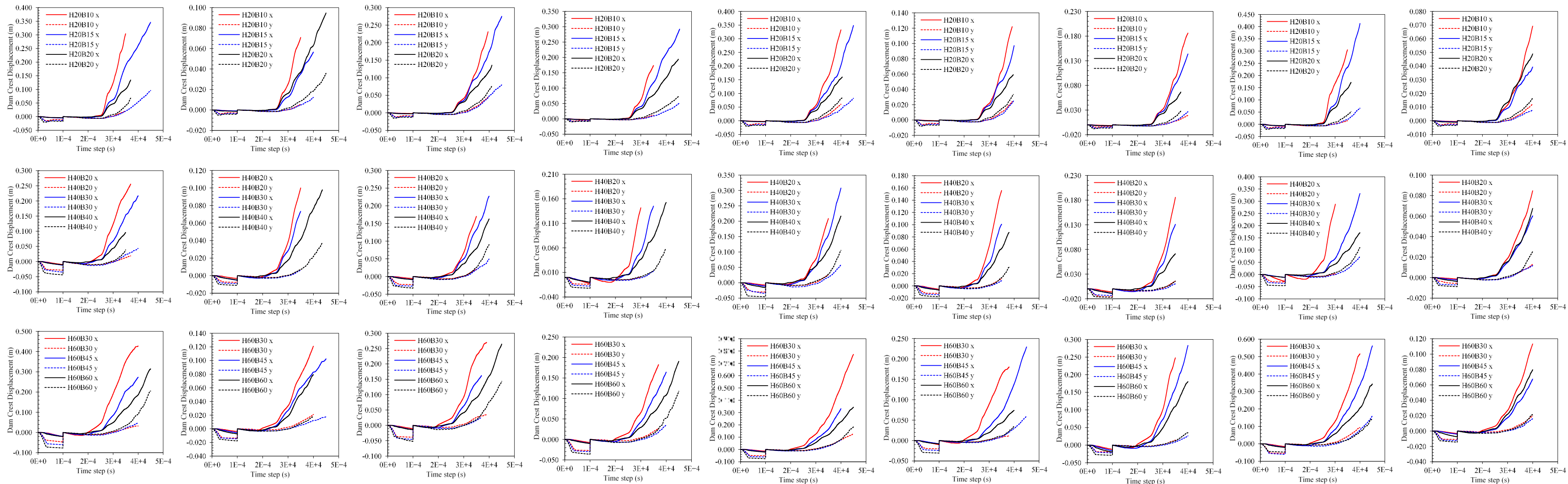


H60B60 H60B45 H60B30



Déplacements horizontaux et verticaux pour un tiers des modèles

Spostamenti orizzontali e verticali per un terzo dei modelli

0.5 τ 1.5 τ

0.5c

1.5c

0.5 ϕ 1.5 ϕ

0.5k

1.5k

Gabiet dam

Proposition d'équations basées sur des algorithmes génétiques
Proposta di equazioni basate su algoritmi genetici



Proposition d'équations basées sur un algorithme génétique

Proposizione di equazioni basate su un algoritmo genetico

En utilisant cette approche, quatre équations finales sont proposées pour prédire la longueur des fissures, notamment :

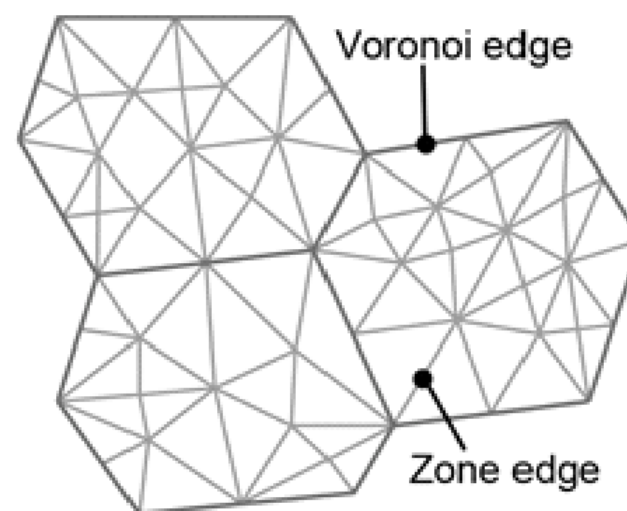
la branche horizontale (L_a),
le segment incliné vers le pied du barrage (L_b),
la pente de la branche L_b par rapport à l'horizon (i),
la position de la fissure principale d'amorçage (h_c).

Utilizzando questo approccio, vengono proposte quattro equazioni finali per prevedere la lunghezza della fessura, tra cui:

il ramo orizzontale (L_a),
il tratto inclinato verso il piede della diga (L_b),
la pendenza del ramo L_b rispetto all'orizzonte (i),
la posizione dell'innesco principale della cricca (h_c).

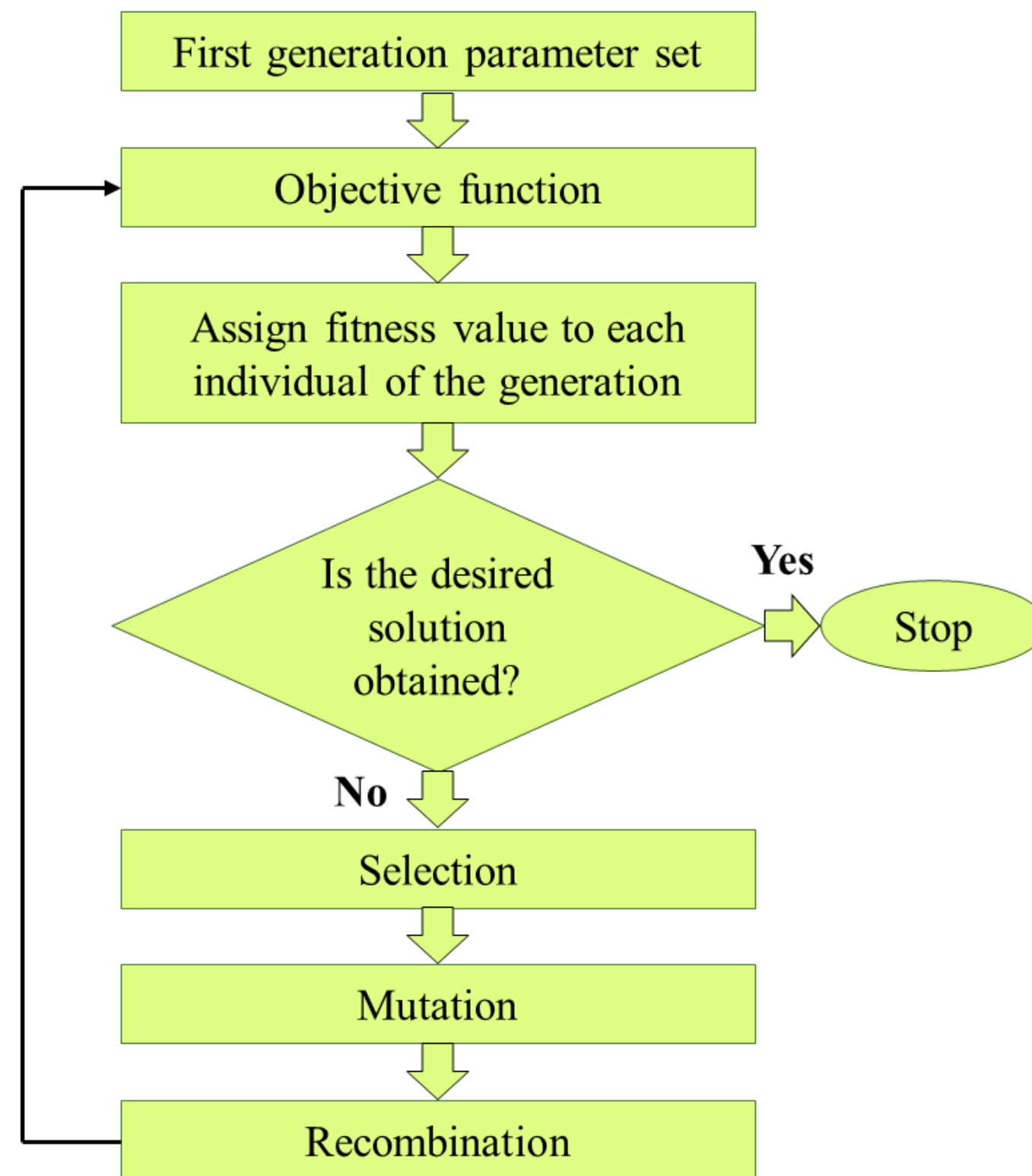
$$\frac{L_b}{H} = \alpha * \left(\frac{H}{B}\right)^{k_1} \left(\frac{\tau}{c}\right)^{k_2} \left(\frac{\phi\pi}{180}\right)^{k_3} \left(\frac{k}{m}\right)^{k_4} \left(\frac{d_{x1}}{d_{y1}}\right)^{k_5} \left(\frac{d_{x2}}{d_{y2}}\right)^{k_6} \left(\frac{d_{x3}}{d_{y3}}\right)^{k_7} + C$$

$$\begin{aligned} \log_{10} \frac{L_b}{H} &= \log_{10} \alpha + k_1 \log_{10} \left(\frac{H}{B}\right) \\ &+ k_2 \log_{10} \left(\frac{\tau}{c}\right) + k_3 \log_{10} \left(\frac{\phi\pi}{180}\right) + k_4 \log_{10} \left(\frac{k}{m}\right) + k_5 \log_{10} \left(\frac{d_{x1}}{d_{y1}}\right) \\ &+ k_6 \log_{10} \left(\frac{d_{x2}}{d_{y2}}\right) + k_7 \log_{10} \left(\frac{d_{x3}}{d_{y3}}\right) + \log_{10} C \end{aligned}$$



m est la longueur de l'arête du bloc de Voronoi, qui est choisie égale à 0,5 m sur la base des modèles numériques qui ont donné un diamètre moyen équivalent de bloc de 0,55 m.

m è la lunghezza del bordo del blocco di Voronoi, selezionata pari a 0,5 m sulla base dei modelli numerici che hanno fornito un diametro medio equivalente del blocco di 0,55 m.





Déplacement en crête
au début de la
fissuration inclinée
*Spostamento della cresta
all'inizio della fessura
inclinata*

Déplacement en crête lorsque la
fissuration est totalement
développée
*Spostamento della cresta quando
la diga è completamente incrinata*

Déplacement en crête à
l'initiation de la
fissuration horizontale
*Spostamento della cresta
all'inizio della fessura
orizzontale*

$$\frac{L_b}{H} = \alpha * \left(\frac{H}{B}\right)^{k_1} \left(\frac{\tau}{c}\right)^{k_2} \left(\frac{\phi\pi}{180}\right)^{k_3} \left(\frac{k}{m}\right)^{k_4} \left(\frac{d_{x1}}{d_{y1}}\right)^{k_5} \left(\frac{d_{x2}}{d_{y2}}\right)^{k_6} \left(\frac{d_{x3}}{d_{y3}}\right)^{k_7} + C$$

$$\frac{L_a}{H} = \alpha * \left(\frac{H}{B}\right)^{k_1} \left(\frac{\tau}{c}\right)^{k_2} \left(\frac{\phi\pi}{180}\right)^{k_3} \left(\frac{k}{m}\right)^{k_4} \left(\frac{d_{x1}}{d_{y1}}\right)^{k_5} \left(\frac{d_{x2}}{d_{y2}}\right)^{k_6} + C$$

$$\frac{i\pi}{180} = \alpha * \left(\frac{H}{B}\right)^{k_1} \left(\frac{\tau}{c}\right)^{k_2} \left(\frac{\phi\pi}{180}\right)^{k_3} \left(\frac{k}{m}\right)^{k_4} \left(\frac{d_{x1}}{d_{y1}}\right)^{k_5} \left(\frac{d_{x2}}{d_{y2}}\right)^{k_6} \left(\frac{d_{x3}}{d_{y3}}\right)^{k_7} + C$$

$$\frac{h_c}{H} = \alpha * \left(\frac{H}{B}\right)^{k_1} \left(\frac{\tau}{c}\right)^{k_2} \left(\frac{\phi\pi}{180}\right)^{k_3} \left(\frac{k}{m}\right)^{k_4} \left(\frac{d_{x1}}{d_{y1}}\right)^{k_5} + C$$

ALGORITHME GÉNÉTIQUE

ALGORITMO GENETICO

$$\frac{L_b}{H} = 0.009 * \left(\frac{H}{B}\right)^{0.109} \left(\frac{\tau}{c}\right)^{3.280} \left(\frac{\phi\pi}{180}\right)^{3.022} \left(\frac{k}{m}\right)^{0.179} \left(\frac{d_{x1}}{d_{y1}}\right)^{0.550} \left(\frac{d_{x2}}{d_{y2}}\right)^{2.859} \left(\frac{d_{x3}}{d_{y3}}\right)^{2.124} + 0.352$$

$$\frac{L_a}{H} = 0.190 * \left(\frac{H}{B}\right)^{0.913} \left(\frac{\tau}{c}\right)^{1.841} \left(\frac{\phi\pi}{180}\right)^{1.796} \left(\frac{k}{m}\right)^{1.145} \left(\frac{d_{x1}}{d_{y1}}\right)^{2.234} \left(\frac{d_{x2}}{d_{y2}}\right)^{1.367} + 0.161$$

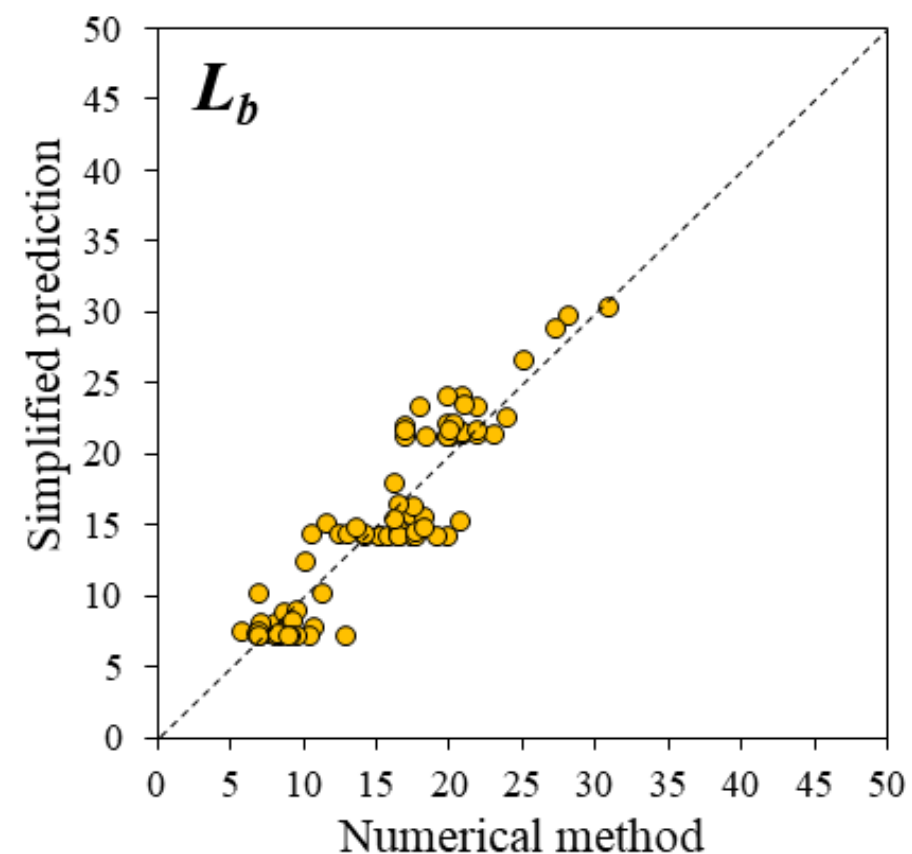
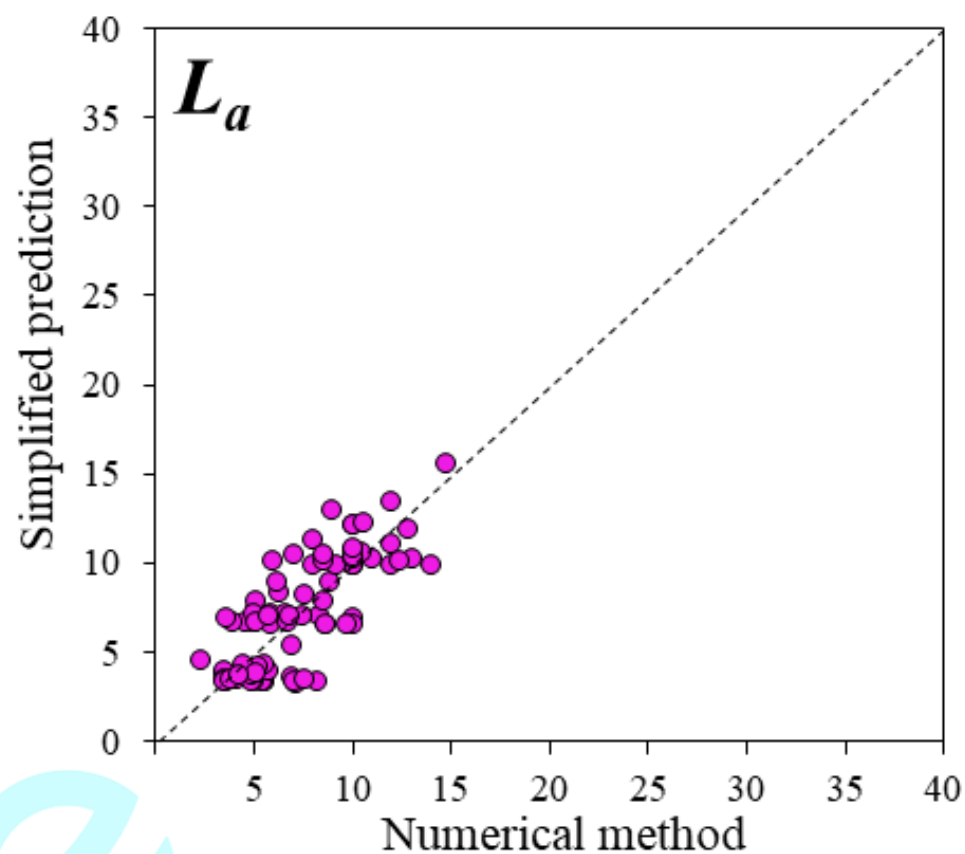
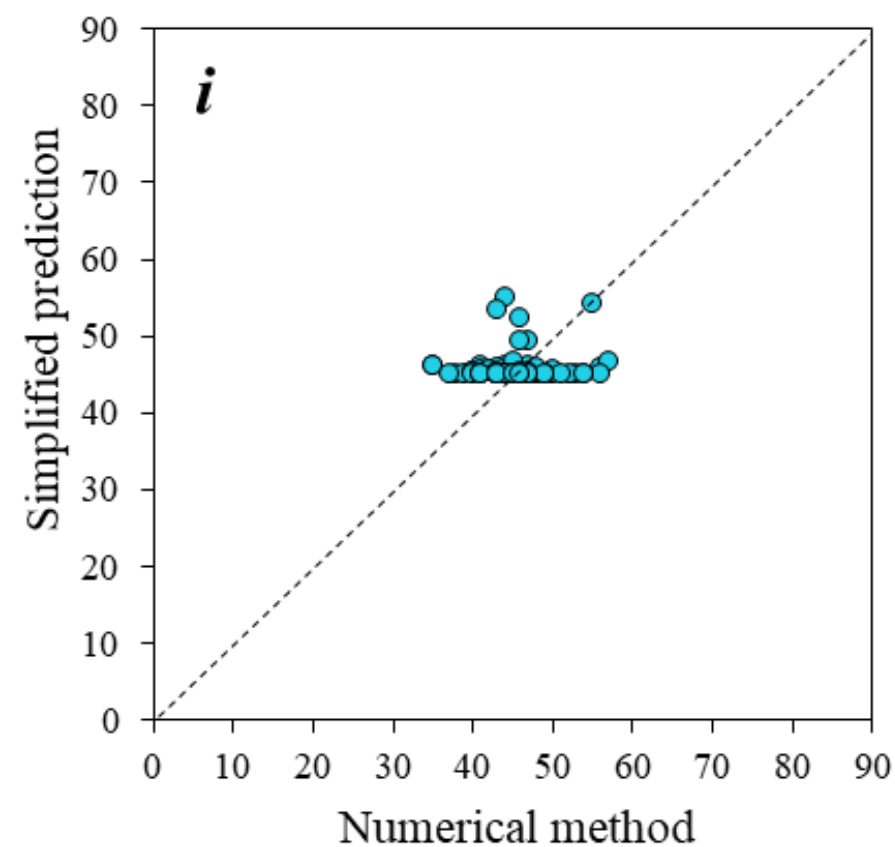
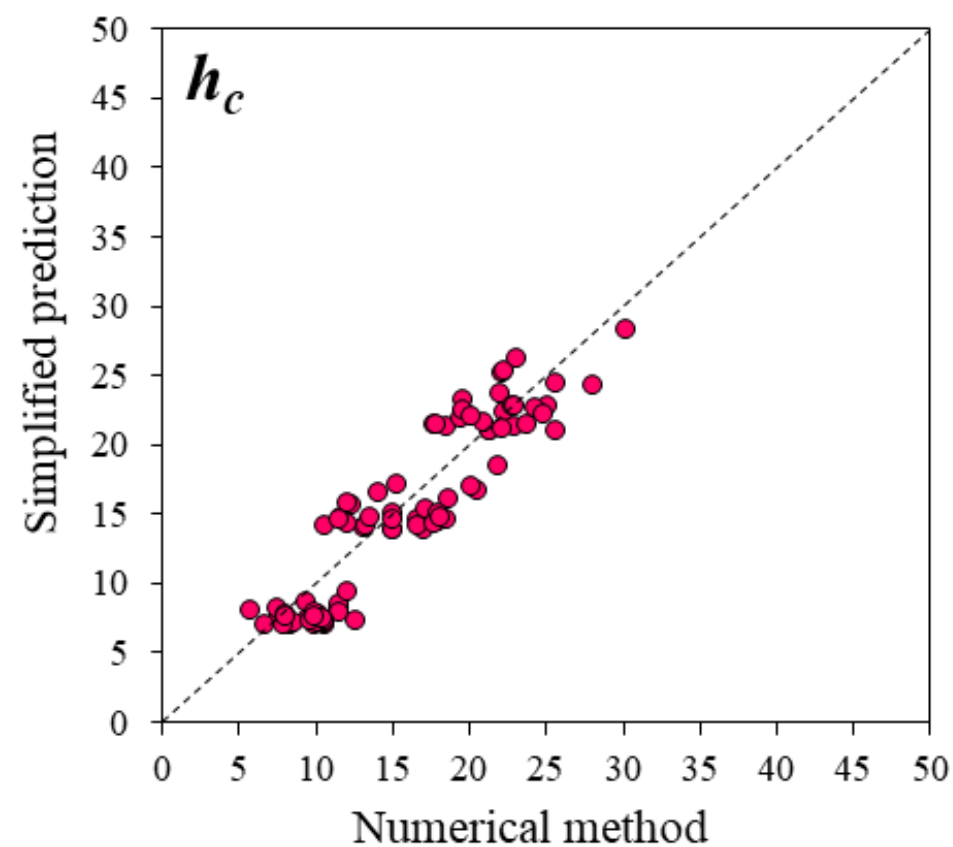
$$\frac{i\pi}{180} = 0.002 * \left(\frac{H}{B}\right)^{1.617} \left(\frac{\tau}{c}\right)^{5.234} \left(\frac{\phi\pi}{180}\right)^{5.990} \left(\frac{k}{m}\right)^{1.081} \left(\frac{d_{x1}}{d_{y1}}\right)^{6.400} \left(\frac{d_{x2}}{d_{y2}}\right)^{1.320} \left(\frac{d_{x3}}{d_{y3}}\right)^{3.299} + 0.785$$

$$\frac{h_c}{H} = 0.140 * \left(\frac{H}{B}\right)^{1.127} \left(\frac{\tau}{c}\right)^{1.299} \left(\frac{\phi\pi}{180}\right)^{1.005} \left(\frac{k}{m}\right)^{0.026} \left(\frac{d_{x1}}{d_{y1}}\right)^{1.125} + 0.339$$



Comparaison entre les valeurs calculées selon les équations proposées et les valeurs issues des modèles UDEC

Confronto tra i valori calcolati secondo le equazioni proposte e i valori risultanti dai modelli UDEC



$$\begin{aligned}d_{x1}/d_{y1} &\approx 10 \\d_{x2}/d_{y2} &\approx 10 \\d_{x3}/d_{y3} &\approx 4\end{aligned}$$

$$d_{x2} \approx 3 d_{x1}$$

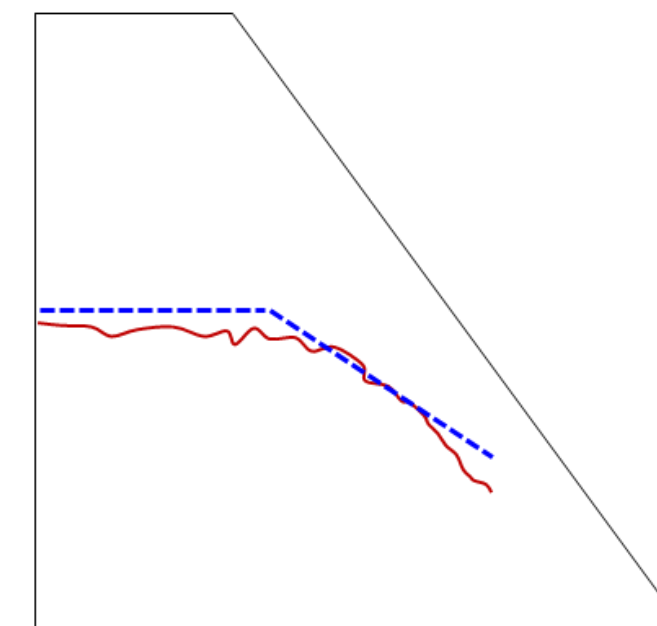
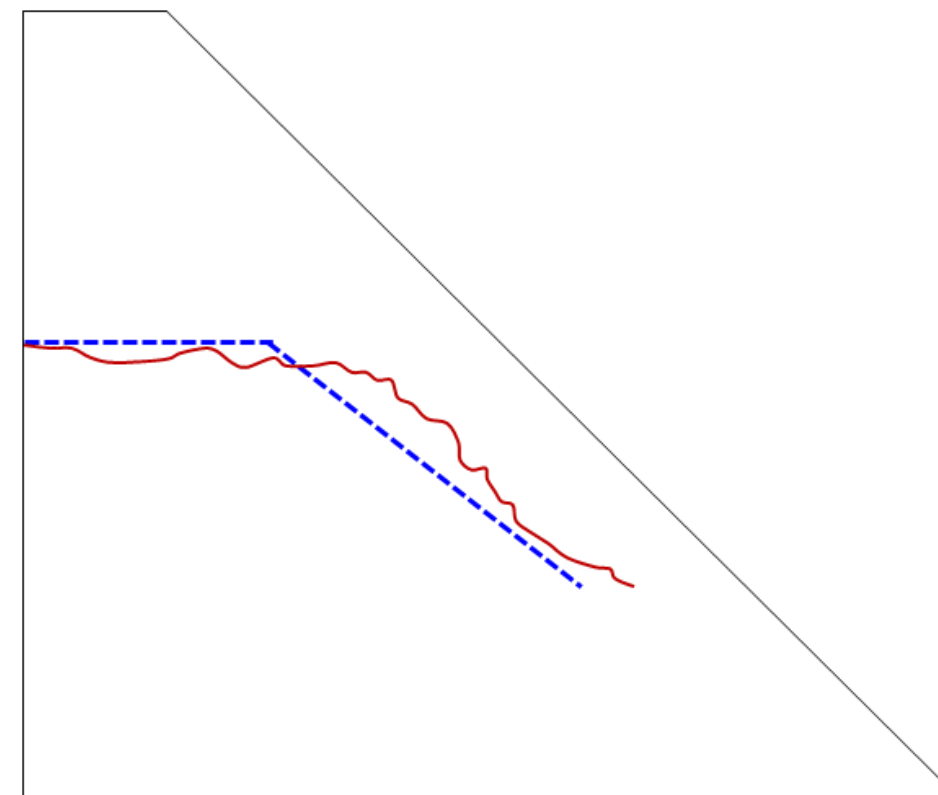
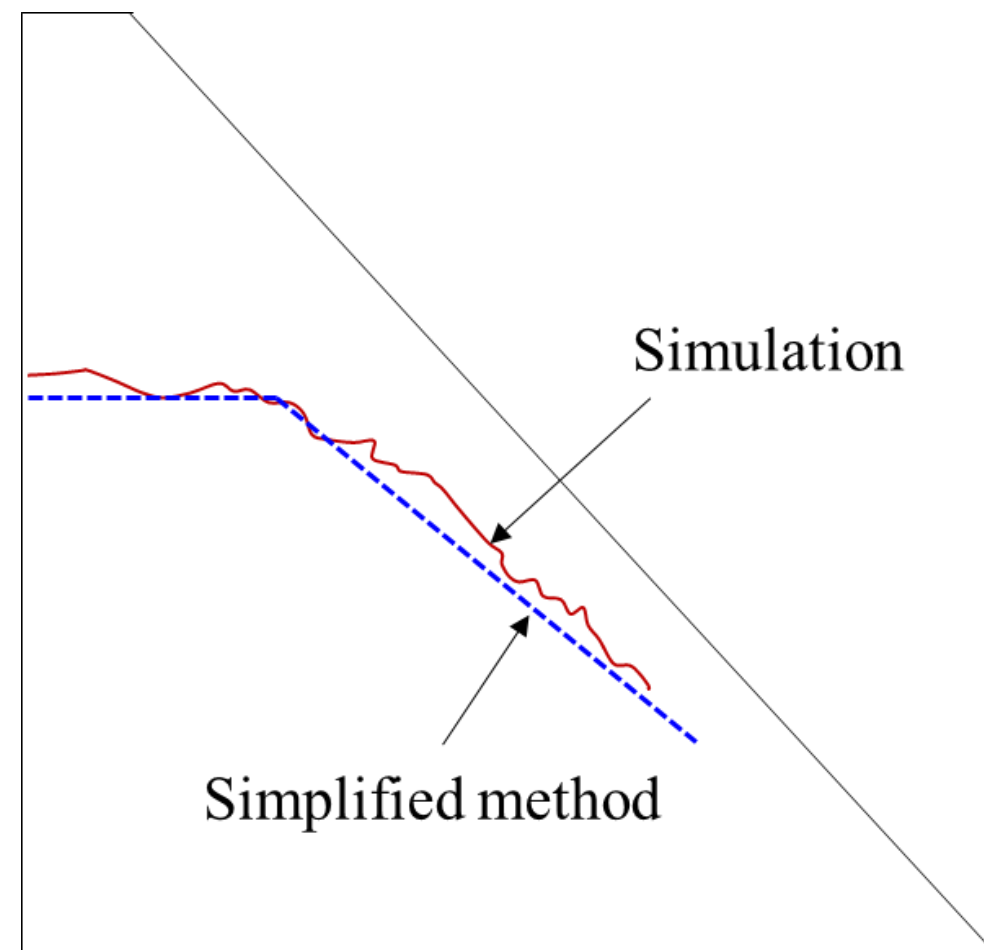
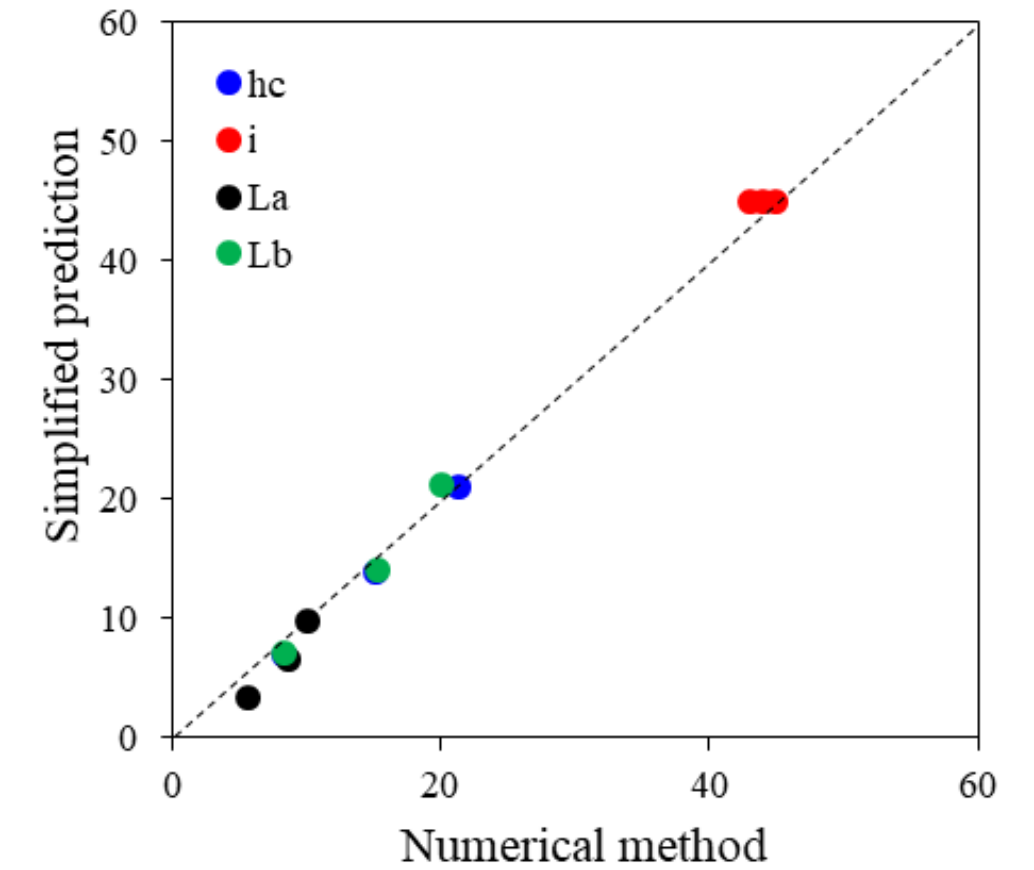
$$\begin{aligned}dx3 &\approx 7.6 dx1 \\ &\approx 2.6 dx2\end{aligned}$$



Vérification des équations proposées
Verifica delle equazioni proposte



Type	Model				Prediction			
Parameter	h_c	i	L_a	L_b	h_c	i	L_a	L_b
H60B60	21.300	45	10.000	20.100	21.001	45.857	9.815	21.198
H40B40	15.077	44	8.662	15.326	13.901	44.935	6.531	14.093
H20B20	8.280	43	5.540	8.280	6.954	43.855	3.299	7.089





Analyse de la stabilité

Analisi di stabilità

$$\alpha = \tan^{-1} \left(\frac{H}{B - b} \right)$$

$$a' = b + \frac{h_c}{\tan \alpha} - L_a$$

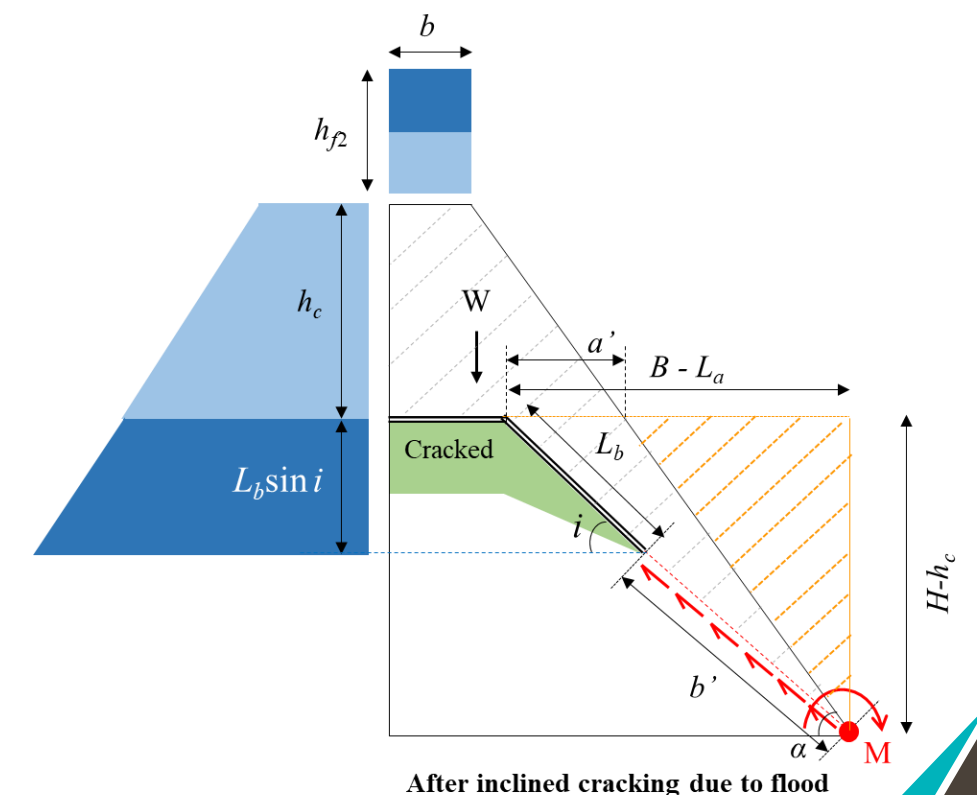
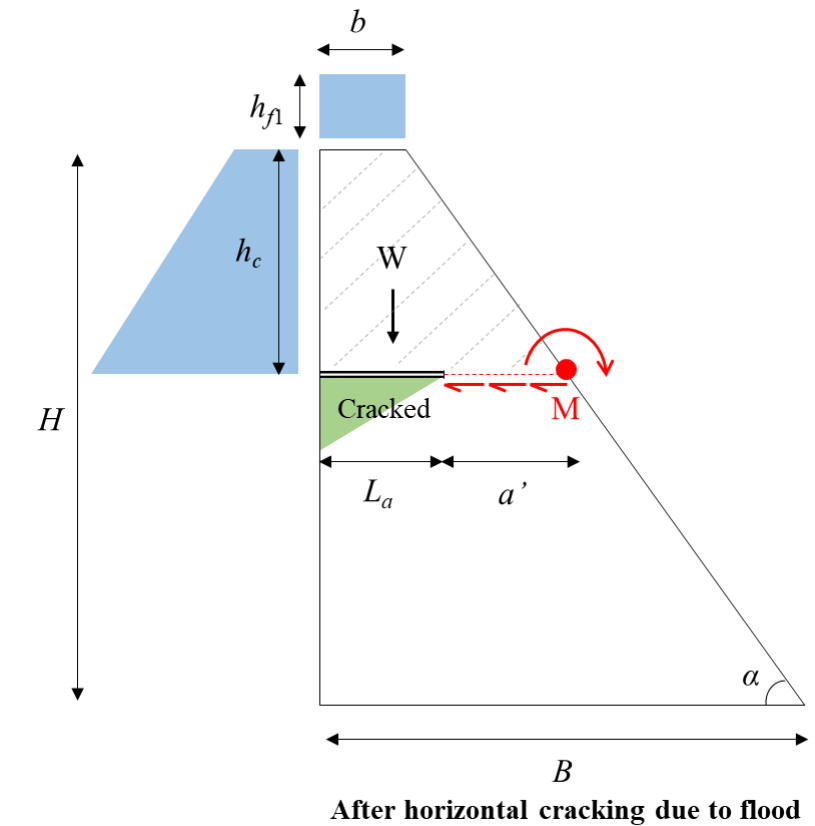
$$B' = L_a + a' = b + \frac{h_c}{\tan \alpha}$$



$$FoS_{sliding} = \frac{\mu [0.5(b + L_a + a')h_c\gamma - 0.5(h_c + h_{f1})L_a\gamma_w + h_{f1}b\gamma_w] + [a']c}{h_{f1}h_c\gamma_w + 0.5h_c^2\gamma_w}$$

 $FoS_{sliding}$

$$= \frac{1}{[h_{f2}(h_c + L_b \sin i) \gamma_w + 0.5(h_c + L_b \sin i)^2 \gamma_w] \cos i} \left(\mu [0.5(b + L_a + a')h_c\gamma + 0.5(H - h_c)a'\gamma - 0.5(h_c + h_{f2})L_a \gamma_w - 0.5(h_c + h_{f2})L_b \cos i \gamma_w + h_{f2}b\gamma_w] + [\sqrt{[H - h_c]^2 + [B - L_a]^2} - L_b]c \right)$$



Conclusions et remarques
Conclusioni e osservazioni

Conclusions



- (1) L'approche GBM-DEM peut être utilisée pour obtenir le comportement des barrages-poids et simuler avec précision le chemin de propagation des fissures.
- (2) La forme des fissures et les courbes de surverse-déplacement des barrages-poids dépendent de divers facteurs. Dans la plupart des cas, la trajectoire de la fissure est initialement presque horizontale, puis l'augmentation des déplacements horizontaux s'inclinera vers le pied aval du barrage.
- (3) Nous avons développé des équations simples pour évaluer la géométrie du modèle de fissure. Les équations dépendent de la géométrie du barrage et des propriétés géotechniques des matériaux du barrage, ainsi que des déformations de la crête en termes de directions horizontales et verticales
- (4) Le modèle de fissuration proposé permet d'estimer les facteurs de sécurité associés à chaque phase de propagation de la fissuration.

- (1) L'approccio GBM-DEM può essere utilizzato per ottenere il comportamento di barrage-poids e simulare con precisione il canale di propagazione delle fessure.*
- (2) La forma delle fessure e le corsie di trabocco-spostamento des sbarrages-poids in relazione al trabocco-spostamento da diversi fattori. Nella maggior parte dei casi, il percorso della fessura è inizialmente quasi orizzontale, poi l'aumento dello spostamento orizzontale si inclina verso la punta della diga a valle.*
- (3) Abbiamo sviluppato equazioni semplici per valutare la geometria del modello di fessura. Le equazioni dipendono dalla geometria dello sbarramento e dalle proprie geotecniche dei materiali dello sbarramento, nonché dalle deformazioni della cresta in termini di direzioni orizzontali e verticali*
- (4) Il modello di fessurazione proposto consente di stimare i fattori di sicurezza associati a ciascuna fase di propagazione della fessurazione*



Merci pour votre attention ...
Grazie per l'attenzione ...