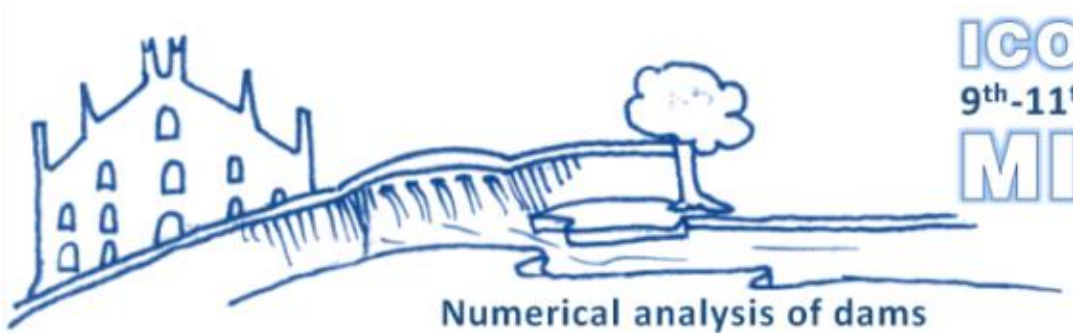

ICOLD-BW 2019
9th-11th September
MILANO

CIGB ICOLD

10th September 2019

Theme B:
Seismic analyses of Menta Embankment dam

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Performed analyses - (1) Methodological approach

MAIN GOALS OF THE NUMERICAL ANALYSES:

LOOK OVER THE DAM BEHAVIOUR, MAKING REFERENCE TO:

- **DAM STATIC BEHAVIOUR**

→ Verify that the amount of **displacements caused by reservoir impounding is neglegible** (as demonstrated by site monitoring activity)

- **DAM DYNAMIC BEHAVIOUR**

→ Inspect the **dam seismic behaviour** (displacements, amplification, possible damage) focusing on the standard input provided by the Contributors:

  - Without scaling (**PHA=0.26g, Tr=475yrs**);
  - After scaling to CLS as per Italian Regulation (**PHA=0.454g, Tr=1950yrs**; NTC 2018, NTD 2014)

→ Effect of the **vertical component of shaking**;

- **BITUMINOUS FACING**: Inspect the **dynamic behaviour of the Bituminous Facing**:
  - Possible damaging
  - Possible effect on the overall dam behaviour, the role of the temperature T / stiffness E*

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Performed analyses - (2) Numerical code and Assumptions

- NUMERICAL CODE: **FLAC 2D v.7.0** (Itasca), based on the Finite Differences Method
- TYPE OF NUMERICAL ANALYSIS: **Dynamic analysis in the time domain**, based on the earthquake time histories provided by the formulators (Friuli 1976, Central Italy 2016)
- MAIN ASSUPTIONS:
  - **Seepage is neglected** (because of the impervious facing and bedrock);
  - As a consequence, the reservoir is modeled by means of a hydrostatic **distributed load**;
  - **Homogeneous rockfill** material;
  - The Bituminous Facing is modeled by means of a **liner**;
  - Model bottom face = **compliant base.**

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Performed analyses - (3) Summary of Dynamic Analyses

n.12 dynamic analyses were carried out:

RUN N.	INPUT TIME HYST.	Tr (yrs)	Ref. Temperature (°C)	MAIN GOALS	
1	Friuli 1976 - HNN	475	13	Dam dynamic behaviour; bit. facing behaviour & damage	DAM
2	Friuli 1976 - HNE	475	13		
3	C.Italy 2016 - HGN	475	13		
4	C.Italy 2016 - HGE	475	13		
5	Friuli 1976 - HNN+NHZ	475	13		
6	Friuli 1976 - HNE+NHZ	475	13		
7	C.Italy 2016 - HGN+NGZ	475	13		
8	C.Italy 2016 - HGE+NGZ	475	13		
9	Friuli 1976 - HNE+NHZ	475	1	Bit. facing behaviour & damage; effect on overall dam behaviour	FACING
10	Friuli 1976 - HNE+NHZ	475	26		
11	Friuli 1976 - HNE+NHZ	1950	1	Dam dynamic behaviour; Bit. facing behaviour & damage; effect on overall dam behaviour	C.L.S.
12	Friuli 1976 - HNE+NHZ	1950	26		

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Rockfill Constitutive model (1)

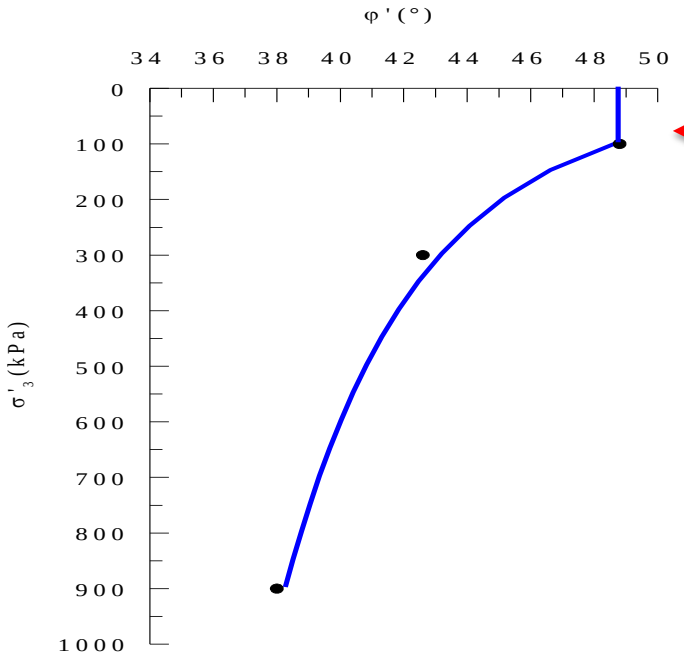
ROCKFILL (Homogenous) = elasto-plastic material
Constitutive Parameters calibrated on the basis of the available data

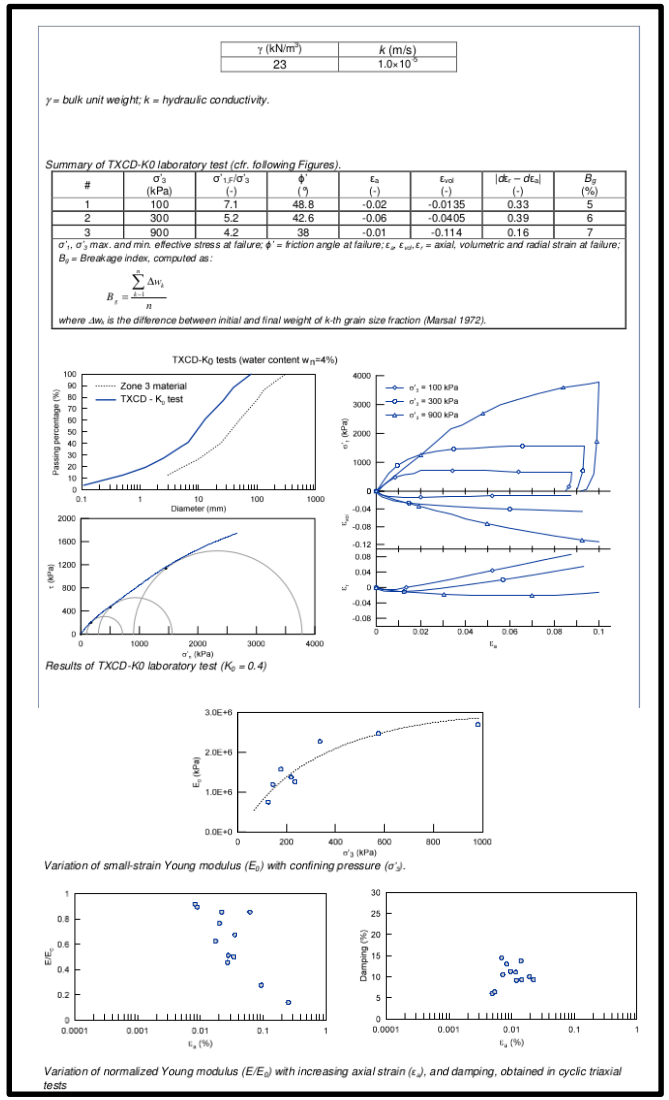
Mohr Coulomb failure criterion
(non associated flow rule, ψ=0)

Friction angle φ' assumed
to vary with minor principal stress

$$\varphi' = \varphi'_0 \cdot (\sigma'_3 / p_{REF})^{-n}$$

[φ'_0 = 48.8°, n=0.11, p_{REF} =100kPa]

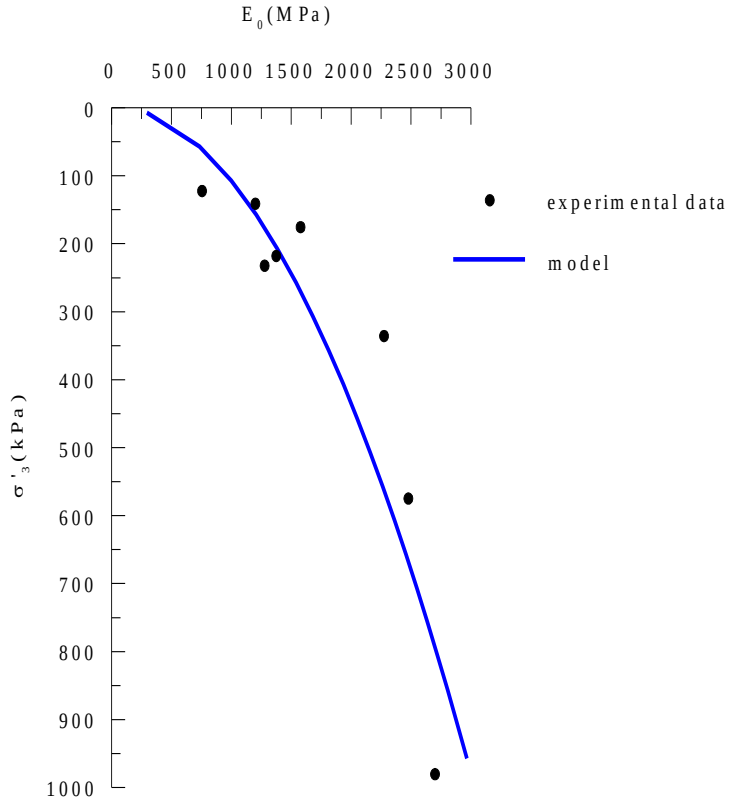




Small-strain Young Modulus

$$E_0 = 2\,(1+\nu) \cdot S \cdot p_{REF} \cdot (\sigma'_3 / p_{REF})^{\alpha}$$

[ν = 0.25, S = 3840, α = 0.50, p_{REF} =100kPa]



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Rockfill Constitutive model (2)

ROCKFILL (Homogenous) = elasto-plastic material
Constitutive Parameters calibrated on the basis of the available data

γ (kN/m³)	k (m/s)
23	1.0×10^{-5}

γ = bulk unit weight; k = hydraulic conductivity.

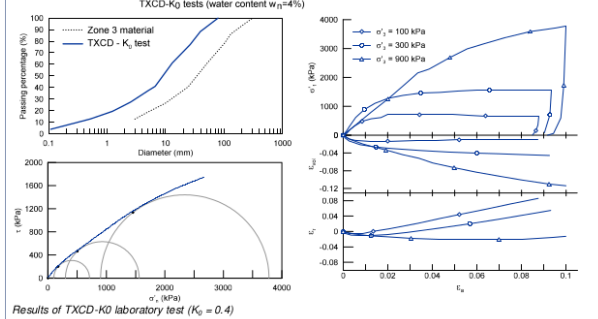
Summary of TXCD-K0 laboratory test (cfr. following Figures).

#	σ'_3 (kPa)	$\sigma'_{1,f}/\sigma'_3$ (-)	ϕ' (°)	ε_a (-)	ε_{vol} (-)	$\lvert d\varepsilon_r - d\varepsilon_a \rvert$ (-)	B_g (%)
1	100	7.1	48.8	-0.02	-0.0135	0.33	5
2	300	5.2	42.6	-0.06	-0.0405	0.39	6
3	900	4.2	38	-0.01	-0.114	0.16	7

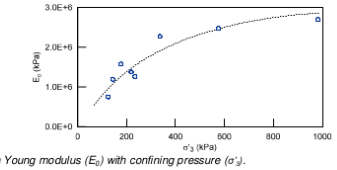
σ'_1, σ'_3 max. and min. effective stress at failure; ϕ' = friction angle at failure; ε_a, ε_{vol}, ε_r = axial, volumetric and radial strain at failure; B_g = Breakage index, computed as:

$$B_g = \frac{\sum_{i=1}^{n} \Delta w_i}{n}$$

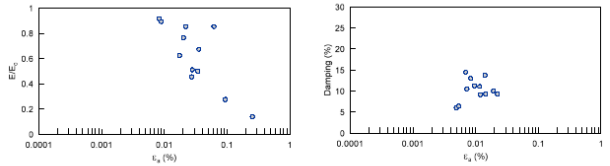
where Δw_i is the difference between initial and final weight of k-th grain size fraction (Marsal 1972).



Results of TXCD-K0 laboratory test ($K_0 = 0.4$)



Variation of small-strain Young modulus (E_0) with confining pressure (σ'_3).

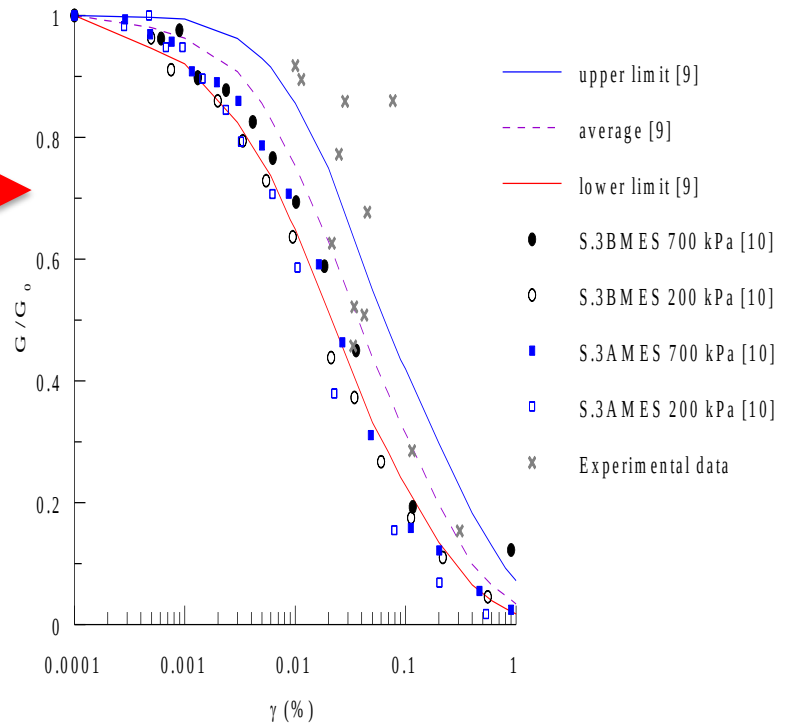


Variation of normalized Young modulus (E/E_0) with increasing axial strain (ε_a), and damping, obtained in cyclic triaxial tests

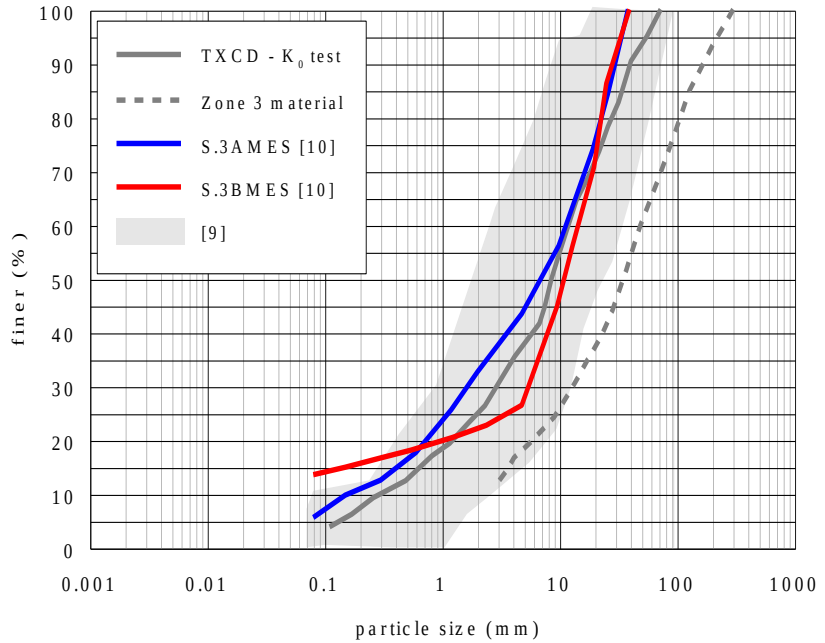
Non linear & dissipative rockfill behaviour:
FLAC Sigmoidal-3 hysteretic model

$$MS = G/G0 = \frac{a}{1 + exp\left[\frac{-(log\gamma - x0)}{b}\right]}$$

[a = 1.00, x0 = -1.7186, b = 0.5062]



SIGMOIDAL-3 parameters calibrated in order to fit the **lower bound curve (red) by Rollins et al. (1998)** → fair approximation of literature data obtained on rockfill material with grain size curve very similar to specimens tested in available TXCD data (allows for **conservative stiffness evaluation**)



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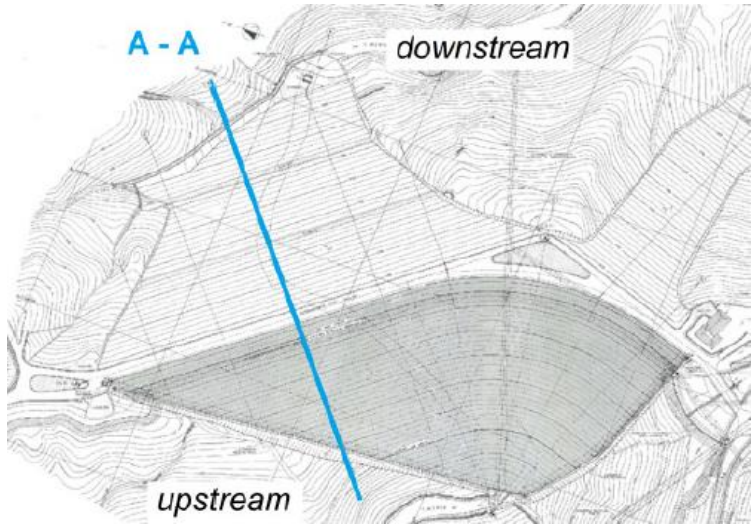
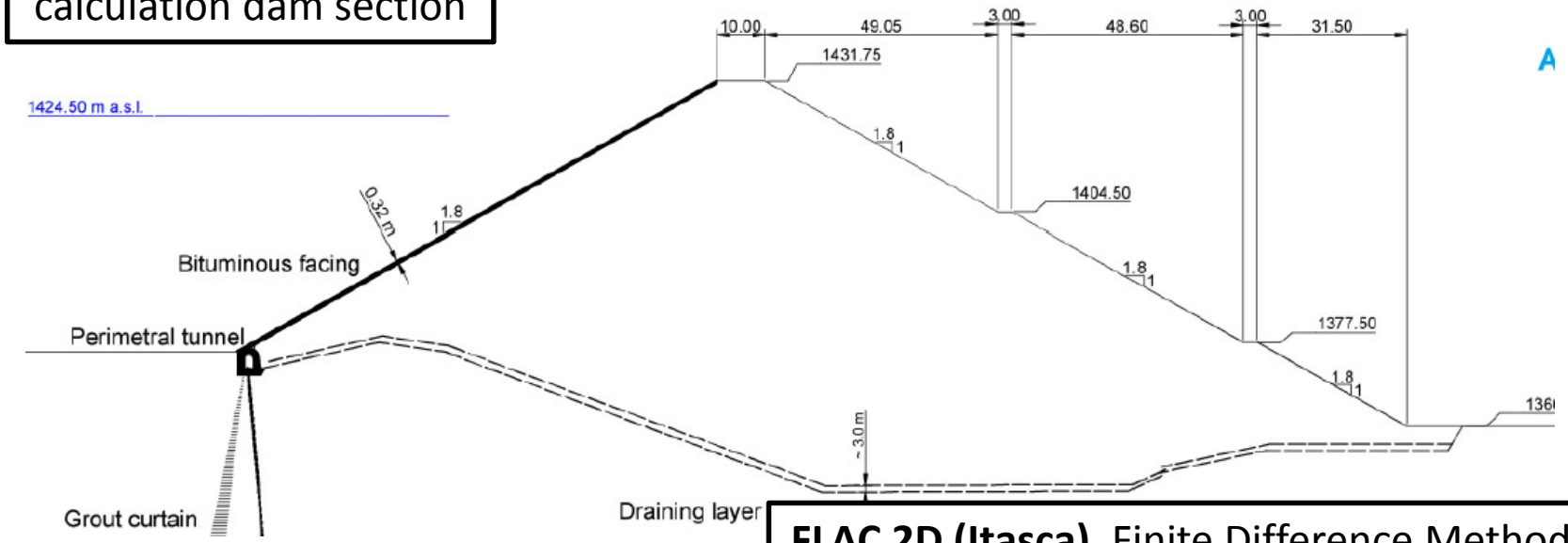
Numerical model



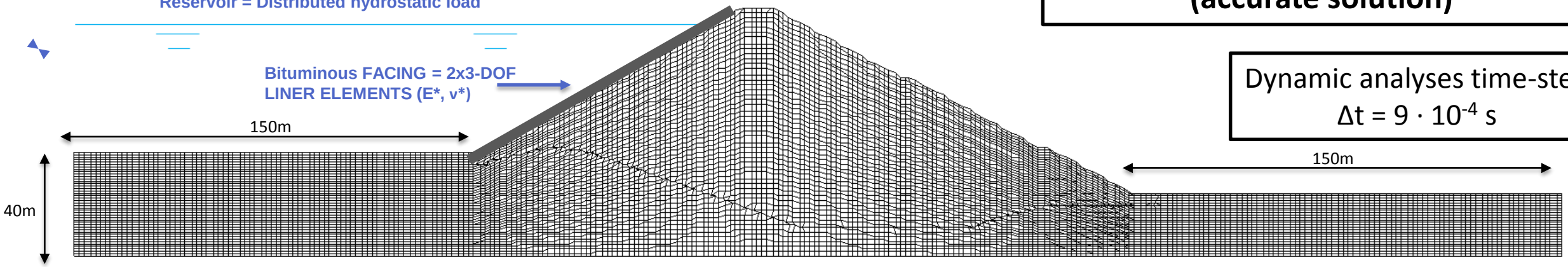
Available common input calculation dam section



FLAC 2D (Itasca), Finite Difference Method
DAM + BEDROCK = **13400 zones**
(accurate solution)

SEEPAGE disregarded (Facing + Bedrock)
Reservoir = Distributed hydrostatic load

Bituminous FACING = 2x3-DOF LINER ELEMENTS (E*, ν*)



Dynamic analyses time-step
$\Delta t = 9 \cdot 10^{-4}$ s

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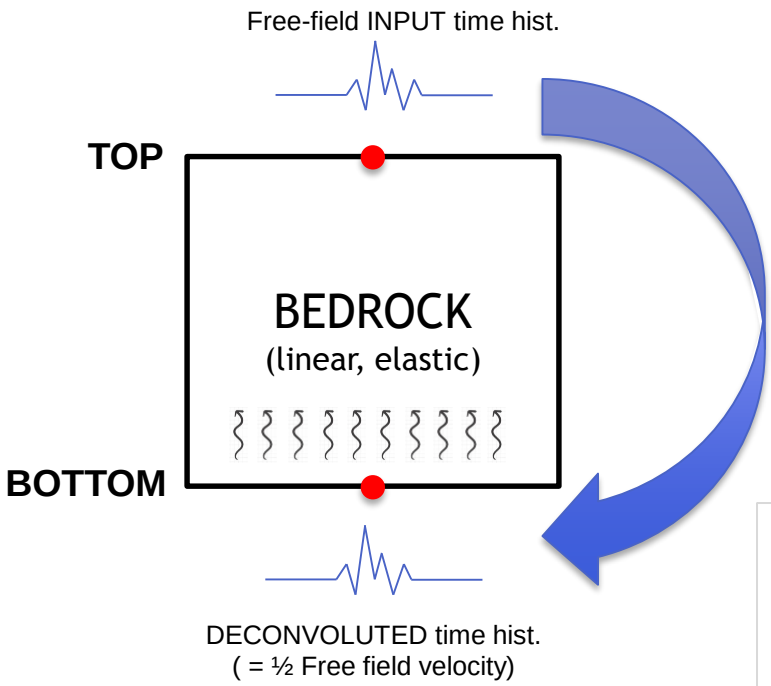
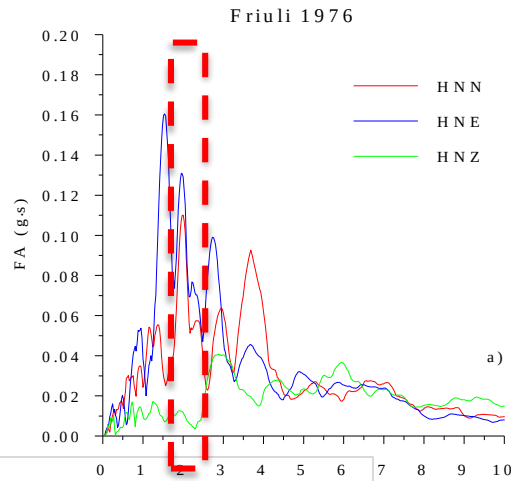
Seismic input (1)

DECONVOLUTION
of the provided input time histories



SCALING
to Collapse Limit State

HNE (Friuli76) = **Most severe** earthquake record in the range of frequencies near to the first natural frequency of the dam

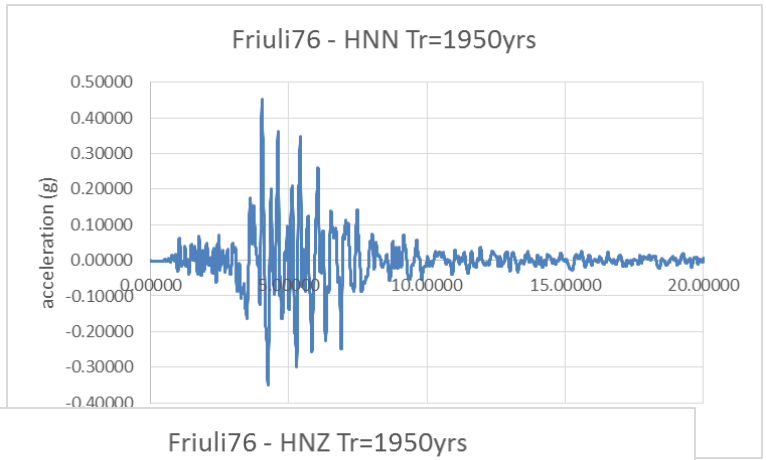


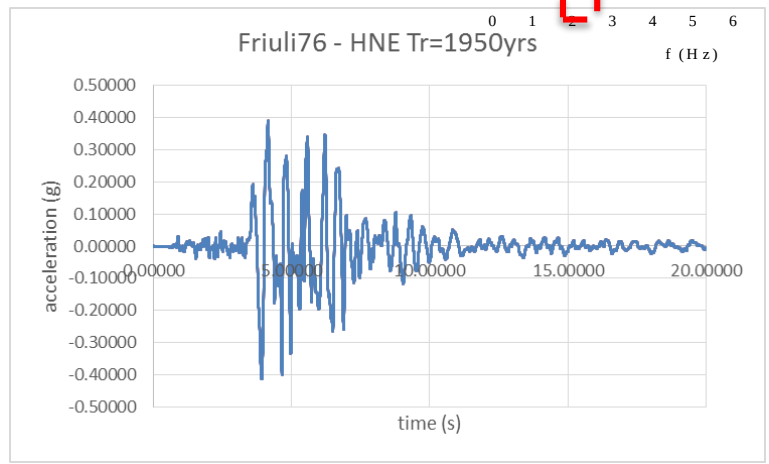
MENTA DAM SITE: values of ag as per Italian Regulation (NTC2018, NTD2014)

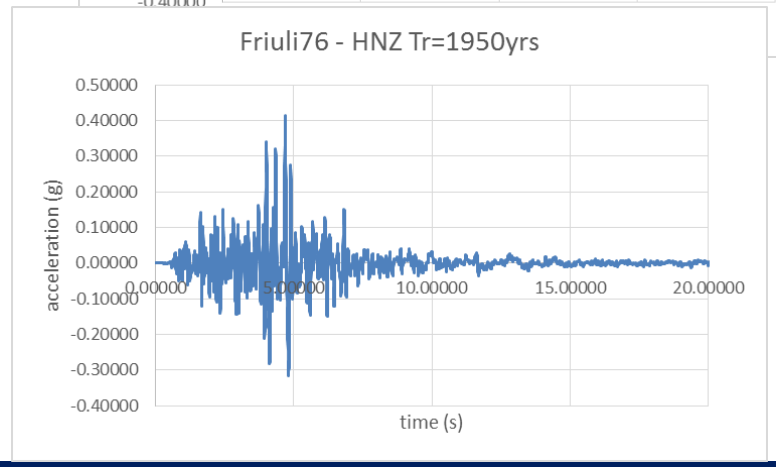
T_R (yrs)	a_g (g)
30	0.065
101	0.127
475	0.262
2475	0.496

Provided INPUT

Limit State	T_R (yrs)	a_g (g)
SLO	60	0.097
SLD	101	0.127
SLV	949	0.347
SLC	1950	0.454







HNE/HNN/HNZ = Friuli 1976 EQK – Tolmezzo Station, May 06th 1976 h.20.00.12s

- Original record scaled by a factor **0.74** to fit Tr=475yrs;
- to be scaled by a factor **1.29 (H)** and **1.51 (V)** to fit Tr=1950yrs;
- scaling factor < 2, fully acceptable

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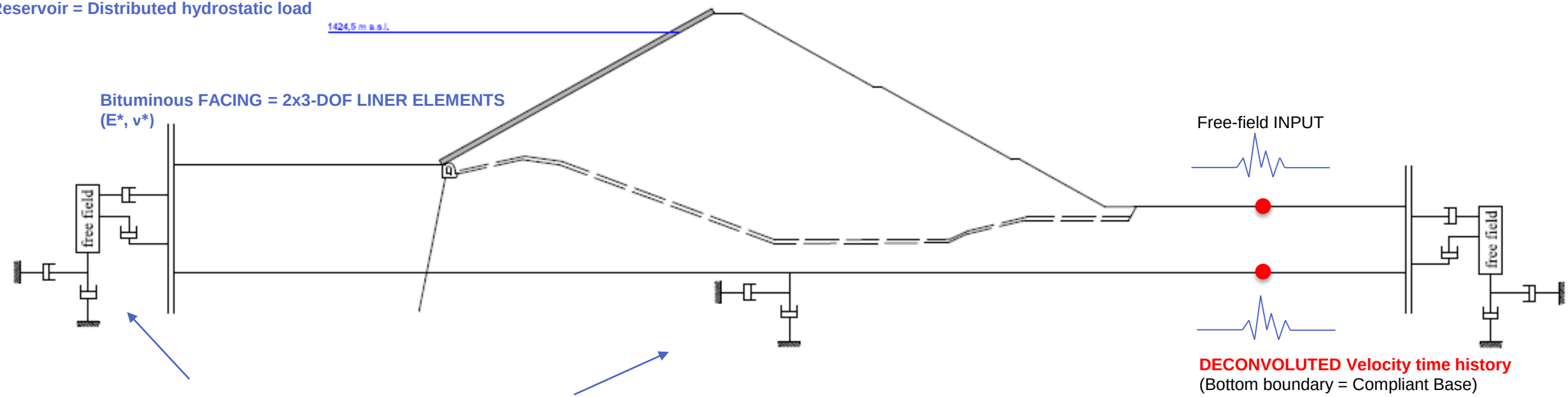
Seismic input (2)

BOUNDARY CONDITIONS

FLAC: velocity wave → stress wave
$\sigma n = 2 \cdot (\rho\ Cp\ ) \cdot vn$ (normal)
$\sigma s = 2 \cdot (\rho\ Cs\ ) \cdot vs$ (shear)

SEEPAGE disregarded (Facing + Bedrock)
Reservoir = Distributed hydrostatic load



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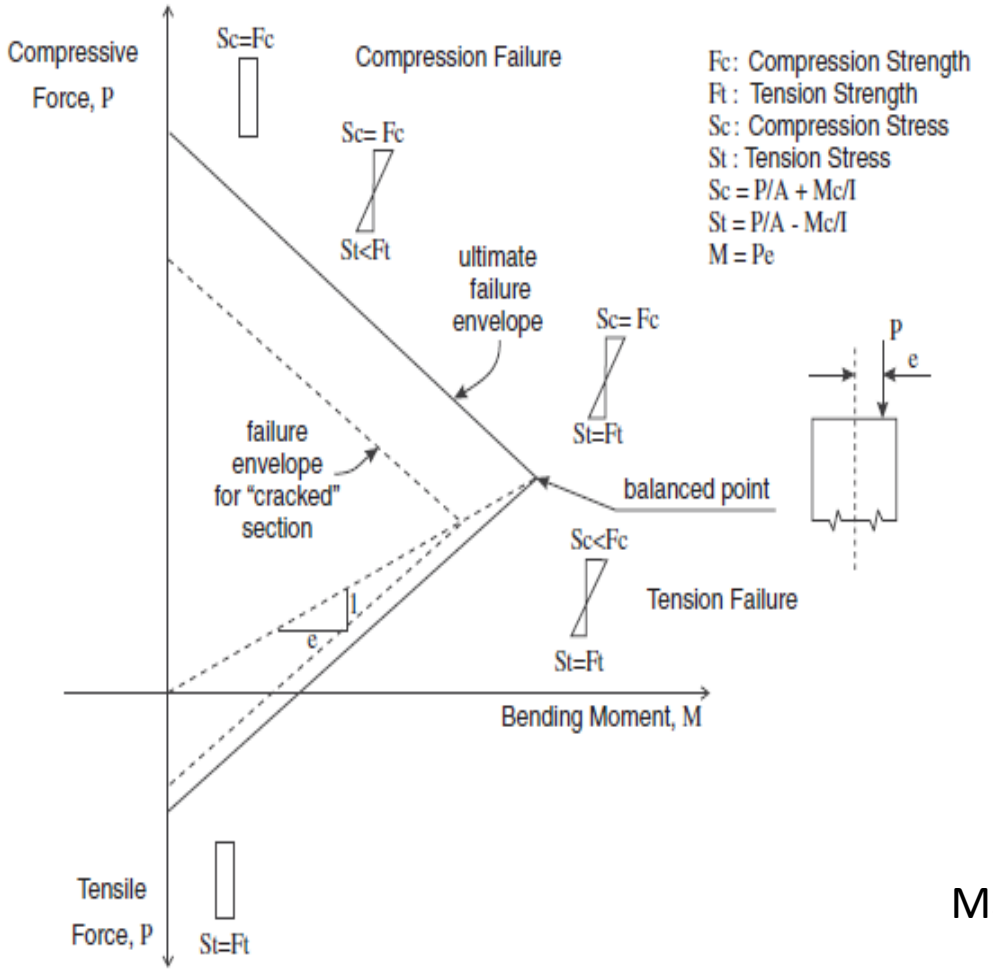
Model for the bituminous concrete facing



BITUMINOUS FACING modeled by means of 2x3-DOF liner elements,
elasto – plastic consitutive model

Characteristics of the bituminous concrete mixture (as single equivalent layer):

γ (kN/m^3)	*Temperature*	*E** (MPa)	ν * (-)	*k* (m/s)
24	1 °C	14	0.16	*Impervious*
	26 °C	2800	0.33	

γ = bulk unit weight; E = complex Young modulus; ν* = complex Poisson ratio; k = hydraulic conductivity.*

Strength characteristics of the bituminous facing, deduced from Marshall test results (sealing layer):

Compressive strength f_t (kPa)	Tensile strength f_t (kPa)
1490	950

Evaluation of Complex Young Modulus & Poisson Modulus at T=13°C:
(provisional model University of Mariland, AASTHO 2004)

$$E_{TS} = E \cdot 10^{\alpha \cdot (T^2 - T_S^2)} = 5770 \text{ MPa}$$

$$\upsilon * = 0.15 + \left[0.35 / \left(1 + e^{-7500 + 2291 \cdot log|E*|}\right)\right] = 0.24$$

Maximum axial load N is calculated as a function of the bending moment M

If **N(t) ≥ NMAX(t) → CRACKED SECTION → POSSIBLE DAMAGE**

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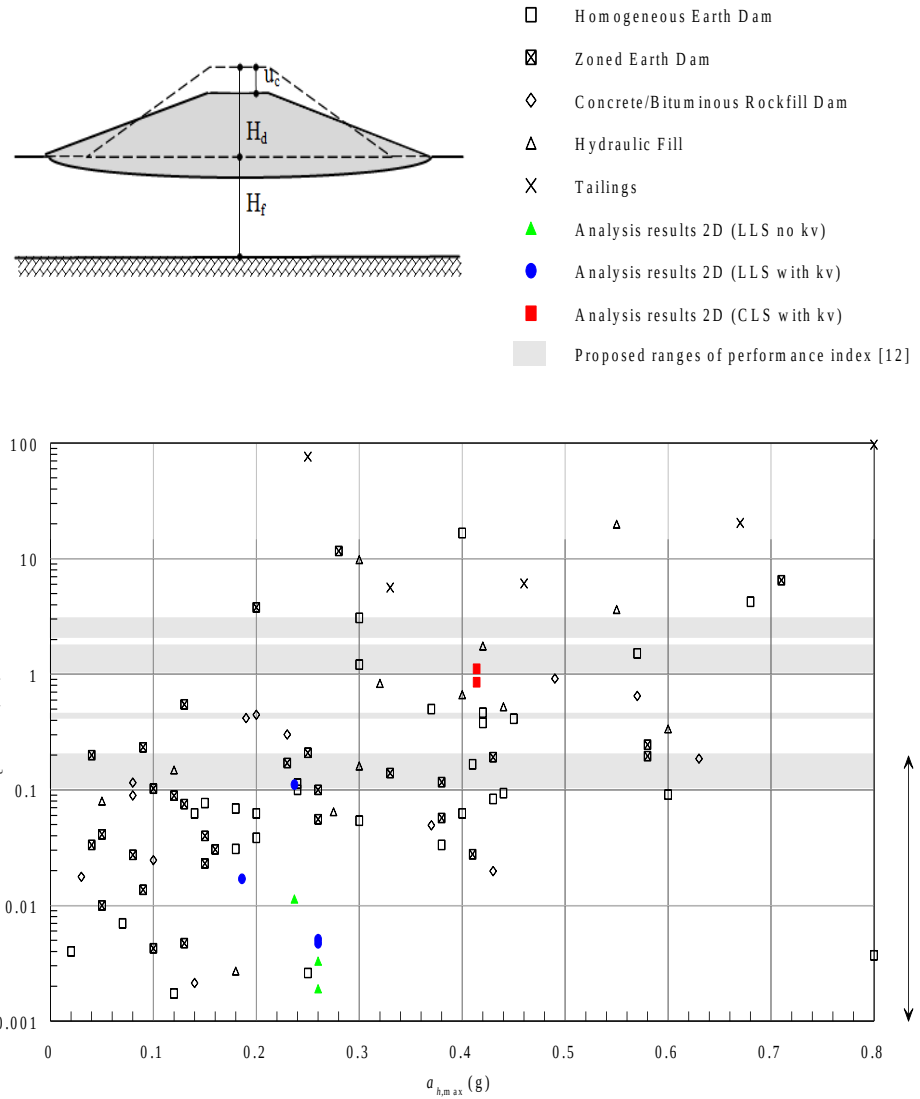
General comments and final remarks

KEY POINTS

- Friuli76 HNE causes the largest displacements (most severe part of Fourier spectrum in the range of the first natural frequency of the dam)
- Vertical component causes severe amplification of dam shaking in both directions
- Dam crest displacements generally negligible except for Friuli HNE
- CLS (Tr=1950yrs) analysis: displacements dramatically increased (6-10X)
- Dam crest settlement = reliable overall dam performance index → negligible / minor damage (Tr=475yrs); moderate / serious damage (Tr=1950yrs) [Aliberti *et al.* 2019]

OPEN QUESTIONS

- Bituminous facing constitutive model: accounts for possible damaging only, it does not allow to estimate cracks opening (equivalent permeability, possible water inflow)



[Aliberti *et al.* 2019]

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