

Contribution of the use of stone columns for liquefaction mitigation

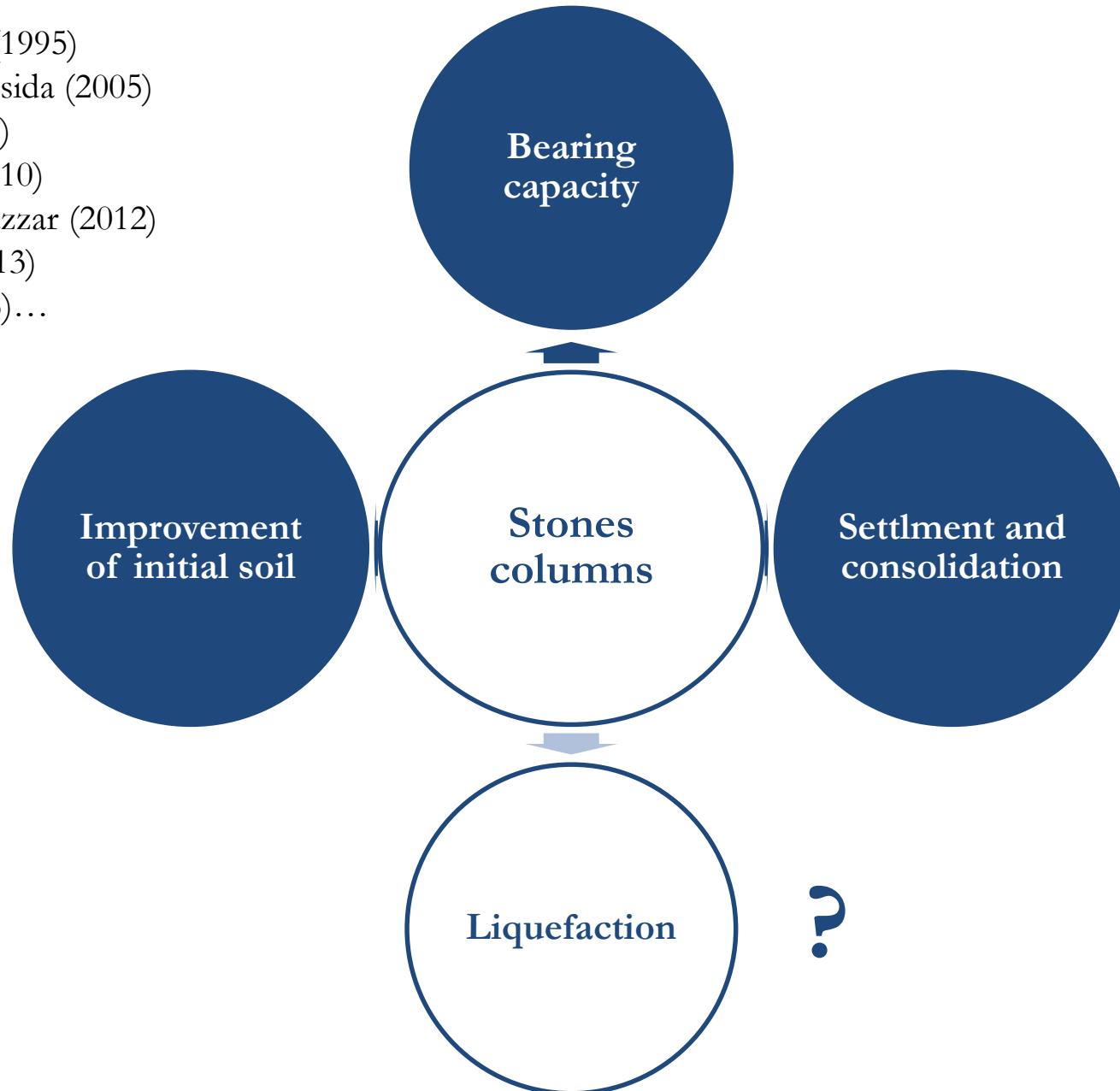
Wisseem FRIKHA

Introduction and problematic

Stone column: technical for soil improvement

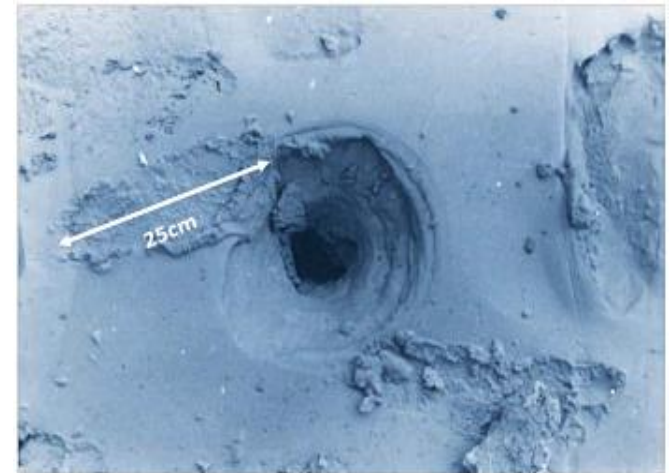


- Bouassida et al.(1995)
- Guetif et Bouassida (2005)
- Jellali et al.(2007)
- Ellouze et al.(2010)
- Bouassida et Hazzar (2012)
- Frikha et al. (2013)
- Bouassida (2016)...





Reverse buildings
Earthquake of Niigata, Japon
1964 (NISEE)



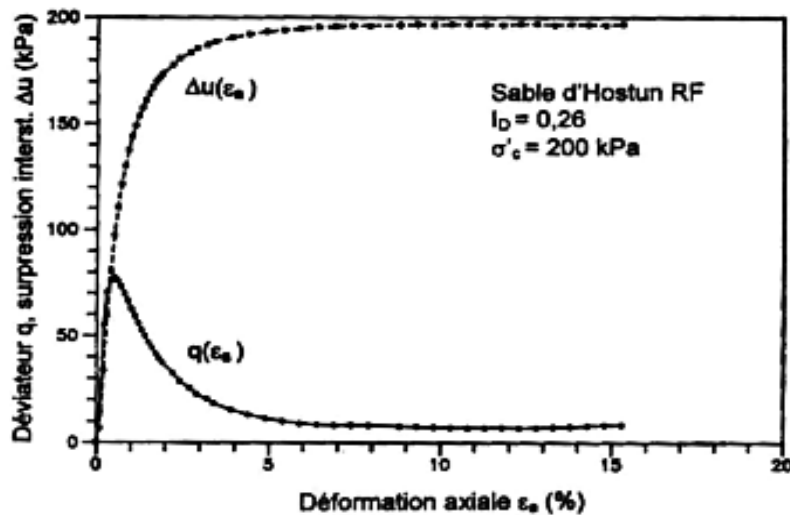
Rise of sandy materials
Sidi Thabet earthquake 1970, Tunisia
(El May et al. 2009)



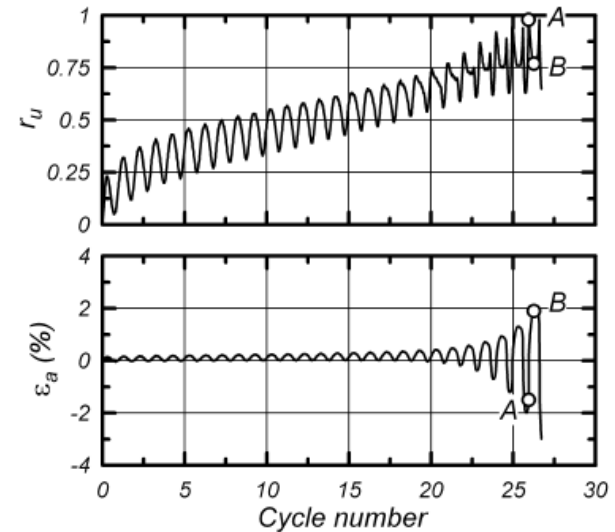
Landslide
Christchurch earthquake
in New Zealand (EERI
2011)

Liquéfaction ?

Phenomenon: Generation of water pore pressure, Loss of shear strength, Disappearance of intergranular contact forces.



Monotonic loading
Canou et al. (1994)



Cyclic loading
Boulanger et Truman (1996)

Criteria of susceptibility to liquefaction:

Granulometry, Relative Density, Degree of saturation, Atterberg limits, etc.

(Seed et Idriss 1982; Andrews et Martin (2000); Bray et al. 2004)

solutions against liquefaction

The liquefaction potential can be reduced by:

- Increasing the compaction of the soil (densification)
- Reinforcing the soil
- Improving drainage capacity

Improvement techniques that can be considered for liquefaction:

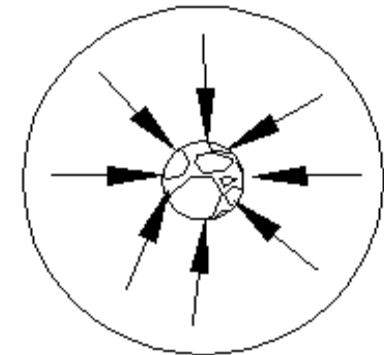
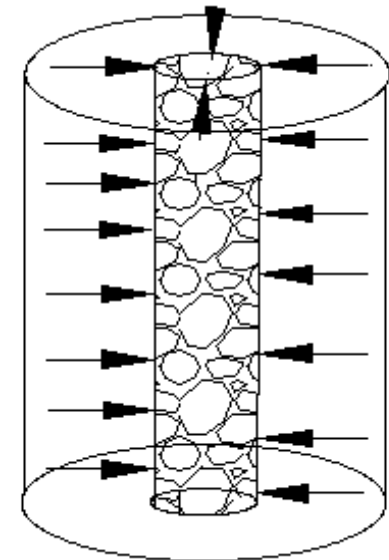
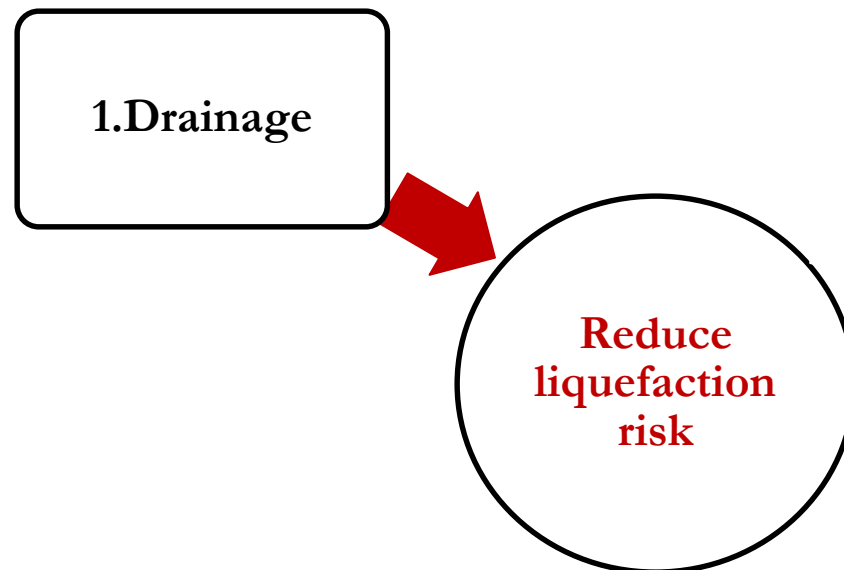
Pre-loading, Vibro-compaction, Rigid inclusions, Deep soil mixing, Jet grouting, Vertical Drains, Stones Columns, etc..

(Baez 1995; Adalier et Elgamal 2004; Green et al. 2008)

Stones columns against liquefaction

Stones columns : vertical drains

- Decrease in the generation of pore pressures
- Acceleration of their dissipation by horizontal drainage



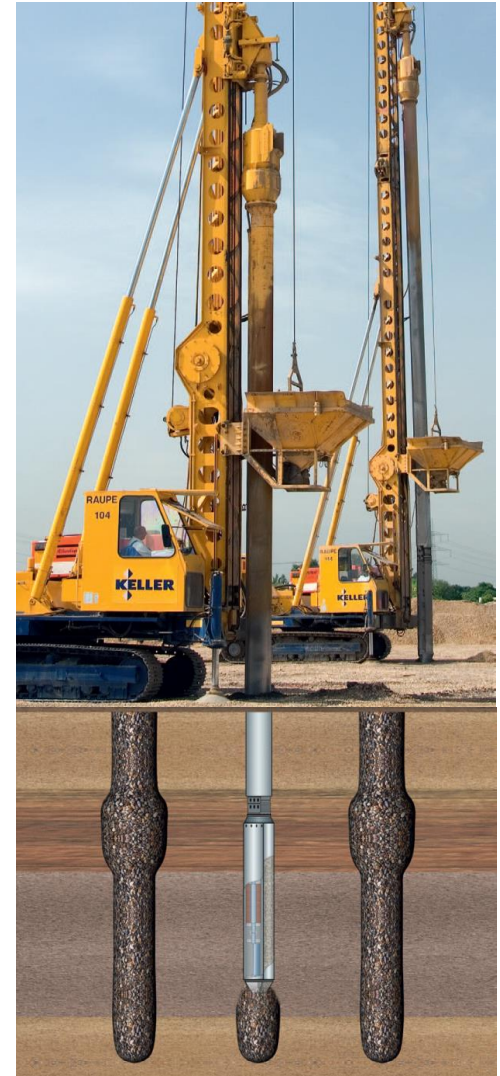
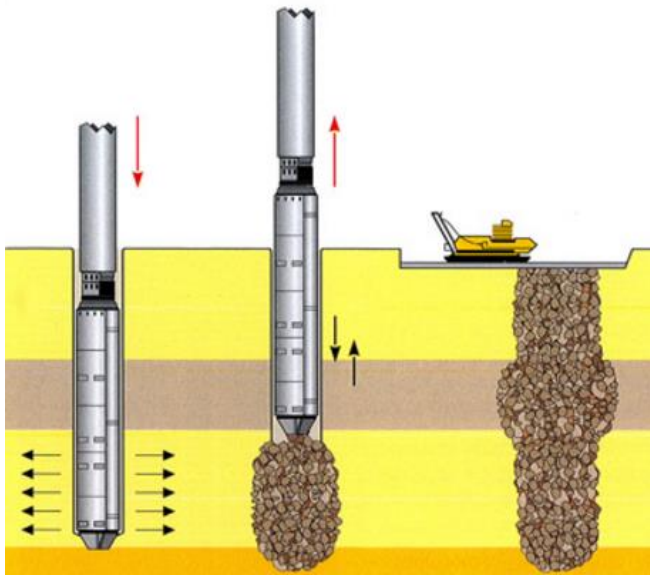
Stones columns against liquefaction

When the installation of SC, the vibration energy generates:

- Reorganization of the granular soil structure
- Reduction of the void ratio and increase of the relative density
- Improvement of the initial properties of the soil (compaction)

2. Densification

Reduce
liquefaction
risk



Stones columns against liquefaction

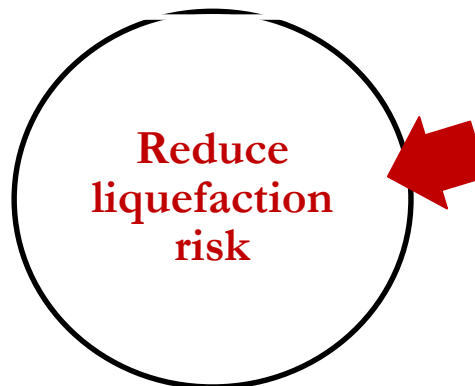
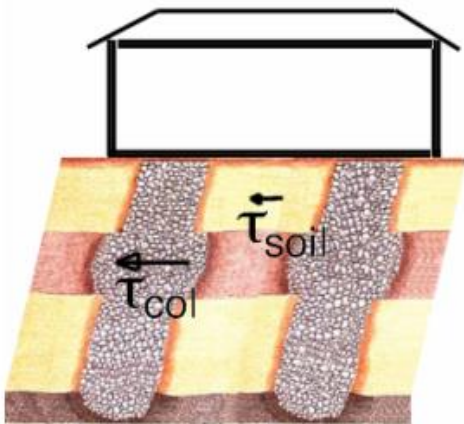
Thanks to the high rigidity of the constituent material of the columns compared to initial soil :

$$\left(G_r = \frac{G_{CB}}{G_{sol}} \text{ varied between 2 to 10} \right)$$

➤ Overall improvement of homogenized characteristics

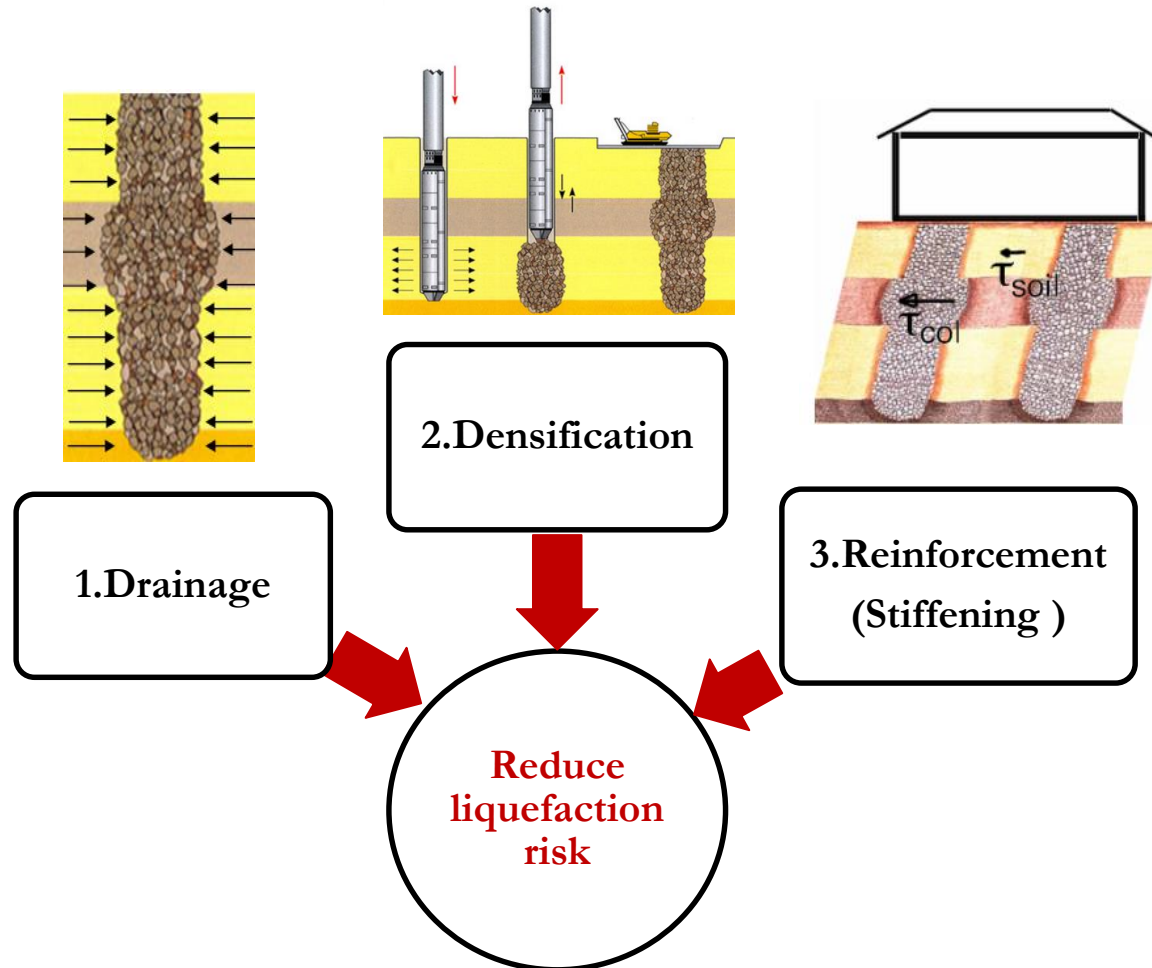
➤ Improvement of soil shear strength

➤ (Baez 1995; Green et al. 2008; Rayamajhi et al. 2012)



**3.Reinforcement
(Stiffening)**

Stones columns against liquefaction



How to quantify the effects of these mechanisms on the efficiency of Stones Columns?

Outline

0. Introduction and Problematic

I. Study of the generation and the dissipation of the pore water pressure of a soil improved by SC

1. Effect of SC Installation

2. Presentation of model

3. Results

II. Study of the effect of densification and Stiffening on the liquefaction potential

III. Numerical study of the liquefaction potential of soil improved by SC

IV. Perspectives

$$r_u = \frac{u}{\sigma'_0}$$



1



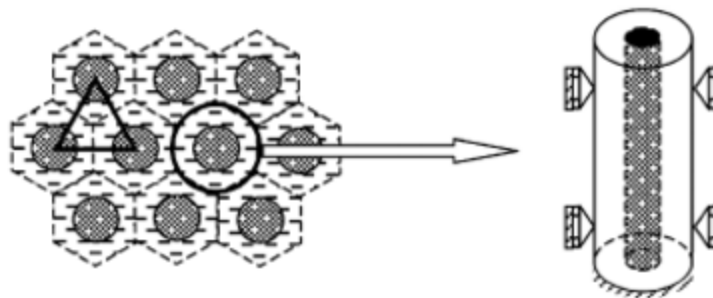
Liquefaction risk

Goal

- Study of the effect of the installation of SC on the variation of r_u

Methods

- Unit cell model



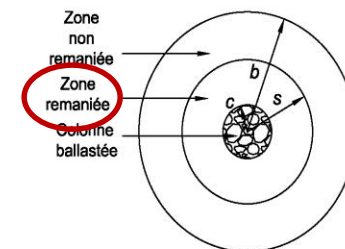
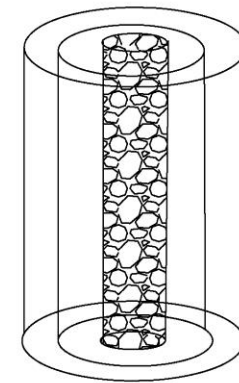
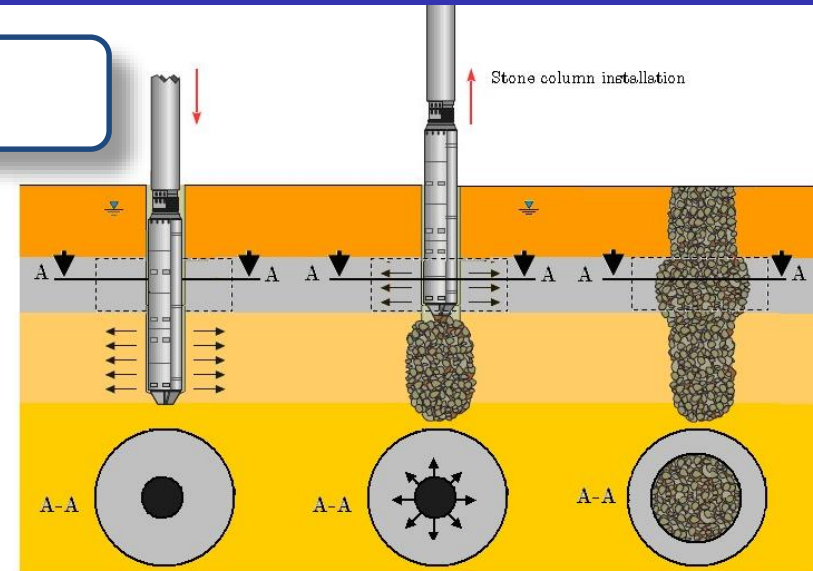
- Study of the generation and dissipation of interstitial overpressures during a cyclic loading

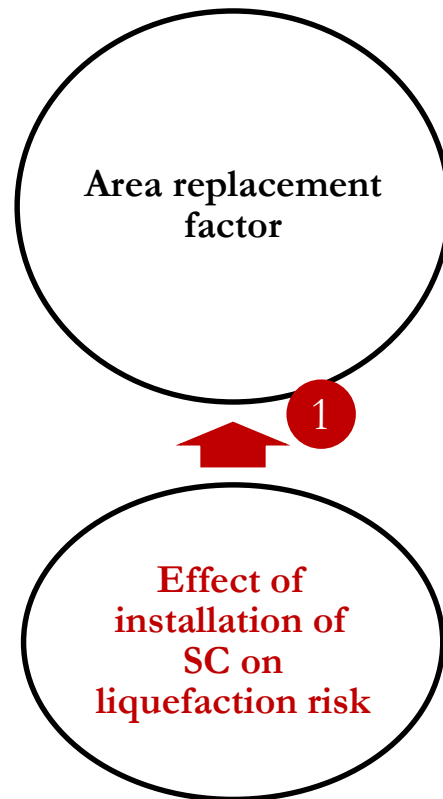
Effect of SC installation

➤ Method of installation of SC :

• Disturbed area around the column (smear zone)

• Variation of Initial Soil properties in Disturbed Area (Example: Horizontal Permeability)

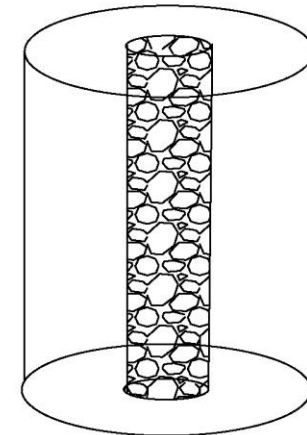
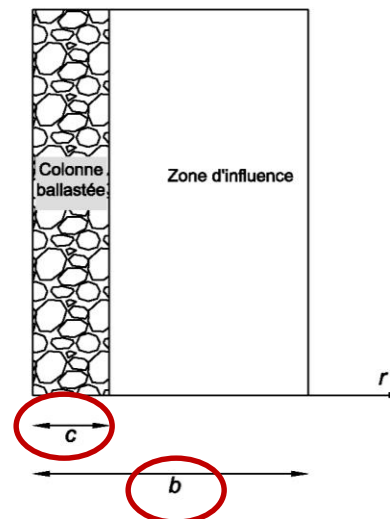
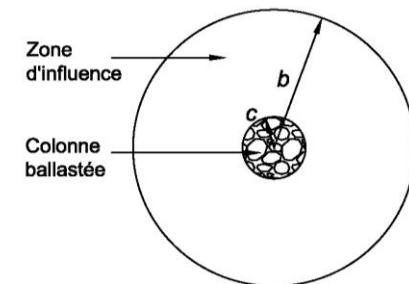
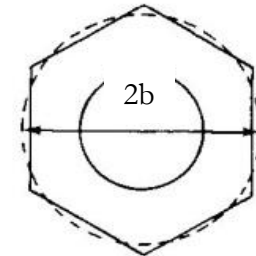
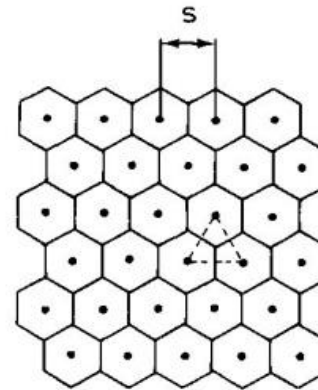


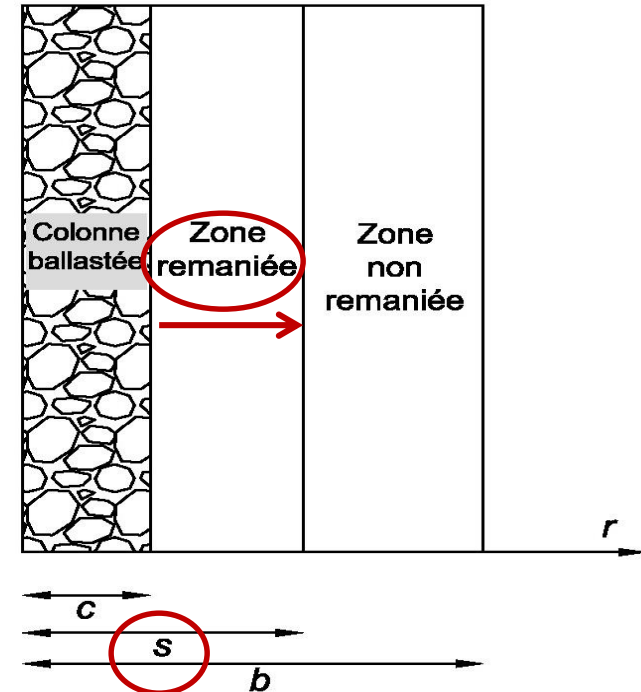
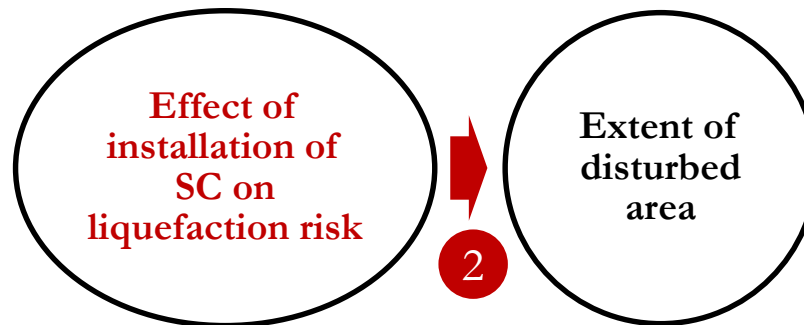
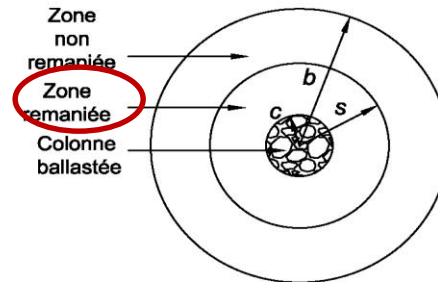
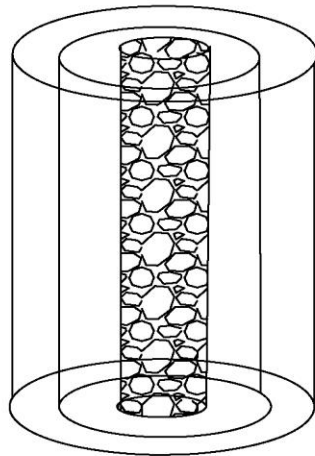


➤ Parameter studied :

ratio « c/b »

Area replacement factor $\eta = \left(\frac{c}{b}\right)^2$





➤ Parameter studied :

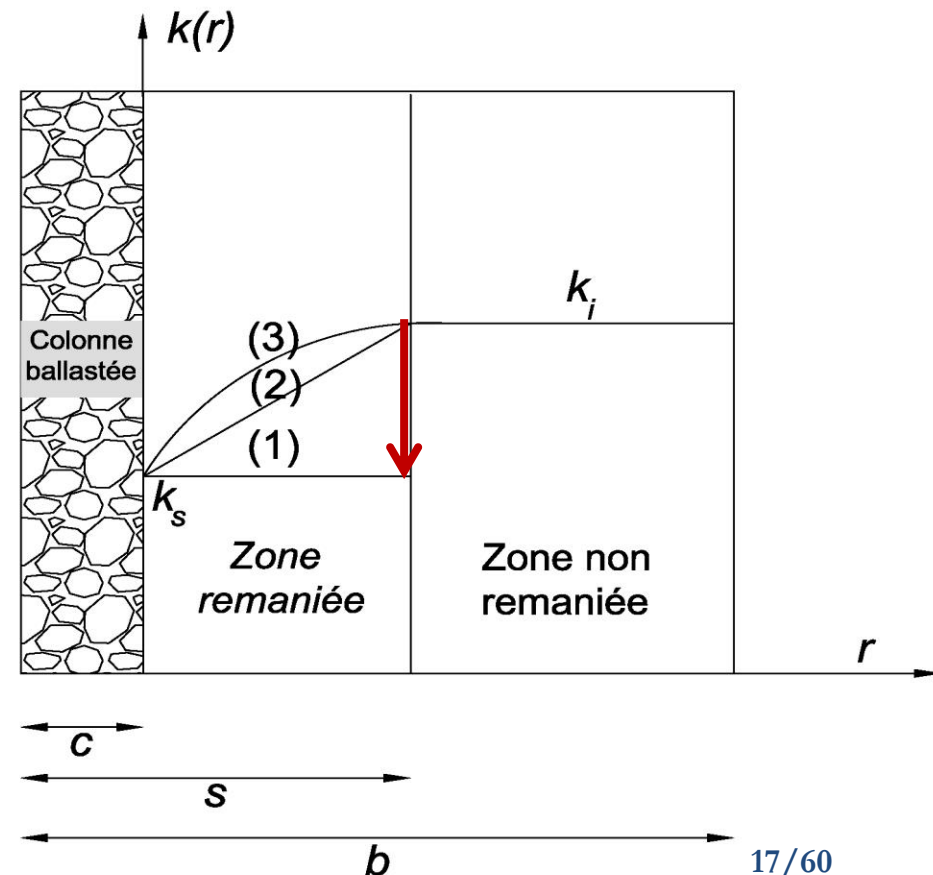
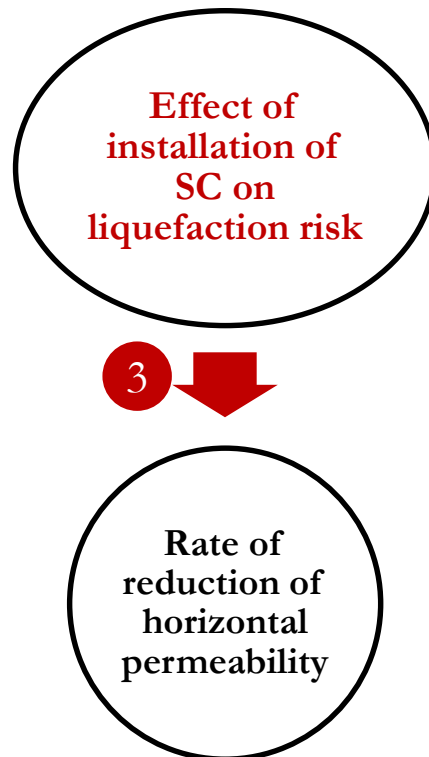
Radius of disturbed area « S »

➤ Parameter studied :

Rate of reduction of horizontal permeability: k_i / k_s

k_i : Initial permeability of soil

k_s : Pemeability in disturbed zone (boundary)



3 models of permeability variation $k(r)$ in the disturbed area : $c \leq r \leq s$

1) Reduced constant permeability

$$k(r) = k_s$$

2) Linear variation

$$k(r) = \frac{k_i - k_s}{s - c} (r - c) + k_s$$

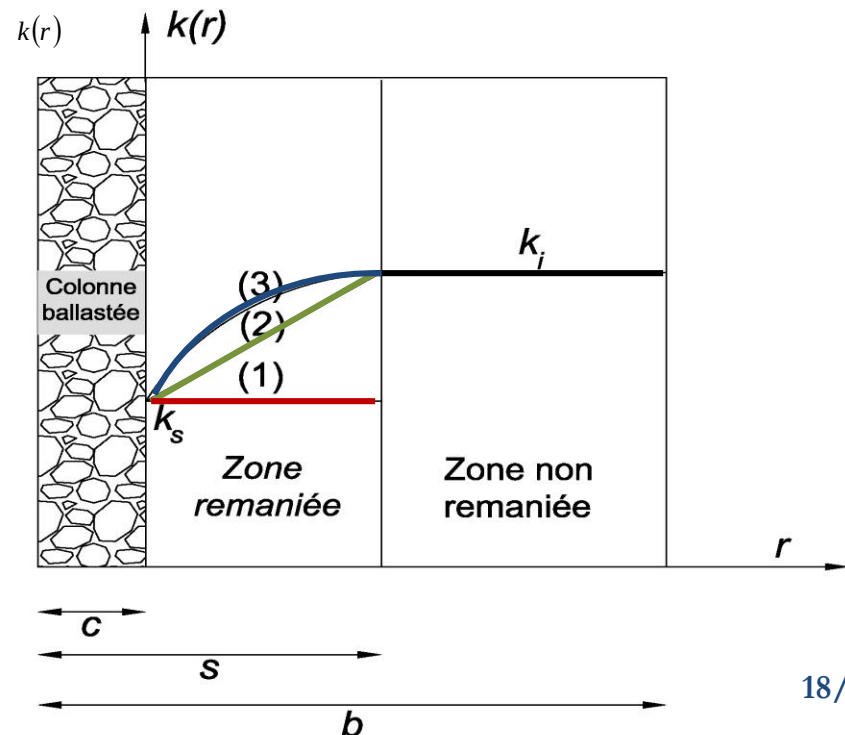
3) Parabolic variation

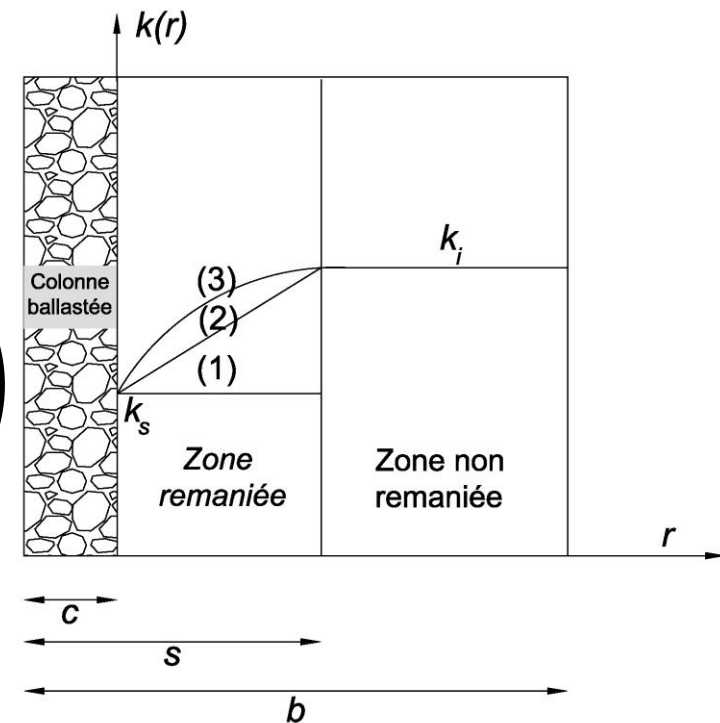
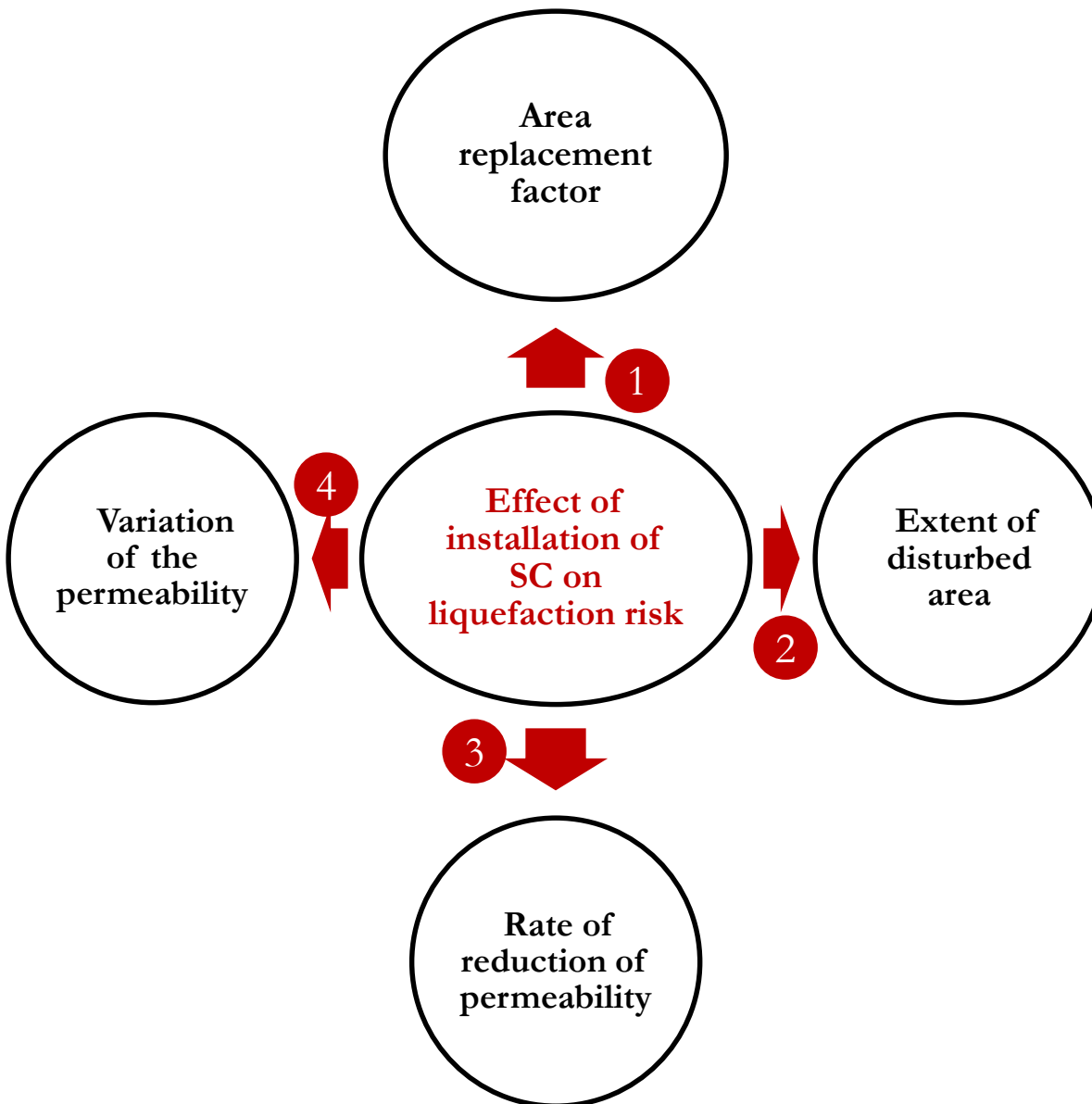
$$k(r) = k_i \left(1 - \frac{k_s}{k_i} \right) \left(A - B + C \frac{r}{c} \right) \left(A + B - C \frac{r}{c} \right)$$

Variation of
of the
permeability

4

Effect of
installation of
SC on
liquefaction risk





Model of generation and dissipation of pore pressures of soil improved by SC

$$\frac{k(r)}{\gamma_w m_v} \left(\frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right) + \frac{1}{\gamma_w m_v} \frac{\partial(k(r))}{\partial r} \frac{\partial u}{\partial r} = \frac{\partial u}{\partial t} - \frac{\partial u_g}{\partial N_{cyc}} \cdot \frac{\partial N_{cyc}}{\partial t}$$



$$T_d K(R) \left(\frac{1}{R} \frac{\partial r_u}{\partial R} + \frac{\partial^2 r_u}{\partial R^2} \right) + T_d \frac{\partial(K(R))}{\partial R} \frac{\partial r_u}{\partial R} = \frac{\partial r_u}{\partial T} - \frac{\partial U_g}{\partial N_{cyc}} \cdot N_{eq}$$

k : horizontal permeability

r : Raduis

u : interstitial pressure

m_v : volumic compressibility

u_g : interstitial pressure generated after loading

t_d : Duration of loading

N_{cyc} : Number of cycles

N_{eq} : Equivlent cyclic number

Dimensionless parameters (united):

$$R = \frac{r}{b} \quad K(R) = \frac{k(r)}{k_i} \quad T = \frac{t}{t_d}$$

$$r_u = \frac{u}{\sigma_0} \quad U_g = \frac{u_g}{\sigma_0}$$

$$\frac{\partial N_{cyc}}{\partial t} = \frac{N_{eq}}{t_d} (0 \leq t \leq t_d), \quad \frac{\partial N_{cyc}}{\partial t} = 0 (t > t_d)$$

$$\frac{\partial U_g}{\partial N_{cyc}} = \frac{1}{\alpha \pi N_l} \cdot \frac{1}{\sin^{2\alpha-1}\left(\frac{\pi}{2} r_u\right) \cos\left(\frac{\pi}{2} r_u\right)}$$

$$T_d = \frac{k_i}{\gamma_w} \frac{t_d}{m_v} \frac{1}{b^2}$$

Model of generation and dissipation of pore pressures of soil improved by SC

$$T_d K(R) \left(\frac{1}{R} \frac{\partial r_u}{\partial R} + \frac{\partial^2 r_u}{\partial R^2} \right) + T_d \frac{\partial(K(R))}{\partial R} \frac{\partial r_u}{\partial R} = \frac{\partial r_u}{\partial T} - \frac{\partial U_g}{\partial N_{cyc}} \cdot N_{eq}$$

➤ Finite difference resolution (Matlab)

➤ Boundary conditions:

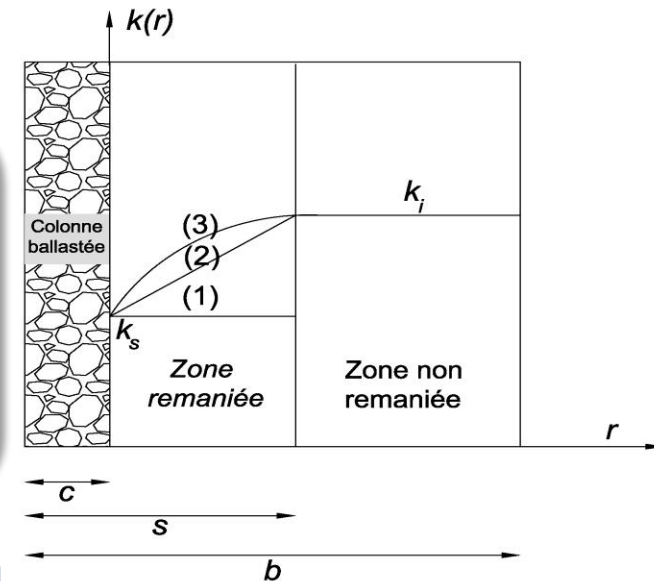
- Due to the symmetry, the rate of change in pore pressure is equal to zero for ($r=b$):

$$\frac{\partial u}{\partial r}(r=b)=0$$

- The pore pressure in the vicinity of the column is zero: $u(r=c)=0$

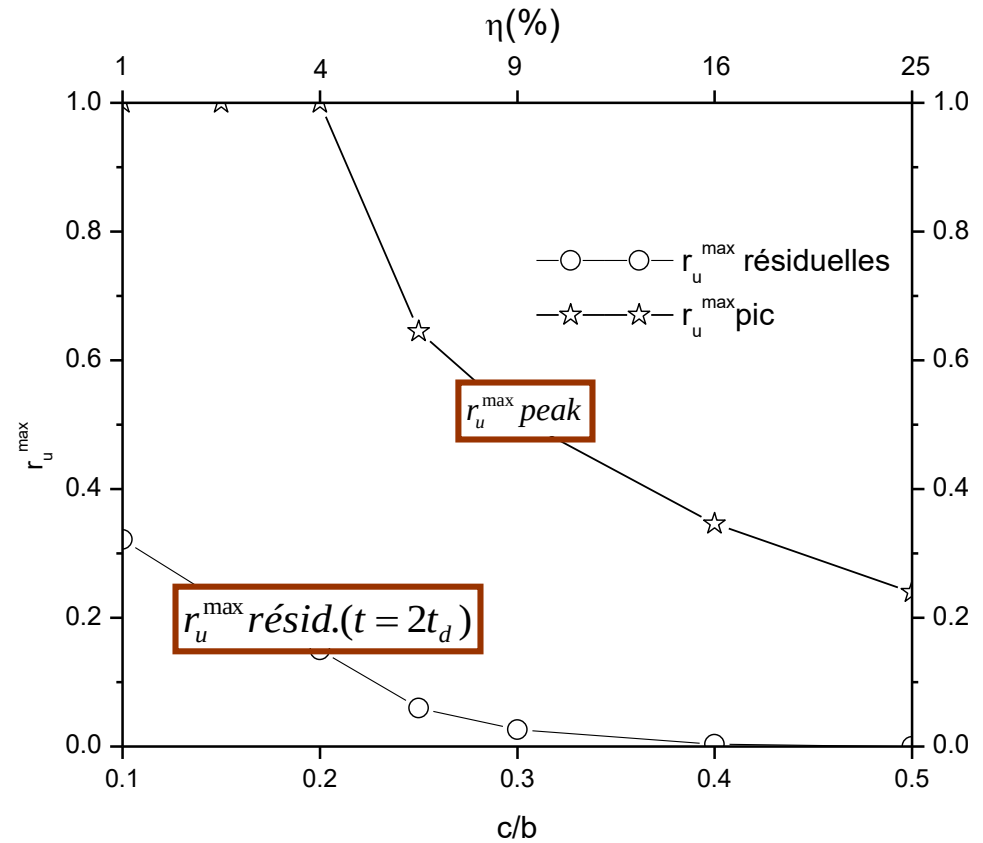
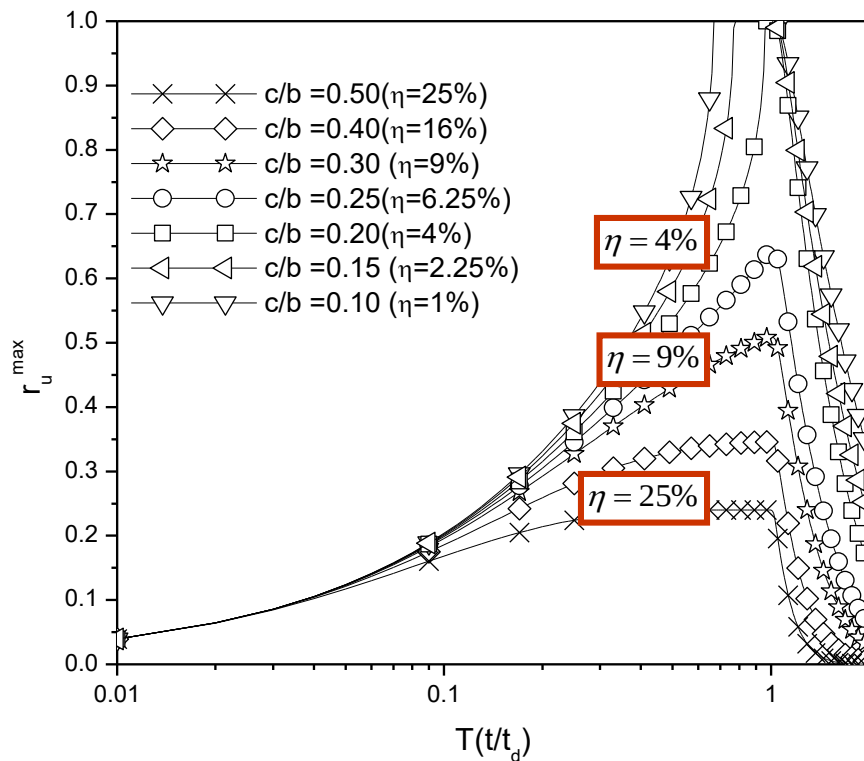
➤ Initials Conditions :

- The pore pressures are equal to the average interstitial pressures generated during an initial time dt .



1 Effect of area replacement factor

❖ Without disturbance

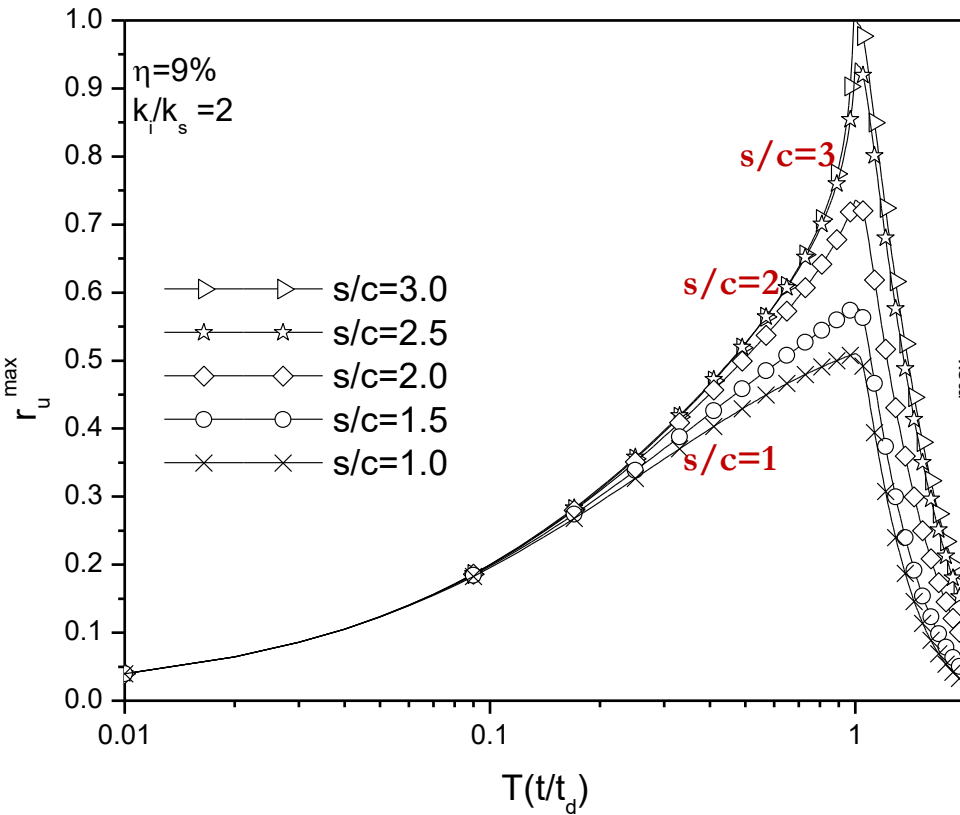


Variation of $r_u^{\max}$ versus normalized time

Variation $r_u^{\max} \text{ peak}$ et $r_u^{\max} \text{ résid.}$ versus η

2

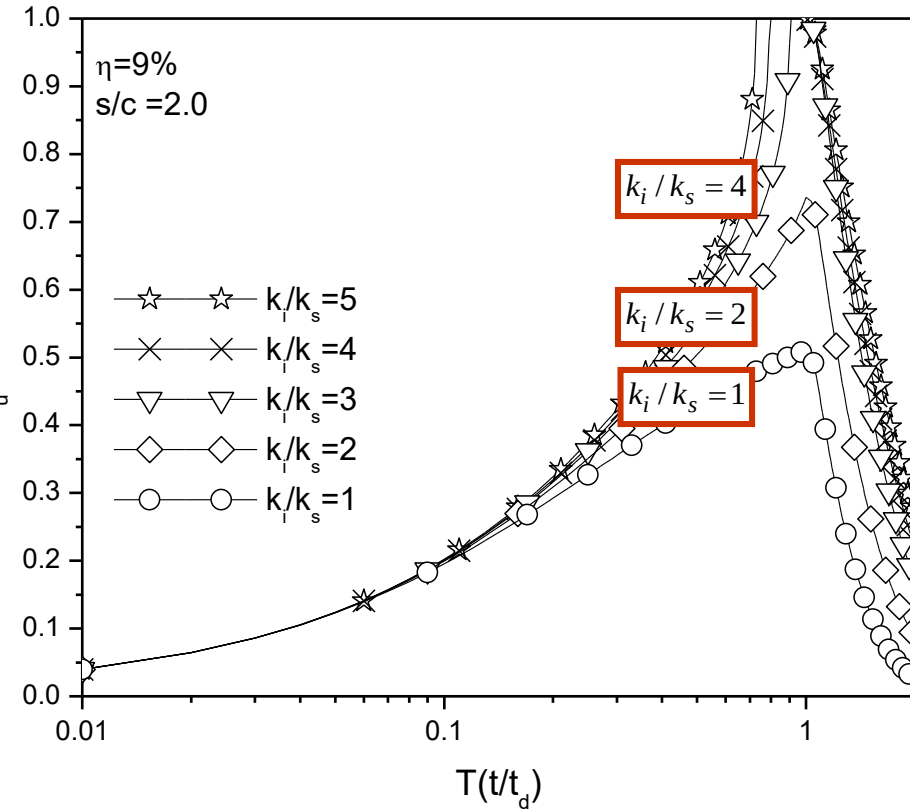
Effect of Extent of disturbed area



Variation of $r_u^{\max}$ versus s/c

3

Influence of Rate of reduction of permeability

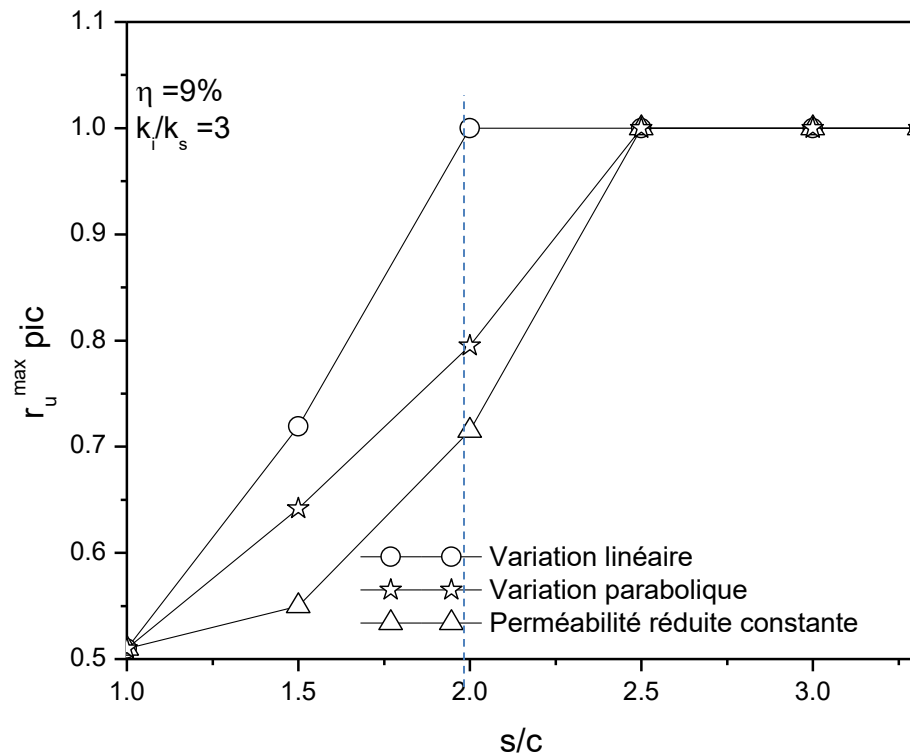


Variation of $r_u^{\max}$ versus k_i/k_s

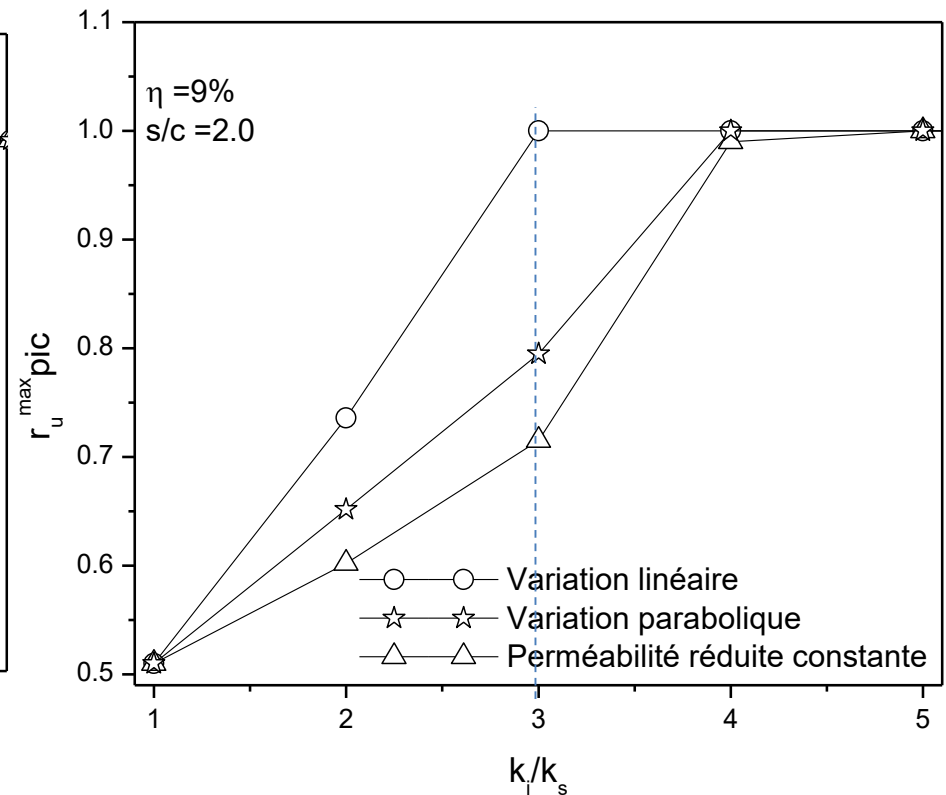
Example: **Linear variation** of permeability in the disturbed area

4

effect of variation of the permeability in the disturbed area

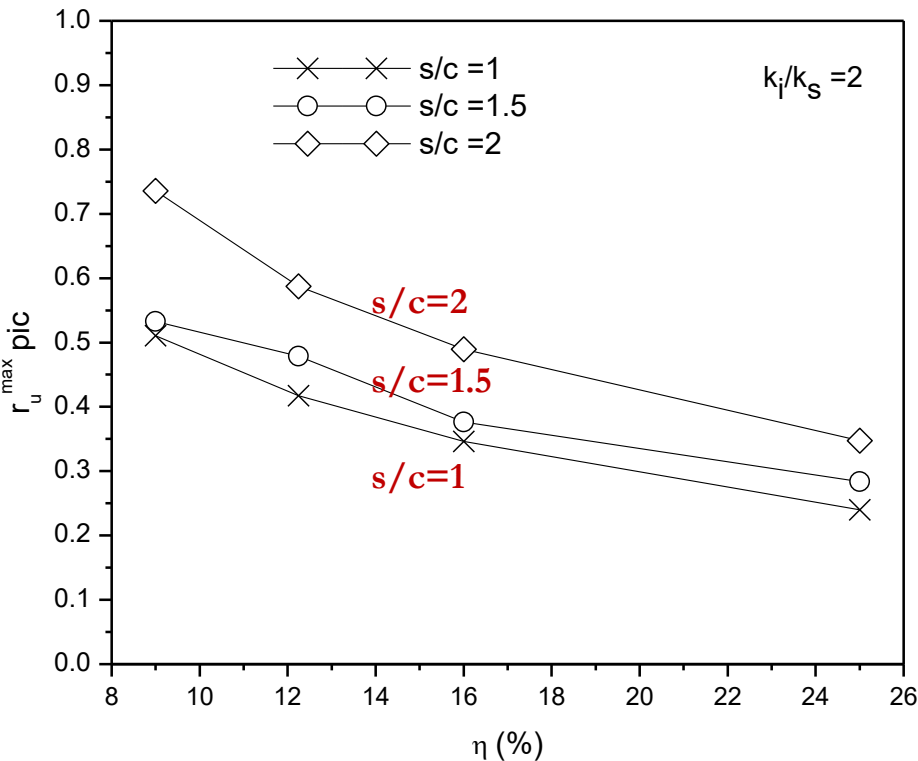


Variation of $r_u^{\max}$ peak as a function of s/c

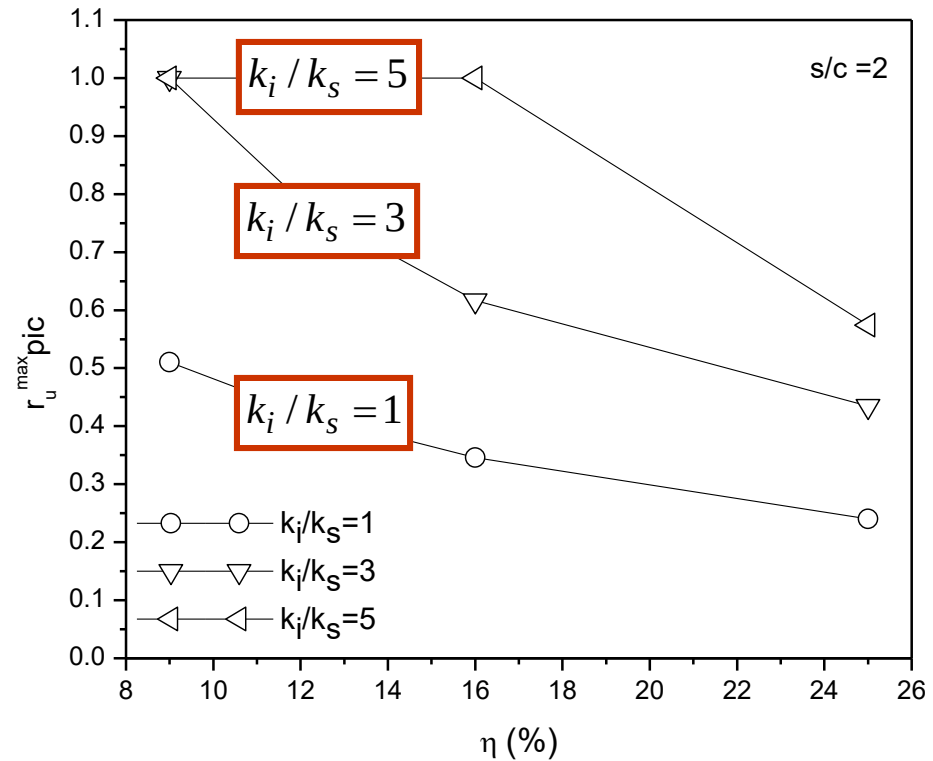


Variation of $r_u^{\max}$ peak as a function of k_i/k_s

Parametric study



Variation of $r_u^{\max}$ peak as a function of η and s/c



Variation of $r_u^{\max}$ peak as a function of η and k_i/k_s

Example: **Linear variation** of permeability in the disturbed area

Conclusion:

- Reduction of the generation of pore pressure and Increase of its dissipation in the presence of SC.
- Efficiency of SCs depend on the area replacement factor (**rate of substitution**), the extent of the disturbed area and the reduction of permeability in this area.
- Increased liquefaction potential when:
 - Area replacement factor is decreased.
 - Extent of the disturbed area is increased.
 - Permeability in this area is reduced.

Outline

0. Introduction and Problematic

I. Study of the generation and the dissipation of the pore water pressure of a soil improved by SC

II. Study of the effect of densification and Stiffening on the liquefaction potential

1. Constitution of the database
2. Evaluation of densification and Stiffening
3. Calculation of the FS factor of safety

III. Numerical study of the liquefaction potential of soil improved by SC

IV. Perspectives

Scope :

- Study of the effect of densification and Stiffening on the liquefaction potential mitigation

Methods:

1. Constitution of a database (soil improved by SC)
2. Quantification of Densification and Stiffening
3. FS calculation: (Densification effect and/or Stiffening effect)

Safety Factor FS

- Evaluation of liquefaction (Behavior of earthquake sites + **In situ tests**):

(Seed et Idriss 1971; Youd et al. 2001; Idriss et Boulanger 2008)

$$FS = \frac{CRR}{CSR}$$

←

Cyclic resistance ratio (The ability of the soil to resist the shear stress)

←

Cyclic shear stress ratio (Earthquake-Induced cyclic shear stress)

- When $FS < 1$: Risk of liquefaction

- Expressions of **CRR** and **CSR**

$$CRR = MSF \cdot K_{\sigma} \cdot CRR_{M=7.5, 1atm}$$

↑

Magnitude Scaling Factor

↑

Overburden Correction factor

Total vertical overburden stresses

$$CSR = \frac{\tau_{ave}}{\sigma_v} = 0,65 \cdot r_d \cdot \left(\frac{\sigma_v}{\sigma_v} \right) \cdot \left(\frac{a_{max}}{g} \right)$$

↑

Shear stress reduction factor

↑

Peak horizontal acceleration

- **SPT** : Corrected SPT blow count

$$CRR_{M=7.5, 1atm} = \exp \left(\frac{N_{1,60,cs}}{14.1} + \left(\frac{N_{1,60,cs}}{126} \right)^2 - \left(\frac{N_{1,60,cs}}{23.6} \right)^3 + \left(\frac{N_{1,60,cs}}{25.4} \right)^4 - 2.8 \right)$$

Idriss et Boulanger (2008)

- **CPT** : Corrected CPT penetration resistance

$$CRR_{M=7.5, 1atm} = \exp \left(\frac{q_{c1Ncs}}{540} + \left(\frac{q_{c1Ncs}}{67} \right)^2 - \left(\frac{q_{c1Ncs}}{80} \right)^3 + \left(\frac{q_{c1Ncs}}{114} \right)^4 - 3 \right)$$

29/60

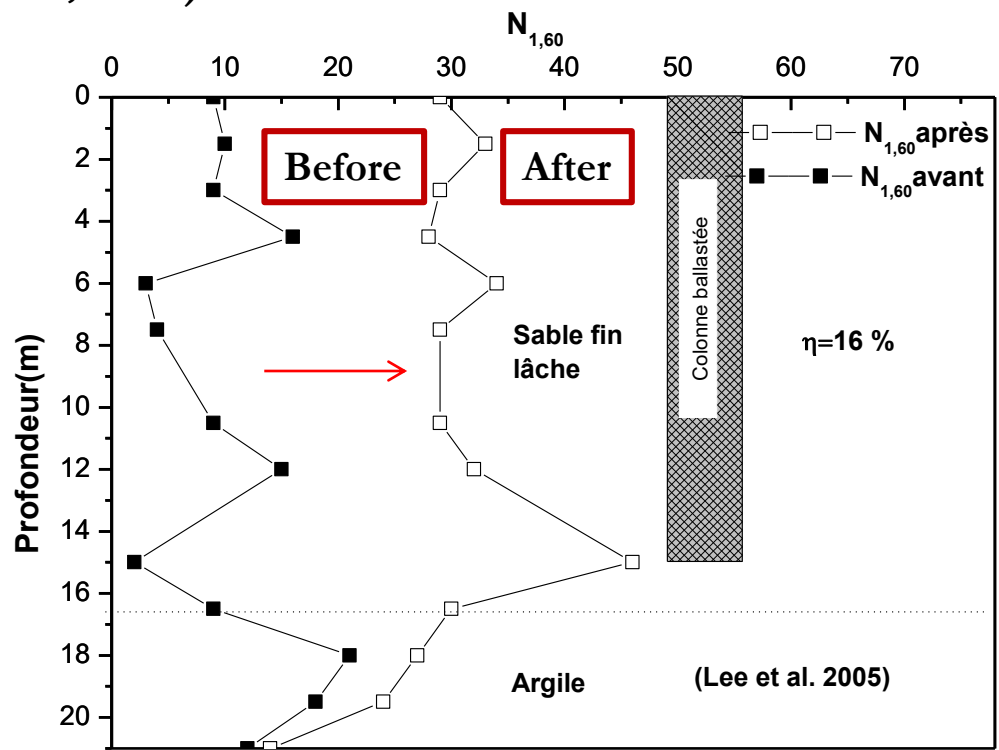
Constitution of database

- **24** case studies collected: SC technique used
- Potentially liquefiable soil
- Sites of construction : $M = 6.2 \text{ à } 7.5$ and $a_{\max} = 0.1g \text{ à } 0.44g$
- CB design parameters (Diameter and length, substitution rate, etc.)
- **in situ test:** 31 SPT et 33 CPT performed **before and after** SC installation

Evaluation of the **Densification after** installation of columns

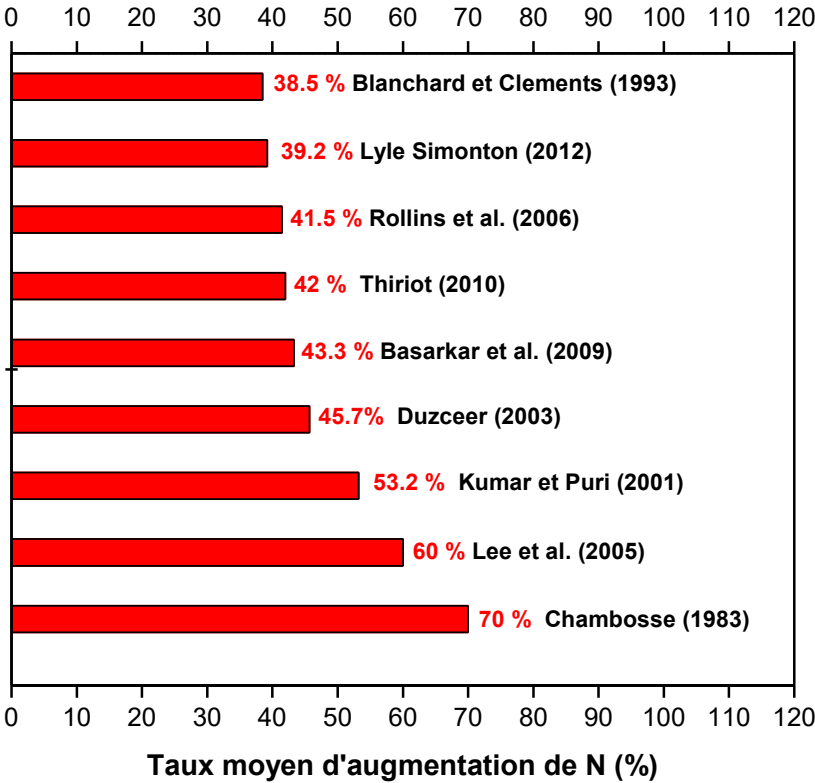
Project: Construction of a tunnel (California, USA)

- Loose fine sand potentially liquefiable
- Triangular mesh
- Spacing= 2.4 m
- Diameter =0.57 m
- $\eta = 16\%$
- Length =15m

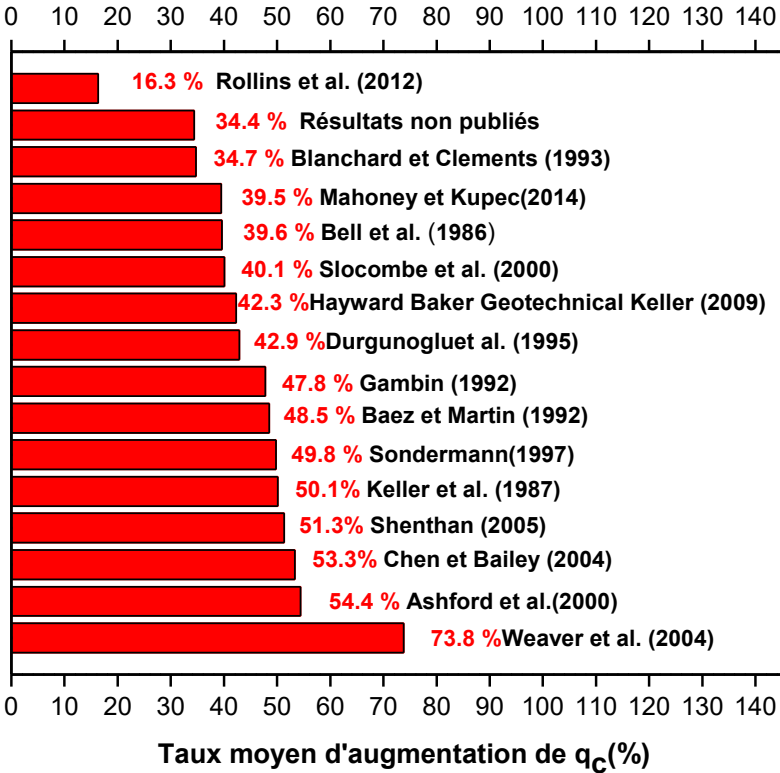


Increased resistance to penetration after SC installation

Evaluation of the **Densification after** installation of columns



SPT



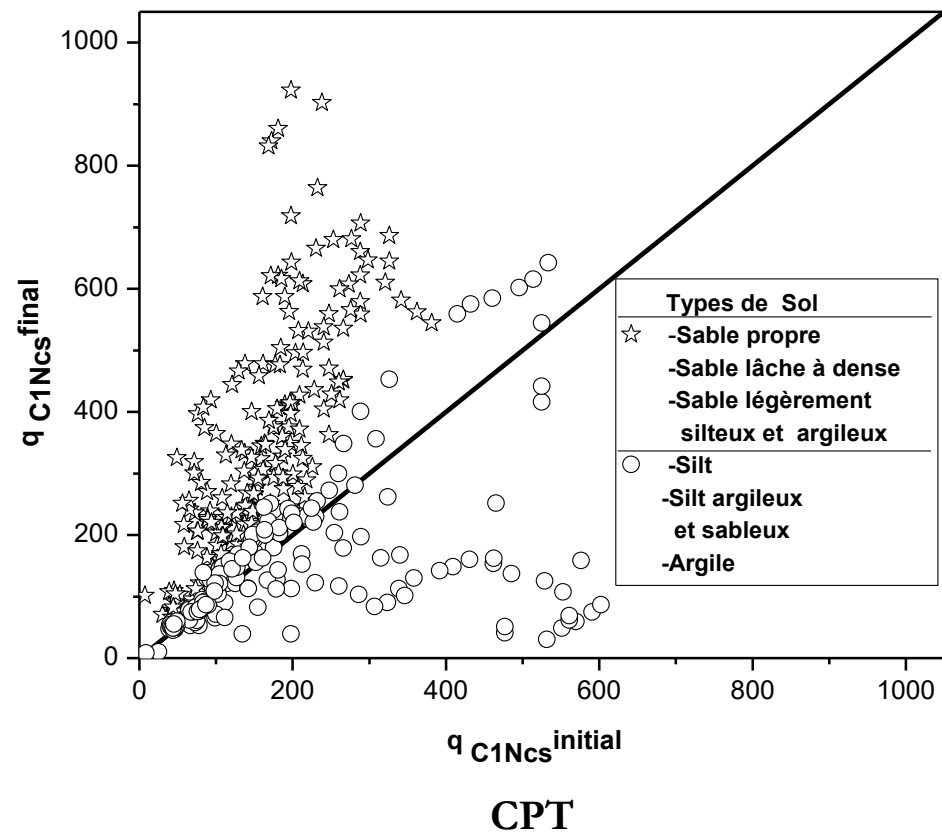
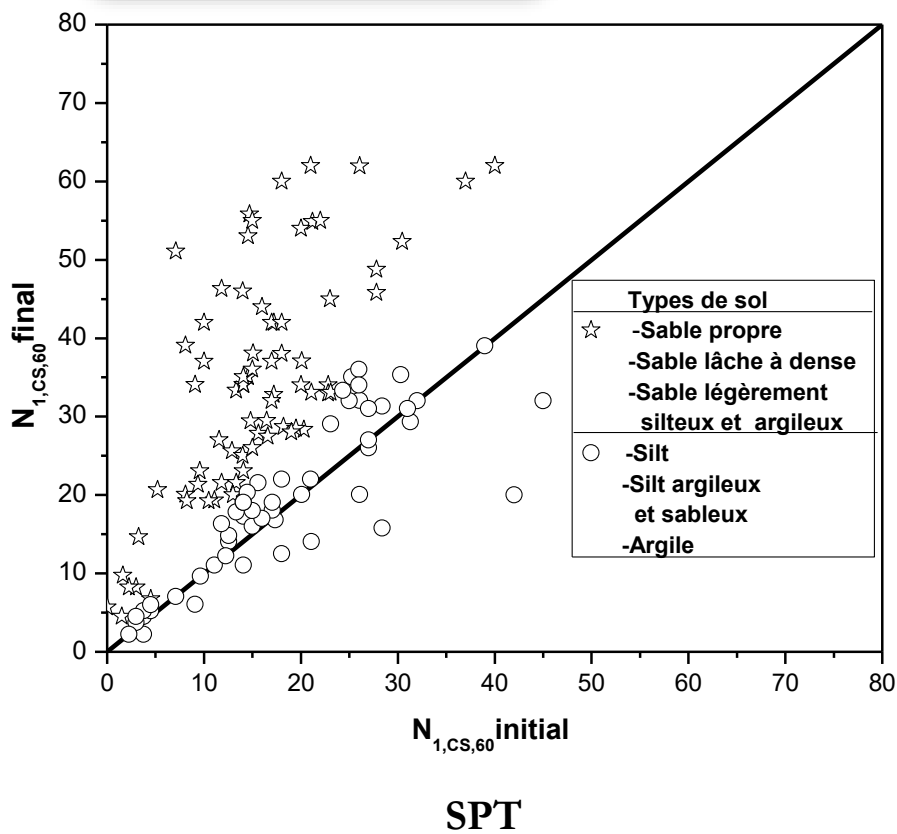
CPT

Summary of results

➤What is the effect of this improvement ?

Determination of some factors influencing Densification

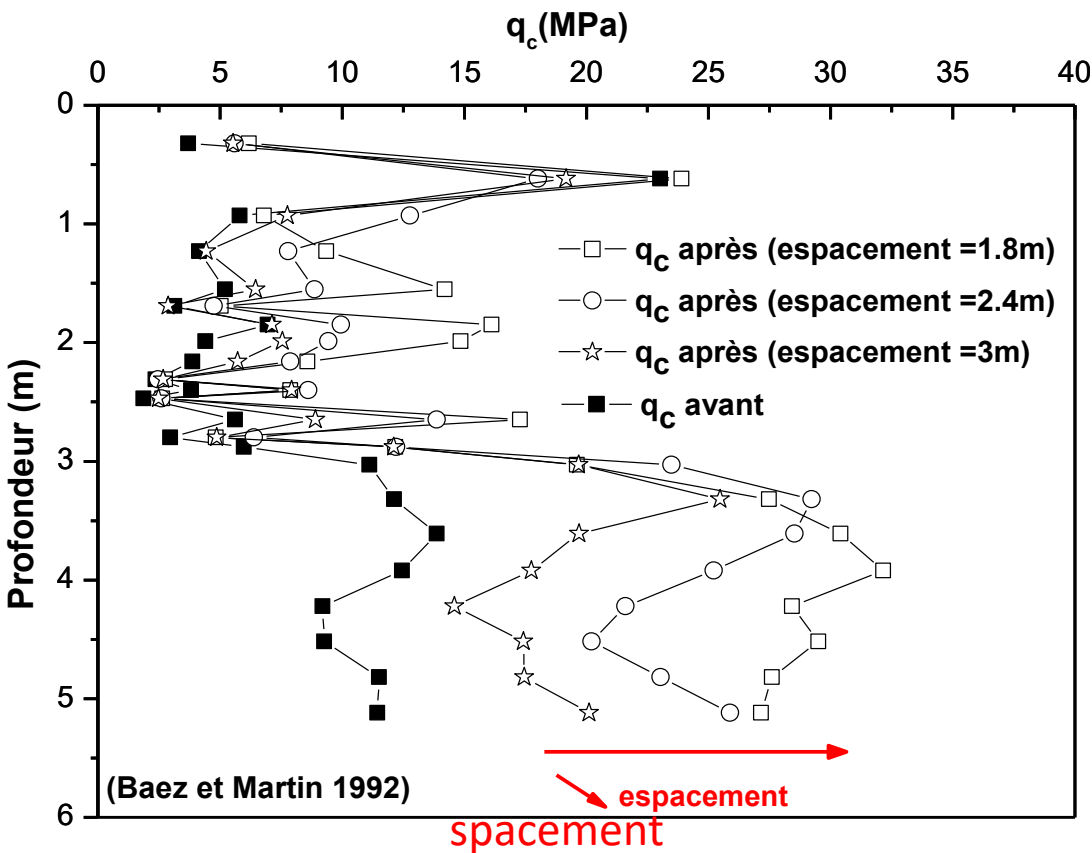
Type of soil



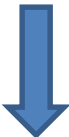
Results of tests before and after SC installation

Determination of some factors influencing Densification

Parameters for SC design



Mechanism of densification



$$FS = \frac{CRR}{CSR}$$

Quantification of the **Stiffening** after columns's installation

- Overall improvement of initial soil characteristics
- Increasing bearing capacity
- Reducing settlement
- **Reduction of the shear stress generated by the earthquake (CSR):**
 - ➔ **Estimation of the reduction of CSR**

Reduced shear stress of soil improved by SC

Concentration of Shear Stresses
on the Column

+

Increased stiffness of soil
improved



**Reduction of cyclic shear stress
CSR**

Mechanism of Stiffening



$$\frac{CRR}{CSR} = FS \uparrow$$

➤ **Estimation of the reduction of CSR**

$$K_G = \frac{CSR_{sc}}{CSR}$$



Cyclic shear stress of **improved soil**



Cyclic shear stress of **initial soil**

Reduced shear stress of soil improved by SC

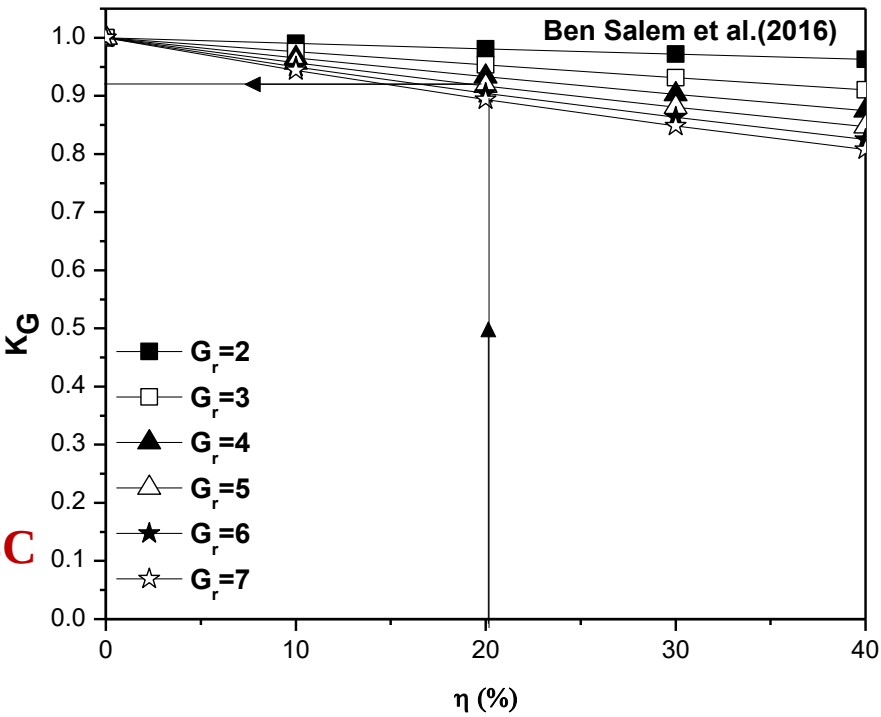
Proposed approach

Evaluation of K_G

Soil and SC react as shear beams
(Priebe (1998), Baez and Martin (1993)...)

Soil and SC deform in a combination of shear and flexure
Goughnour and Pestana (1998) , Rayamajhi et al. (2012)...)

Soil and SC deform in a combination of shear and flexure + Increase of G (after SC installation
Ben salem et al.

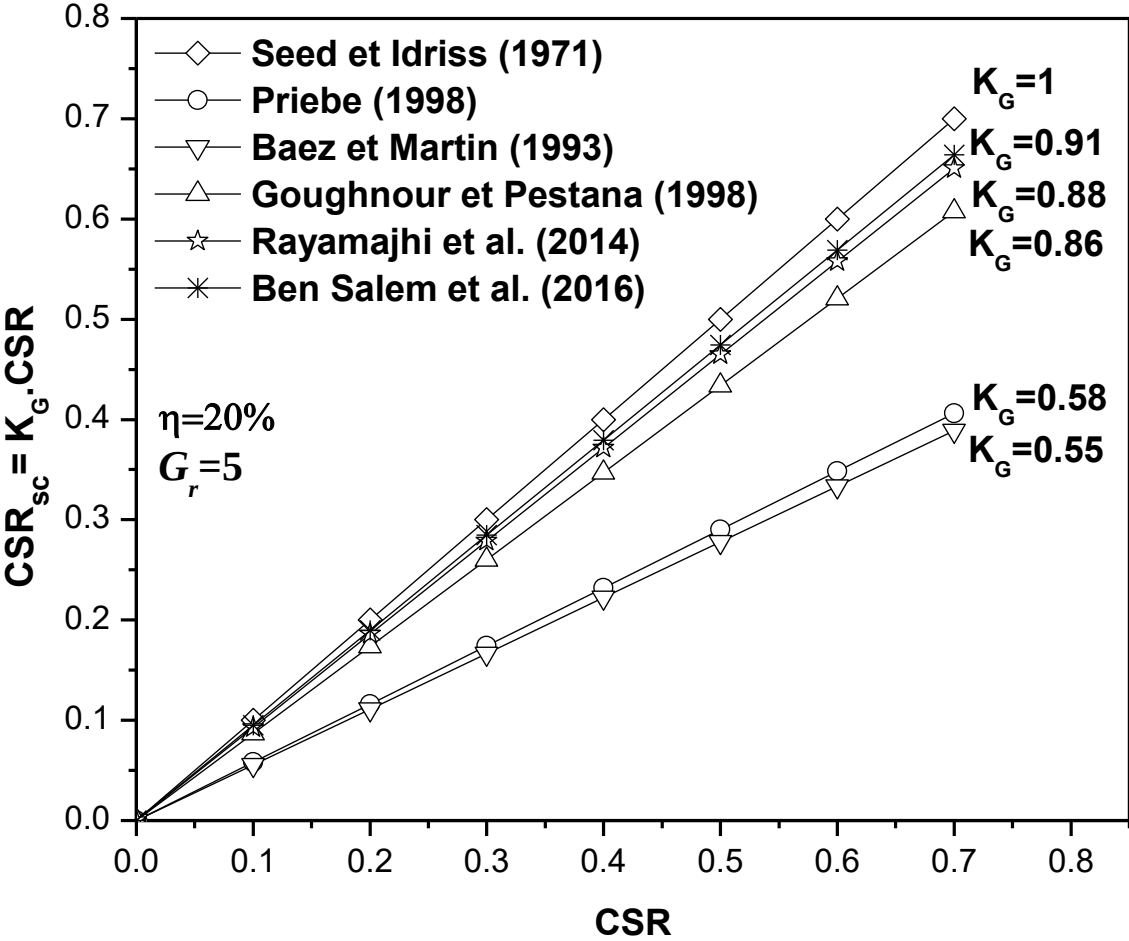


➤ Hypotheses: Increase of G_{sol} after installation of CB

➤ Estimation : $G_{sol} = 14.12 N^{0.68}$ (Imai et Tonouchi 1982)

$$K_G = \frac{1}{G_{r,improved} \left[\eta \cdot \gamma_r + \frac{1}{G_{r,improved}} (1 - \eta) \right]}$$

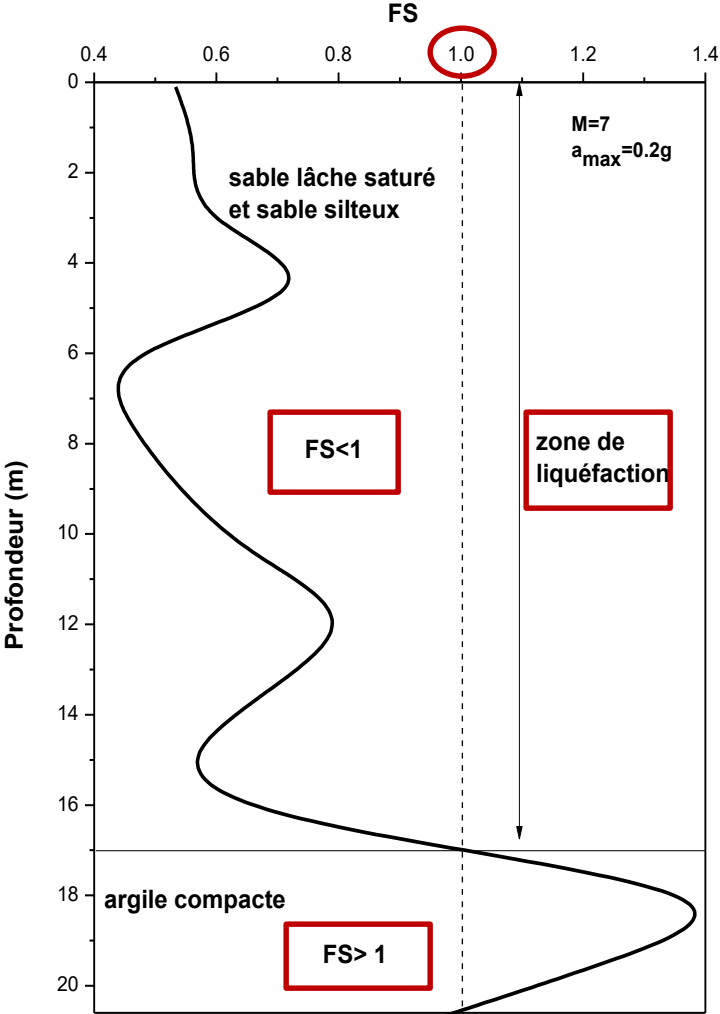
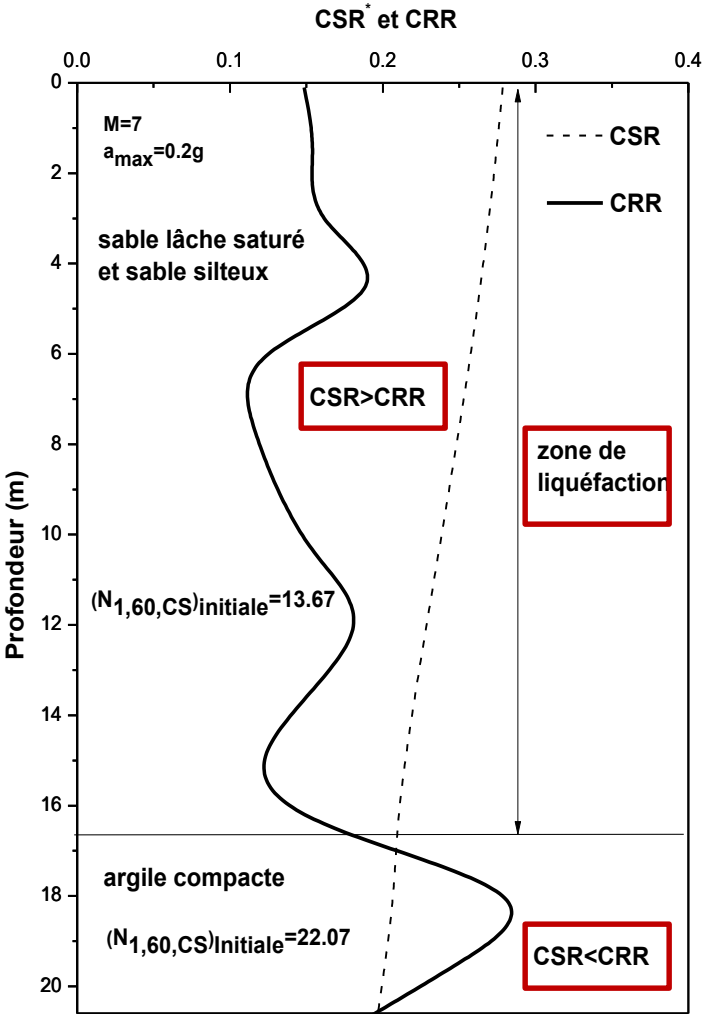
Reduced shear stress of soil improved by SC



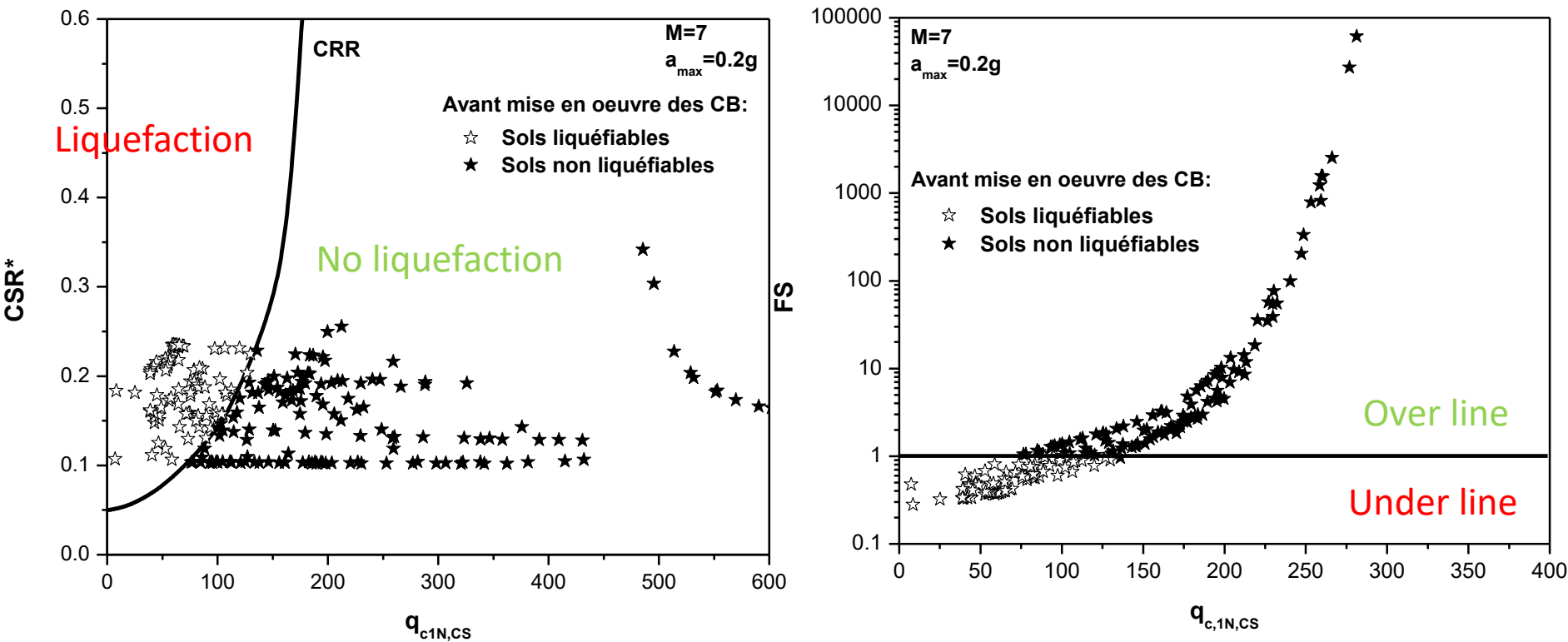
Variation of the cyclic shear stress of a soil improved by SC

Estimation of the risk of liquefaction before SC installation

Example : Project of tunnel construction , Lee et al. (2005)



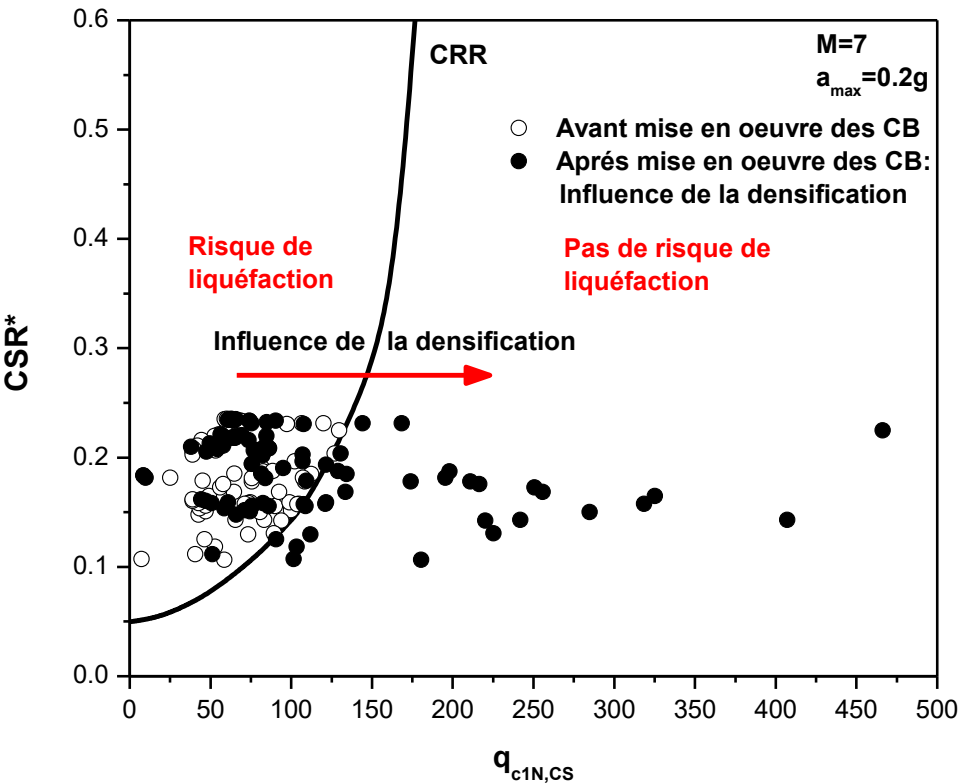
Estimation of the risk of liquefaction **before** SC installation



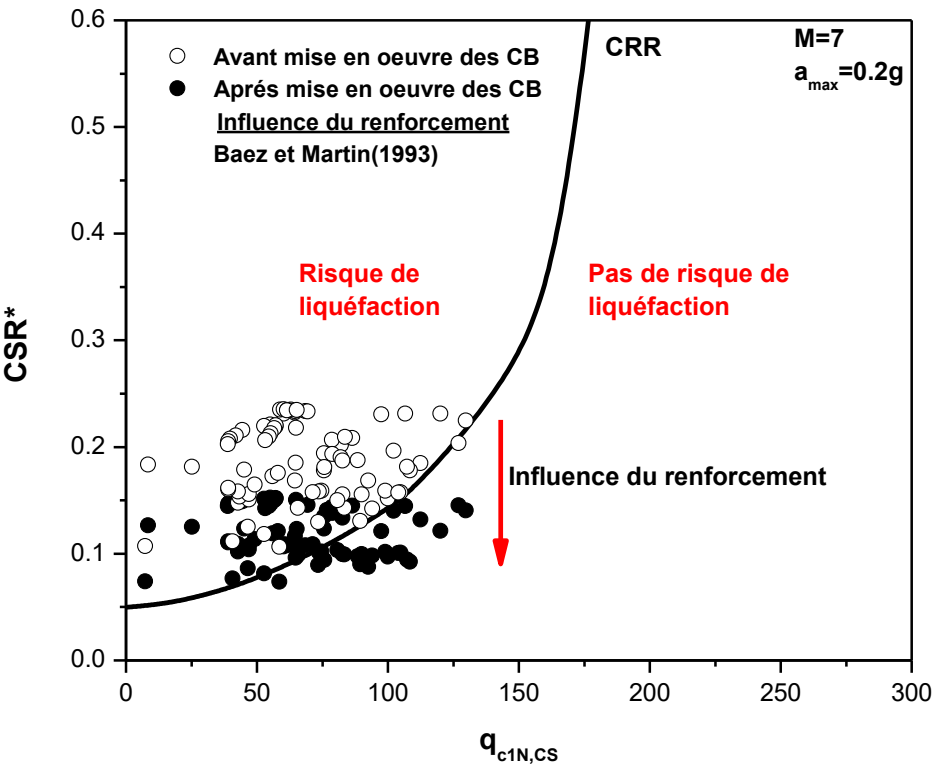
Potential for liquefaction **before** the installation of SC
CPT

Estimation of the risk of liquefaction **after** SC installation

1 effect of Densification



2 effect of Stiffening

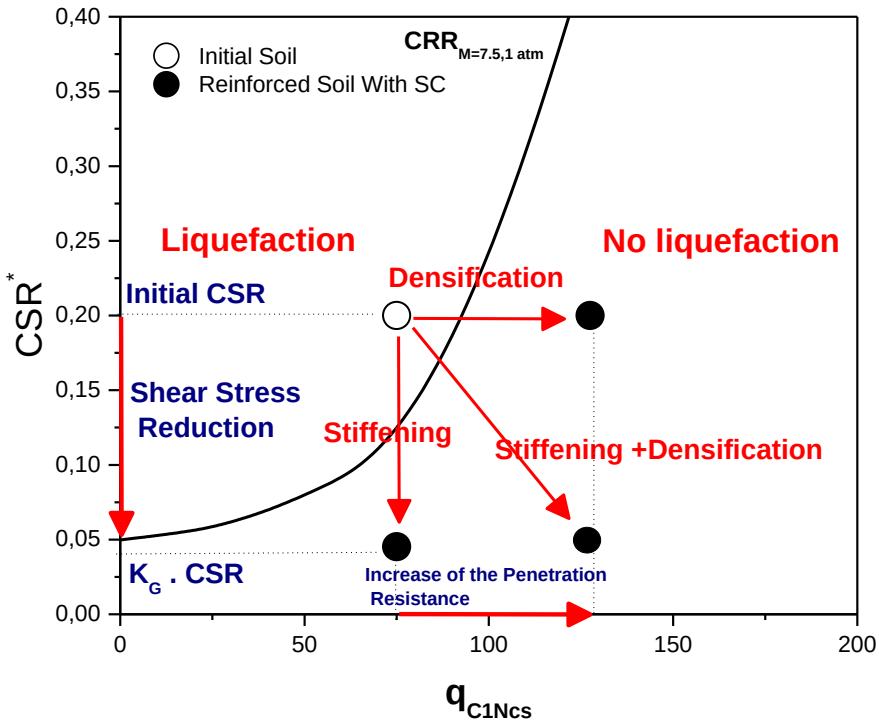
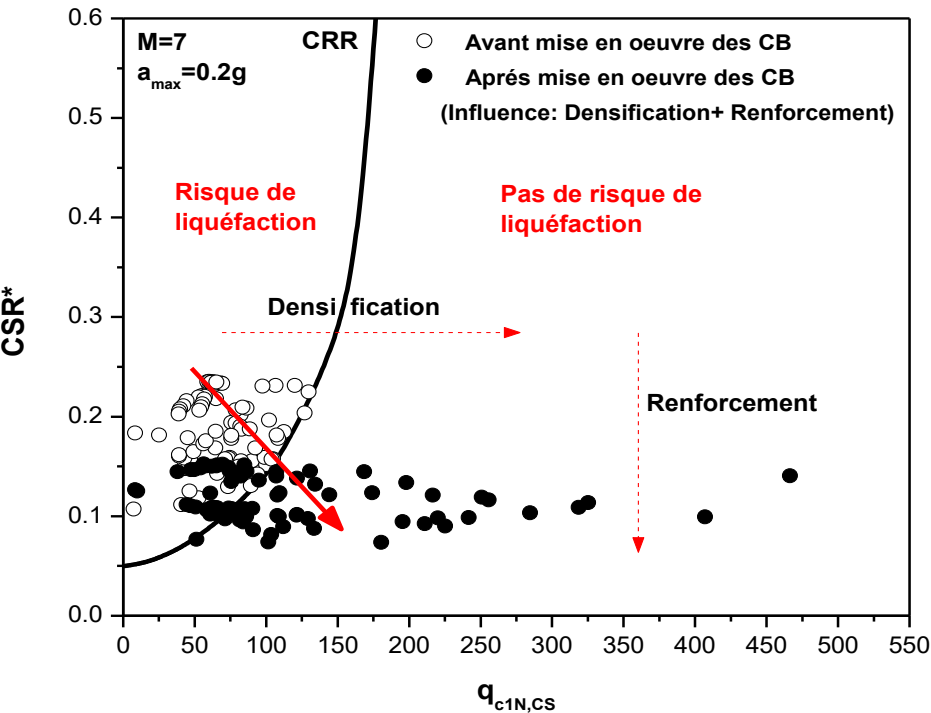


Potential for liquefaction **after** the installation of SC
CPT

Estimation of the risk of liquefaction **after** SC installation

3

effect Densification + Stiffening



Potential for liquefaction **after** the installation of SC
CPT

Synthesis:

- Densification rate (in situ measurements) variable and depend on several factors (type of the soil, design parameters, etc.).
- Evaluation of the reduction of CSR.
- Evaluation of the liquefaction potential from (before and after SC intallation).
- Reduction of the liquefaction potential of soils reinforced by SC :

$$FS \nearrow = \text{Densification (} \nearrow \text{CRR)} + \text{Stiffening (} \searrow \text{CSR)}$$

Outline

I. Study of the generation and the dissipation of the interstitial pressures of a ground improved by SC

II. Study of the influence of densification and reinforcement on the liquefaction potential

III. Numerical study of the liquefaction potential of soil improved by SC

- 1. Presentation and validation of the numerical model**
- 2. Study of the liquefaction potential**
- 3. Parametric study**

IV. Perspectives

Scope :

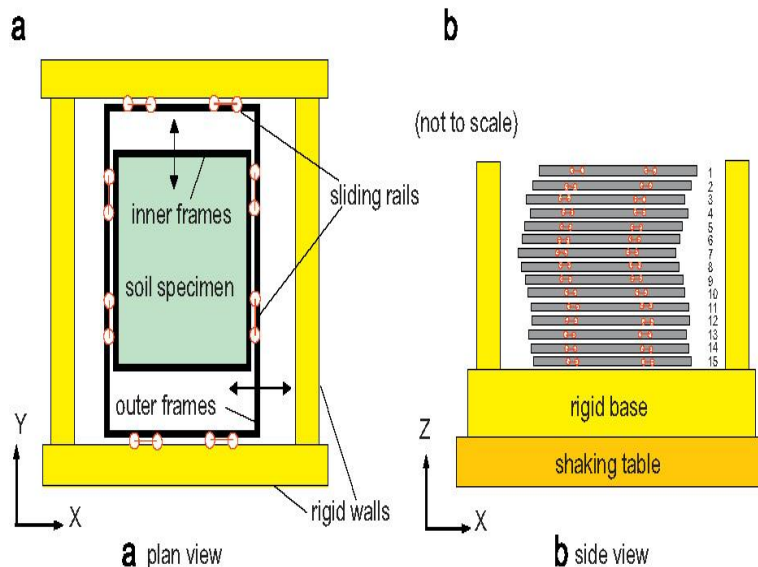
- Numerical study of the liquefaction potential of soil improved by SC

Method :

- Numerical model with FLAC2D of the vibration table test
- Validation of the numerical model
- Application on a case of the database

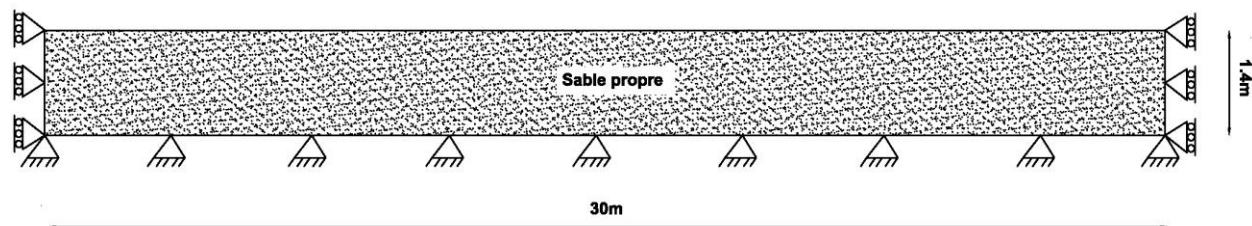
➤ Numerical model with FLAC2D of the vibration table test

❖ Experimental model (Ueng et al. 2010)

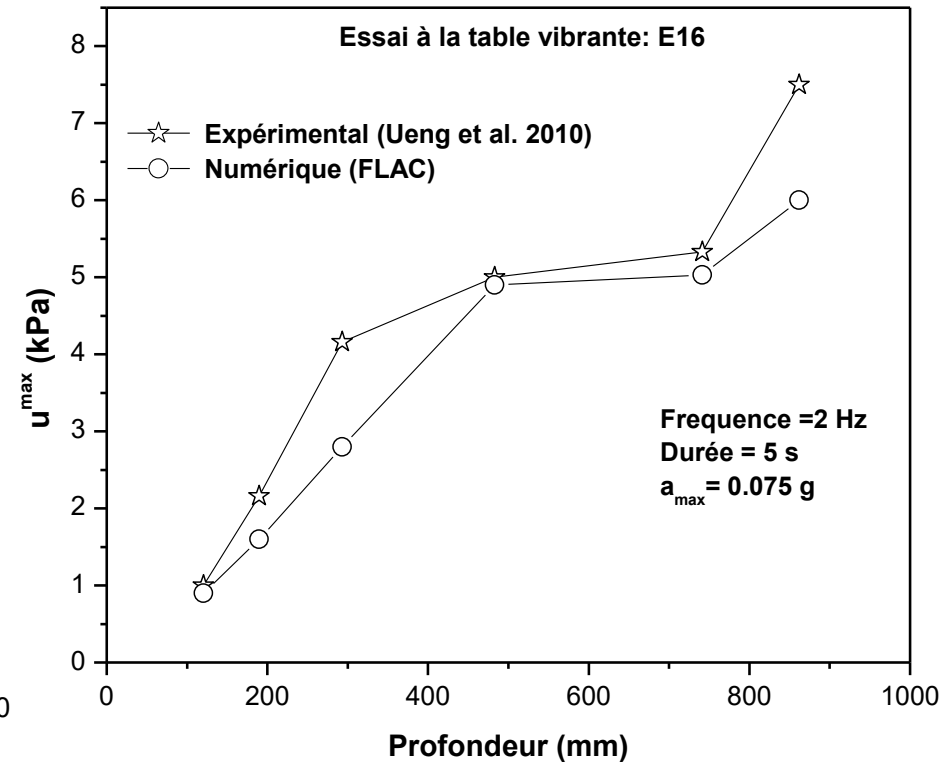
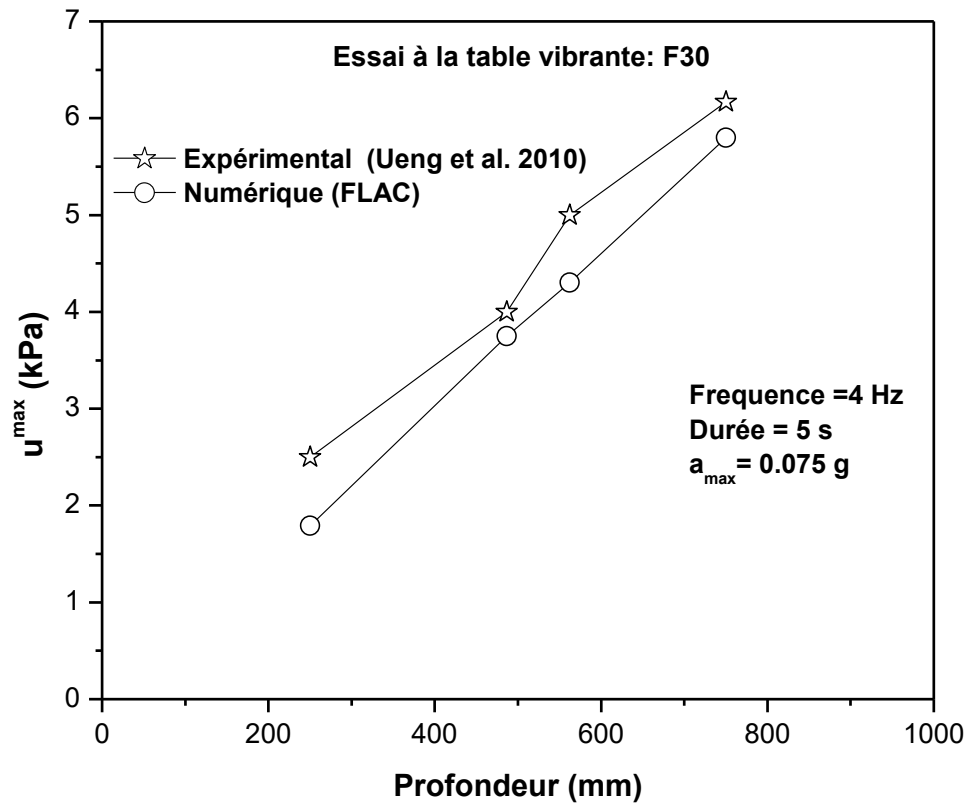


- Sinusoidal excitations
- saturated silica sand of Vietnam
- Pore overpressure measurements
- Byrne's model (1991) for the evaluation of liquefaction potential

❖ Numerical model



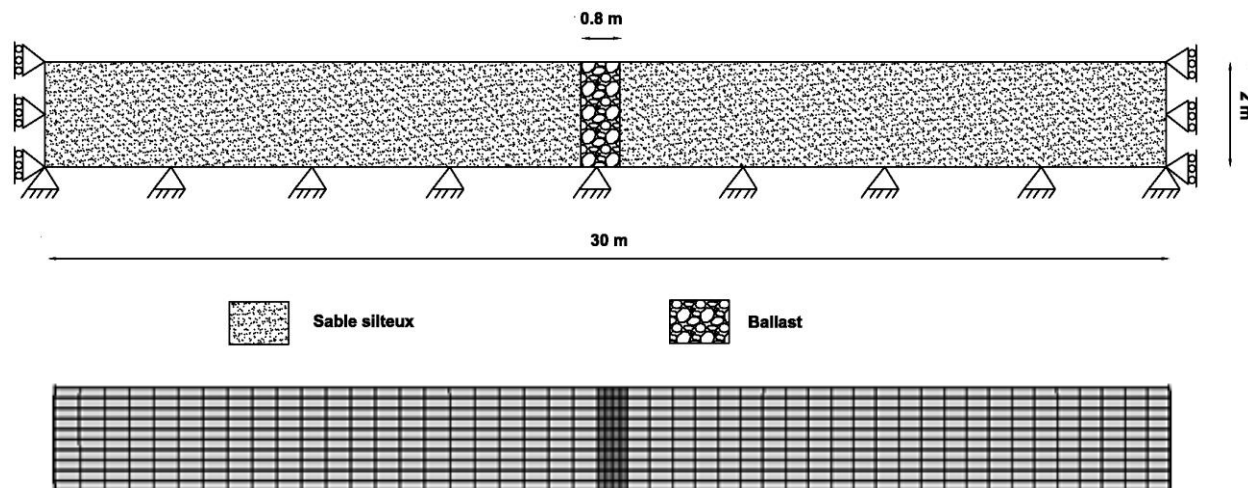
Validation of numerical model - FLAC

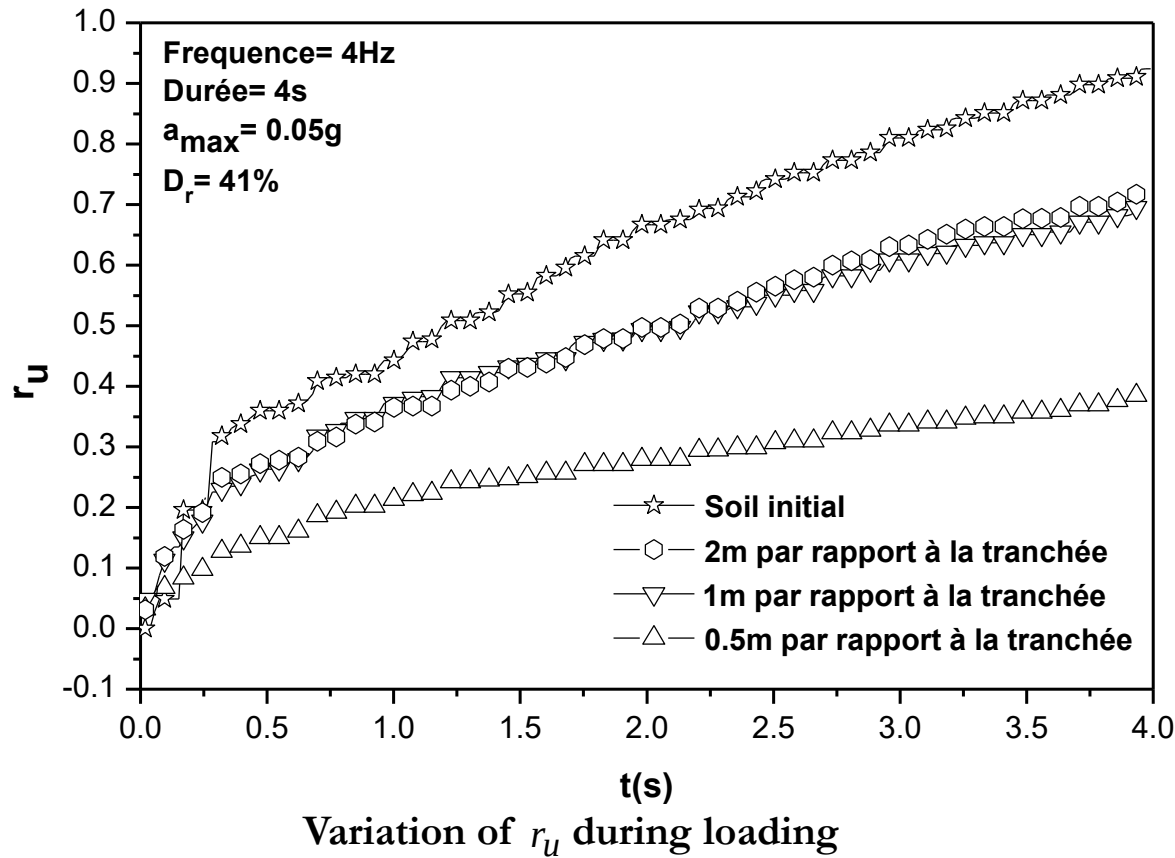
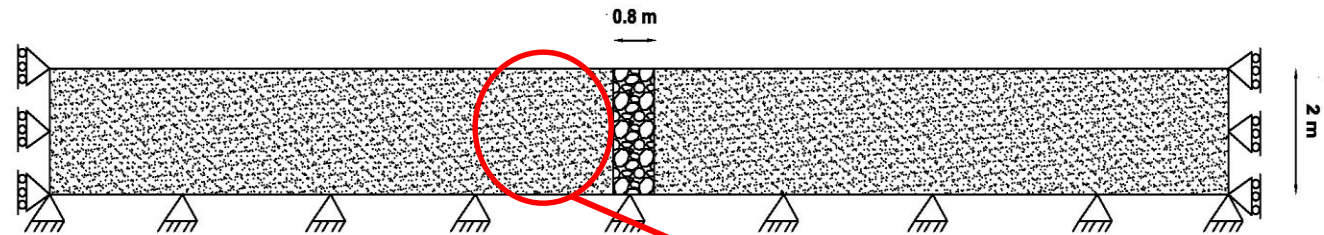


Experimental and numerical results of the variation of $u_{\max}$

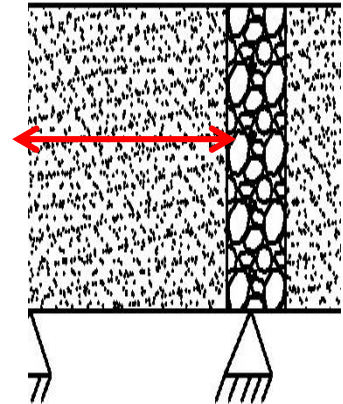
Numerical modeling of soil enhanced by SC

- **Project N12:** Building a tank (Duzceer 2003)
- **Silty sand improved by SC**
- **Trench model in plane strain**
- Sinusoidal excitation

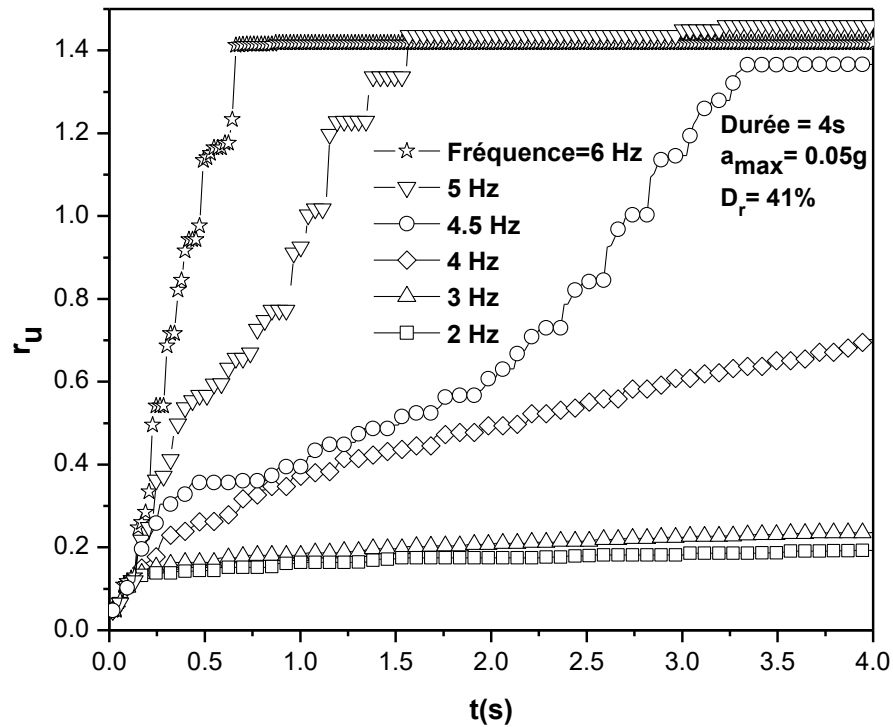




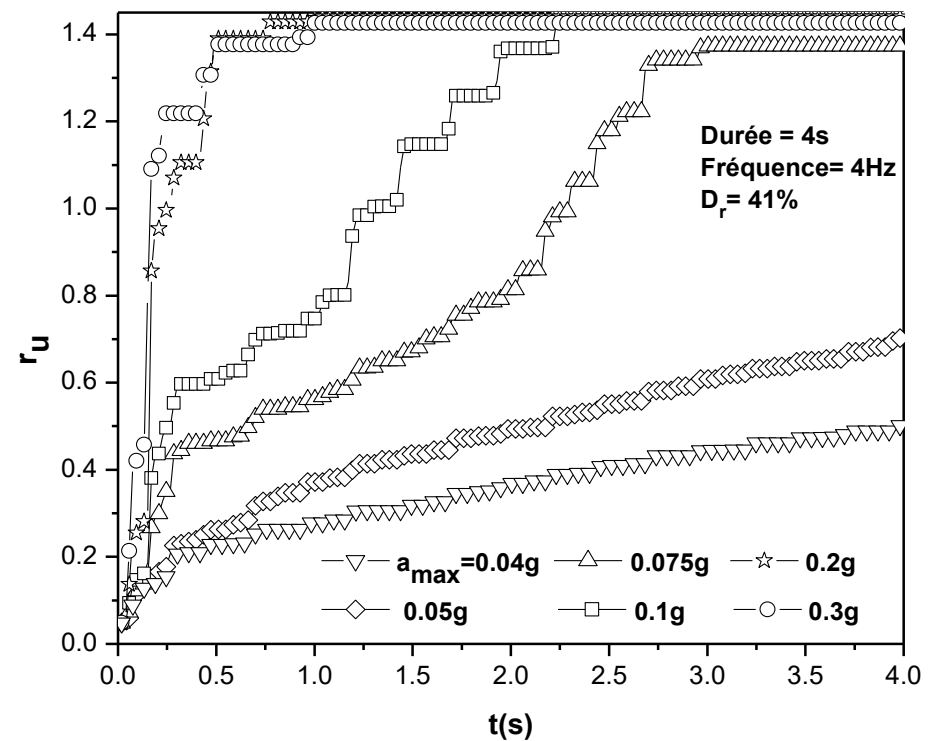
1 m



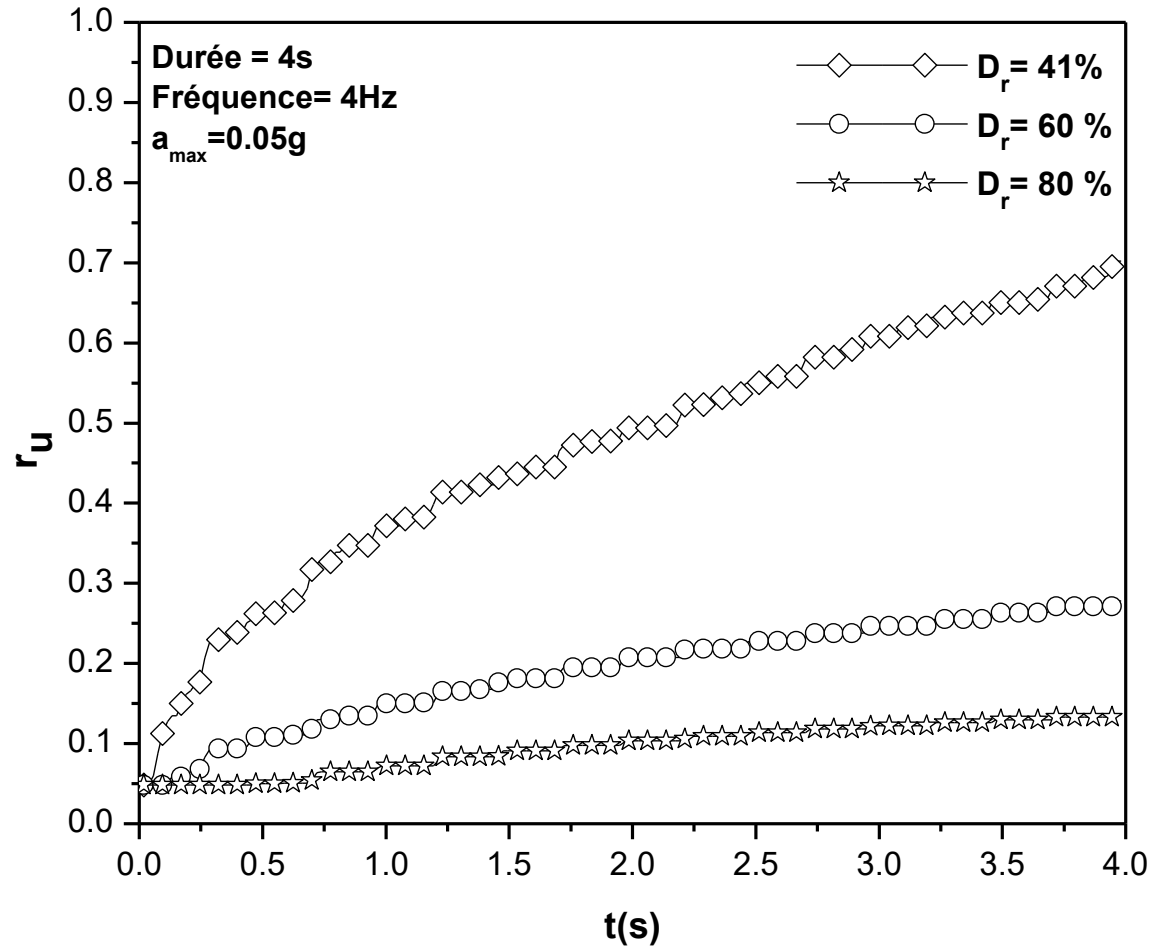
1 effect of the loading frequency



2 effect of loading amplitude



3 Influence de la mise en place des colonnes



Variation of r_u as a function of D_r

Synthesis:

➤ Results of numerical analyzes :

- ✓ Reduced liquefaction potential with improvement by SC.
- ✓ More Reduction around the column . The decrease depends on the horizontal distance.
- ✓ Risk of liquefaction potential proportional dependant to the frequency and amplitude of loading applied.
- ✓ Reduced liquefaction potential when the effect of densification is taken into account.

Outline

I. Study of the generation and the dissipation of the interstitial pressures of a ground improved by SC

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IV. Perspectives

- Identification of all the parameters influencing the Densification (Position of the tests in situ, CB, position and thickness of the liquefiable layers, sizing of the SC, etc.)
- Experimental study for a better characterization of the effects of implementation and estimation of the reduction of the shear stresses.
- Numerical study taking into account the influence of all the mechanisms (Drainage, Densification and Stiffening).

 Development of a liquefaction potential evaluation method integrating the effects of Drainage, Densification and Stiffening.

 Formulation of a SC design methodology that encompasses both bearing capacity, settlement and especially liquefaction.

If you want more details :

- Z. Ben Salem, W. Frikha, M. Bouassida (2016). Effect of Granular Columns installation on Excess Pore Pressure Variation During Soil Liquefaction, **International Journal of Geomechanics**,16(2). DOI:10.1061/(ASCE)GM.1943-5622.0000516, 04015046.
- Z. Ben Salem, W. Frikha, M. Bouassida (2017). Effects of densification and stiffening on Liquefaction Risk of Reinforced Soil by Stone Columns. **Journal of Geotechnical and Geoenvironmental Engineering (ASCE)**. [Vol. 143, Issue 10 \(October 2017\)](#)
- Z. Ben Salem, W. Frikha, M. Bouassida (2014). Evaluation of Liquefaction Risk of Reinforced Soil by Stone Columns. Proc. 17th Brazilian Conference on Soil Mechanics and Geotechnical Engineering–COBRAMSEG2014, Golania/GO Brazil.
- Z. Ben Salem, W. Frikha, M. Bouassida (2015). Use of Stone columns for liquefaction mitigation. Proceedings of the 16th African Regional Conference on Soil Mechanics and Geotechnical Engineering. Innovative Geotechnics for Africa; eds Bouassida et al. Tunisia, Hammamet 27-30 April, 387- 392.
- Z. Ben Salem, W. Frikha, M. Bouassida (2017). Numerical analysis of liquefaction susceptibility of reinforced soil with stone columns. Submitted to the GeoMEast 2017 International Conference ‘Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology’, Sharm Elsheikh ,Egypt.
- Z. Ben Salem, W. Frikha, M. Bouassida (2017). Densification and stiffening effects on liquefaction Risk of Reinforced Soil by Stone Columns. Submitted to the 19th International Conference on Soil Mechanics and Geotechnical Engineering ICSMGE, Seoul, Republic of Korea.

Thank you for your attention