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Back analysis of Rio Fucino dam

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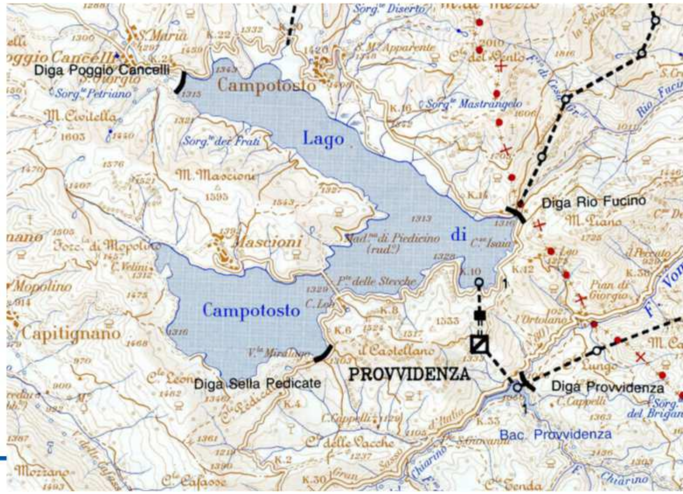
Objective

- Back analysis on the Rio Fucino concrete gravity dam (reservoir of Campotosto, L'Aquila, Central Italy) after the earthquake of April 6, 2009 (main shock Mw=6.3).
  - Campotosto reservoir, delimited by the Rio Fucino, Sella Pedicate and Poggio Cancelli dams, was the nearest to the epicenter of the mainshock and it was followed by several aftershocks
  - Rio Fucino dam is the nearest to the Campotosto fault.
  - A seismic assessment of the three dams (required by Authority) has also been carried out using the Maximum Credible Earthquake (MCE) specifically studied for the area oh the dams. This analysis is not a subject of this presentation



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Rio Fucino concrete dam

Downstream

Upstream

Sella Pedicate concrete dam

Upstream

Downstream

Back analysis - Focus

Focus of back analysis of Rio Fucino dam is to improve the knowledge of physical and mechanical properties of materials under dynamic conditions, in particular:

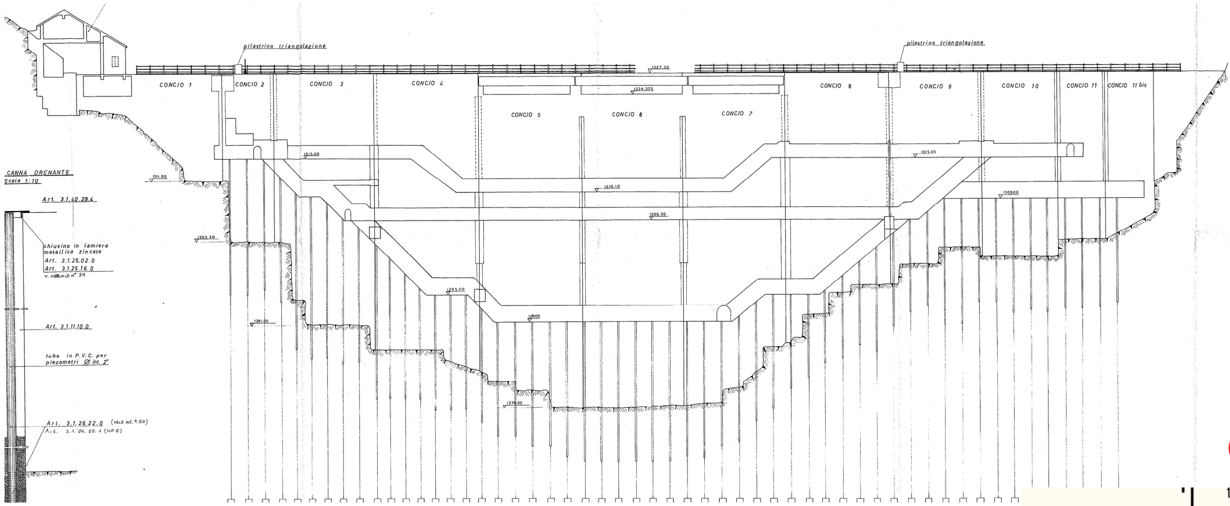
- Shear strength at the contact surface between the dam and rock foundation
- Shear strength of rock foundation

Some references for an estimate of static shear strength parameter are:

•EPRI – Electrical Power Research Institute, TR-100345, Project 2917-05, 1992

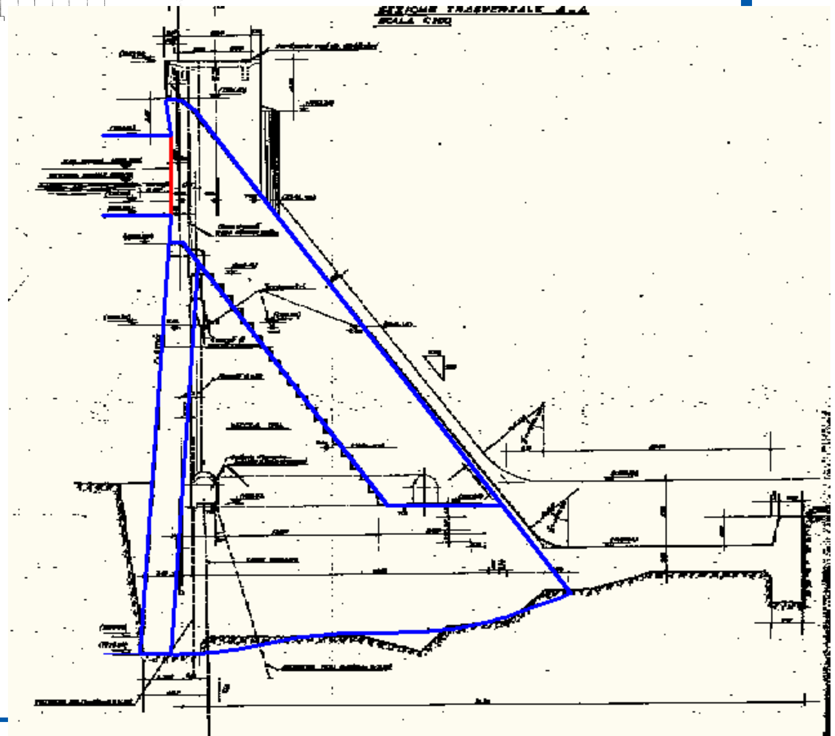
•European Club of ICOLD, “Report of the European Working Group”, Canterbury 2004

Rio Fucino dam – Description



Longitudinal section

Overflowing section (studied)



Elevation of top of dam: 1327.50 m a.s.l.
Length: 154.00 m
Height on the foundation: 49.00 m
Height on the riverbed: 36.70 m
Max. water level elevation: 1318.25 m a.s.l.
Max. retention water level: 1317.50 m a.s.l.
Min. retention water level: 1294.00 m a.s.l.

Rock foundation: subvertical alternation of compact sandstone (prevalent) and marl

Rio Fucino dam – FEM

Set up of a plain strain model of the highest overflowing block

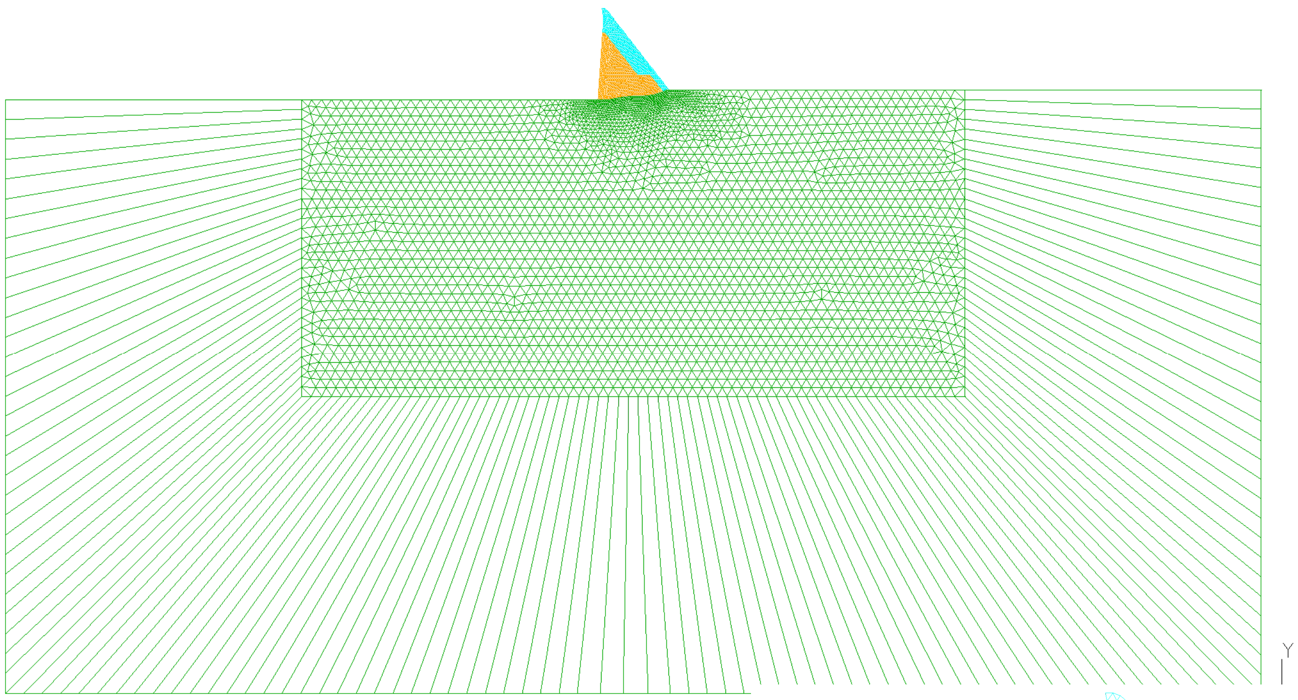
- Detailed simulation of available geometric data

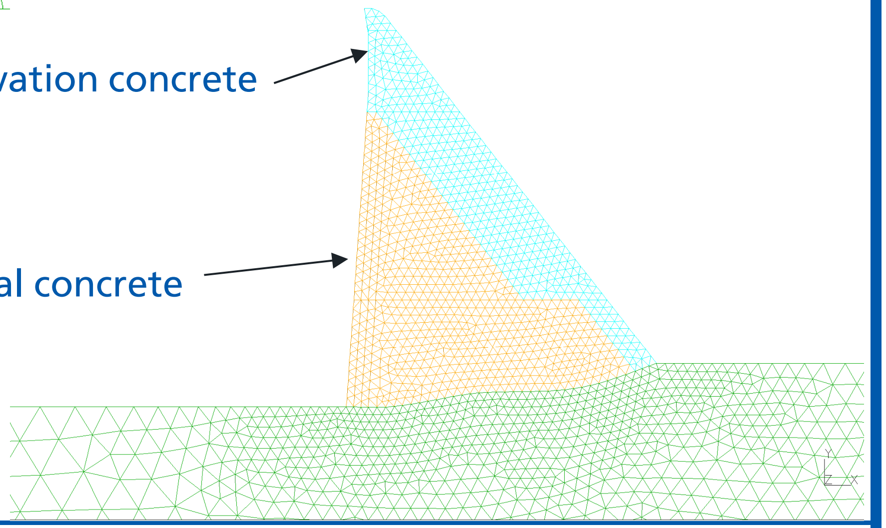
FEM includes:

- Interface between pre-existing dam (built in the period 1950-1951) and raising (realised in the period 1966-1971)
- Rock mass volume (elastic isotropic and homogeneous half space)
    - Rock mass volume equipped with the Infinite Elements of ABAQUS in order to correctly simulate not only the seismic waves propagation but also the dissipation of seismic radiation energy
    - The top of the rock volume model has been placed at the base of the concrete block
- Joint at the interface block-rock able to simulate a no-tension condition and slipping (by friction angle)

Phisical and mechanical properties were derived from experimental data (in situ survey campaign and laboratory tests, 1996) and then calibrated

Rio Fucino dam – FEM





Rio Fucino dam – FEM

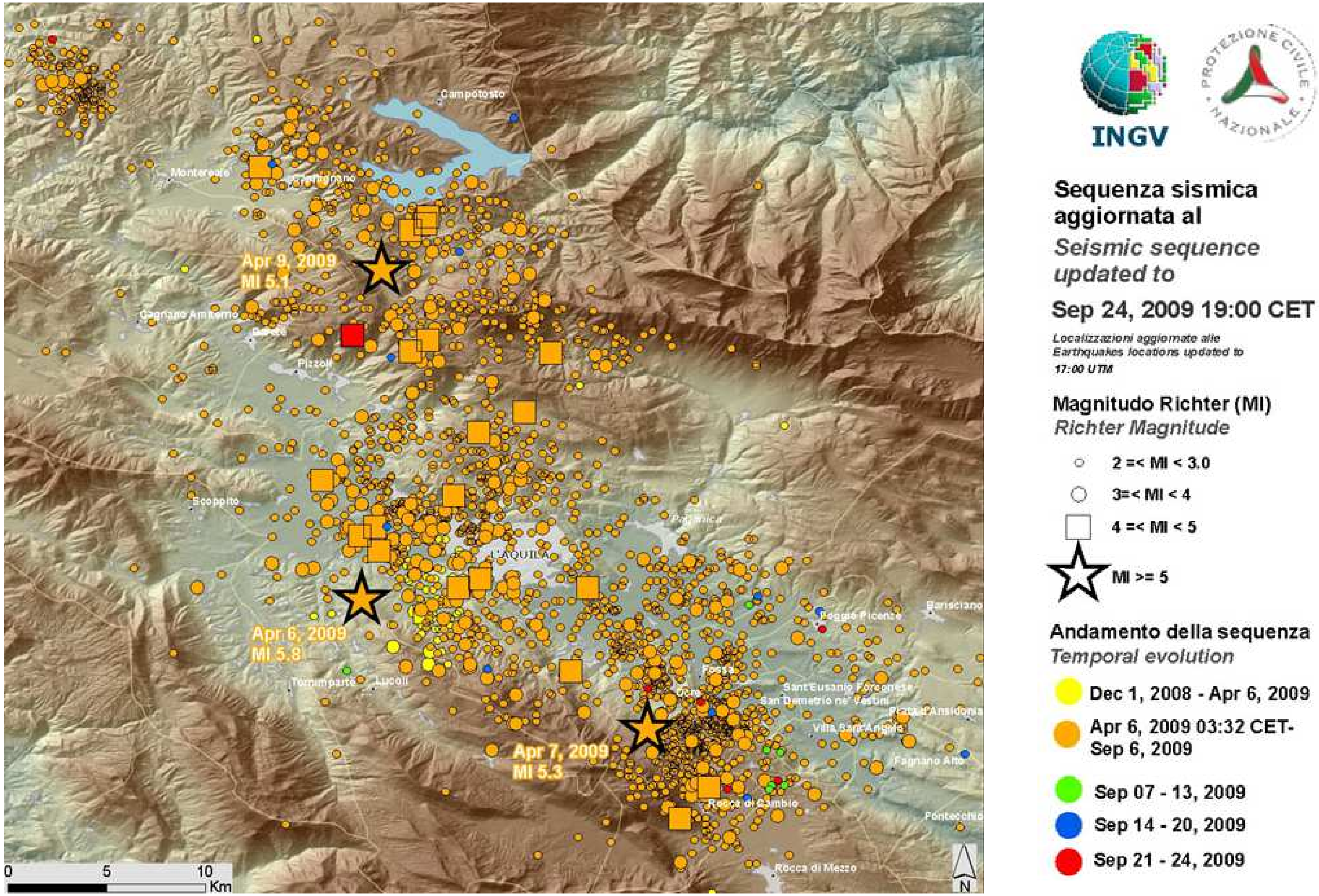
Calibrated materials properties

		Original concrete	Raising concrete	Rock
Elastic Modulus static	(MPa)	23752.0	36420.0	15330.0
Elastic Modulus dynamic	(MPa)	40275.0	47100.0	23000.0
Coeff. di Poisson's coeff.		0.20	0.20	0.35
Unit weigth (kN/m^3)	Static loads	23.58	24.20	/
	Dynamic loads	23.58	24.20	22.56
Uniaxial compressive strenght f_{cm}	(MPa)	27.70	40.13	/
Uniaxial tensile strenght f_{tm}	(MPa)	0.80	1.82	/
Linear thermal expansion coeff.	α (oC-1)	1 10^{-5}	1 10^{-5}	1 10^{-5}
Conductivity	J/m kg K	9146.0	12763.0	10459.0
Diffusivity	m^2/h	0.00351	0.00487	0.00477

Thermal parameters used only for calibration analysis

Earthquake

Seismic sequence of l’Aquila earthquake updated to Sept 24, 2009 (INGV)



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Rio Fucino dam – Aftershocks

Main shock of April 6, 2009 Mw=6.3 (Ml=5.8)

At Campotosto site no recorded data were available for the main shock

- Many aftershocks were recorded by accelerometric stations installed near to the dams by Civil Protection after the main shock
  - Poggio Cancelli station (RAN), close to right bank, recorded aftershock with Ml ranging from 4.9 and 5.1

The strongest aftershocks occurred on April 9 (Ml=5.1, Mw=5.4 PGA_h=0.30g)

- Epicentral distance of 6.7 km from Poggio Cancelli station
- Closest dam; Sella Pedicate

Aftershocks recorded by PC station

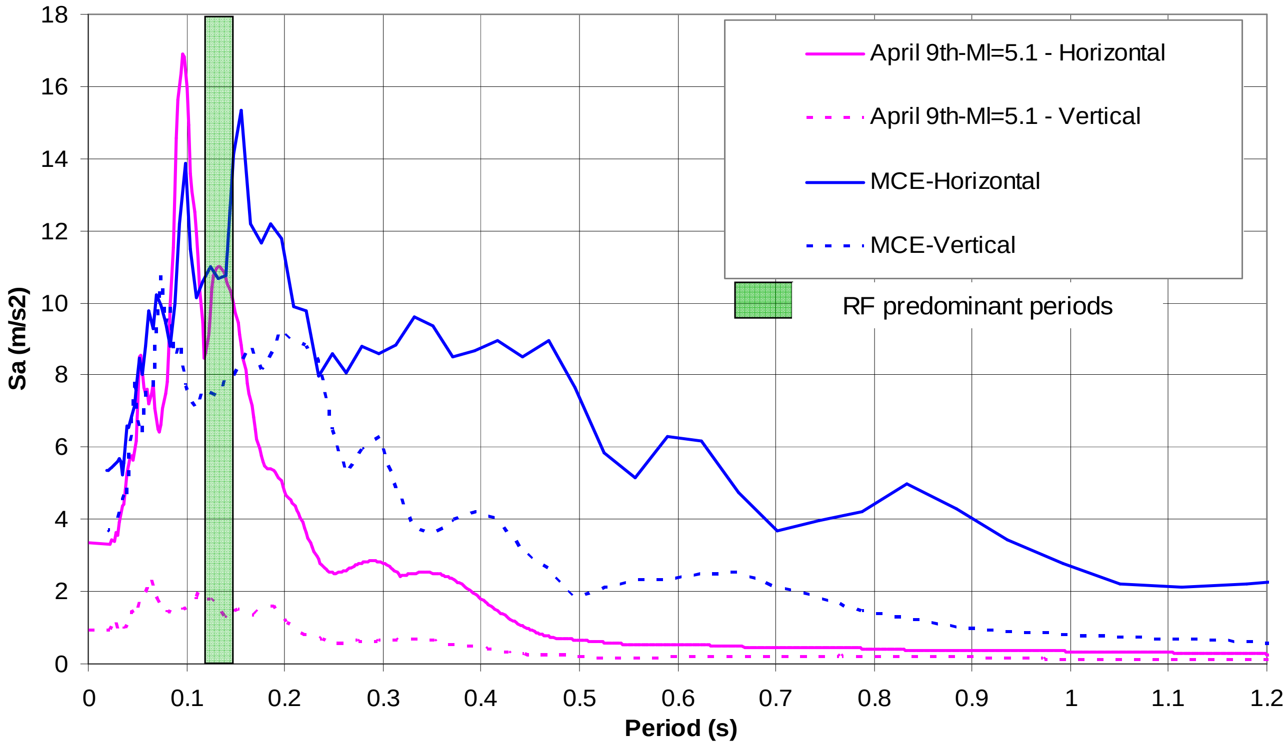
N	Data	Ora	Distanza epicentrale (km)	Ml	PGA (cm/s^2)
1	09/04/2009	02.52	6.70	5.1	296.004
2	09/04/2009	21.38	7.10	4.9	341.92
3	13/04/2009	23.14	6.30	4.9	271.26
4	14/04/2009	20.17	5.20	4.1	44.08
5	22/06/2009	20.58	12.50	4.5	75.445
6	24/09/2009	16.14	11.68	4.1	56.39

Rio Fucino dam – Earthquake /2

Comparison between MCE and aftershock of April 9, 2009

	Aftershock	MCE
PGA_h	**0.30g**	**0.52g**
I_A	**0.432 m/s**	**1.915 m/s**
I_H	**23.54 m/s**	**103.44 m/s**

- Aftershock has been a demanding event for the dam but its damage capacity was much lower compare to MCE

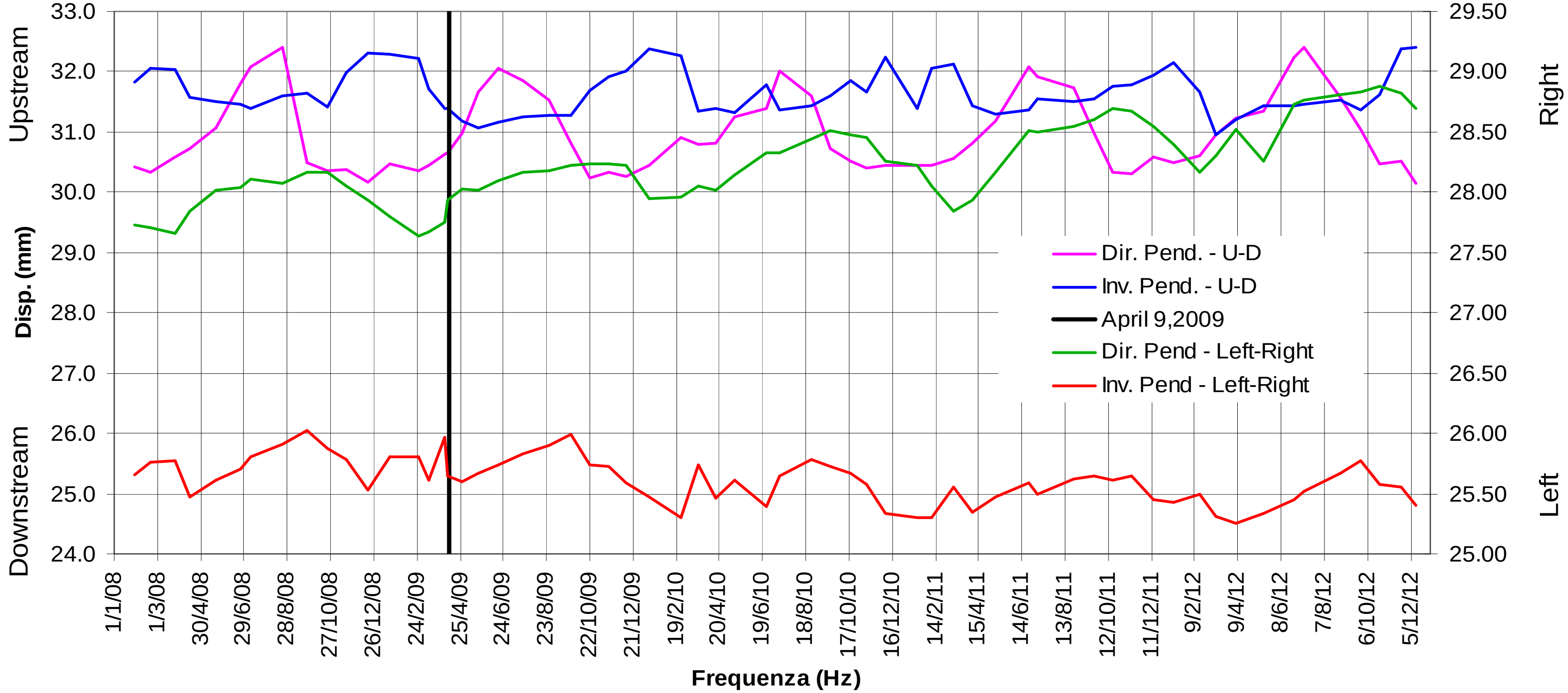


Rio Fucino dam – Monitoring data

The monitoring system installed on the dam (direct ad inverted pendulum, extensometers, piezometers, etc.) made it possible to understand the effects of the mainshock and aftershocks.

- Dam didn't show any unusual behaviour

Highest overflowing block – Direct and inverted pendulum



Rio Fucino dam – Back analysis

Measurements highlited a dynamic response almost linear under main shock and aftershocks.

Hence dynamic FEM response should be in agreement with the observed behavior and this requires:

- **Joint at the contact**: friction angle should be able to avoid permanent displacements
  - Searching for the minimum value to complay with this requirement
- **Mass Rock**: Mohr-Coulomb's failure criteria.
  - Maximum stresses should be enveloped by Mohr's Coulomb failure curve, in turn depending on friction angle and cohesion.
    - Searching for the minimum values of these parameters to complay with this requirement

Rio Fucino dam – Back analysis /1

Analysis has been performed in two steps:

- First step: application of static loads giving the initial state of stress
- Second step; application April 9 earthquake

Static loads:

- Self weight

- Hydrostatic load at 1310.20 a.s.l, measured on April 9
  - about 10 m below the max water retention

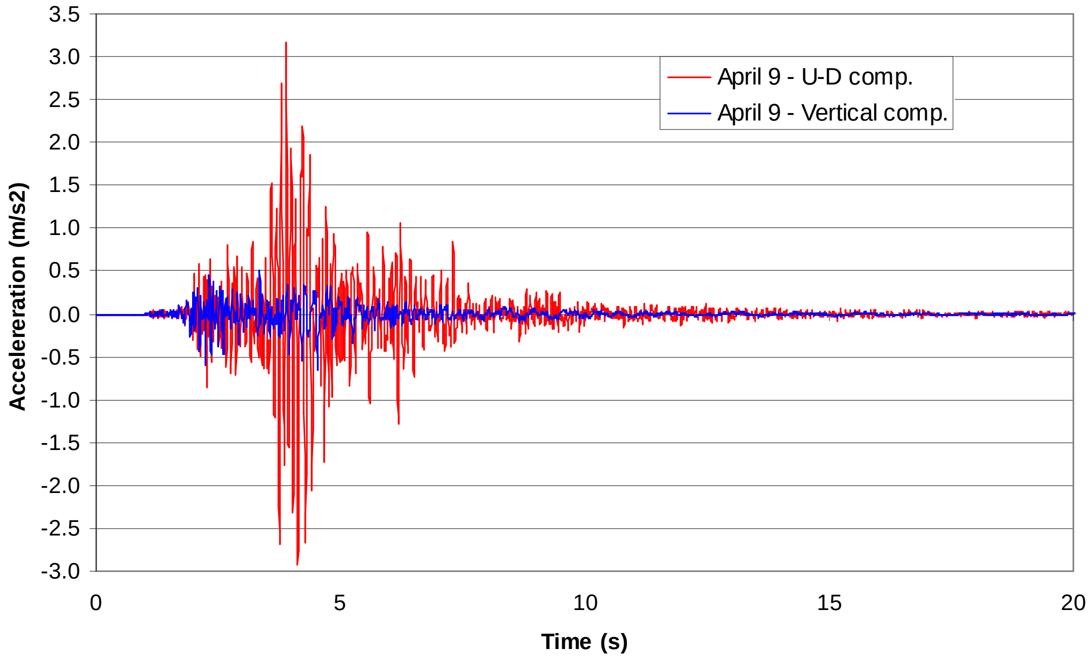
- Uplift force at the contact between dam - rock foundation. Values linearly vary from the water level in the basin to 65% of this value on the line of drainage system until reaching zero at the downstream toe

Earthquake:

- Accelerometric time-histories (horizontal and vertical components)
  - Horizontal EW and NS recorded components composed to provide U-D component for the analysis
- Hydrodynamic water load (Westergaard’s formulation)

- Viscous damping: Rayleigh approach

Rio Fucino dam – Back analysis /2



Aftershock of 9 April,2009 - Time Histories

Typical vibration of the block is a quite rigid rocking on the rock foundation with opening and closing of the joint

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Rio Fucino dam – Results – Friction angle at joint /1

Static analysis: ϕ=60°

Dynamic analysis:

- Initial value: ϕ=45° (the same used for analysis under MCE)
  - Permanent displacement: ≅ 1 mm
- **Final value: ϕ=60°**
  - Permanent displacement : ≅ 0 mm

ϕ=60° provides the best estimate of the global dynamic shear resistance mobilized along the interface between block and rock foundation.

To support this estimate the Barton-Choubay equation for rock joint was used:

$$\tau = \sigma_n \tan[JRC \log(JCS/\sigma_n) + \phi_r]$$

σ_n = normal stress
τ = shear stress at failure
ϕ_r = residual friction angle
JRC = Joint Roughness Coefficient
JCS = average Joint wall compressive stress

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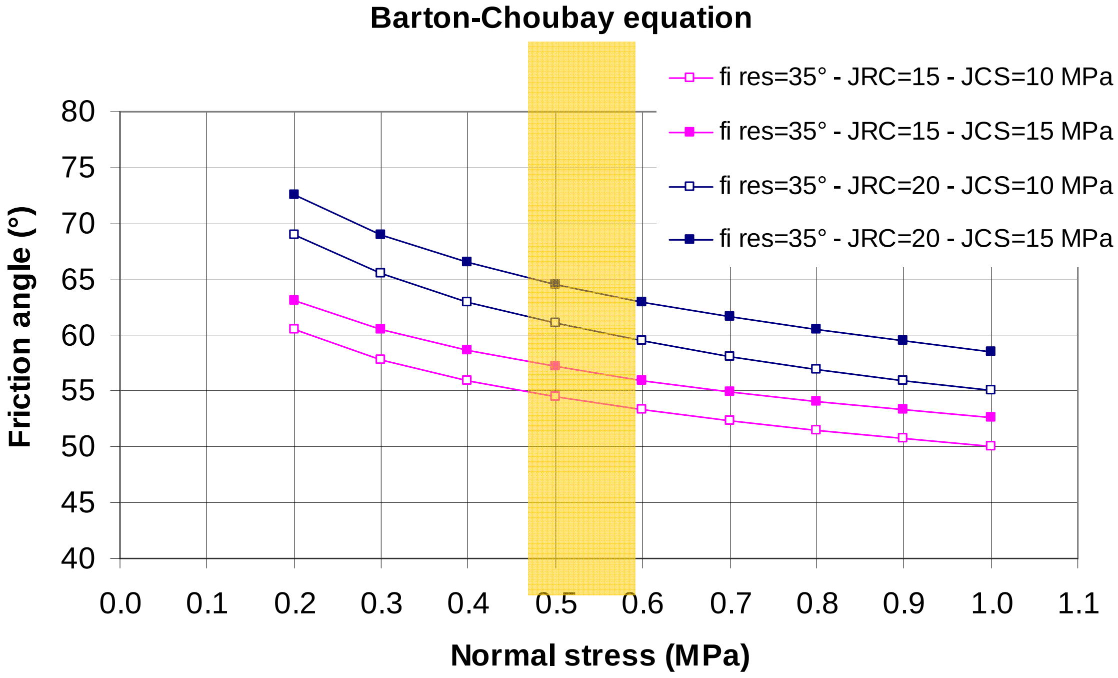
Rio Fucino dam – Results – Friction angle at joint /2

- Medium normal stress: 0.50-0.60 MPa (retrieved from the dynamic analysis)

- Residual friction angle; ϕ_r = 35° (triaxial tests carried out in the past on the rock foundation of Stecche bridge crossing the lake.

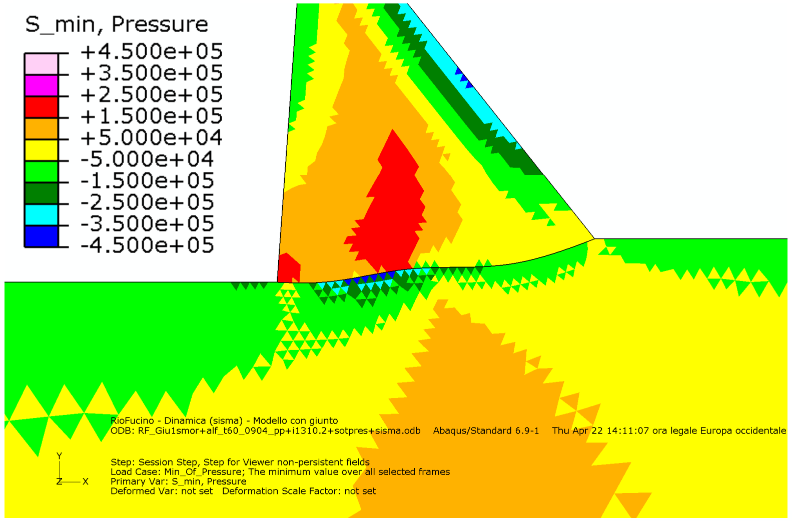
- JCS ranging from 10 to 15
- JRC ranging from 15 to 20 (MPa)

Peak friction angle ranges between 55° and 65°

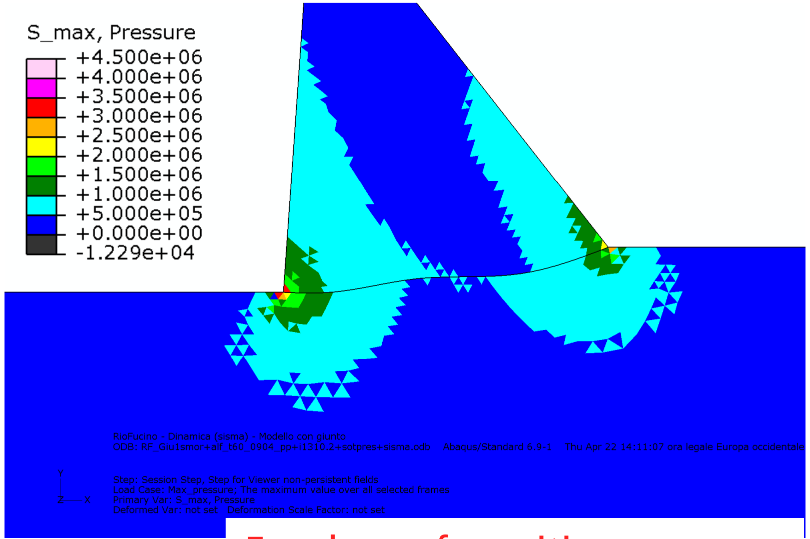


Rio Fucino dam – Results – Rock shear strenght

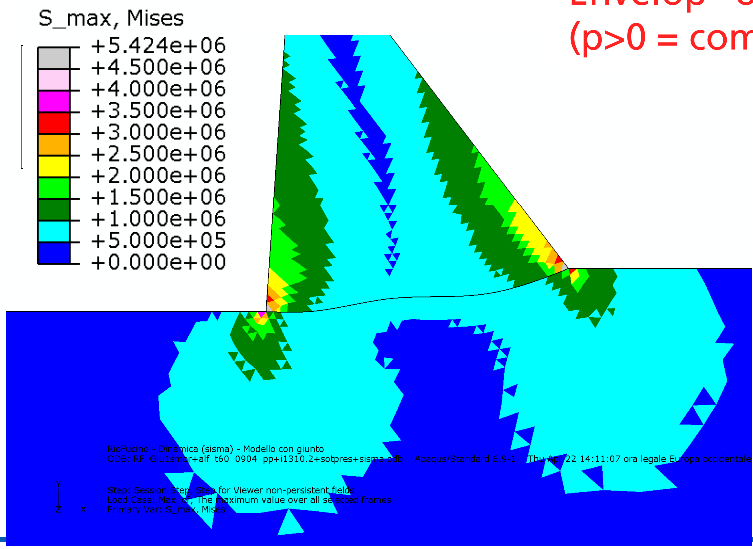
Envelop of “p” (isotropic component or pressure) and “q”(deviatoric component or Mises)



Envelop of negative pressure (p>0 = compression)



Envelop of positive pressure (p>0 = compression)



Envelop of deviatoric comp.

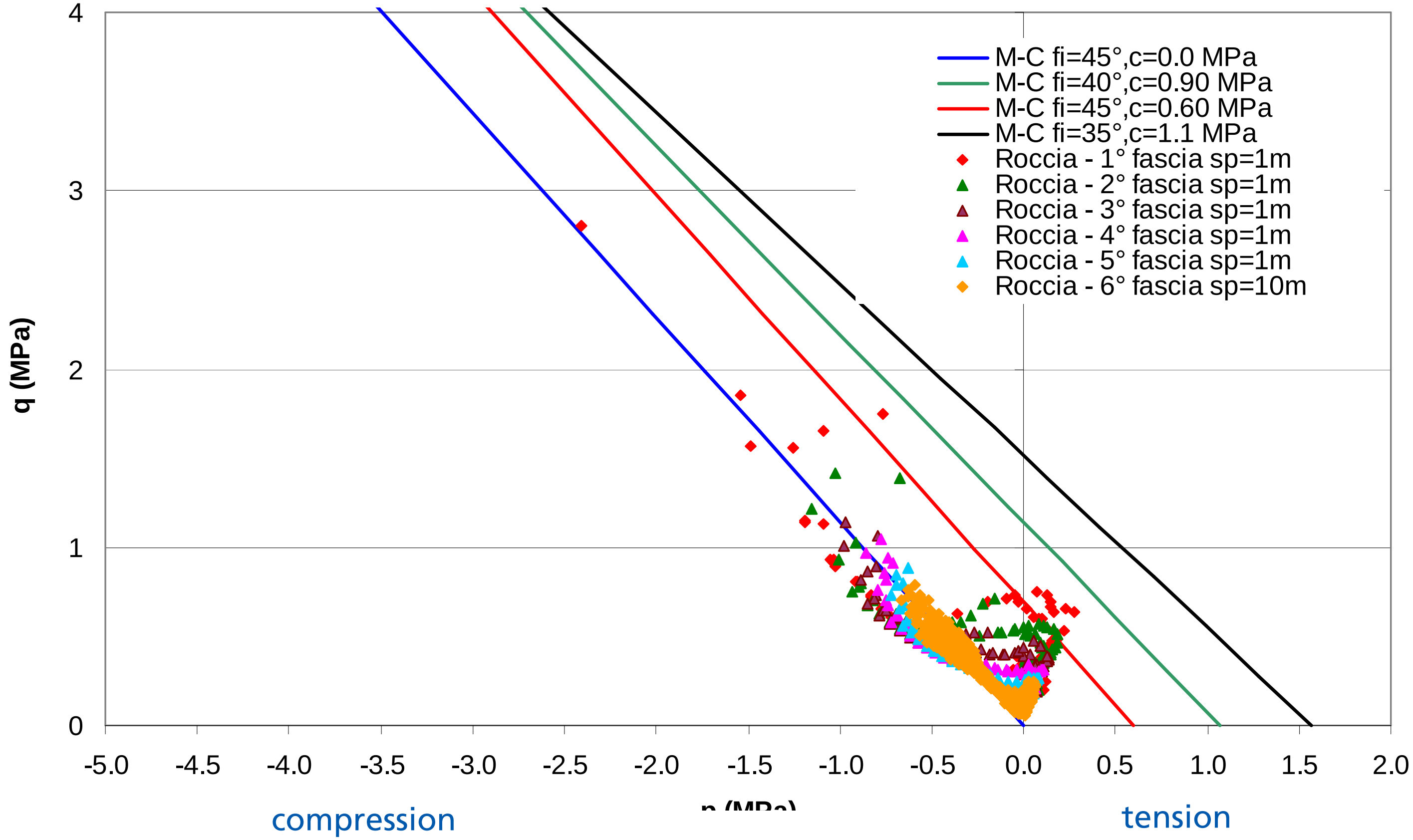
Rio Fucino dam – Results – Rock shear strenght /1

The flow of the activities for the identification of the best couple of shear strenght parameters is shown:

- Choosing of the most significant instants
    - maximum deviatoric and isotropic values, corresponding to maximum openings at upstream and downstream toe. These instants were selected for the evaluation of “p” and “q”
- Choosing of a reasonable range of variation of friction angle and cohesion
    - Literature and experimental data retrieved from the rock foundation of Stecche bridge, crossing the lake, with similar geological condition
    - Range considered in our evaluation
        - Friction angle: 35°-45°, cohesion: 0-1.1 MPa
- Stresses and failure lines reported in the “p-q” plane
    - Six rock layers with increasing deepness has been considered

Rio Fucino dam – Results – Rock shear strenght /2

Instant of maximum opening at upstream toe



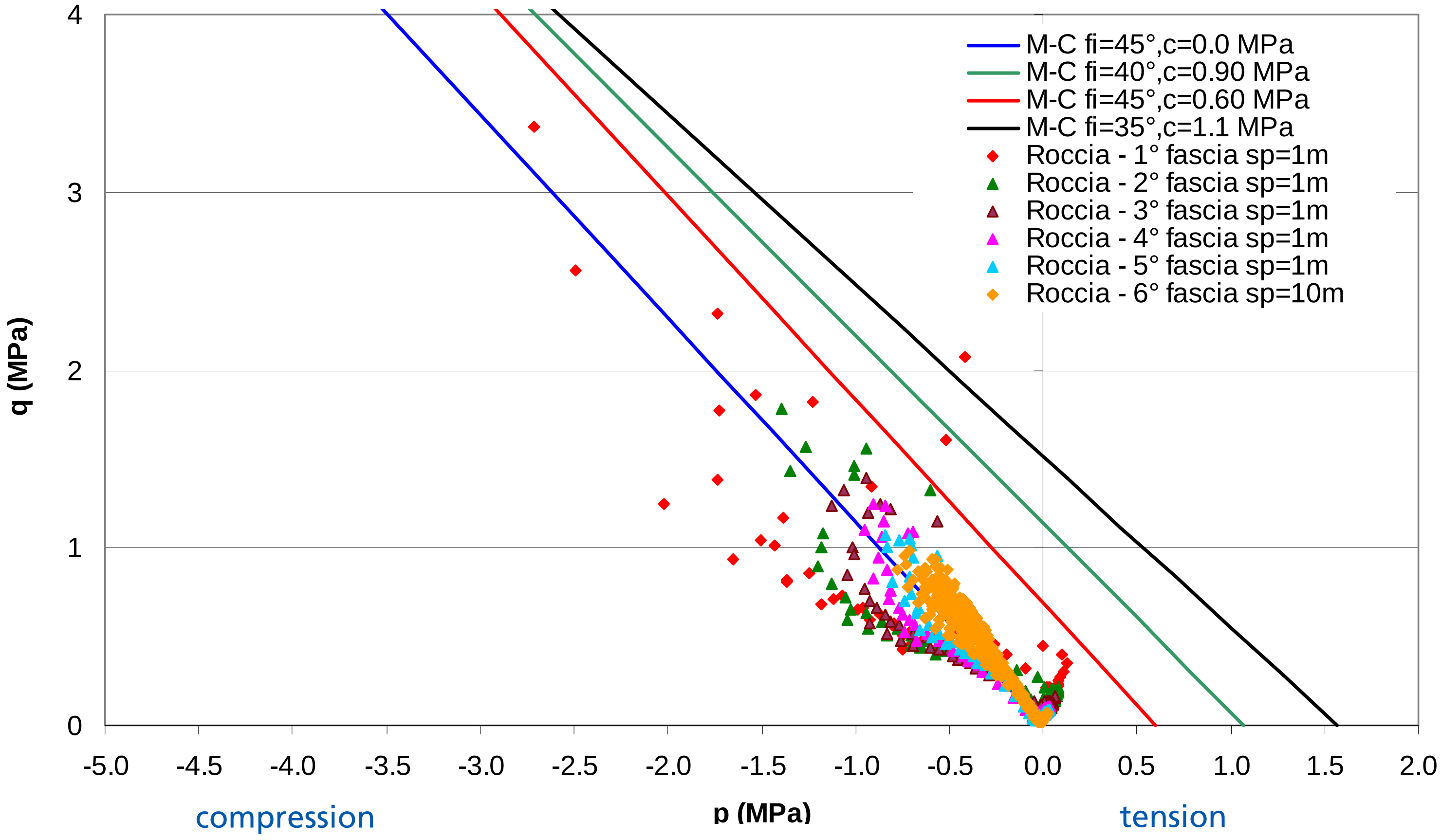
More credible couples of values satisfying Mohr's-Coulomb criterion:

ϕ=40° **c=0.90 MPa** (green line)

ϕ = 35° **c = 1.10 MPa** (black line)

Rio Fucino dam – Results – Rock shear strenght /3

Instant of maximum opening at downstream toe



More credible couples of values satisfying Mohr's-Coulomb criterion:

ϕ=40° c=0.90 MPa (green line)

ϕ = 35° c = 1.10 MPa (black line)

Main conclusions

Back analysis on the Rio Fucino concrete gravity dam under strongest aftershock of seismic sequence of l'Aquila (Ml=5.1) provided a reliable estimate of the global shear strenght of the rock foundation and along the interface between dam and rock for the highest block

- **Rock mass**: credible couples of friction angle-cohesion values satisfying Mohr's Coulomb criterion are ϕ=40°, *c*=0.90 MPa and ϕ =35°, *c*=1.10 MPa
- **Interface block-rock**; friction angle of 60° that includes all the contributes affecting the global shear strenght

Strongest aftershock didn't activate the limit strenght capacity:

- Dynamic response highlighted by measurements and visual observation was consistent with a **global linear dynamic dam behaviour**

These estimates are strictly connected with earthquake used for the analysis:

- The **effective shear strenght could be different but not lower**