International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

Luc Boutonnier

Dino Mahmutovic

Session : Qualification of seismic analysis of embankment dams

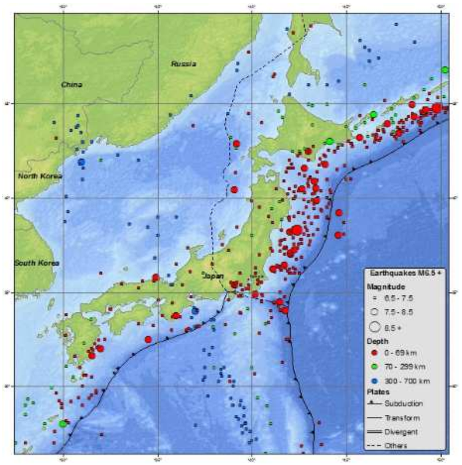
Dynamic analysis of Aratozawa dam including the effect of occluded air and pore fluid compressibility

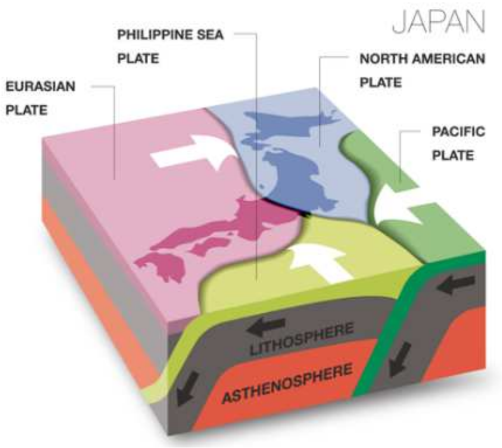
SUMMARY

Introduction

Earthquakes and Japan

- **Illustration of tectonic plate movement in Japan**





Seismicity Map - 1900 to Present

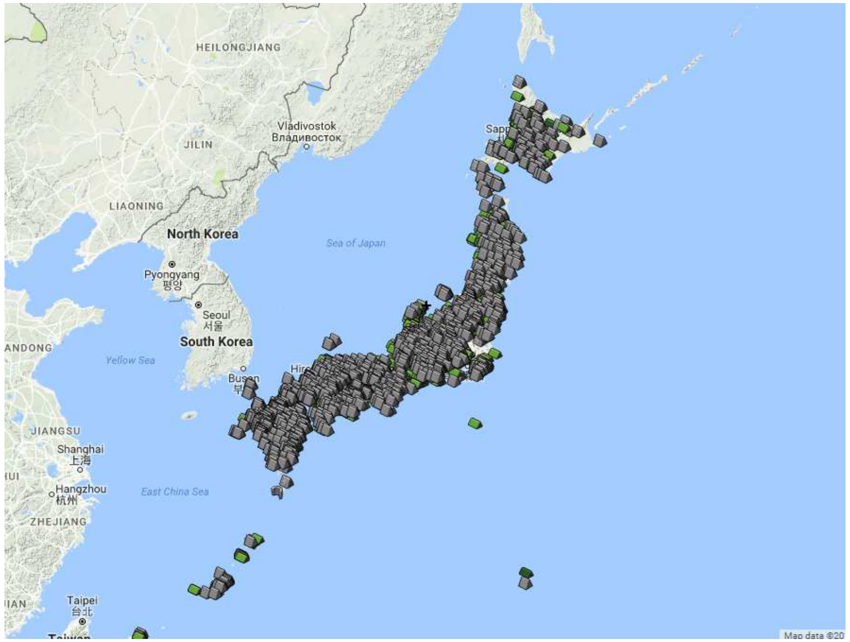
http://geographymapsjapan.weebly.com/landscape.html

Japan ➔ an area of high seismicity with a long history of earthquake

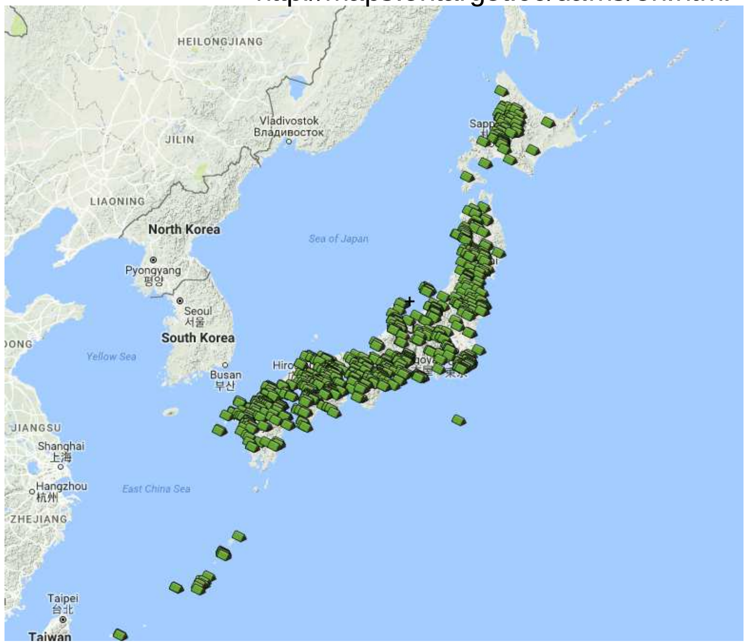
Many dams in Japan

- **Localisation of main dams in Japan**

http://maps.ontarget.cc/dams/en.html



Map of all types of dams

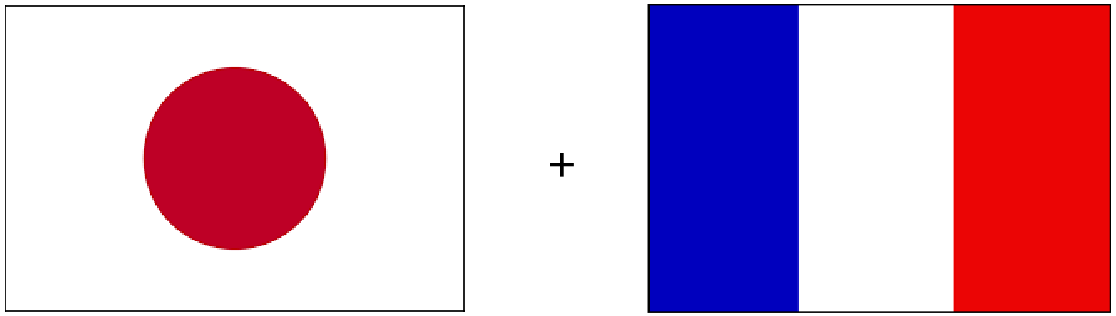


Map of earthfill dams

Japan ➔ many acceleration history measurements available during earthquakes

JCOLD / CFBR collaboration

- **Share data and experiences in design**



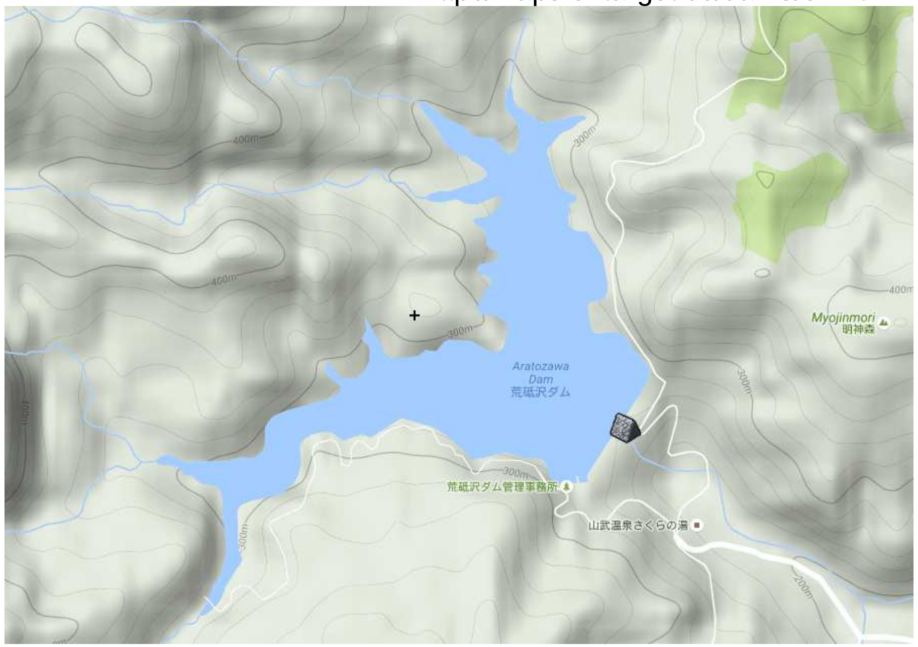
- **Improve the calculation procedures using data from real seismic events with high energy earthquake**

Aratozawa Dam

Description of Aratozawa Dam

- **Localisation of Aratozawa dam**

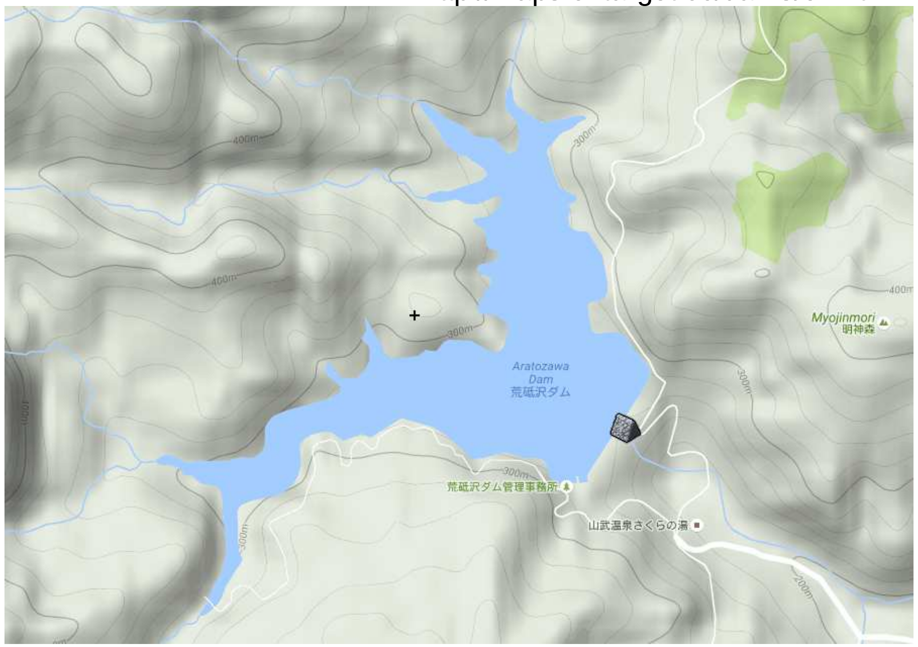
http://maps.ontarget.cc/dams/en.html



Description of Aratozawa Dam

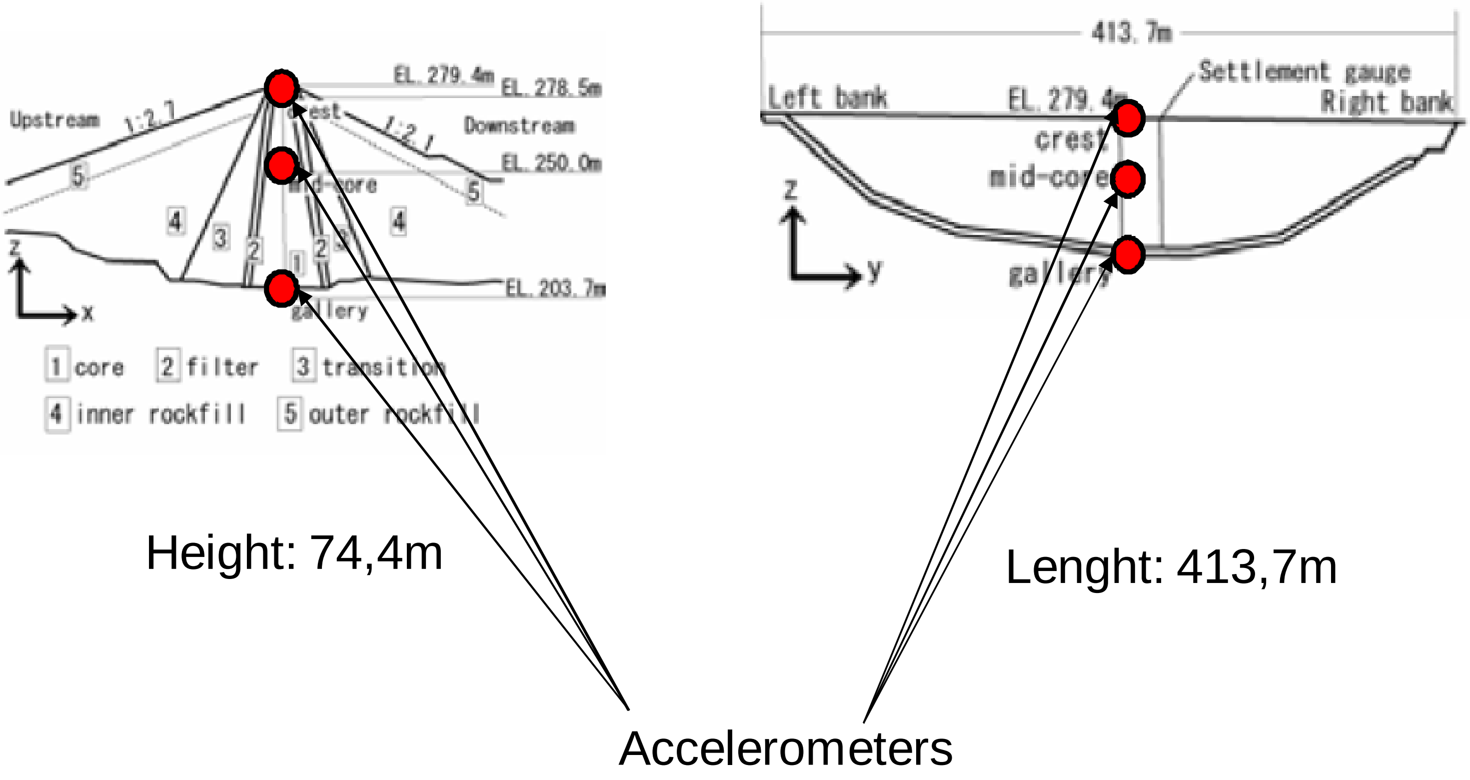
- **Localisation of Aratozawa dam**

http://maps.ontarget.cc/dams/en.html



Description of Aratozawa Dam

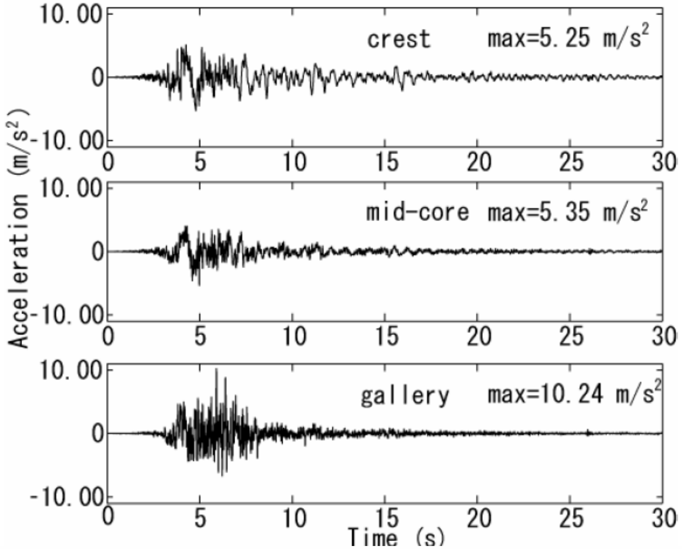
- **Geometry of Aratozawa dam (Ohmachi and Tahara, 2011)**



Description of Aratozawa Dam

- **Main earthquake (Ohmachi and Tahara, 2011)**

No	Date (time)	Magnitude M	Peak acceleration at gallery (m/s²)
1	1996.8.11(3:12)	5.9	0.28
2	1996.8.11(8:10)	5.7	0.33
3	1996.8.11(15:01)	4.8	0.30
4	2008.6.14(8:43)	7.2	10.24
5	2008.6.14(9:00)	4.7	0.99
6	2008.6.14(9:01)	4.0	4.82
16	2008.6.14(12:10)	4.7	0.79
19	2008.6.14(19:11)	4.1	2.29
36	2008.6.16	5.3	0.76
62	2008.6.19	3.2	0.36
118	2008.7.18	3.0	0.53
127	2008.7.24	6.8	0.24
137	2008.7.29	3.9	0.90
149	2008.8.4	3.5	0.78
169	2008.9.25	4.1	1.19
176	2008.12.15	3.4	0.39
183	2009.7.1	3.2	0.02
189	2009.8.4	1.6	0.02



➔ Estimation of seismic wave velocity Vs :

$$V_s = \frac{distance\ between\ 2\ accelerometers}{delay\ between\ 2\ accelerometers}$$

Description of Aratozawa Dam

- **Main earthquake episods(Omashi 2011)**

No	Date (time)	Magnitude M	Peak acceleration at gallery (m/s²)
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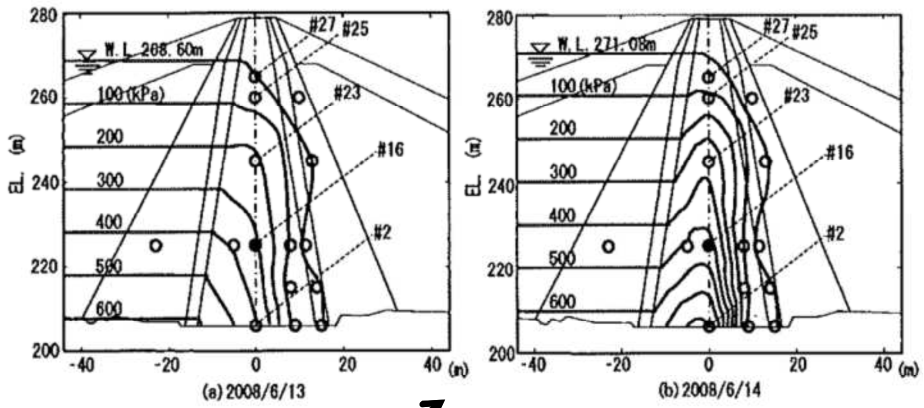
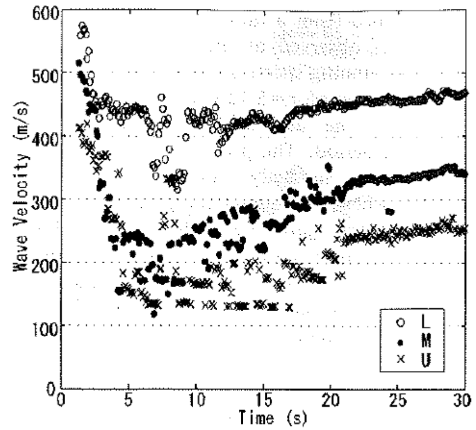
At the end of the earthquake:



u_w ↗



V_s ↘

Description of Aratozawa Dam

- **Main earthquake episods**

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At the end of the earthquake:

u_w ↗ V_s ↘

How to explain these phenomena?

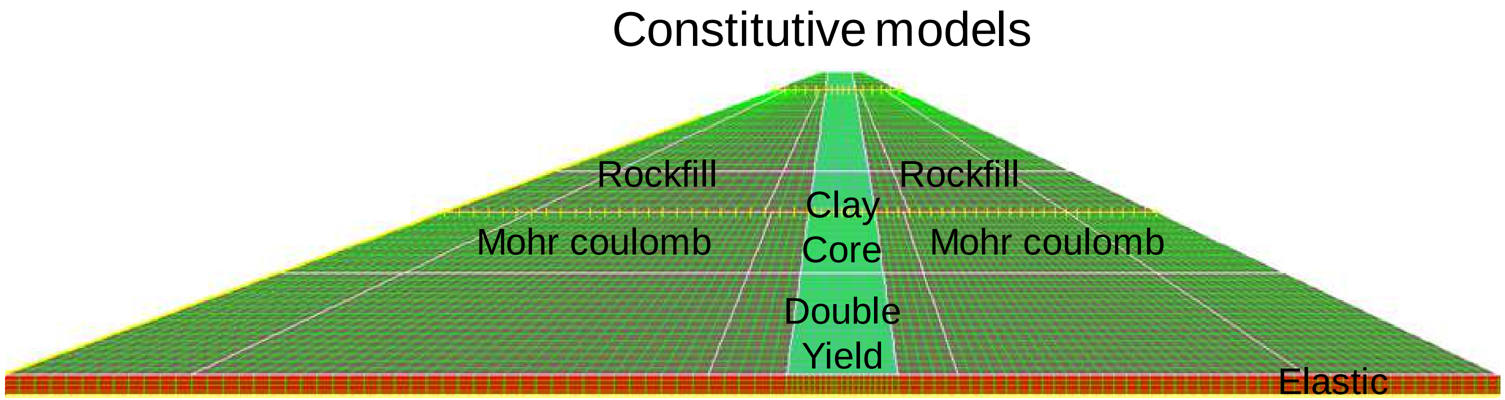
Anisotropy?

Irreversible plasticity ?

Dynamic analysis of Aratozawa Dam

Dynamic analysis of Aratozawa Dam

- **Construction**



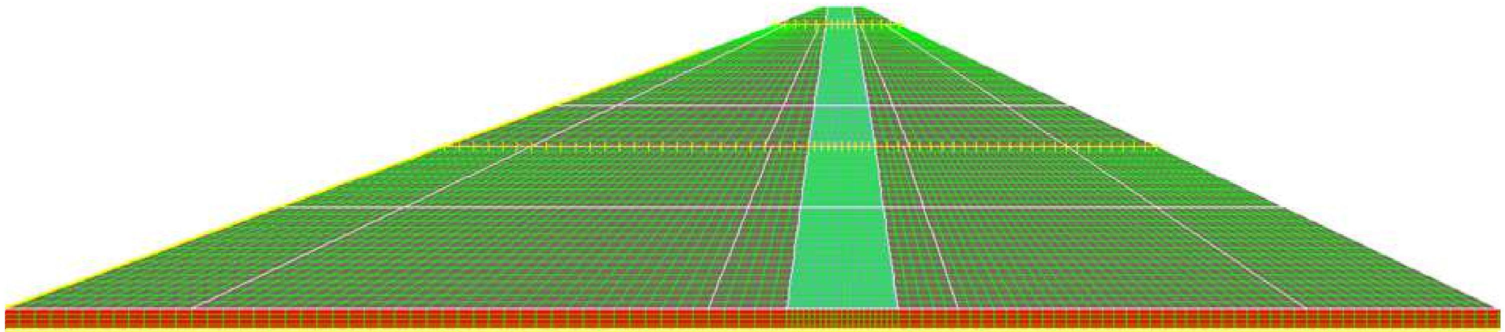
Dynamic analysis of Aratozawa Dam

- **Main stages in the numerical model calculations**

Stage	Hydraulic	Mechanical calculation	Comment

Dynamic analysis of Aratozawa Dam

- **Construction**



Numerical construction by step

Initial state of soil after compaction

$$\sigma'_{vini} = -u_{w,ini}$$

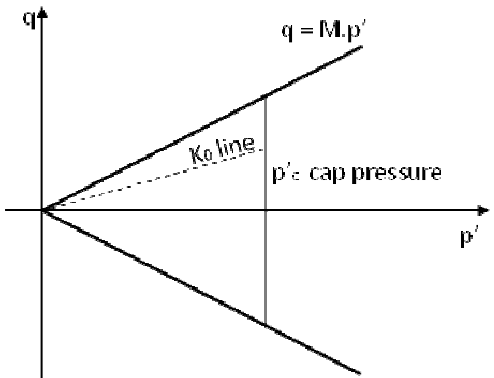
$$\sigma'_h = K0 * \sigma'_v$$

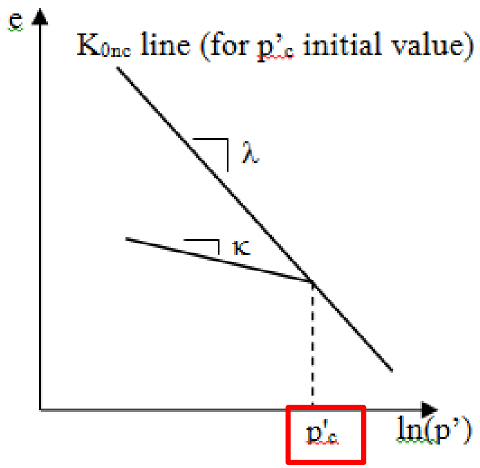
$$K0 = (1 - \sin(\phi')) * \left(\frac{\sigma'_p}{\sigma'_{vini}}\right)^{0.5}$$

Dynamic analysis of Aratozawa Dam

- **Construction**

Skeleton compressibility parameters in the core of the dam parameters





	λ	κ	comment
Fine soil fraction of the core	0.14	0.025	PI=32. WL = 32/0.73+13 = 57 (estimated from Casagrande, 1947) Correlations using WL and PI : Biarez and Favre (1975), Fleureau and al. (2002), Favre et al. (2002)
Real soil of the core Assumption 1	0.035	0.006	$\lambda_{real\ soil} = \lambda_{fine\ soil\ fraction} * \mu_{cl}$ $\kappa_{real\ soil} = \kappa_{fine\ soil\ fraction} * \mu_{cl}$ $\mu_{cl} = 25\%$
Real soil of the core Assumption 2	0.14	0.025	$\lambda_{real\ soil} = \lambda_{fine\ soil\ fraction} * \mu_{cl}$ $\kappa_{real\ soil} = \kappa_{fine\ soil\ fraction} * \mu_{cl}$ $\mu_{cl} = 100\%$

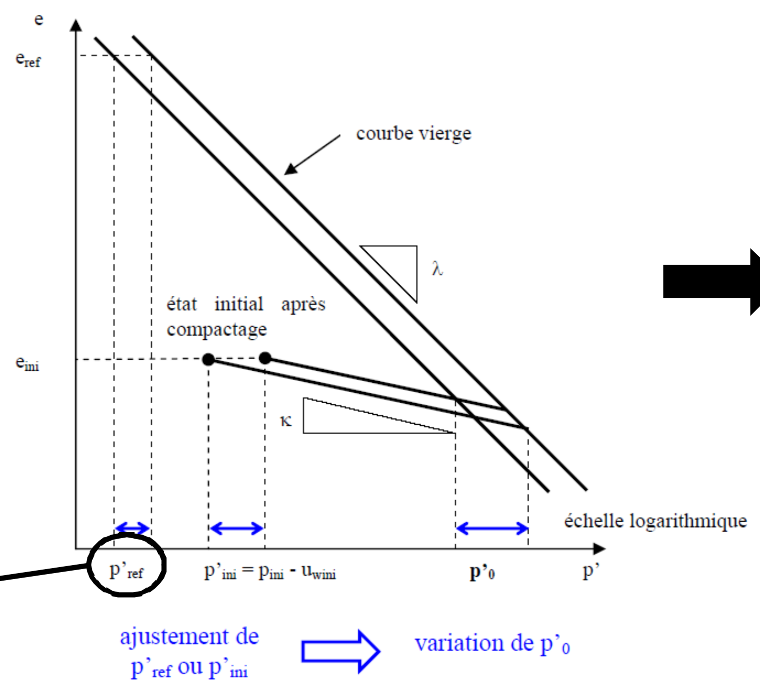
➔ $p'_c = 250$ kPa (W_{OPN} + 1%)

Dynamic analysis of Aratozawa Dam

- ## Construction

Skeleton compressibility parameters in the core of the dam parameters

Boutonnier 2007



W_{OPN} + 1%?

W_{OPN} + 3%?

Uncertainty

Parametric study

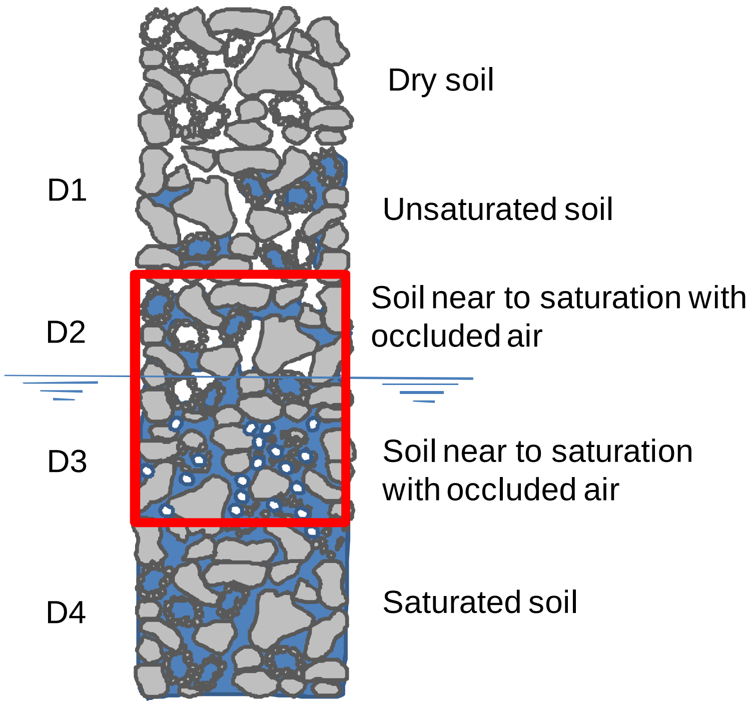
p'c = 250 kPa

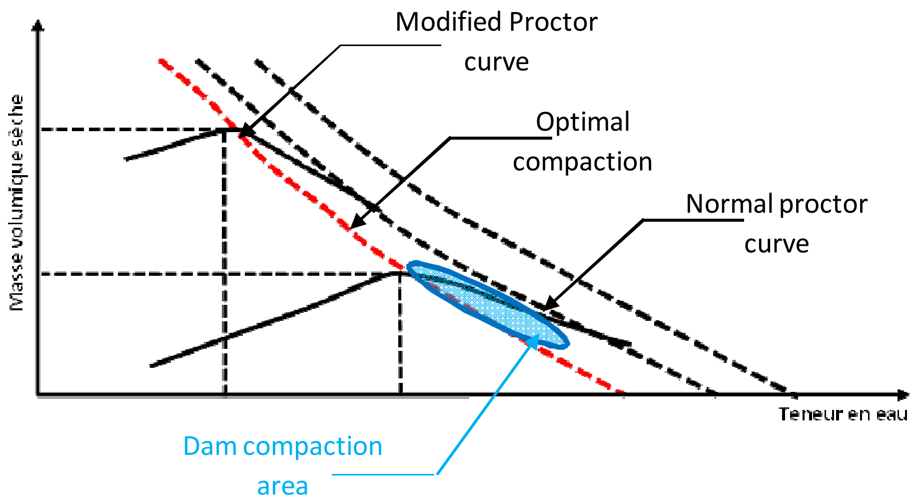
p'c = 150 kPa

Dynamic analysis of Aratozawa Dam

- **Construction**

Fluid compressibility





$$c_f = \frac{1}{S_r} \cdot \frac{dS_r}{du_w} + c_w$$

$$B = \frac{1}{1 + n\, c_f\, E} = \Delta u_w / \Delta \sigma$$

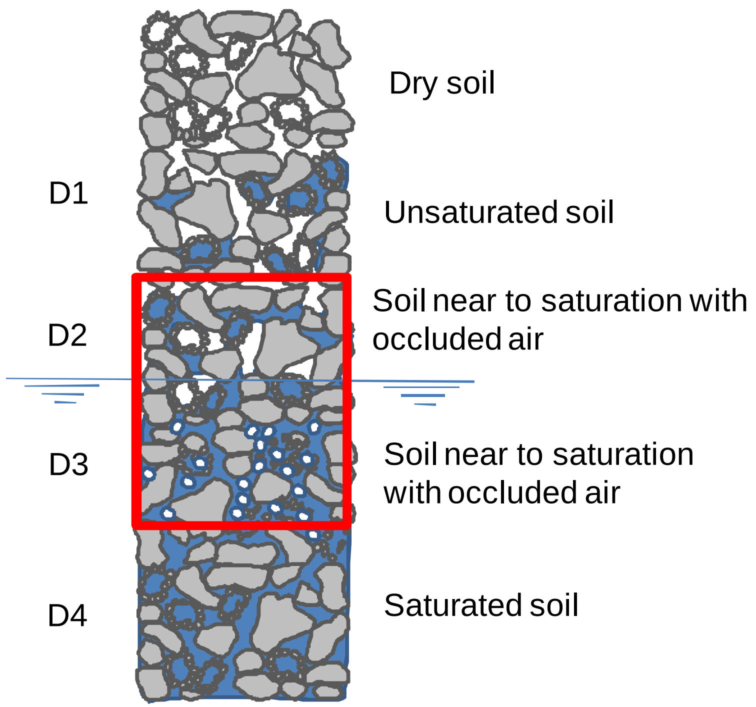
➔ Prediction of pore pressure build-up in the core

Dynamic analysis of Aratozawa Dam

- **Construction**

Fluid compressibility

$$c_f = \frac{1}{S_r} \cdot \frac{dS_r}{du_w} + c_w$$



$$S_r = S_{re} - u_w \frac{(S_{re} - S_{rair})}{u_{wair}}$$

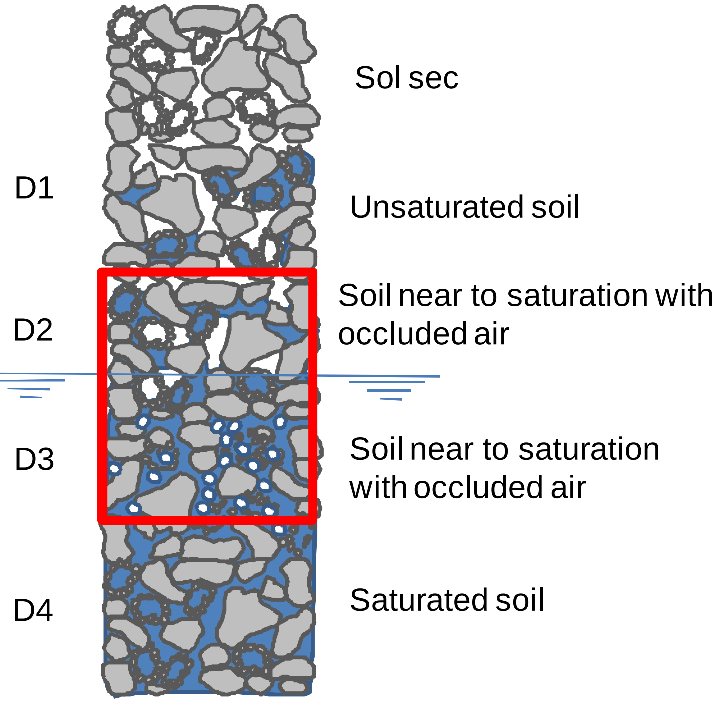
$$S_r = \frac{1}{1 - h + \left(\frac{1 - S_{re} + h.S_{re}}{S_{re}}\right) \cdot \left(\frac{s_{bm} + p_a - u_{wg}}{u_w + s_{bm} + p_a - u_{wg}}\right)}$$

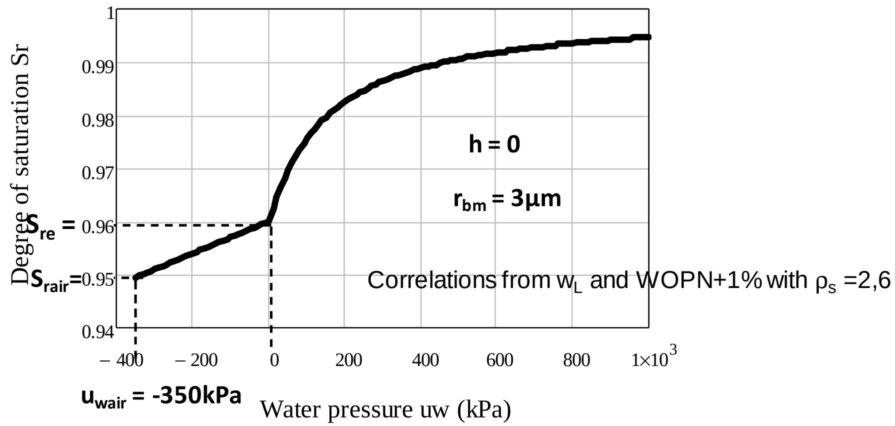
$$S_r = 1$$

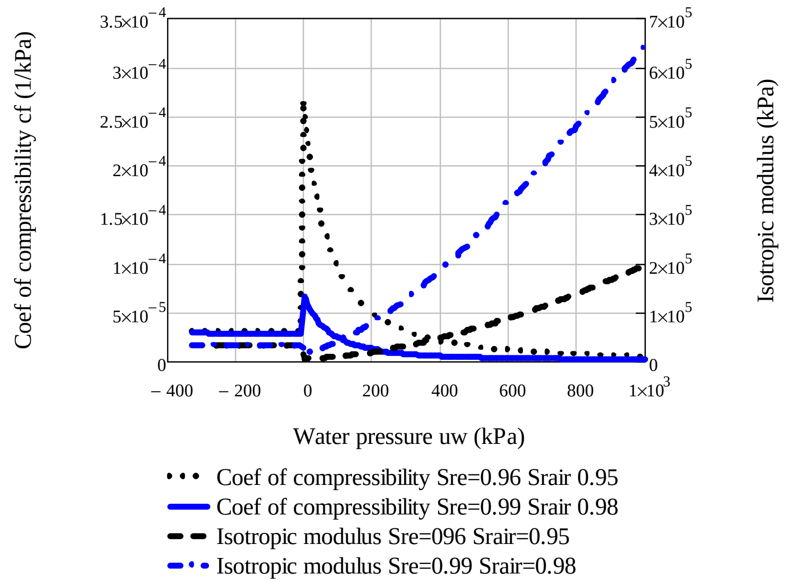
Dynamic analysis of Aratozawa Dam

- ## Construction

Fluid compressibility



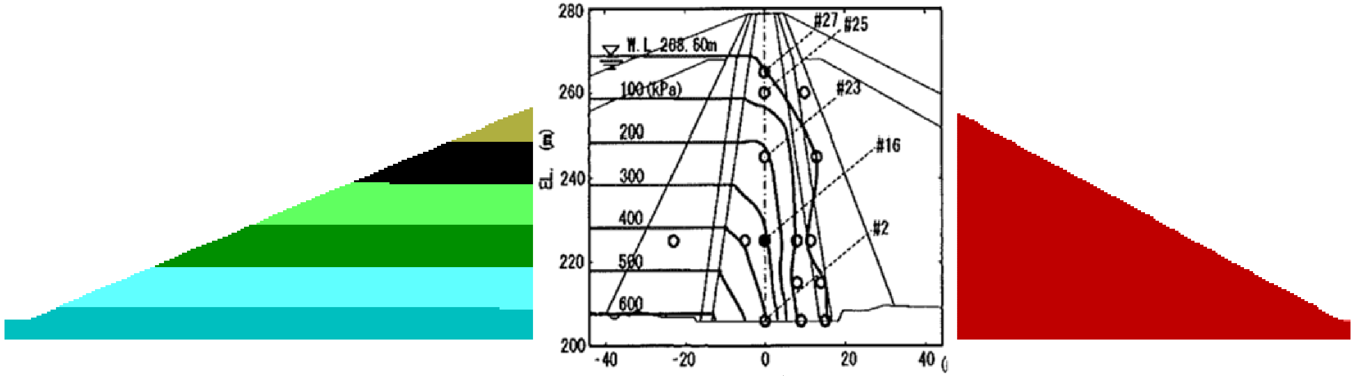




Dynamic analysis of Aratozawa Dam

- **Impoundement**

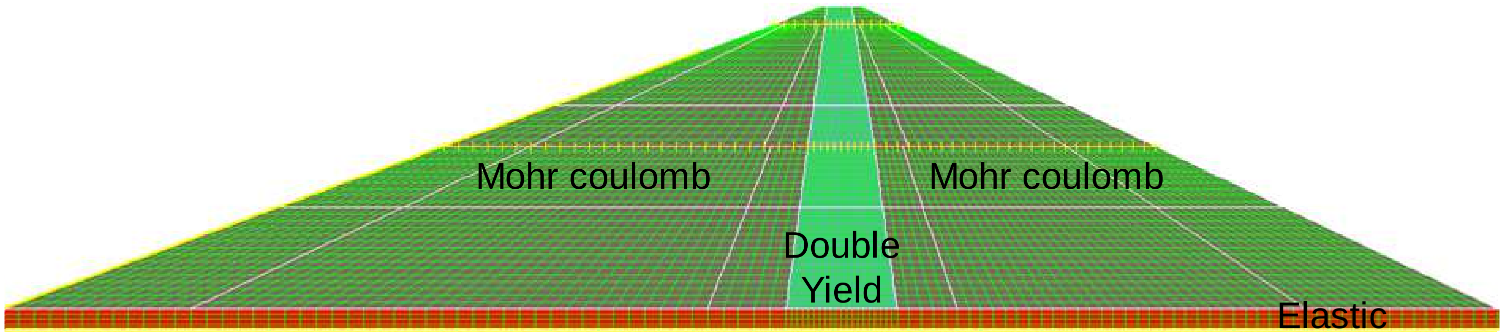
Pore pressure set up in the numerical model



Measured pore pressure before earthquake

Dynamic analysis of Aratozawa Dam

- **Construction**



Elastic parameters

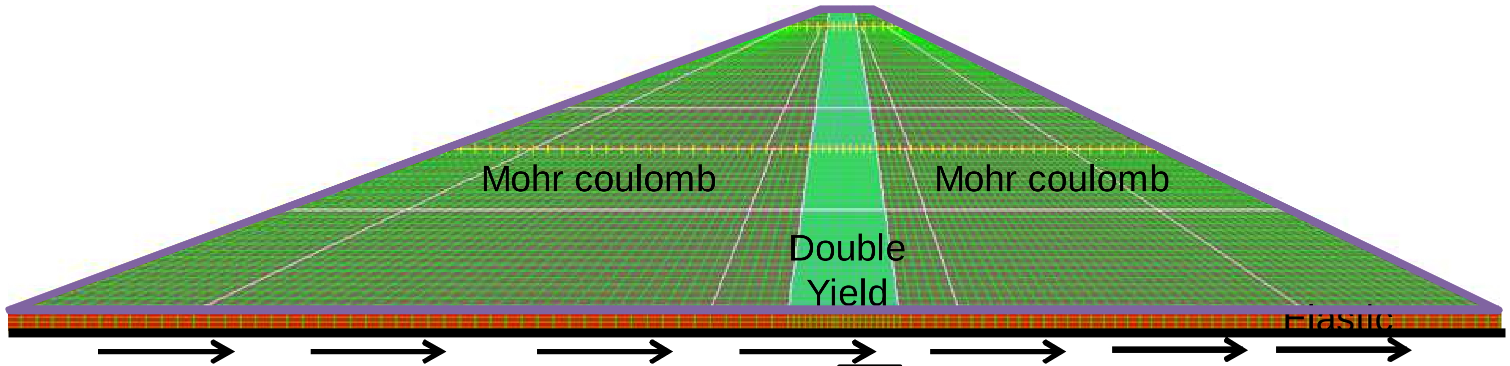
$$G_{max} = \rho * V_s^2$$

Values of V_s from Sawada and Takahashi (1975)

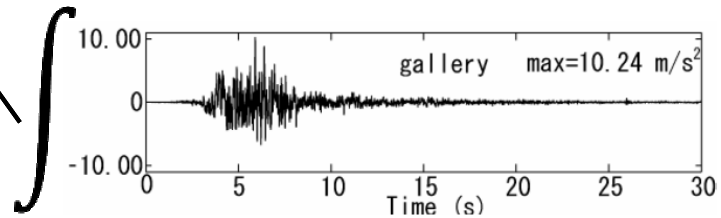
Depth z (m)	Clay core V_s (lower bond) (m/s)	Clay core V_s (upper bond) (m/s)	Saturated rockfill+ transition V_s (m/s)	Unsaturated rockfill + transition V_s (m/s)
0-5m	$V_s = 210$		$V_s = 245$	
5-30m	$V_s = 180.z^{0.35}$	$V_s = 140.z^{0.34}$	$V_s = 250.z^{0.2}$	$V_s = 250.z^{0.2}$
>30m			$V_s = 200.z^{0.31}$	$V_s = 250.z^{0.2}$

Dynamic analysis of Aratozawa Dam

- **Dynamic stage (simulation of the earthquake)**



$$\tau_b = -2 \times \rho \times V_s \times V_{acc}$$



Hysteretic damping

Attenuation of shear modulus G with distortion

$$G/G_{max} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)}$$

Dynamic analysis of Aratozawa Dam

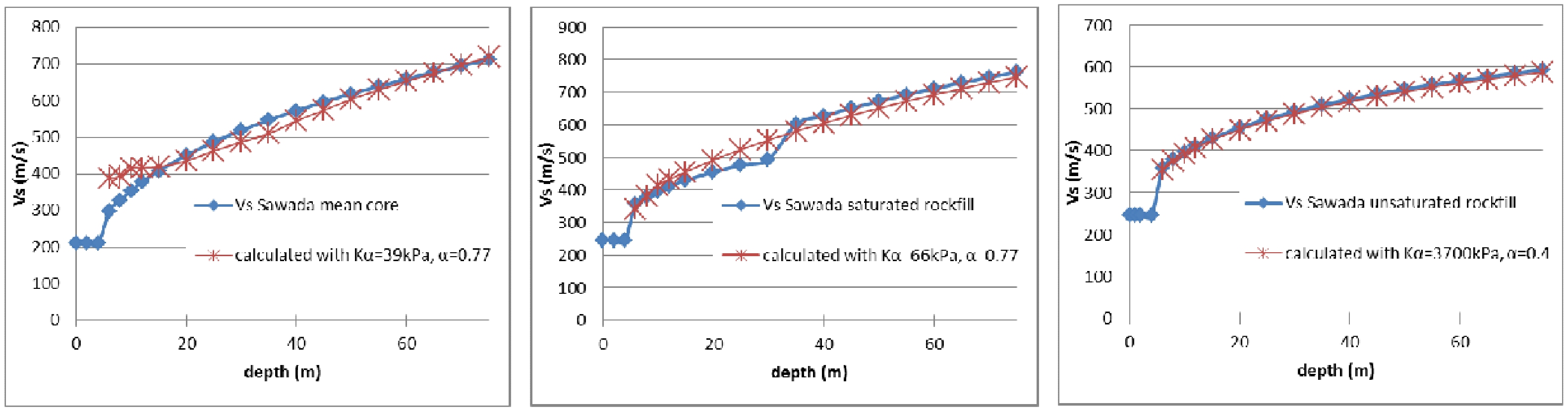
- **Dynamic stage**

Elastic parameters

$$G_{max} = K_{\alpha} * \left(\frac{\sigma_3'}{p'_{ref}} \right)^{\alpha}$$

Use of a power law with minor effective stress σ'_3 in order to obtain a value of Gmax depending on the depht

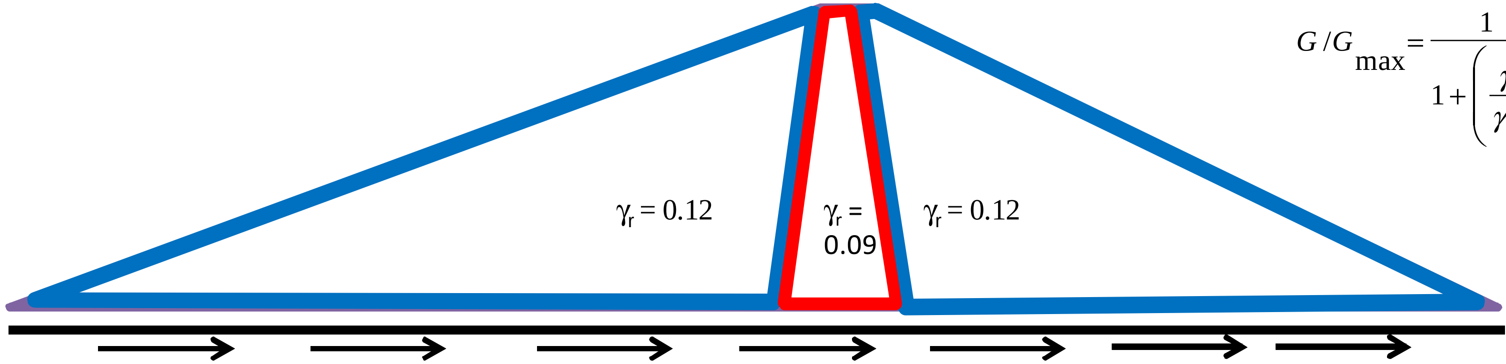
Comparison between V_s from Sawada and Takahashi (1975) and V_s calculated from $G_{max}(\sigma'_3)$



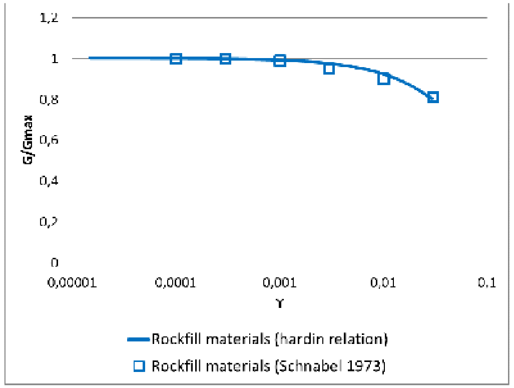
$\gamma_r = 0.09$

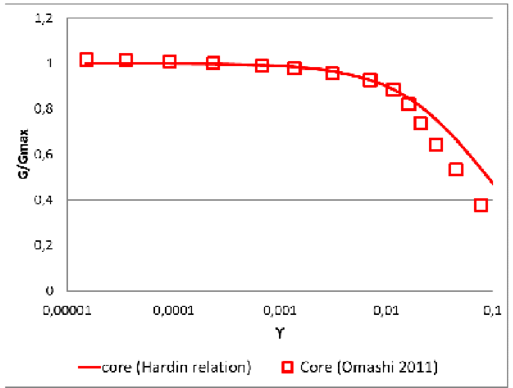
Dynamic analysis of Aratozawa Dam

- **Dynamic stage (simulation of the earthquake)**



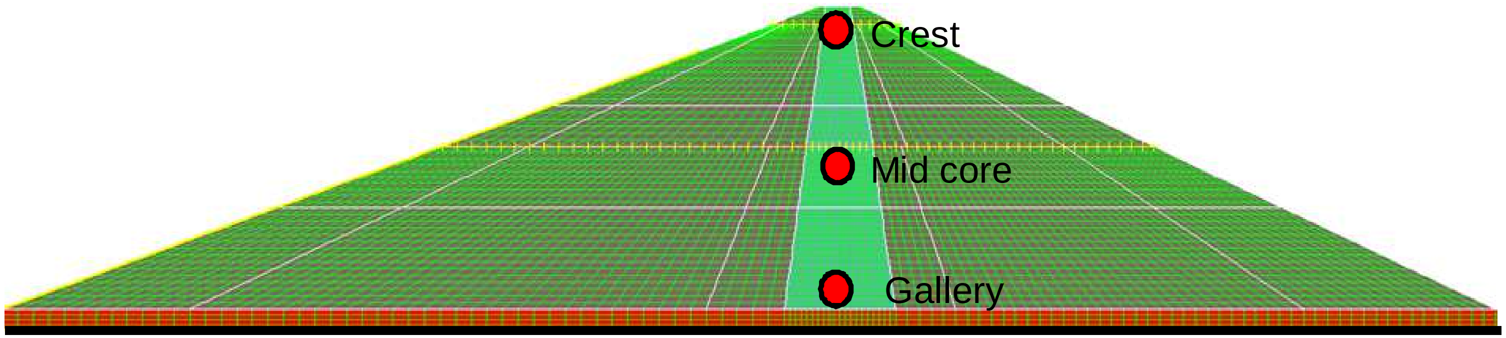
$$G/G_{max} = \frac{1}{1 + \left(\frac{\gamma}{\gamma_r}\right)}$$

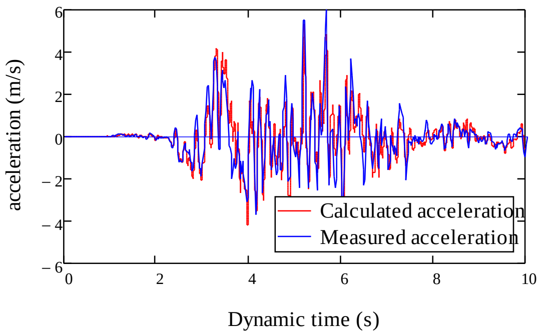


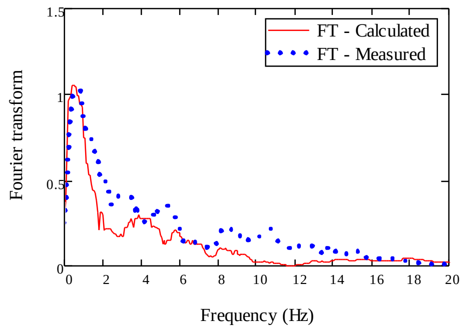


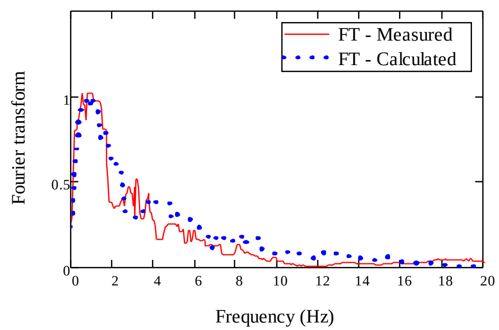
Dynamic analysis of Aratozawa Dam

- **Dynamic stage (simulation of the earthquake)**



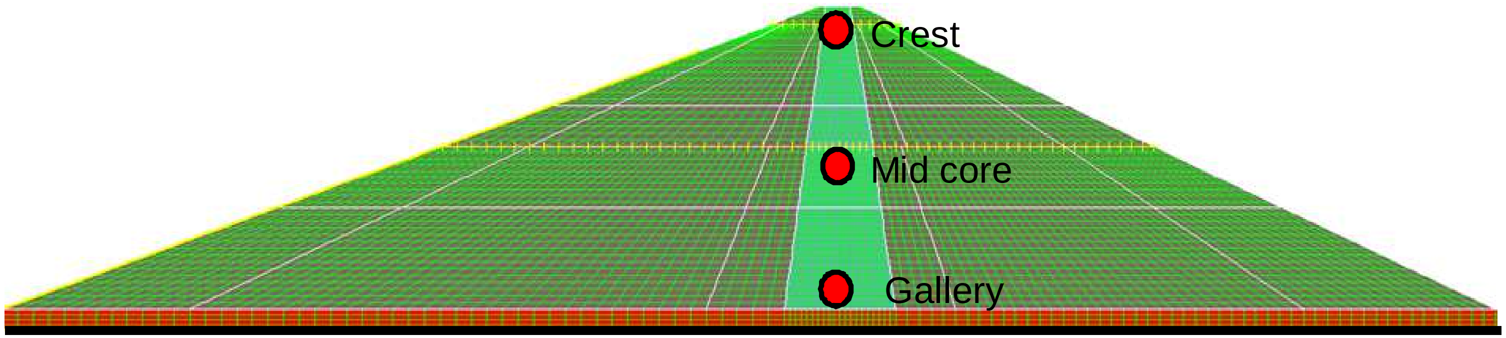




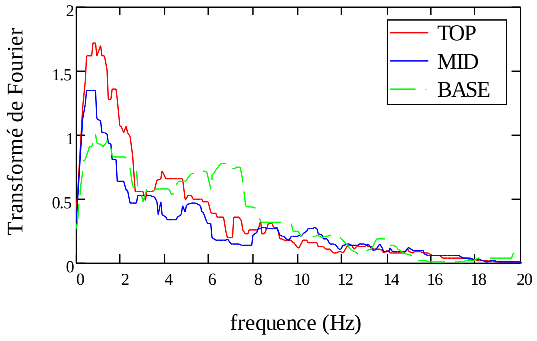


Dynamic analysis of Aratozawa Dam

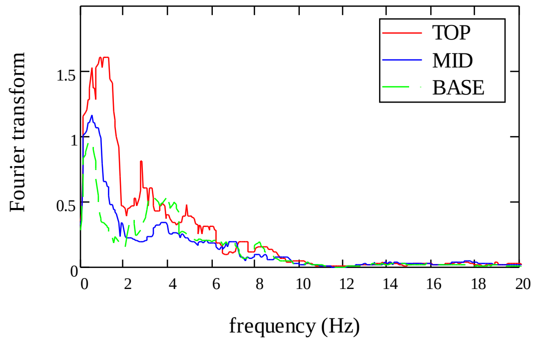
- **Dynamic stage (simulation of the earthquake)**



Measured spectral ratio

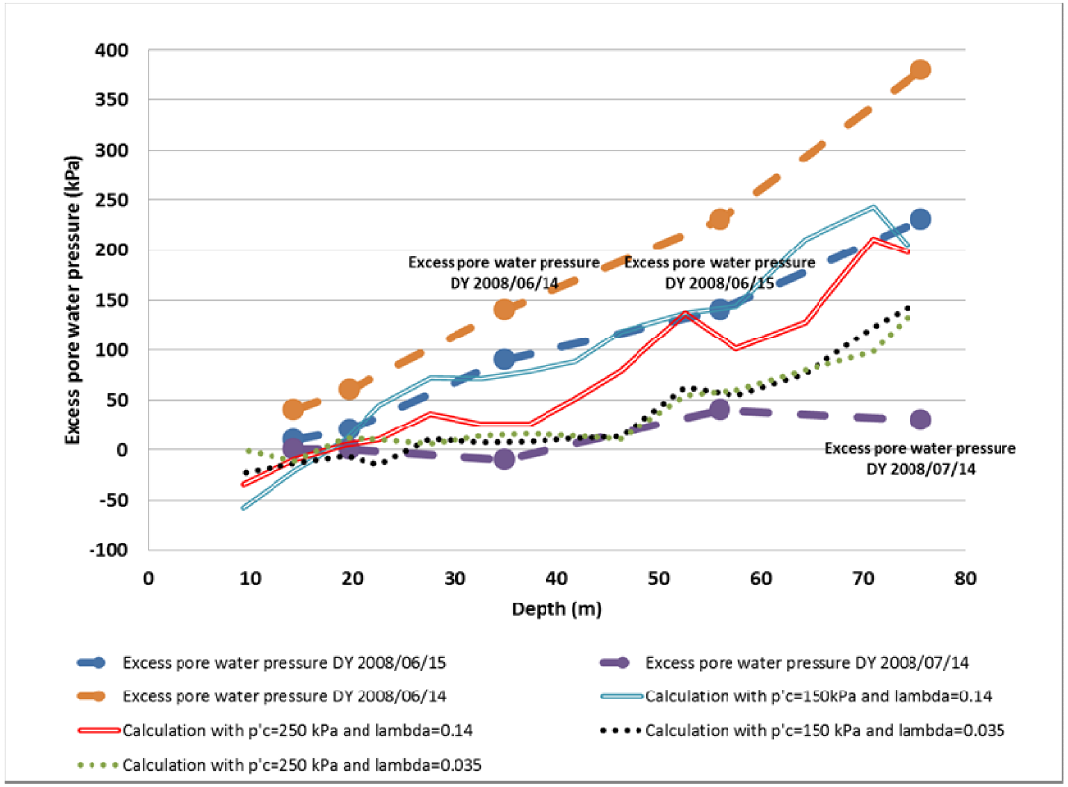


Calculated spectral ratio



Dynamic analysis of Aratozawa Dam

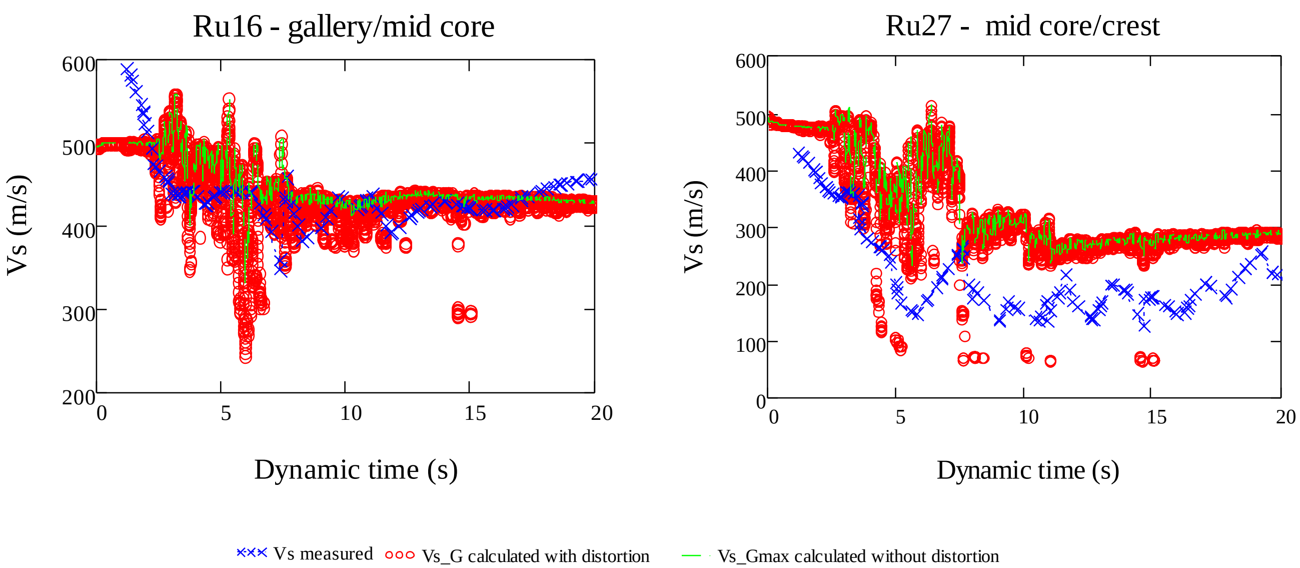
- **Estimation of pore pressure excess**



Dynamic analysis of Aratozawa Dam

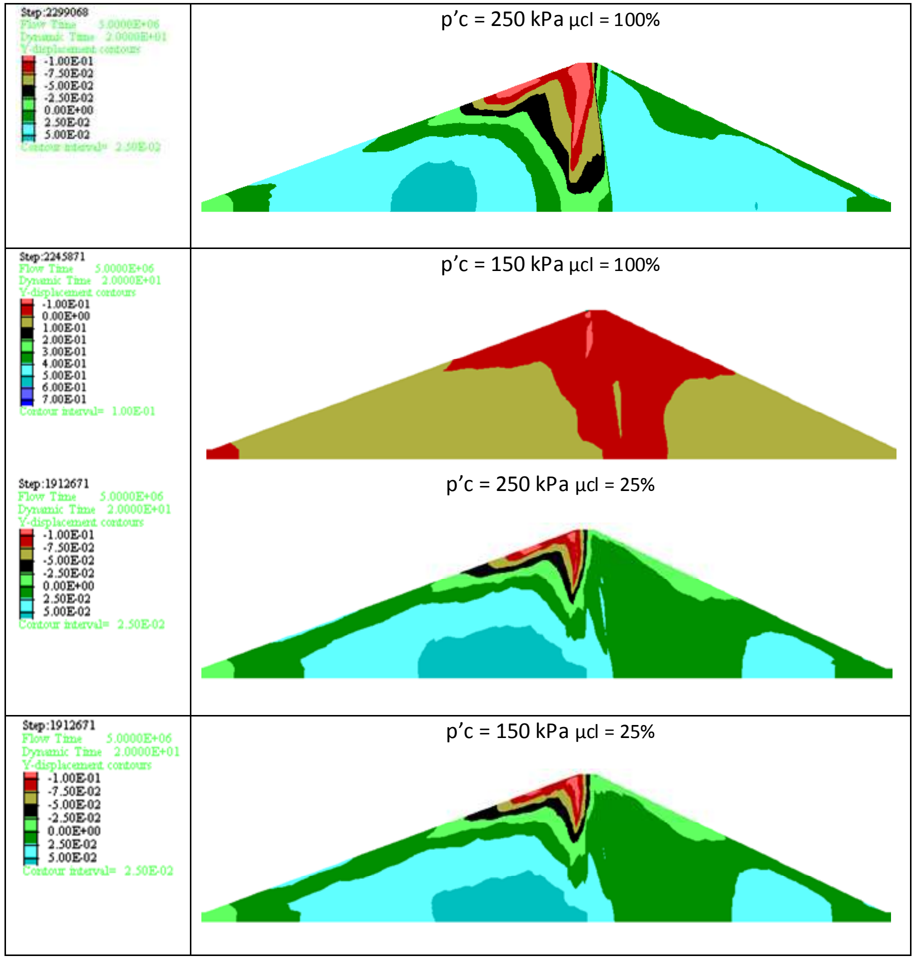
- **Estimation of shear wave velocity Vs**

p'c = 150 kPa - μ_{cl} = 100%



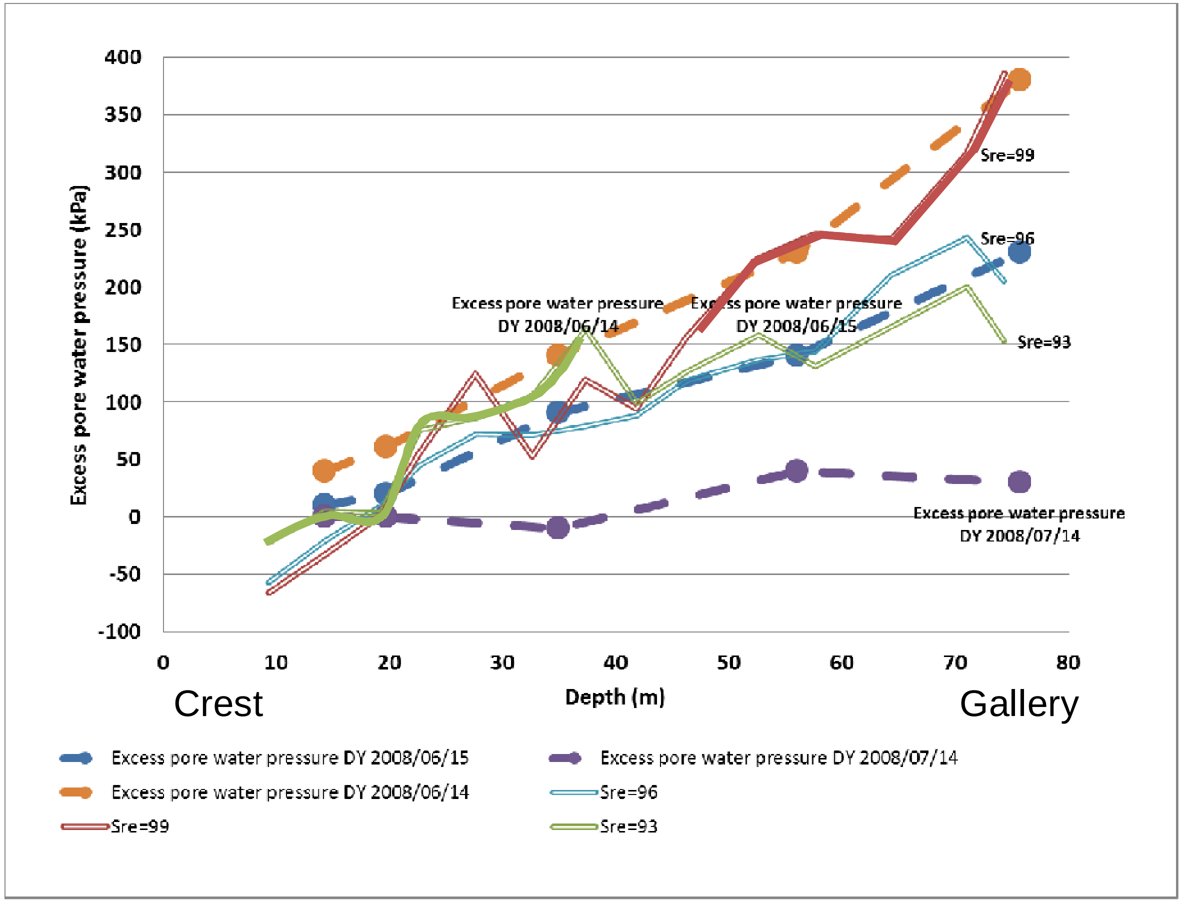
Dynamic analysis of Aratozawa Dam

- **Estimation of Settlements at the end of earthquake (before consolidation)**



Dynamic analysis of Aratozawa Dam

- **Effect of the occluded air**



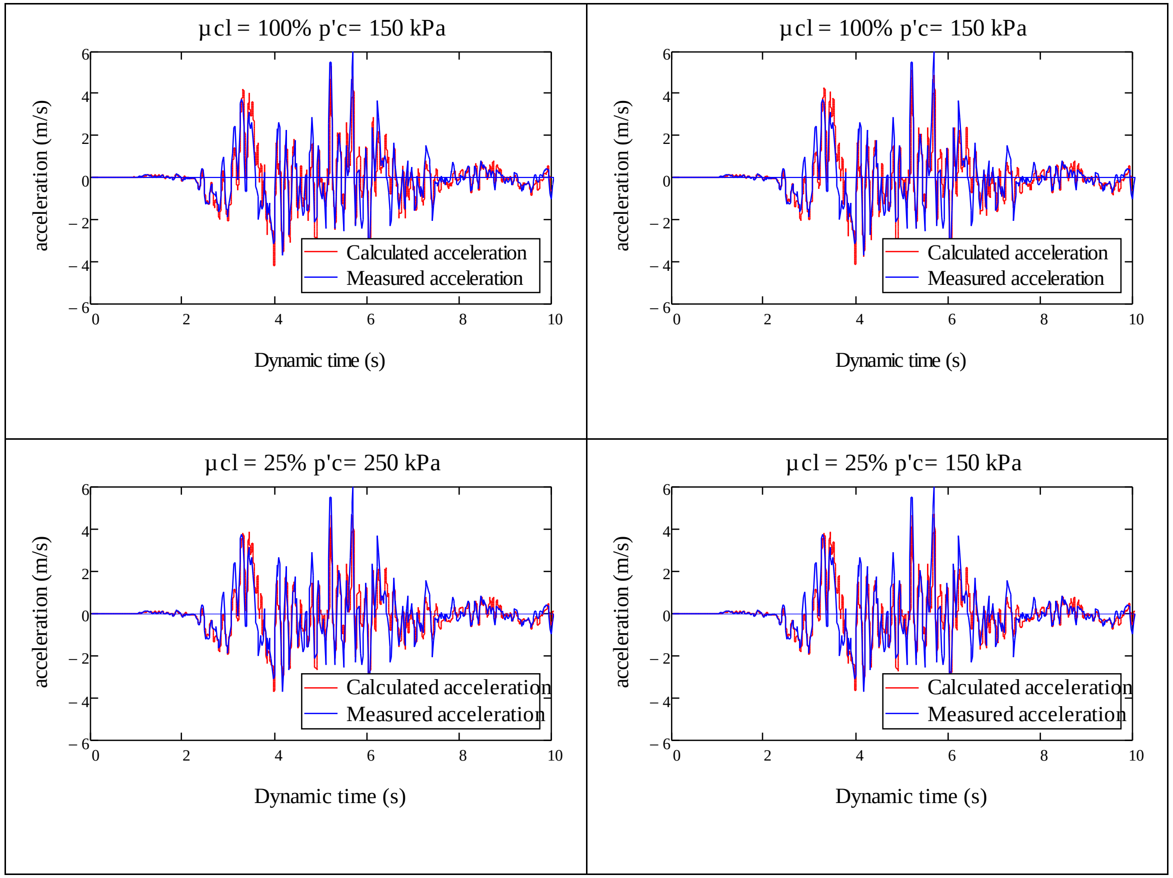
Evolution of the ratio of occluded air as a function of depth ➔ dissolution of part of the occluded air in the water

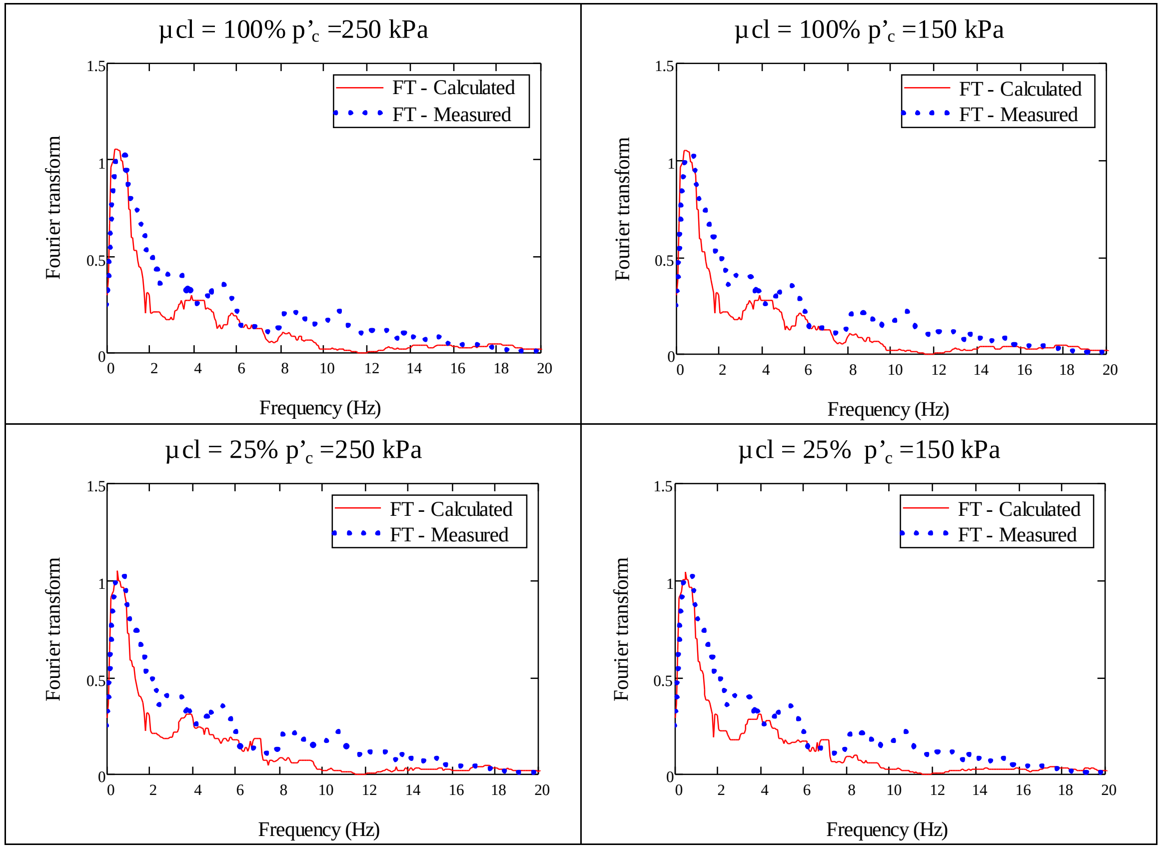
Conclusion

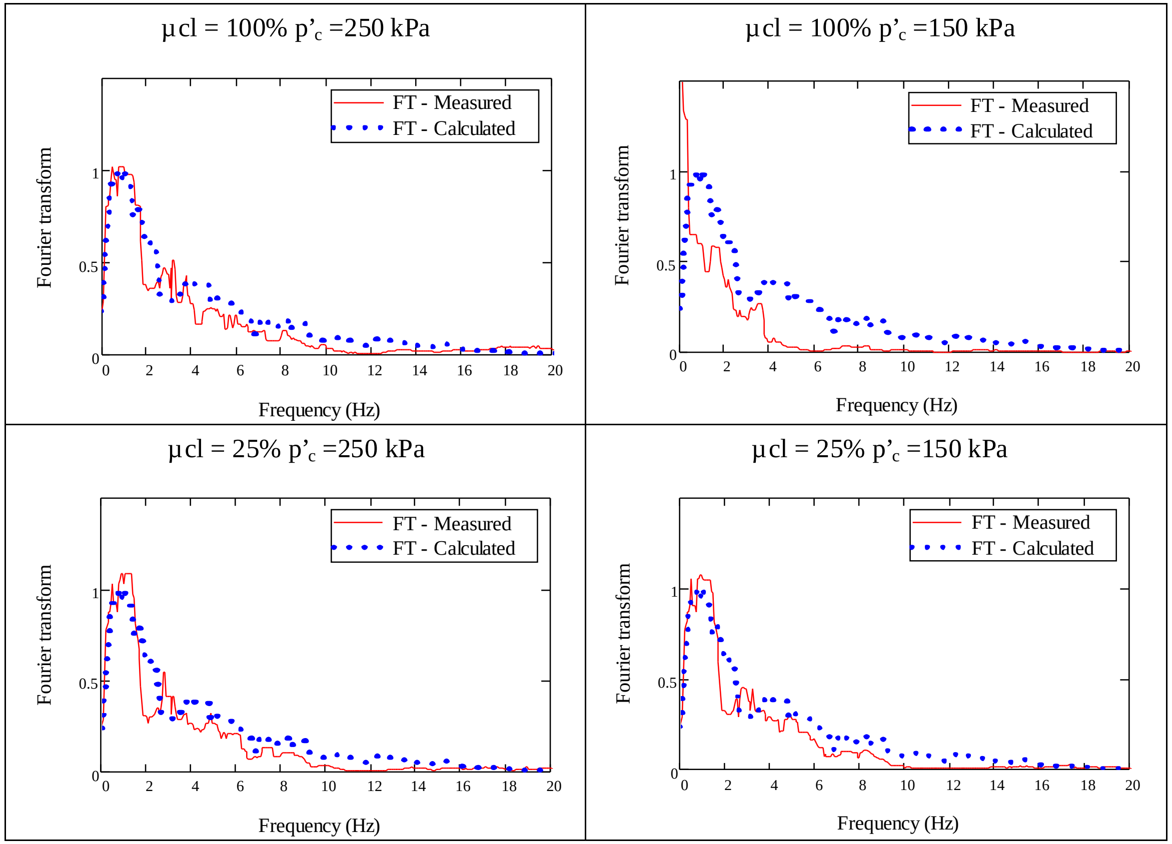
Conclusion

- Attenuation of acceleration at mid height and at the crest of the dam = hysteretic damping + irreversible plasticity during strong earthquake;
- ↗ u_w = the pore fluid compressibility (occluded air) + isotropic hardening in the fine soil fraction of the core during earthquake;
- ↘ G_{max} & V_s <==> ↗ uw
- $V_s(t) = V_s(\gamma, p'(u_w))$
- Irreversible settlement = isotropic hardening during earthquake + differed settlement during dissipation of pore pressure


THANK YOU FOR
YOUR ATTENTION


μcl = 100% p'c= 150 kPa
μcl = 100% p'c= 150 kPa
μcl = 25% p'c= 250 kPa
μcl = 25% p'c= 150 kPa
acceleration (m/s)
Dynamic time (s)
Calculated acceleration
Measured acceleration


µcl = 100% p'c =250 kPa
µcl = 100% p'c =150 kPa
µcl = 25% p'c =250 kPa
µcl = 25% p'c =150 kPa
FT - Calculated
FT - Measured
Fourier transform
Frequency (Hz)


μcl = 100% p'c =250 kPa
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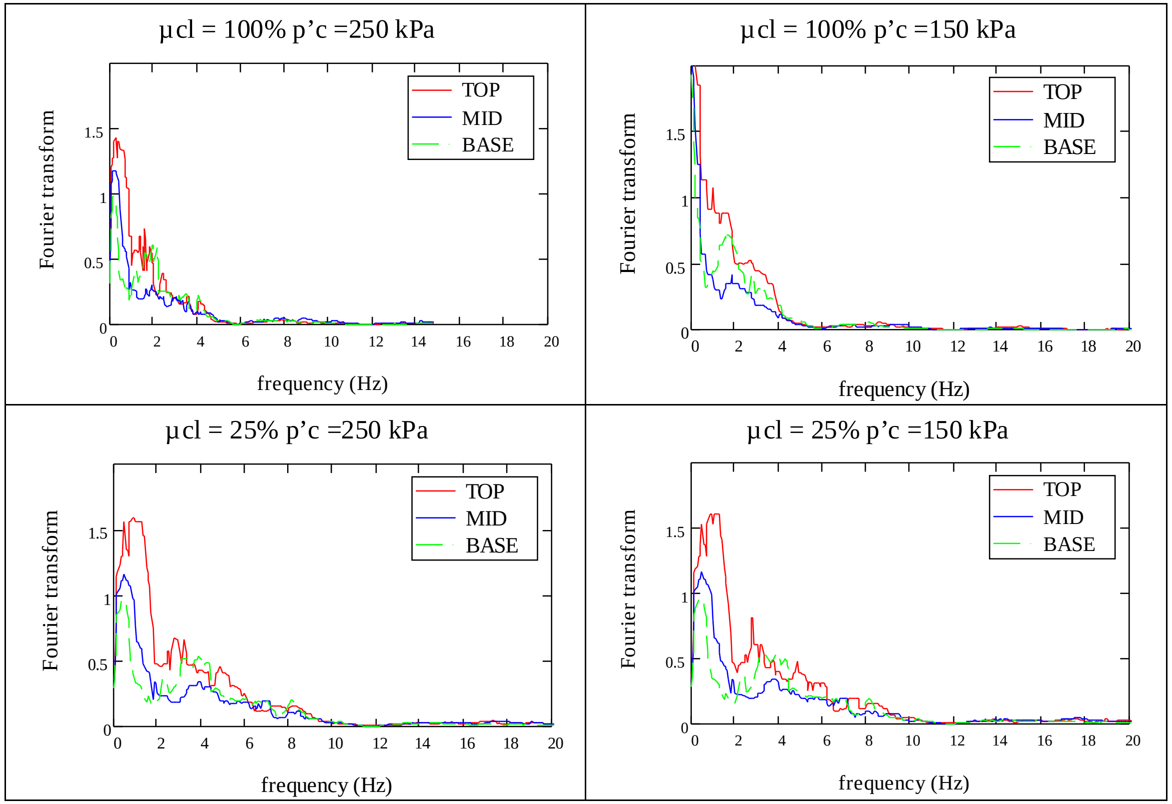
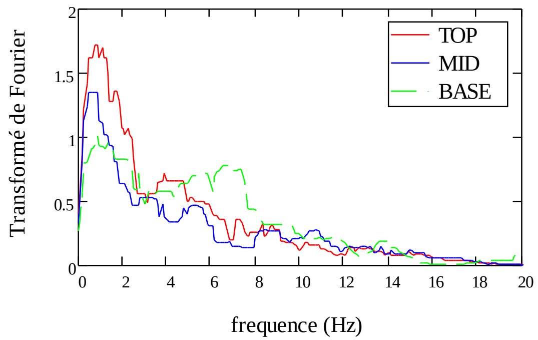
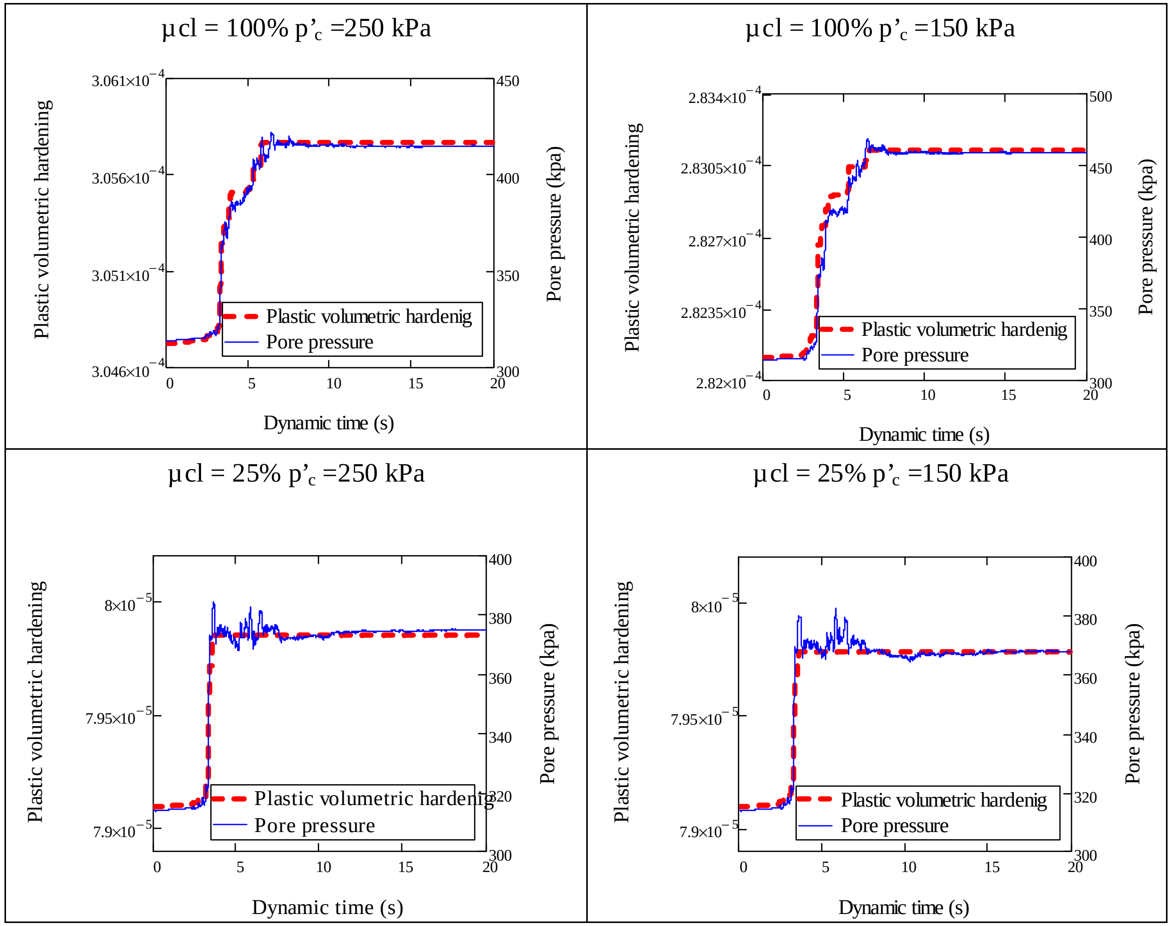
μcl = 25% p'c =250 kPa
μcl = 25% p'c =150 kPa
FT - Measured
FT - Calculated
Fourier transform
Frequency (Hz)
0
0.5
1
0
2
4
6
8
10
12
14
16
18
20



Measured spectral ratio




µcl = 100% p'c =250 kPa
µcl = 100% p'c =150 kPa
µcl = 25% p'c =250 kPa
µcl = 25% p'c =150 kPa
Plastic volumetric hardening
Pore pressure (kpa)
Dynamic time (s)
Plastic volumetric hardenig
Pore pressure