Modélisation des écoulements dans un réseau discret de fractures par une approche continue

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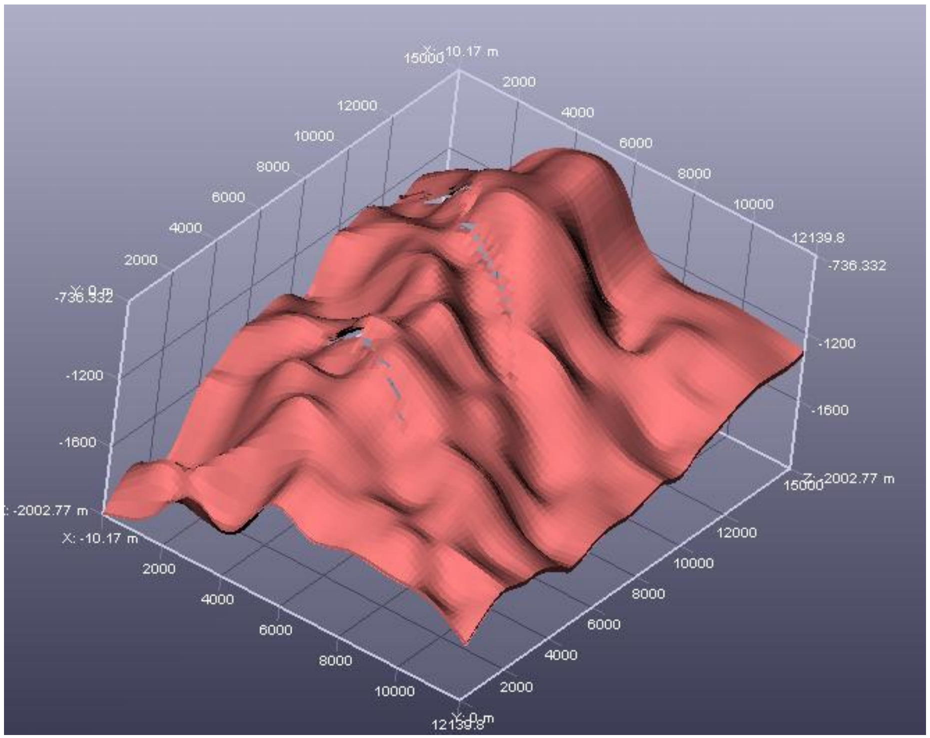
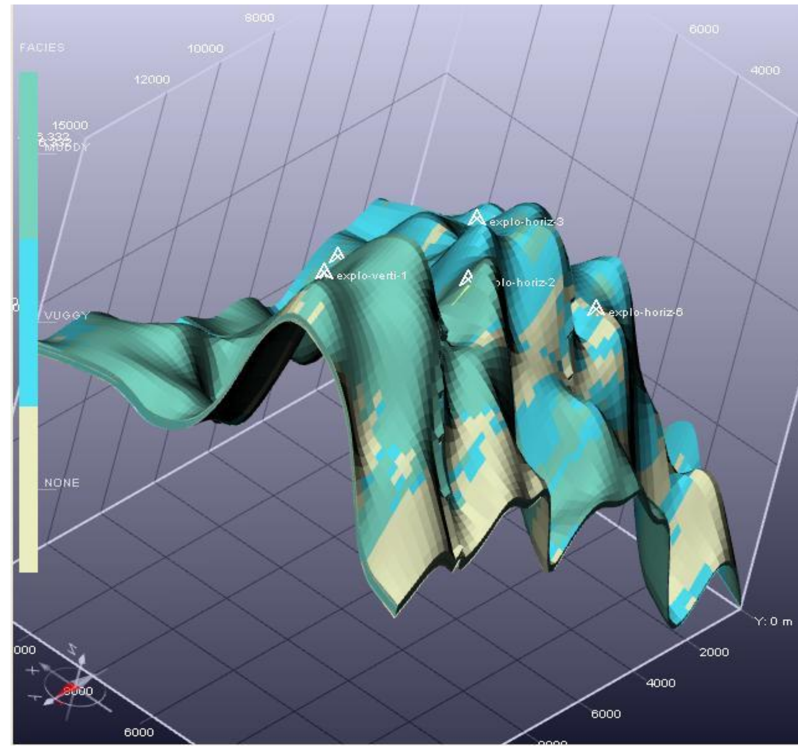
H. Benabderrahmane, B. Noetinger

Geological context



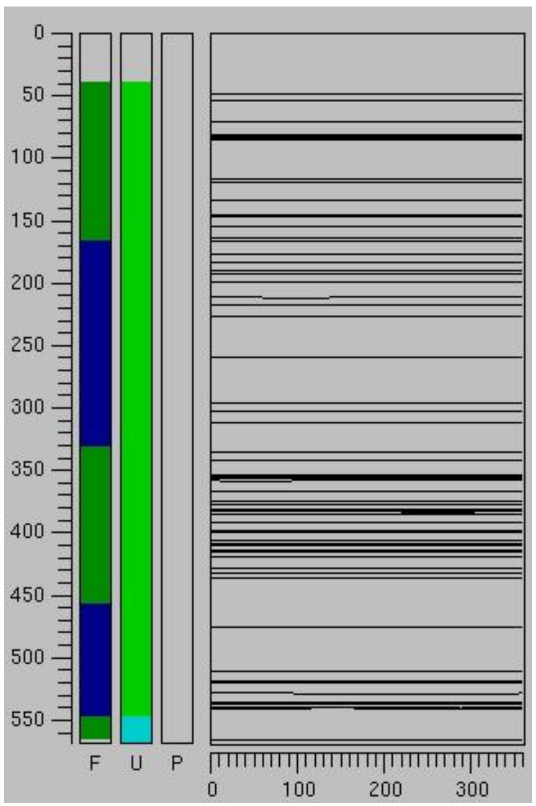


→**Complex geological structures**
→**Different Rock types**
→**High heterogeneities (porosity, permeability)**

Fractured reservoir

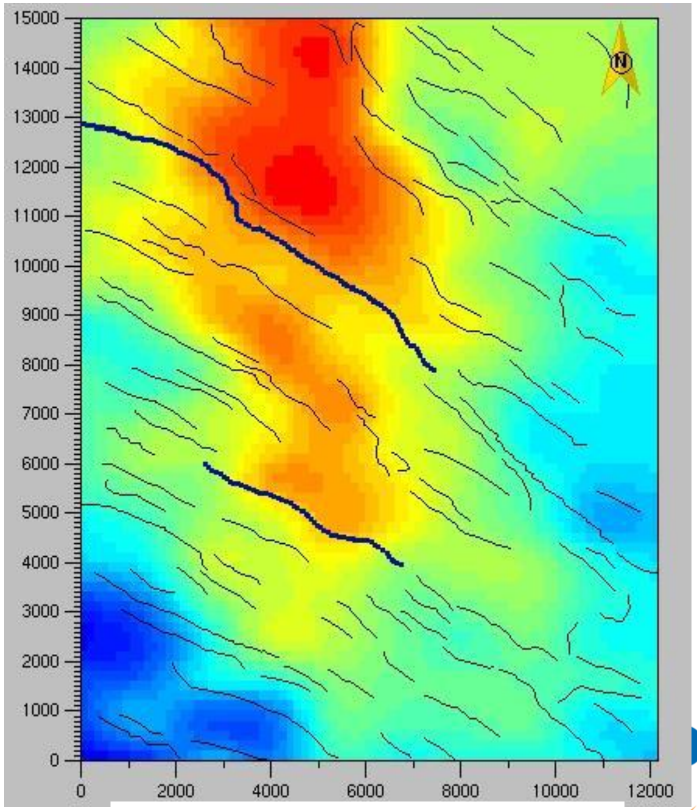
Some reservoirs present complex fracture network

Local scale (well)



Fracture log

Field scale



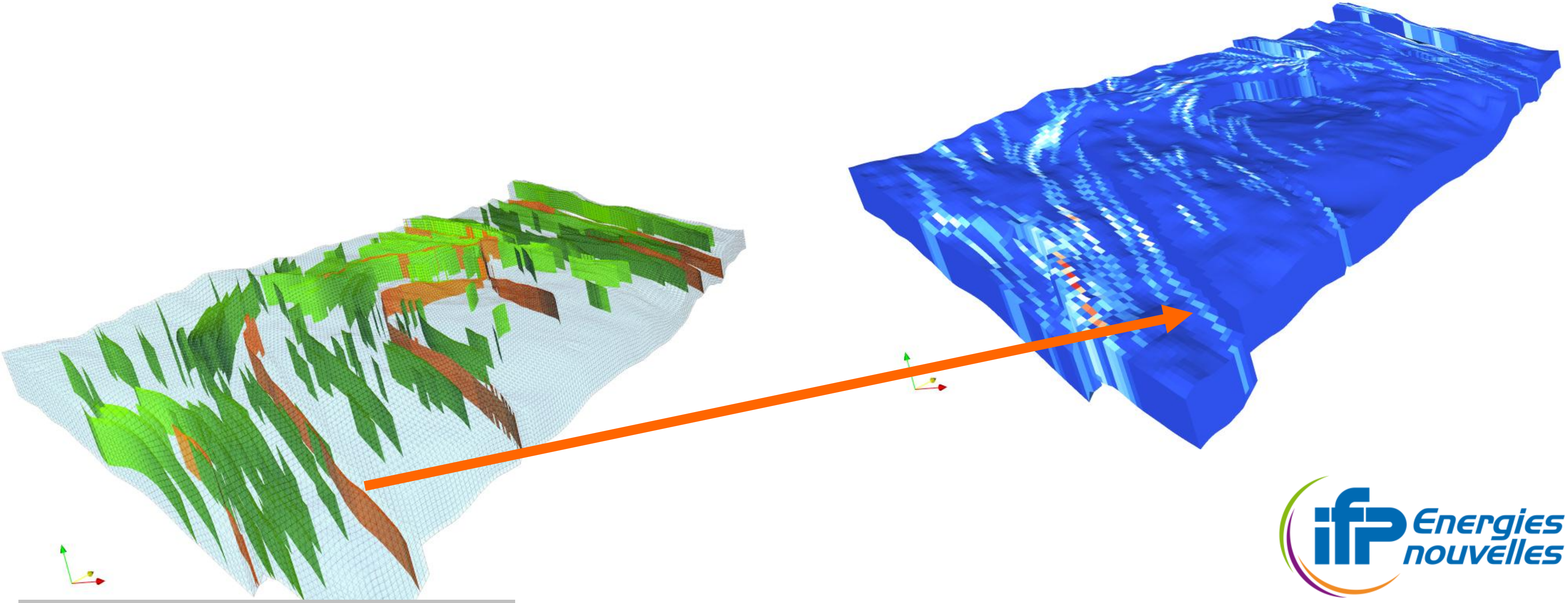
Faults and structural maps

Energies nouvelles

Flow simulation model : equivalent properties

Reservoir modeling softwares don't model flow on discrete fracture network.

→ **Equivalent flow properties have to be computed for each cell**

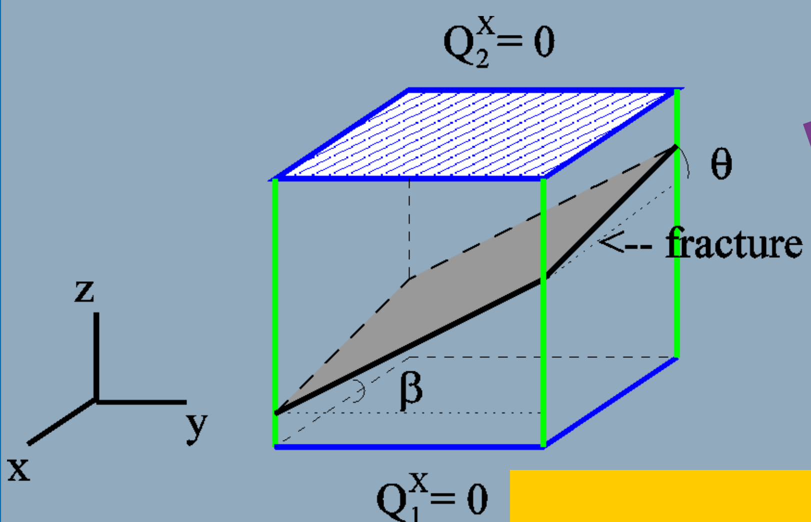


From M. Verscheure PHD work (2010)

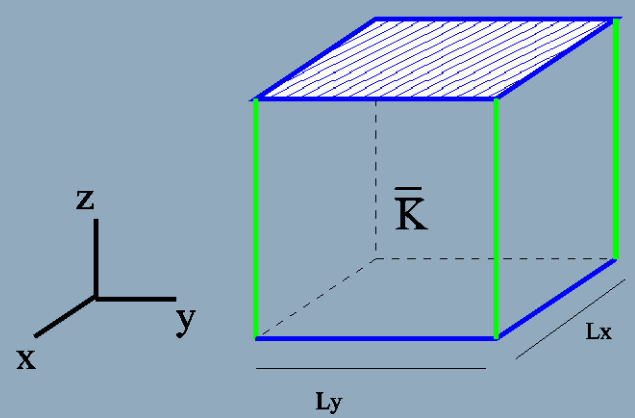
Goal :
to propose a new equivalent permeability

Flow : $\vec{q} = -k.\vec{\nabla}h$

$$Q_i^{frac} = -\sum_{fractures} k\vec{\nabla}h.\vec{n}_i^{\,f}.S_i^{\,f}$$

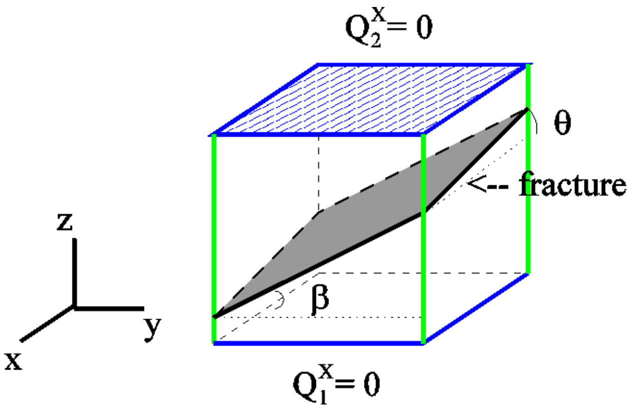


$$Q_i^{eq} = -\overline{\overline{K}}\vec{\nabla}h.n_i.S_i$$



$$\overline{\overline{K}} = -\frac{k.a}{(\cos^2\beta + \sin^2\beta\cos^2\phi)^{\frac{1}{2}}}\begin{bmatrix} \dfrac{\cos\theta}{L_z\cos\beta} & \dfrac{\sin\beta\sin\theta}{L_z} & 0 \\ \dfrac{\sin\beta\sin\theta}{L_z} & \dfrac{\cos\beta}{L_z\cos\theta} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Some comments



$$\overline{\overline{K}} = -\frac{k.a}{(\cos^2\beta + \sin^2\beta\cos^2\phi)^{\frac{1}{2}}}\begin{bmatrix} \frac{\cos\theta}{L_z\cos\beta} & \frac{\sin\beta\sin\theta}{L_z} & 0 \\ \frac{\sin\beta\sin\theta}{L_z} & \frac{\cos\beta}{L_z\cos\theta} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

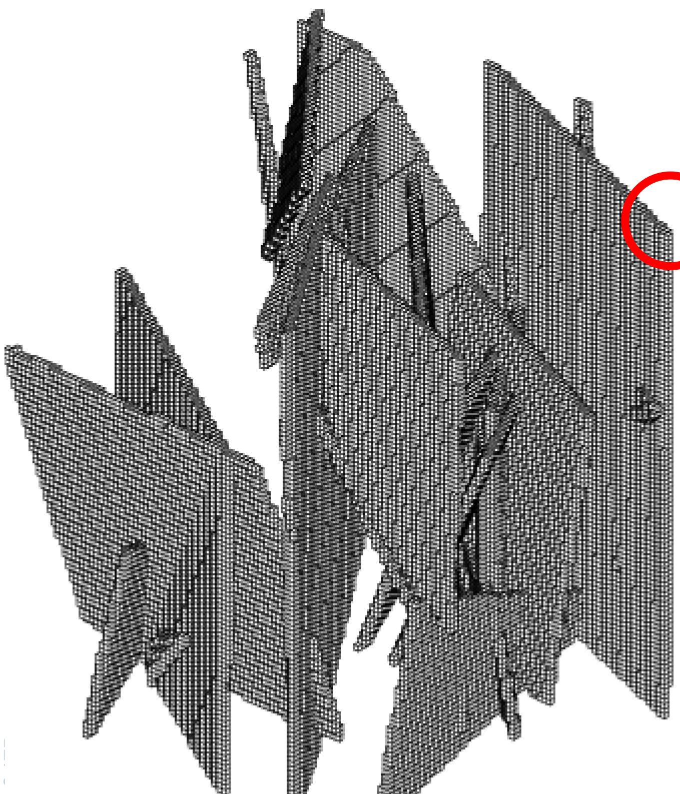
- **To correctly take into account a fracture, a full tensor have to be used by cells**

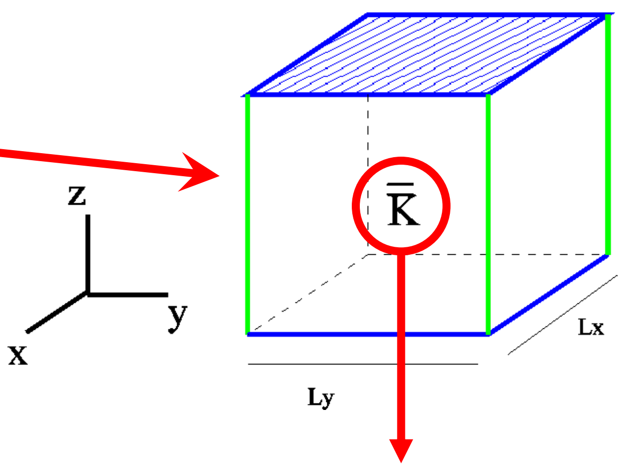
Nevertheless

- **If the dip or azimuth is closed to 0, K can be approximated by a diagonal tensor.**

Smeared Fractures
This work was initiated by CEA (DEN/DM2S/MTMS)

The idea behind this approach is to represent a fracture network by heterogeneous properties on a regular mesh



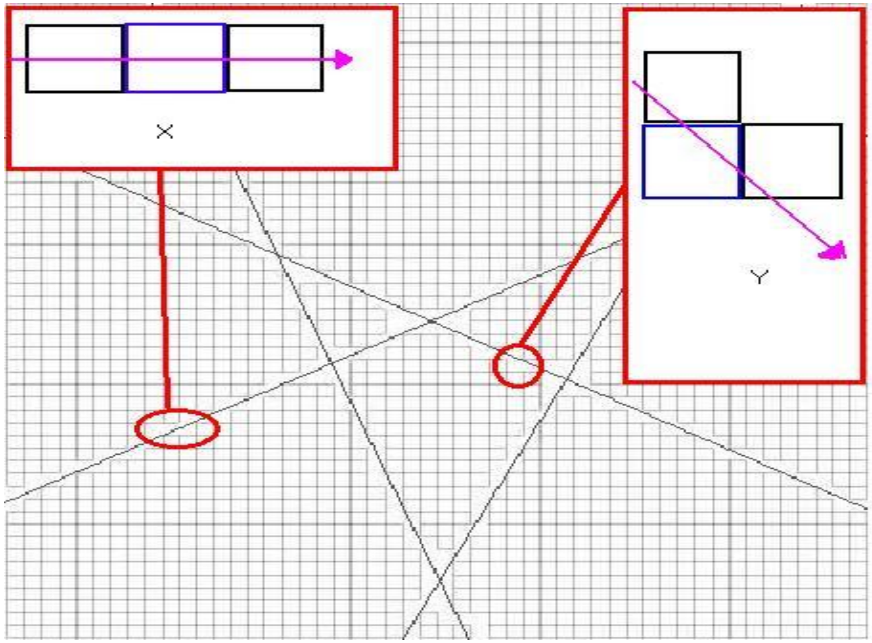


$$\bar{\bar{K}}_{SF} = \begin{bmatrix} K_1^{SF} & 0 & 0 \\ 0 & K_2^{SF} & 0 \\ 0 & 0 & K_2^{SF} \end{bmatrix}$$

From A. Fourno PHD work (2005)

Exemple for the 2D

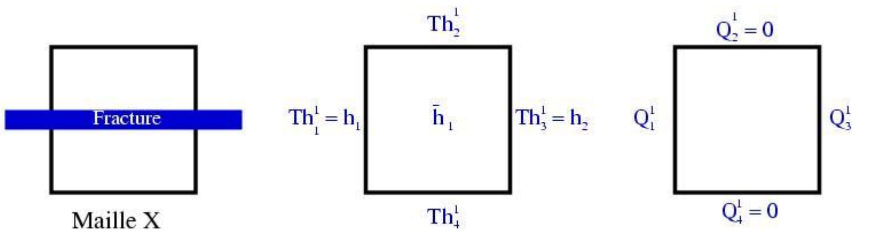
- **Two sets of cell are identified**



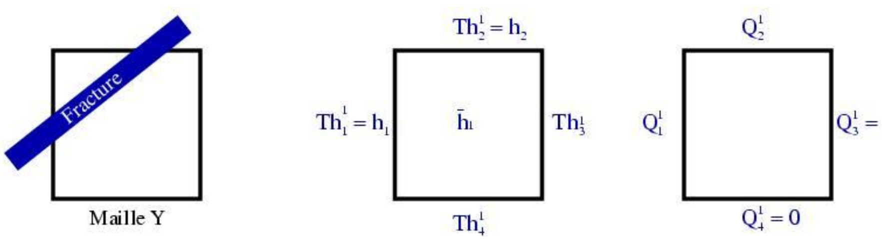
Equivalent permeability K_{MHFE}

$$Q_i = \int K.\vec{\nabla} h.\vec{n_i}.\partial s \rightarrow \quad Q_i = \bar{h}_i \sum_j M_{ij}^{-1} - \sum_j M_{ij}^{-1} Th_j$$

- Mixed and Hybrid Finite Element scheme (MHFE) Flow



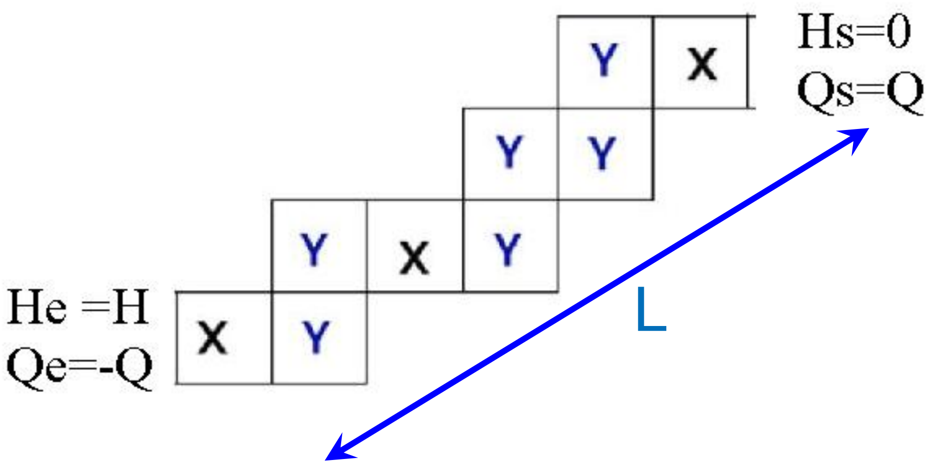
$$\rightarrow \quad Q_{MHFE} = K_{MHFE} \Delta h$$



$$\rightarrow \quad Q_{MHFE} = \frac{3}{2} K_{MHFE} \Delta h$$

2D: equivalent permeability K_{MHFE}

The flow balance give the equivalent permeability

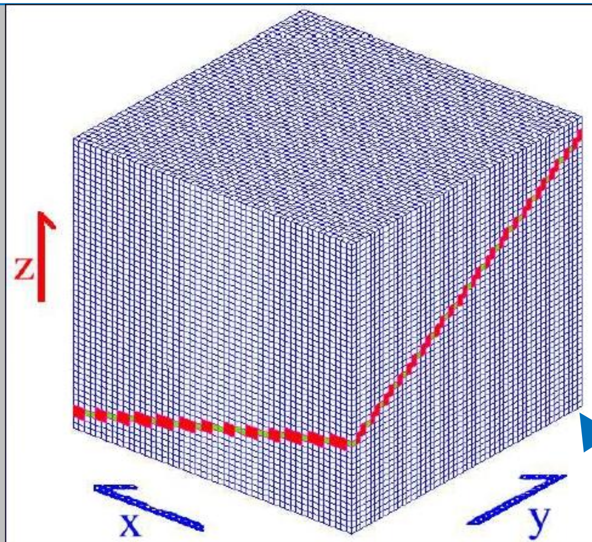


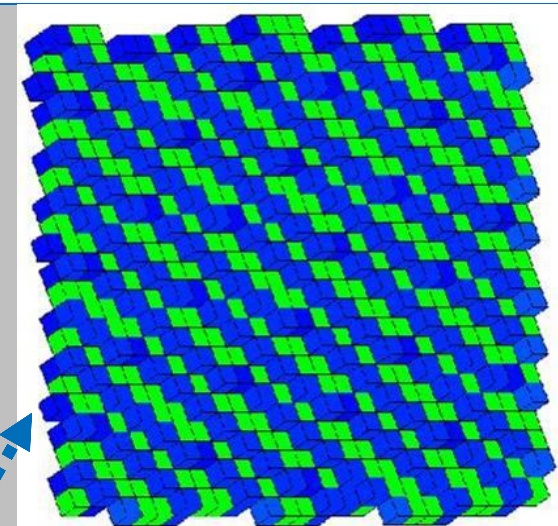
- a = fracture aperture
- k = fracture permeability
- L = fracture length
- Δh = head difference

- Nb_x = number of X cells
- Nb_y = number of Y cells

$$Q_{MHFE} = -\frac{3}{3Nb_X + 2Nb_Y} K_{MHFE} \Delta h \Leftrightarrow Q_{ref} = -\frac{a}{L} k \Delta h$$

3D fracture mesh

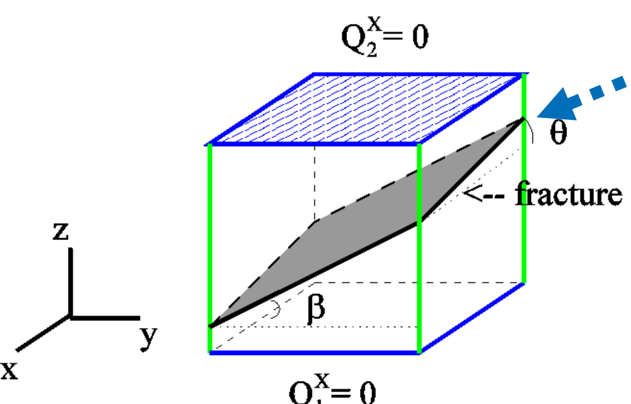


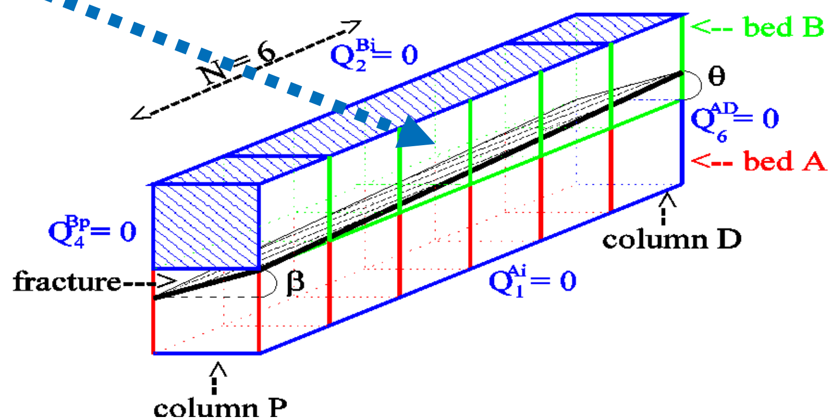


S Cells (green)

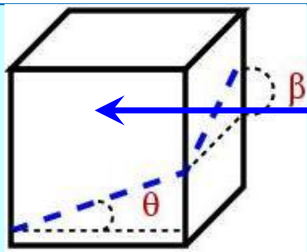
Fracture

C Cells (blue)

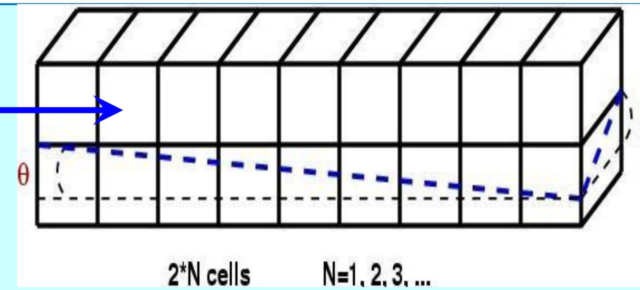




Analytical and MHFE flow



$$\overline{\overline{K}}_{SF} = \begin{bmatrix} K_1^{SF} & 0 & 0 \\ 0 & K_2^{SF} & 0 \\ 0 & 0 & K_2^{SF} \end{bmatrix}$$



S (simple) cell

C (complex) cells

S Cells (green)

$$Q_1^{MHFE,X} = \Delta.K_1.\Delta h \quad \leftarrow\rightarrow \quad Q_1^{ref,X} = \frac{a}{c_n}\frac{\cos\theta}{\cos\beta}.k.\Delta h$$

$$Q_2^{MHFE,X} = \Delta.K_2.\Delta h \quad \leftarrow\rightarrow \quad Q_2^{ref,X} = \frac{a}{c_n}\frac{\cos\beta}{\cos\theta}.k.\Delta h$$

$$N = \frac{\tan\beta}{\tan\theta}$$

$$c_n = (\cos^2\beta + \sin^2\beta\cos^2\theta)^{\frac{1}{2}}$$

C Cells (blue)

$$Q_2^{MHFE,Y} = -\frac{3}{4}N.\Delta.K_2.\Delta h \quad \leftarrow\rightarrow \quad Q_2^{ref,Y} = -N\frac{\cos\beta}{\cos\theta}.a.k.\Delta h$$

$$Q_1^{MHFE,Y} = -\frac{2K_2}{(N+1-\frac{2}{3N})K_2 + \frac{4}{3N}K_1}.\Delta.K_1.\Delta h \quad \leftarrow\rightarrow \quad Q_1^{ref,Y} = -\frac{1}{N}\frac{\cos\theta}{\cos\beta}a.k.\Delta h$$

A 3D equivalent permeability

$$\overline{\overline{K}}_{SF} = \begin{bmatrix} K_1^{SF} & 0 & 0 \\ 0 & K_2^{SF} & 0 \\ 0 & 0 & K_2^{SF} \end{bmatrix}$$

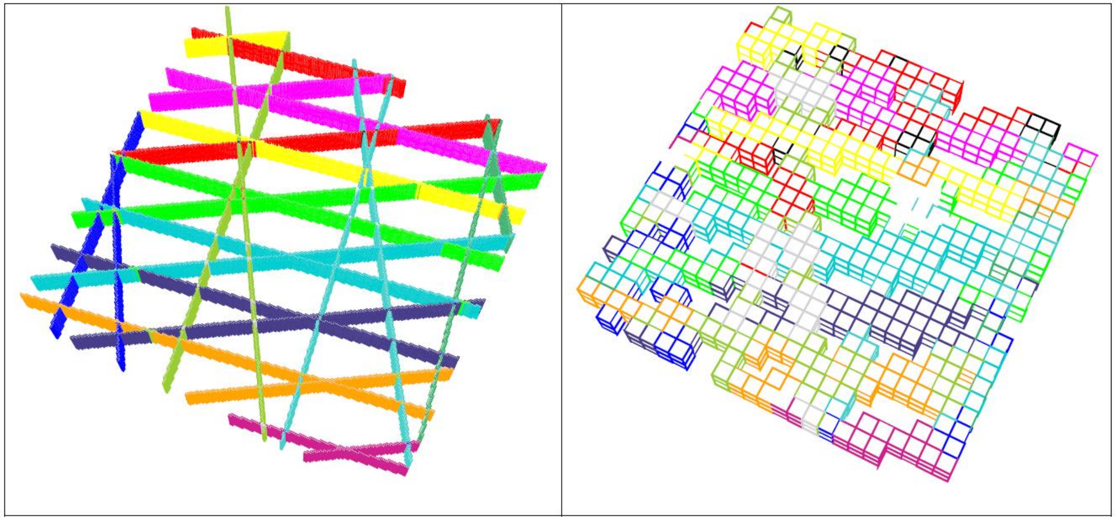
S Cells	$K_1^{SF} = \frac{\cos\theta}{c_n \cos\beta} \frac{a}{\Delta} k$	$K_2^{SF} = \frac{\cos\beta}{c_n \cos\theta} \frac{a}{\Delta} k$	$K_3^{Sf} = K_2^{Sf}$
C Cells	$K_1^{SF} = \frac{\cos\theta}{c_n . \cos\beta} \frac{(1 + \frac{\tan\theta}{\tan\beta} - \frac{2}{3} \frac{\tan^2\theta}{\tan^2\beta})}{(2 - \frac{\sin^2\theta}{\sin^2\beta})} \frac{a}{\Delta} k$	$K_2^{SF} = \frac{4}{3} \frac{\cos\beta}{c_n \cos\theta} \frac{a}{\Delta} k$	$K_3^{Sf} = K_2^{Sf}$

Validation case

Sensitivity study on the dip and azimuth value. Numerical and analytical equivalent permeabilities are compared

- Single fracture : dip and strike

- Regular fracture network : cubic element size



Precision of the results : single fracture

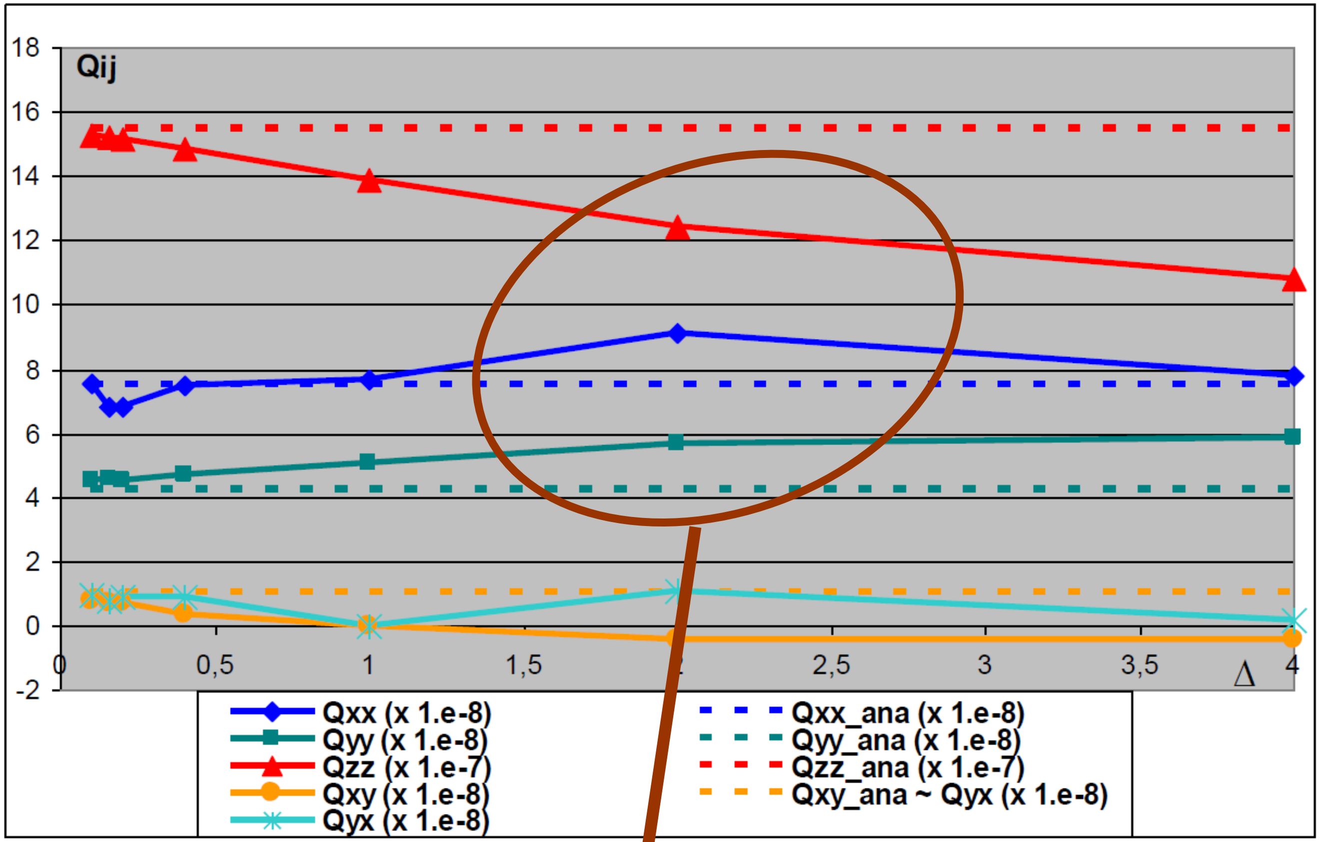
Err %		Strike (°)			
	k_{max} k_{int} k_{min}	0	15	30	45
Dip(°)	0	0 0 0	0. 0.6 0.	0. 2.8 0.	0. 13.8 0.
	10		0 1.1 8.7	0 5.1 4.4	0 15.2 3.7
				0 8.5 9.2	0 24.2 13.9
	30				0. 22.4 11.9

Increase of the error

$$\overline{\overline{K}} = -\frac{k.a}{(\cos^2\beta + \sin^2\beta\cos^2\phi)^{\frac{1}{2}}}\begin{bmatrix} \frac{\cos\theta}{L_z\cos\beta} & \frac{\sin\beta\sin\theta}{L_z} & 0 \\ \frac{\sin\beta\sin\theta}{L_z} & \frac{\cos\beta}{L_z\cos\theta} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

As attempted, error depends on dip and strike values due to extra diagonal terms that are neglected in our approach

Precision of the results : regular fracture network



Huge and minor connectivity changes due to the spatial cell size

Conclusions

☆ Performance of the method

→ **Fractured media mesh easily obtained**

→ **Quick results and low computer cost (coarse discretizations)**

→ **Precision depends on head gradient orientation, discretization.**

🕐 Modeler point of view

→ **For huge fracture density, weak space discretization have to be required (increase the computer cost).**

→ **The number of cell required is frequently an handicap**

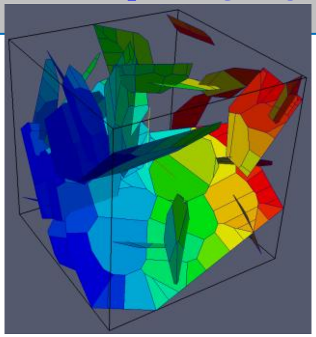
Perspectives

☼ Perspectives :

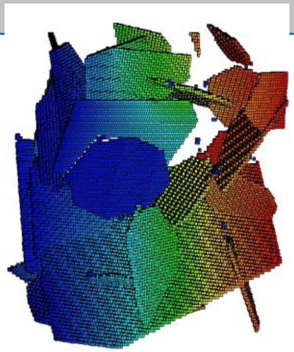
→ **Reduce the number of cells**

→ **Simulations of transfers in the fractured media**

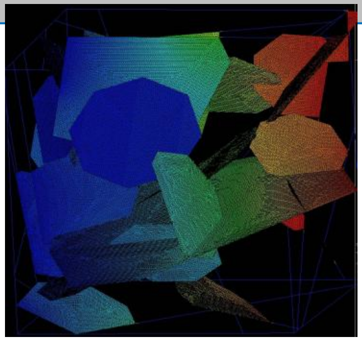
→ **Benchmark**



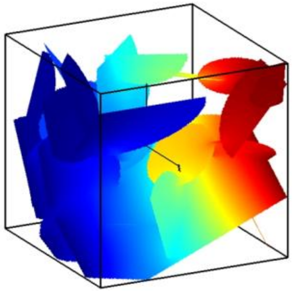
Approche « explicite optimisée »
MD, NK,[1] (100 mailles)



Approche « Voxel »
AF et al., (10^6 mailles)



Approche « explicite fin »
AF et al. [2] (2.10^5 mailles)



Approche extérieure
JRD, [3]

[1] N. Khvoenkova & M. Delorme (2011), méthode pour construire le maillage d'un réseau de fractures a partir de diagrammes de voronoï,FR11/01.686

[2] A. Fourno, B. Noetinger, C. La Borderie. Publication prévue

[3] G. Pichot, J. Erhel and J. R. de Dreuzy, A mixed hybrid Mortar method for solving flow in discrete fracture networks, Applicable Analysis An International Journal, 89 Issue 10, 1629, doi:10.1080/00036811.2010.495333

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- 2011. A. Fourno, C. Grenier, F. Delay, H. Benabderrahmane. A novel and efficient 3D fracture continuum model for flow in fracture networks. MAMERN11: 4th International Conference on Approximation Methods and Numerical Modelling in Environment and Natural Resources. Saidia (Morocco).
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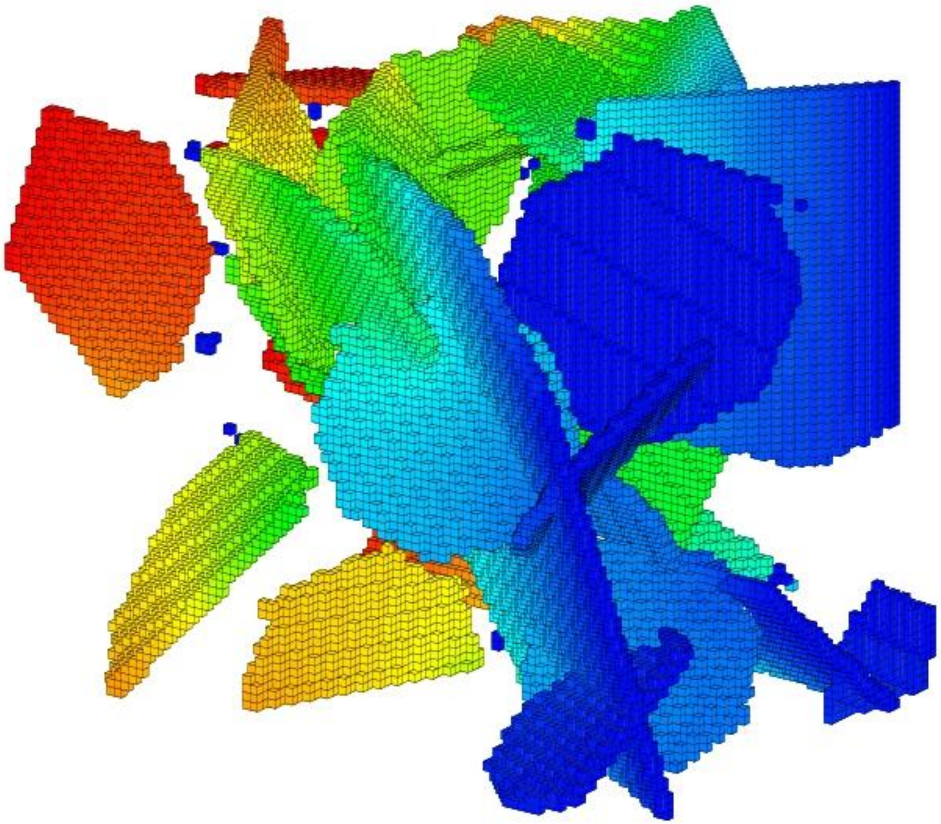
- 2005. A. Fourno, directeur de thèse F. Delay, responsable C. Grenier. Modélisation multi-échelles de l'écoulement et du transport dans un milieu granitique ; application au site d'Äspö en Suède. Thèse financée par l'ANDRA et effectuée au CEA/DEN dans le laboratoire de Modélisation des Transferts en Milieux Solides.

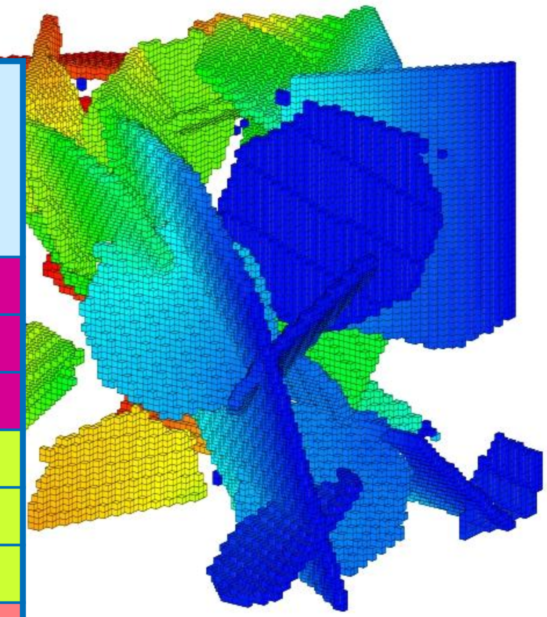
Spatial sensitivity study



The DFN was generated using J.R. de Dreuzy tools

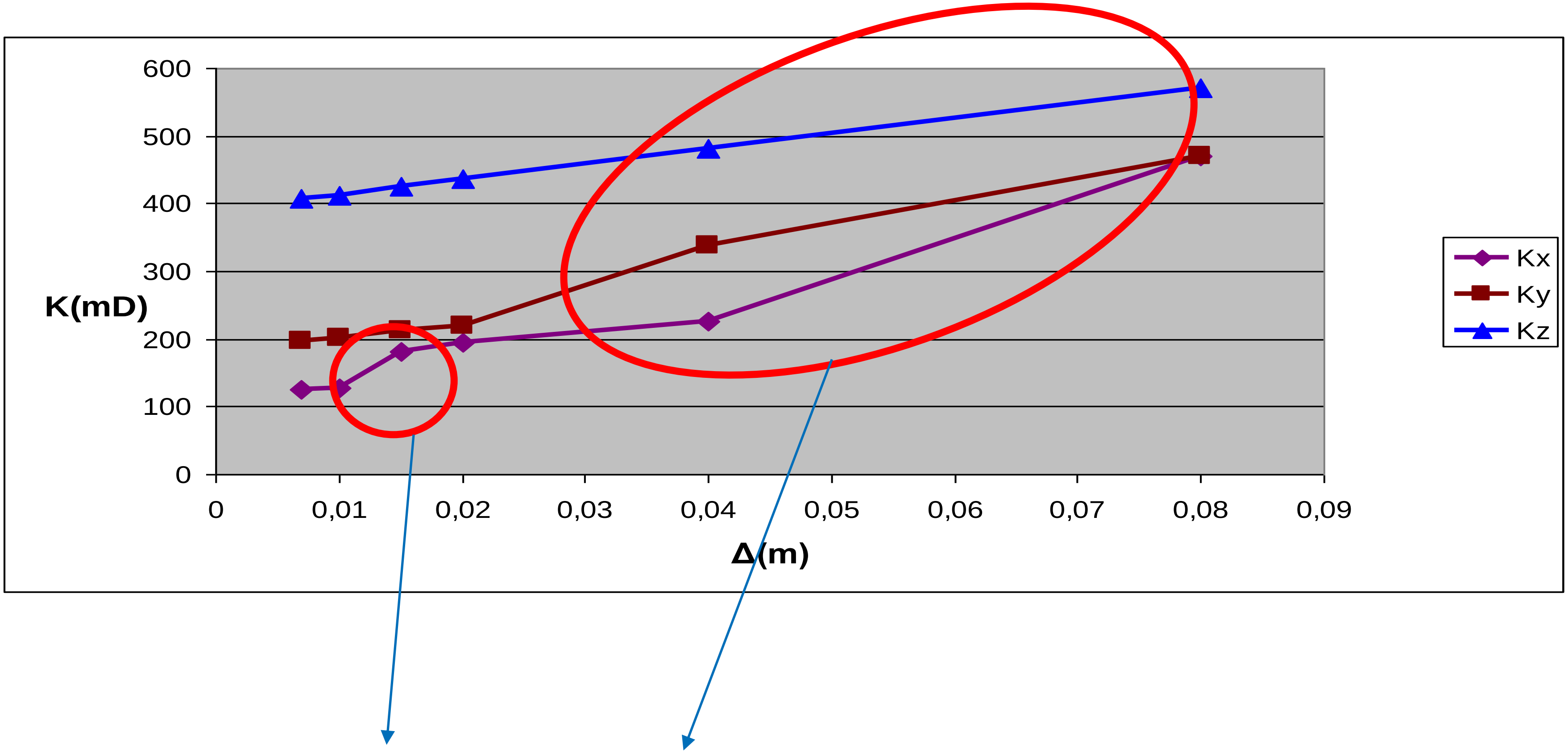
Spatial sensitivity study
Equivalent permeability tensor

Δ (m)	Equivalent permeability K (mD)			Diagonal tensor (mD) Kmin	Kmax	Kz
0.007	313.37	-88.67	-36.6	211		
	-56.381	289.64	-174.20		374	
	-38.72	41.92	540.78			559
0.01	320	-90	-37.5	218		
	-56.5	298.6	-173.5		382	
	-37.7	42	548			566
0.02	351	-92	-43	243		
cell number	-57	326	182		413	
(1.628.973)	-37	35	580			601
0.04	386	-115	74	296		
	-53	425	166		491	
	-45	33	633			657
0.08	590	-59	-14	495		
	-35	533	-175		615	
	-9	54	821			833



Fracture conductivities
Cf = 1000 mD.m

Spatial sensitivity study
sensitivity analysis



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