European Commission
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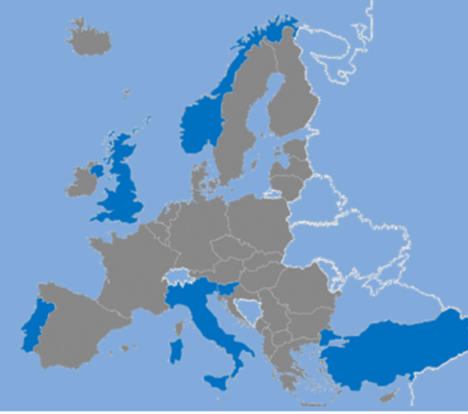
liquefACT



ASSESSMENT AND MITIGATION OF LIQUEFACTION POTENTIAL ACROSS EUROPE

A holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters

Ground improvement to mitigate liquefaction susceptibility

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Presentation outline

1. Liquefaction: mechanisms and design checks
2. Evidences from LIQUEFACT field trial tests
3. Goals of ground improvement
4. Design procedures for Horizontal Drains (HD) and Induced Partial Saturation (IPS)
5. Concluding remarks

1. **Liquefaction: mechanisms and design checks**
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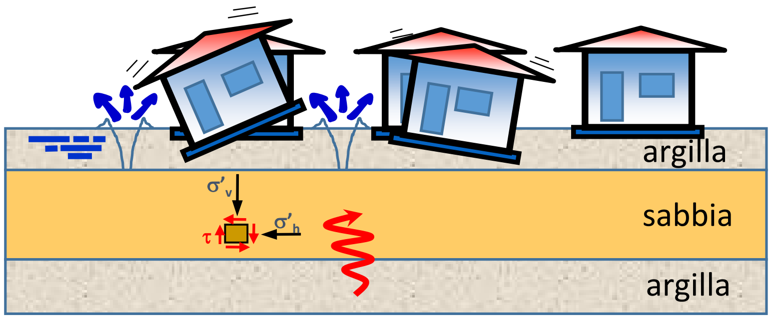
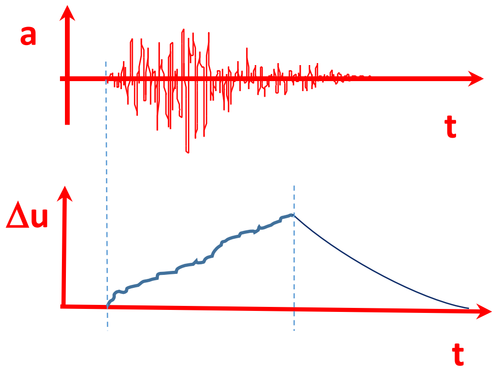
What is liquefaction?

It is a temporary loss of shear strength and stiffness of a saturated loose sandy soil in response to an applied stress, usually earthquake shaking.





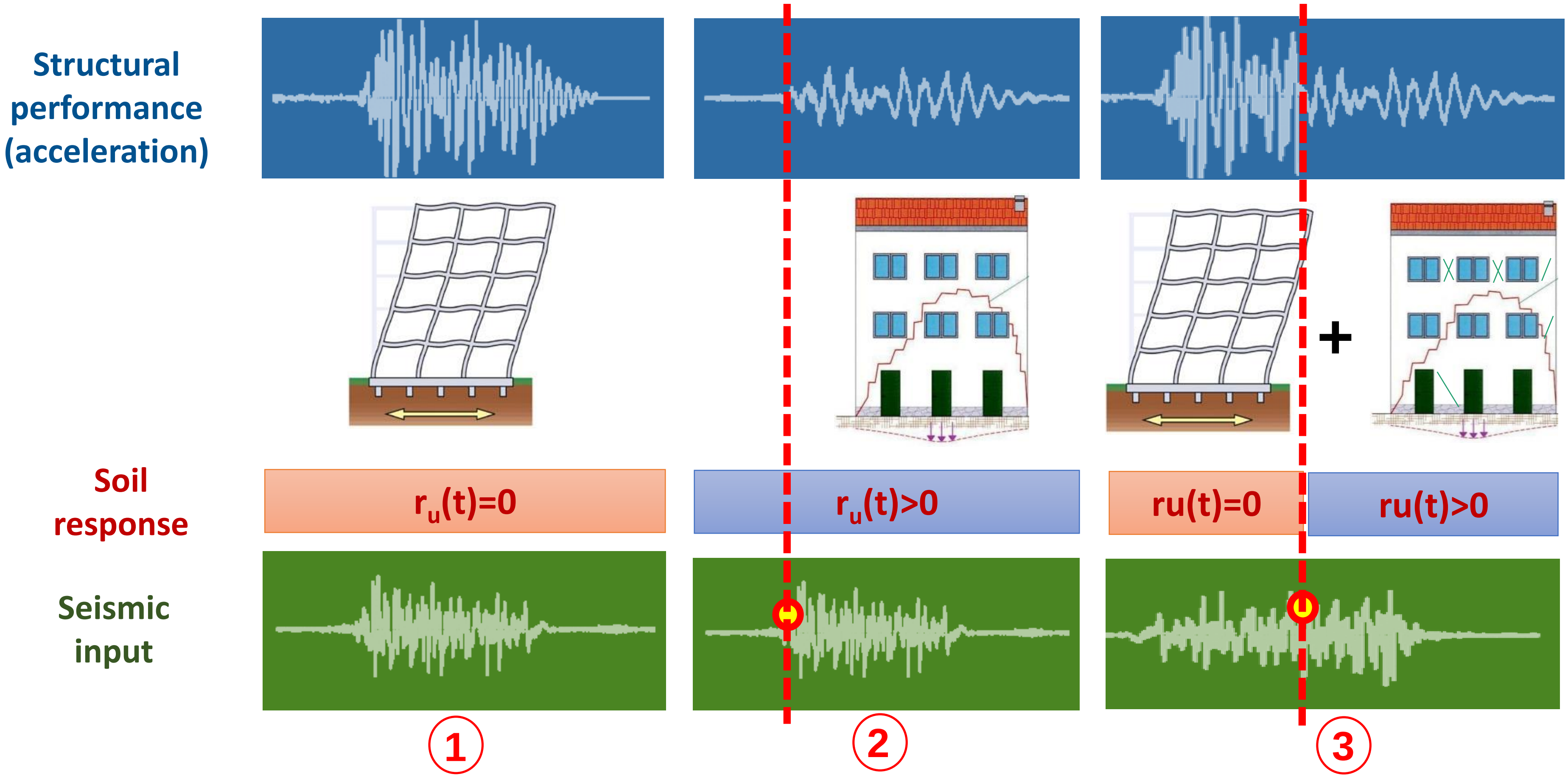
$$\sigma'(t) = \sigma'_0 - \Delta u(t)$$

$$r_u(t) = \frac{\Delta u(t)}{\sigma'_0} \longrightarrow 1$$

$$G(t) = G\big(\sigma'(t)\big) = G\big(\sigma'_0 - \Delta u(t)\big) \longrightarrow 0$$

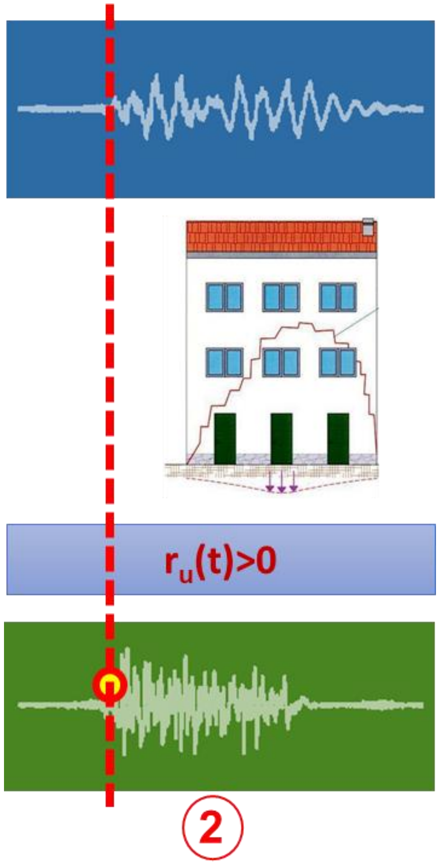
$$\tau_f(t) = \sigma'(t) \cdot \tan\varphi = \big(\sigma'_0 - \Delta u(t)\big) \cdot \tan\varphi \longrightarrow 0$$

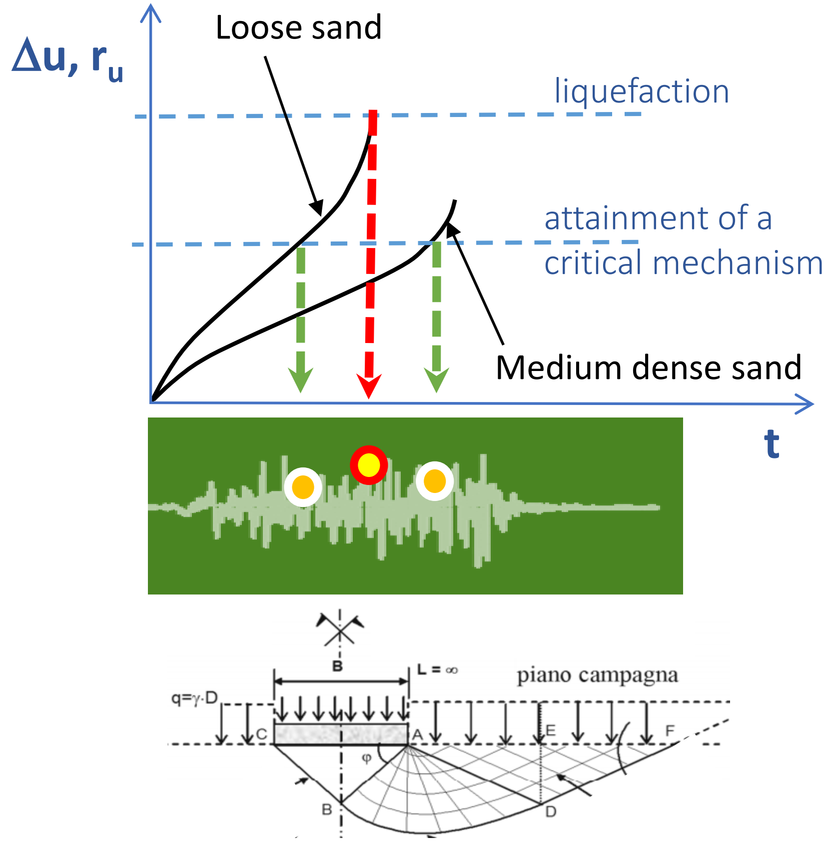
Mechanisms



a. Damage depends on the mechanism.
b. Liquefied soil behaves as a natural isolator.

Mechanisms



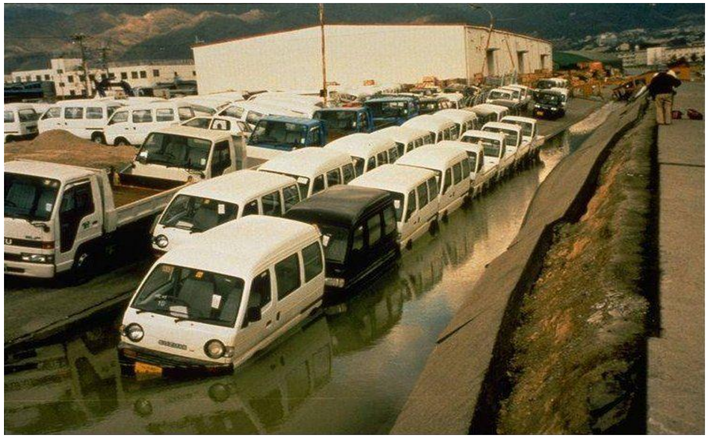


During seismic shaking, ultimate limit states may be activated before liquefaction, or even in non liquefiable soils

Catastrophic effects of liquefaction

Niigata, Giappone 1964

Kocaeli, Turchia 1999

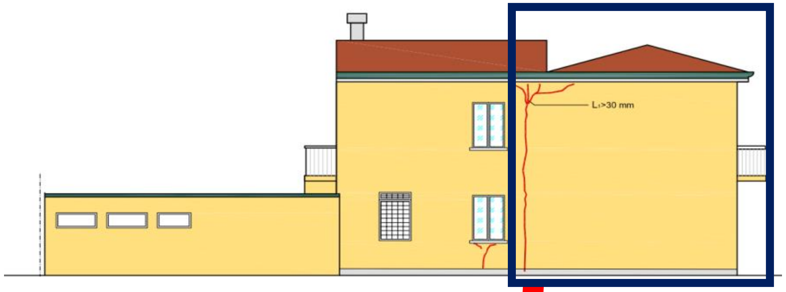


Kobe, Giappone 1995

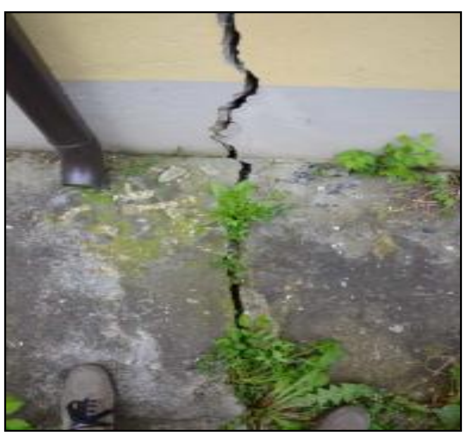
Christchurch, Nuova Zelanda 2011

Relevant (but not catastrophic) effects of liquefaction

Prospetto nord-est



Prospetto sud



Damage caused by differential settlements

Liquefaction susceptibility

PREDISPOSING FACTORS

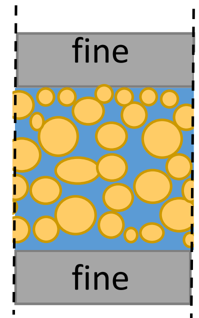
✓ Soil and water

- **Density**
- **Cementation**
- **Grading**
- **Saturation**
- **Drainage**

✓ Stress state

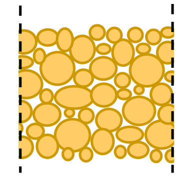
- **Low initial effective stress (shallow soils)**

POSSIBLE

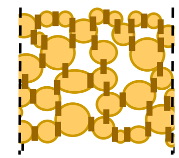


- loose
- uncemented
- little or no fines
- saturated
- undrained

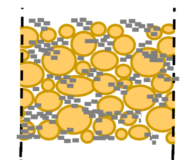
UNLIKELY TO HAPPEN



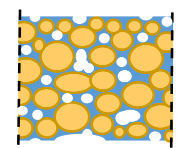
- dense



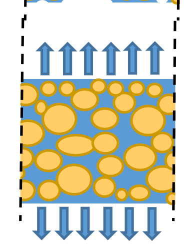
- cemented



- with fines



- unsaturated



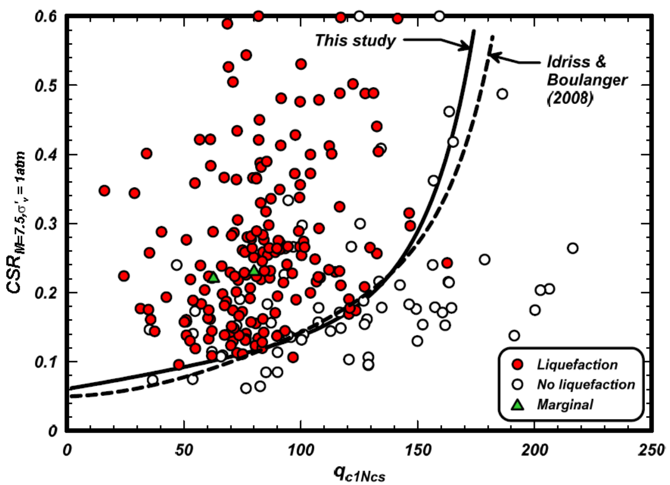
- drained

Check of liquefaction triggering

Factor of safety against liquefaction triggering

$$FS_{liq} = \frac{\text{capacity}}{\text{demand}}$$

CRR



$$CRR_{M=7.5,\sigma'_v=1atm} = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.80\right)$$

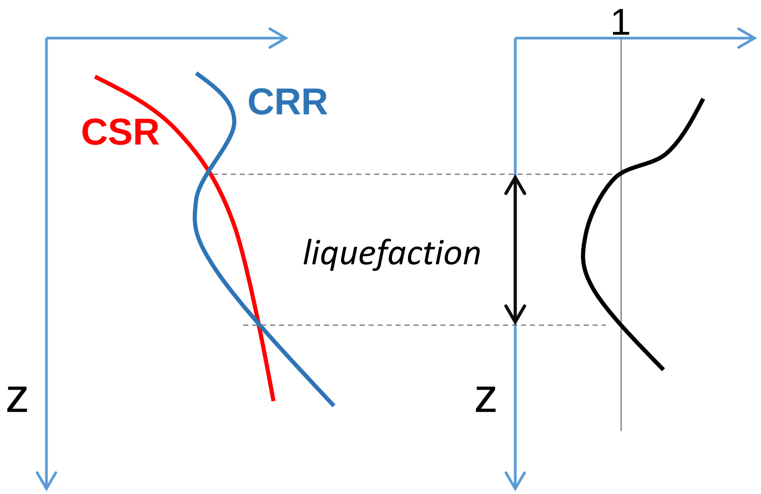
CSR

can be quantified via seismic site analysis or using empirical correlations

$$CSR = \frac{\tau_{eq}}{\sigma'_{v0}} = 0.65\frac{a_{\max}}{g}\frac{\sigma_{v0}}{\sigma'_{v0}}r_d$$

$$CSR_{M=7.5,\sigma'_v=1} = \frac{CSR_{M,\sigma'_v}}{MSF \cdot K_\sigma}$$

Effects at ground level



$$FS_{liquef}(z) = \frac{CRR}{CSR}$$

Integral indicators

Liquefaction potential index IL
(Iwasaki, 1978)

$$I_L = \int_0^{20} F_L(z) w(z) dz$$

Liquefaction severity index Ls
(Sonde & Gokceoglu, 2005)

$$L_S = \int_0^{20} P_L(z) W(z) dz$$

Liquefaction Severity Number *LSN*
(Van Ballegooy et al. 2014)

$$LSN = 1000 \int \frac{\varepsilon_v}{z} \mathrm{d}z$$

I_L	Risk
$I_L=0$	Very low
$0<I_L\leq 5$	moderate
$5<I_L\leq 15$	high
$15<I_L$	Very high

Mitigation of the risk of liquefaction

1. Liquefaction: mechanisms and design checks

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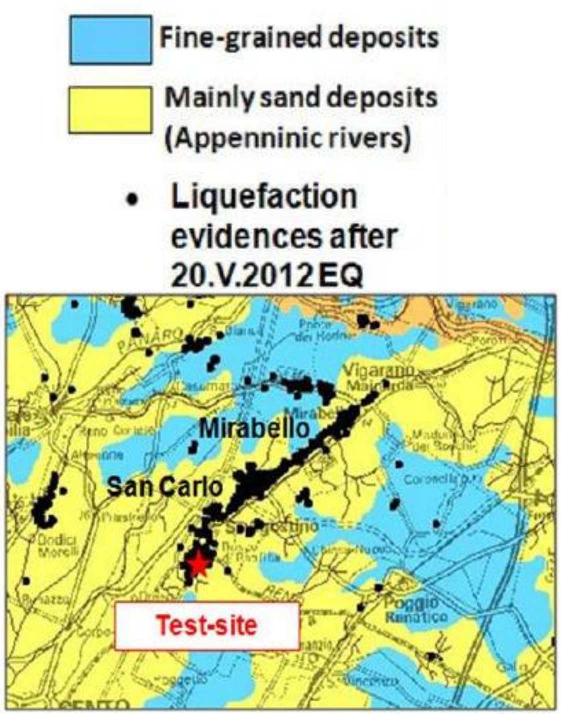
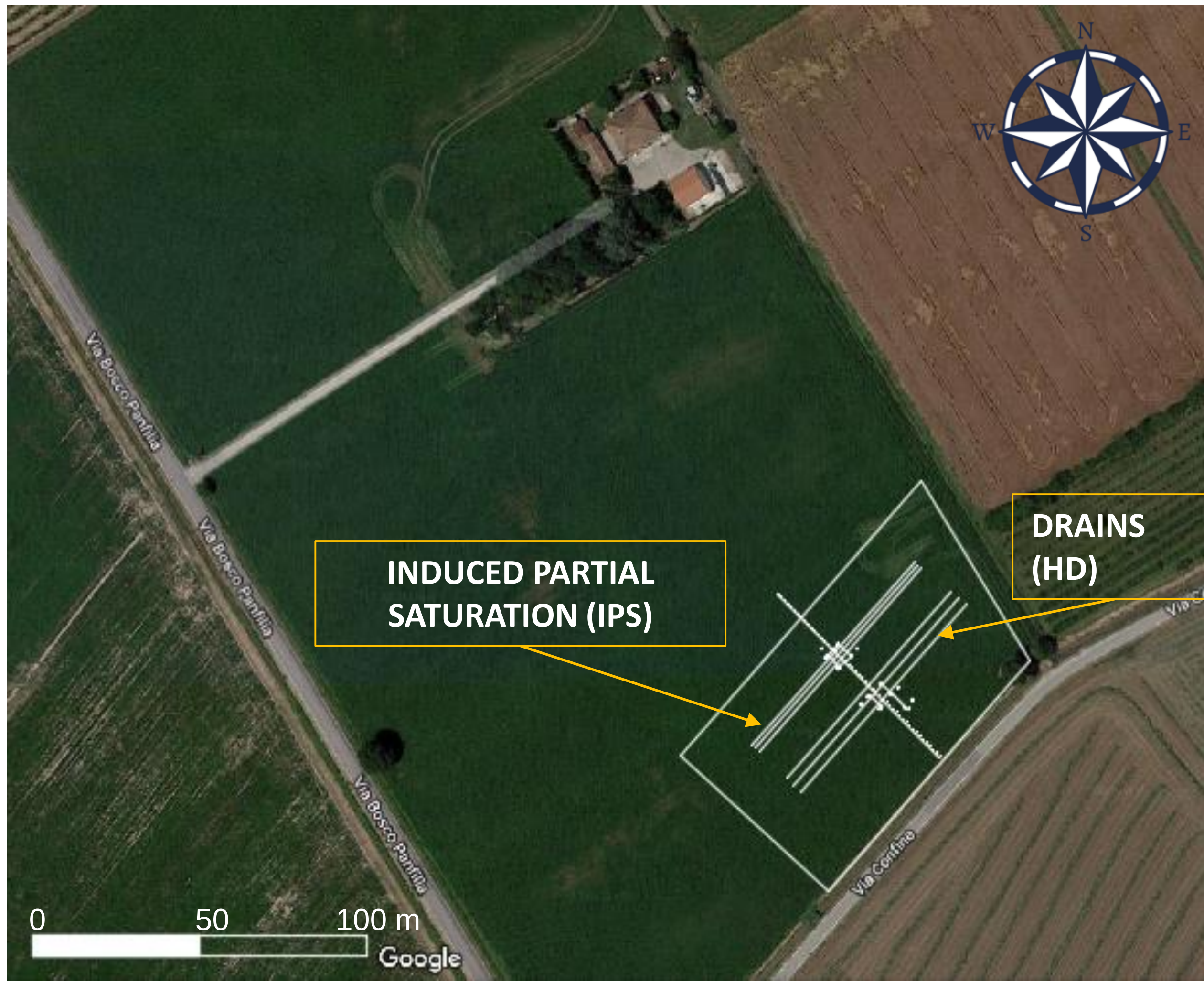
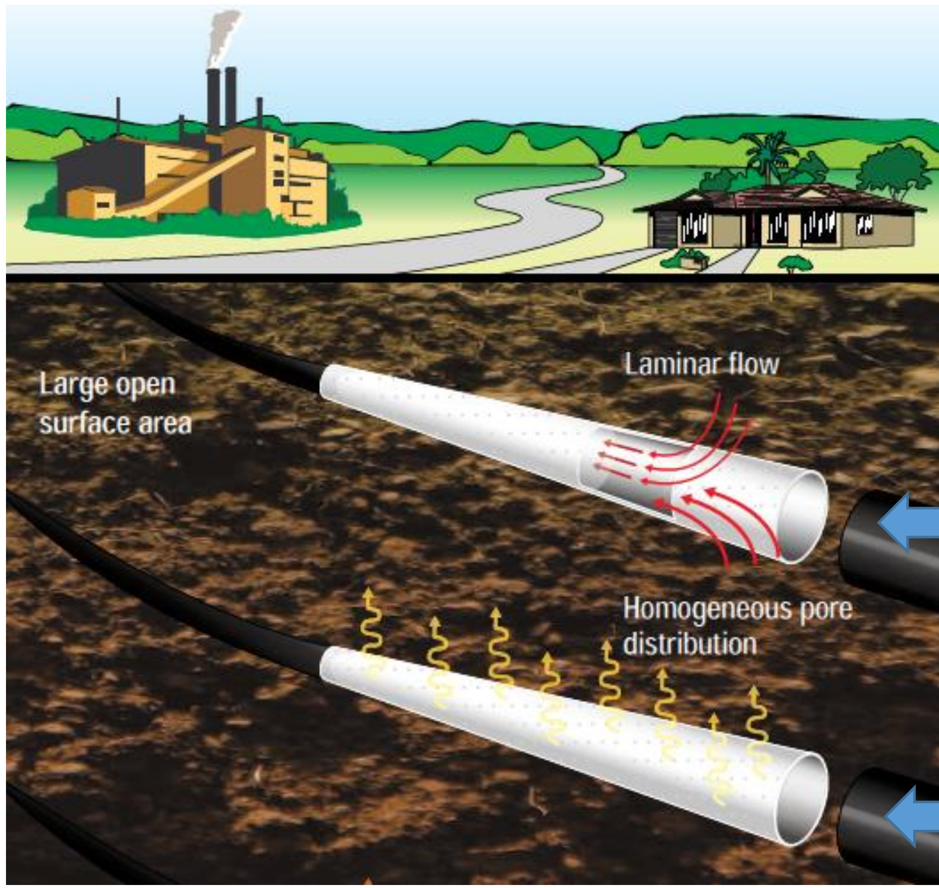
Field tests site





Field tests – the technologies

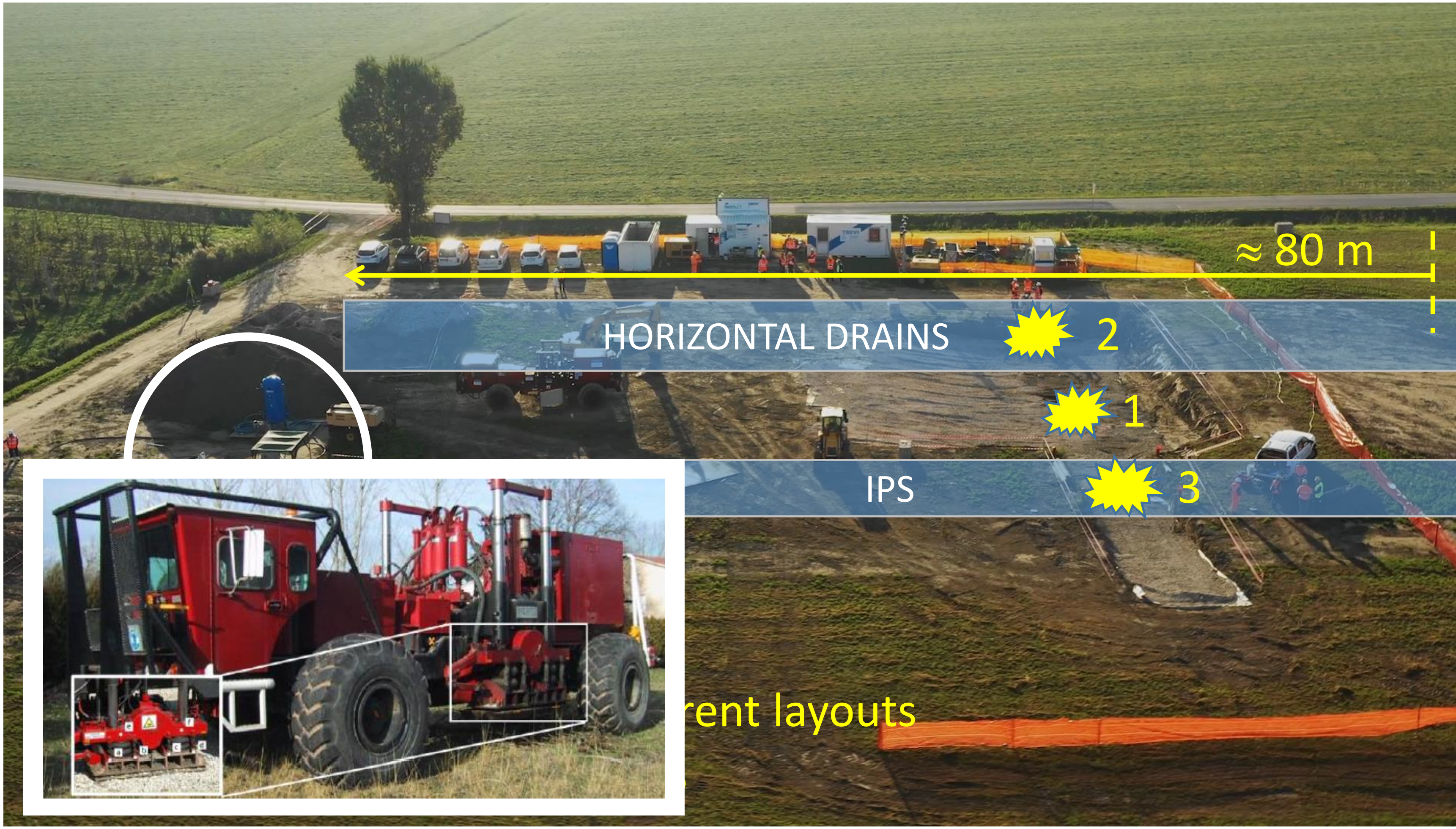
TREVI (LIQUEFACT partner) installed the horizontal drains and IPS pipes



Drainage (Ø 180mm)

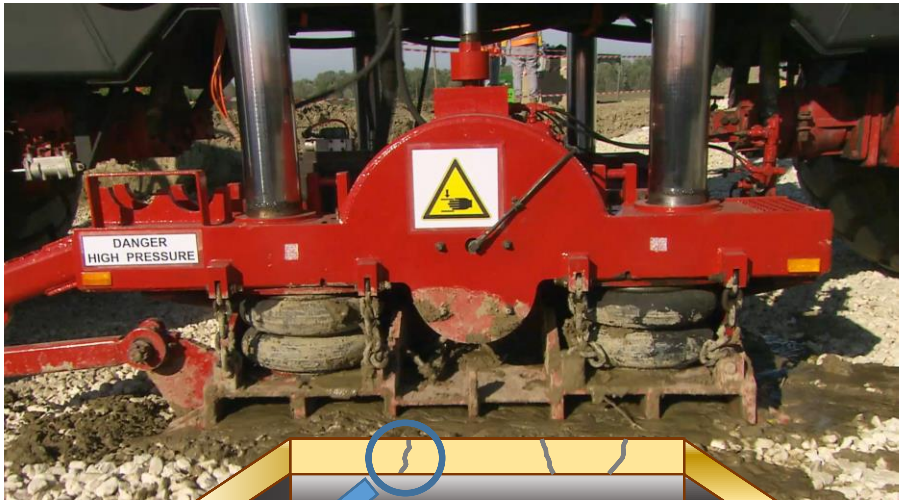
Desaturation (Ø 75 mm)

Field tests



Field tests results

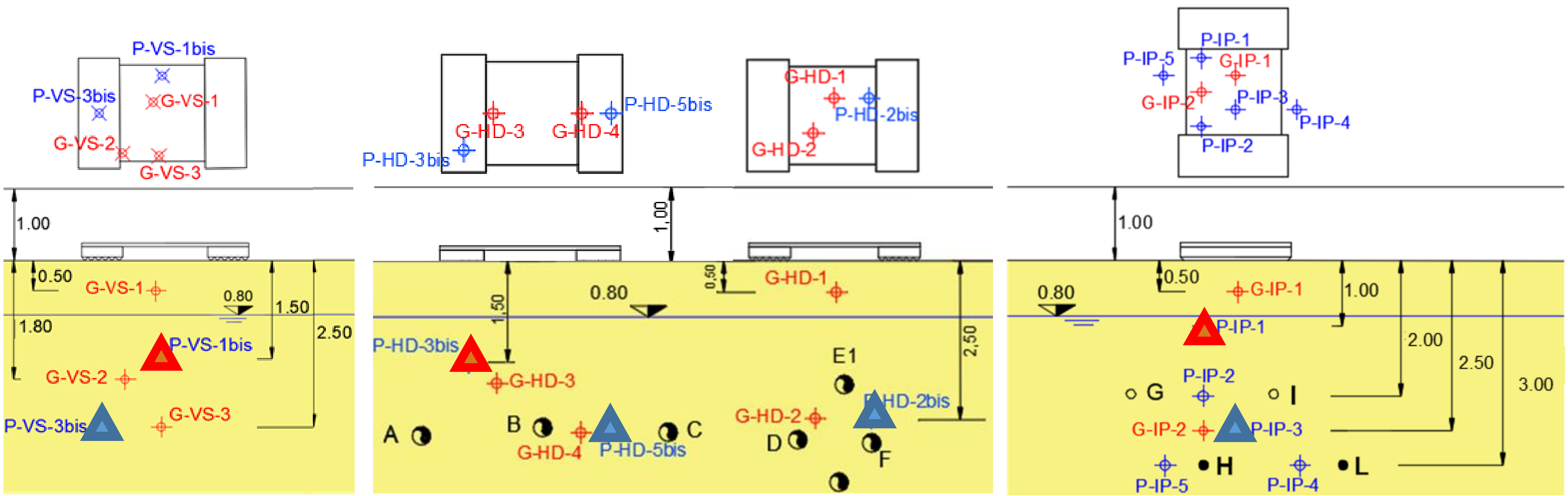
Test on virgin soil



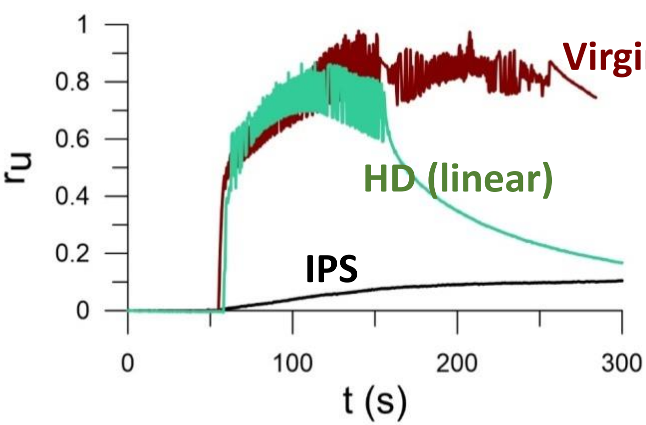
Test on IPS treated zone

- Clear evidence of liquefaction on virgin soil
- Wet behaviour with HD
- No liquefaction and dry behaviour with IPS

Field tests results

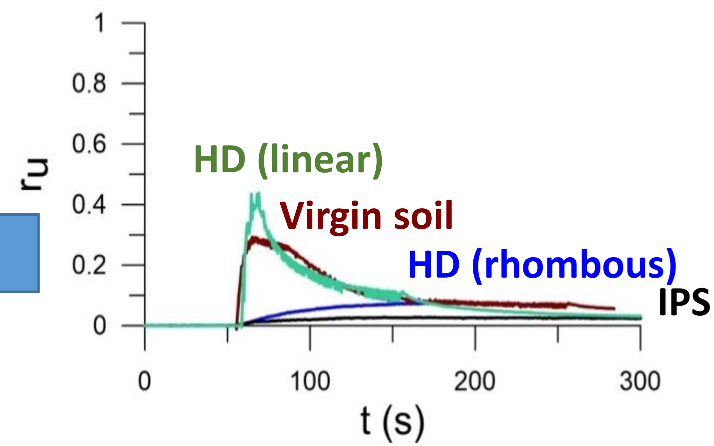


virgin soil | HD (linear) | HD (rhombus) | **IPS** (70%<S_r<90%)



z=1-1.5 m

z=2.5 m



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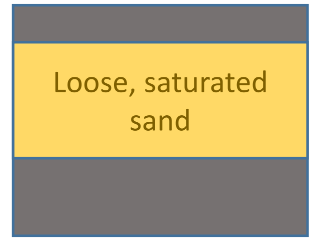
What do we want?

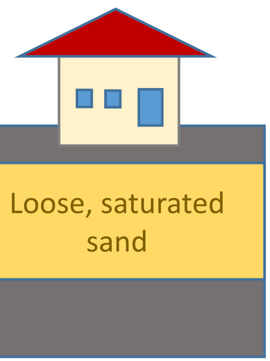
a) Increase safety factor against liquefaction triggering



Free field check
(check on the soil)

b) Limit reduction of bearing capacity

c) Reduce settlements



Checks on the soil-structure system (SSI)

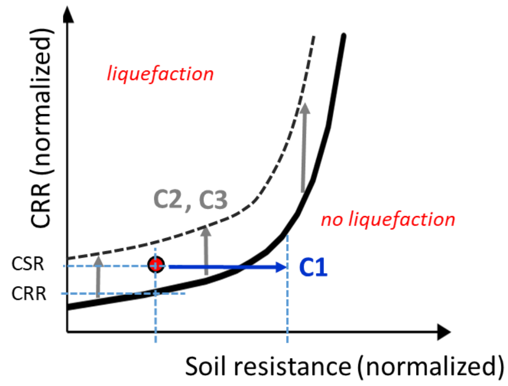
What do we want?

Case 1: liquefaction

$FS_{liq}(z) < FS_{liq,min}$

LPI, LSN,… too high

increase $FS_{liq}(z)$

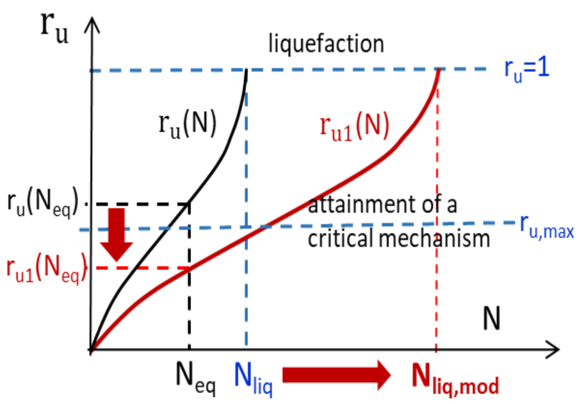


Case 2: no liquefaction

$FS_{liq}(z) > Fs_{liq,min}$

$r_u \geq r_{u,max}$

reduce $r_u(z)$



Do we have everything we need to design HD and IPS?

Design needs

Initial checks

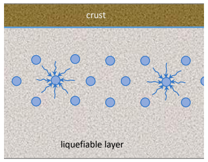
With the free field safety check ($FS_{liq,ff}$=CRR/CSR) we know how far we are from liquefaction.

1 • What is the pore pressure ratio $r_{u,ff}$ for $FS_{liq,ff}>1$ ($S_r=1$)?

Ground improvement checks

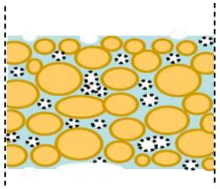
We need tools for case 1 ($FS_{liq}<FS_{liq,min}$) and case 2 ($FS_{liq}\geq FS_{liq,min}$ and $r_u \geq r_{u,max}$) design checks.

Horizontal drains are designed with a target maximum value of Δu (or r_u).



1 • What is the effect in terms of $FS_{liq,ff}$?

IPS reduces the tendency to accumulate positive pore pressure increments.



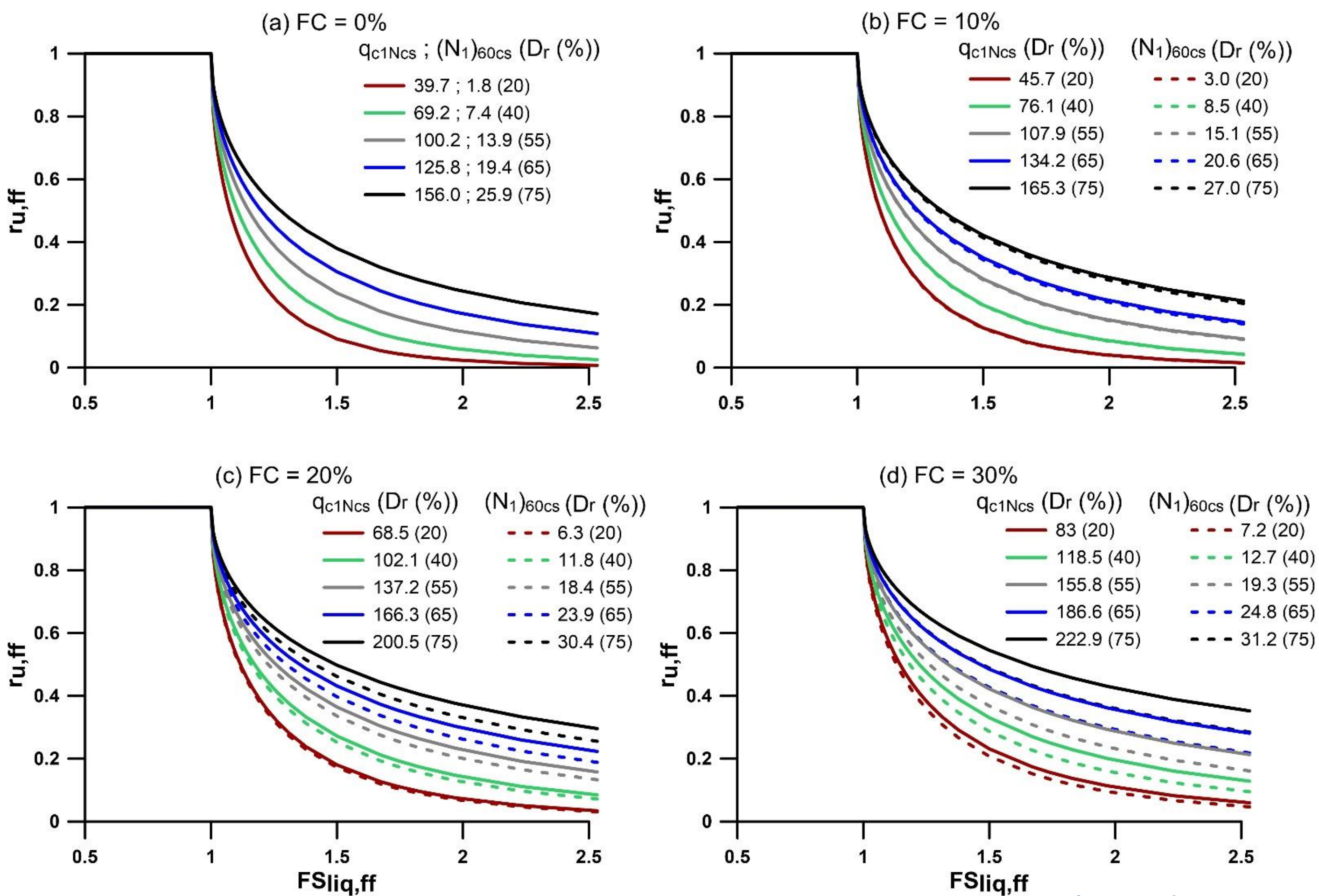
2 • What is the effect of $S_r<1$ on $FS_{liq,ff}$?

3 • What is the pore pressure ratio $r_{u,ff}$ for $FS_{liq,ff}>1$ and $S_r<1$?

1

Issues related to safety checks

link between r_u and FS_{liq} for saturated soils



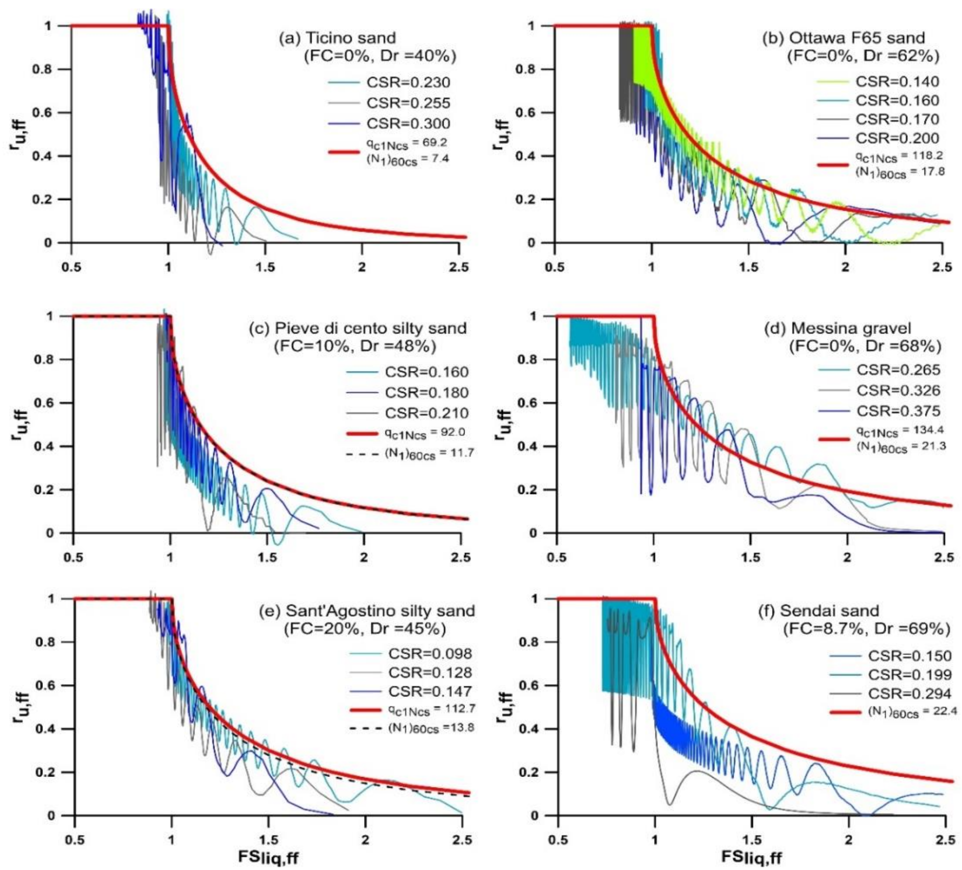
Chiaradonna and Flora (2019)

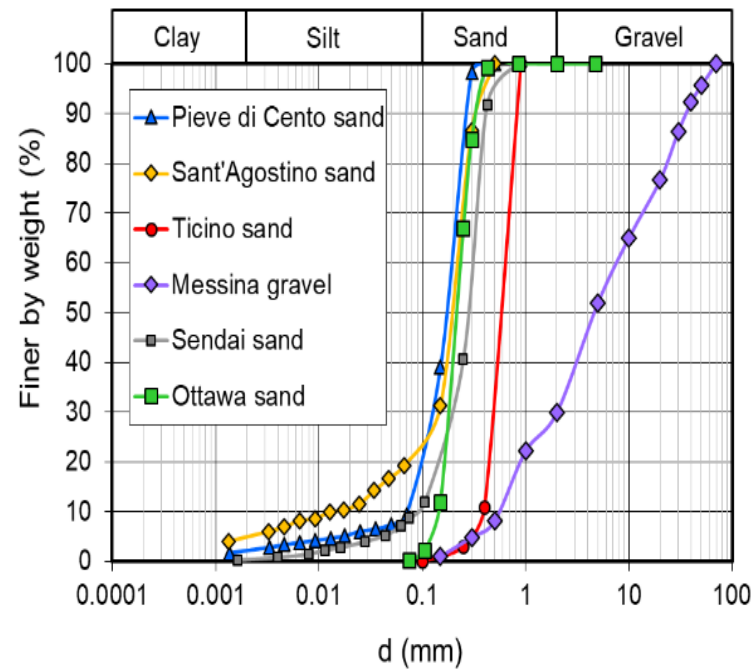
1

Issues related to safety checks

link between r_u and FS_{liq} for saturated soils

Experimental verification



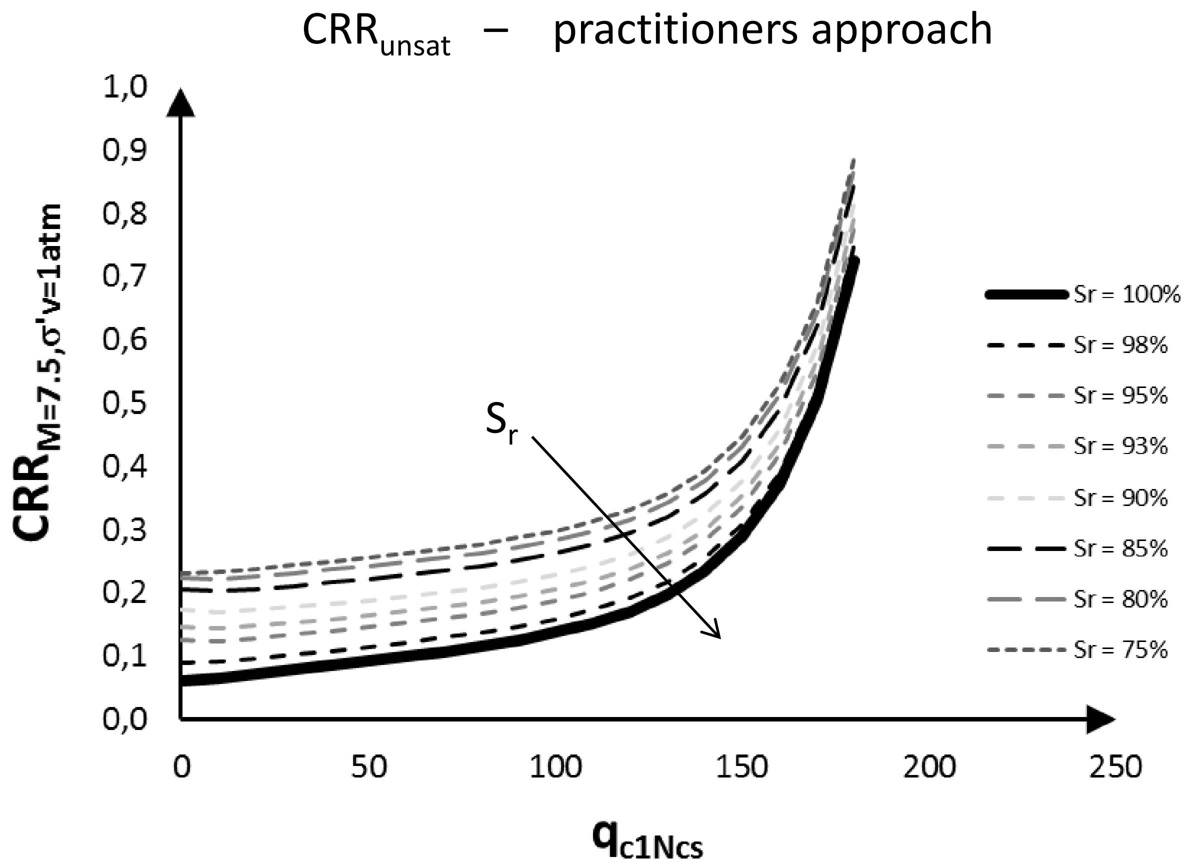


Chiaradonna and Flora (2019)

2

Issues related to safety checks

Effect of desaturation on soil capacity



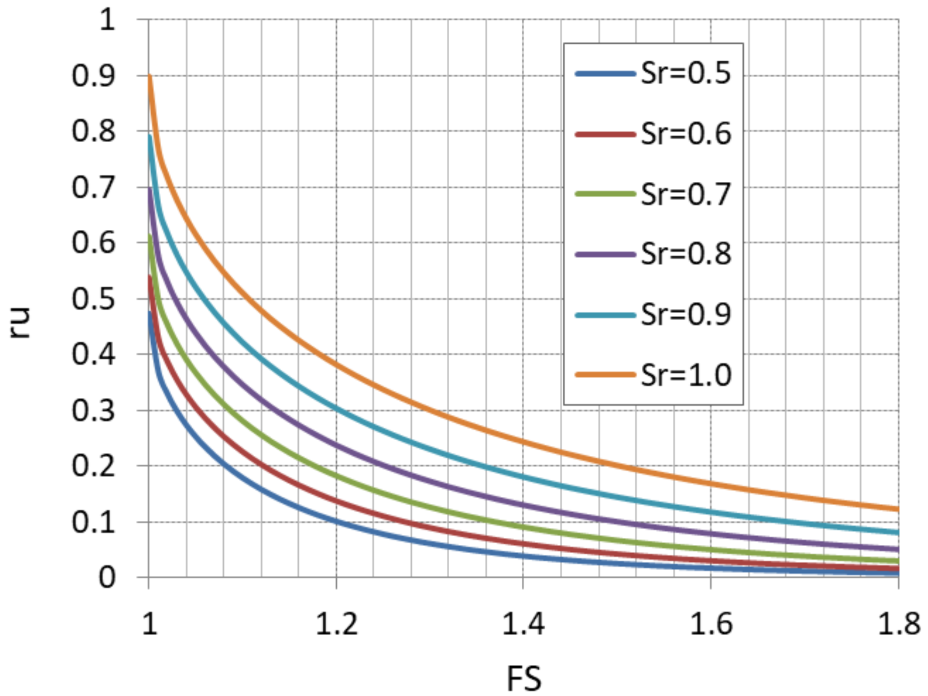
simple safety check design tool for S_r<100%

3

Issues related to safety checks

link between r_u and FS_{liq} for unsaturated soils

The example of Sant'Agostino sand



b=0.19

q_{c1Ncs}=80

$$FS \geq 1, \qquad S_r \leq 100\%$$

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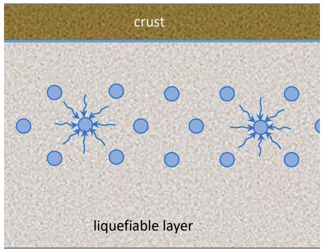
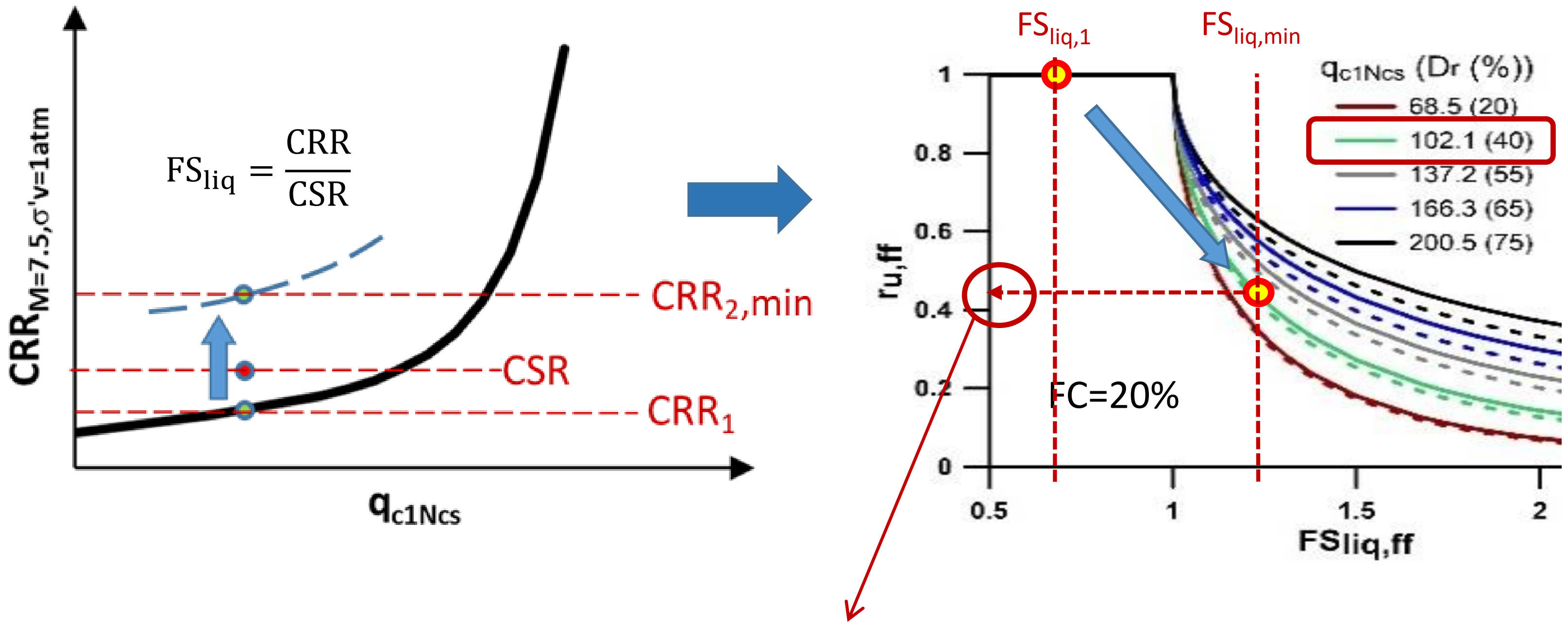
Design of horizontal drains (HD)

Horizontal drains are designed with a target maximum value of Δu (or r_u).

(Fasano et al. 2019)



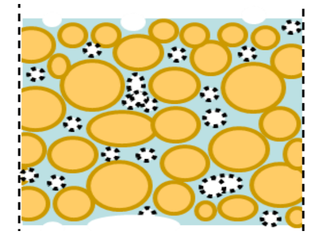
How to assign spacing and depth if $FS_{liq} < FS_{liq,min}$, having $FS_{liq,min}$ as a goal?



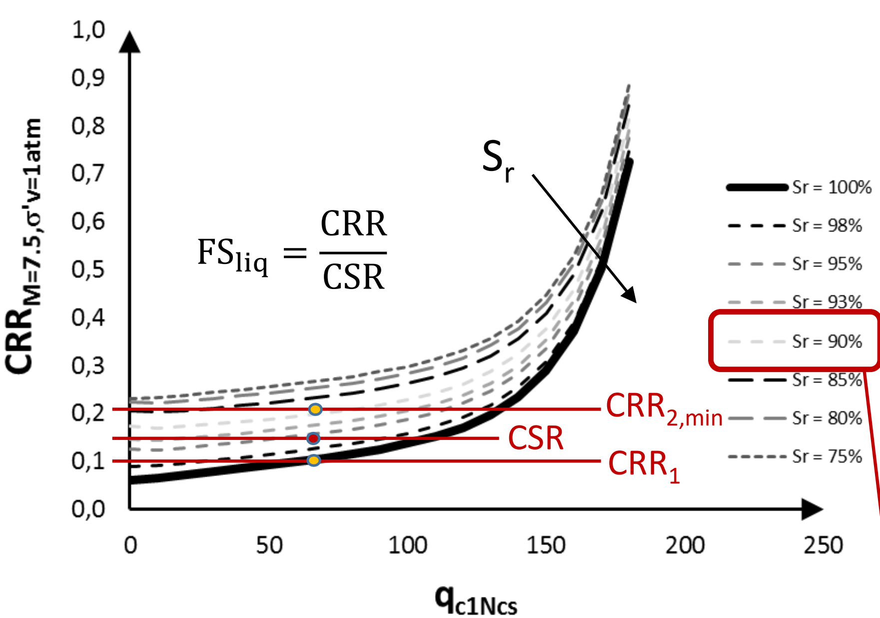
Design value of $r_{u,ff}$

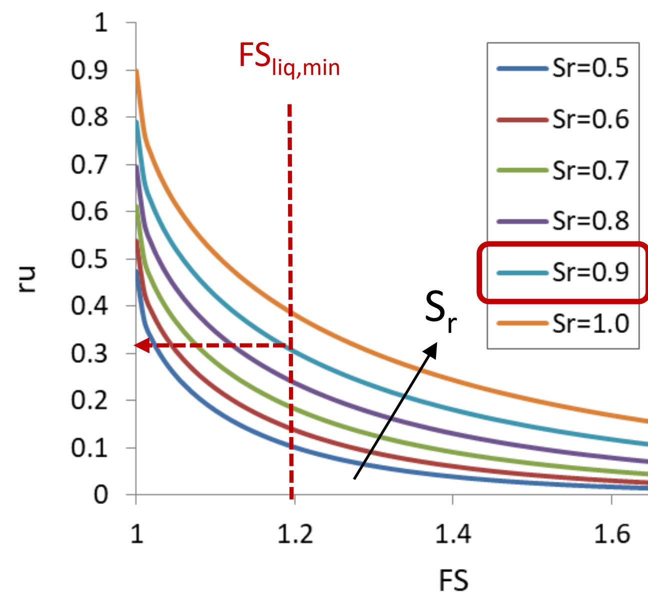
Design of induced partial saturation (IPS)

IPS reduces the tendency to accumulate positive pore pressure increments.



What is the value of S_r to assign if $FS_{liq} < FS_{liq,min}$, having $FS_{liq,min}$ as a goal?





Design value of S_r

Concluding remarks …

- ✓ HD and IPS are innovative technologies that can be of extreme interest in urbanized areas
- ✓ Experimental evidences indicate that IPS is very effective even at high S_r
- ✓ Design procedures are available for the two technologies (HD and IPS) in the case of full liquefaction or just critical pore pressure increments and no liquefaction

… and things still to do

- ✓ IPS generation? Duration?
- ✓ Reliable in situ estimate of S_r
- ✓ New field trials


Thank you