Assessment of seismic performance and fragility of a CFRD: Workflow for Potrerillos dam in Mendoza (Argentina)

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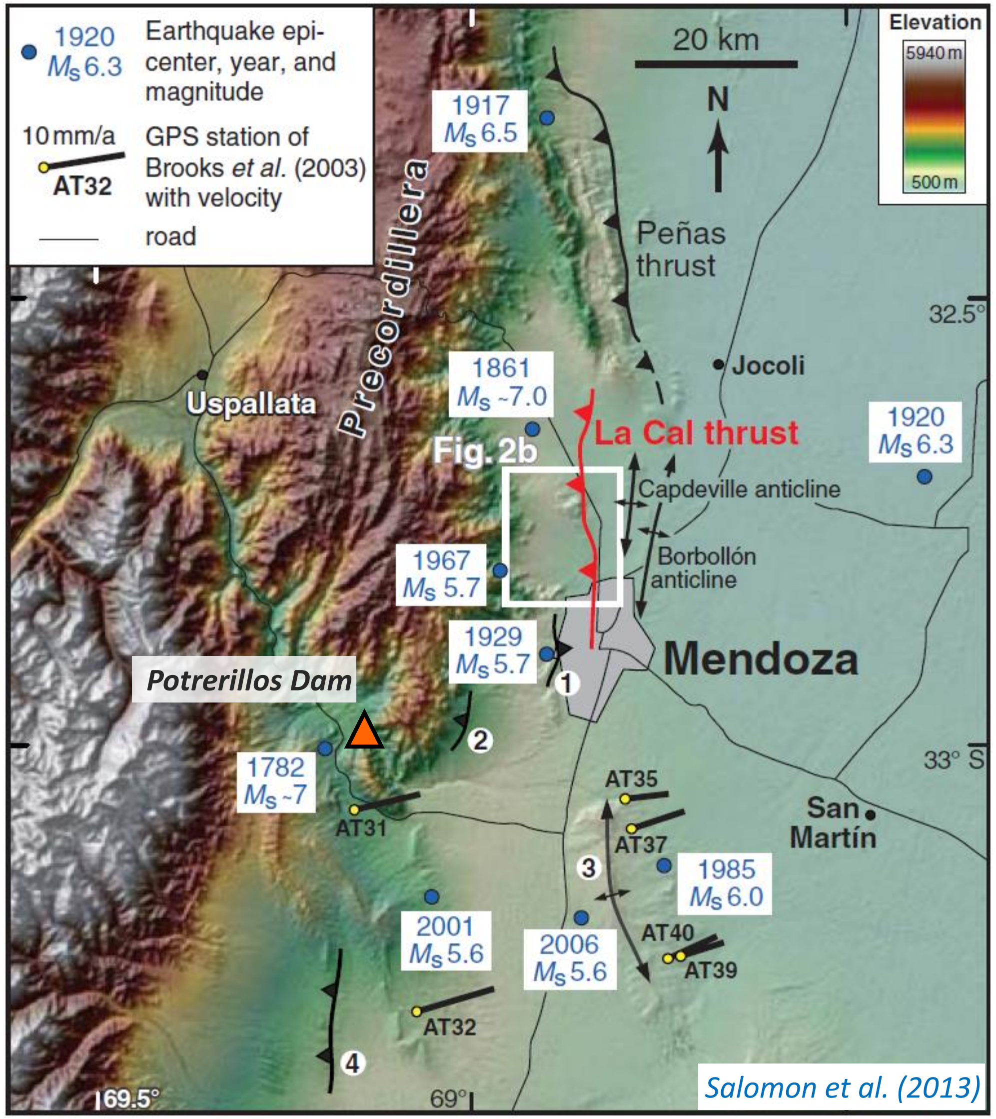
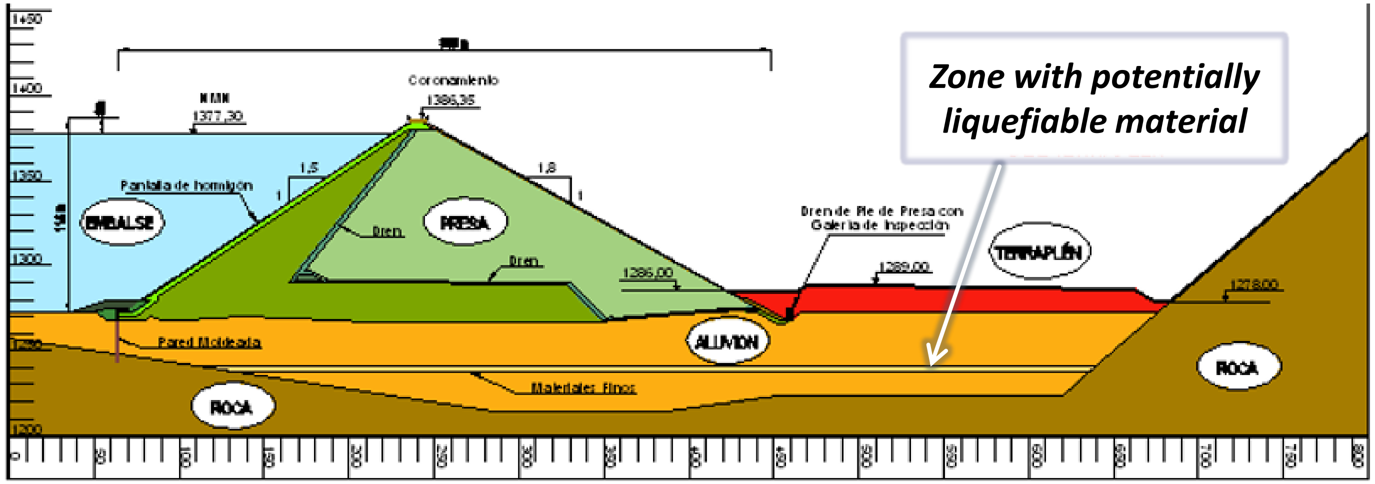
Potrerillos dam: location and main characteristics

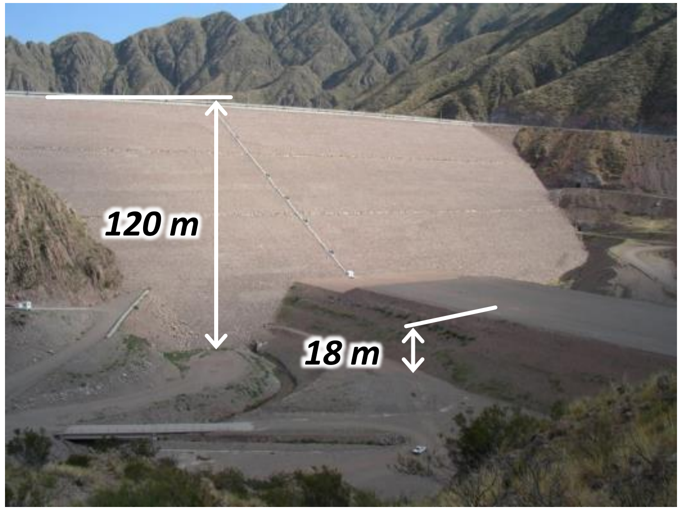
Largest earthquakes and main active structures in the vicinity



Sand and silty-sand lenses found in the alluvium during construction stage



Stabilizing embankment downstream the dam as a countermeasure

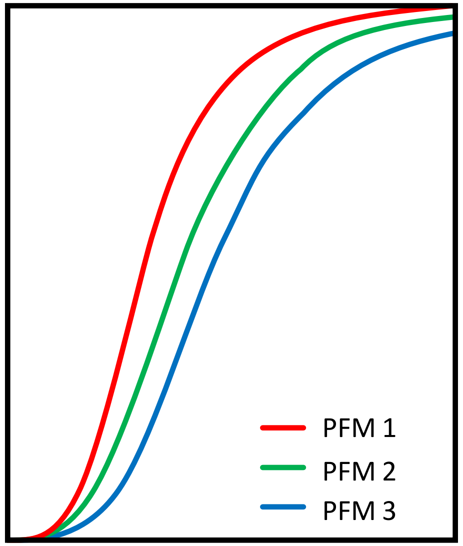


Archive Prof . A Barchiesi

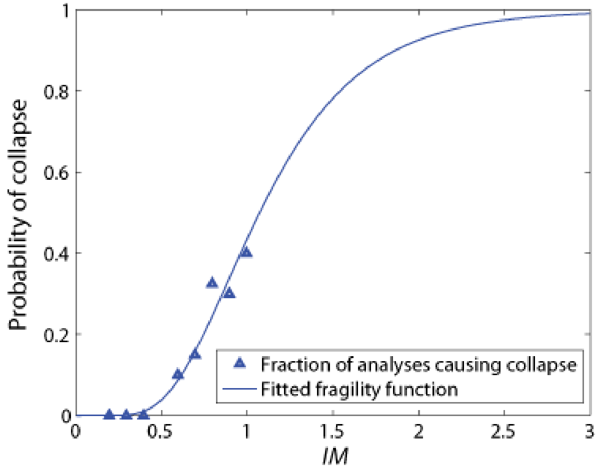
Development of dam-specific fragility functions: Main components

Site-specific seismic hazard analysis and record selection

Dam-specific Fragility Functions

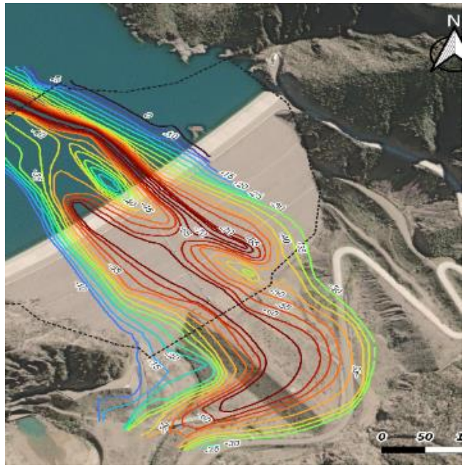


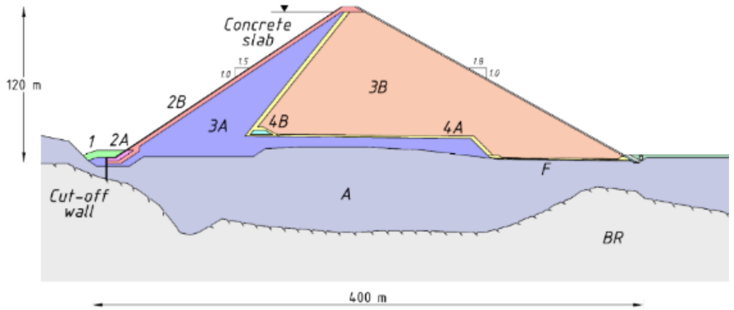
Fragility functions fitting



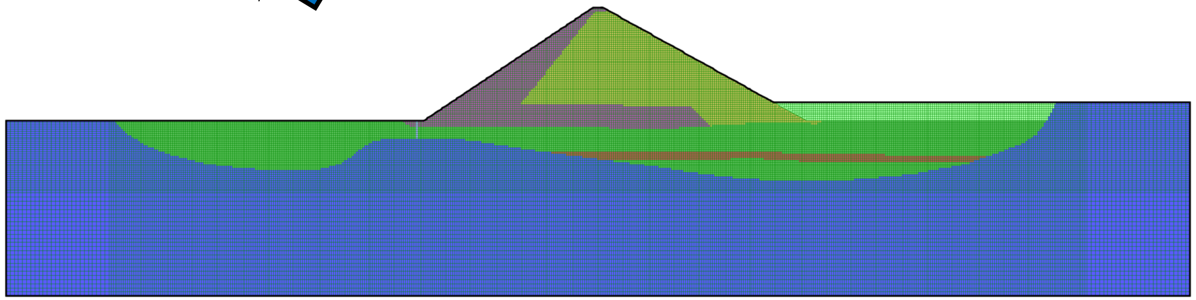
Baker (2015)

Geological-Geotechnical model





Advanced Numerical Model

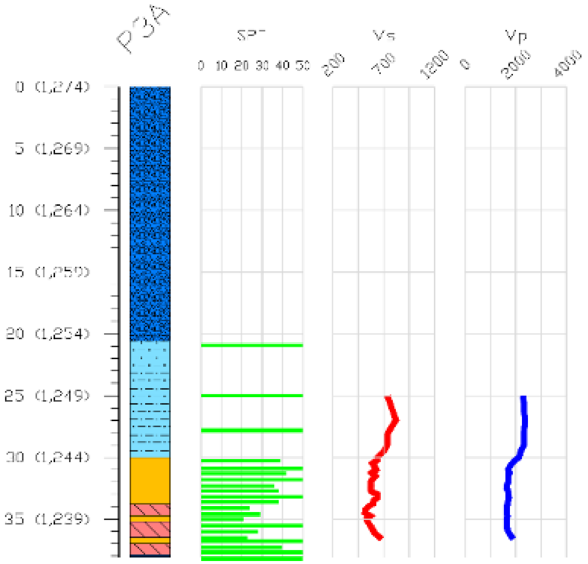


Workflow for building numerical models for seismic performance and fragility evaluation

Geometrical and geotechnical characterization

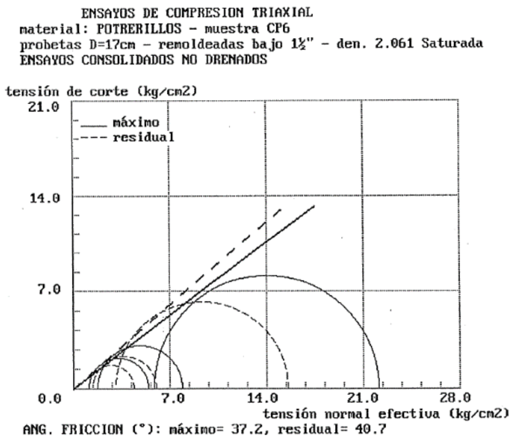
Field surveys and in-situ tests

Boreholes, SPT and Cross-hole

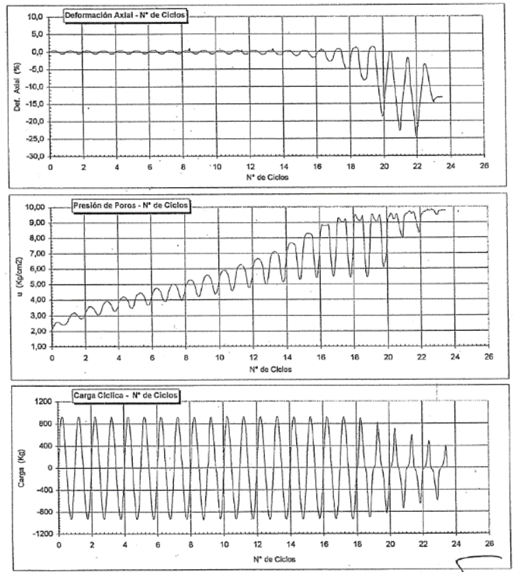


Laboratory tests

Static triaxial test – TX CU

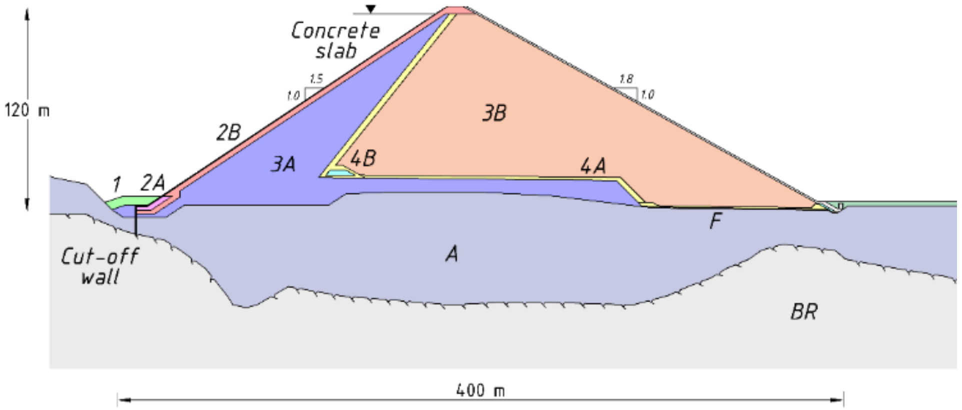


Cyclic triaxial test – CTX



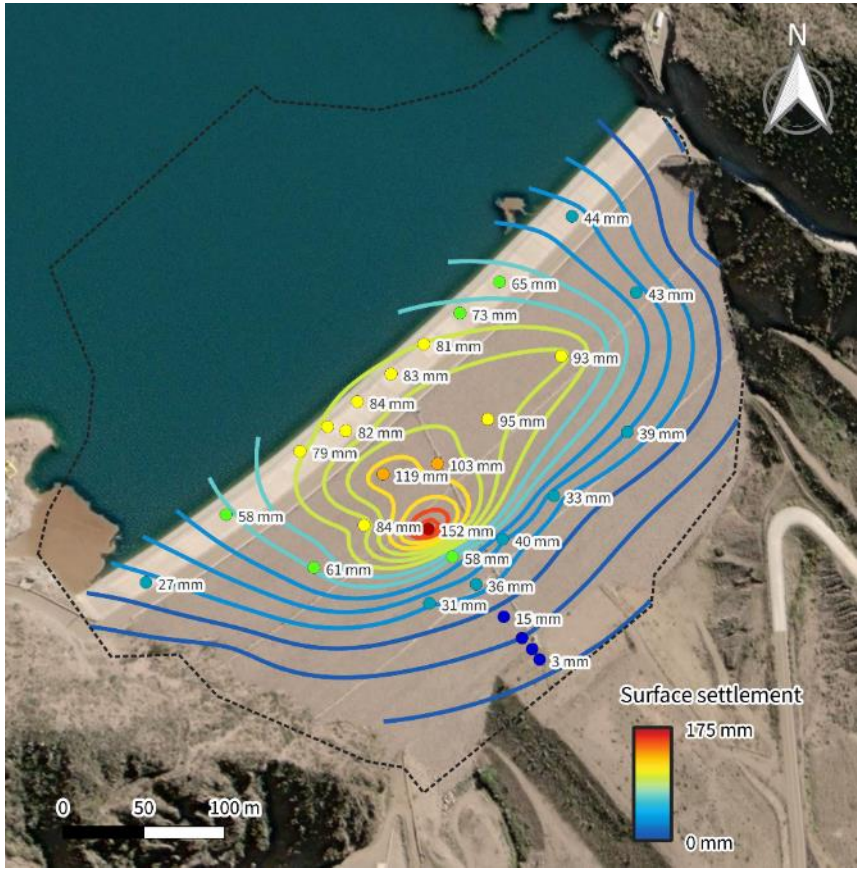
Real conditions at the dam site

Geometry and material zoning for analysis



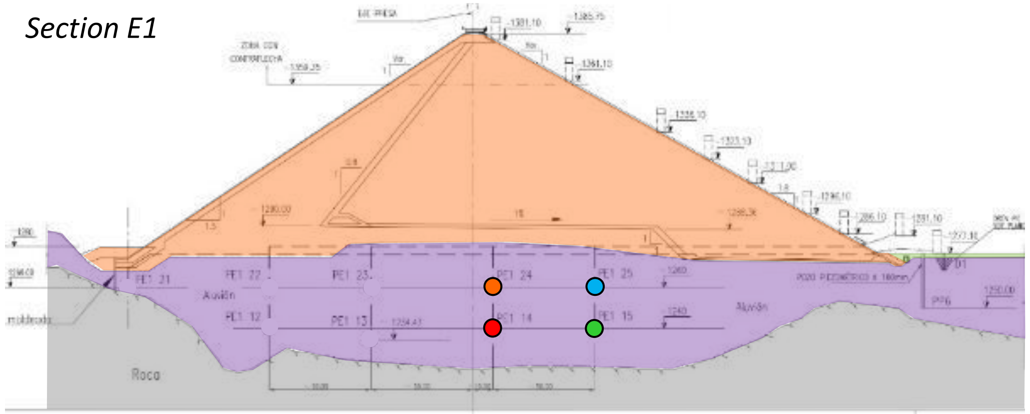
Geometrical and geotechnical characterization → History of loads and hydraulic conditions

Topographic survey of surface settlement

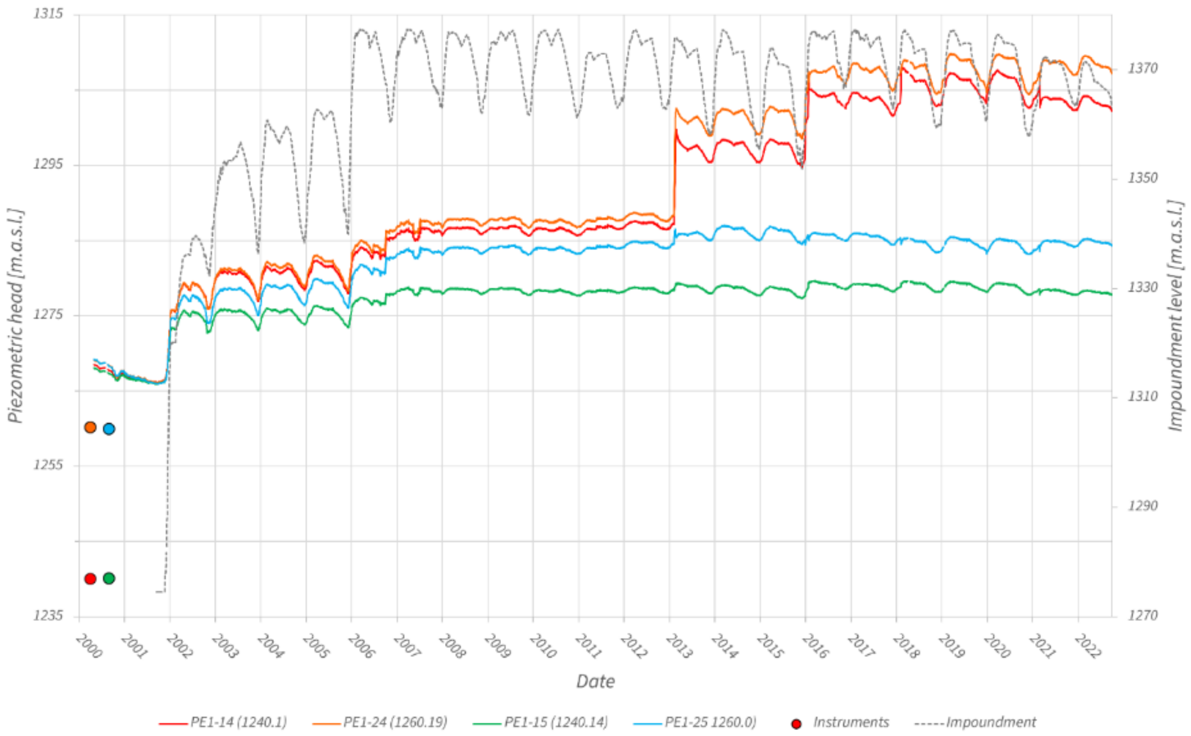


Analysis of pore water pressure records from piezometers

Section E1



PWP & impoundment level vs. time

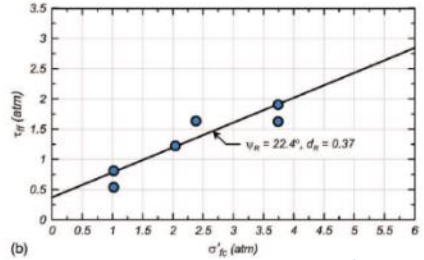


Workflow for building numerical models for seismic performance and fragility evaluation

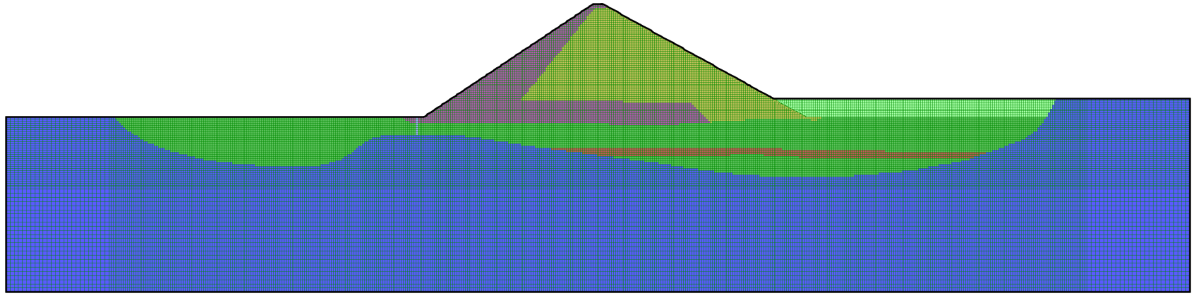
Geometrical and geotechnical characterization → History of loads and hydraulic conditions → Definition of the numerical models

Calibration

Calibration of material models using laboratory tests

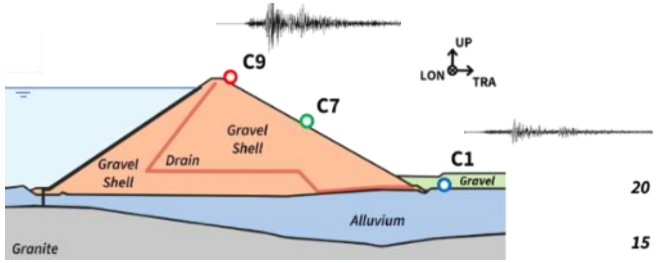


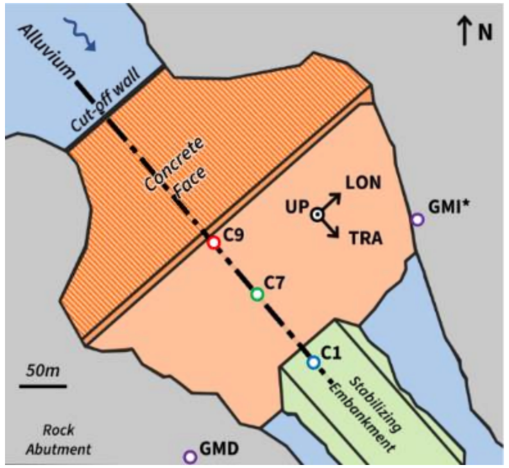
Boulanger (2019)



Finite Difference Model (FLAC 8.0)

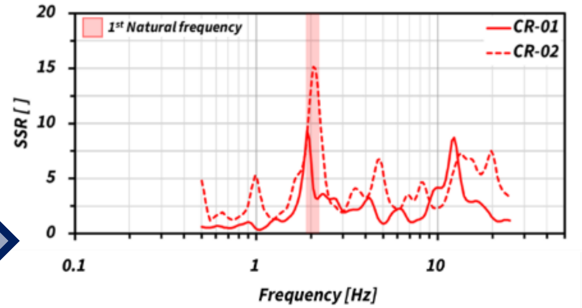
Calibration of global parameters

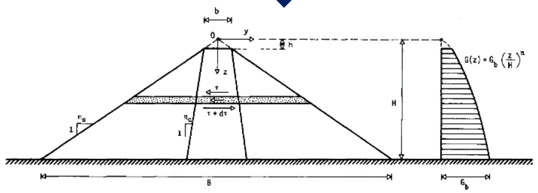




Barbagelata et al. (2024)

Natural frequencies

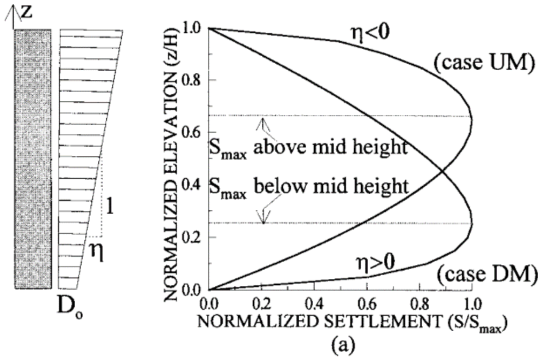




Dakoulas & Gazetas (1985)

- *Selection of 2D sections*
- *Definition of soil regions*
- *Discretization*
- *Boundary conditions*
  - *Mechanical*
  - *Hydraulic*

Vertical stiffness by back-analysis of settlement profiles

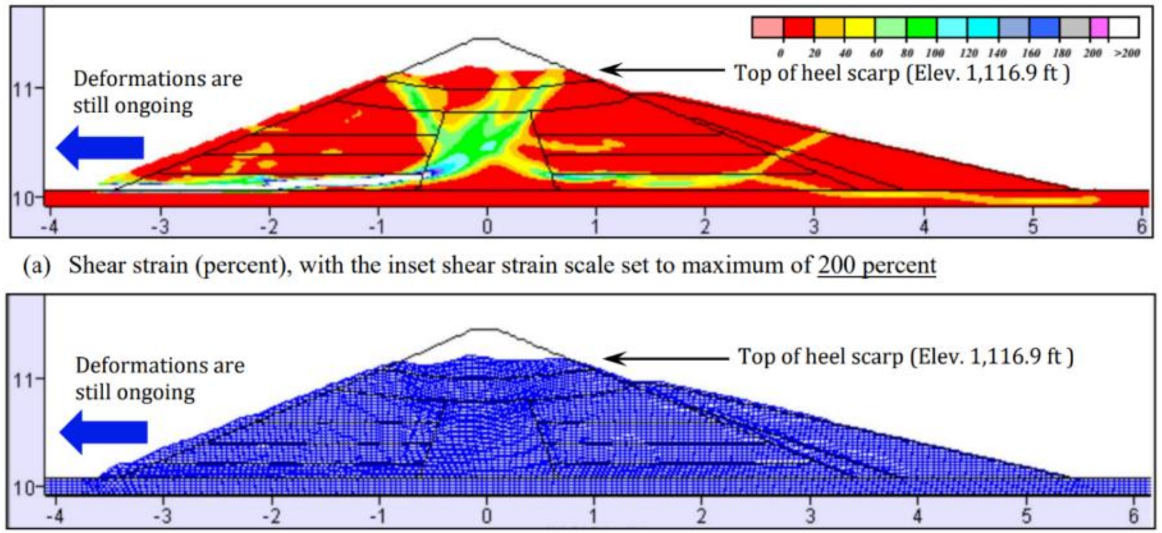


Pagano et al. (1998)

Workflow for building numerical models for seismic performance and fragility evaluation

Geometrical and geotechnical characterization → History of loads and hydraulic conditions → Definition of the numerical models → Nonlinear Dynamic Analyses

Output examples from NDAs in embankment dams

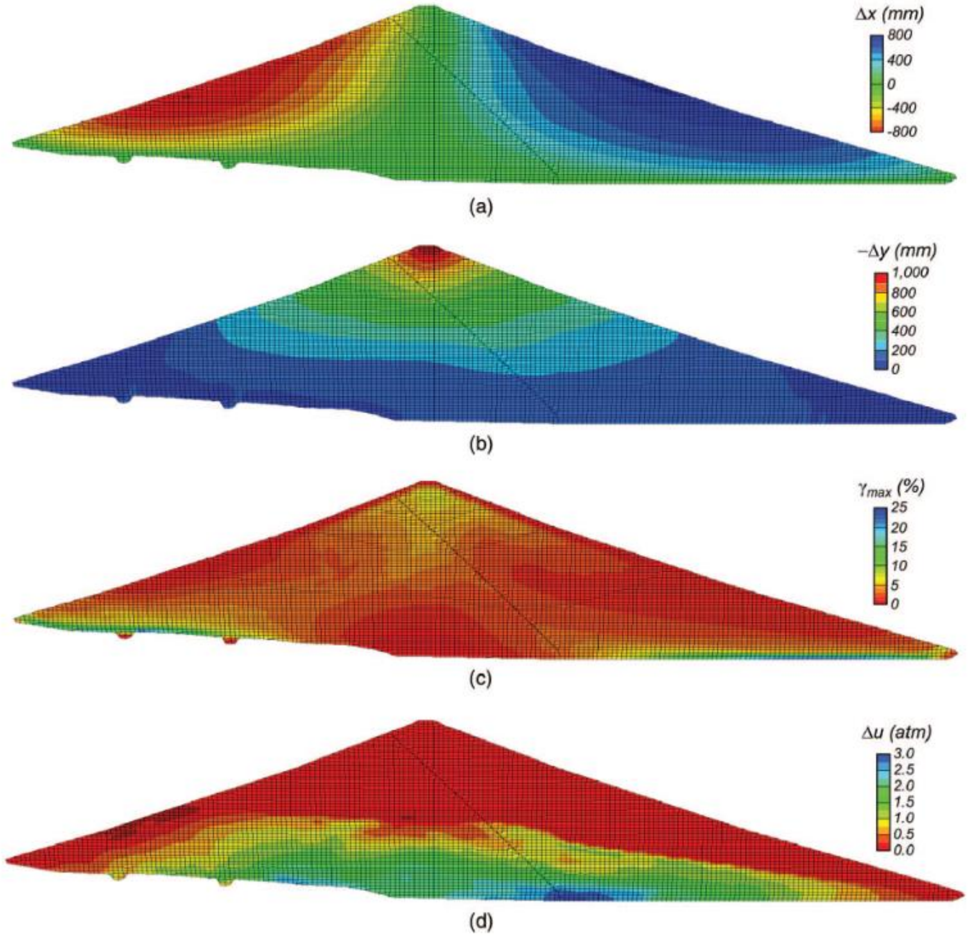


(a) Shear strain (percent), with the inset shear strain scale set to maximum of 200 percent

(b) Deformed mesh

Lower San Fernando Dam (Chowdhury et al., 2019)

The models are able to capture the complex response of the dam during strong ground motions

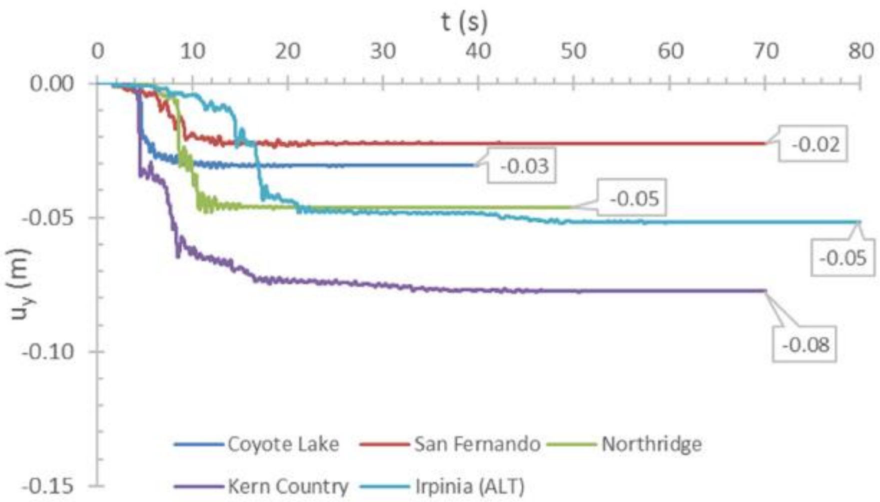


Austrian Dam (Boulanger, 2019)

Workflow for building numerical models for seismic performance and fragility evaluation

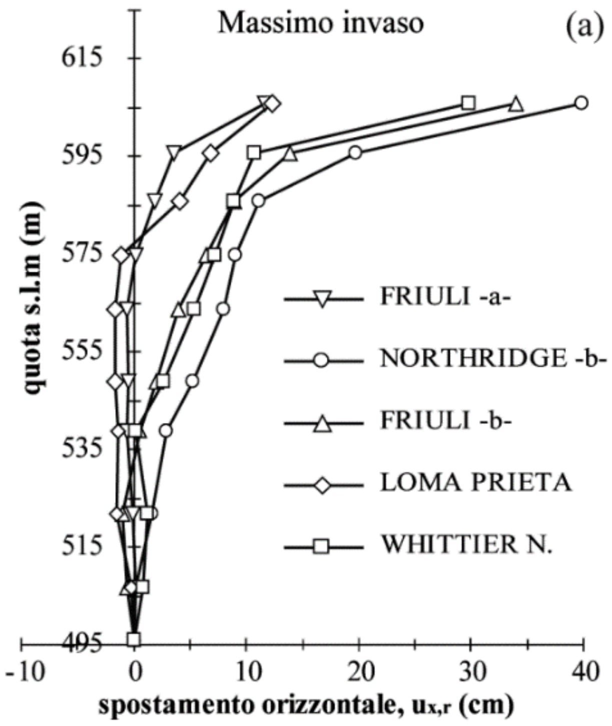
Geometrical and geotechnical characterization → History of loads and hydraulic conditions → Definition of the numerical models → Nonlinear Dynamic Analyses → Summary and evaluation of results

Time histories of vertical settlements at the crest of the dam



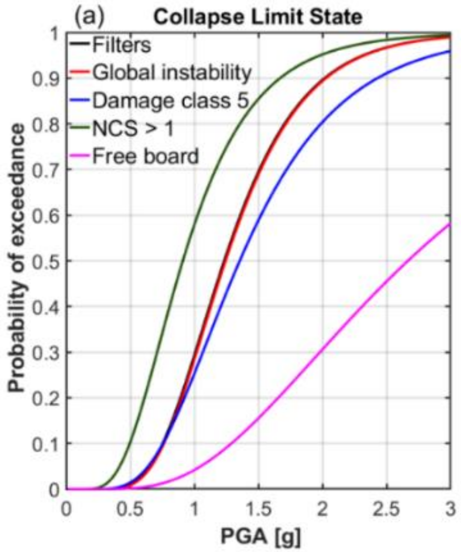
Monte Cotugno rockfill dam (Costigliola, 2017)

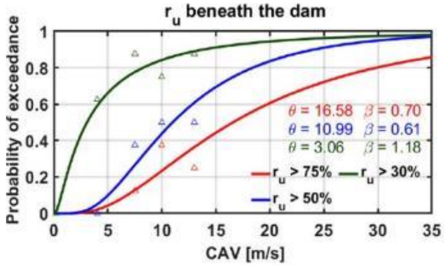
Horizontal residual displacements at the center line of the dam



Melito rockfill dam (Costanzo et al., 2011)

Fragility functions for different Potential Failure Modes (PFMs)





Farneto zoned dam (Regina et al., 2022)

Potrerillos dam geotechnical model: summary of information

1 – Filling material - Silt
- Granulometric analyses

2B - Transition gravel
- Granulometric analyses
- Dry unit weight (during constr.)
- Laboratory permeability

2A/F – Clean sand filter
- Granulometric analyses
- Laboratory permeability
- In-situ permeability (Test Embk.)

4A/4B - Clean gravel drain
- Granulometric analyses
- In-situ permeability (Test Embk.)
- Dry unit weight (Test Embk.)
- Load-plate tests (Test Embk.)

BR – Bedrock - Granite
- Unconfined compression test
- Ultrasonic tests (sample)

3A - Coarse gravel shell
- Granulometric analyses
- Max and Min density
- Laboratory permeability
- In-situ permeability (Test Embk.)
- Load-plate tests (Test Embk.)
- **TX CD Ø 205 mm (d_{max} 20 mm)**
- Dry unit weight (during constr.)

3B - Coarse gravel shell
- Granulometric analyses
- Max and Min density
- Laboratory permeability
- In-situ permeability (Test Embk.)
- Load-plate tests (Test Embk.)
- **TX CU Ø 75 mm (d_{max} 12.7 mm)**
- **TX CD Ø 205 mm (d_{max} 20 mm)**
- Dry unit weight (during constr.)

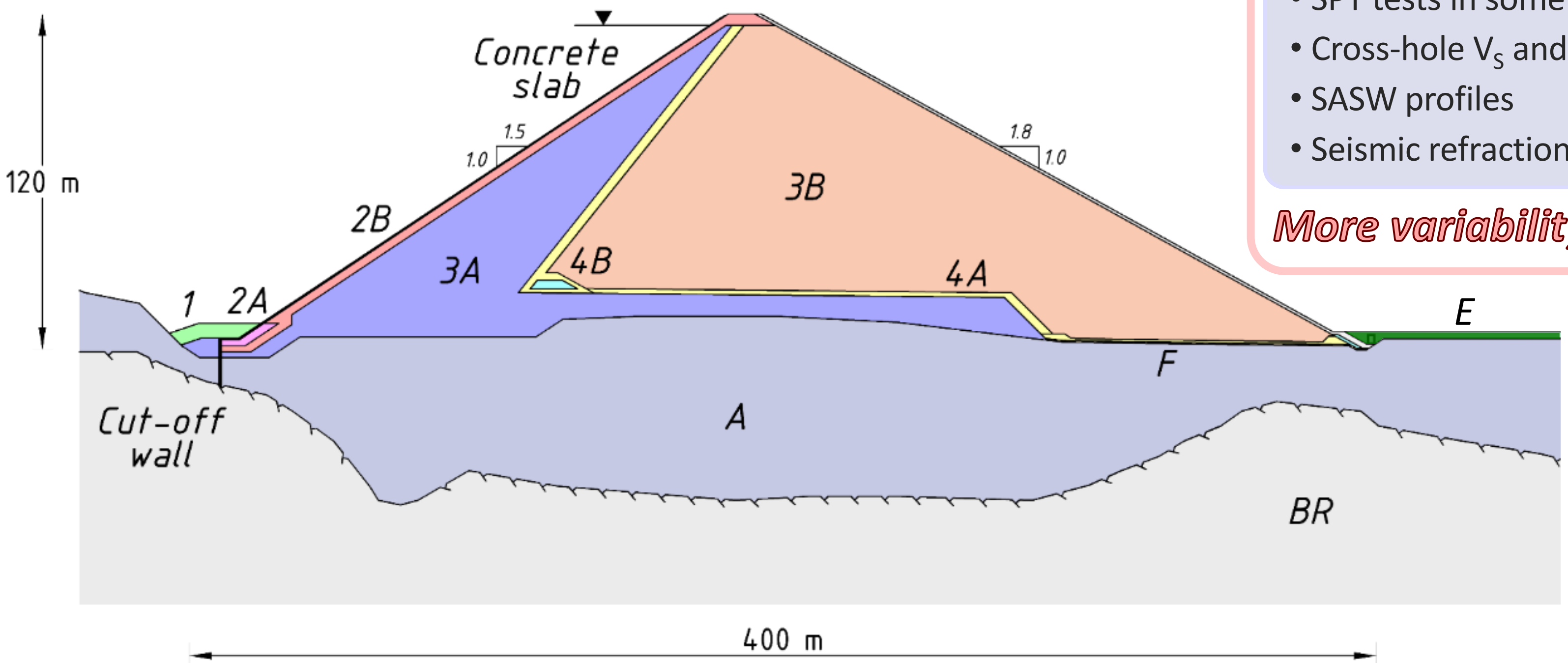
Less variability in properties

E –Stabilizing embankment
- Same coarse gravel as **3B**

A - River alluvium
- Shallow test pits
- Granulometric analyses
- Laboratory permeability
- **TX CD Ø 170 mm (d_{max} 38 mm)**
- **TX CU Ø 170 mm (d_{max} 38 mm)**
- **CTX Ø 180 mm (d_{max} 38 mm)**
- Boreholes w/log profile
- SPT tests in some boreholes
- Cross-hole V_S and V_P profiles
- SASW profiles
- Seismic refraction sections

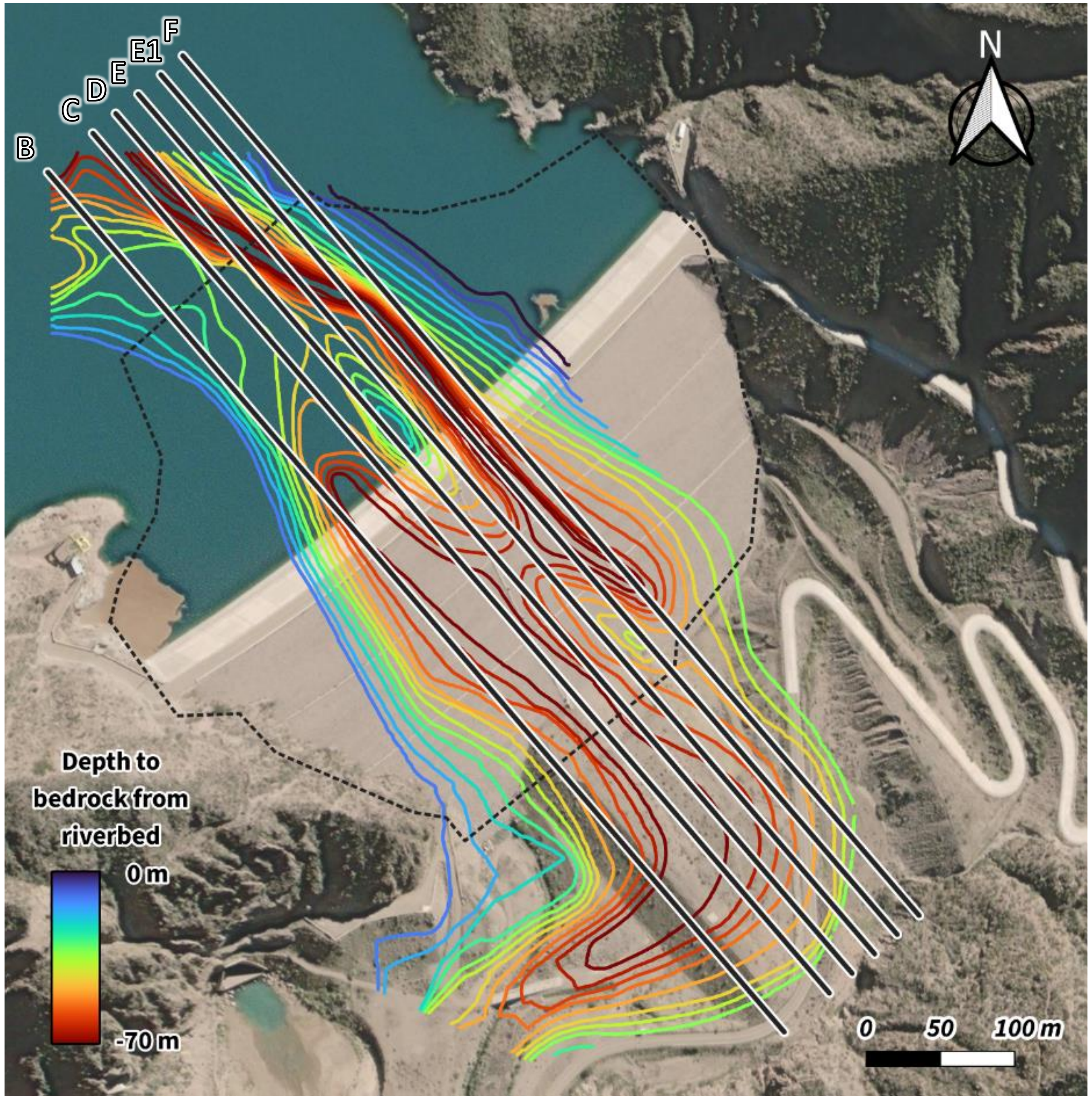
More variability in properties

Center-left section of the dam

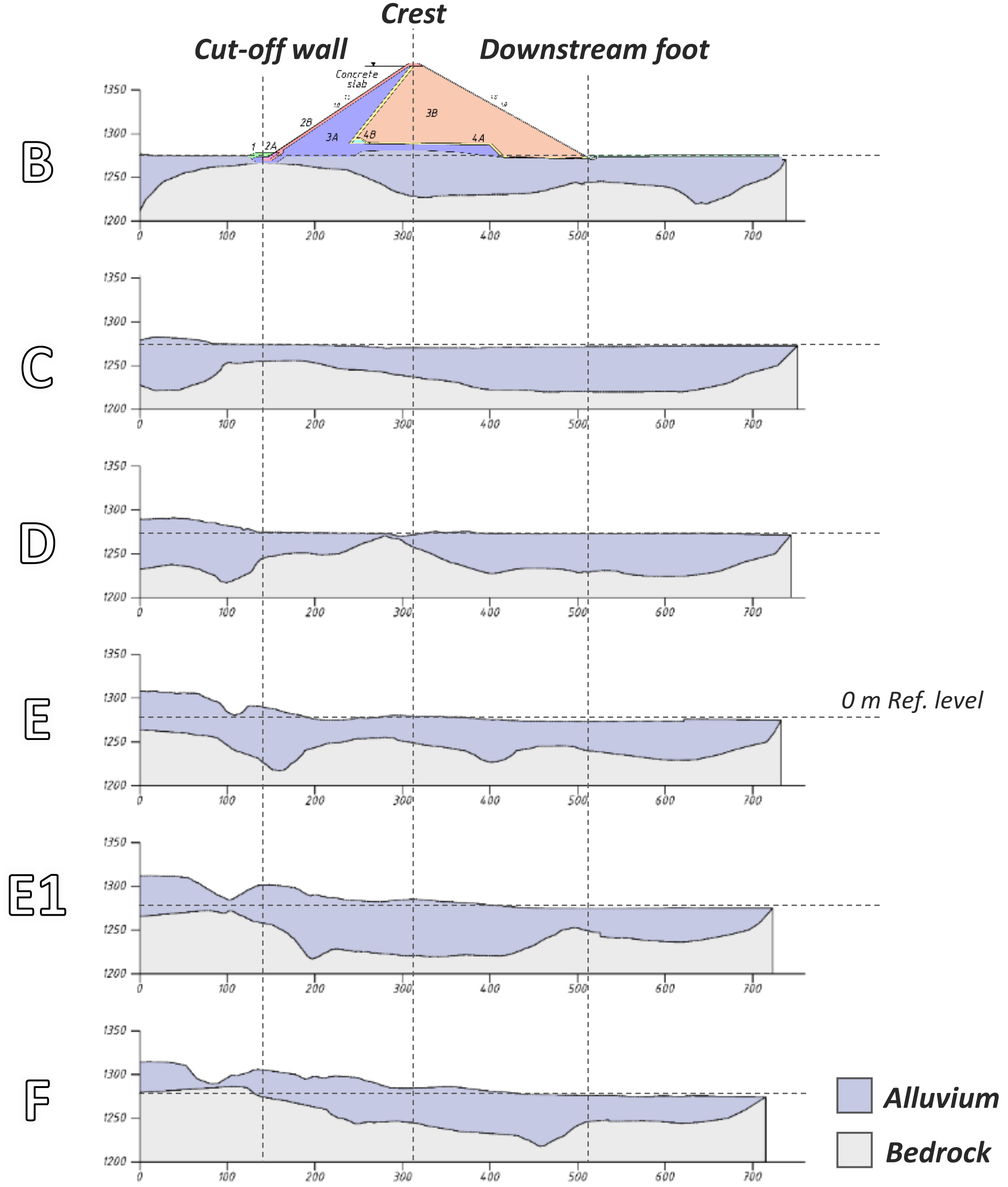


Potrerillos dam geotechnical model: Foundation, riverbed depth and bedrock variability

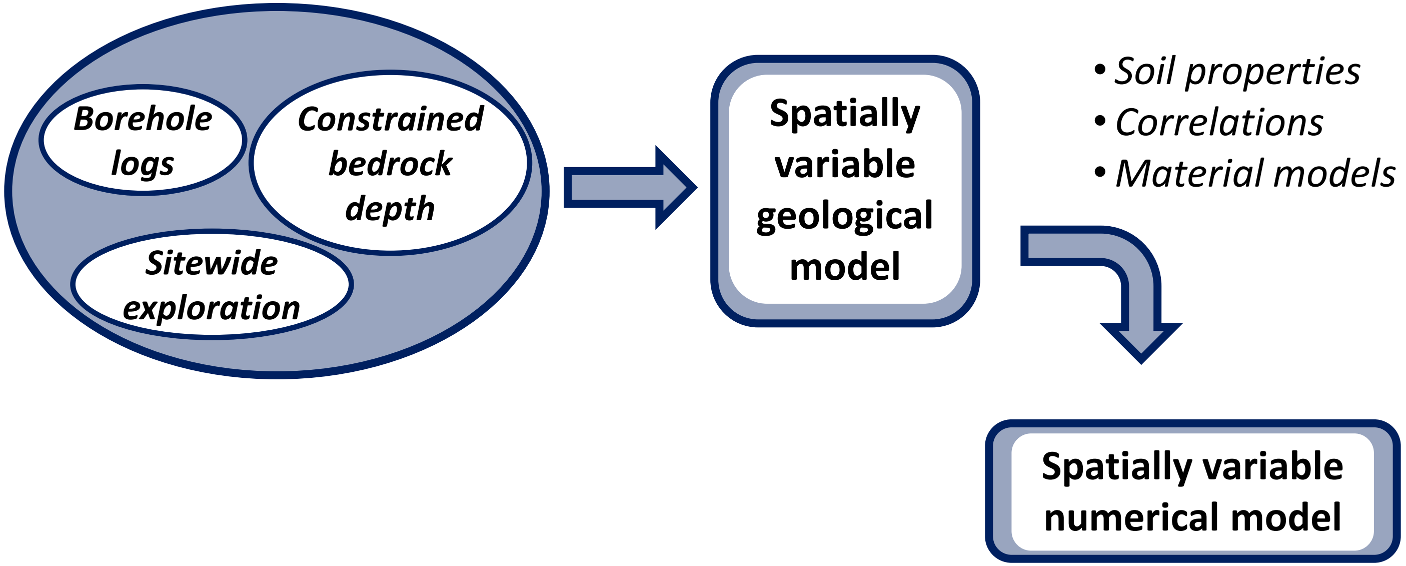
Contours of bedrock depth under dam foundation level



Cross sections

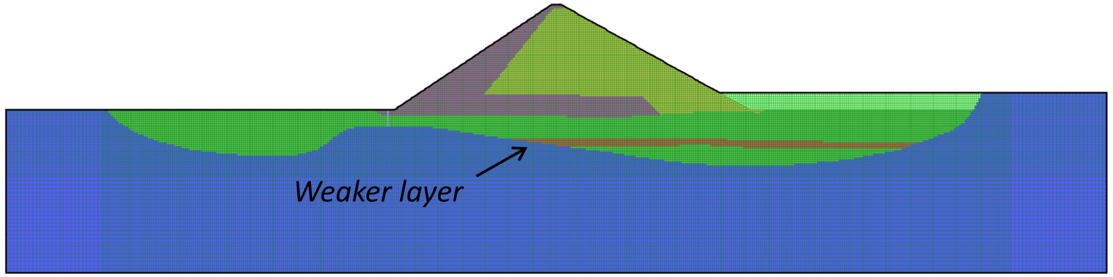


Potrerillos dam geotechnical model: Foundation spatial variation of soil type and properties

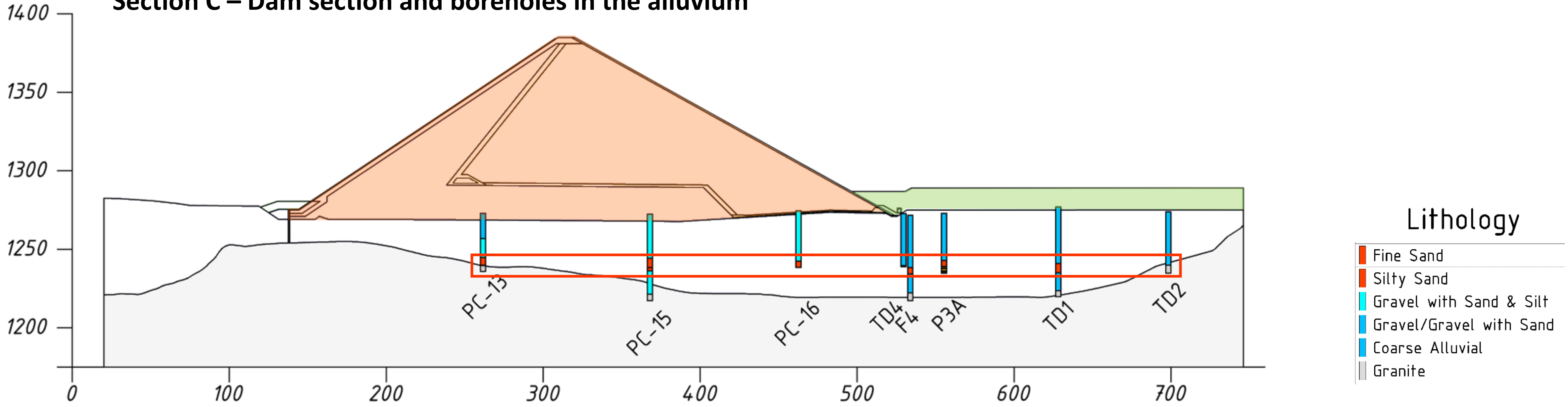


- *Soil properties*
- *Correlations*
- *Material models*

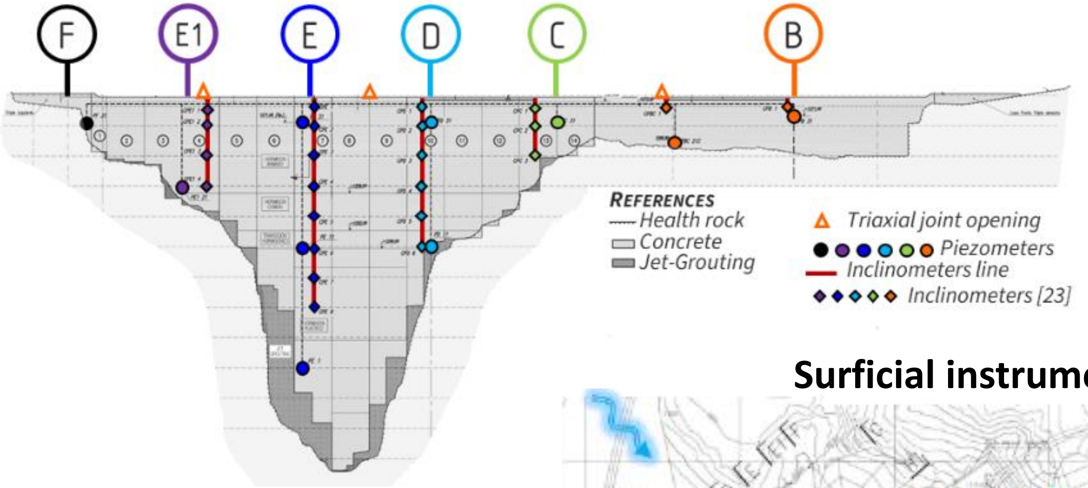
Example of numerical model that considers spatial variability

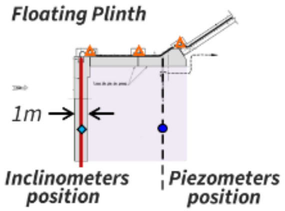


Section C – Dam section and boreholes in the alluvium

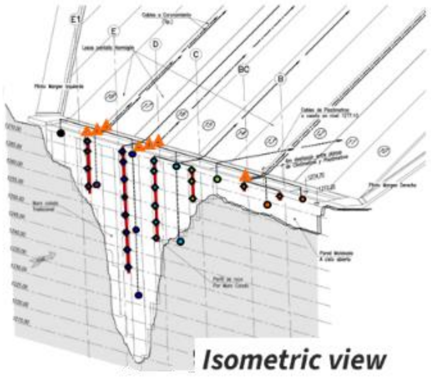


Monitoring system of the dam – Description of the instruments

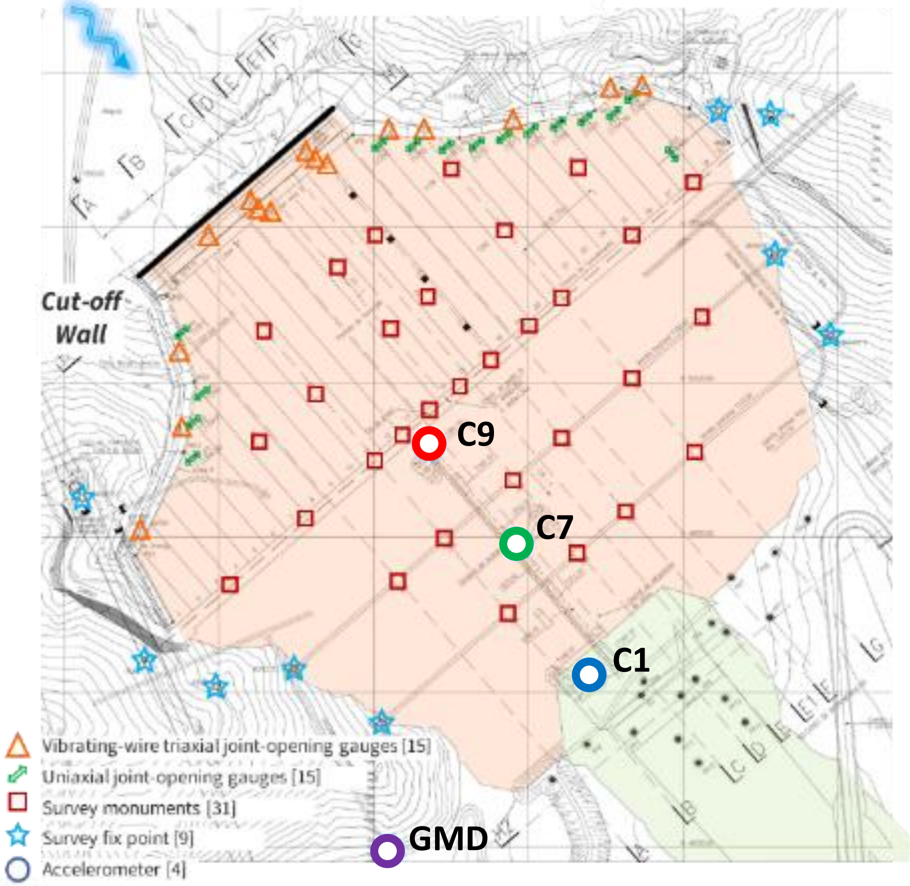




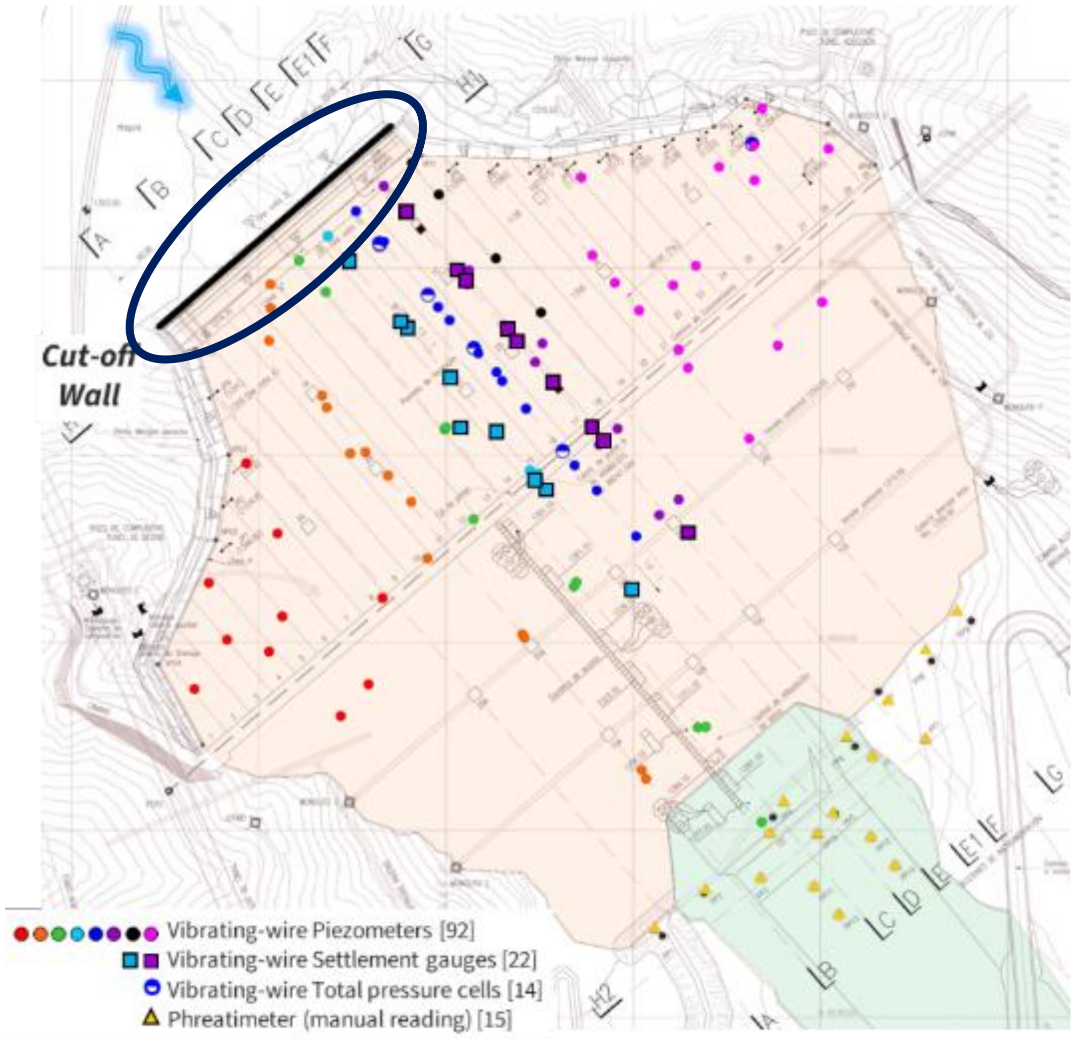
Instruments within the cut-off wall



Surficial instruments

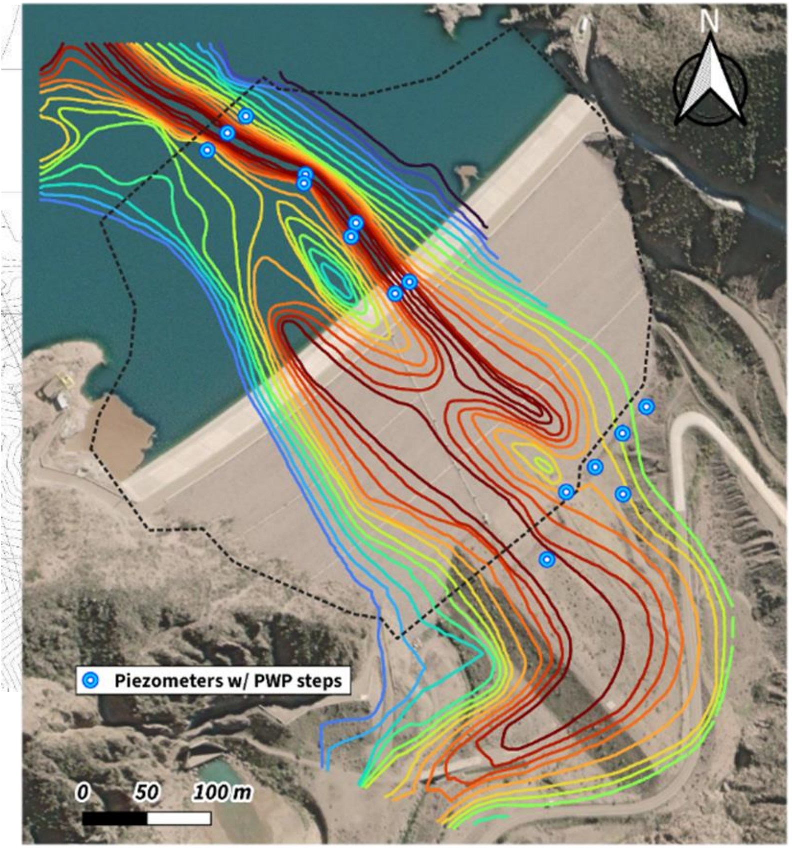


Buried instruments

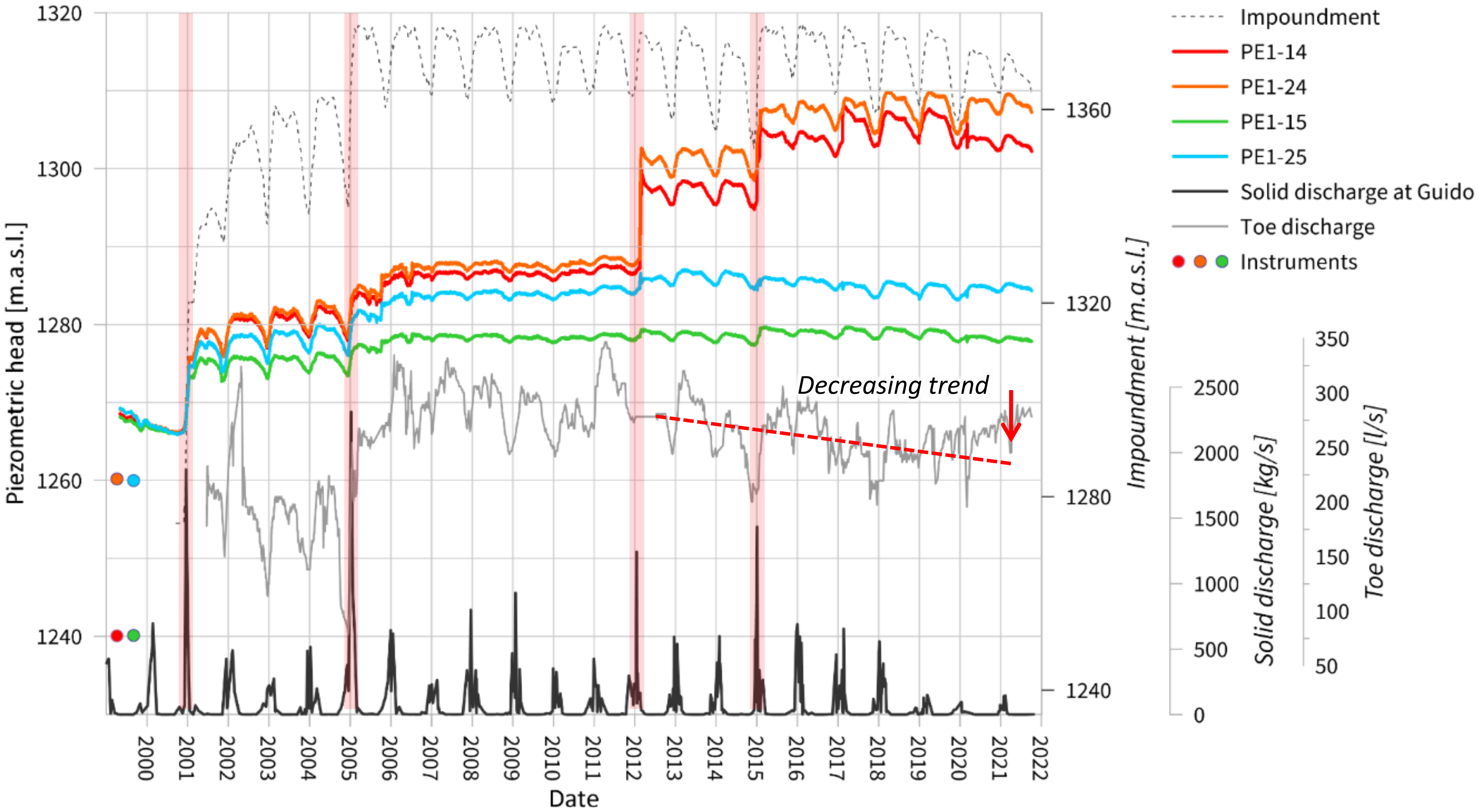


Example of monitoring records analysis: Piezometers – Section E1

Piezometers with PWP steps aligned in the left-margin



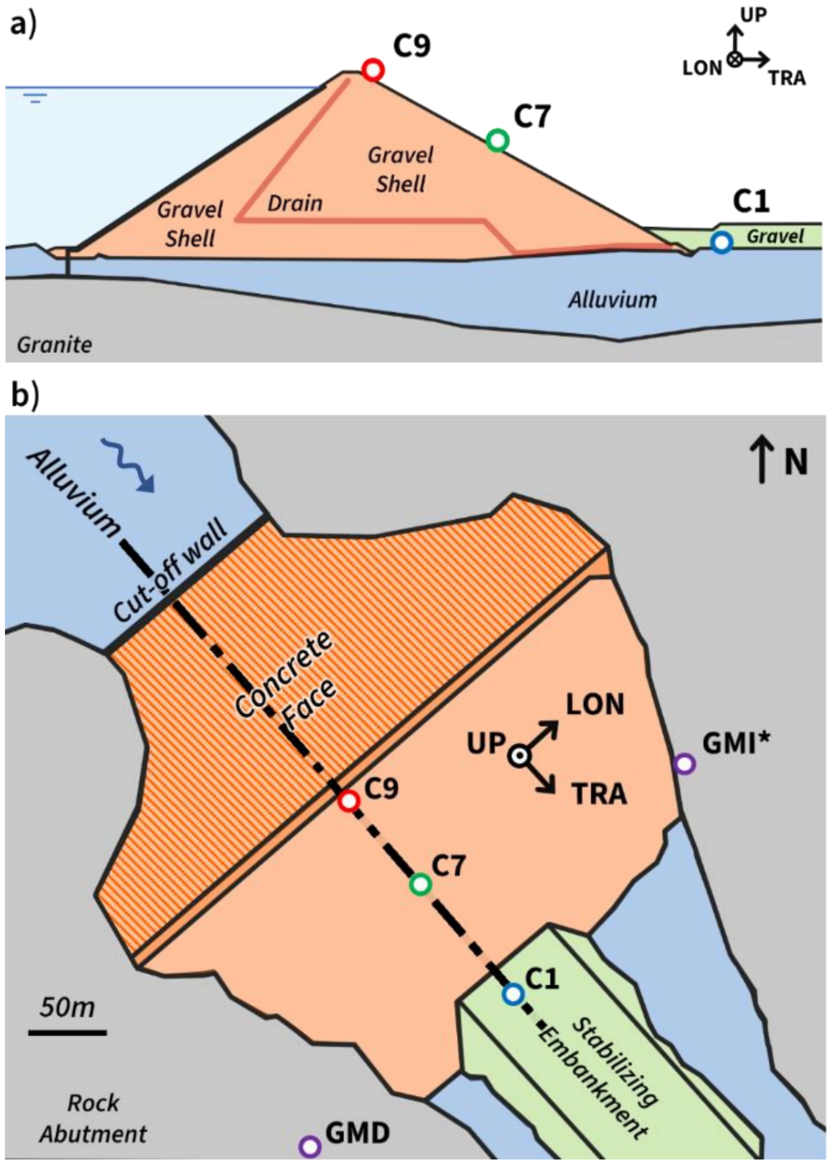
Integrated graphic



Likely reason: non-uniform change in the permeability due intrusion of fines from solid discharge in the alluvium

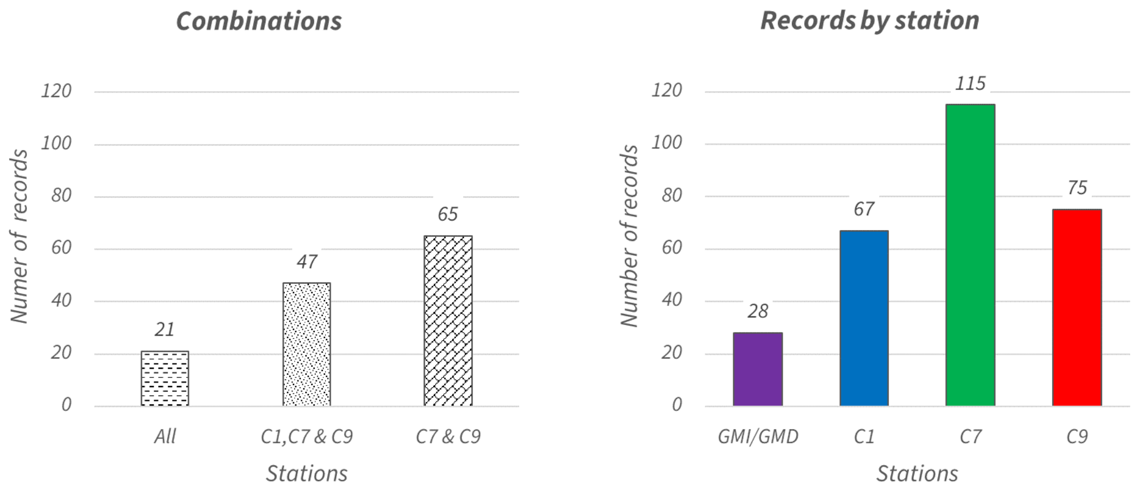
Seismic monitoring – System description and dam response versus weak motions

Seismic monitoring system: Instrument location and components

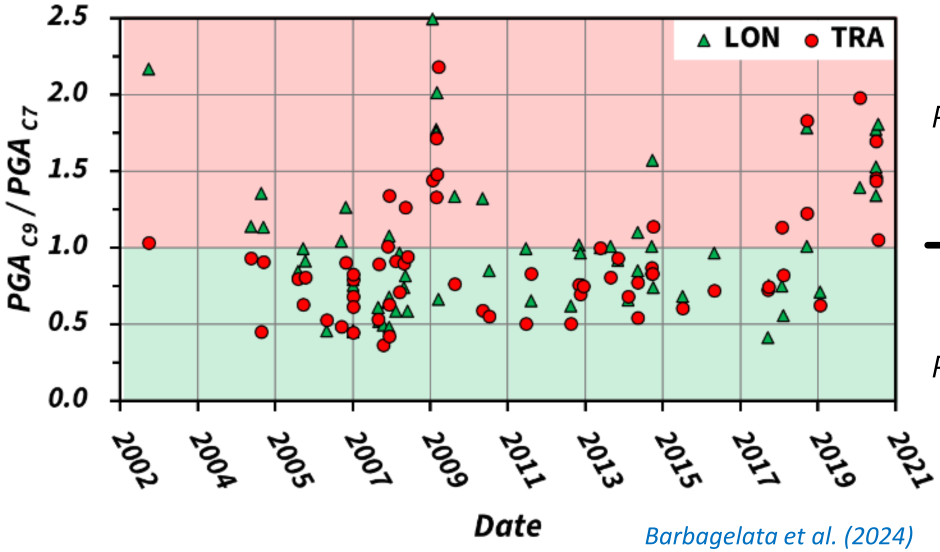


Barbagelata et al. (2024)

Records by station and combinations



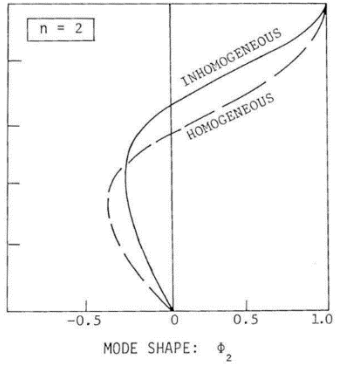
Ratio of peak acceleration at C9 and C7 for TRA and LON components



Barbagelata et al. (2024)

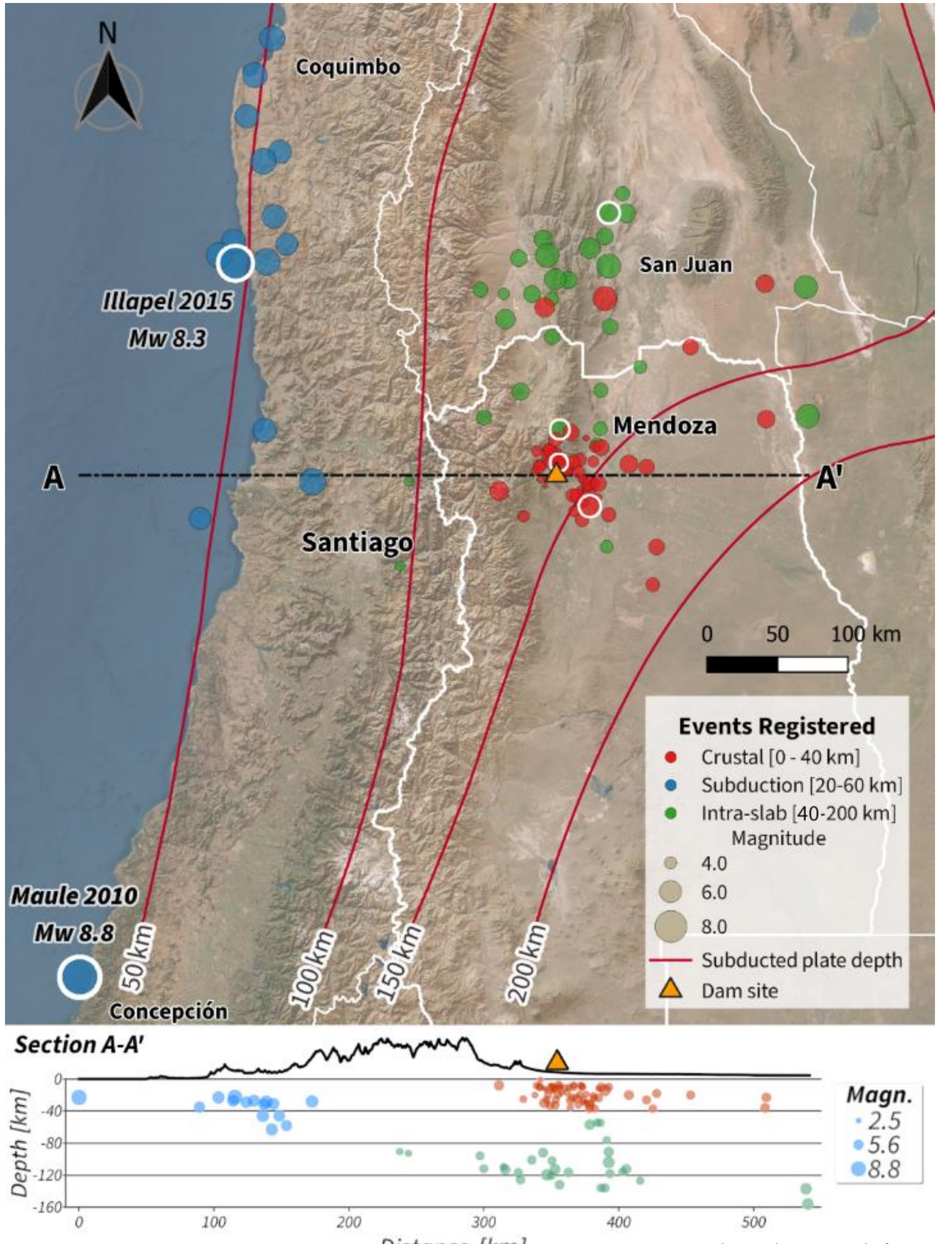
$PGA_{C9} > PGA_{C7}$

$PGA_{C7} > PGA_{C9}$



Gazetas (1981)

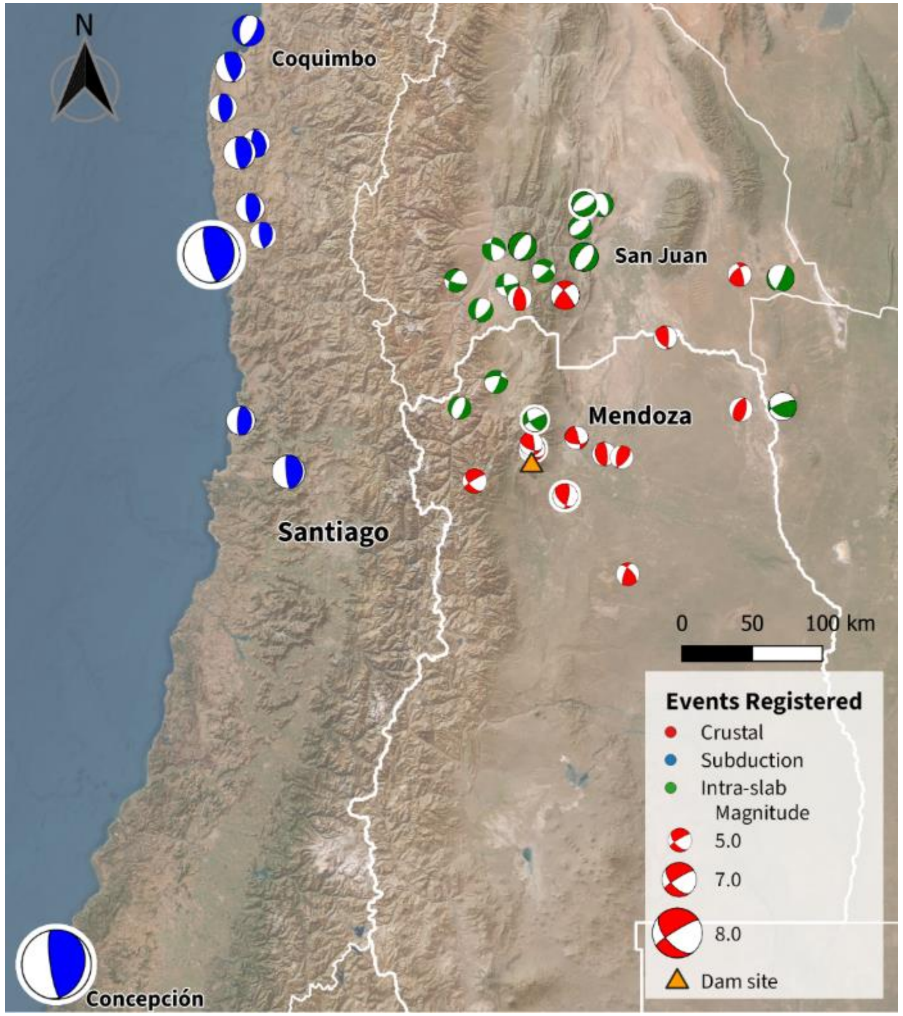
Seismic monitoring - Characterization of seismicity and seismic sources



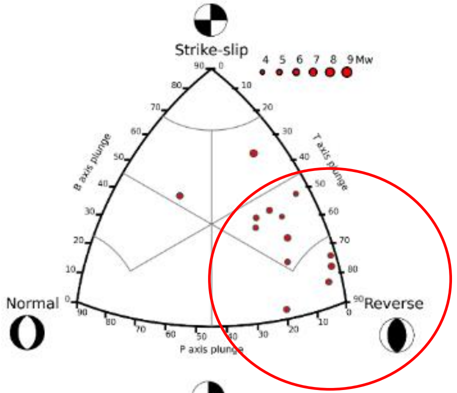
Barbagelata et al. (2024)

Location and characteristics of the weak-motions events recorded by the seismic monitoring system of the dam

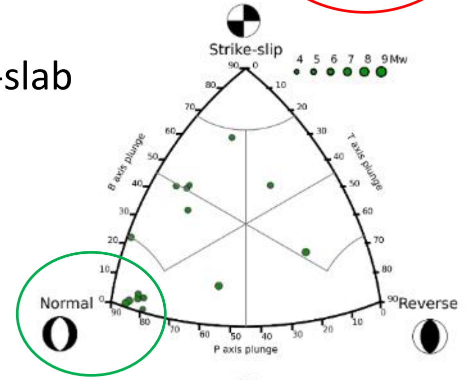
Focal mechanism for the events recorded



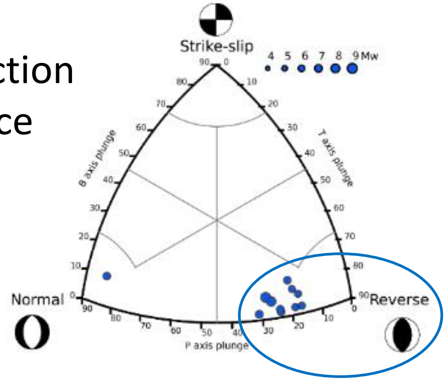
Crustal



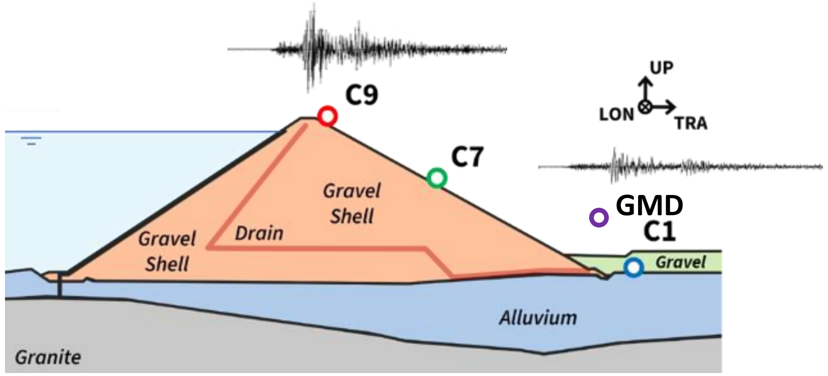
Intra-slab



Subduction Interface



Barbagelata et al. (2024)

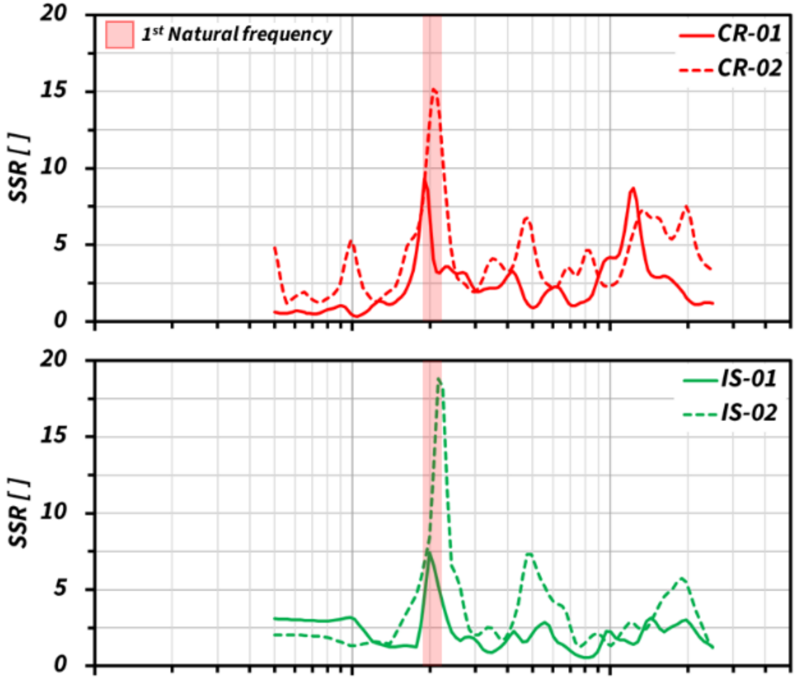


Selected events for record processing

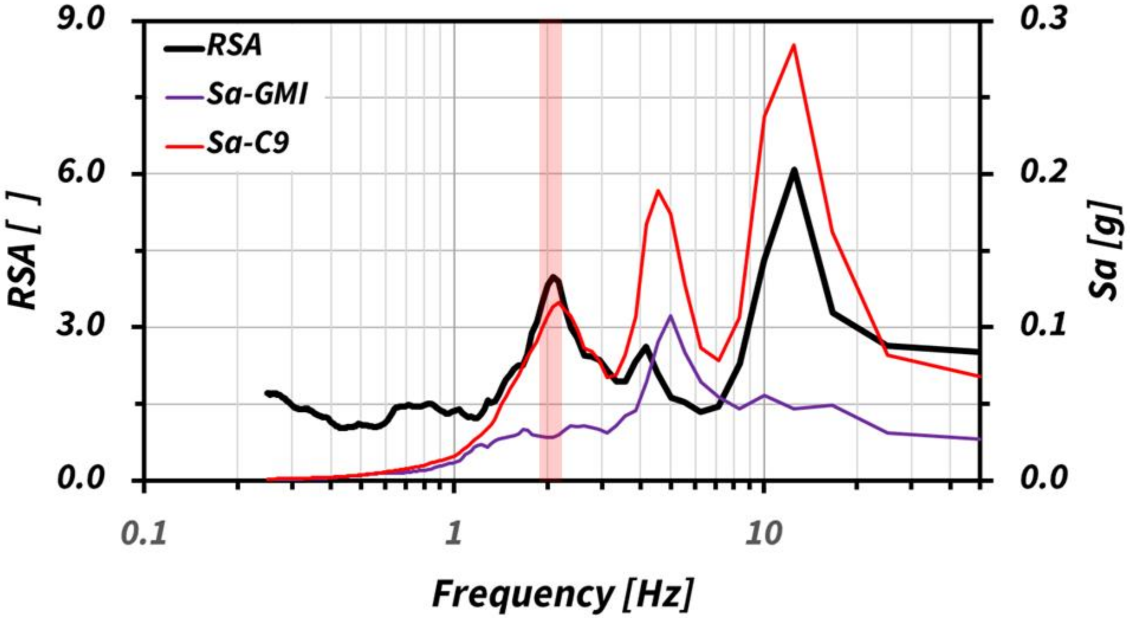
Event	Date	magn. [Mw]	ep.dist. [km]	depth [km]	*PGA* C9 [g]	*AI* C9 [m/s]	f_D GMD [Hz]
CR-01	5/8/2006	5.6	33.7	32.0	0.065	0.0379	5.0
CR-02	23/6/2021	4.6	12.0	19.0	0.094	0.0283	10.0
IS-01	26/4/2009	5.1	33.9	132.0	0.007	0.0003	7.1
IS-02	18/1/2010	5.5	199.6	91.0	0.027	0.0050	3.6
SD-01	27/2/2010	8.8	502.3	22.9	0.024	0.0533	2.3
SD-02	16/9/2015	8.3	287.1	22.4	0.016	0.0326	4.2

Barbagelata et al. (2024)

Standard Spectral Ratio (SSR)



Ratio of Spectral Acceleration (RSA)



Barbagelata et al. (2024)

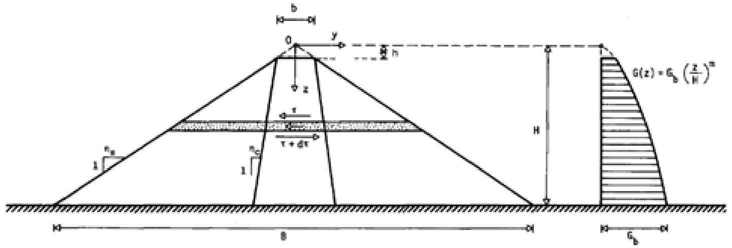
$$SSR(f) = \frac{A(f)_{C9}}{A(f)_{GMD}}$$

$$RSA(f) = \frac{Sa(f)_{C9}}{Sa(f)_{GMD}}$$

$$\boxed{f_1 \cong 2.0\ Hz}$$

$$f_1 = \frac{V_s}{2.57 \times 0.9 \times H}$$

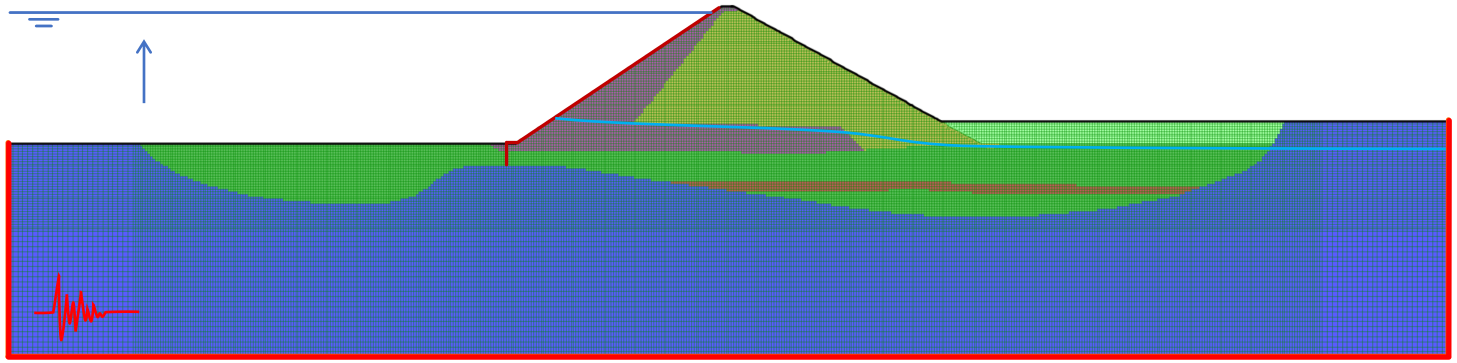
$$\boxed{V_s = 550\ m/s}$$



Dakoulas & Gazetas (1985)

Nonlinear Dynamic Analyses (NDAs)

Finite Difference Numerical model (FLAC) – Section C



	Geomaterials	Material model
	Granite bedrock	Elastic
	3A – Sand-Gravel-Pebble mixture	MC + Hyst. Damp.
	3B – Sand-Gravel-Cobble mixture	MC + Hyst. Damp.
	Foundation gravelly alluvium	PM4Sand
	Sand/Silty sand alluvial material	PM4Sand
	Stabilizing embankment	MC + Hyst. Damp.
	RC Slab / Cut-off wall	Elastic / MC

1. *Definition of the **geometry** of the regions and model **discretization***
2. *Designation of **mechanical and hydraulic properties** for every region based on laboratory and in-situ tests*
3. *Setting up of mechanic and hydraulic **boundary conditions***
4. *Reproduction of the **construction sequence** and calibration*
5. *Gradual increase of the **reservoir level***
6. *Set the **dynamic properties** and **input motions***
7. ***Running** the analyses*
8. ***Evaluating** the **results** and comparison with simplified analysis*

Key points when running NDAs

- The model should **capture** the **response** of the dam and be **representative** of the selected Potential Failure Modes (PFMs)
- The material models can reproduce the complex behavior of the soils under seismic actions
- The selected Engineering Demand Parameters (EDPs) are informative about the damage condition given for every PFM

Final scope: use monitoring and fragility into the post-event Emergency Action Plan

Current procedure after an EQ

ICOLD B-166 criteria to start the inspections following earthquakes

Magnitude	*Distance (km)*
> 4.0	*25*
> 5.0	*50*
> 6.0	*80*
> 7.0	*125*
> 8.0	*200*
Or MMI ≥ 4	

ICOLD B-166 (2016)

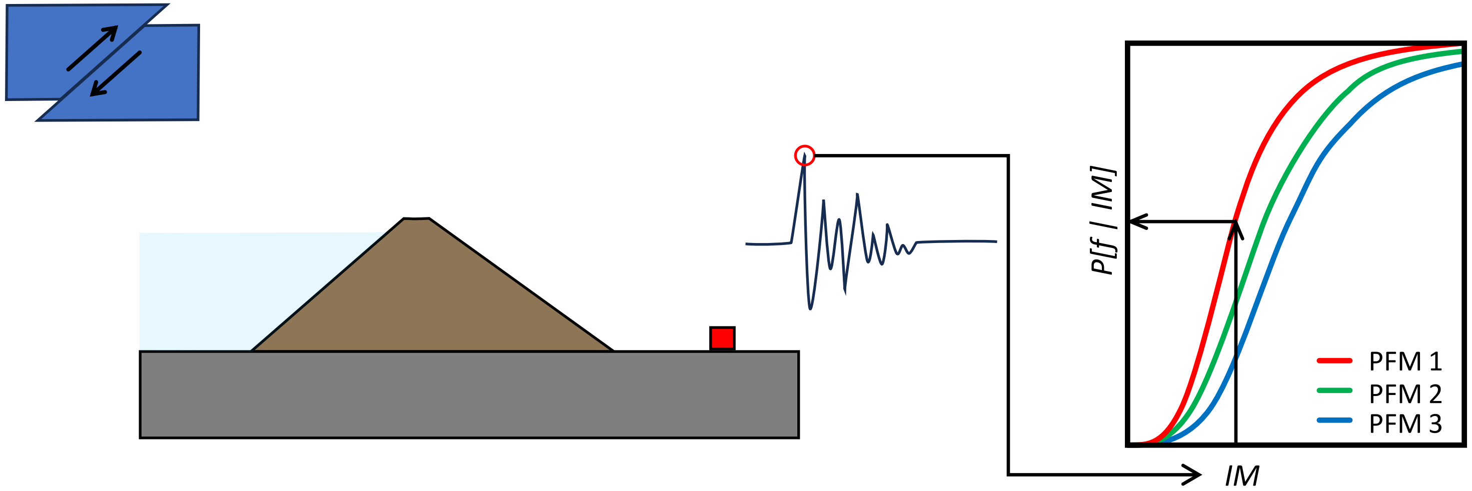
Emergency Action Plan Initiation

- Visual inspections of dam, appurtenant and reservoir
- Increase of recording rates of the instruments
- Evaluation of the evolution of the concerning features
- Communication with authorities and specialists

Is the dam at risk? Beginning or not of countermeasures

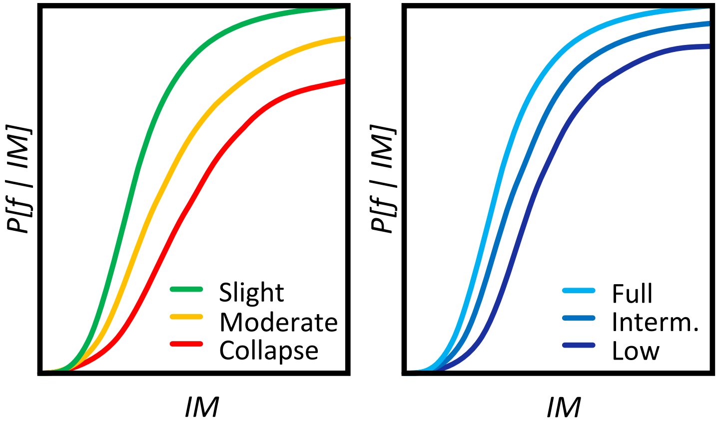
Can we bring more information about the dam performance, for a better decision making?

Dam-specific Fragility Functions



Information about the dam performance

Groups of fragility functions



- A **geotechnical model** representative of the **dam-subsoil system** that **integrates** all the information available (geological surveys, in-situ and laboratory geotechnical tests, analysis of monitoring records) is **essential** to describe the **complexity** of the dam and **site conditions**

- A **numerical model** able to **capture** the complex response and selected **Potential Failure Modes** of the dam is **decisive** in the **assessment** of the **performance** and **fragility** of the dam during strong ground motions

- **Evaluating the seismicity** and the **dynamic dam response** using the records from the **monitoring system** supports the **calibration** and validation of the **numerical dam-subsoil model**

- Coupling the **seismic monitoring** data records with the **fragility functions** is a promising innovative approach that could help the managers of infrastructure to take **safer decisions** during **post-event Emergency Actions Plans** after **seismic events**, moving towards the use of digital twins for dam safety in seismic regions

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Question time…

Potrerillos dam and reservoir, July 2022

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