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Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
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C. Durand, E. Chaljub, P.-Y. Bard, L. Baillet,
J.-J. Fry, R. Granjon, F. Renalier

Session : Soils properties and simplified analysis

REVISITING SARMA'S METHOD FOR THE SEISMIC RESPONSE OF EMBANKMENTS ON SOFT SOILS: PRELIMINARY RESULTS FROM A PARAMETRIC STUDY

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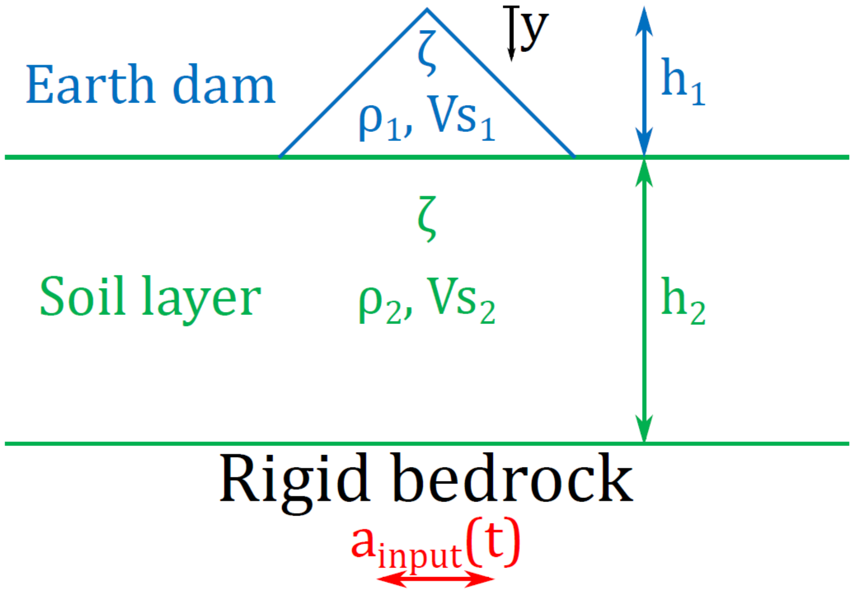
FRAMEWORK

- **Simplified methods to get seismic coefficients/damages are attractive…**
  - Easy
  - Fast
  - Affordable
- **… especially for seismic assessment of embankments…**
  - Large length along rivers
- **… but are they reliable ?**
- **What is the possible safety margin to consider ?**

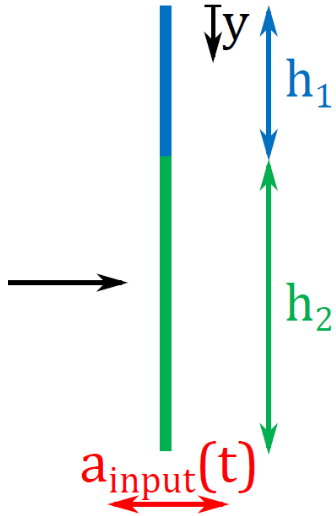
NO LIQUEFACTION

SARMA'S METHOD (1/3)

- **Assumptions:**



- Linear viscoelastic, viscous damping (same damping in the dam and in the layer of foundation)
- Rigid bedrock
- Shear beam approach: only horizontal displacements and simple shearing deformations + uniform shear strains across the dam



- **Motion equations:**

$$\frac{\partial^2 u_1}{\partial y^2}(y,t) + \frac{1}{y}\frac{\partial u_1}{\partial y}(y,t) = \frac{1}{Vs_1^2}(\ddot{u_1} + \zeta\,\dot{u_1} + a_{input}(t))$$

$$\frac{\partial^2 u_2}{\partial y^2}(y,t) += \frac{1}{Vs_2^2}(\ddot{u_2} + \zeta\,\dot{u_2} + a_{input}(t))$$

$m = \frac{\rho_1 Vs_1}{\rho_2 Vs_2}$ (impedance contrast)

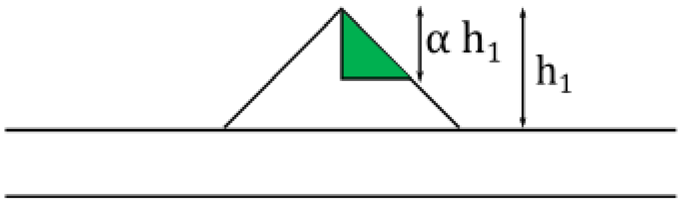
$q = \frac{Vs_1\, h_2}{Vs_2\, h_1}$ (contrast in time to cross the layer/embankment)

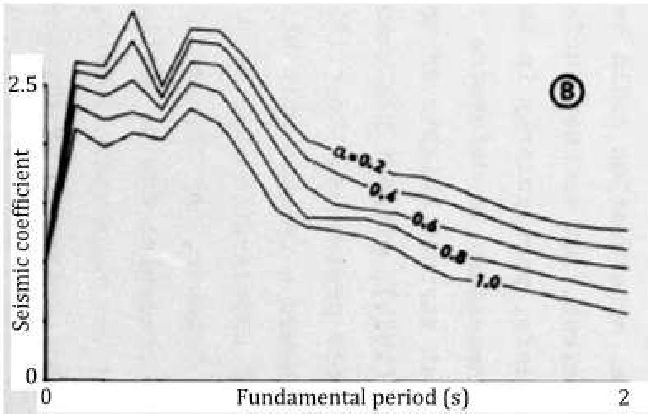
SARMA'S METHOD (2/3)

- **Main analytical results:**
  - Resonance frequencies:
    For the n[th] mode: $\omega_{0n} = \frac{\overline{a_n} V s_1}{h_1}$ where: $\frac{J_0(\overline{a_n})}{J_1(\overline{a_n})} = m \tan(q\overline{a_n})$
  - Mode shapes: $\Phi_n(y)$ in the embankment and $\Psi_n(y)$ in the layer for the n[th] mode
  - Displacements (and then accelerations):

$$u_1(y,t) = \sum_{n=1}^{\infty} \Phi_n(y) S_{dn}(t) \quad \text{and} \quad u_2(y,t) = \sum_{n=1}^{\infty} \Psi_n(y) S_{dn}(t)$$

- **Design curves:**
  - Deduced from analytical results, considering several combinations of parameters m and q, 9 real accelerograms and a viscous damping of 20%
  - Example for m=0.5 and q=0.75:





SEISMIC COEFFICIENTS FOR ONE-PARAMETER SLIDING WEDGE

SARMA'S METHOD (3/3)

- **Three main attractive features of this simplified method:**
  - It is not limited to the few cases solved to get the design curves
  - It takes into account an underlying layer of soil (mostly the case for embankments)
  - It may be possible to improve it by modifying some assumptions

ISSUES OF THIS WORK

- **What are the possible limits of the assumptions made in Sarma's method ?**
- **Is the dynamic behavior predicted by Sarma's method realistic ?**
- **What possible safety margin could be associated to this method?**

Limits imposed

- **Work limited to dynamic response (strains and accelerations) → no estimation of damages (displacements)**
- **Direct use of the analytical results obtained by Sarma → no utilization of the design curves deduced from the analytical resolution**

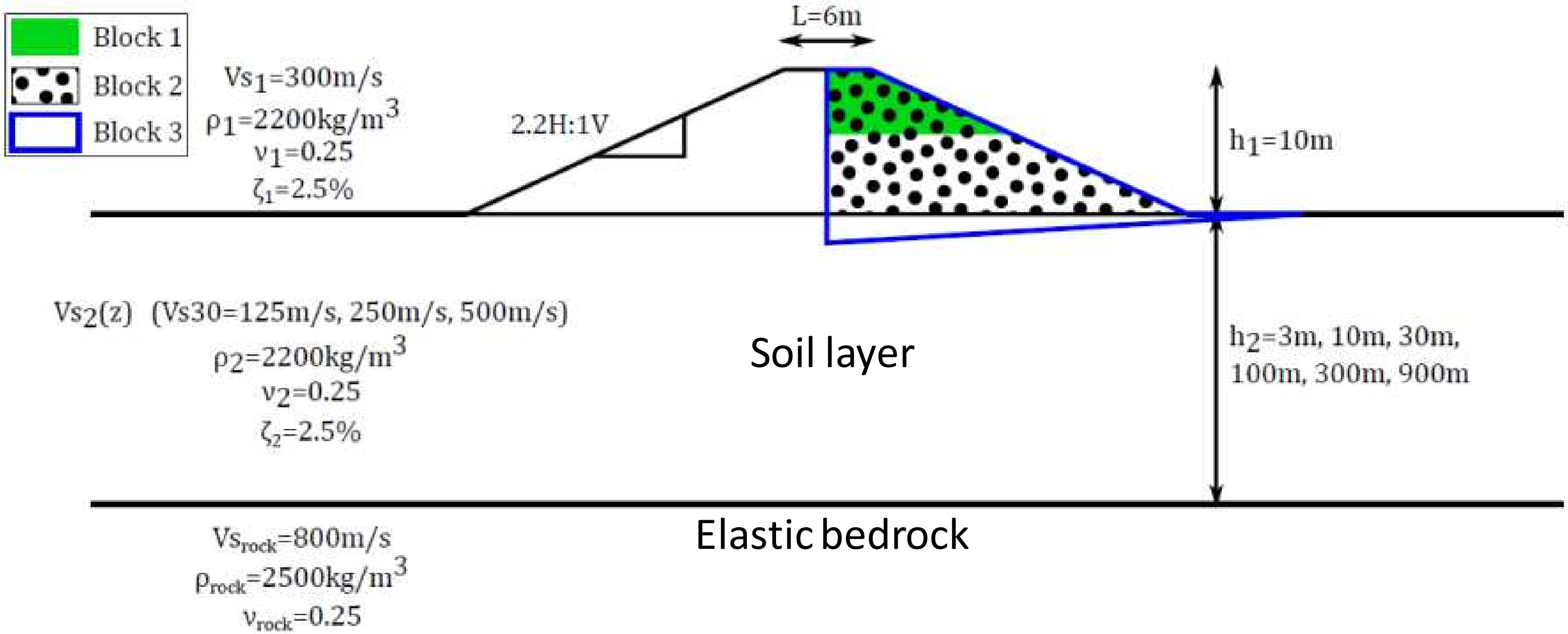
SUMMARY

2. METHODOLOGY

→ **Comparison between numerical results and results given by Sarma's method**

PARAMETRIC STUDY (1/3)

- **18 geometries for the comparison :**
  - 6 thicknesses of soil layer : 3m, 10m, 30m, 100m, 300m and 900m
  - 3 values of Vs_{30} in soil layers : 125m/s, 250m/s and 500m/s



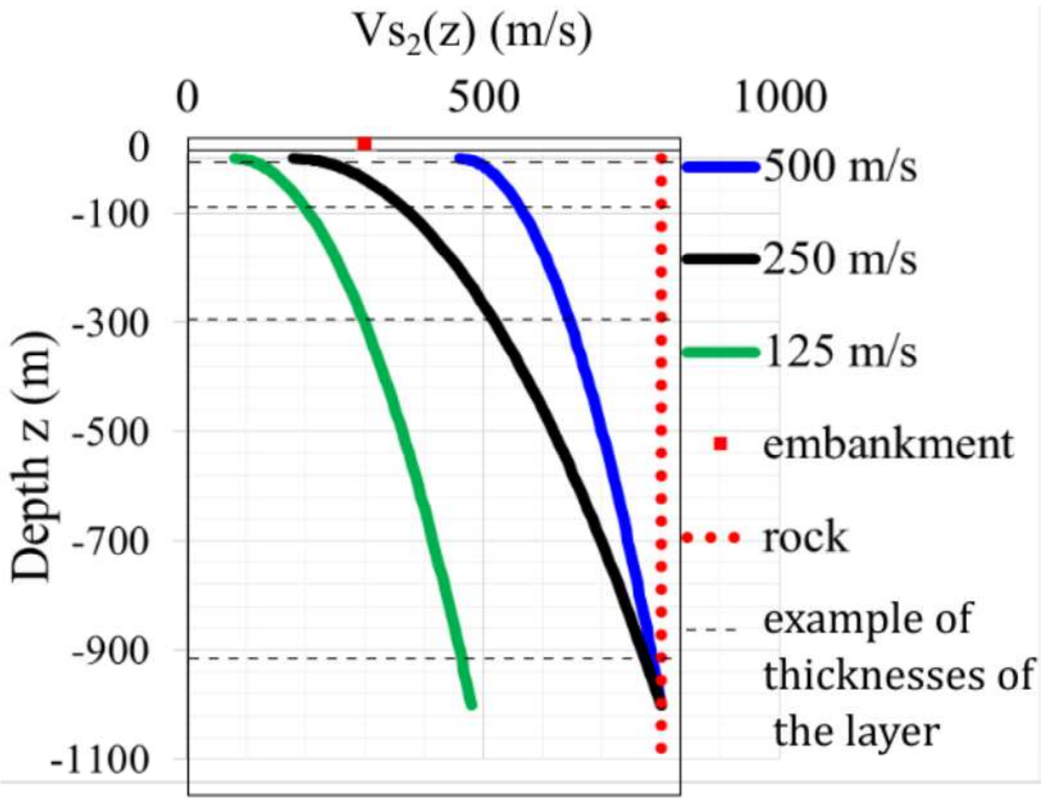
PARAMETRIC STUDY (2/3)

- **Velocity gradients :**

$$Vs_2(z) = Vs_a + (Vs_b - Vs_a)\sqrt{\frac{z - z_a}{z_b - z_a}}$$

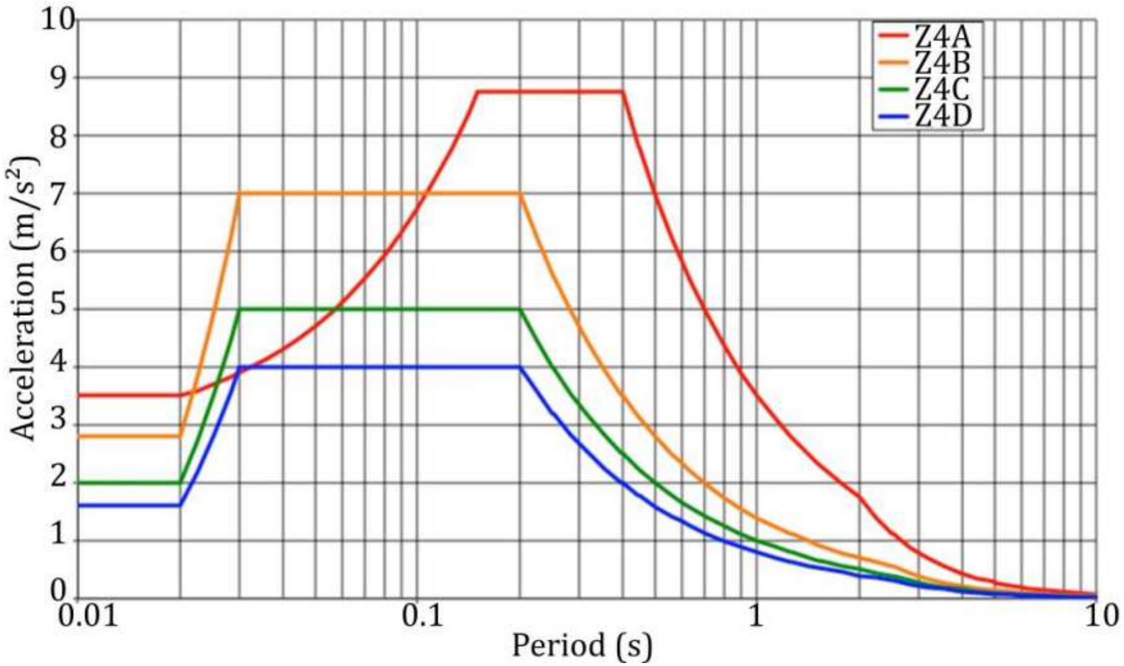
z_a = 0m ; z_b = 1000m

Vs_{30} (m/s)	Vs_a (m/s) at $z=z_a$=0m	Vs_b (m/s) at $z=z_b$=1000m
125	80	480
250	160	950
500	434	1000



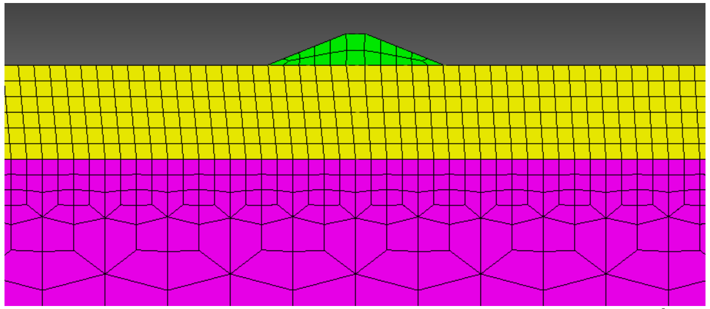
PARAMETRIC STUDY (3/3)

- **Input accelerograms :**
  - 26 real accelerograms (horizontal component)
  - Fitted on French design spectra (based on Eurocode 8): design spectra Z4D, Z4C, Z4B and Z4A (6 or 7 accelerograms per design spectra)
  - Magnitude from 4.5 to 6

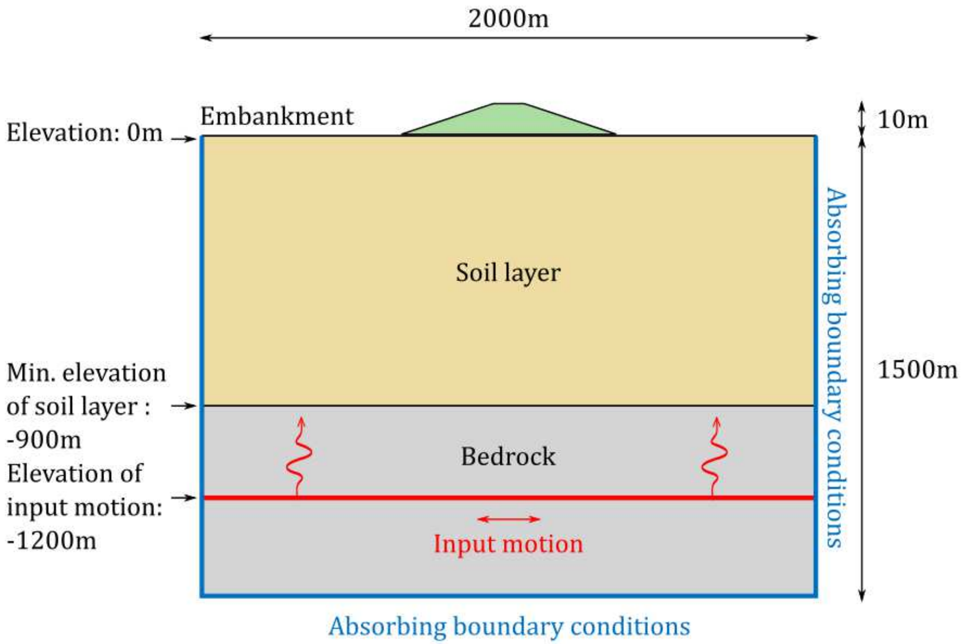


NUMERICAL ANALYSIS (1/2)

- **2D spectral-element solver SPECFEM 2D**
- **Spectral element method in space (polynomial order N=4)**
- **Explicit 2nd order finite-difference method in time**
- **Mesh: quadrangles, size function of Vs value → max. frequency=30Hz**



Example: Layer of 30m, Vs30=250m/s



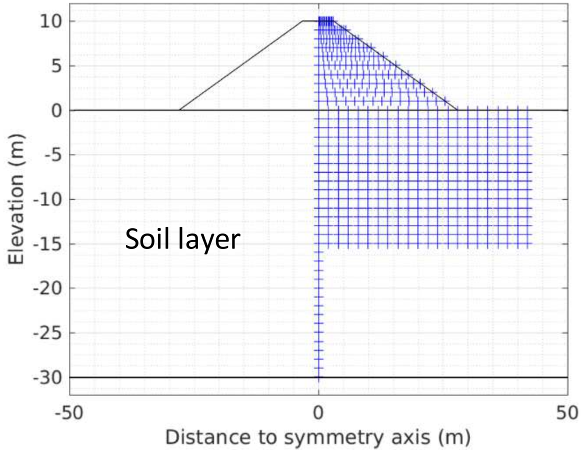
NUMERICAL ANALYSIS (2/2)

- **Receivers**
  - Data are saved at each receiver

Horizontal velocity: V_x

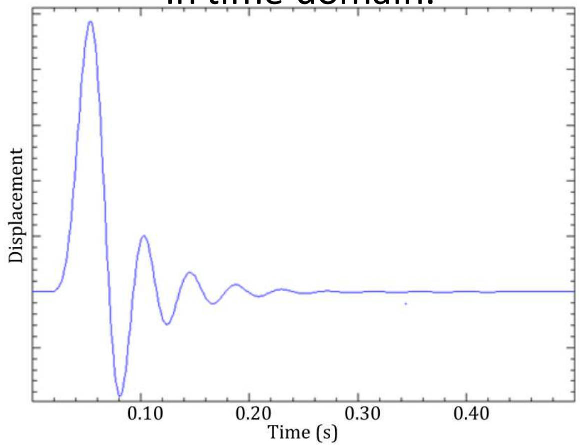
Spatial derivatives: $\frac{dU_z}{dx}$ and $\frac{dU_x}{dz}$

→ Shear strain: $\gamma = \frac{1}{2}\left(\frac{dU_z}{dx} + \frac{dU_x}{dz}\right)$

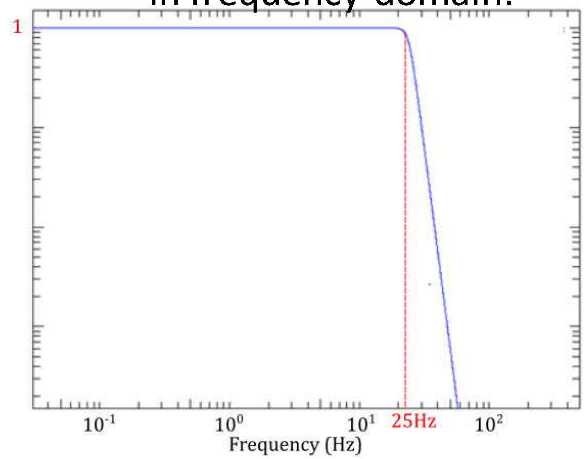


- **Impulse response to a Dirac fonction**

In time domain:



In frequency domain:

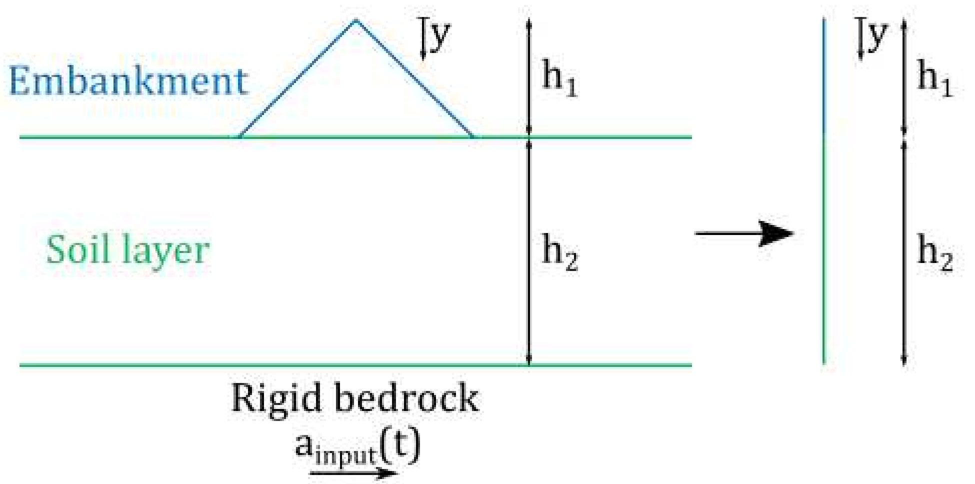


- **Convolution with the 26 accelerograms → accelerations and strains in each case at each receiver**

METHODOLOGY

APPLICATION OF SARMA'S METHOD

- **Use of analytical results from Sarma's method**
- **Use of the 26 choosen accelerograms as inputs**
- **No velocity gradient (assumption of an homogenous layer) → use of Vs_{30} values**
- **No lateral variations in the response → the motion is calculated every 1m along the vertical axis**



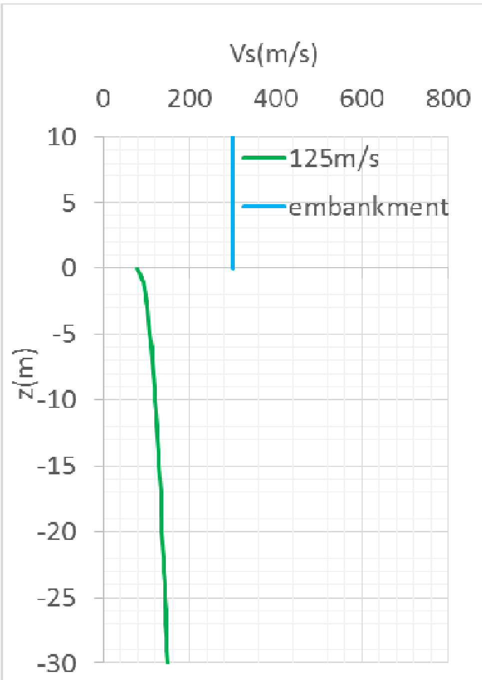
3. RESULTS

RESULTS

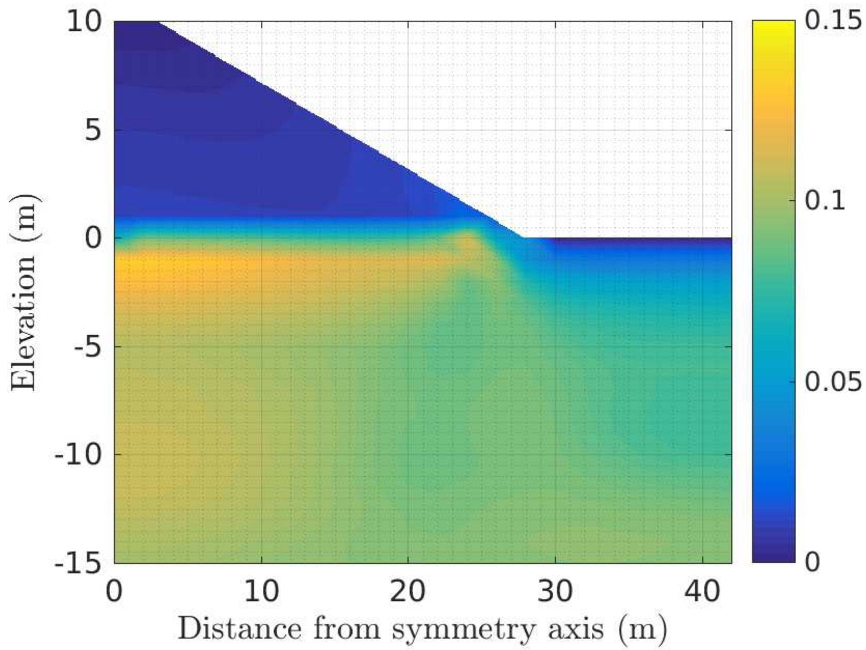
SHEAR STRAINS (1/3)

- **Main results shown by numerical analysis**

Example: peak shear strain reached at each point (not synchronous) – mean values (6 accelerograms) for the design spectra Z4B (PGA = 0.29g)



Peak shear strain (%)

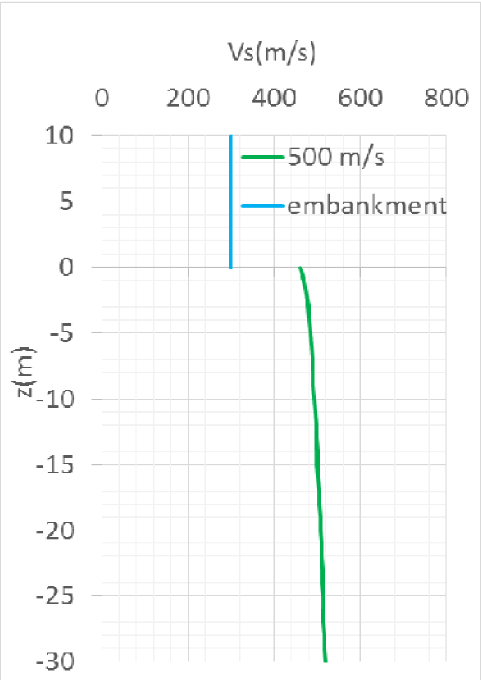


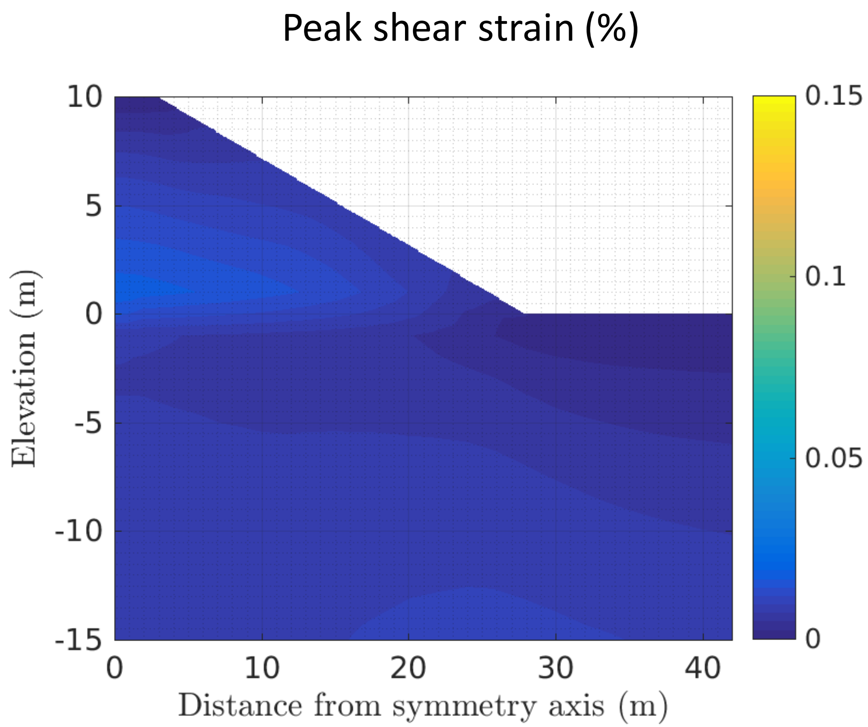
RESULTS

SHEAR STRAINS (2/3)

- **Main results shown by numerical analysis**

Example: peak shear strain reached at each point (not synchronous) – mean values (6 accelerograms) for the design spectra Z4B (PGA = 0.29g)





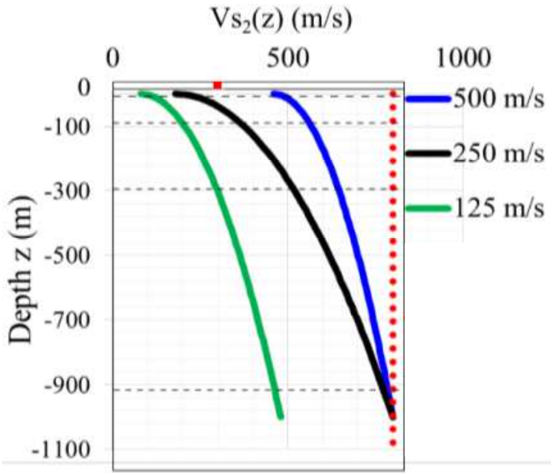
RESULTS

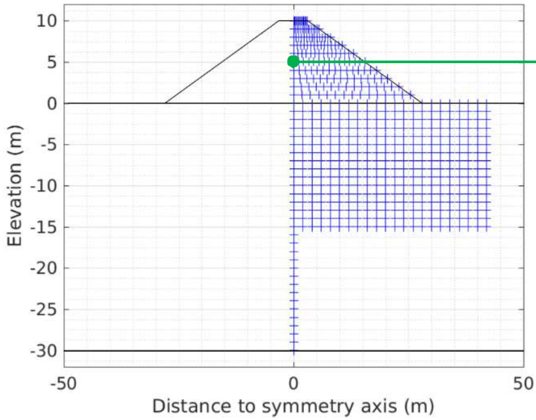
SHEAR STRAINS (3/3)

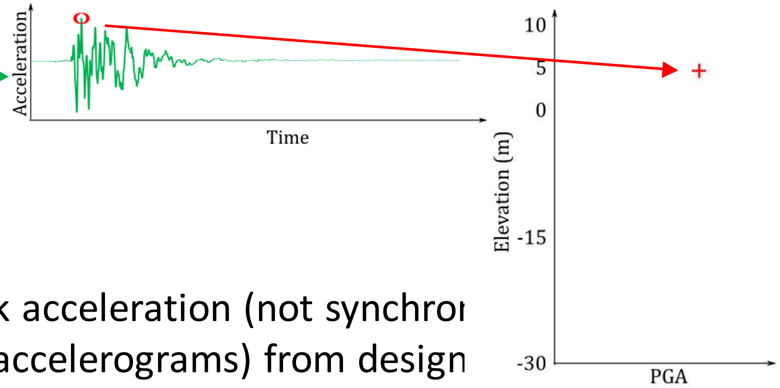
- **Main results shown by numerical analysis**

  - Peak shear strains remain globally the same at a given elevation (to the advantage of the shear beam assumption)
  - Peak shear strains are mostly controlled by shear modulus values (<-> Vs), for a given loading level
  - In all non-linear constitutive models, damping is related to shear strains → for strong loadings, it may be unrealistic to consider an homogeneous viscous damping (the same in the embankment and the soil layer)

ACCELERATIONS: COMPARISON WITH SARMA (1/4)

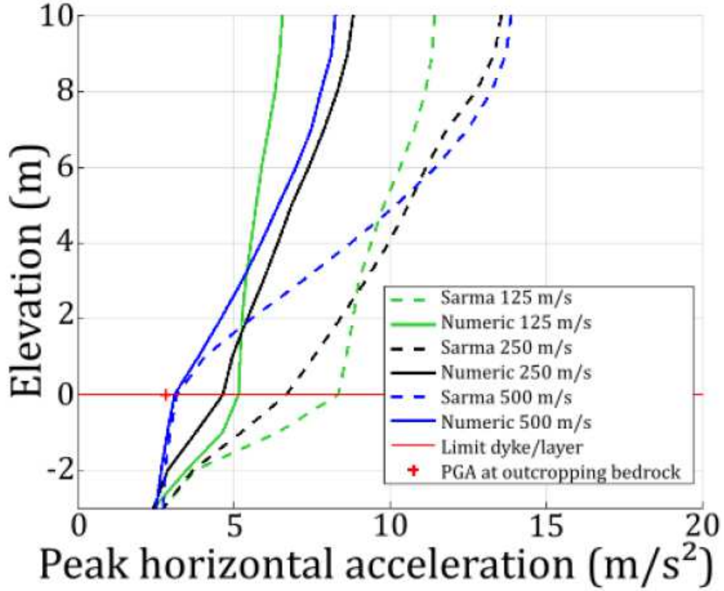




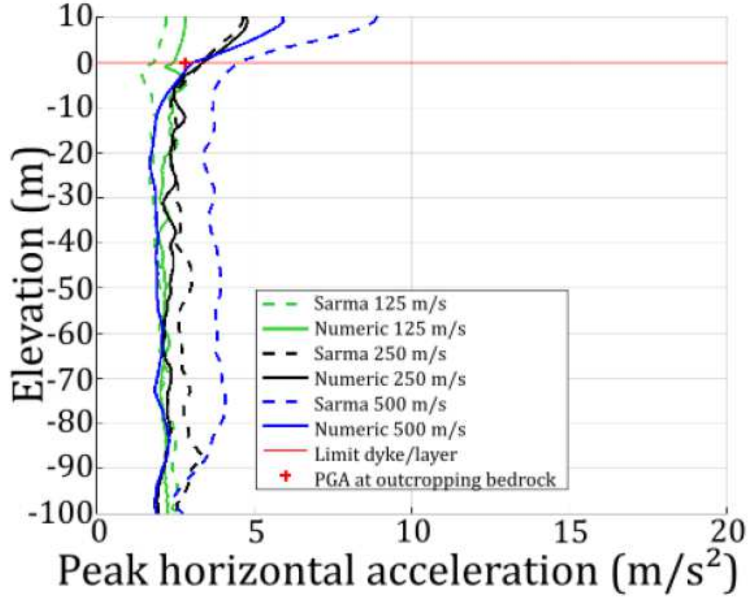


eak acceleration (not synchroı
6 accelerograms) from desigı
PGA = 0.29g)

Layer of 3m



Layer of 100m

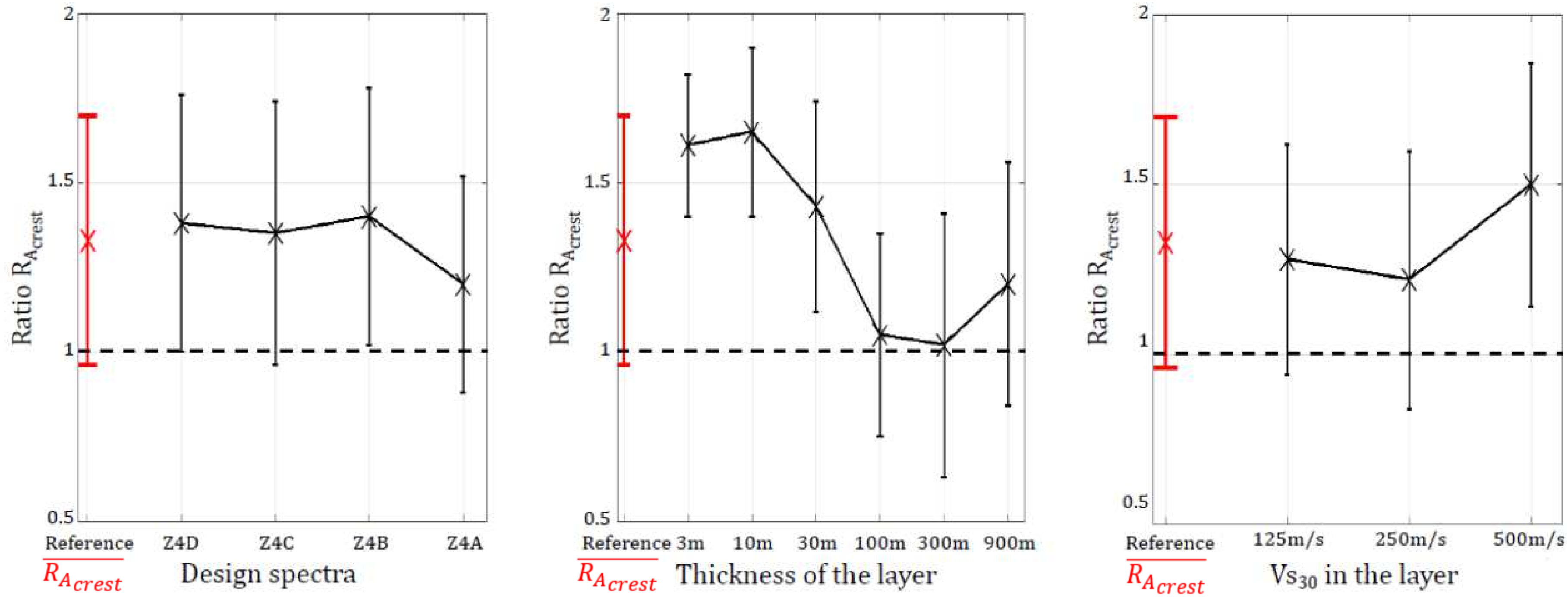


ACCELERATIONS: COMPARISON WITH SARMA (2/4)

- **Quantification of the error on peak acceleration at crest:**

$$Ratio\ R_{A\,crest} = \frac{Peak\ acceleration\ at\ crest\ from\ Sarma}{Peak\ acceleration\ at\ crest\ from\ numerical\ analysis}$$

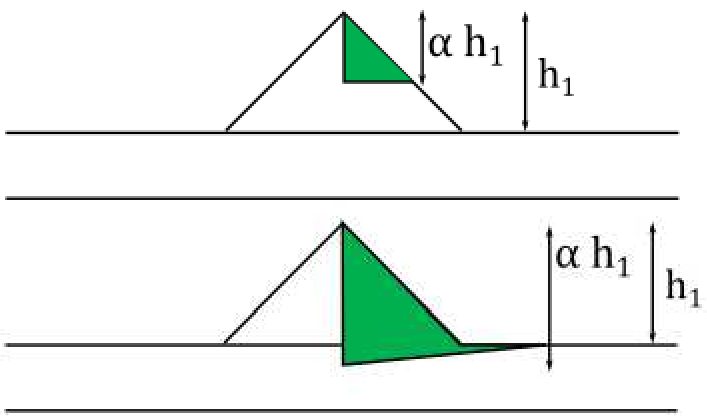
Mean value (all cases): $\overline{R_{A_{crest}}} = 1.33,\ \sigma = 0.37$



ACCELERATIONS: COMPARISON WITH SARMA (3/4)

- **Quantification of the error on peak acceleration of a possible sliding block:**

$$Ratio\ R_{A_{block}} = \frac{Peak\ acceleration\ of\ the\ block\ from\ Sarma}{Peak\ acceleration\ of\ the\ block\ from\ numerical\ analysis}$$



alpha	$\overline{R_{A_{block}}}$	σ
0.5	1.40	0.39
1	1.44	0.38
1.2	1.49	0.39

ACCELERATIONS: COMPARISON WITH SARMA (4/4)

- **Main results shown by the comparison:**

  - Trend (attenuation/amplification) of the dynamic response is well caught by Sarma's simplified method

  - Sarma's method leads globally to an overestimation of peak acceleration at crest (by 30% in average) and mean acceleration of a possible sliding block (by 40-50% in average).

  - The discrepancies may be explained by:
    - The assumption of a rigid bedrock
    - The assumption of an horizontal motion (far from the reality for higher modes)
    - The non-consideration of the velocity gradient in the soil layer

3. CONCLUSIONS

MAIN RESULTS

- **About assumptions made in Sarma's method:**
  - Rigid bedrock → infinite impedance contrast, greater amplification, no radiation of the energy in the bedrock
  - Shear beam assumptions → less accurate at higher frequencies. According to Gazetas(1987), this can explain the discrepancies regarding peak acceleration at crest.
  - Homogeneous viscous damping → the damping could be different in the embankment and the soil layer, according to the shear modulus values

- **About the dynamic behavior obtained when using Sarma's method**
  - Behavior realistic: trend of attenuation/amplification similar to numerical analysis

- **About the possible safety margins (on peak accelerations):**
  - In most cases, larger amplification of the input especially for soil layers relatively thin (3 to 30m)
  - In average, the seismic coefficient is overestimated by a factor of 50%
  - The thickness of the layer has a large influence on the possible safety margin (greater effect of the velocity gradient ?)

CONCLUSIONS

LIMITATIONS AND PERSPECTIVES

- **Impact of the velocity gradient ?**
  → Adapt Sarma's equations to take into account a velocity gradient ?

- **Effect of compaction of the layer by the embankment ?**
  → Consider Vs values in the layer more realistic in numerical analysis
  → In Sarma's simplified method, it is not specified where should be chosen the Vs(z) profile (far or under the embankment)

- **Model damping in numerical analysis ?**
  → Major impact on the results: large attenuation, especially for thicker layer
  → Not realistic to always choose the same value in the embankment and the soil layer
  → Linear equivalent analysis to find a more realistic value of damping ?

- **Design curves**
  → Sarma's design curves are developed for a viscous damping of 15%-20% (global value to also take into account radiation of energy)
  → What would be the results of a comparison between Sarma's simplified method (design curves) and numerical results (with a damping more realistic) ?


THANK YOU FOR
YOUR ATTENTION