A macro-element for a shallow foundation to simulate Soil-Structure Interaction

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Presentation progress

1. *Introducing the soil-structure interaction problem*

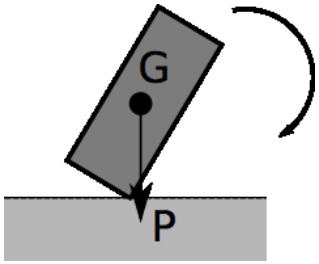
2. *Description of 3D macro-element for SSI*
   - *Description of the model: plasticity & uplift*
   - *Mechanisms coupling and radiative damping*
   - *Parameters*

3. *Results: static, cyclic and dynamic*

4. *Conclusion and way forward*

1. Introducing the SSI problem

⇒ Residual displacements can occur



Which can be dramatic in case of:

- Structure where P-δ effect is important
- slender structures and tall structures
- structures lying on soils with very low characteristics (V_s<100m/s)

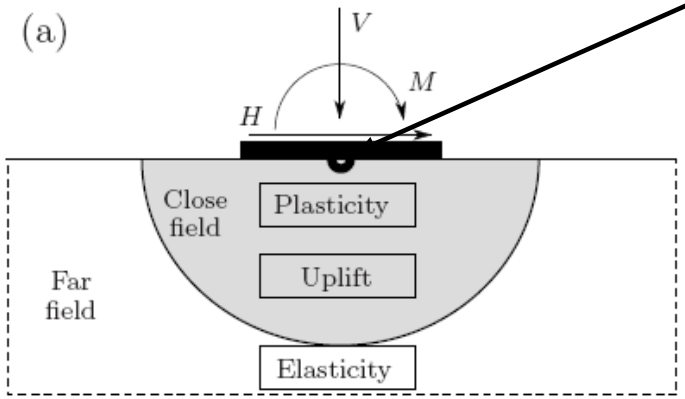
Elastic analysis is not sufficient for safety related structures: for SMA and seismic PSA analyses, with beyond design EQ levels, strong non linearities may occur, due to basemat uplift and soil plastification.

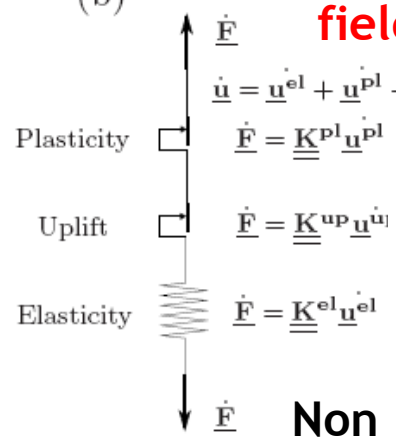
⇒ Development of a macro-element for soil-structure interaction Analysis in term of displacements « **Displacement based design** »

2. Description of SSI 3D Macro-element

Macro-element concept

Rigid shallow foundation



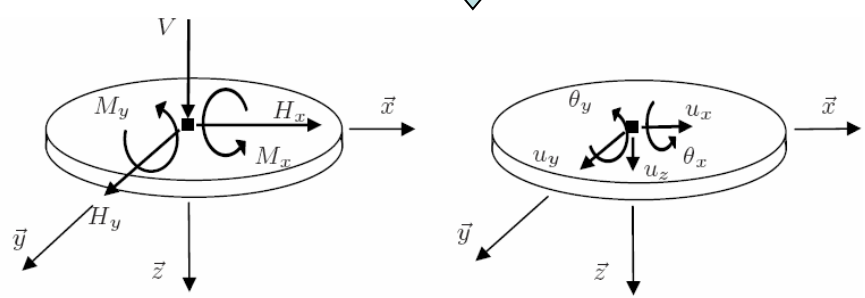


2 sub-domains: close field and far field

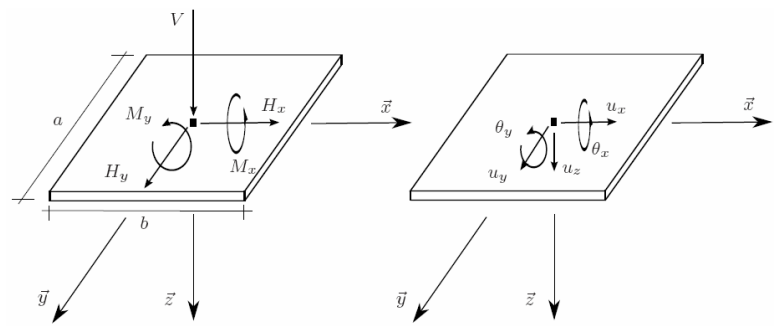
2 non linearities: plasticity and uplift

Non linearities are nevertheless coupled

[Nova et al.1991]
[Houlsby, Butterfield, Martin, et al. 1994, 2002, 2004]
[Pedretti, 1998]
[Crémer, 2001]
[di Prisco, Galli, 2006]
[Chatzigogos, Pecker, 2008]



Global forces Global displacements



circular, rectangular or strip foundations

2. Description of the model: Plasticity

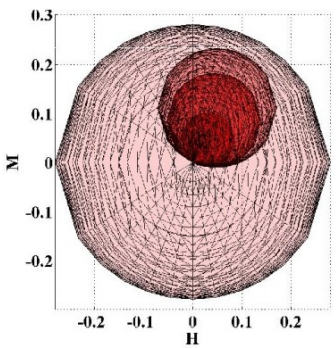
- Failure criterion (developed by C. Crémer and A. Pecker for plasticity with rocking)

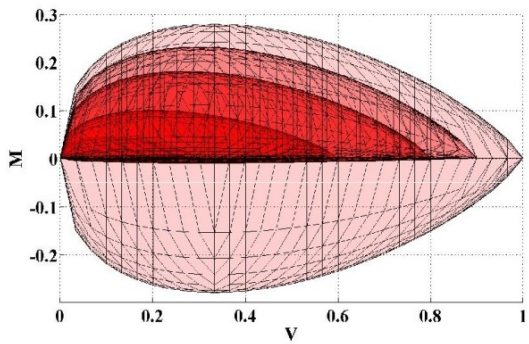
$$f_\infty \equiv \left(\frac{H'_x}{aV'^c(1-V')^d}\right)^2 + \left(\frac{M'_y}{bV'^e(1-V')^f}\right)^2 + \left(\frac{H'_y}{aV'^c(1-V')^d}\right)^2 + \left(\frac{M'_x}{bV'^e(1-V')^f}\right)^2 - 1 = 0$$

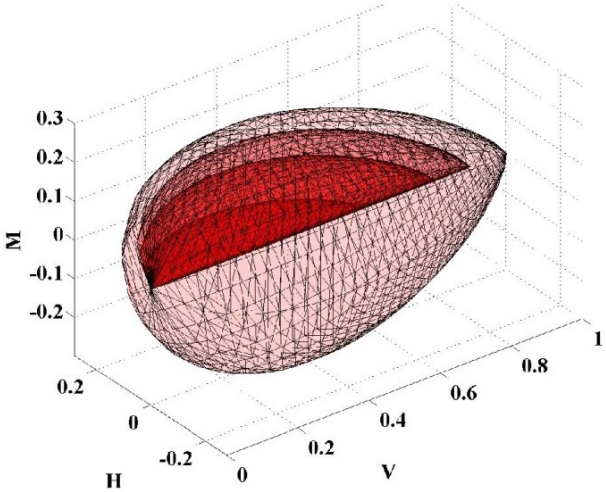
- Loading surface

$$f_c(\underline{\mathbf{F}},\underline{\tau},\rho,\gamma) \equiv \left(\frac{H'_x}{\rho aV'^c(\gamma-V')^d} - \frac{\alpha}{\rho}\right)^2 + \left(\frac{M'_y}{\rho bV'^e(\gamma-V')^f} - \frac{\beta}{\rho}\right)^2 + \left(\frac{H'_y}{\rho aV'^c(\gamma-V')^d} - \frac{\delta}{\rho}\right)^2 + \left(\frac{M'_x}{\rho bV'^e(\gamma-V')^f} - \frac{\eta}{\rho}\right)^2 - 1 = 0$$

Interaction in the H'x_H'y and M'x_M'y planes: circles

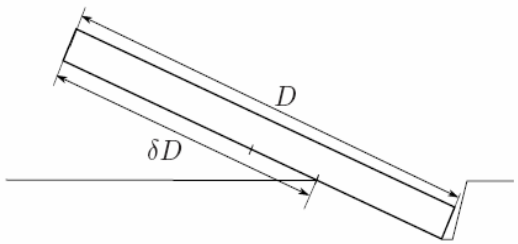






Dimensionless variables →axial symmetry

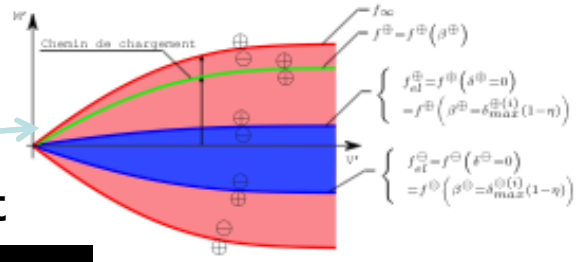
2. Description of the model: Uplift

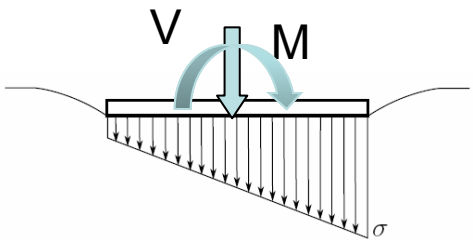


δ percentage of uplift → state variable for the uplift mechanism

On a plastic soil:

-Overturning moment

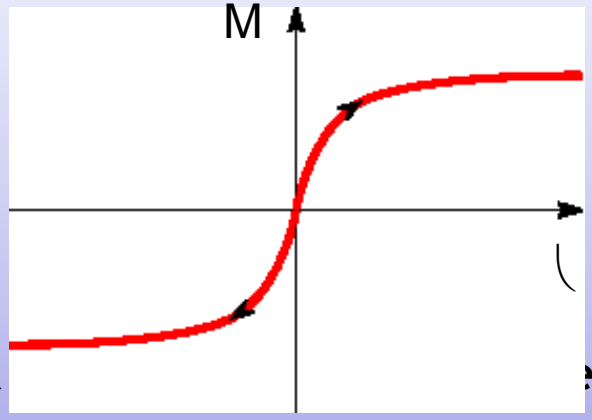




-Uplift initiation moment

(rectangular-strip):

(circular):

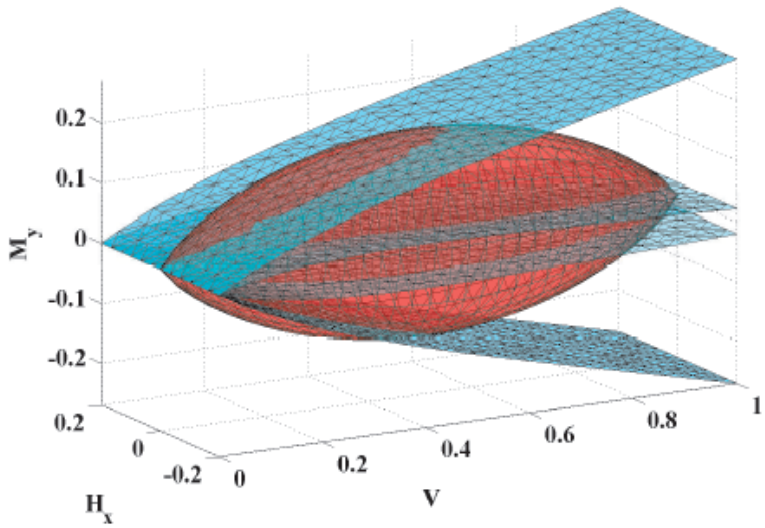


Even with a plastic soil ear but reversible uplift behavior

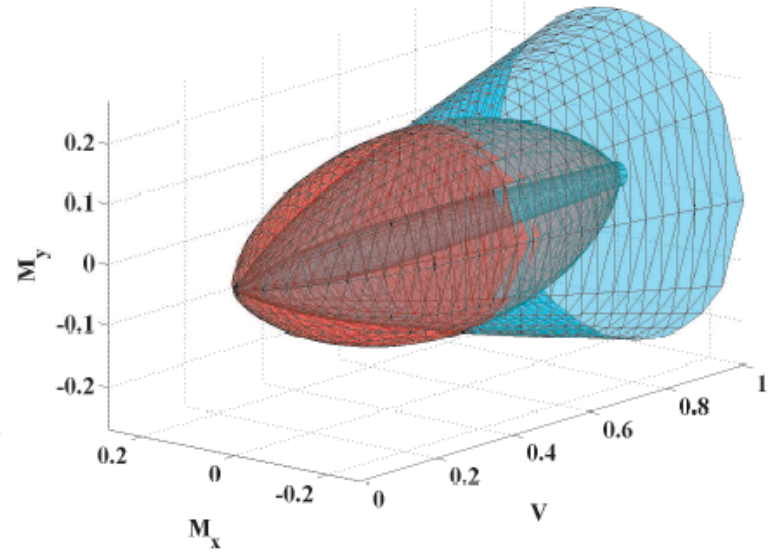
2. Description: Coupling, Radiative damping

Coupling between the two mechanisms

Space M-H-V

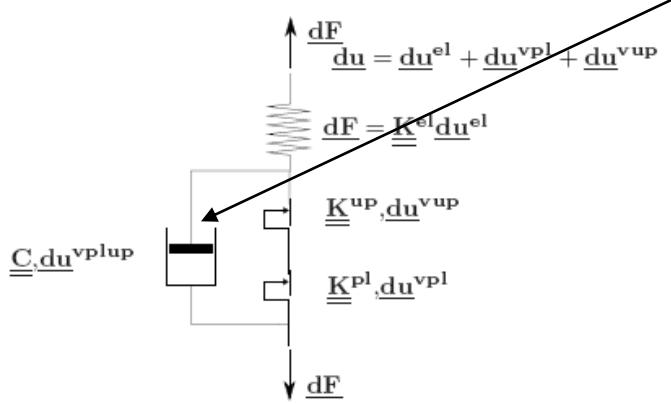


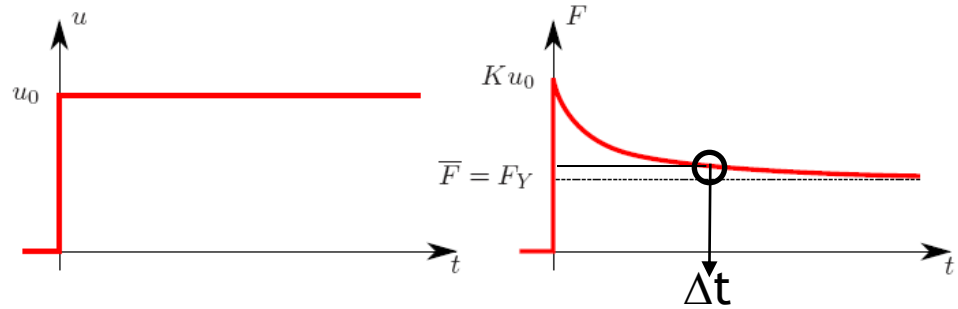
Space M-M-V



Radiative damping

A dashpot is added in parallel of the plasticity model and uplift





Effect of the dashpot during a step time

2. Description: Parameters of the macro-element

Foundation impedance [G. Gazetas]

CAST3M
FedeasLab

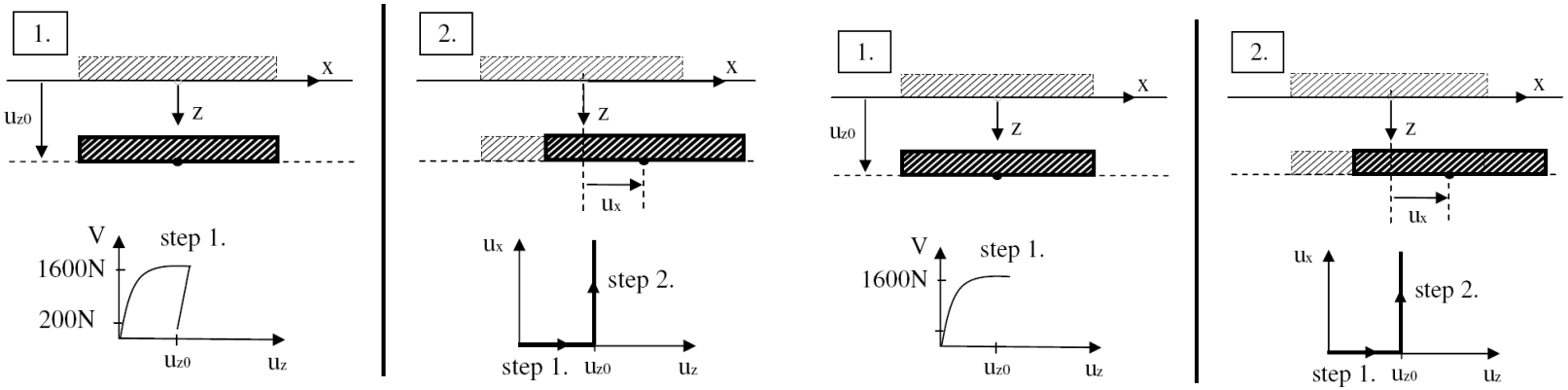
[redacted]

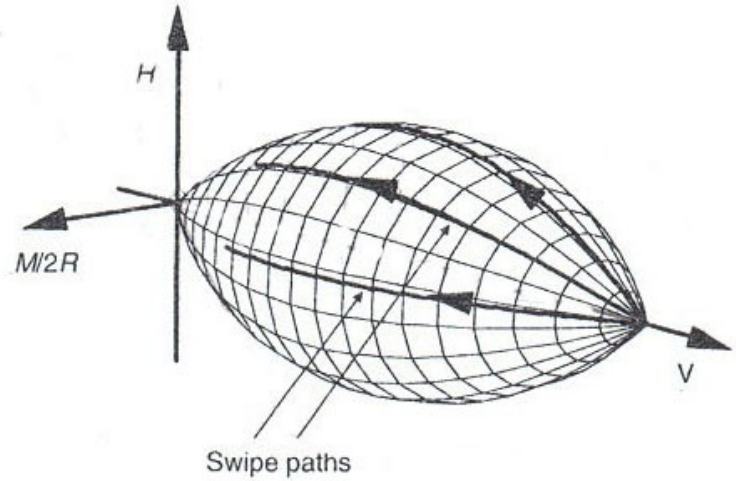
$$\eta_v = \frac{C_z}{K_{el_z}}$$

Most of theses parameters keep unchanged

3.1 Results: Swipe tests 1/2

Displacements imposed tests
→ allow determining the failure criteria of plasticity and uplift mechanisms

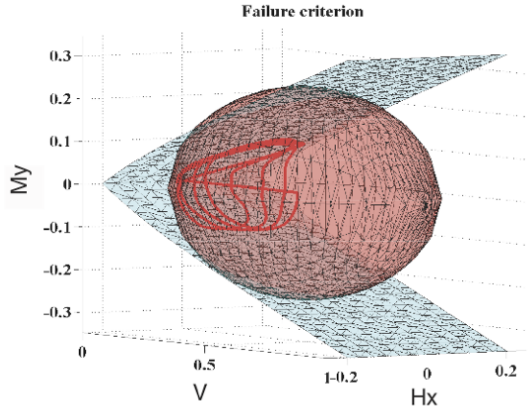


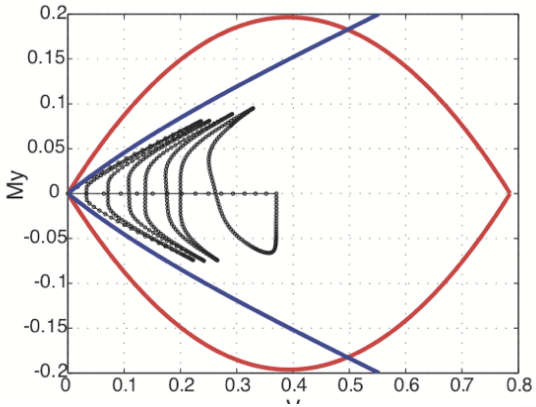


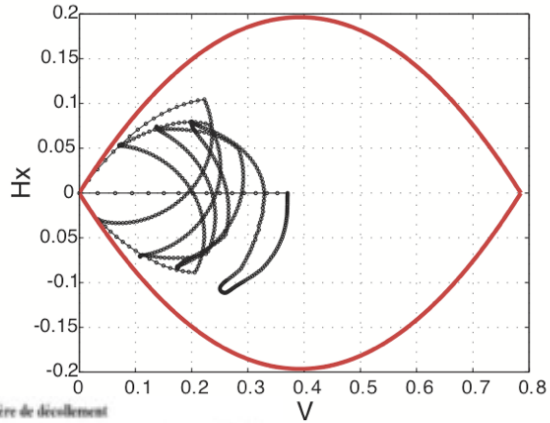
3.1 Results: Swipe tests 2/2

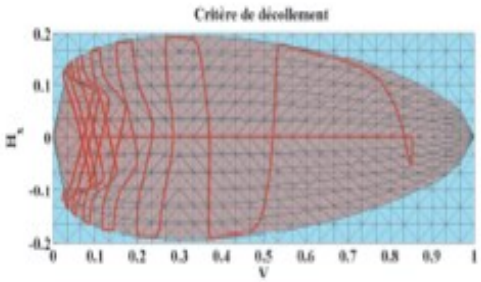
Numerical response of the macro-element submitted to cyclic displacements (swipe test)

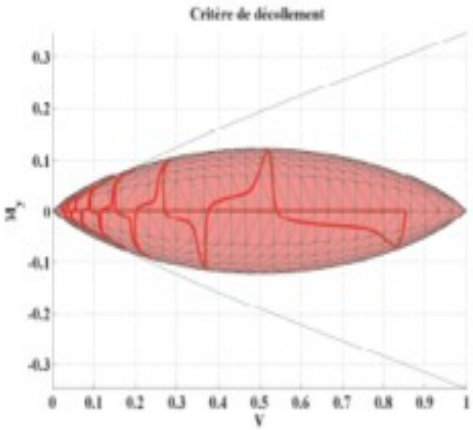
→The response path follows the bounds of the failure criteria of plasticity and uplift mechanisms



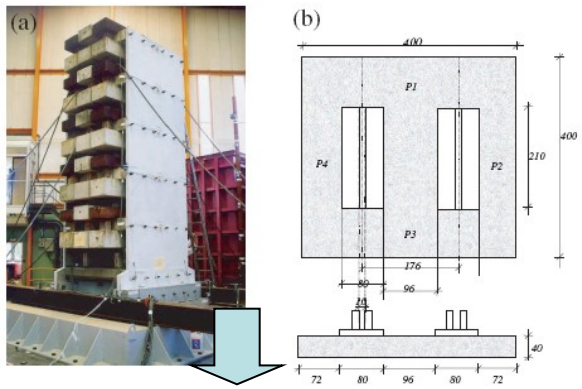




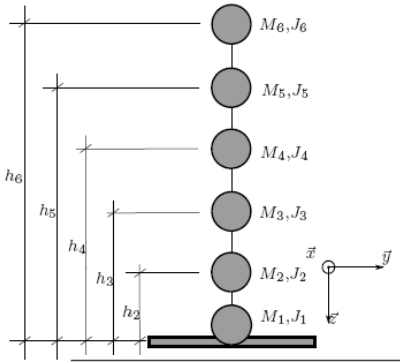




3.2 Dynamic behavior on sand: Camus IV tests (CEA Saclay)

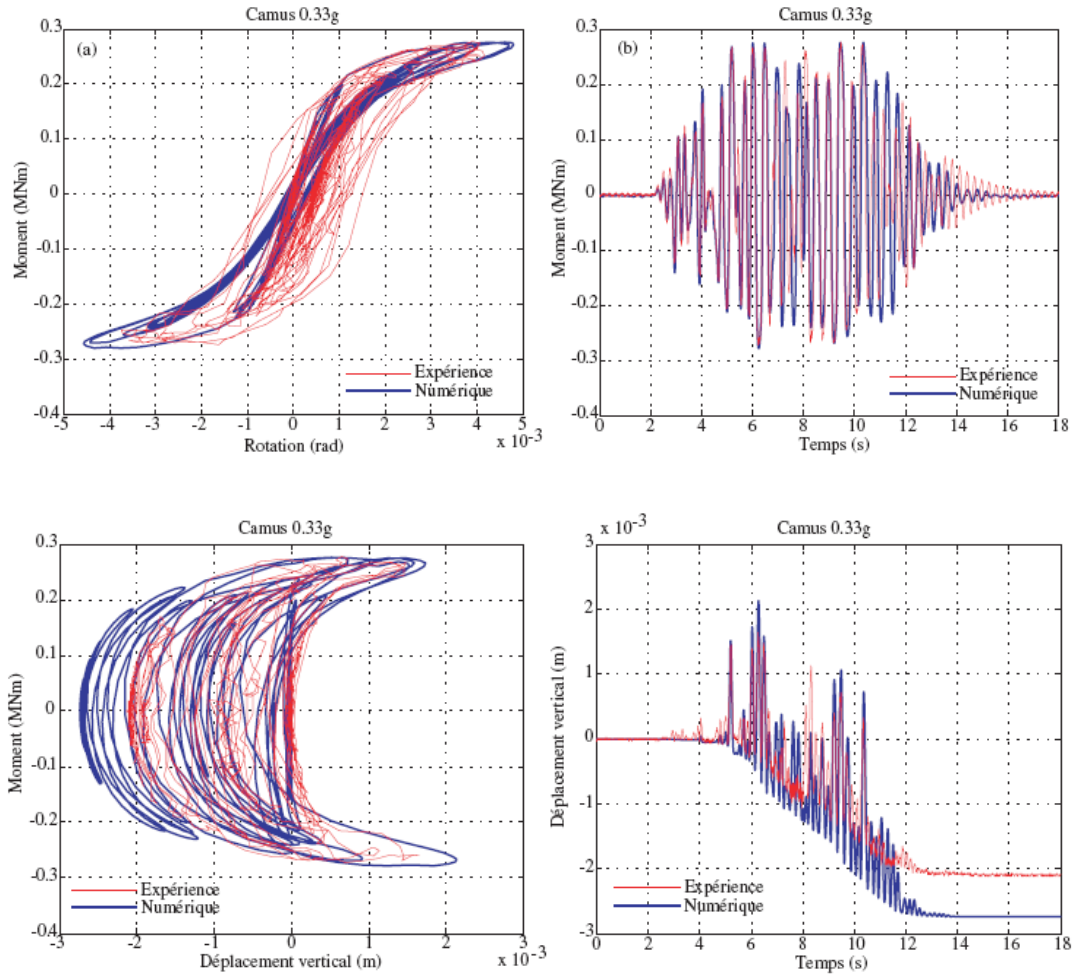


Lumped mass modeling

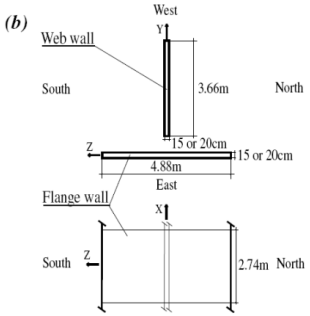


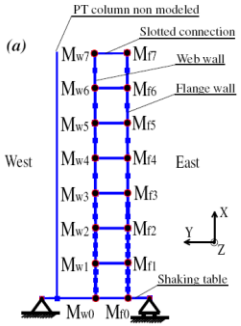
mode	frequency Hz	
	Experimental	Numerical
1 (bending)	3.5	3.5
2 (pump)	13	14.8

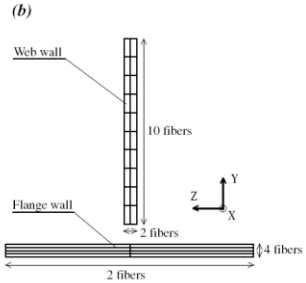
Numerical vs experimental results

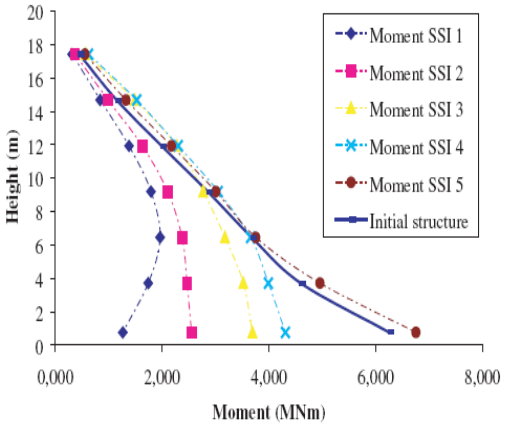


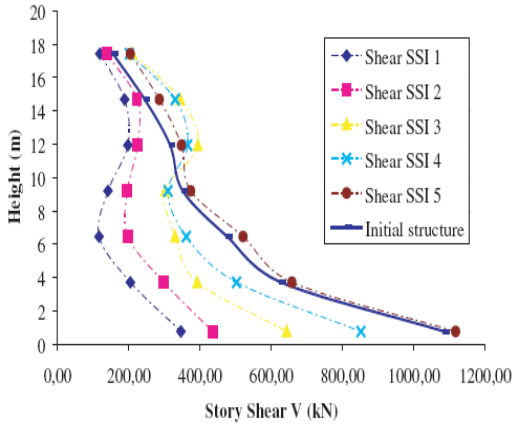
3.3 Dynamic behavior: NEES test (UC San Diego), effect of the characteristics of the soil

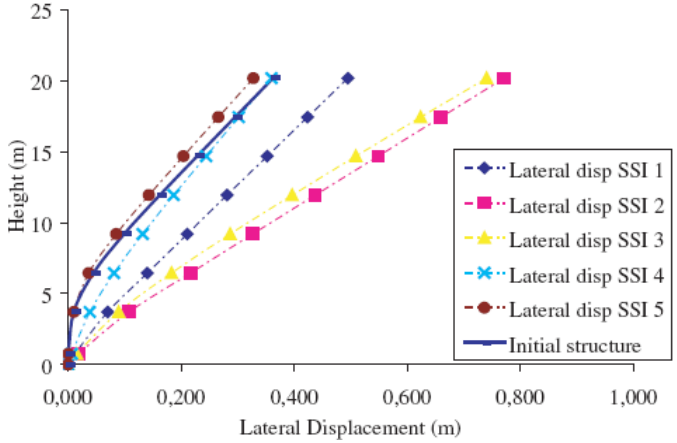








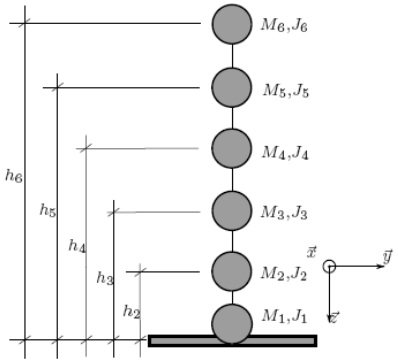




3.4 Study of a Reactor building. 1/4

Influence of the bearing capacity of the soil

Lumped mass modeling



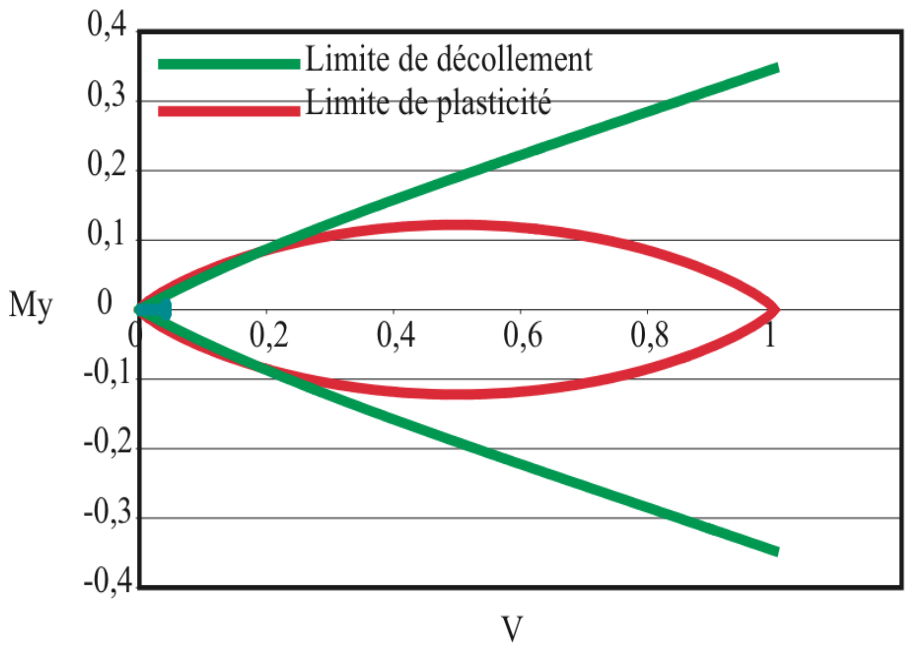
Modal analysis taking into account the softness of the soil

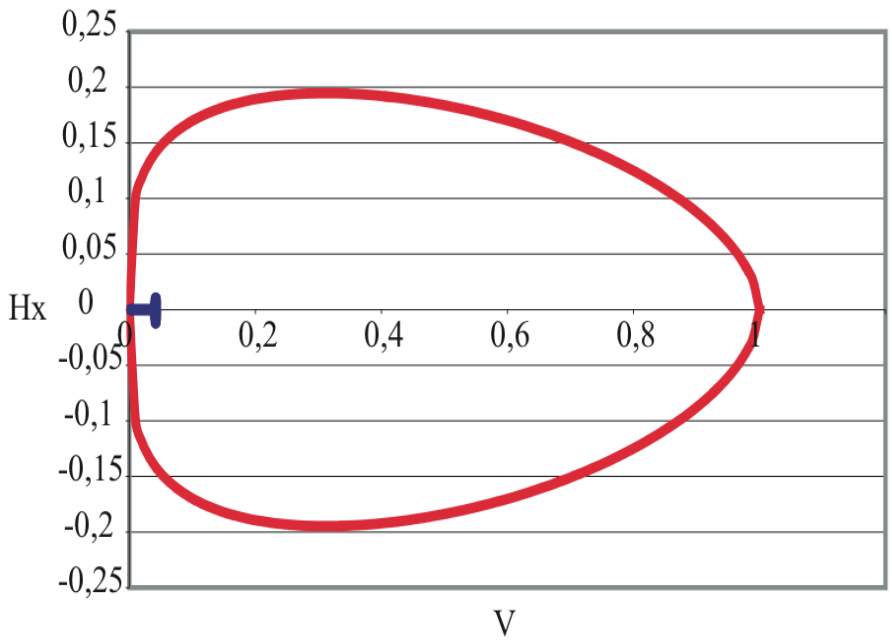
	frequency
Rocking	1,89Hz
Pumping	4,48Hz

Accelerogram: NUREG 0,3 g

3.4 Study of a Reactor building 2/4

With the actual soil





The soil under the building behaves quasi elastically

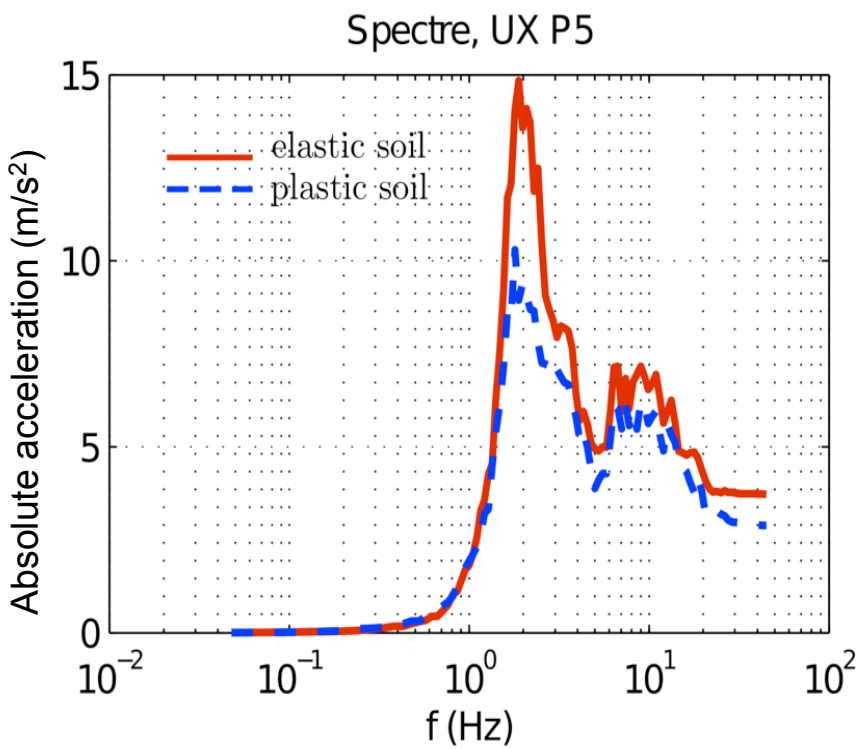
3.4 Study of a Reactor building 3/4

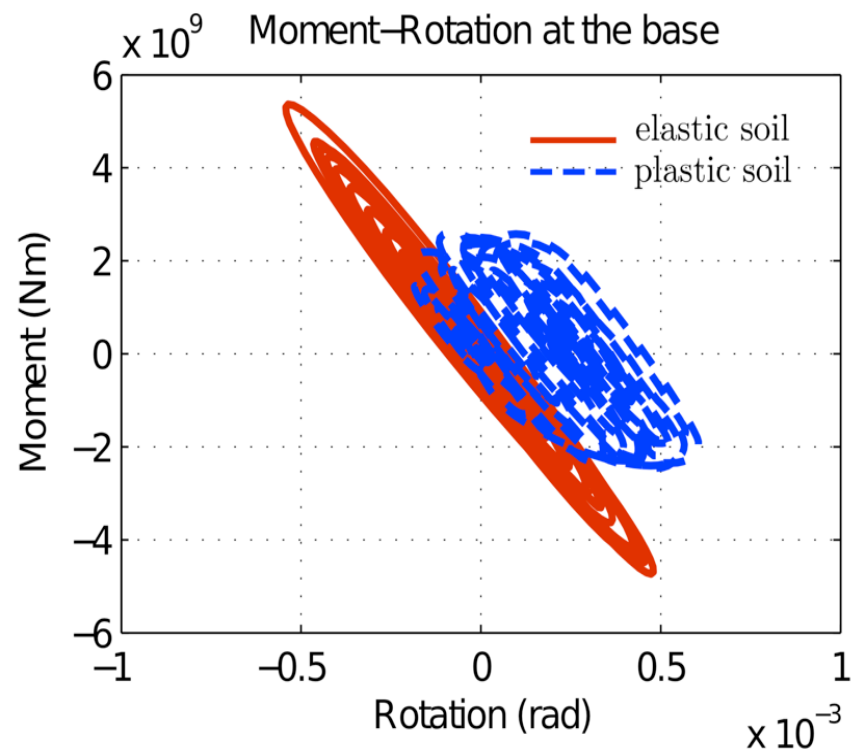
Influence of the bearing capacity of the soil

q_{max}=11546 kPa is decreased to q_{max}= 600 kPa

For: -an elastic soil
-a plastic soil

In this case, taking into account non-linearities into the soil allows better estimating of the internal forces and also the floor response spectra



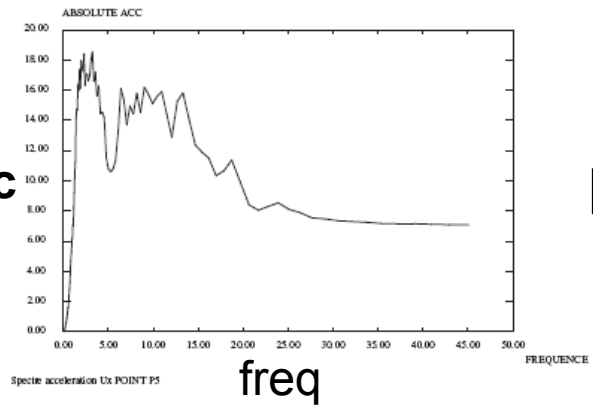


3.4 Study of a Reactor building 4/4

Parametrical study
- ↘ the characteristic of the soil
- ↗ the seismic level

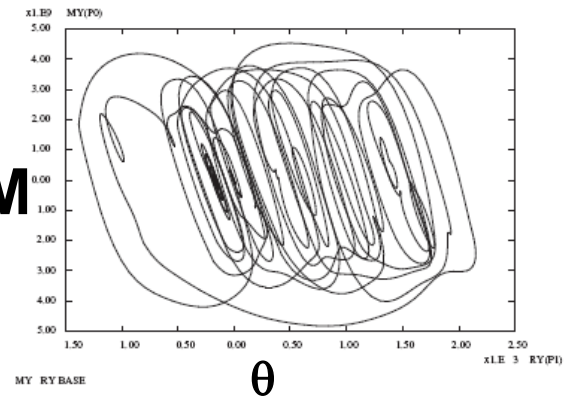
Decreasing the bearing capacity

acc



freq

M



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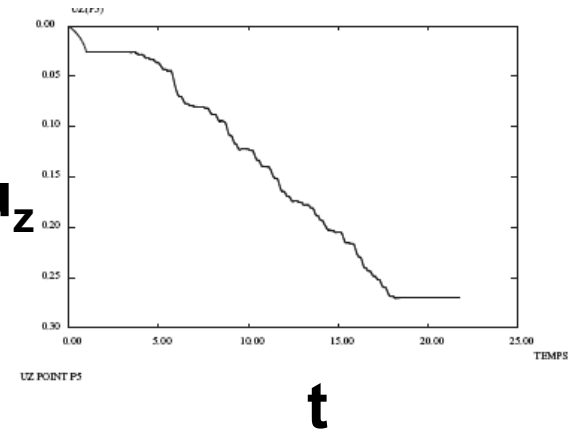

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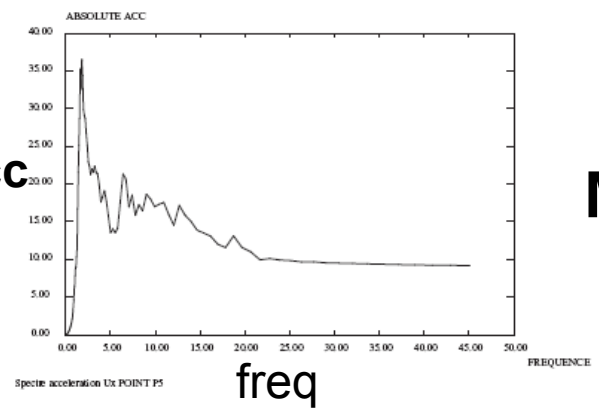
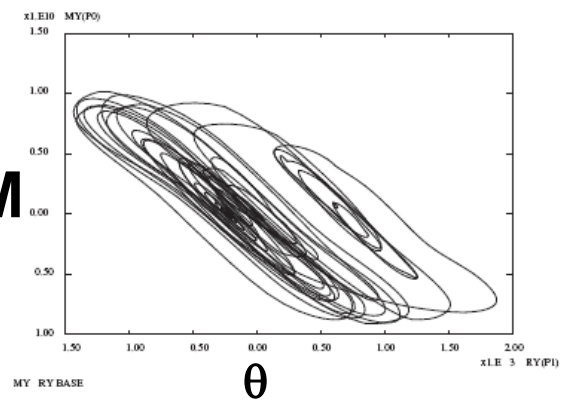
Increasing the seismic level

acc



freq

M



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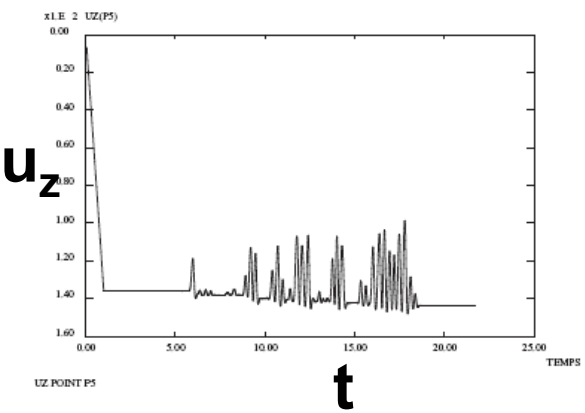

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4. Conclusion and way forward

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- The 3D SSI macro element gives good trends for **monotonic, cyclic and dynamic** behavior.
- Low computational costs allow to perform parametrical studies to investigate a wide range of boundary conditions
- Adaptation of the model to simulate **base-isolators** have been computed
- It takes into account, plasticity, uplift, radiative damping and allows determining residual displacements

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Nevertheless, various improvements could be made concerning:

- the fitting of the parameters (stiffness, shape of the loading surface, radiation damping)
- development of macro-element for deep foundations or improved ground with deep piles or mixed columns

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Thank you for your attention