Numerical analysis of dams

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Theme B:
Seismic analyses of Menta Embankment dam

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Performed analyses

- The methodological approach includes definition of the following:
  - **Type of analyses** to be carried out for best modelling of the dam-foundation-reservoir system response to:
    - Static loads; and
    - Earthquake.
  - **Most suitable material models** to be used for:
    - Embankment (elasto-plastic behaviour)
    - Bituminous face (elasto-plastic viscous behaviour)
    - Foundation (linear elastic behaviour).
  - **Fluid-structure interaction approach** to be used.
  - **Application of the specified seismic input**
  - **Criteria** for dam behaviour evaluation (static and dynamic)

Performed analyses

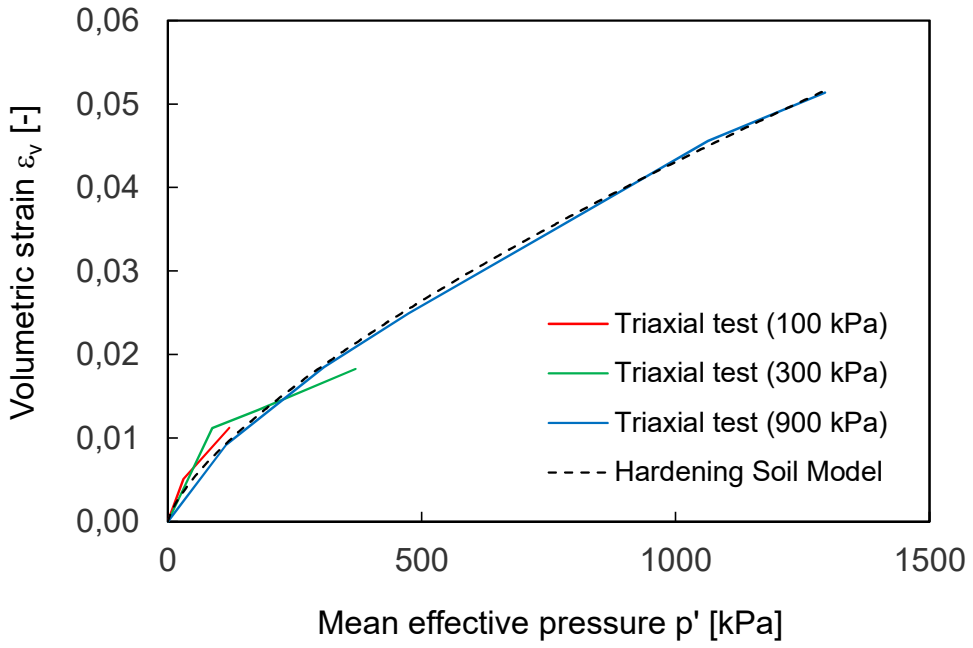
- Numerical code: **DIANA 10.3**
- Type of analyses performed: **full nonlinear static and seismic FEM analysis on a 2D model**
- Application of the static loads: **staged construction (7 stages) and staged impounding (2 stages)**
- Material models used in the current work:
  - Embankment: **Hardening Soil Model** considering also **Small Strain Non-linearity**
  - Bituminous face: **Linear-Elastic Model**
  - Foundation: **massless, Linear-Elastic Model**
- Fluid-structure interaction: **incompressible fluid ➔ hydrodynamic effect by a consistent mass matrix**
- Seismic input: **acceleration-time histories** applied on the **outer vertical and bottom boundaries**
- **Direct integration** of the EM in the time-domain by the α **−method** (Hughes, Hilbert Taylor) α =-0.3.
- **Rayleigh viscous damping:** 5% of the critical one for the 1-st and the 12-th vibration modes
- Criteria:
  - Horizontal and vertical displacements (available freeboard)
  - Bituminous face strains
  - Overall stability of the dam

Rockfill constitutive model

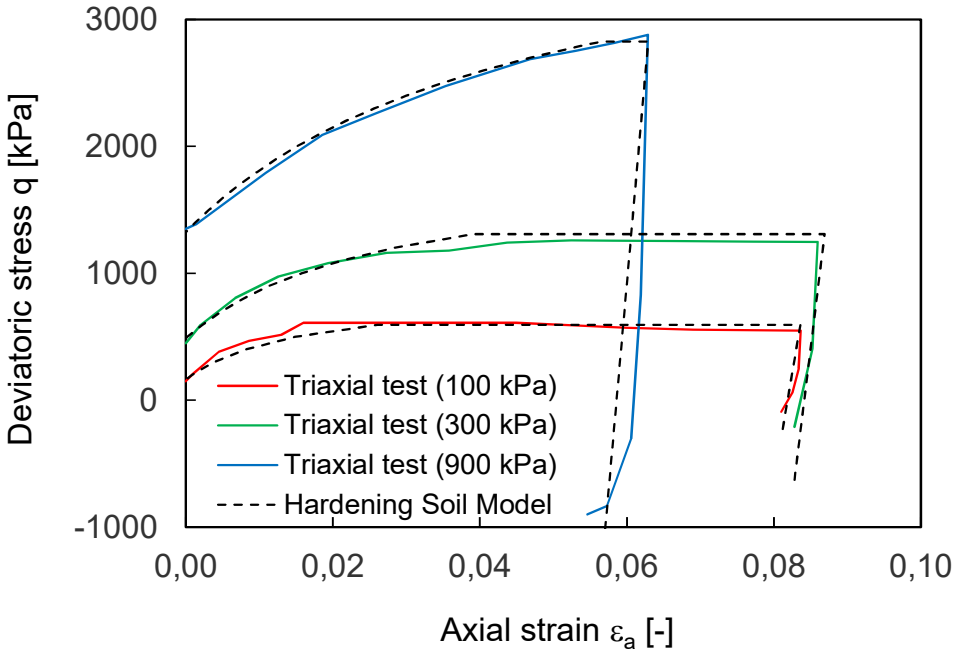
Elasto-plastic behaviour: Hardening Soil model

(So-called Modified Mohr Coulomb model in DIANA)

Calibration of the volumetric behaviour
on the K0-consolidation phase of triaxial tests



Calibration of the deviatoric behaviour
on triaxial compression tests



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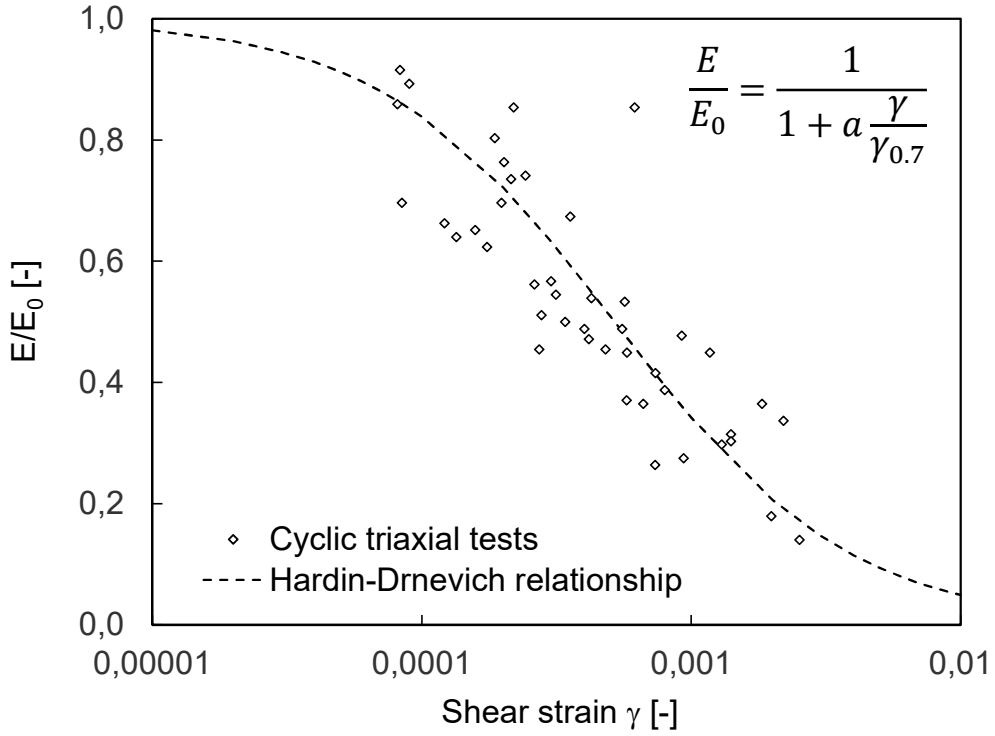
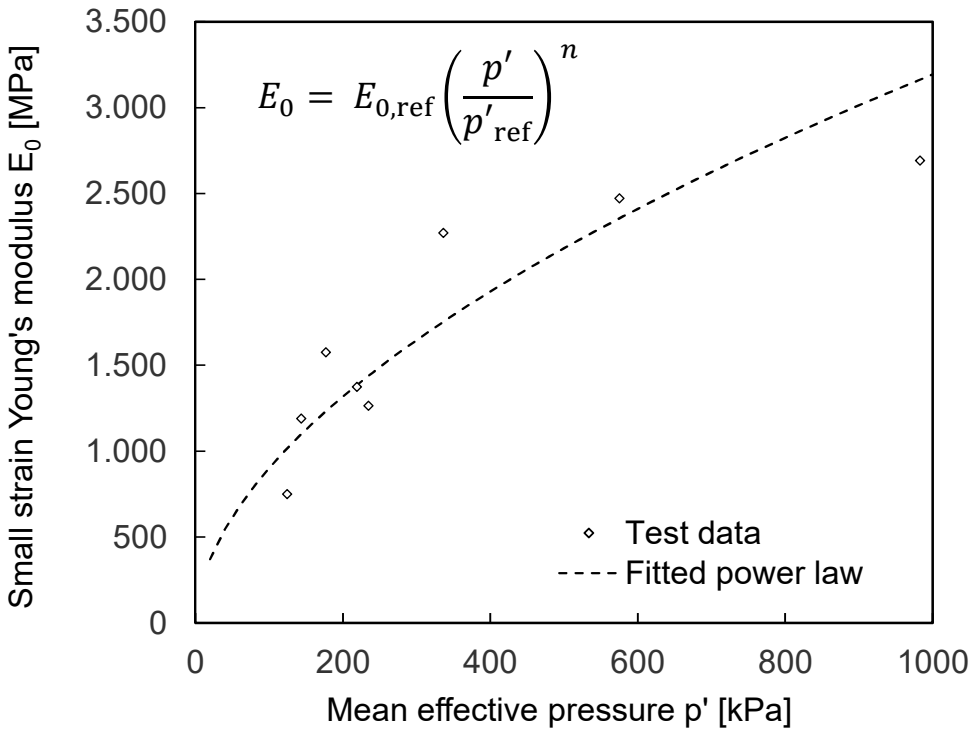
Rockfill constitutive model

Small strain non linearity: Hardin-Drnevich relationship

(So-called Small Strain model in DIANA)

Calibration on cyclic triaxial shear tests:





Rockfill constitutive model

Additional assumptions regarding the shear strength

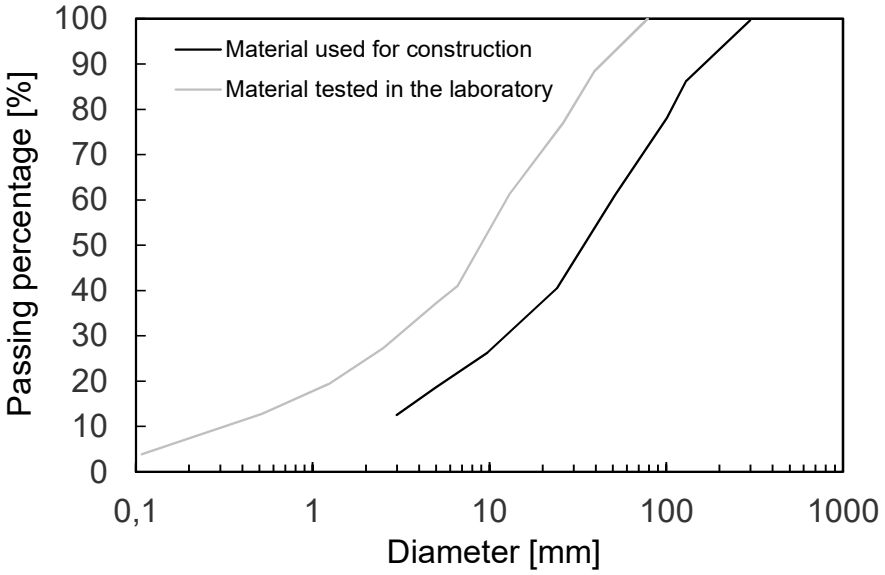
- Pressure level dependent friction angle
  (to account for the curved shape of the observed failure envelope)

$$\varphi(p') = A \log\left(\frac{p'}{p'_{\text{ref}}}\right) + B \leq B \qquad p'_{\text{ref}} = 100 \text{ kPa}$$

- Reduction of the friction angle by 3.3°
  (to account for scale effects due to the different particle size of the material tested in the laboratory)

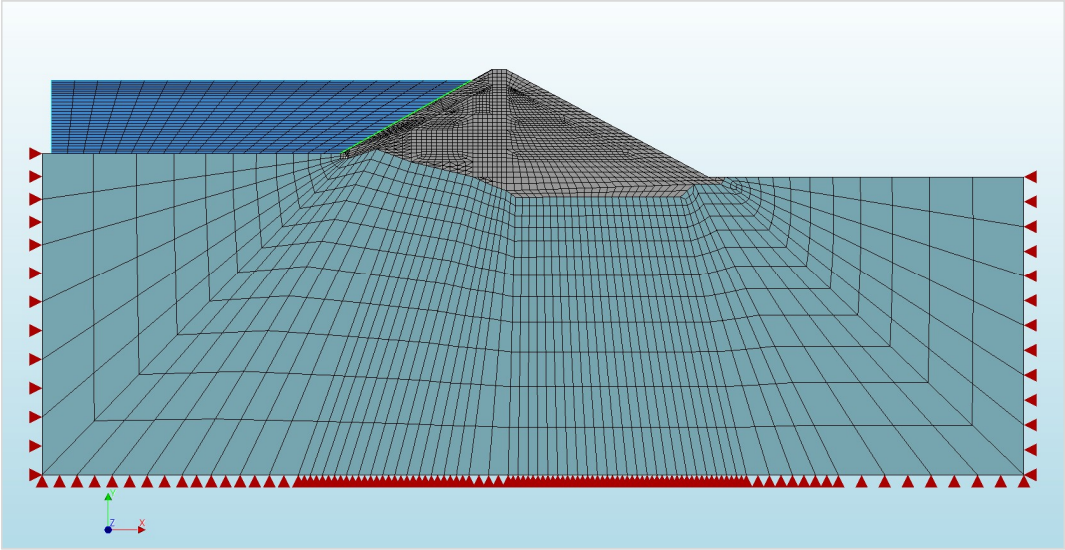
$A = -13.7$

$B = 51.7°$



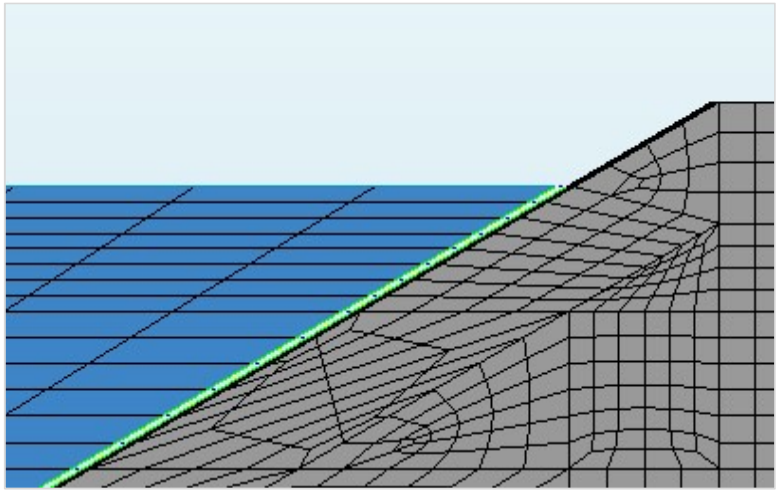
Finite element mesh

- Structural system (dam – foundation system):
  - Second order quadrilateral plain strain elements
- Reservoir:
  - second order quadrilateral potential flow elements
- Reservoir – bituminous face interface: fluid-structure interface elements



Seismic input

- Boundary conditions:
  - Mechanical:
    - Static : kinematic constraints in direction normal to the rock outer boundaries
    - Dynamic: base excitation with a horizontal and a vertical acceleration time-history
  - Fluid:
    - Hydrodynamic pressure = 0 at the far-field and the free surface of the reservoir
    - Hydrodynamic pressure gradient = 0 in direction normal to reservoir bottom



Seismic input

- Numerical procedure for seismic input:
  - The **foundation** is assumed **massless (conservative approach)**
  - The provided **acceleration-time histories** are applied on the **outer vertical and bottom boundaries**
  - **Four seismic excitation cases** are considered in the 2D FEM analysis:

Investigated case	Description	PGA, g	Acceleration time histories applied on the 2D model foundation boundaries	
			X-direction	Y-direction
Case 1	Friuli 1976 EZ	0.26	Friuli 1976 HNE	Friuli 1976 HNZ
Case 2	Friuli 1976 NZ	0.26	Friuli 1976 HNN	Friuli 1976 HNZ
Case 3	Central Italy 2016 EZ	0.26	Central Italy 2016 HGE	Central Italy 2016 HGZ
Case 4	Central Italy 2016 NZ	0.26	Central Italy 2016 HGN	Central Italy 2016 HGZ

Model for the bituminous concrete facing

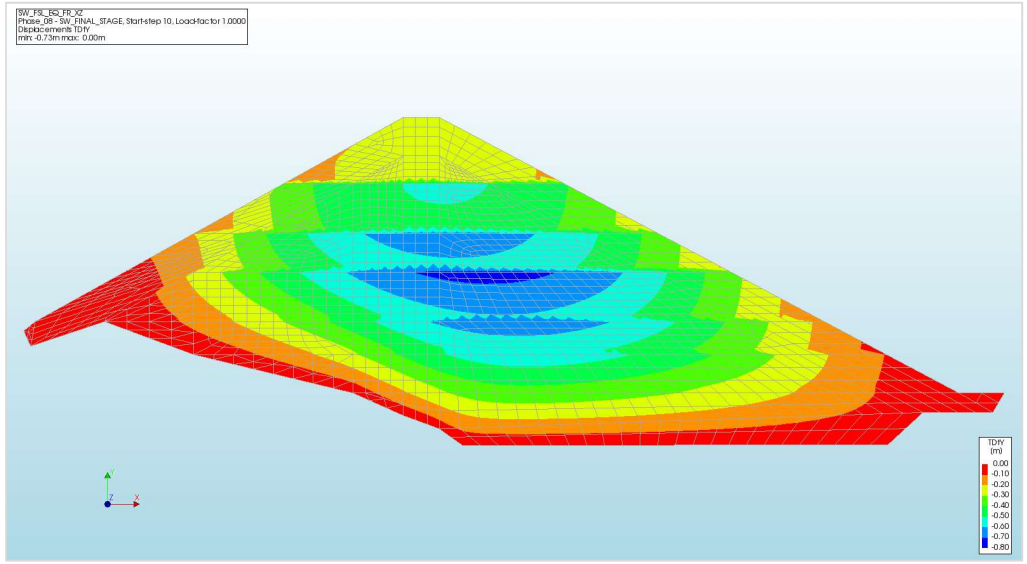
- FEM mesh: two rows of plain-strain elements
- Material model: linear-elastic:

Parameters	Description	Unit	Value
$E_{T=26°}$	Complex modulus at 26°C	[MPa]	2'800
$\nu_{T=26°}$	Complex Poisson's ratio at 26°C	[-]	0.33
γ	Density	[kN/m^3]	24.0

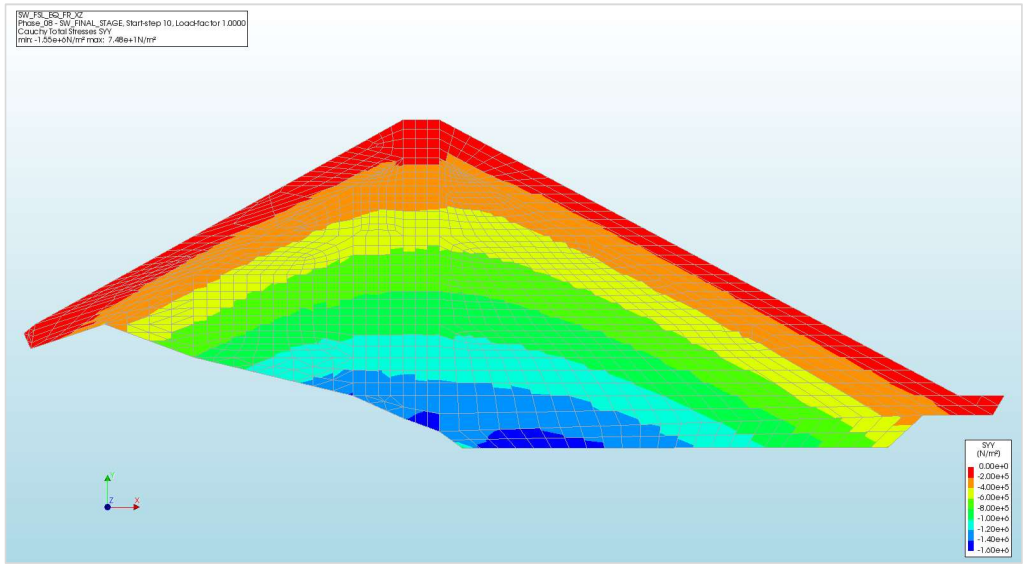
Results

- End of Construction:

Vertical displacements (max 0.73 m in centre)



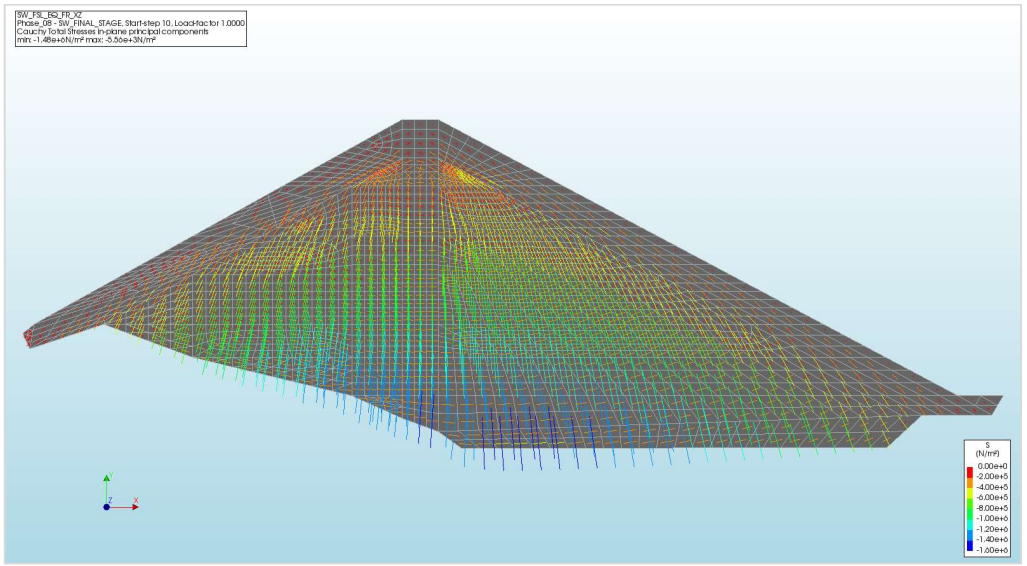
Vertical stresses



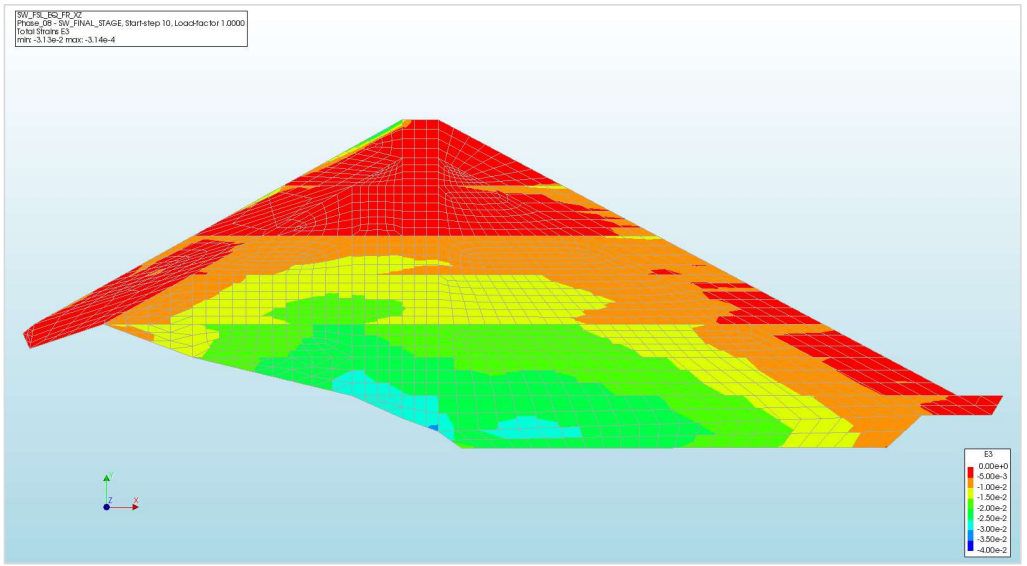
Results

- End of Construction:

Principal stress trajectories



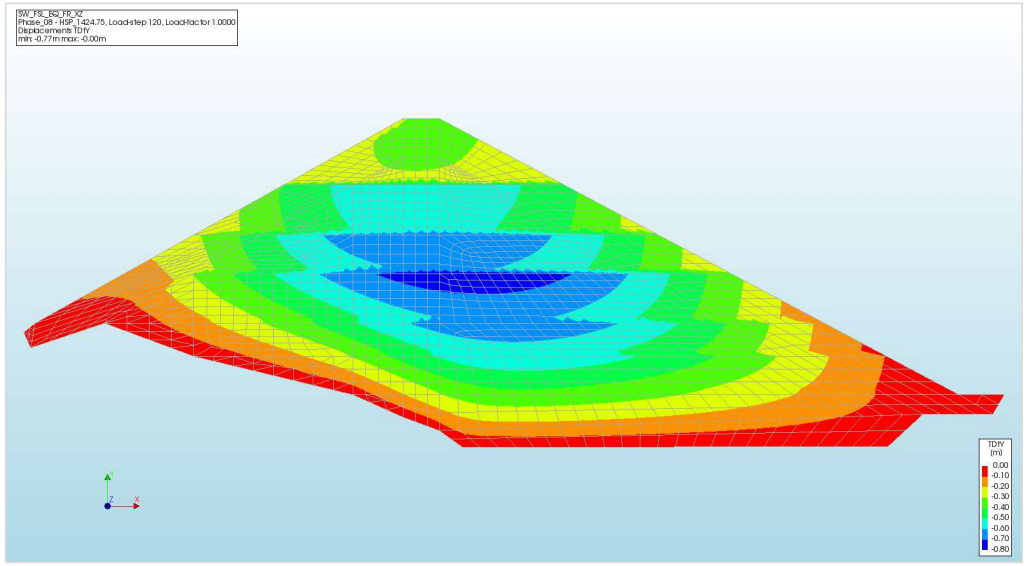
Total strains



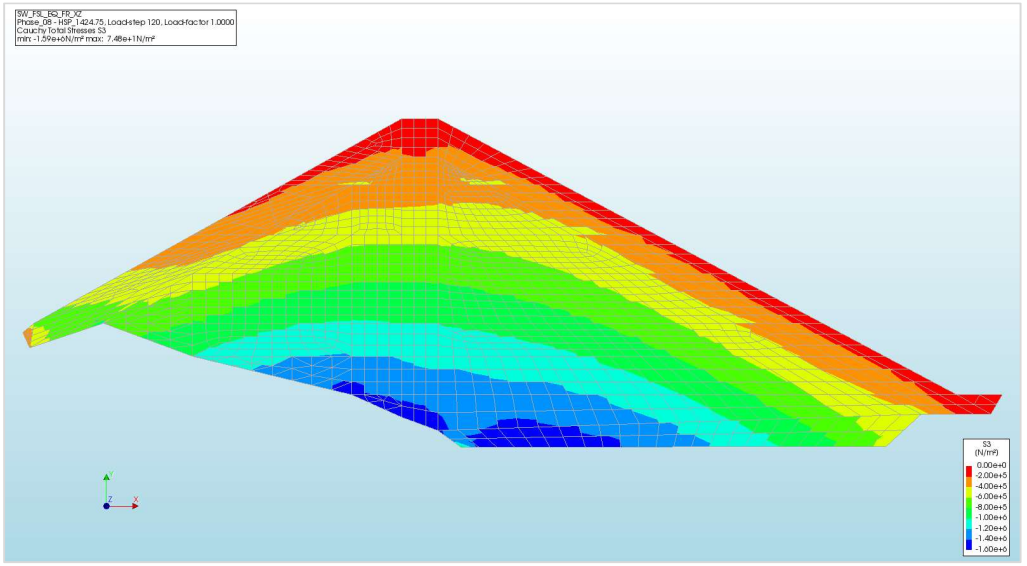
Results

- End of First Impoundment:

Vertical displacements (max 0.77 m at centre)



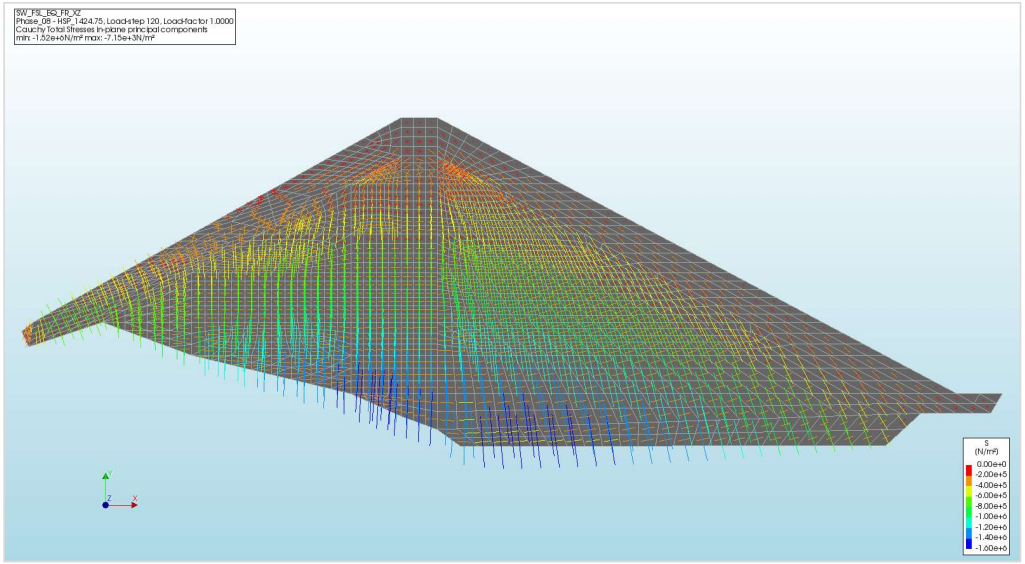
Vertical stresses



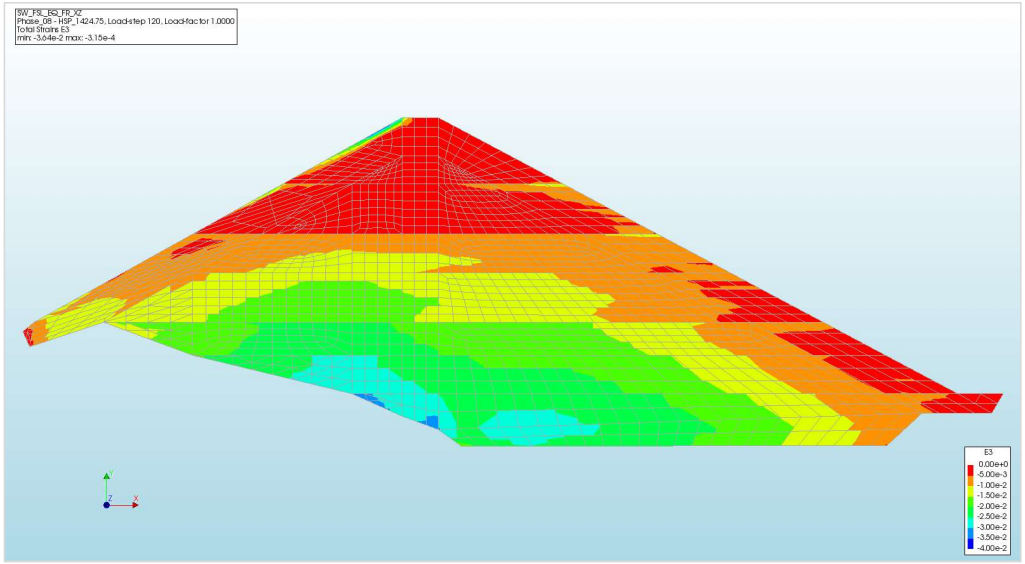
Results

- End of First Impoundment :

Principal stress trajectories



Total strains



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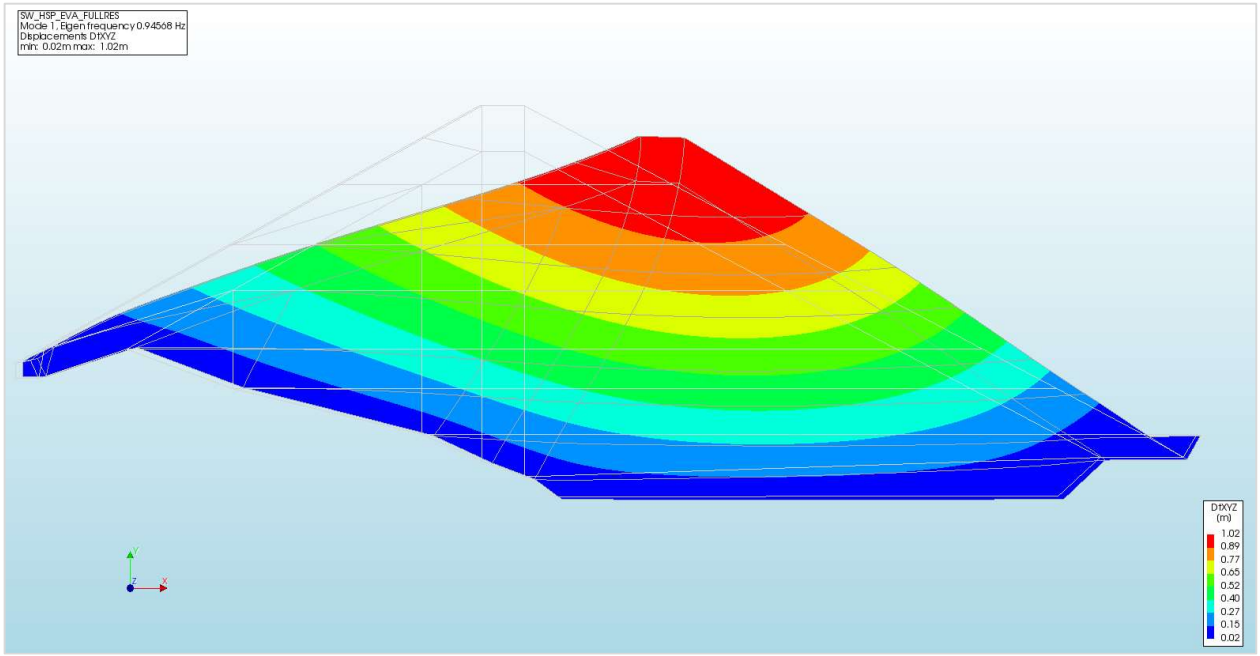
Results

- Eigenvalue analysis:

f1= 952 Hz (empty reservoir) *f1=0.945 (full reservoir)*

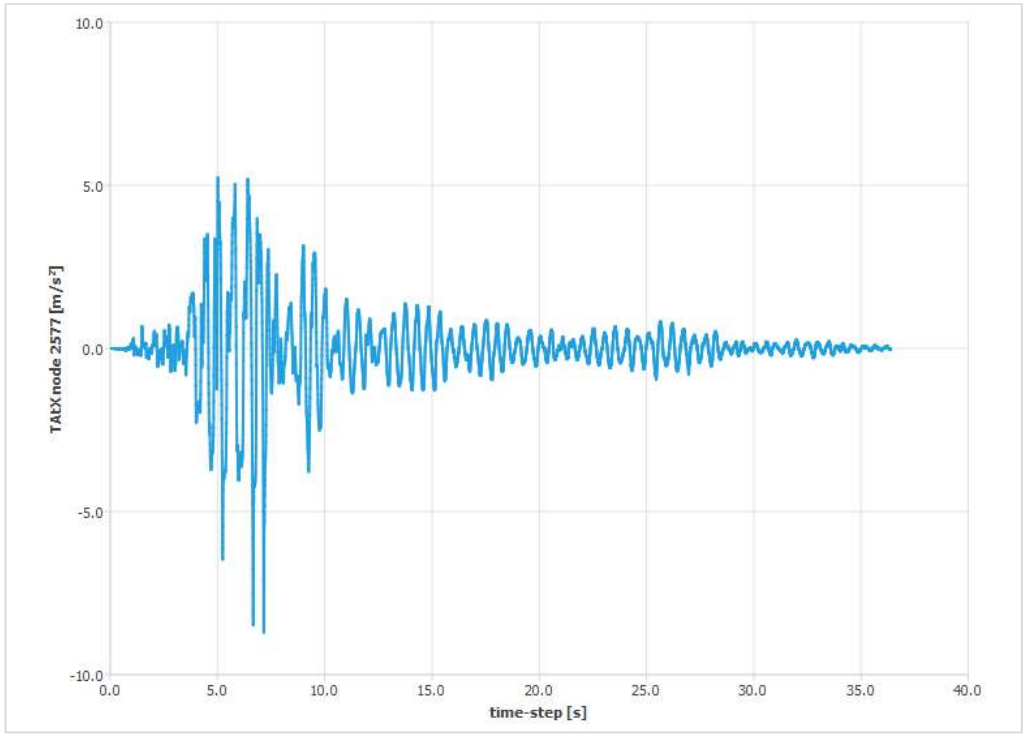


Results

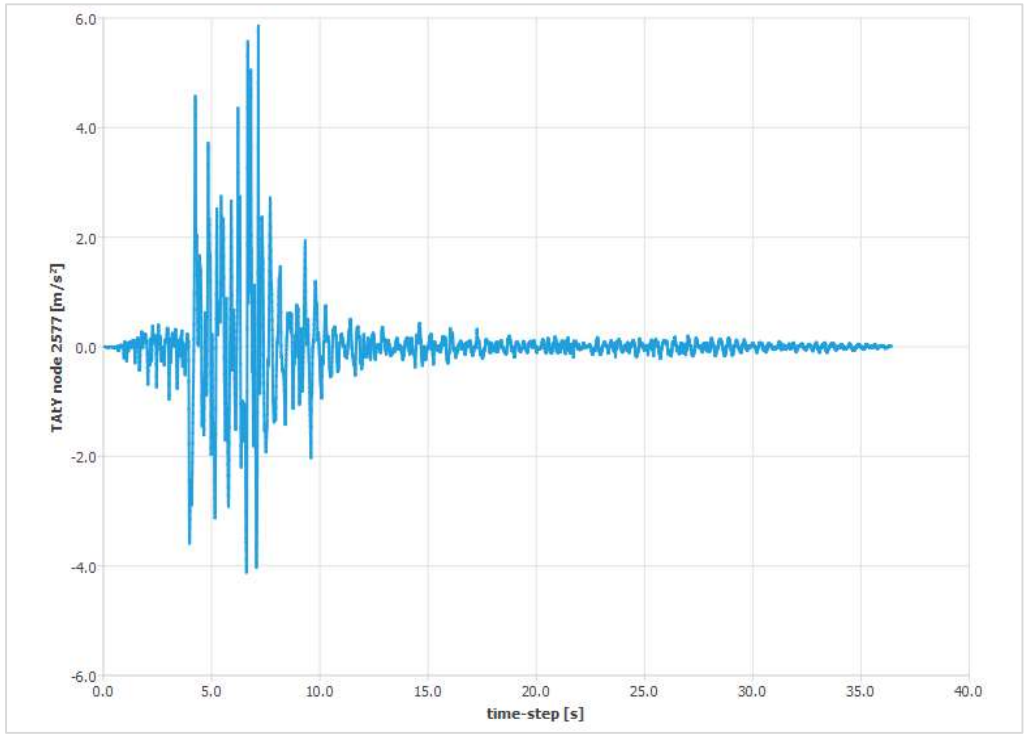
- Seismic analysis:

  The maximum structural response is obtained for Case 1 = **Friuli 1976 HNE + Friuli 1976 HNZ**

*Crest horizontal acceleration time history (**βmax=3.41**)*



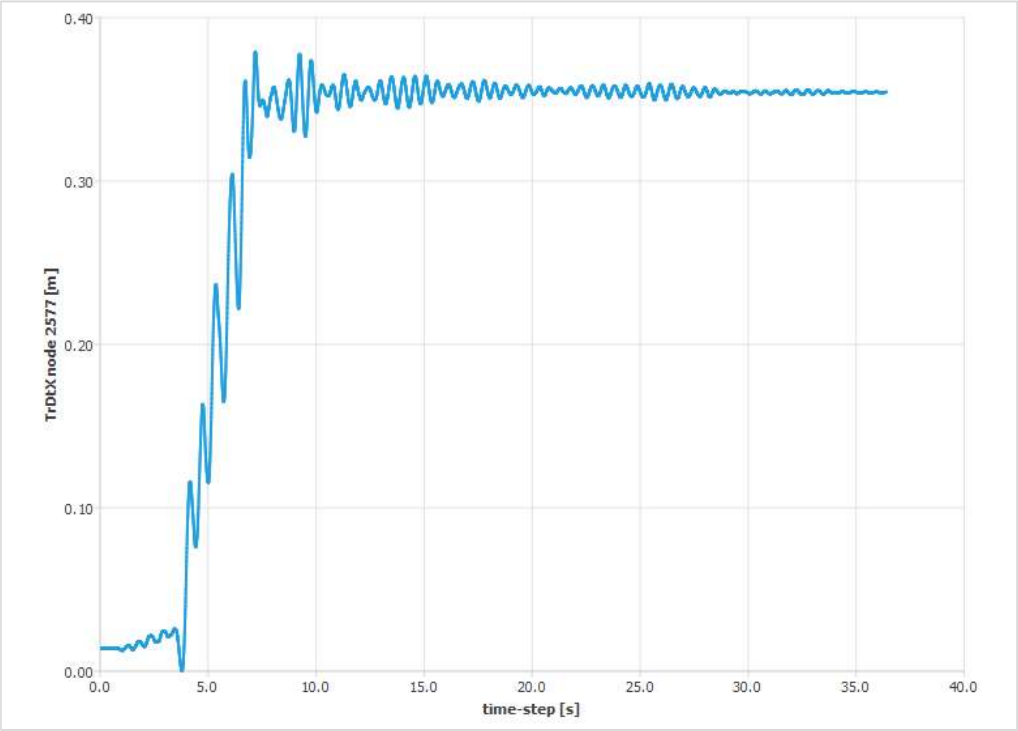
*Crest vertical acceleration time history (**βmax =2.88**)*



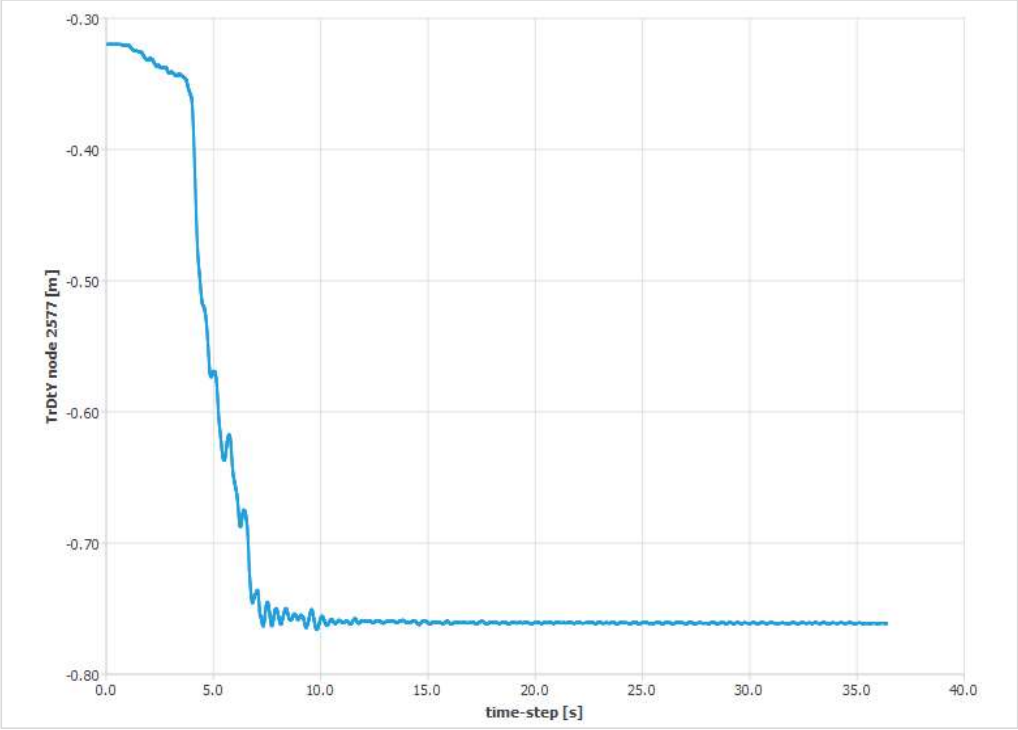
Results

➢ Seismic analysis:

Crest horizontal displacement time history ***(max 0.35 m)***



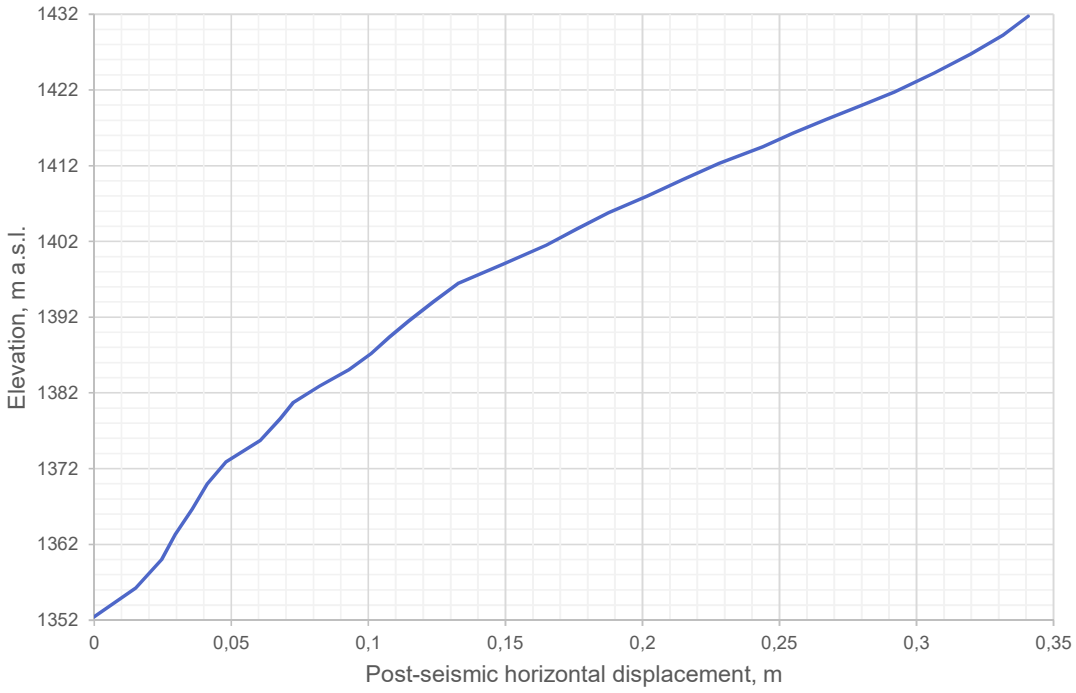
*Crest vertical displacement time history (****max 0.45 m****)*



Results

- Seismic analysis:

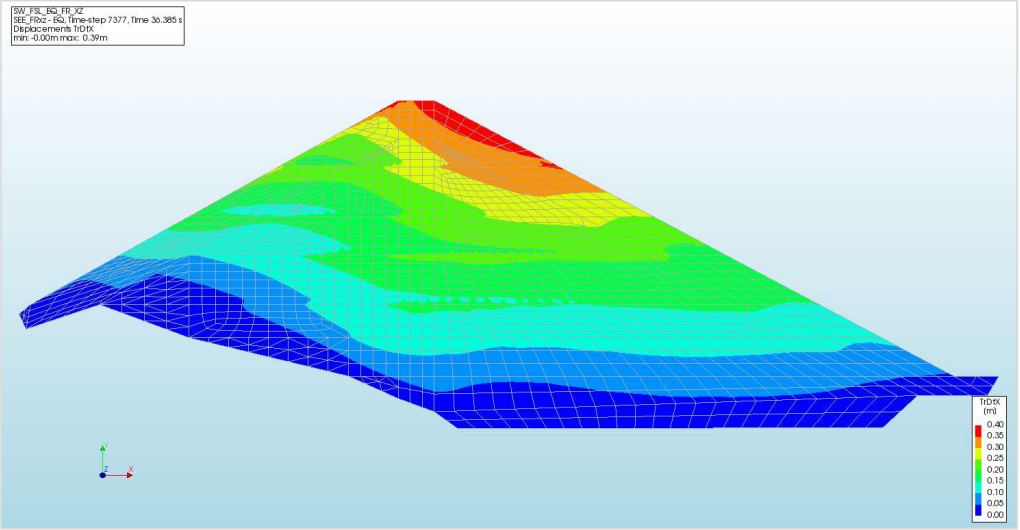
*Post-seismic horizontal displacement at dam axis (**max = 0.34 m** at crest)*



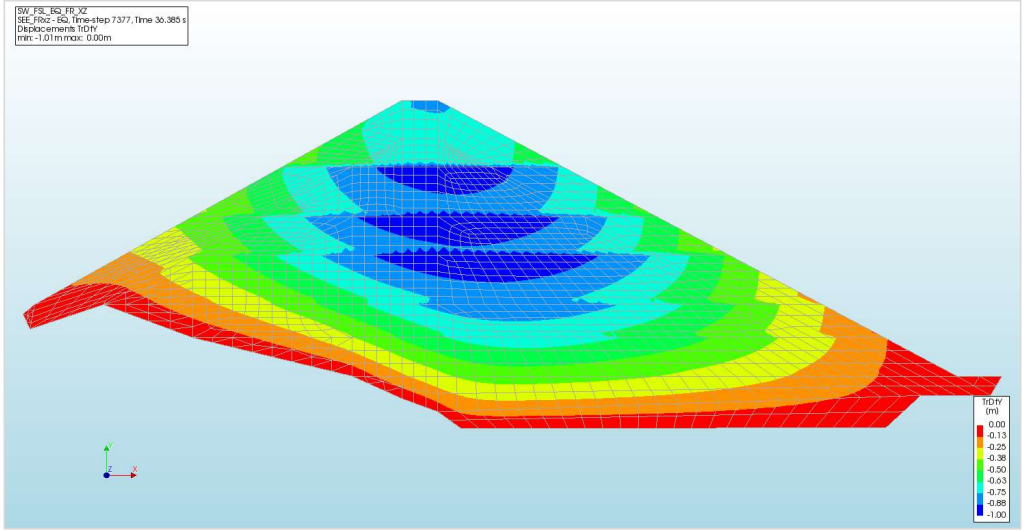
Results

- Seismic analysis:

Permanent total horizontal displacements



Permanent total vertical displacements

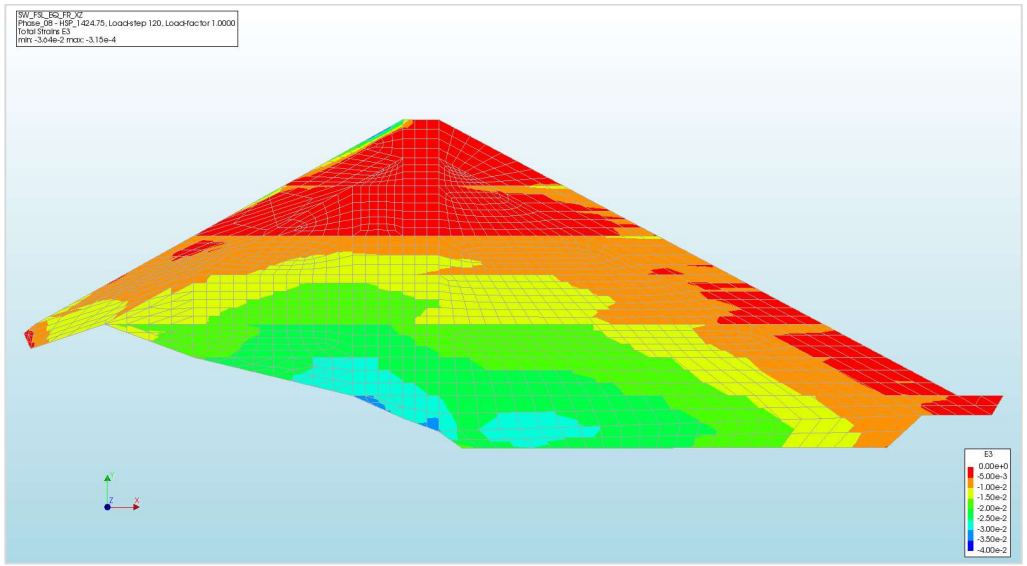


Results

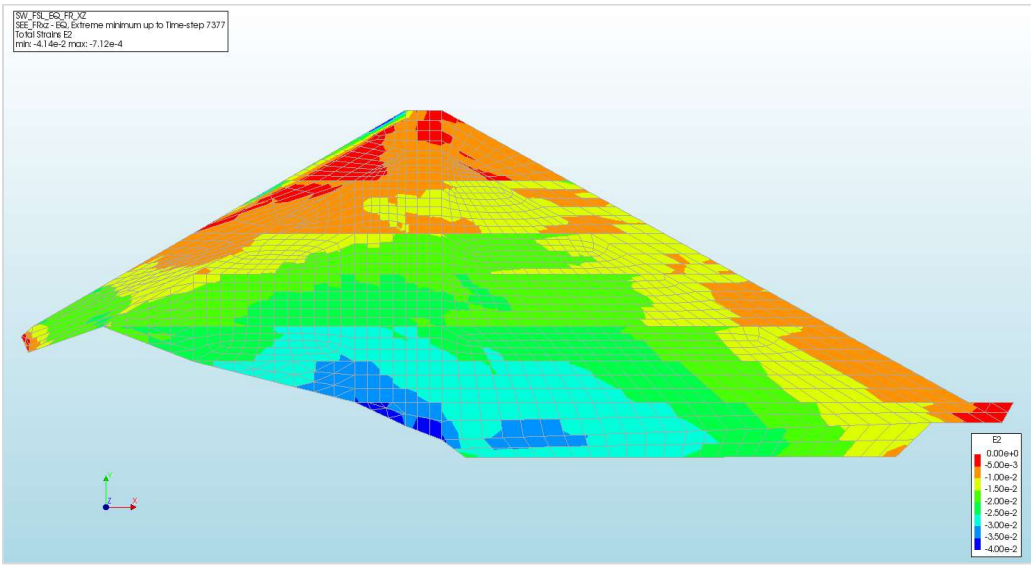
- Seismic analysis:

  Increase of the static strains by 0.05

  End of impounding total strains (max 0.030)



  *End of ground motion total strains (**max 0.035**)*



General comments and final remarks

- Construction phase: maximum settlement of 0.73 m; maximum strains in the embankment of 0.03
- First impoundment: no significant increase of the structural response. Pronounced rotation of the stress trajectories in the whole upstream part of the embankment
- Eigenvalue analysis: the reservoir does not influence significantly the eigenfrequencies
- Seismic response
  - maximum for **Friuli 1976 HNE + Friuli 1976 HNZ**
  - Moderate additional permanent displacements and strains
  - Additional settlements: well within the freeboard of the dam
  - No unstable wedges in the embankment
  - Moderate strains in the bituminous face

General comments and final remarks

- Constitutive model of the embankment material:
  - Use of full elasto-plastic for the rockfill material is recommended.
  - Incorporating plasticity allows for considering realistic stiffness and dissipation within a nonlinear seismic analysis performed in the time-domain.
  - The effects due to the failure envelope being curved in direction of the hydrostatic axis should be considered for rockfill material.
  - Ideally, a constitutive model having such curved failure envelope implemented is to be used.
  - An acceptable approximation: introducing a friction angle in function of the pressure level.
- It is recommended to consider the difference in the grain-size distribution of laboratory tests material and the construction material when defining the shear strength.