ICOLD
INTERNATIONAL COMMISSION ON LARGE DAMS

ICOLD COMMITTEE ON COMPUTATIONAL ASPECTS OF ANALYSIS AND DESIGN OF DAMS

15th INTERNATIONAL BENCHMARK WORKSHOP ON NUMERICAL ANALYSIS OF DAMS

Theme A - Formulation

SEISMIC ANALYSIS OF PINE FLAT CONCRETE DAM

9 September 2019, Milan, Italy

Simplified use of Viscous Spring boundaries and anisotropic damage in the principal directions with the ability of cracks re-closure

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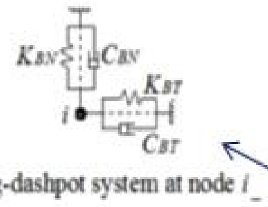
Summary of the presentation

- Simplified assumptions for the use of viscous spring boundaries for earthquake analyses
- Modal analyses when modal analyses are not possible
- Non-linear analyses with anisotropic damage and crack re-closure

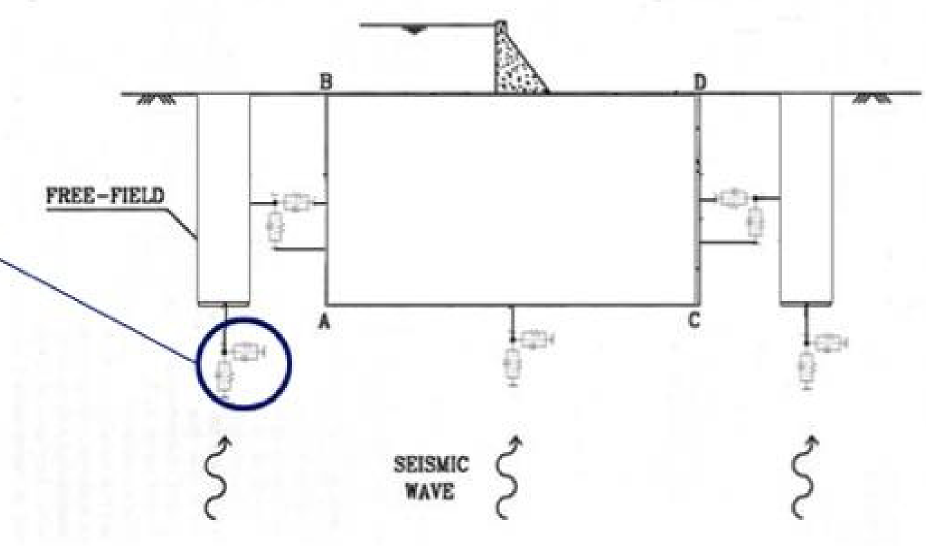
Viscous-spring boundaries for dynamic analyses

- Earthquake input as compression and shear waves, vertically propagating from bottom to top of the foundation



$$K_{BN} = A\frac{1}{1+\alpha}\frac{\lambda+2G}{2R_b} \quad K_{BT} = A\frac{1}{1+\alpha}\frac{G}{2R_b}$$

$$C_{BN} = A\beta\rho c_p \quad C_{BT} = A\beta\rho c_s$$



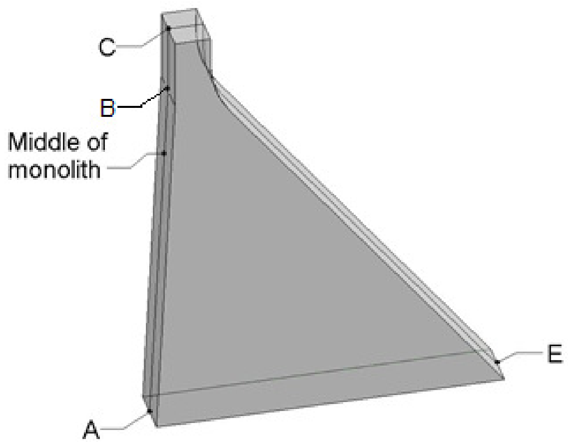
  - Homogenous foundation + no damping : acceleration of the free-field column is theoretically known
  - If the foundation is non homogenous and/or with damping, acceleration of every point of the free-field column has to be computed first. In addition, deconvolution should be perform to evaluate the input at the bottom to get the wanted signal at the top.

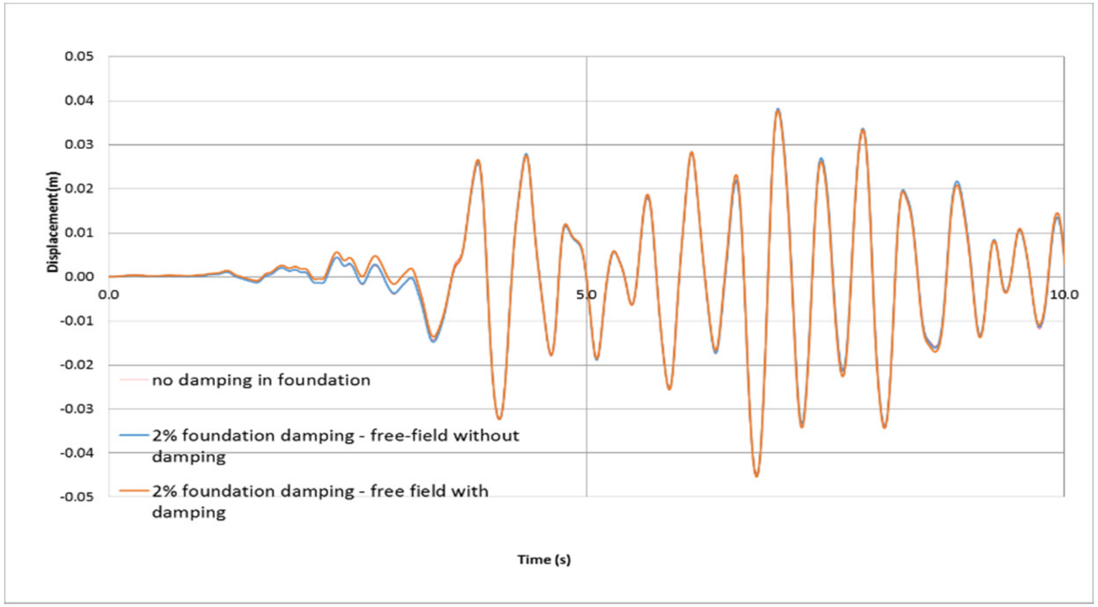
Viscous-spring boundaries for dynamic analyses

- From the engineering point of view, non homogenous and/or damping in the foundation requiert additionnal steps in the analyses :
  - Computation of the free-field column
  - Deconvolution (to evaluate the input at the base of the column)
- Is it really useful?

- Sensibility analyses
  - No damping for the foundation material,
  - 2% Rayleigh damping in the foundation but no damping for the free field (directly evaluated from the analytical solution)
  - 2% Rayleigh damping in the foundation including the free field (computed first as a soil column with input at the base).

Analyses of Pine Flat under Taft earthquake





- Comparison of the displacements at the crest of the dam
  - No significant differences,
  - For low value of damping in the foundation (<5%) : damping can be neglected → simplified use of the viscous-spring boundaries

Analyses of Pine Flat under Taft earthquake

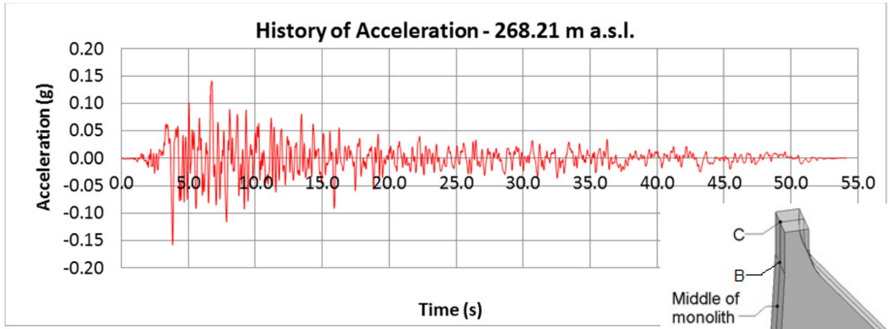
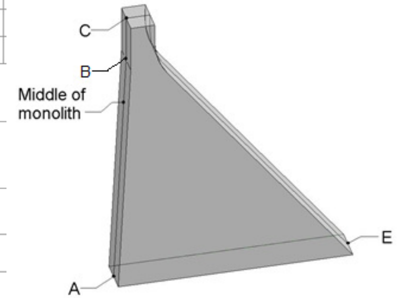


Figure D-1.4 - History of Acceleration at Point A - 268.21 m a.s.l.



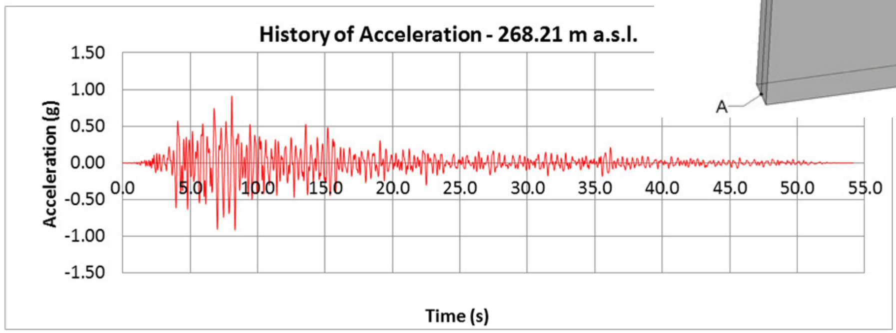
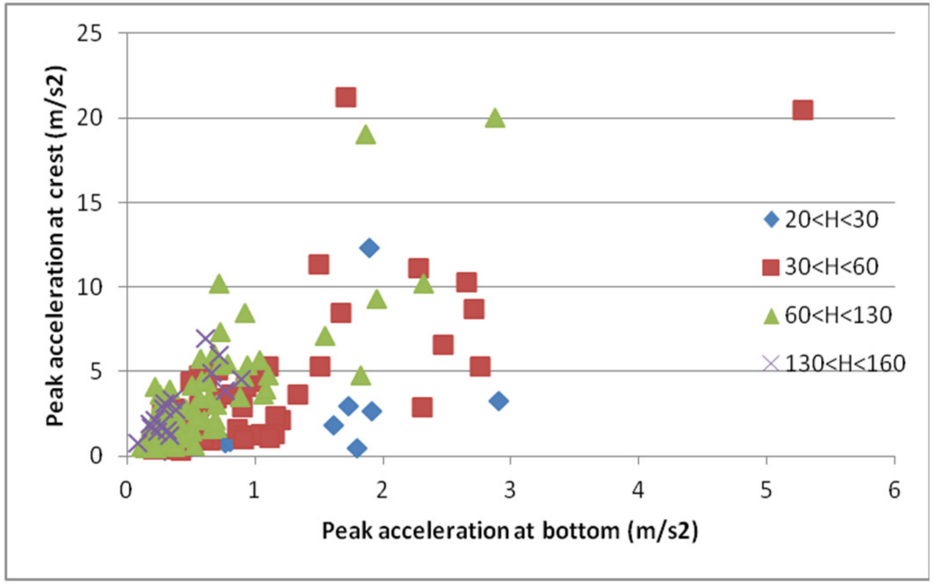


Figure D-1.5 - History of Acceleration at Point C 268.21 m a.s.l.

- Pga about 0.15g at the bottom
- 1 g at the crest



Simplified formula from eq records in Japan

$$Peak\ crest\ acc = 0.07 \times H \times PGA$$

For PineFlat with 0.15g at the base

→1.3g at the crest

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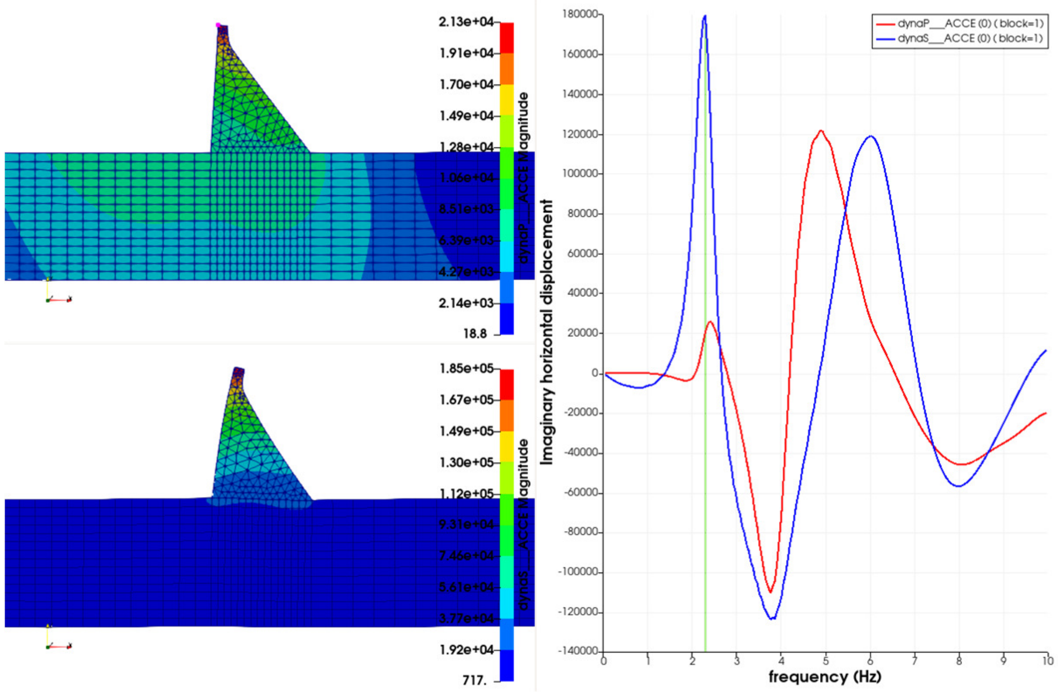
ICOLD-BW 2019
9th-11th September
MILANO
Numerical analysis of dams

Modal analyses with viscous-spring boundaries model

- Modal analyses can not be performed with viscous-spring boundaries
  - Use of harmonic analyses with compression or shear waves
  - visualize the imaginary part of the structure displacements function of the frequency
  - point-pick the natural frequencies of the dam

- Similar value for the 1st mode with conventional analyze with restrained boundaries of the foundation



Mode	Modal analysis (Hz)	Harmonic analysis (Hz)
1	2.35	2.3–2.4(*)
2	3.42	
3	3.94	3.8
4	4.38	
5	4.92	4.9
6	5.49	
7		6.0

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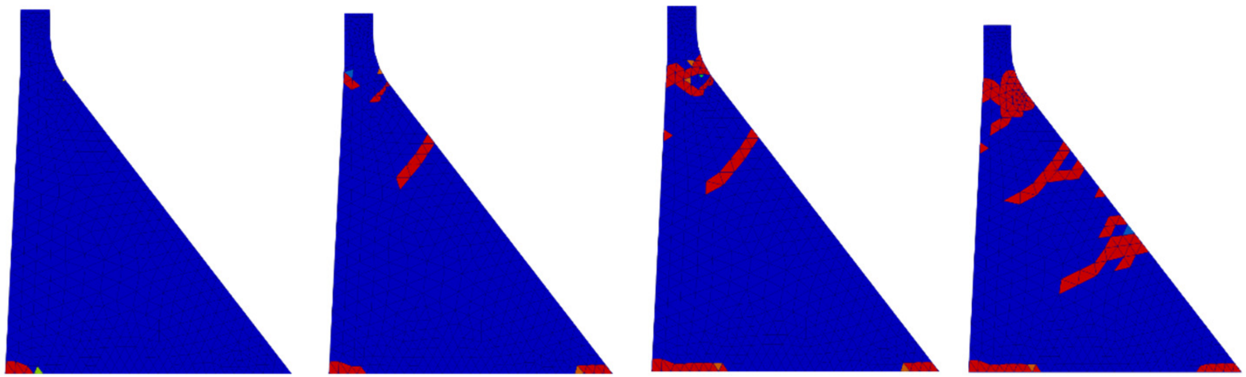
EDF

Non linear Analyses with damage model

- Use of ENDO_PORO_BETON in Code_Aster
  - Damage affecting tensile stresses
    - Pre peak isotropic damage
    - Orthotropic damage following Rankine criteria during post-peak corresponding to the localization of the tensile cracks (in the principal direction)
    - Cracks can be re-closed under chosen compressive strength (5 MPa)

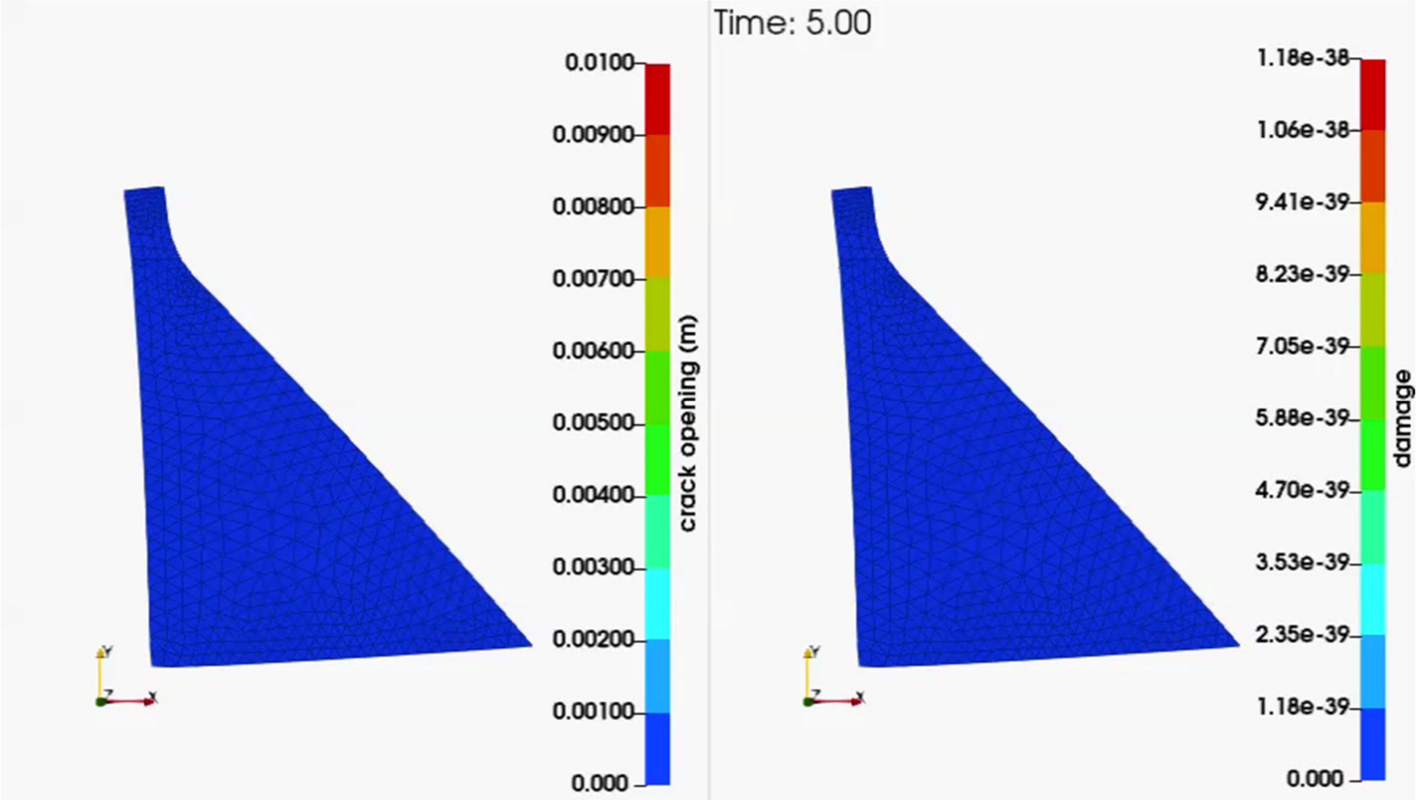


Cracks at the bottom probably underestimated because it doesn't take into account uplift

Figure 1 maximum of the density of cracks du to tensile stresses in the main directions: blue = no cracks; red fully cracked. t= 6s, 9s, 12s, 15s

Non linear Analyses with ETAF signal

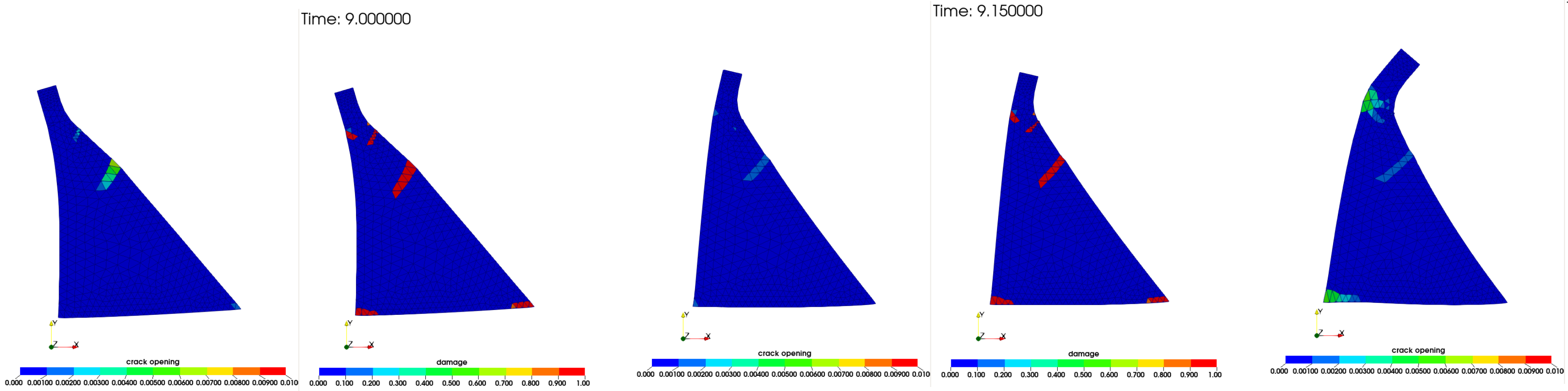
Maximum of cracks opening in the 2 principal directions



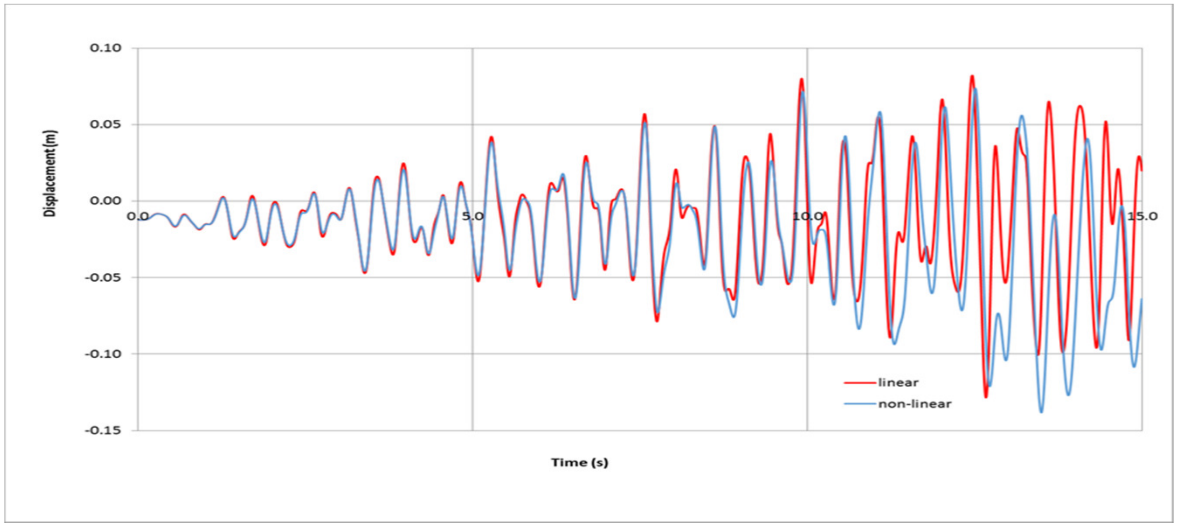
Maximum of the density of cracks in the 2 principal directions

Time – history of the non-linear analyze with ETAF signal from 5 → 15s

Non linear Analyses with ETAF signal



- Time-history displacement comparison between linear and non linear analyses



Conclusion

- Analyses using viscous-spring boundaries with simplified assumptions (homogenous without damping foundation) allows to perform more realistic earthquake analyses but remain no to complicated (for engineering purpose)
- Spring in viscous-spring boundaries allow to easily run static analyze followed by dynamic analyse.
- Good opportunity to evaluate the damage model provided by Code_Aster combined with viscous-spring boundaries and fluid element