ESTP PARIS

L'ÉCOLE DES GRANDS PROJETS

Simplified method for calculating the induced settlements and the liquefaction rate in a soil profile under seismic loading

EDF

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Overview of the Project

Objective :

Developing two predictors, one quantifies the risk of liquefaction and the other gives an estimate of the earthquake-induced settlements in a dam or a foundation under seismic loading.

Input Data:

- Time accelerogram: a seismic event characterized by its magnitude and its distance from the site is selected from a corresponding set of seismic signals in the EDF RESORCE database;
- Geometry and characteristics of the material constituting a structure (dam or foundation);
- Results of cyclic tests experimented on this material to calibrate the parameters of the chosen constitutive model.

Validation

- Transient analysis :

• Equivalent linear analysis of a soil column with post-treatment using the Sawicki model;

• Nonlinear analysis of a homogeneous soil column using the Hujeux model;

- Real measurements of instrumented dams.

Summary

I. Pore pressure build up computation by a transient analysis

- Soil profiles
- Compaction/Liquefaction model By Sawicki
- Equivalent linear analysis of a soil column with post-treatment using the Sawicki model;
- Nonlinear analysis of a homogeneous soil column using the Hujeux model;

II. 2D model of Aratozawa dam

I. Simplified estimation of the pore pressure build up under seismic loading

1. SOIL PROFILES UNDER CONSIDERATION

The soil profile under consideration has a thickness H = 10 m and overlies a bedrock regarded as perfectly rigid and subjected to a horizontal acceleration.

We will be studying three types of soil profile in the following :

- Profile 1 :

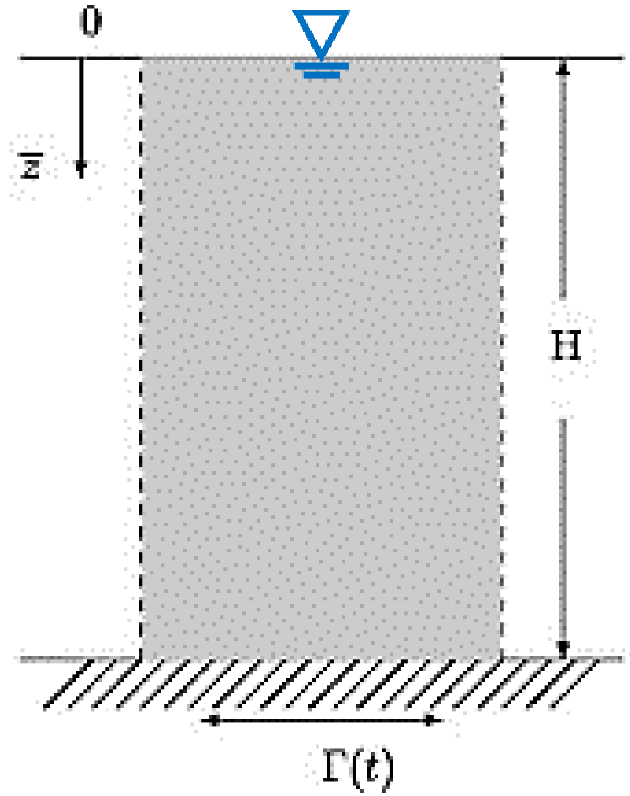
- Loose sand with specific saturated density ρ = 2105 Kg/m^3.
- G is assumed to be constant throughout the soil profile.

- Profile 2 :

- Loose sand with specific saturated density ρ = 2105 Kg/m^3.
- G is assumed to be a function of $\sqrt{z}$ throughout the soil profile.

- Profile 3 :

- Heterogeneous profile : Loose and dense sand layers.



- Sawicki Parameters C_1= 0,009 et C_2= 55000.

I. Simplified estimation of the pore pressure build up under seismic loading

2. Objective of the study

we aim this study to **predict the settlement and the liquefaction rate** in a soil profile under a horizontal seismic motion applied at the bedrock.

We choose 65 acceleregrams recorded with a PGA ranging between 0,03g and 0,54g

- As a way to validate the predictor, we compute the liquefaction rate by a transient analysis +Sawicki

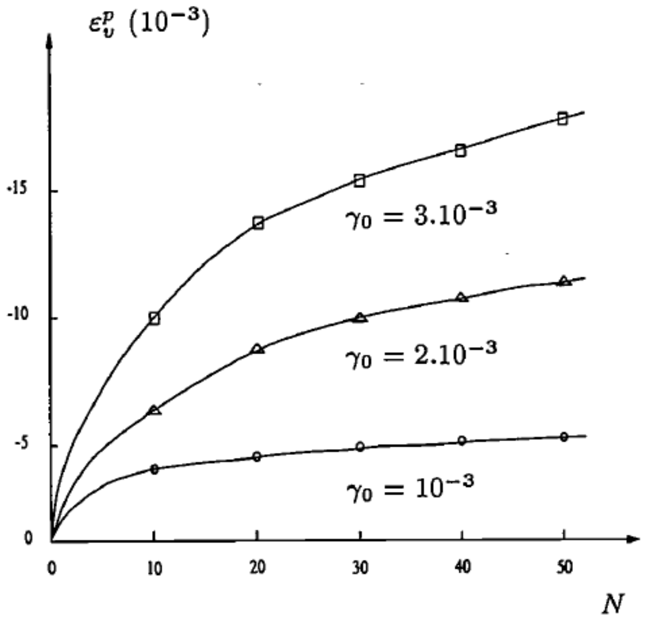
  → 65 values of calculated liquefaction rates ;

- We will build the liquefaction predictor based on :
  - Profile features;
  - Sawicki's constitutive model;
  - Response spectrum and duration of input motion

  → 65 values of predicted liquefaction rates ;

Compaction / Liquefaction model by SAWICKI, (1987-1989):

1. Compaction model (Sawicki, 1987)



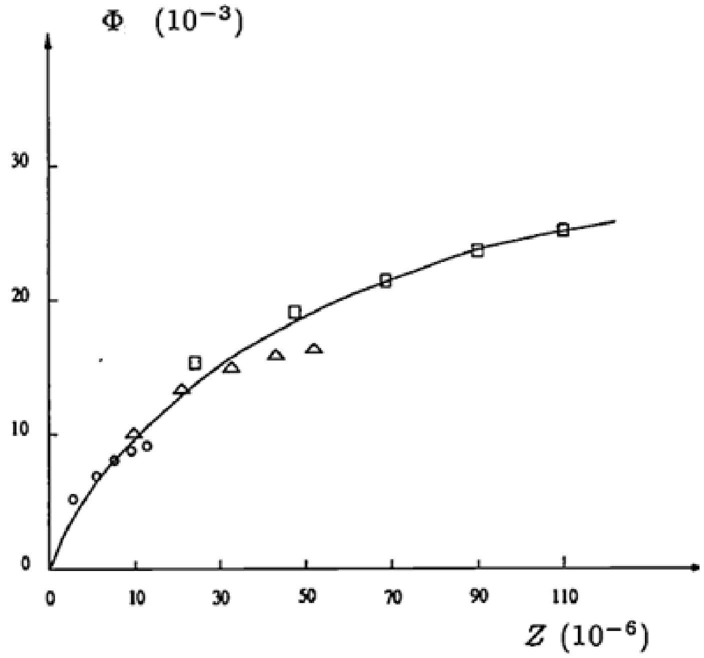
Sawicki et al. (1989)

$$\Phi = \frac{1-n_0}{n_0}\varepsilon_v^p, Z = \frac{1}{4}\gamma_0{}^2 N$$

Φ : the relative compaction

n_0: the initial porosity

ε_v^p: volumetric deformation



Sawicki et al. (1989)

Relative compaction : $\boxed{\Phi = C_1 \ln(1 + C_2 Z)}$

Where C_1 and C_2 are the parameters of Sawicki's model depending on the sand and its given initial relative density.

Compaction / Liquefaction model by SAWICKI, (1987-1989):

2. Liquefaction model (Sawicki,1989)

Sawicki model also provides a method to assess the generation of pore pressure under cyclic loading:

$$\frac{du}{dN} = \frac{1}{a}\frac{d\Phi}{dN} \Longrightarrow \frac{du}{dN} = K\frac{d\varepsilon_v^p}{dN}$$

where u is the pore pressure.

a is a constant calculated using: $a = \frac{1-n_0}{n_0}k_s$

with n_0 the initial porosity, k_s the elastic compressibility of the soil $k_s = \frac{1}{K}$ and K is the compression modulus

So if we already know the variation of the relative porosity in cycles (volumetric deformations), we can find the generation of pressure.

Otherwise, Sawicki proposed a formula that derives directly the pore pressure build up from the shear strain, which reads:

$$\frac{du}{dN} = \frac{D_1\gamma^2}{4a}\exp(-D_2 au)$$

D_1 and D_2 are deduced from C_1 and C_2

I. Pore pressure build up computation by a transient analysis

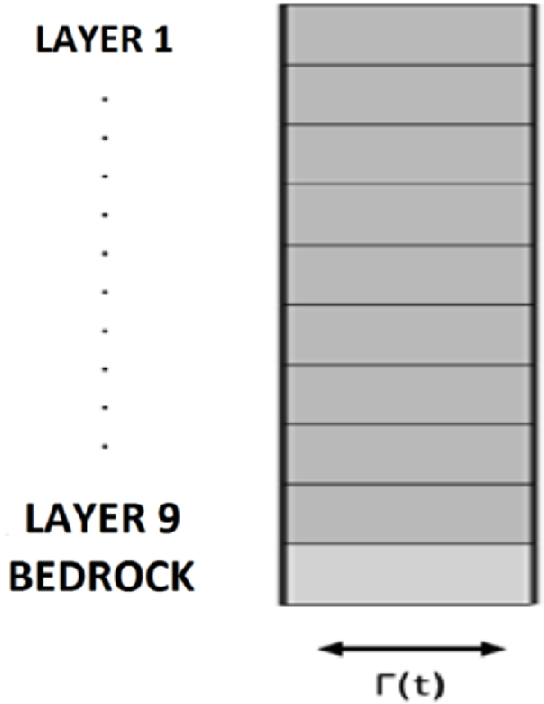
Step 1

Linear equivalent computation

We have launched an equivalent linear computation on the EDF software Code_Aster.

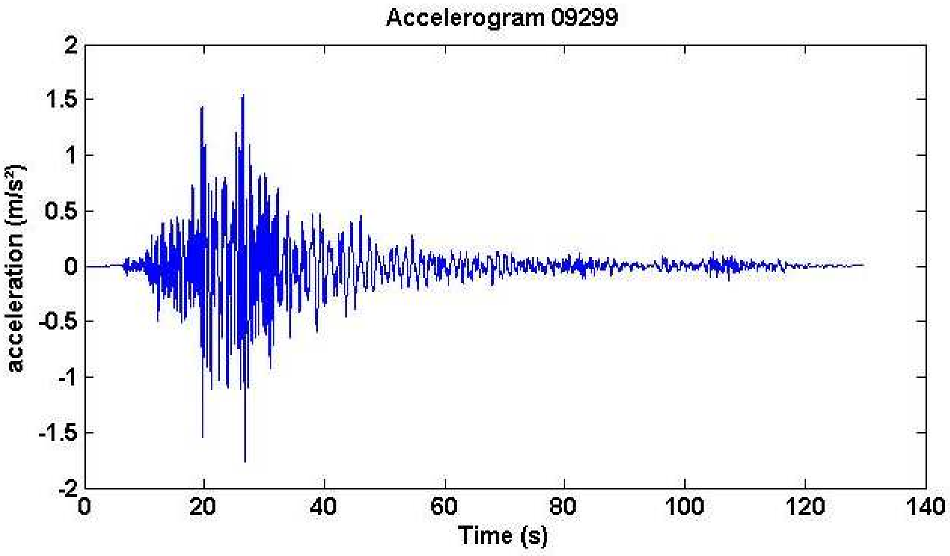
The calculation requires the following information as input data:

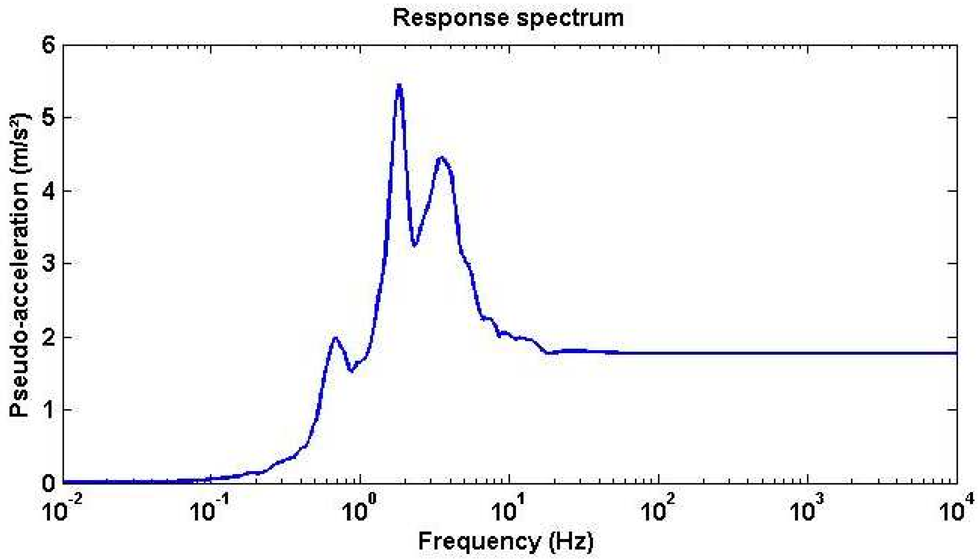
- A table containing the geotechnical characteristics of each layer: density, initial Young's modulus, Poisson coefficient, initial hysteretic damping.
- The degradation curves of the modulus of shear and damping for the material used.



I. Pore pressure build up computation by a transient analysis

Input signal:





Earthquake'sname	Mw	Distance (km)	a_{max} (g)	Strong phase duration (s)
Razan 09299	6.4	24	0,176	28,52

I. Pore pressure build up computation by a transient analysis

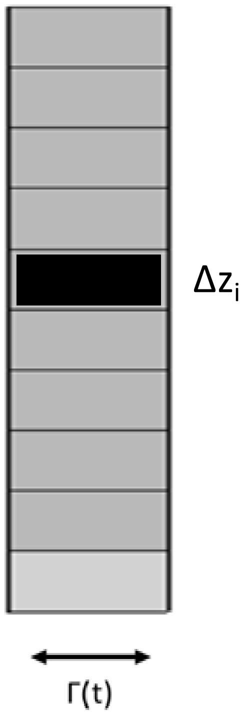
Step 2

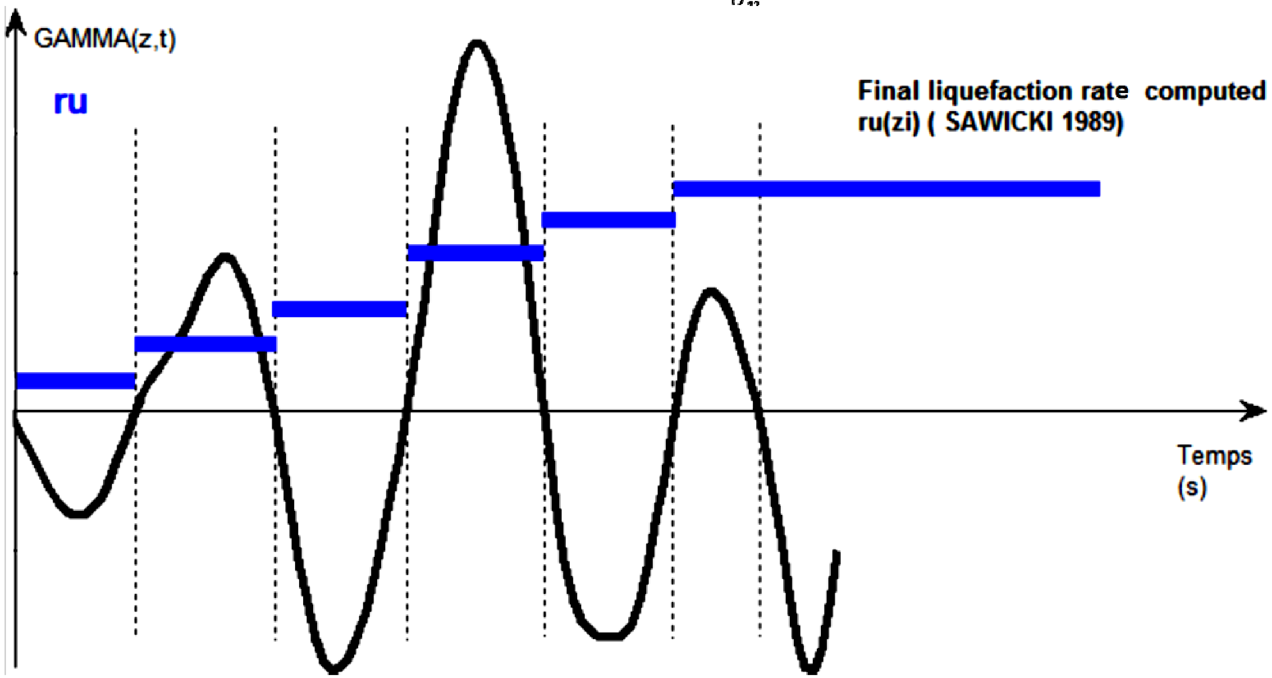
- The Sawicki liquefaction model is used to calculate the pore pressure rise following the history of the shear strain
- For each layer i (Δz_i), the shear strain time history is decomposed into a succession of half-cycles.
- Each half-cycle contributes to the value of:

Volumetric deformation increment: $\Delta\varepsilon_{v\ (half-cycle)} = \frac{n_o}{1-n_o} \times C_1 \times \ln(1 + C_2(\frac{1}{4}\gamma_{max}{}^2)^{\frac{1}{2}})$

Pore pressure rise : $\Delta u_{(half-cycle)} = K \times \Delta\varepsilon_v$

Liquefaction rate at the depth z : $r_{u\ i} = \frac{\Delta u}{\sigma'_v}$





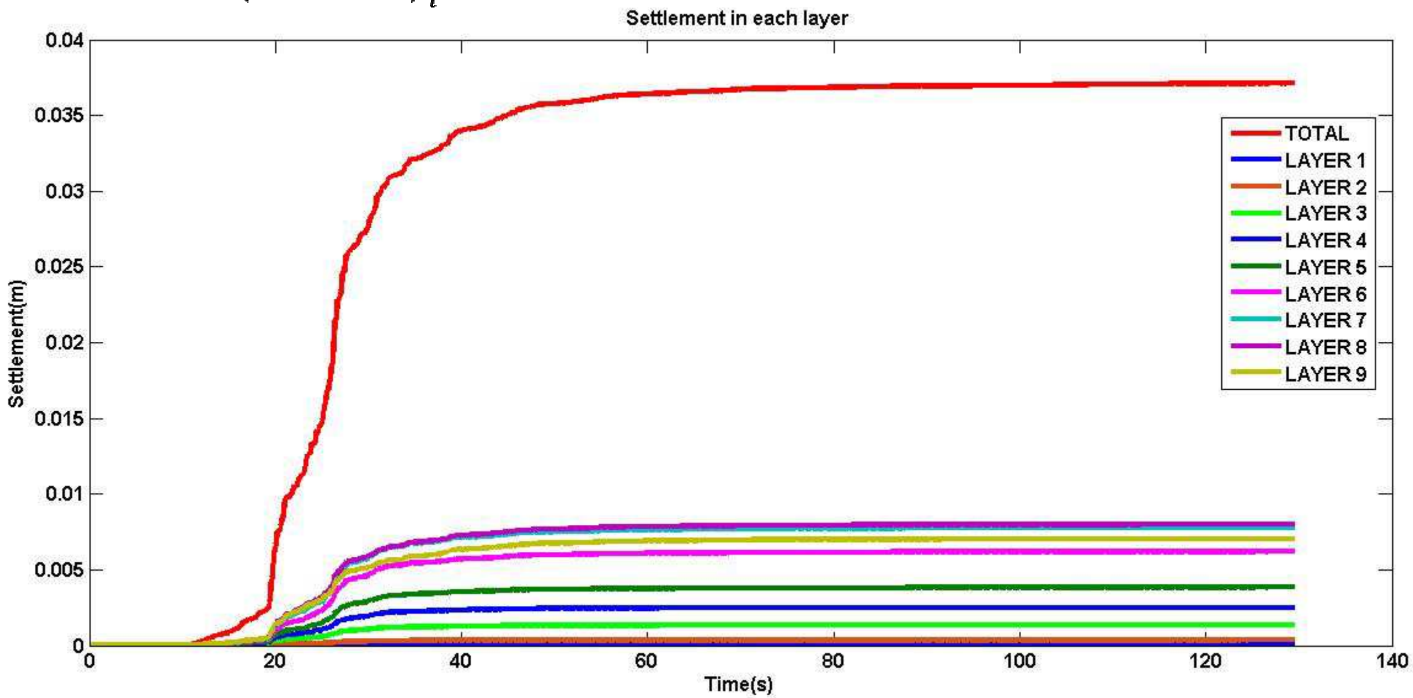
I. Pore pressure build up computation by a transient analysis

Settlement computation

- To compute the settlement induced in each layer, the volumetric deformation generated at the end of the signal is taken up in each layer i:

Volumetric deformation increment: $\Delta\varepsilon_{v\,(half-cycle)} = \frac{n_o}{1-n_o} \times C_1 \times \ln(1 + C_2(\frac{1}{4}\gamma_{max}{}^2)^{\frac{1}{2}})$

Settlement in each layer $S_i = \left(\varepsilon_v\left(t_{final}\right)\right)_i \times \Delta z_i$

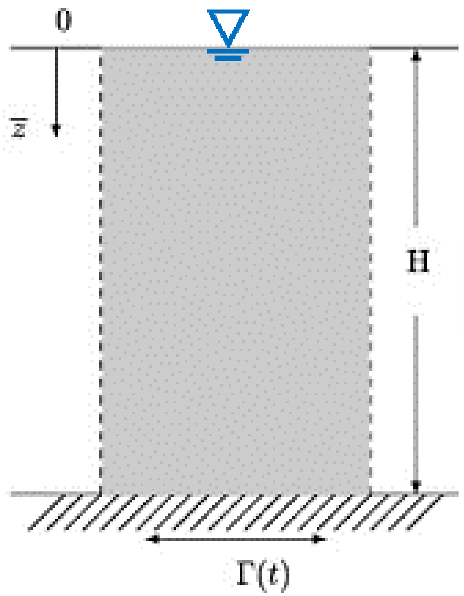


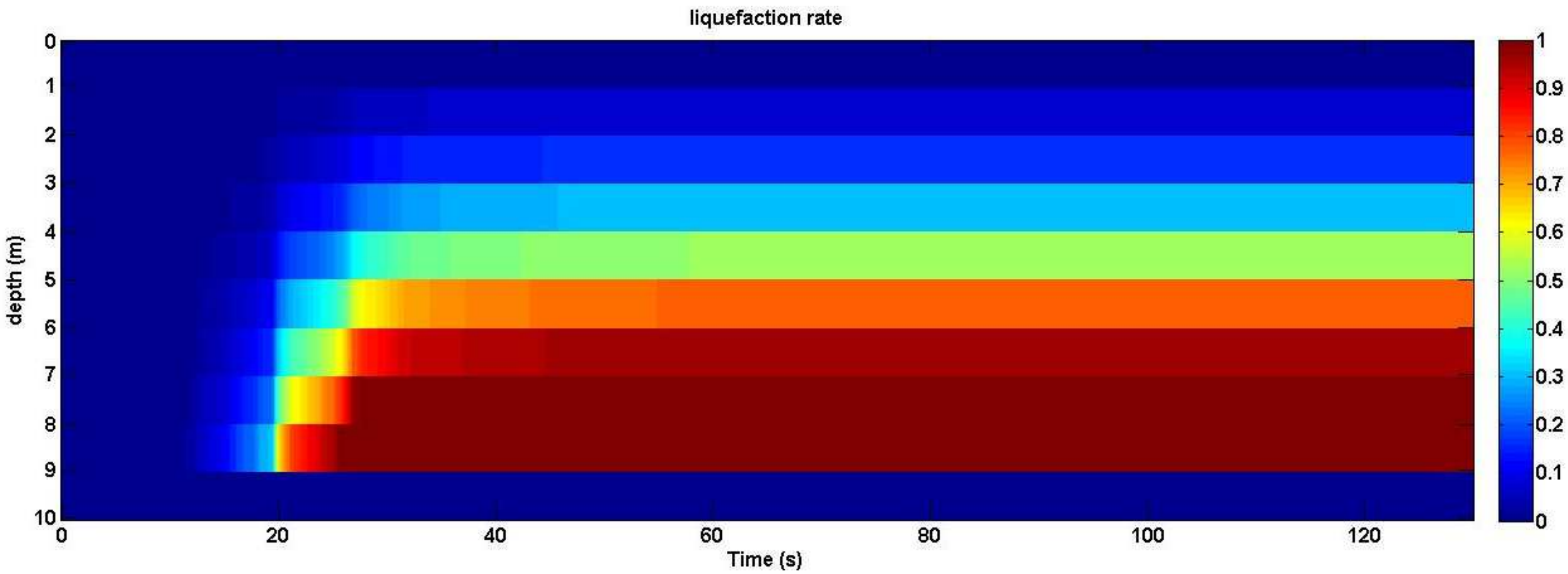
The total settlement in the entire profile is the sum of the settlements in all layers= $\sum_i S_i$

I. Pore pressure build up computation by a transient analysis

Output: liquefaction rate

Profile 1 (G assumed constant in the entire profile)



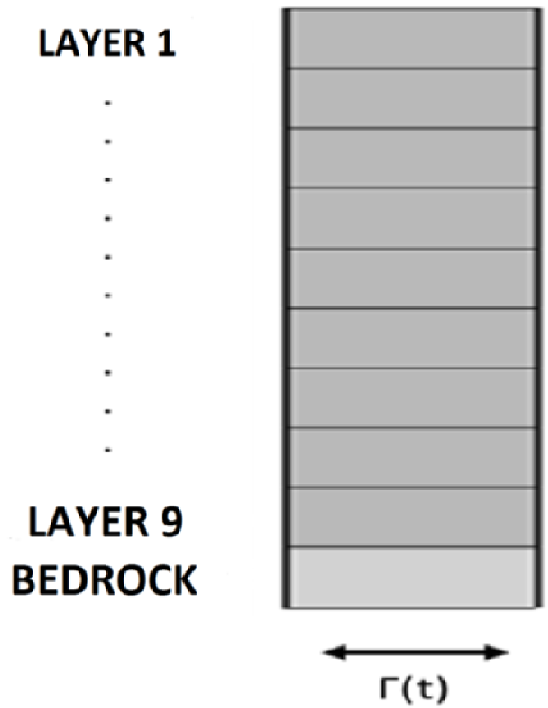


I. Pore pressure build up computation by a transient analysis

Profile 2 of soil column

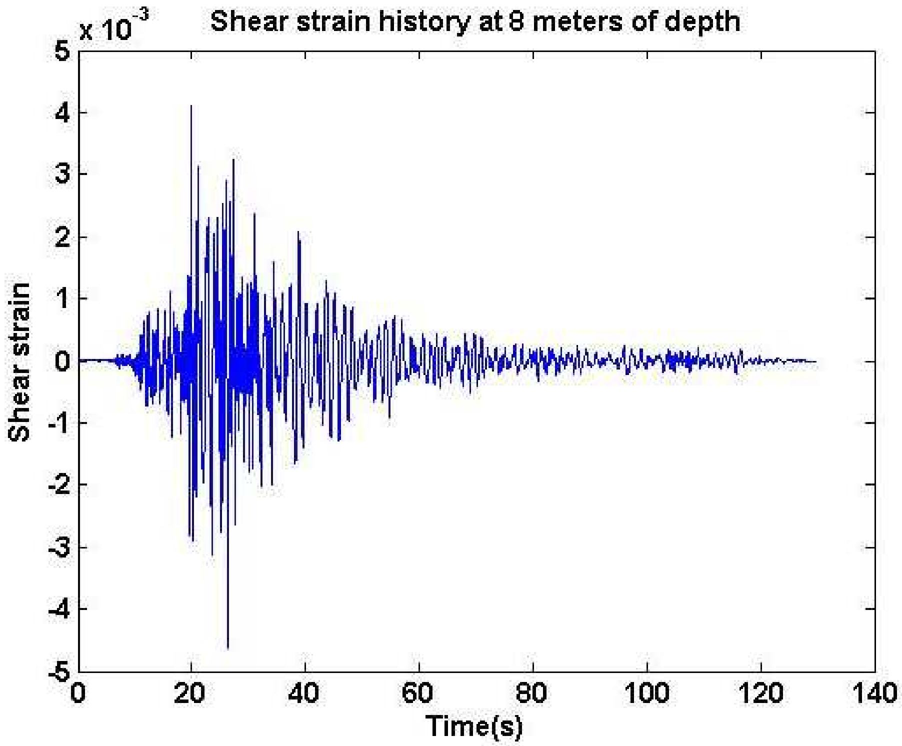
❖ the Young's modulus is a function of $\sqrt{z}$

Layer	RHO	E_{max} (MPa)
Layer 1	2105	70
Layer 2	2105	99
Layer 3	2105	122
Layer 4	2105	140
Layer 5	2105	157
Layer 6	2105	172
Layer 7	2105	186
Layer 8	2105	199
Layer 9	2105	211
Layer 10	2365	5 600



I. Pore pressure build up computation by a transient analysis

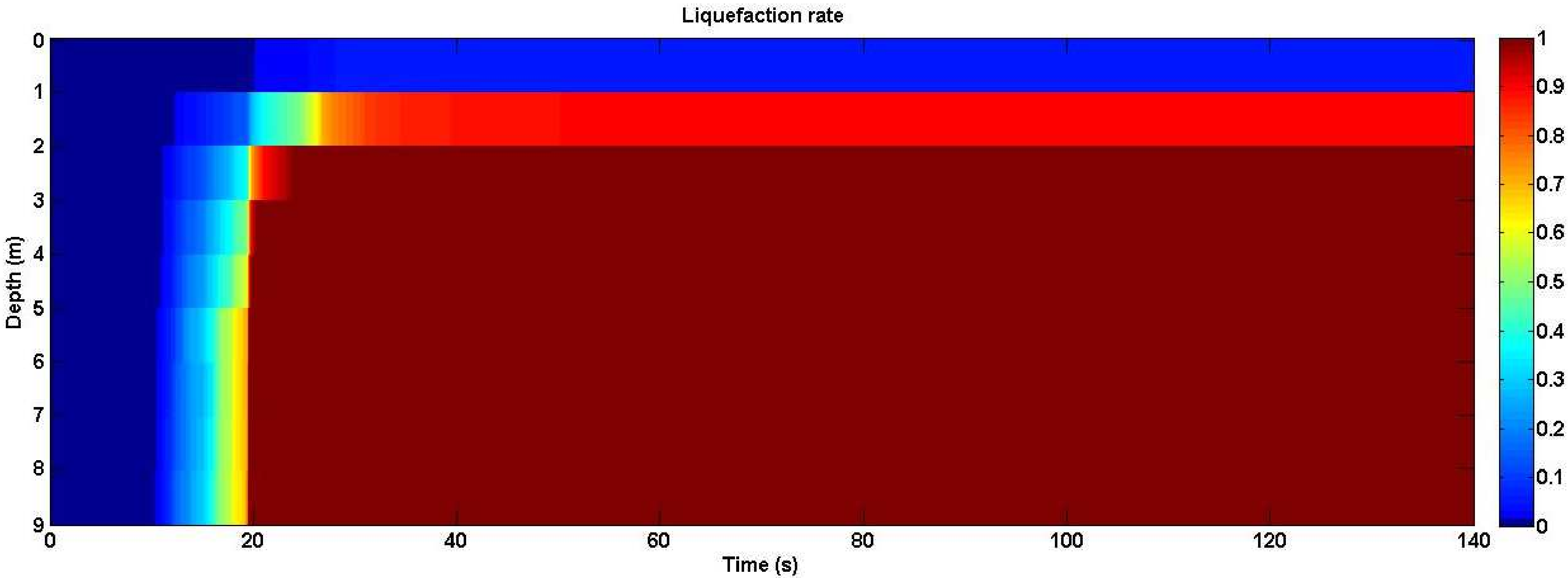
Output of the linear equivalent computation of the profile 2



Layer	G/Gmax	γ_{max}
Layer 1	0,45	1,51E-04
Layer 2	0,16	8,08E-04
Layer 3	0,11	1,56E-03
Layer 4	0,09	2,14E-03
Layer 5	0,07	2,78E-03
Layer 6	0,06	3,85E-03
Layer 7	0,05	4,53E-03
Layer 8	0,05	4,63E-03
Layer 9	0,05	4,24E-03
Layer 10	1,00	0

I. Pore pressure build up computation by a transient analysis

Profile 2: Liquefaction rate

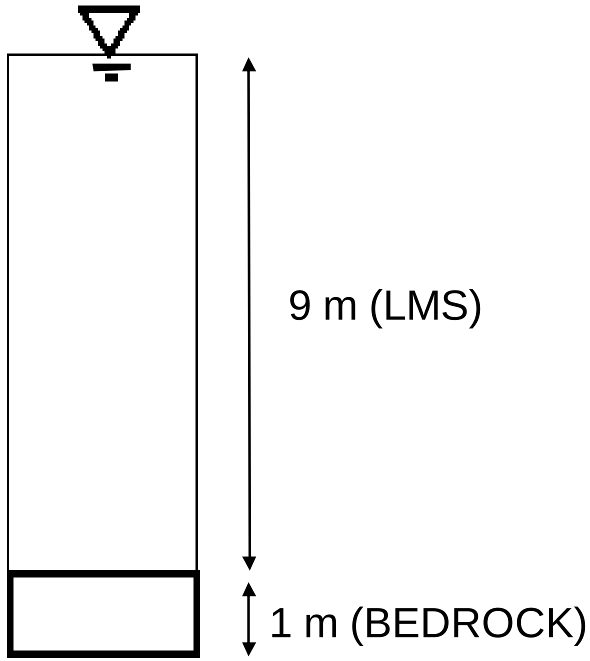


I. Pore pressure build up computation by a transient analysis

Nonlinear computation of the profile 2 response

A nonlinear calculation was performed on a column of soil under undrained conditions using the Hujeux model embedded in Code Aster, as a way to validate the computation that we use (linear equivalent + Sawicki)

The column is composed of a loose sand, and has the same elastic characteristic as the one studied previously.



Boundary conditions:

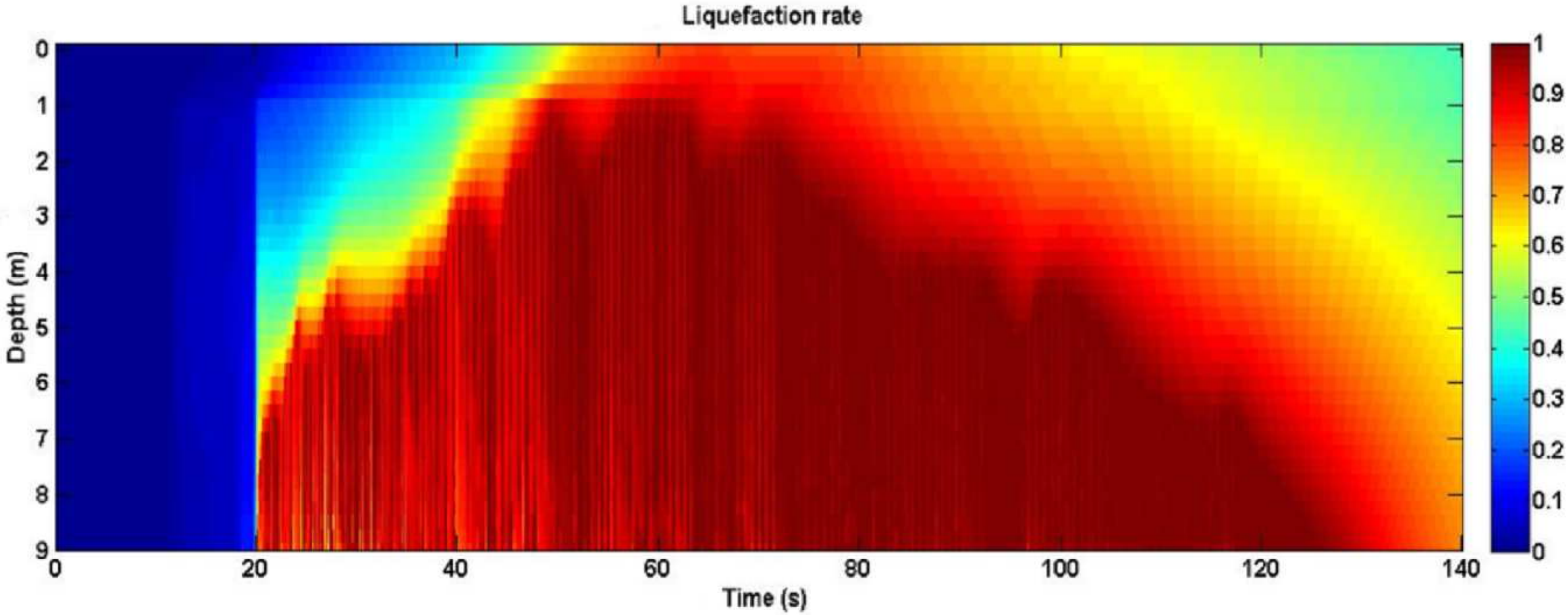
- Absorbing borders at bedrock;
- Periodicity conditions on the lateral sides;

And the Seismic signal is imposed as a plane wave loading

I. Pore pressure build up computation by a transient analysis

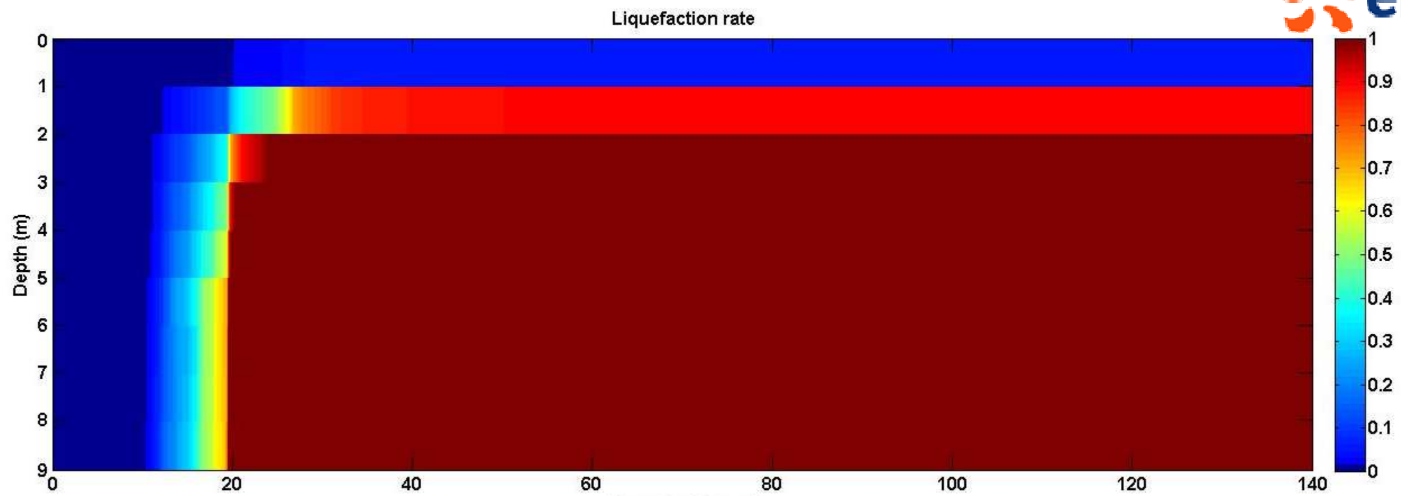
Nonlinear computation of the profile 2 response

Profile 2: Liquefaction rate

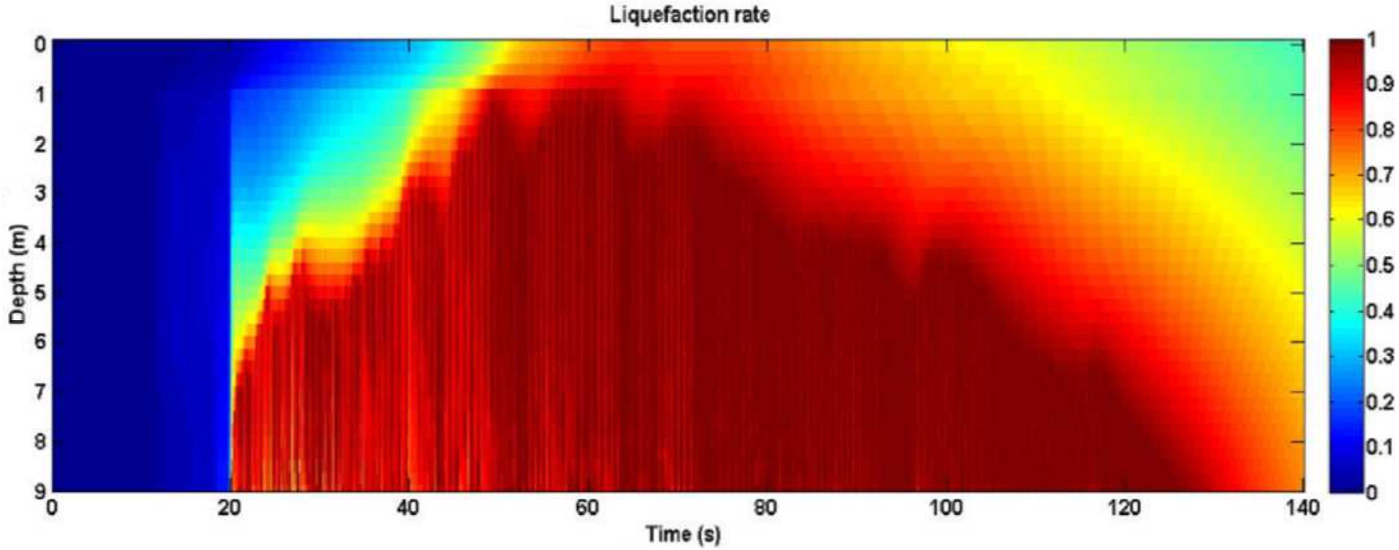


Comparing the two methods : linear equivalent computation + Sawicki and the non linear computation for the profile 2

Linear equivalent computation + Sawicki



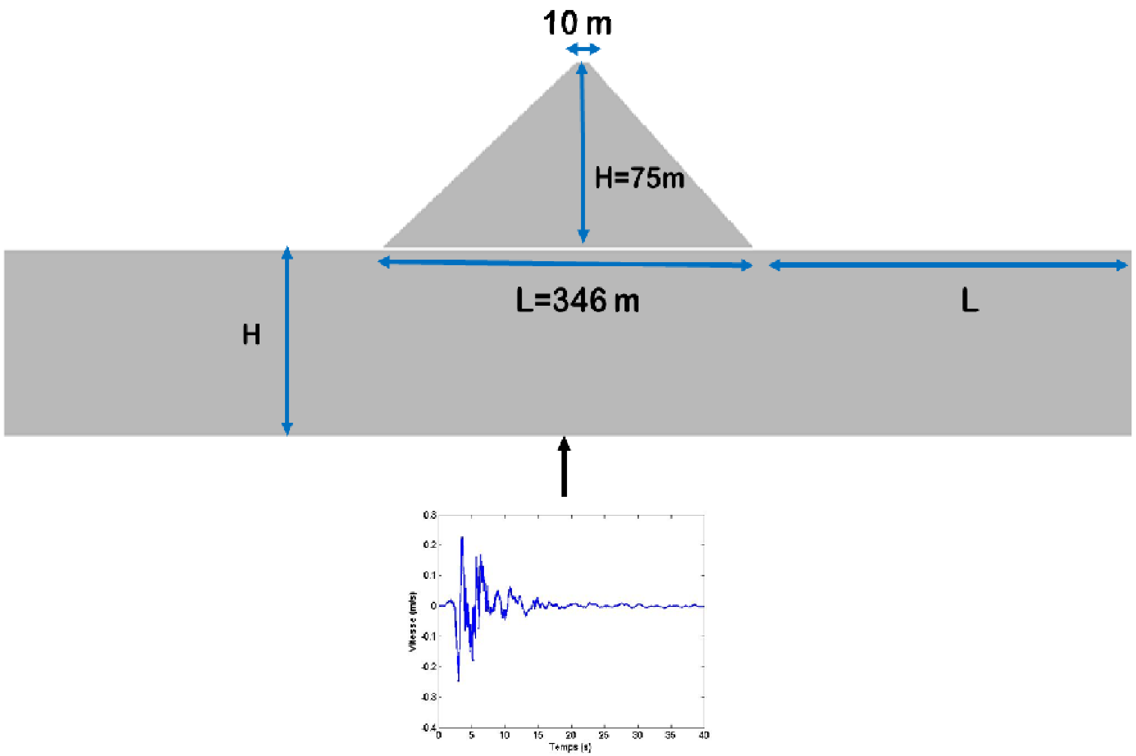
Non linear computation (Hujeux)



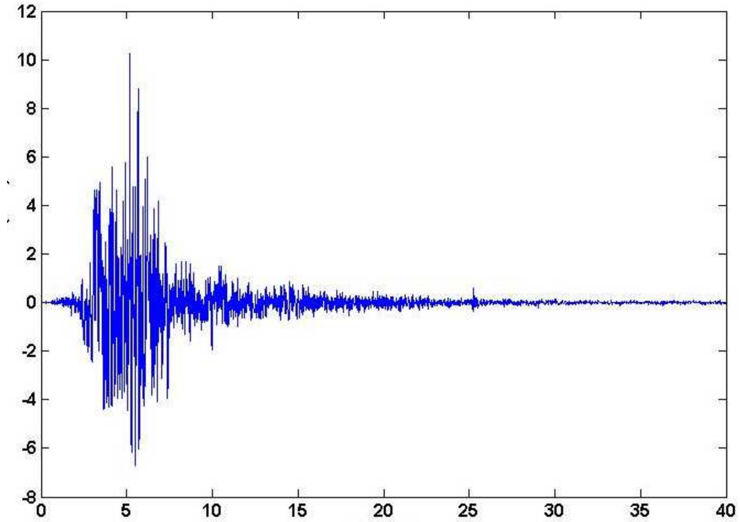
III. 2D Model of Aratozawa dam

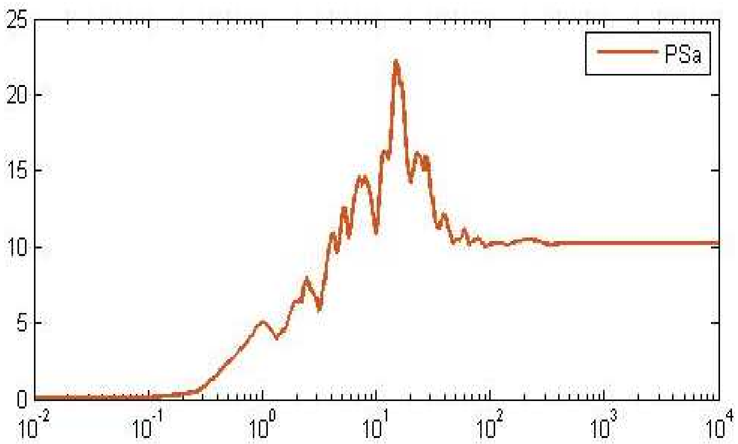
The main objective of our project is to build a pore pressure predictor that allows us to estimate the liquefaction risk in a dam under seismic loading.

So in the next part of our work we will be extending our method to consider a 2D dam model



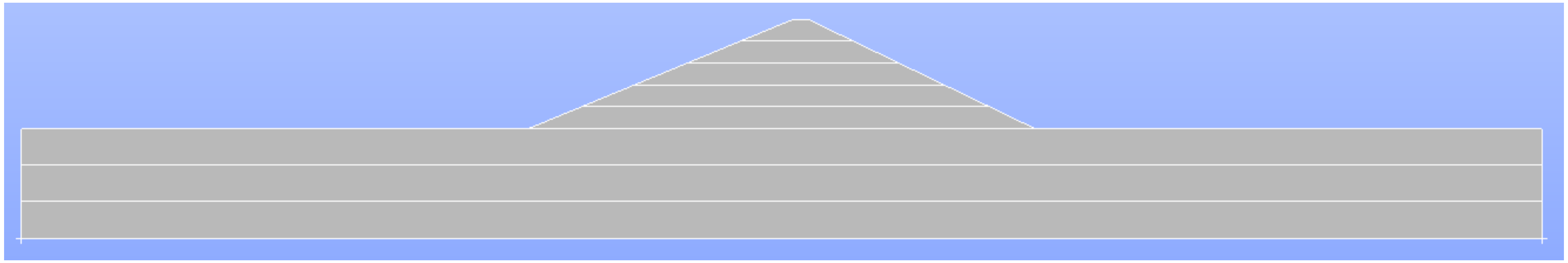
Accelerogram of the 2008- earthquake



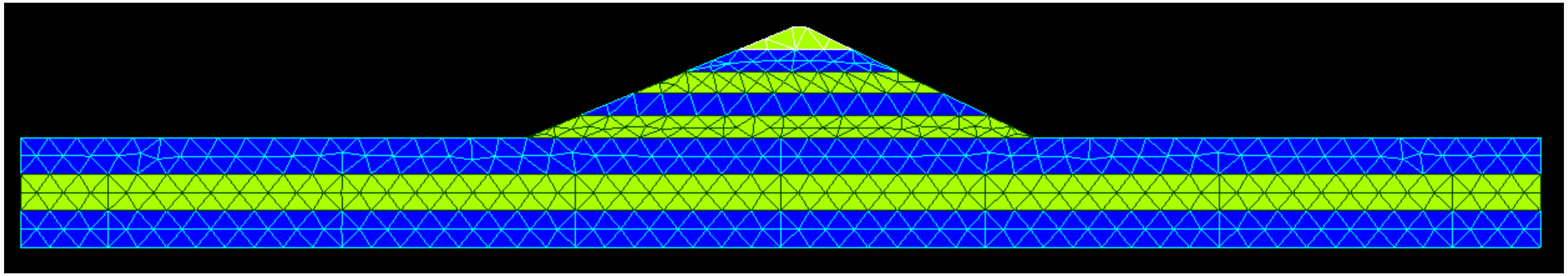


III. 2D Model of Aratozawa dam

Dividing the dam model to layers



And each layer is meshed



III. 2D Model of Aratozawa dam : coupled analysis

- Linear calculation for each layer and calculate the shear strain history in each layer.
- Post-treatment with the Sawicki model to calculate the rise of pore pressure.
- Update of the characteristics of the layer: G/G max by considering the degradation soil curves and the impact of the pore pressure rise.
- Repeat the linear calculation with the new features in an iterative way until reaching the convergence.

⇨ The distribution of the liquefaction rate in the entire dam

AFTER developing the validation method, we proceed to build our liquefaction and settlement predictors.

Thank you for your attention