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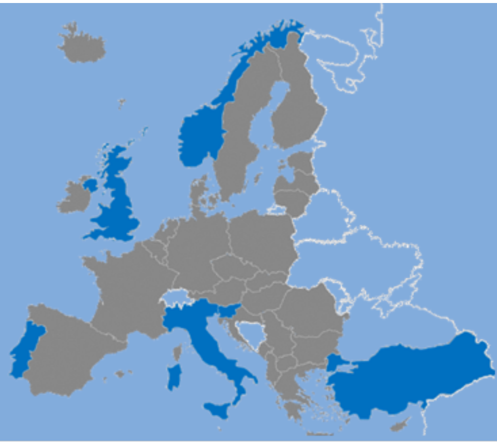
liquefACT



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 potential

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SUMMARY OF PRESENTATION

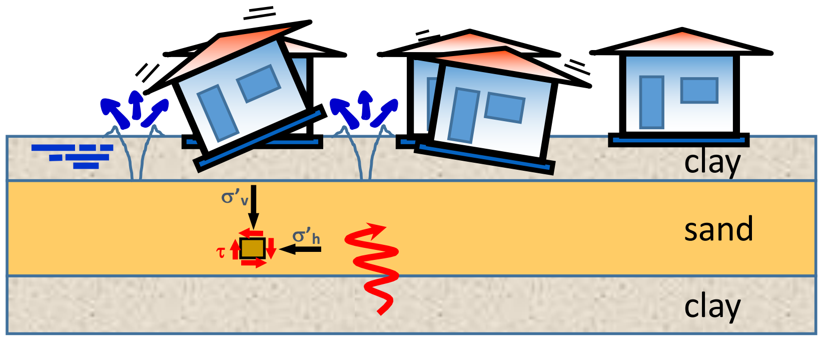
1. Liquefaction

2. Two innovative mitigation techniques

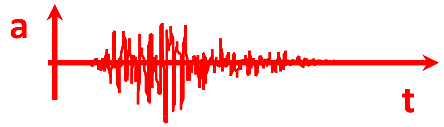
3. Pieve di Cento (Italy) field trial design

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.



$$R_u = \frac{\Delta u}{\sigma'_o} \to 1 \Rightarrow \begin{cases} \tau_f = \sigma' \tan\varphi' = (\sigma_o - \Delta u)\tan\varphi' \to 0 \\ G = G(p') \to 0 \end{cases}$$



The consequences on the built environment can be catastrophic

WHY DOES LIQUEFACTION HAPPEN?

PREDISPOSING FACTORS

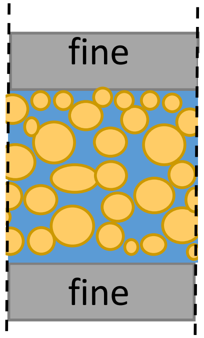
✓ Soil and water
- Density
- Cementation
- Grading
- Saturation
- Drainage

✓ Stress state
- Low initial effective stress (shallow soils)

TRIGGERING FACTOR

✓ Earthquake
- High ground acceleration

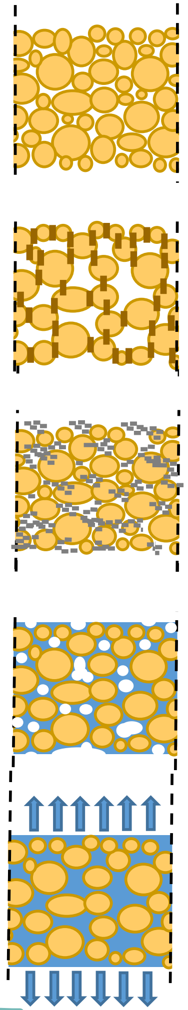
POSSIBLE



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

Some of the possible goals of ground improvement

UNLIKELY TO HAPPEN

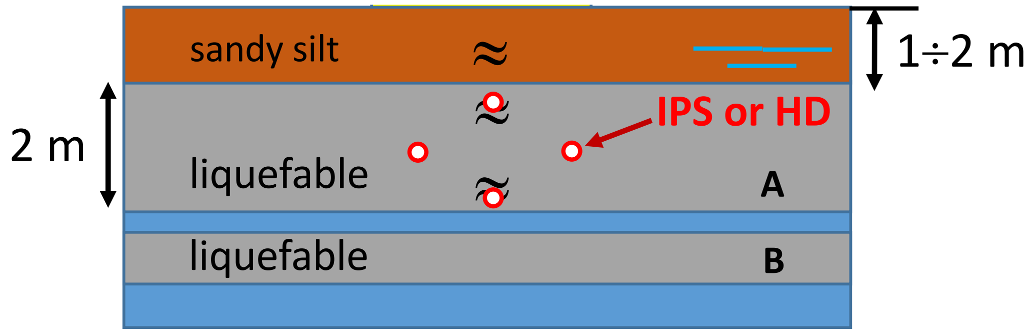


- dense
- cemented
- with fines

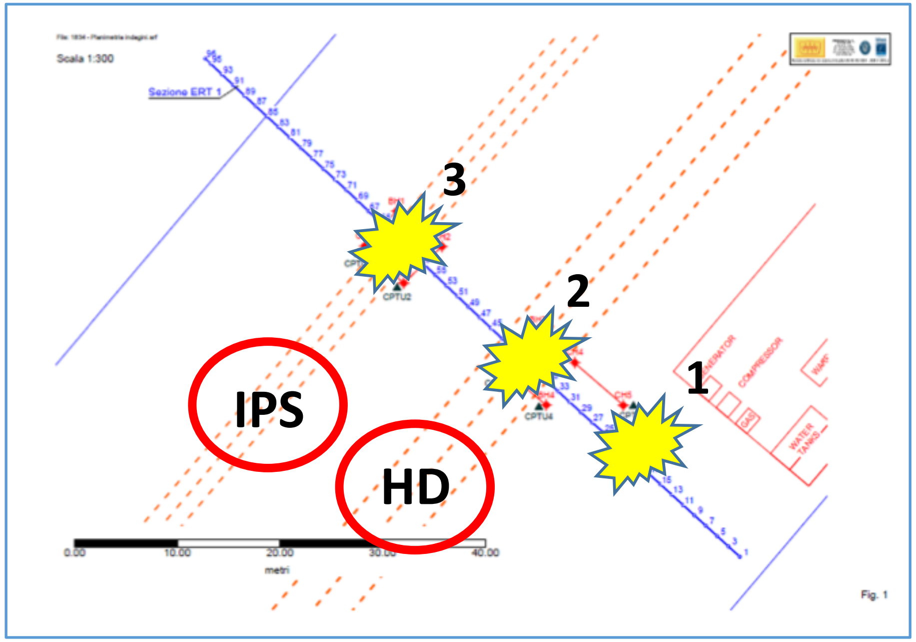
IPS
- unsaturated

HD
- drained

TEST SITE AND FIELD TRIAL



test site plan view



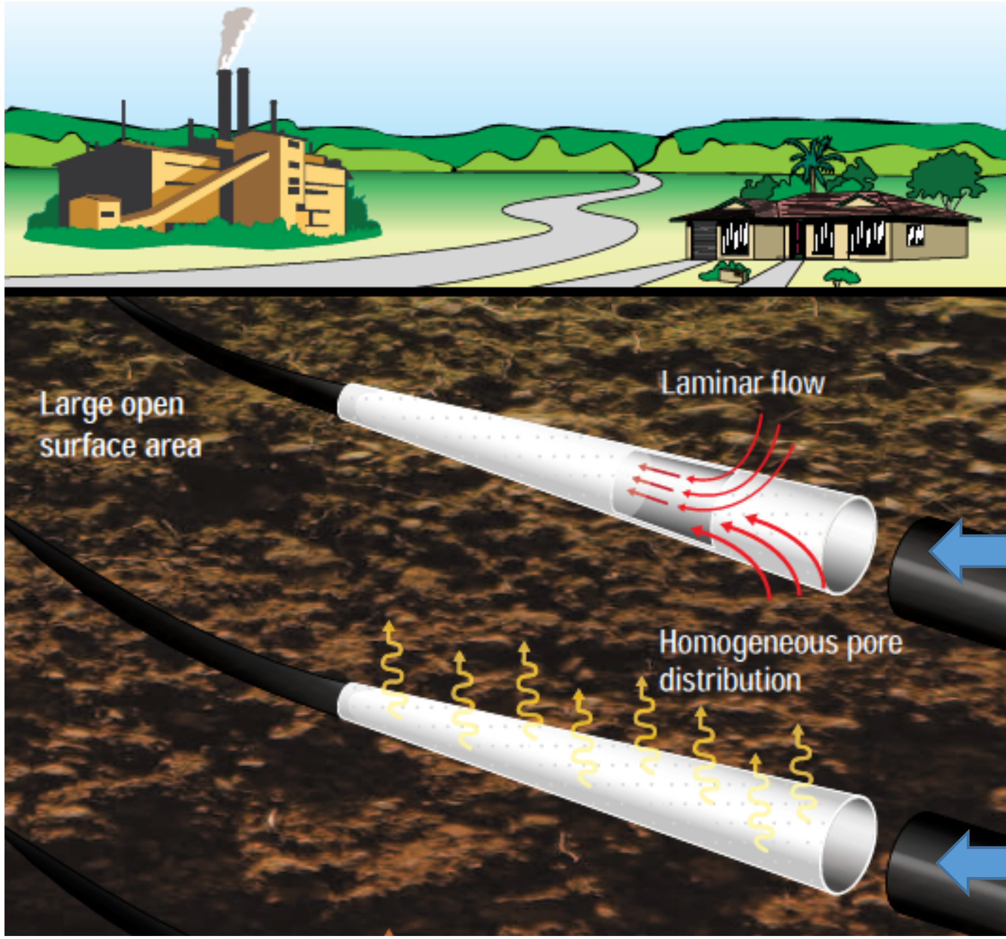
Goals of the field trial:

- Induce relevant pore pressure build up in layer A with a shaker (TEST 1);
- Repeat shaking using mitigation techniques (HD and IPS, TEST 2 and TEST 3) to reduce pore pressure buildup.

The technologies to be used are not conventional. Their design is one of the main geotechnical challanges of LIQUEFACT

FIELD TRIAL: the technology

TREVI (LIQUEFACT partner) will take care of the installation of the subhorizontal drains



drainage

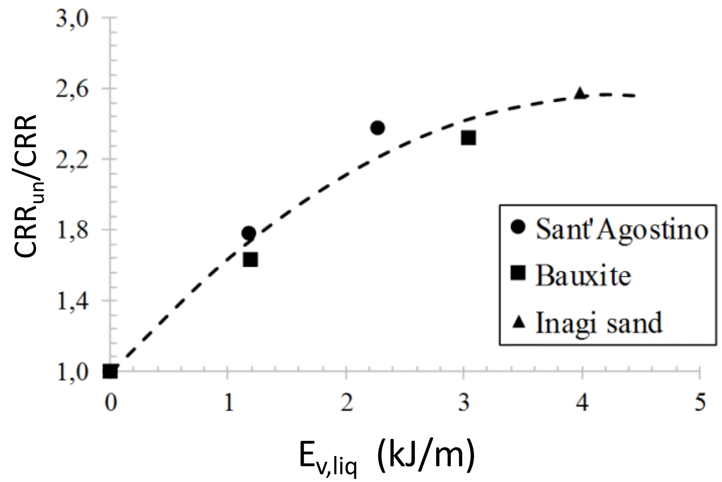
desaturation

INDUCED PARTIAL SATURATION: gas bubbles in the water

Design

A possible way is to use the theoretical formulation proposed by Mele et al. (2018), to express the value of CRR_{un} of the unsaturated soil as a function of the volumetric energy needed to liquefy

$$E_{v,liq} = E_{v,sk} + E_w + E_{air}$$



$$E_{v,sk} = \int_0^{\varepsilon_{v,liq}} \left[\left(\sigma - u_a + sS_r \right) \right] \cdot d\varepsilon_v$$ → Soil

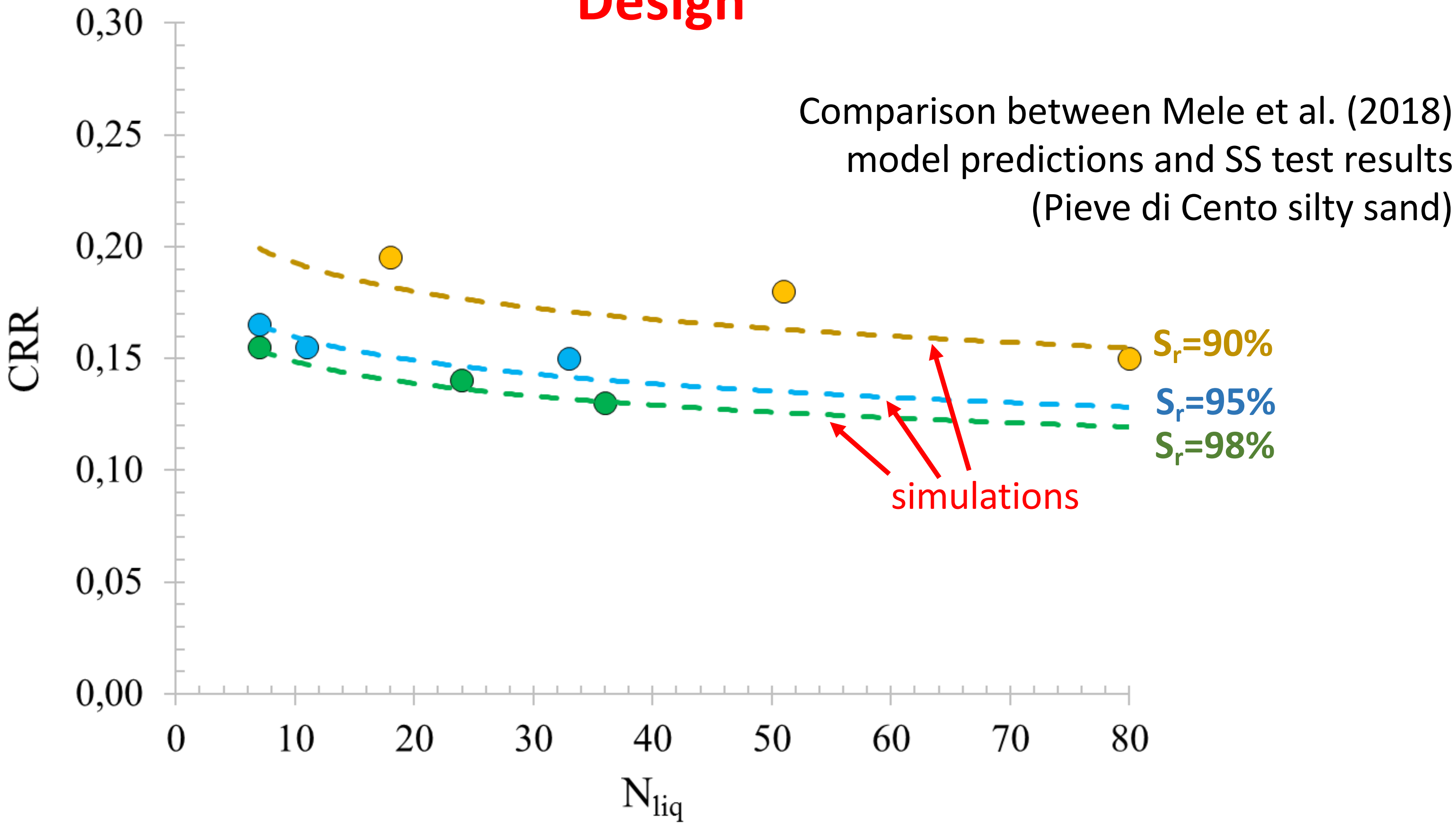
$$E_w = -\int_{S_{r0}}^{S_{r,liq}} \frac{e}{1+e} sS_r$$ → Water

$$E_{air} = \frac{e_0}{1+e_0} \left(1 - S_{r,0} \right) u_{a,liq} d\left(\ln \rho_{a,liq} \right)$$ → Air

Once CRR=CRR(N) is known for S_r=1, with this approach it is possible to plot CRR_{un}=CRR(N, S_r) for any value of S_r just by calculating the corresponding value of $E_{v,liq}$

INDUCED PARTIAL SATURATION: gas bubbles in the water

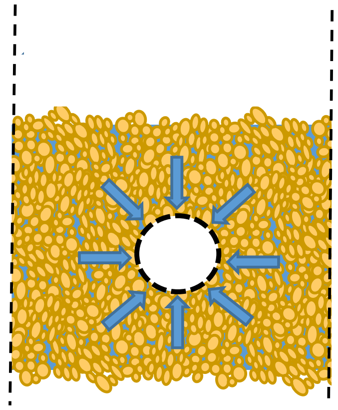
Design



The good fitting allows to draw design charts of cyclic resitance curves at different values of S_r just knowing the saturated cyclic resistance curve

HORIZONTAL DRAINS

Design



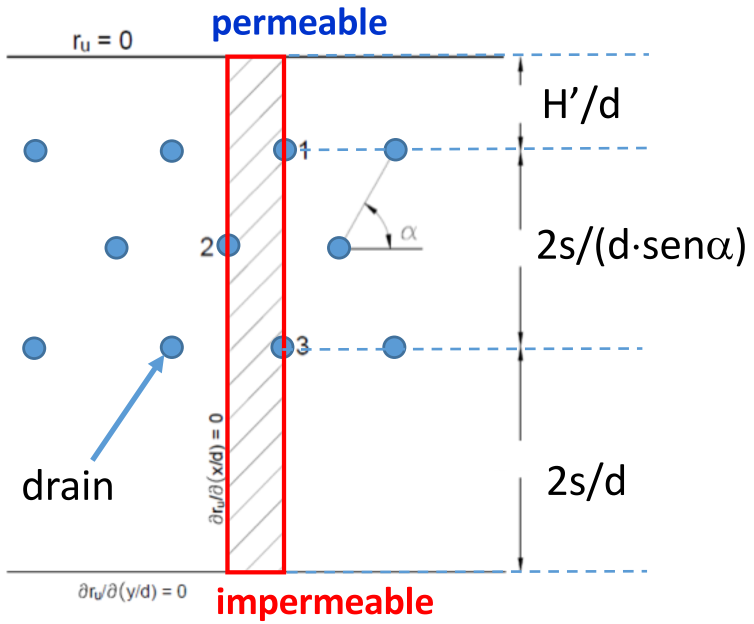
Seed e Booker (1977)

$$\frac{k}{\gamma_w}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=m_v\left(\frac{\partial u}{\partial t}-\frac{\partial u_g}{\partial N}\frac{\partial N}{\partial t}\right)$$

Bouckovalas et al. (2009)

$$\frac{\partial u_g}{\partial N}=\frac{\sigma_0'}{\pi A N_l}\frac{1}{\left(\frac{t}{t_d}\frac{N_{eq}}{N_l}\right)^{1-\frac{1}{2A}}\cos\left(\frac{\pi}{2}r_u\right)}$$

$$\frac{\partial N}{\partial t}=\frac{N_{eq}}{t_d};$$



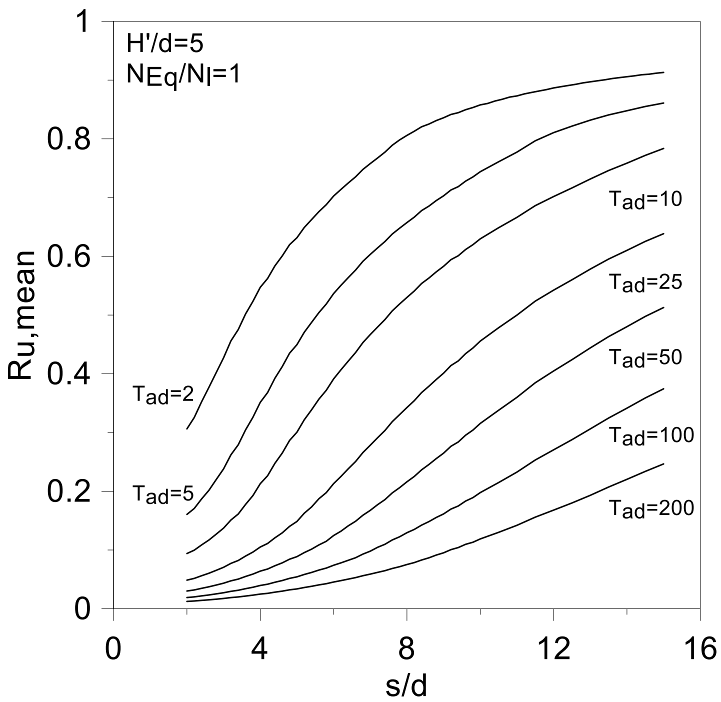
HORIZONTAL DRAINS

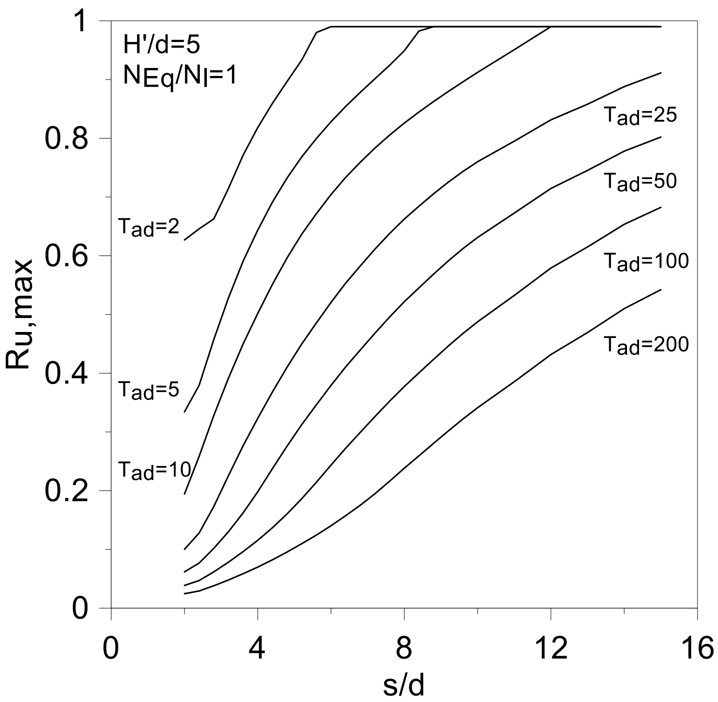
Design

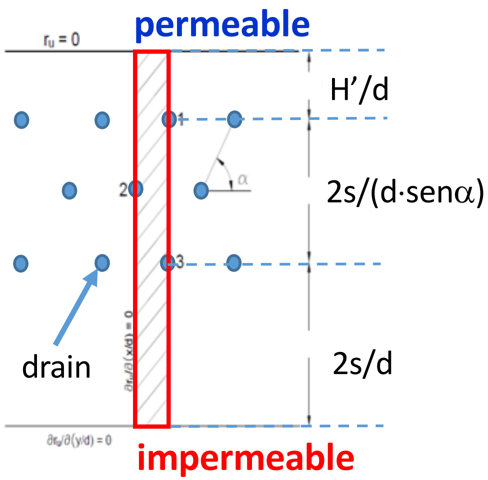
Inputs:
- seismic input (t_d, N_{eq})
- soil properties
- number of cycles to liq (N_{liq})
- diameter of drains (d)
- geometry (H')

Goal:
- Maximum tolerable value of $R_{u,mean}$ or $R_{u,max}$

Design choice:
- Spacing among drains
- In case, iterate (change H')



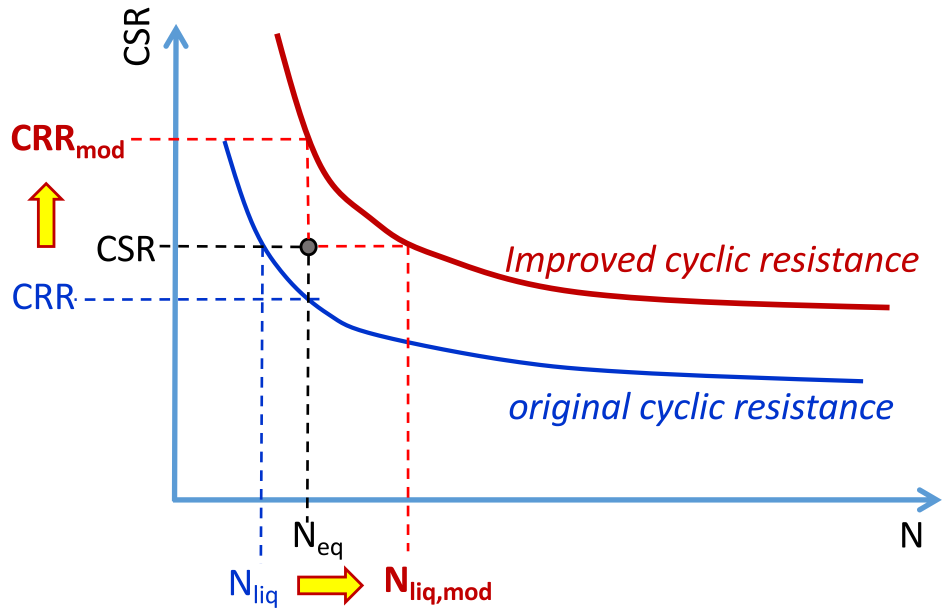




$$T_{ad} = \frac{c_v \cdot t_d}{d^2}$$

DESIGN OF GROUND IMPROVEMENT

1. Evaluate action (CSR, N_{eq})
2. Evaluate safety conditions (CRR, N_{liq})
3. If unsatisfactory (CSR>CRR, N_{liq}<N_{eq}), improve resistance enough to allow action (CSR, N_{eq}) with the desired safety margin



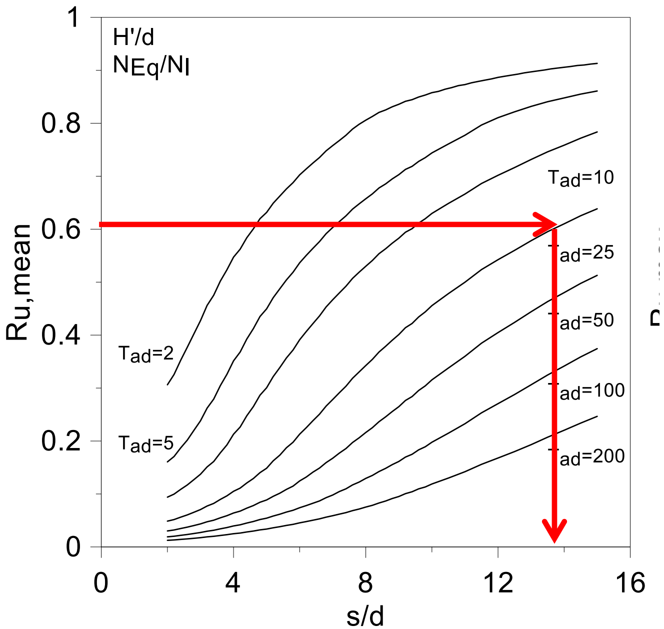
Design of ground improvement to improve resistance (step 3) →
- Increase N_{liq} to $N_{liq,mod}$ (approach 1)
- Increase CRR to CRR_{mod} (approach 2)

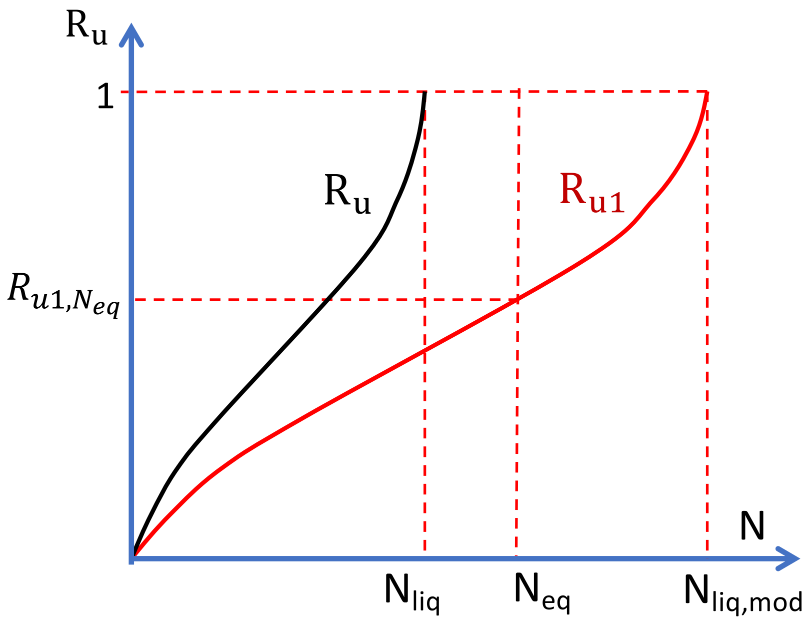
DESIGN APPROACH 1 (N_{liq} ➡ $N_{liq,mod}$)

Horizontal drains (HD)

1. Assume a limit value $R_{u1,Neq}$ (considering the critical mechanism, e.g. bearing capacity)

2. Select drains, spacing, depth, etc. using the proposed charts





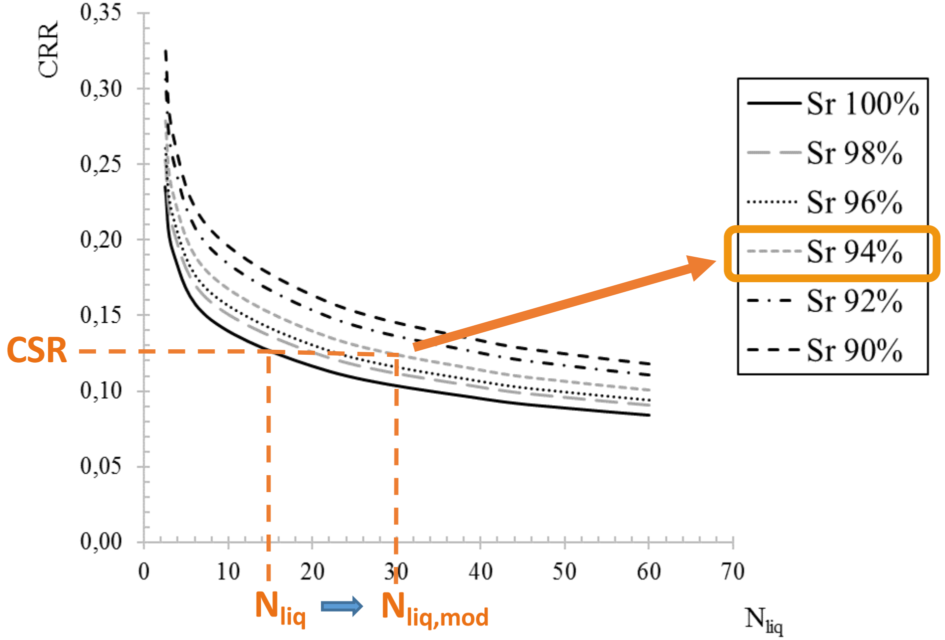
DESIGN APPROACH 1 (N_{liq} ➡ $N_{liq,mod}$)

Induced Partial Saturation (IPS)

1. Assume a limit value $R_{u1,Neq}$ (considering the critical mechanism, e.g. bearing capacity)
2. Calculate $N_{liq,mod}$ from eq. (1):

$$R_{u1,N_{eq}} = \frac{2}{\pi}\arcsin\left(\frac{N_{eq}}{N_{liq,mod}}\right)^{1/2\beta} \quad (1)$$

3. Select desired saturation degree as $S_r=S_r(N_{liq,mod}, CSR)$



DESIGN APPROACH 2 (CRR ➡ CRR_{mod})

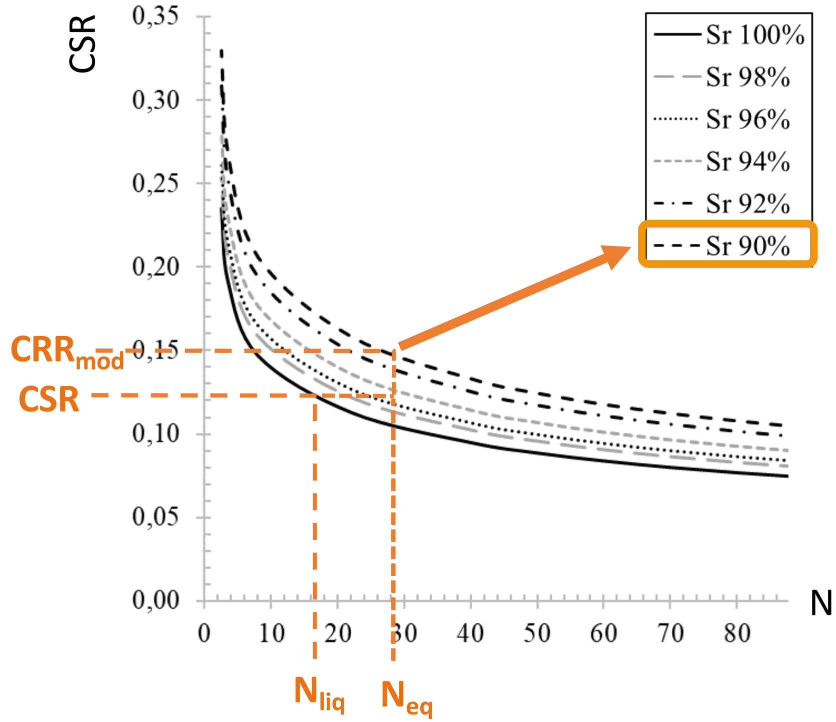
Induced Partial Saturation (IPS)

1. Assume a safety factor FS_{liq} on CSR (against liquefaction)

2. Calculate CRR_{mod} as:

$$CRR_{mod} = FS_{liq} \cdot CSR$$

3. Select the needed value of S_r



APPLICATION OF DESIGN APPROACHES TO FIELD TEST - 1/2

For a given shaking input at ground level

1. With reference to a bearing capacity preservation design (approach 1):

Factor of safety FS_{bc}	IPS: $S_{r,fin}$ (%)	HD, s (m)
1.00	94	1.05
1.50	93	1.00
1.90	91	0.96

2. With reference to a design having the goal to avoid liquefaction (approach 2):

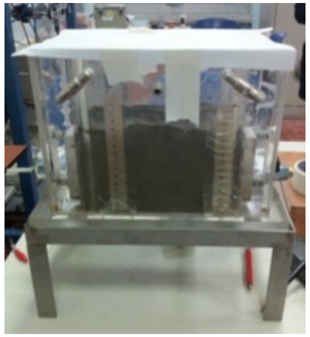
Factor of safety FS_{liq}	IPS: $S_{r,fin}$ (%)
1.00	94
1.25	90

We will go for $S_{r,fin}$=90% (IPS) and s≈1 m (HD)

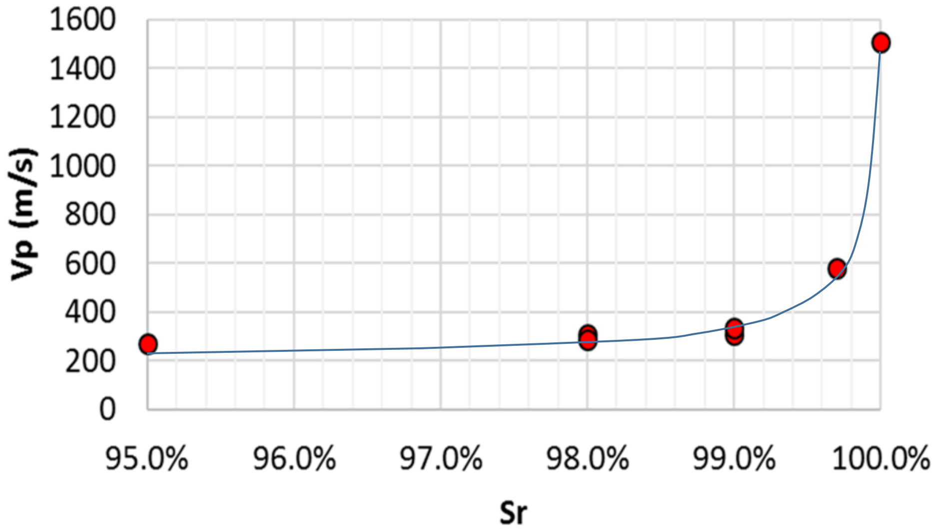
APPLICATION OF DESIGN APPROACHES TO FIELD TEST - 2/2

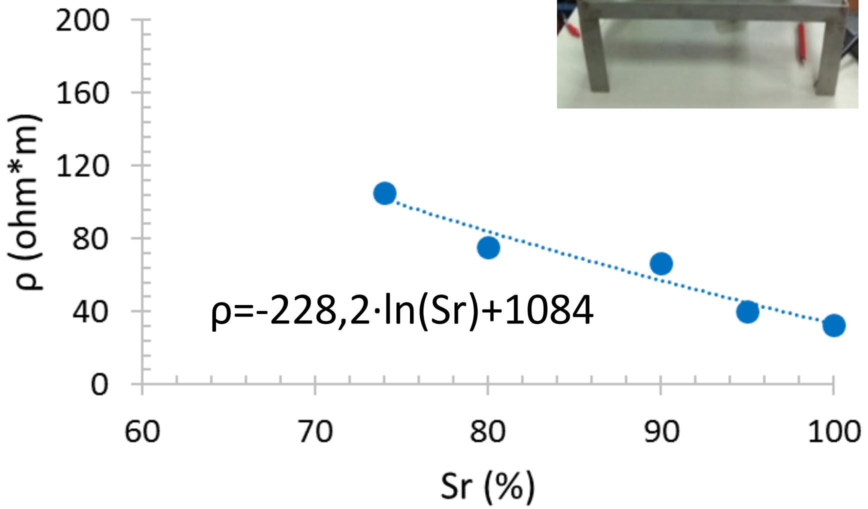
For a given shaking input at ground level

INDUCED PARTIAL SATURATION – Need to check S_r on site



Pieve di Cento – Grey Sand, D_r=40%





For very high values of S_r (>95%) V_p measurements are very sensitive to S_r

For lower values of S_r (<95%) resistivity measurements are more sensitive to S_r