

Interventi di consolidamento dei terreni: tecnologie e scelte di progetto

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COSA E' IL CONSOLIDAMENTO DEI TERRENI?

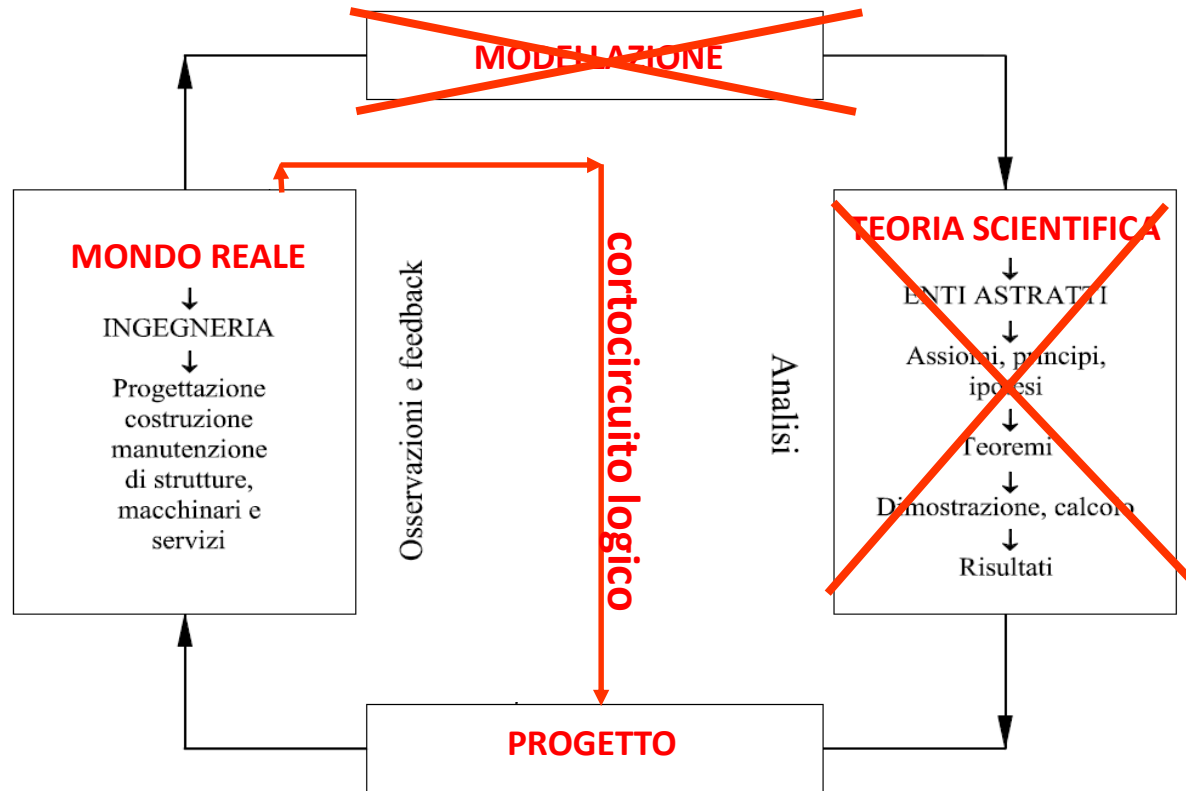
TC250/SC7 - EG14: *“the modification of ground properties in order to bring the effects of actions within ultimate and serviceability requirements”*

Una modifica temporanea o permanente del comportamento meccanico di un determinato volume di terreno, effettuata per contribuire alla soluzione di problemi di ingegneria geotecnica

PERCHE' FARLO?

1. Ignoranza
2. Spinta del mercato
3. Mancanza di alternative convenienti
4. Soluzioni “nuove” o meno invasive

Il progetto secondo il metodo scientifico ... e il consolidamento?



spesso zona d'ombra del progetto!

(Modificata da Viggiani, 1999)

CLASSIFICAZIONE DEGLI INTERVENTI

Evangelista (1995), Burghignoli (1995), Flora e Lirer (2011)

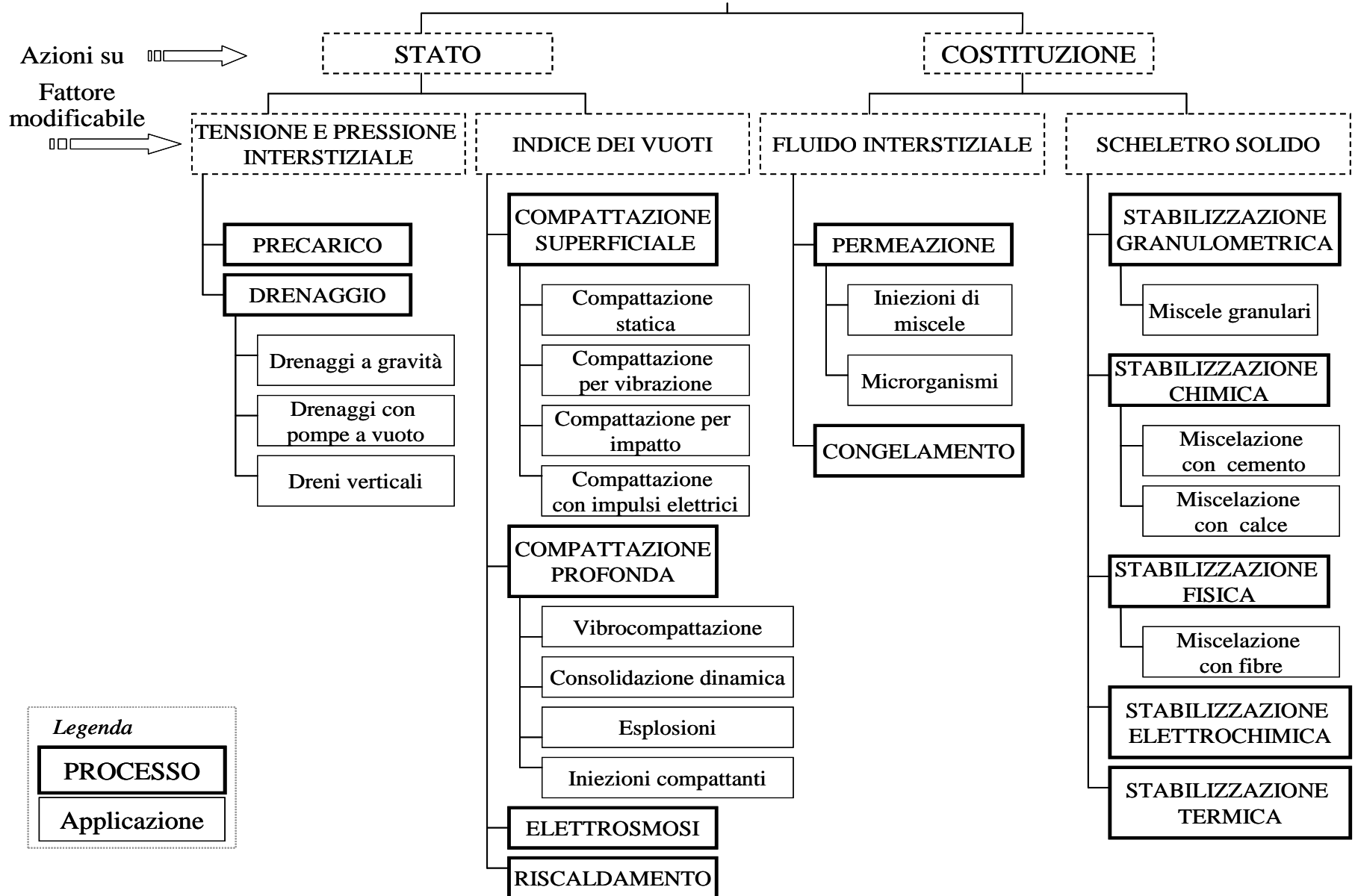
1. Interventi di miglioramento
2. Interventi di rinforzo

EG14, CEN250 – EC7 (2015)

1. *Not creating inclusions*
2. *Creating inclusions*

CLASSIFICAZIONE DEGLI INTERVENTI

TRATTAMENTI DI MIGLIORAMENTO

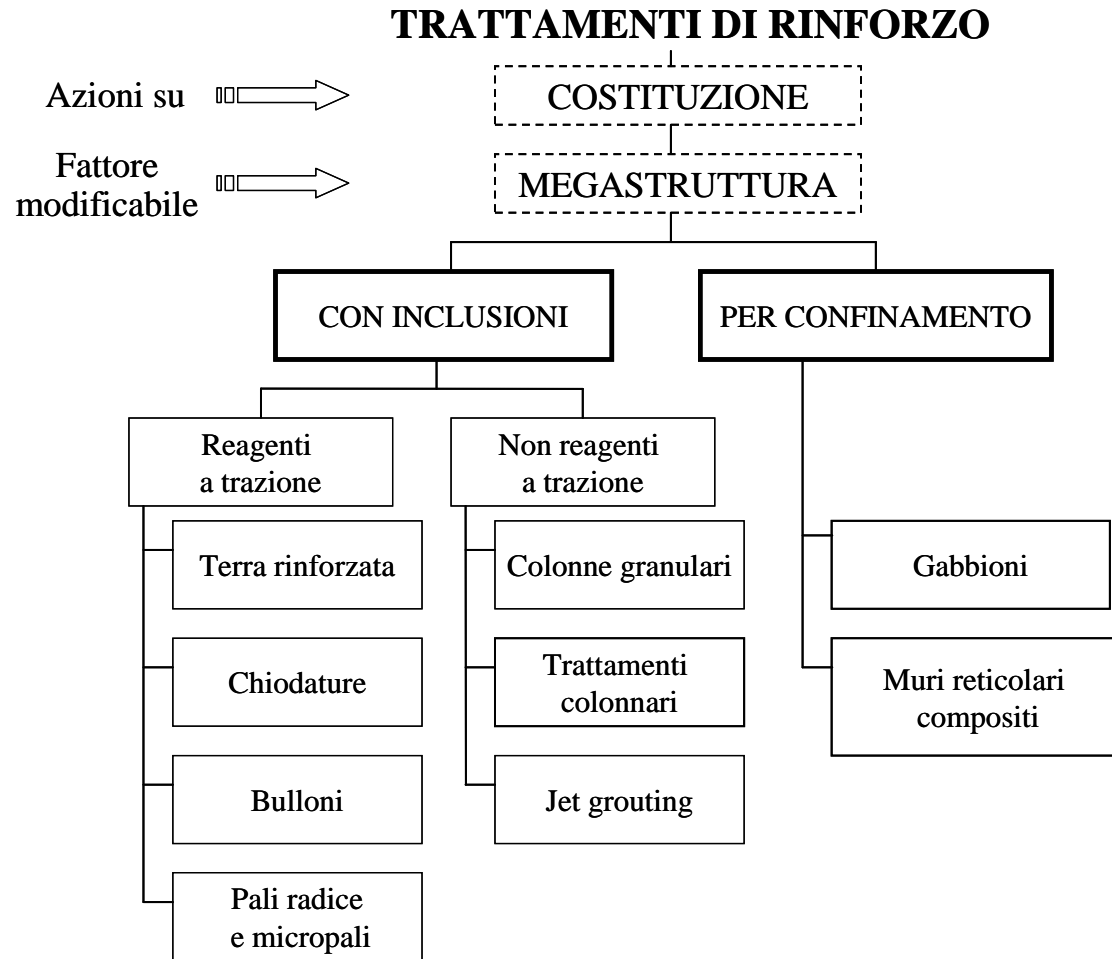


Legenda

PROCESSO

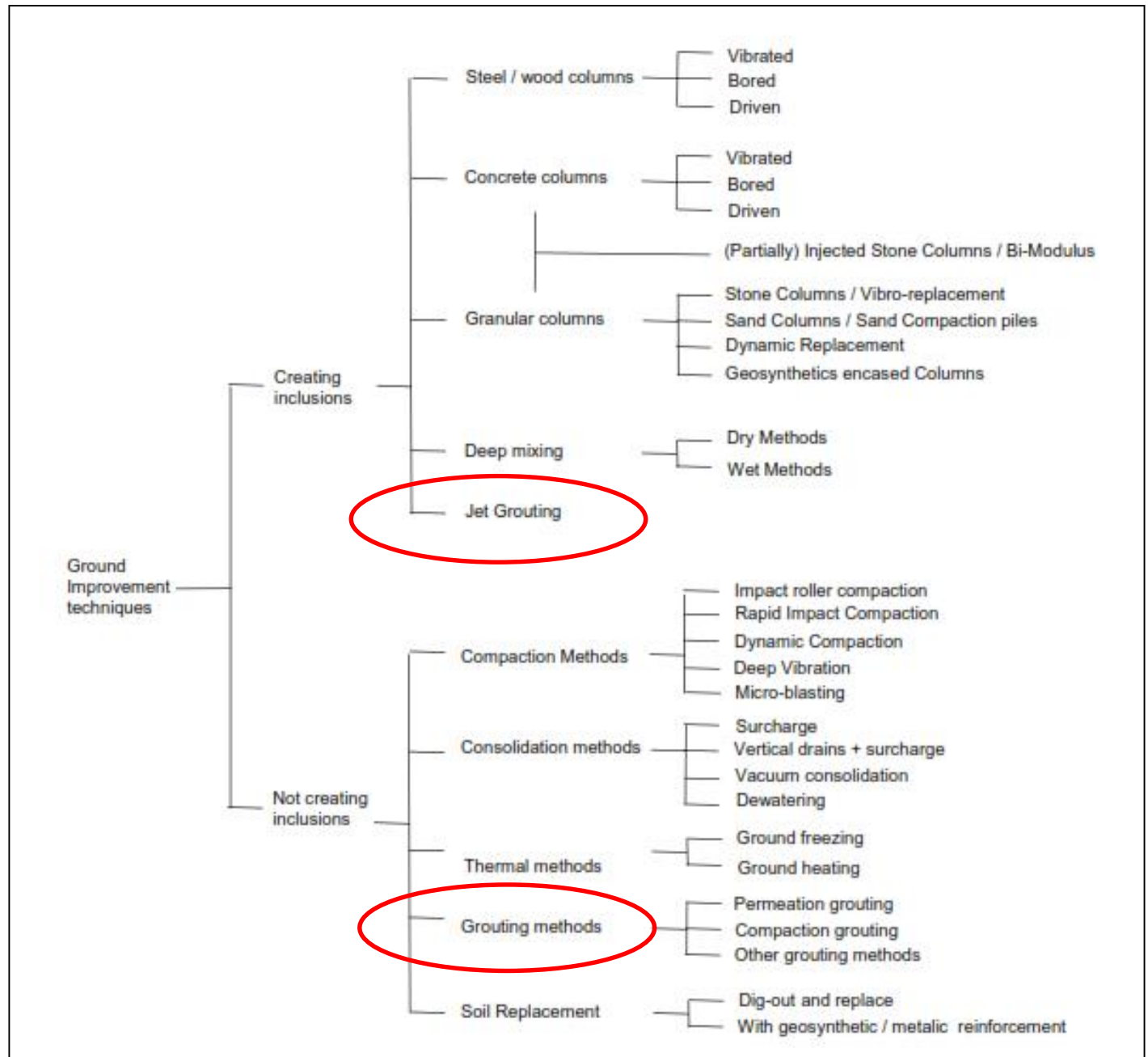
Applicazione

CLASSIFICAZIONE DEGLI INTERVENTI



CLASSIFICAZIONE DEGLI INTERVENTI

EG14 (2015)



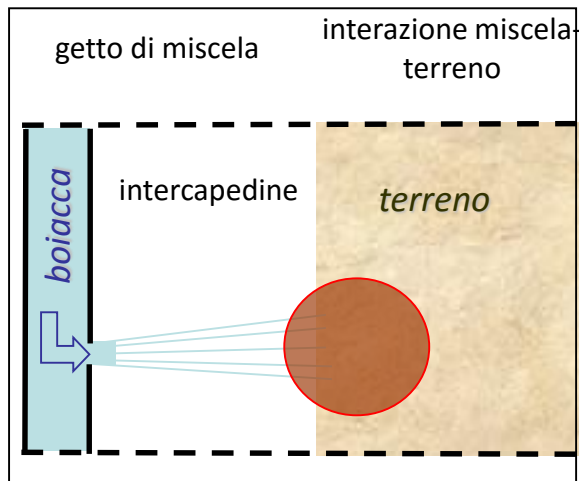
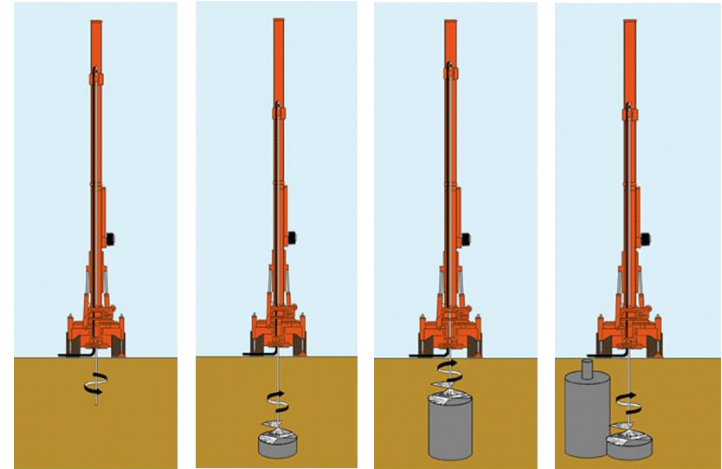
Esempio di intervento di consolidamento con rinforzo

JET GROUTING

JET GROUTING

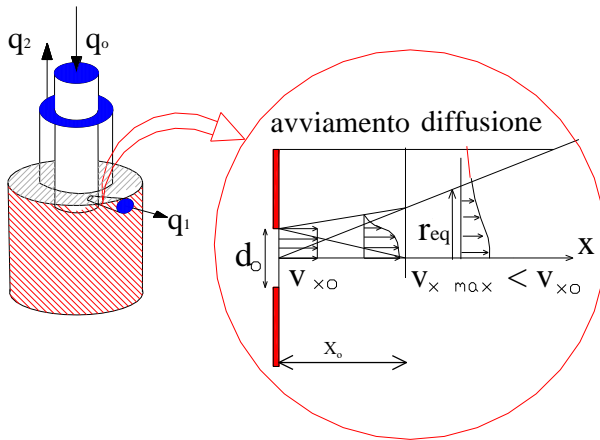
METODOLOGIA

iniezione ad alta velocità

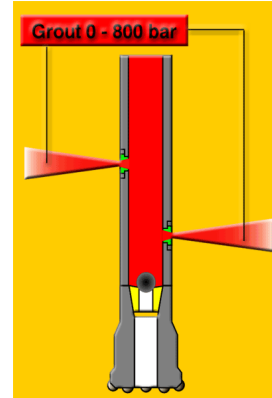


JET GROUTING

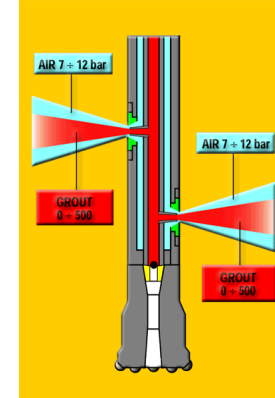
Il monitor



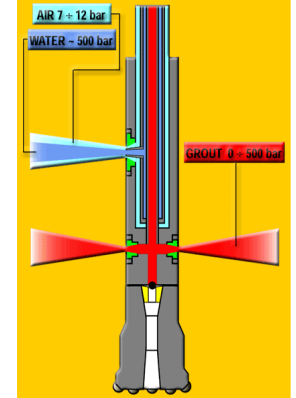
monofluido



bifluido

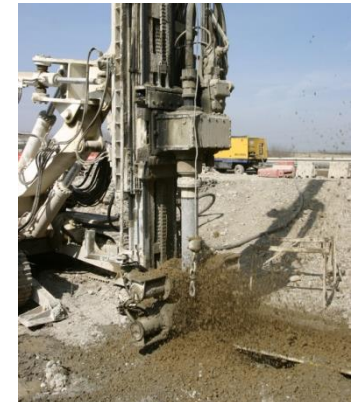
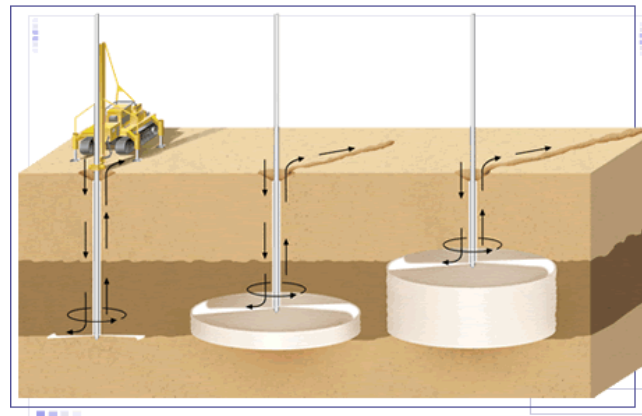


trifluido



L'importanza dello spurgo

L'intercapedine deve sempre essere libera, e il terreno eventualmente sostenuto



JET GROUTING

Evoluzioni tecnologiche

Esempi relativi agli utensili



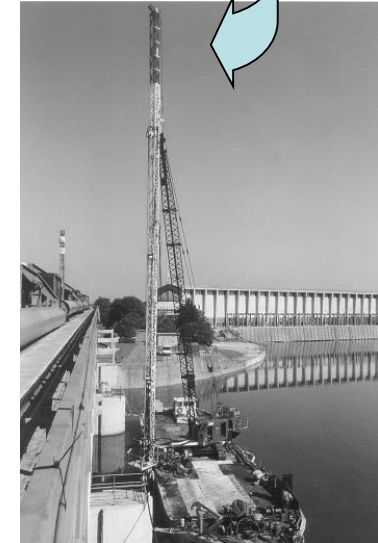
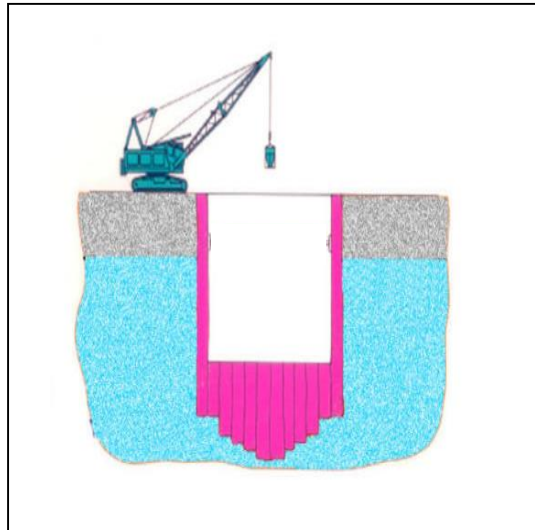
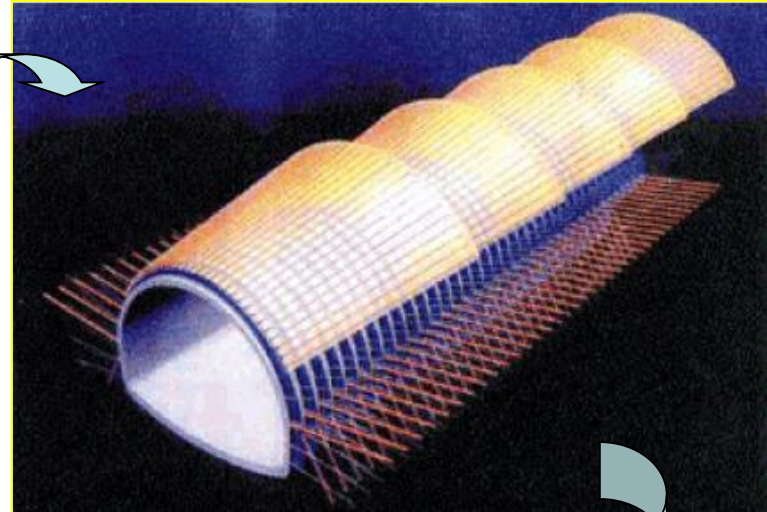
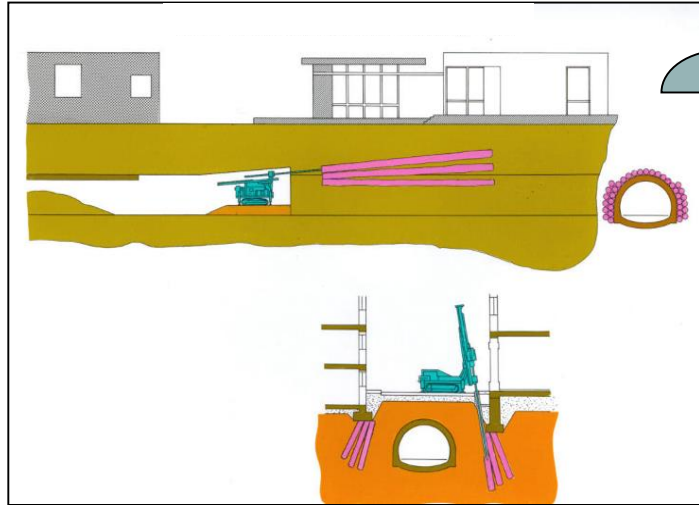
e poi le tecniche a
energia maggiorata:

- *super midi jet*,
- *super jet*,
- ...

Esempi relativi al processo

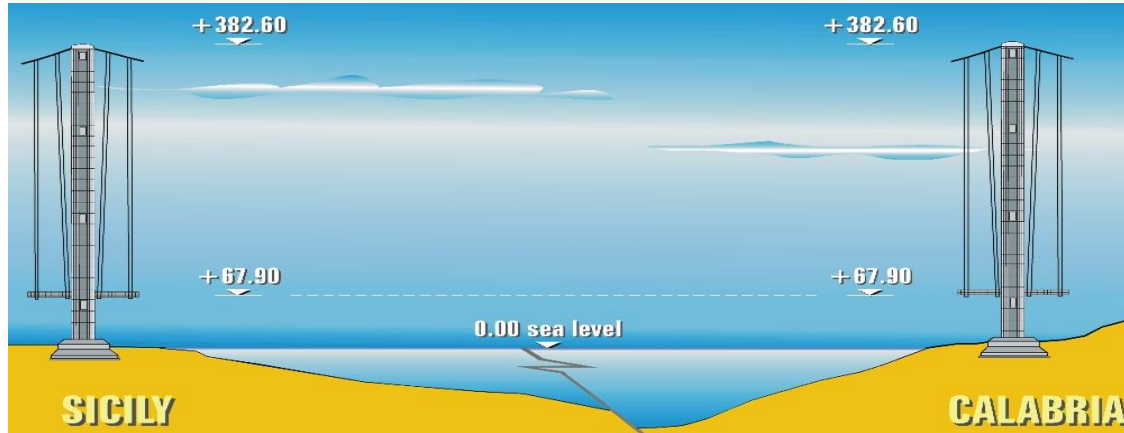


Applicazioni tipiche della tecnica

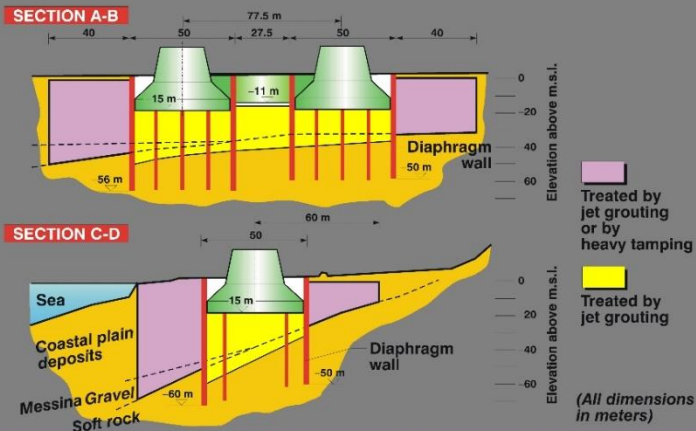


Applicazioni innovative

Protezione dalla liquefazione
L'esempio del ponte sullo stretto di Messina



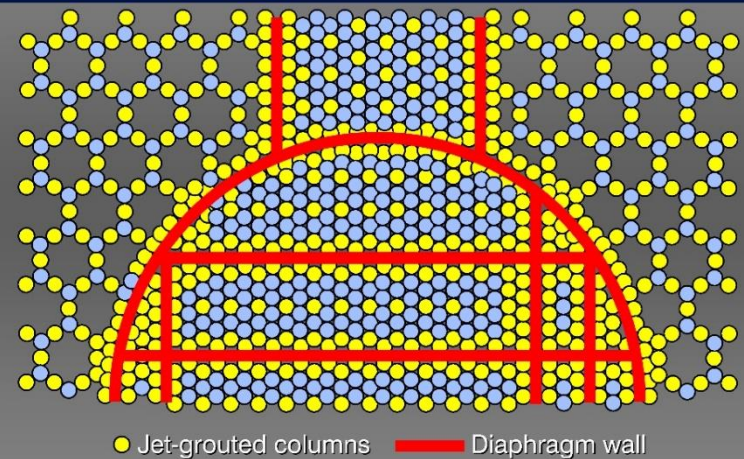
ONE-SPAN SUSPENSION BRIDGE OVER MESSINA STRAITS TOWER FOUNDATION ON CALABRIAN SHORE



G-106

ZUR-12

ONE SPAN SUSPENSION BRIDGE OVER MESSINA STRAITS TOWERS FOUNDATIONS - JET-GROUTING TREATMENT SCHEME

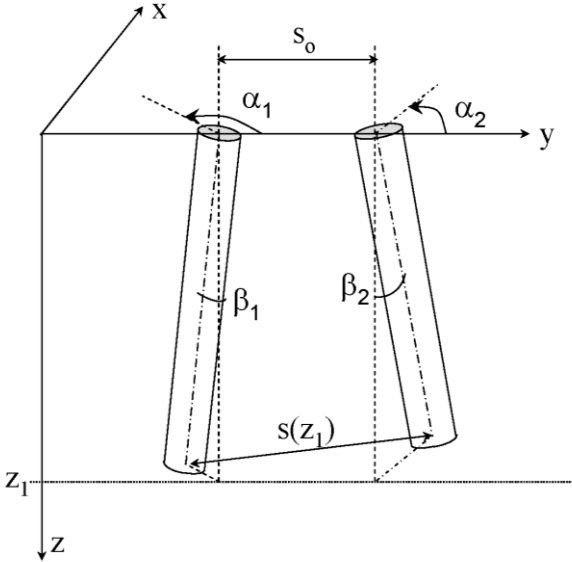
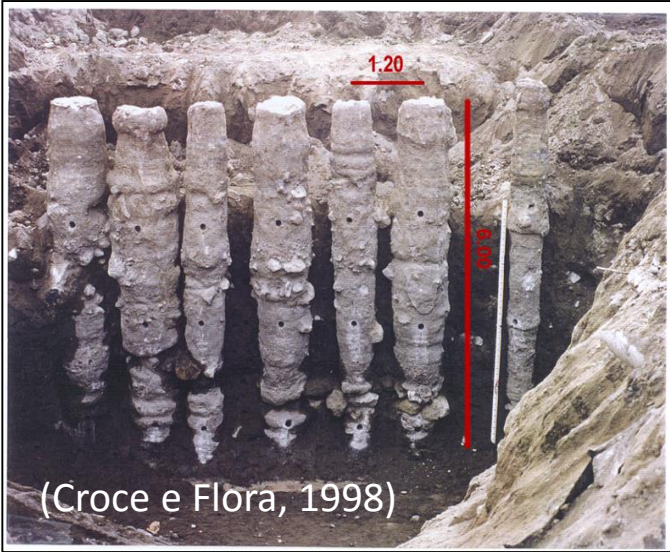


A-142

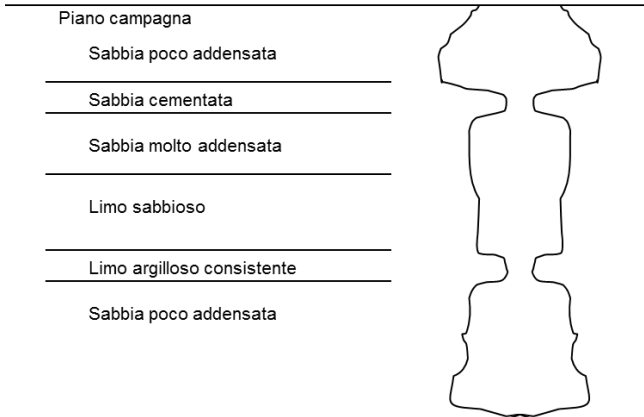
MES-24

DIFETTI DELLE COLONNE

Difetti di tipo casuale



Difetti di tipo sistematico



PROGETTO DI STRUTTURE IN JET GROUTING

1. scelta del diametro medio della colonna singola
2. stima dei difetti previsti (diametro, posizione, composizione) e dei possibili effetti collaterali
3. Applicazione dei metodi classici dell'ingegneria tenendo conto dei passi 1 e 2.

Principalmente legati a:

- posizionamento macchine
- parametri di trattamento
- procedura esecutiva

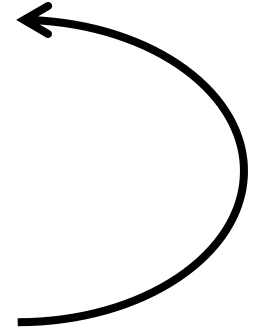


Possono essere risolti (o comunque) in modo relativamente facile

- posizione asse
- variabilità del diametro
- variabilità proprietà meccaniche



Difficili da evitare. Da considerare necessariamente in fase di progetto



APPROCCIO DETERMINISTICO O SEMIPROBABILISTICO

PROPRIETA' GEOMETRICHE E MECCANICHE DELLE SINGOLE COLONNE

Dimensioni:

- Diametro

EC7: when deviations in geometrical data have a significant effect, design values of geometrical data (a_d) shall be either assessed directly (not possible in our case) or be derived from the nominal values as:

$$a_d = a_{\text{nom}} \pm \Delta a$$

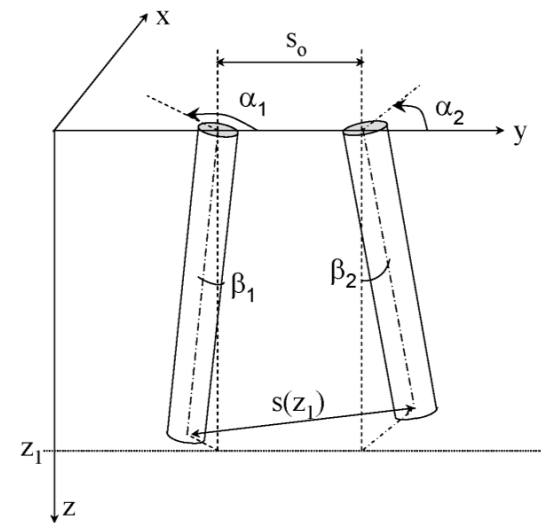
$$D_d = \frac{D_k}{\gamma_D}$$

Posizione dell'asse delle colonne:

- Azimut α
- Inclinazione β

α_d : scelta cautelativa (ma fisicamente realistica),
funzione del problema in analisi

β_d : scelta cautelativa (ma fisicamente
realistica), funzione del problema in analisi



Proprietà meccaniche:

- Resistenza a compressione semplice (σ_c) oppure coesione e angolo di attrito (c, φ)
- Rigidezza (E, G)

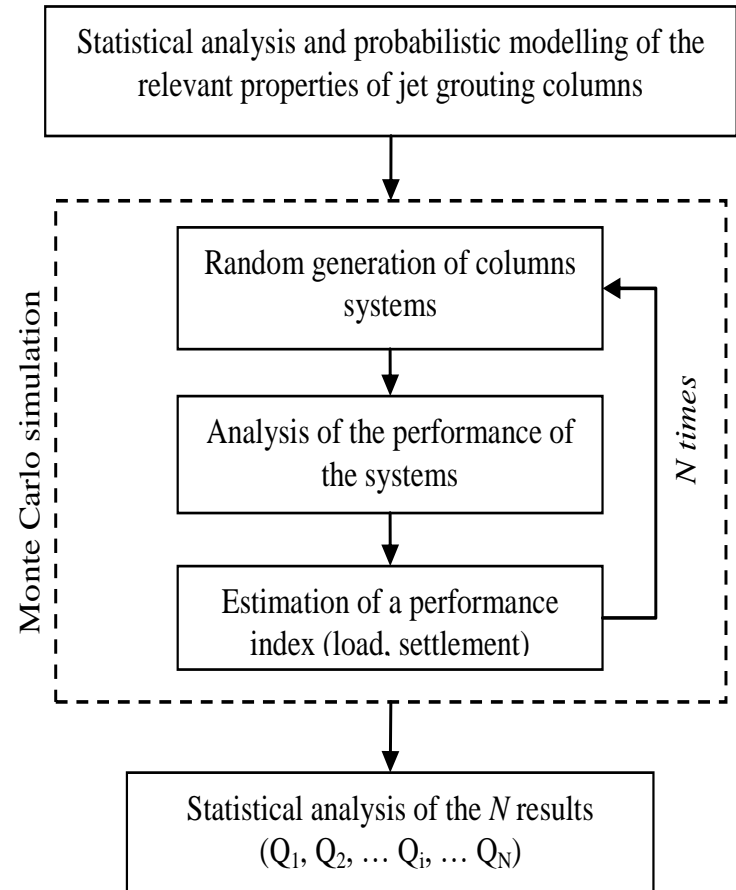
$$\sigma_{c,d} = \frac{\sigma_k}{\gamma_\sigma}$$

APPROCCIO PROBABILISTICO

Con le strutture tipiche dell'ingegneria civile è molto comodo l'uso della tecnica di analisi cosiddetta "Monte Carlo".

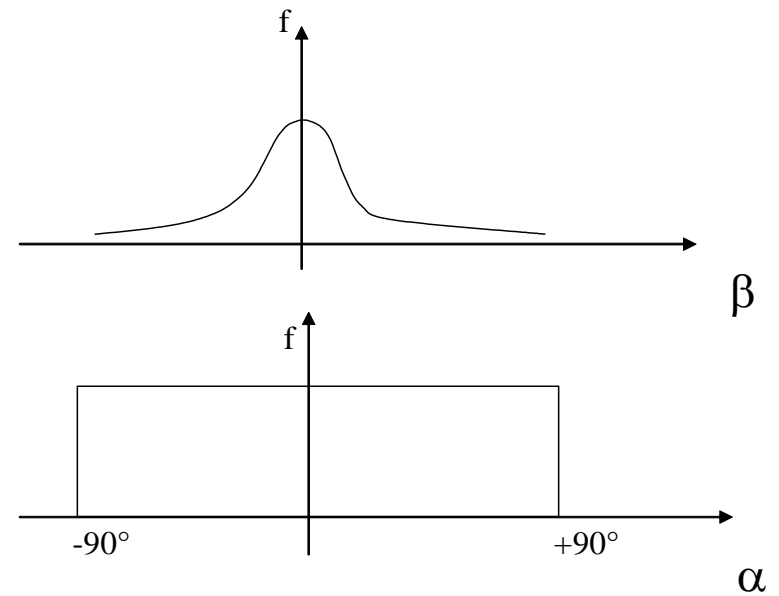
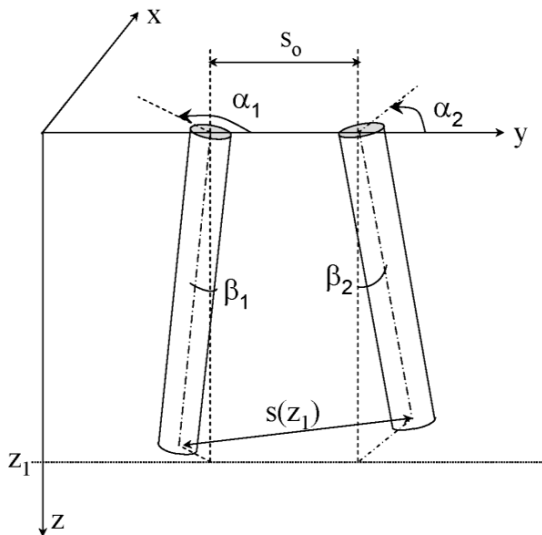
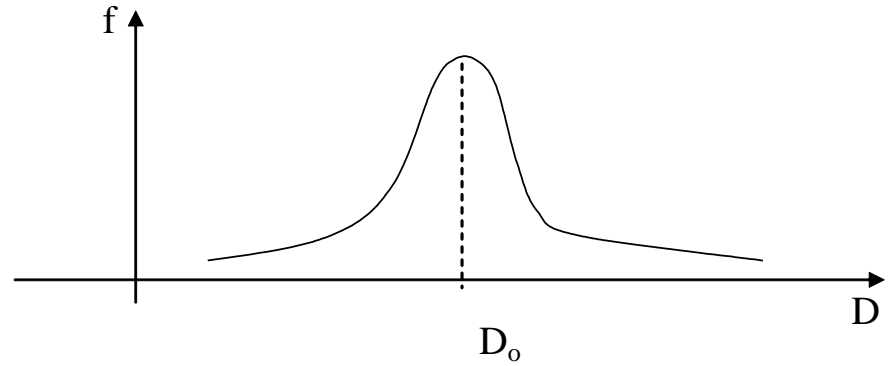
Il metodo Monte Carlo:

1. Definire le variabili casuali (D_{col} , α , β)
2. Quantificare i parametri statistici
3. Generare un insieme di variabili casuali
4. Valutare il problema deterministicamente
5. Estrarre informazioni probabilistiche da N valutazioni



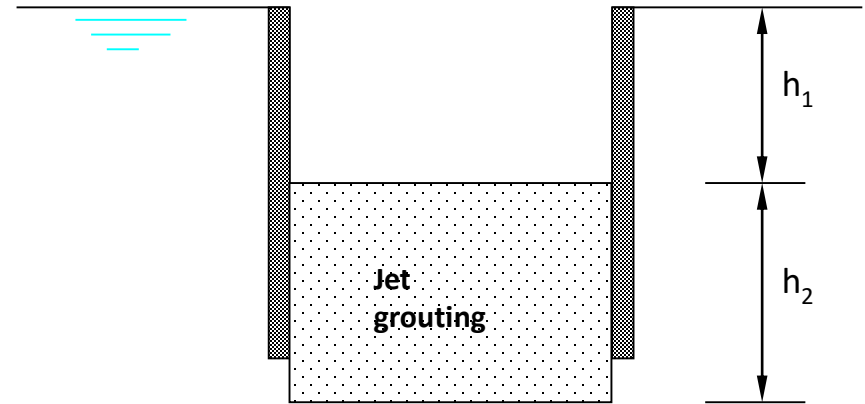
APPROCCIO PROBABILISTICO

Necessario stimare le leggi di distribuzione del diametro (D) e dell'inclinazione (α, β)



UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

Struttura continua realizzata con colonne parzialmente sovrapposte in modo da trattare completamente un volume di terreno per renderlo impermeabile e resistente



Utile per:

- impermeabilizzazione
- Sostegno strutturale

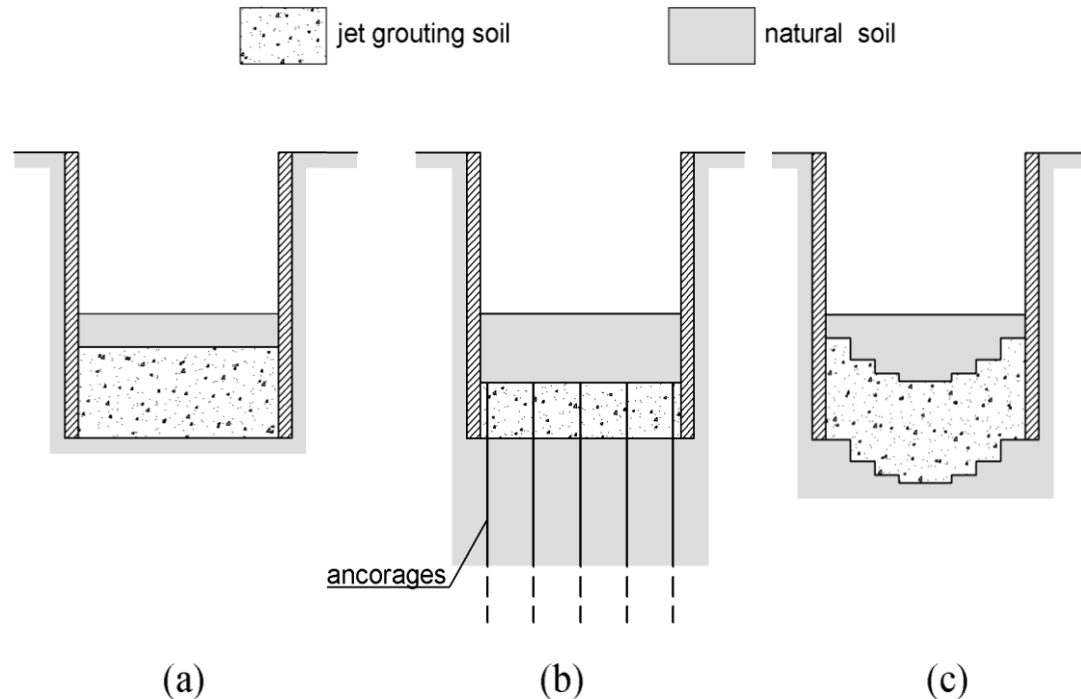
Obiettivi del progetto:

- $h_2 > 0$ (impermeabilità)
- Resistenza alla sottospinta ($\Gamma_u > 1$)

UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

L'obiettivo di resistere alla sottospinta dell'acqua sottostante con un volume di terreno completamente trattato potrebbe essere troppo gravoso dal punto di vista economico. Esistono quindi possibili schemi alternativi:

- a) terreno non trattato al di sopra del tampone (molto frequente)
- b) tiranti di fondo (possibile ma complesso)
- c) struttura sagomata per resistere meglio alle sottospinte (possibile)

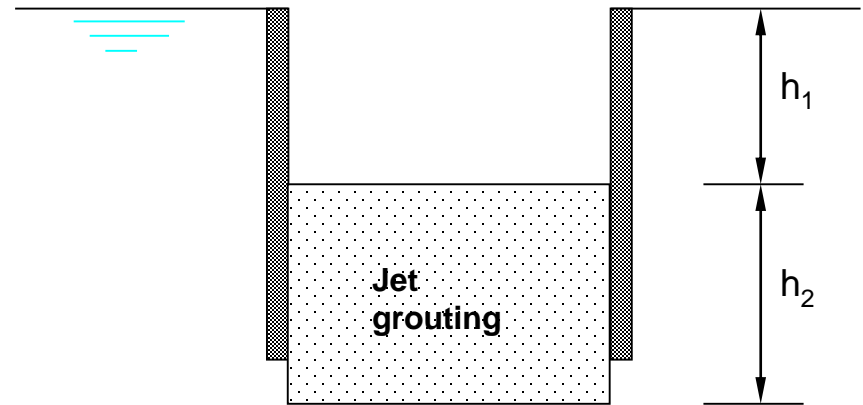


UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

Il tappo di fondo è una struttura che deve garantire l'impermeabilità (in teoria) e resistere alle sottospinte dell'acqua.

Il progetto di questa struttura si pone l'obiettivo di determinare lo spessore h_2 tale che:

$$V_d \leq G_d + R_d$$



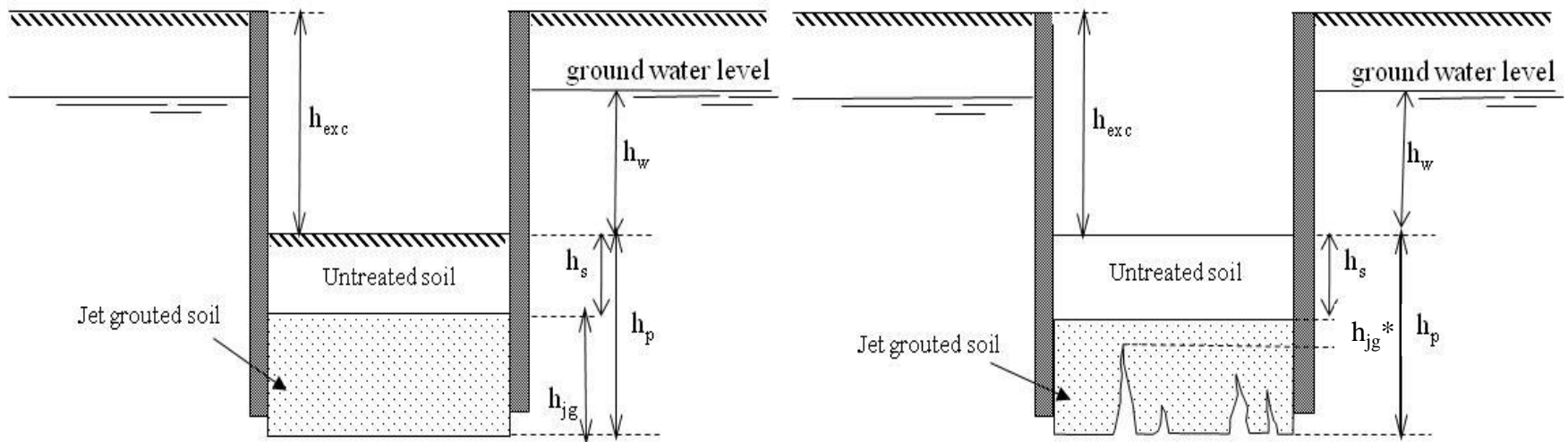
Con V azione instabilizzante (sottospinta), G contributo stabilizzante per peso proprio e R contributo stabilizzante dovuto agli sforzi di taglio all'interfaccia tra il tappone e la struttura di sostegno. Si può anche scrivere:

$$\Gamma \cdot V_d = G_d + R_d$$

$$\Gamma = \frac{G_d + R_d}{V_d}$$

UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

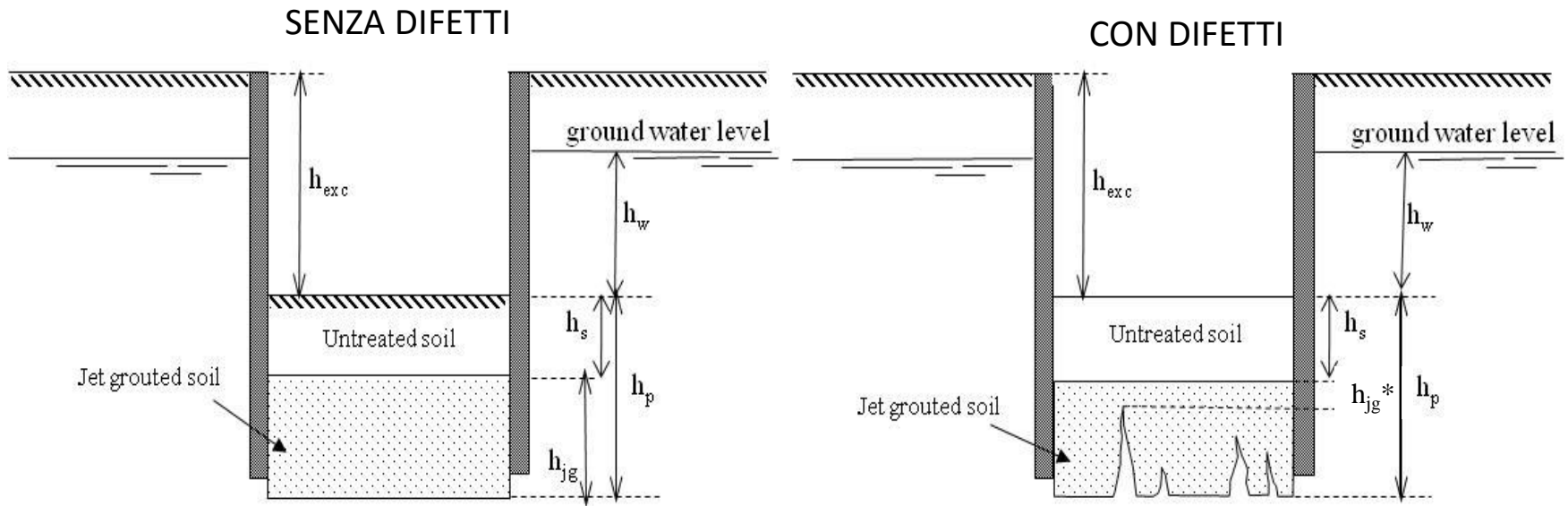
Consideriamo il caso più logico e generale: tampone di fondo non completamente trattato. Il problema di progetto è determinare i valori di h_{jg} e h_s (vedi figura sottostante) tali che la struttura resista alla sottospinta e sia impermeabile. IL MINORE SPESSORE DELLA PARTE TRATTATA AUMENTA IL RISCHIO DI INEFFICIENZA DELLA STRUTTURA.



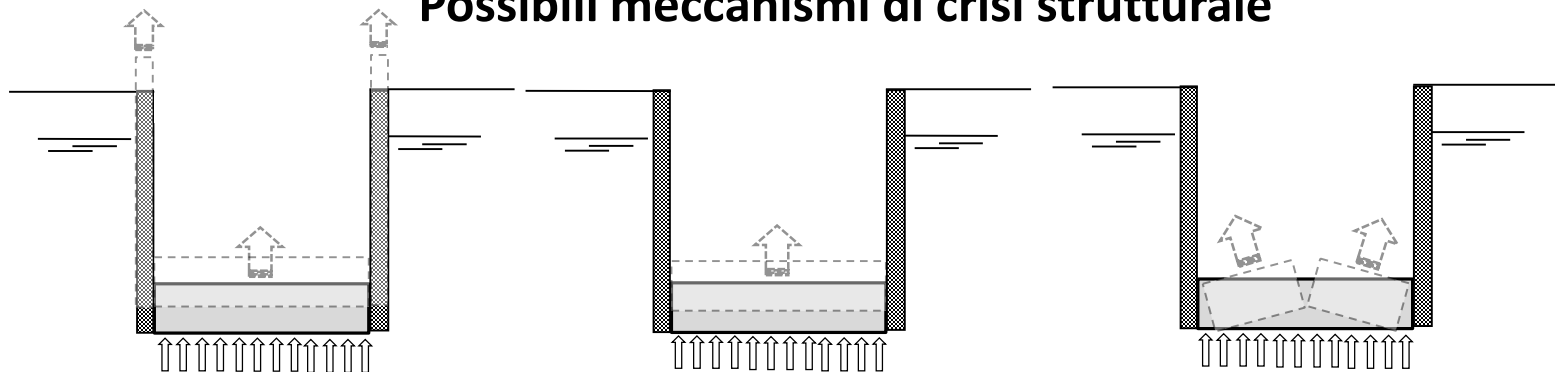
La presenza di difetti fa sì che la reale altezza trattata sia diversa e minore della ideale ($h_{jg}^* < h_{jg}$), e che comunque ci sia il rischio di parti non trattate passanti (Perdita di impermeabilità). Bisogna considerarne l'effetto dal punto di vista dell'equilibrio e dell'eventuale afflusso di acqua all'interno dello scavo.

UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

Equilibrio al sollevamento



Possibili meccanismi di crisi strutturale



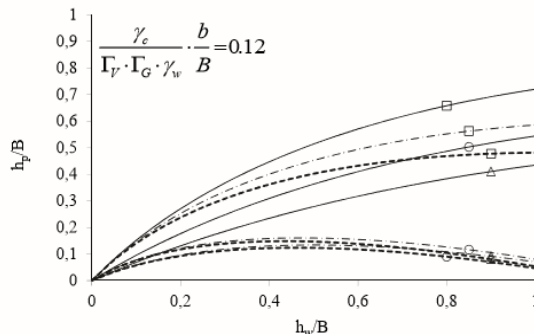
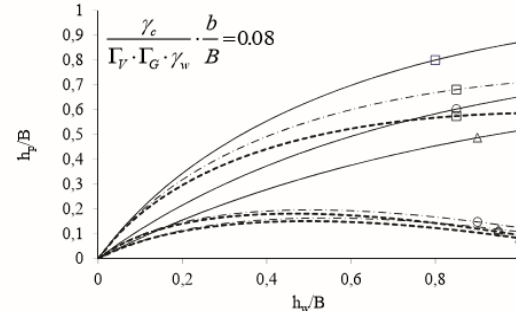
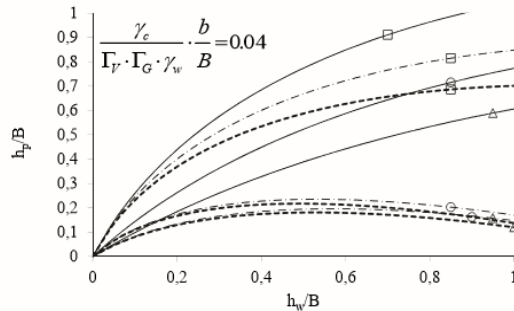
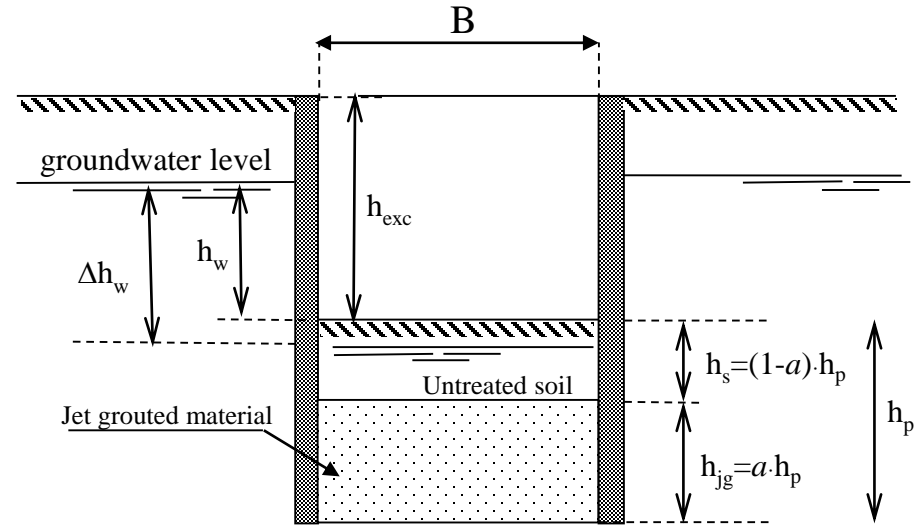
(a)

(b)

(c)

UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

In tamponi ben progettati le condizioni di equilibrio non risultano eccessivamente influenzate dalle variabilità casuali. Si può quindi procedere al progetto con un semplice approccio deterministico.



- $k_s \cdot \tan \phi'_a \cdot \frac{\gamma'_s}{\Gamma_V \cdot \Gamma_R \cdot \gamma_w} = 0.15$ □ $\frac{\gamma_{jg}}{\Gamma_V \cdot \Gamma_G \cdot \gamma_w} = 1.2$
- - $k_s \cdot \tan \phi'_a \cdot \frac{\gamma'_s}{\Gamma_V \cdot \Gamma_R \cdot \gamma_w} = 0.20$ ○ $\frac{\gamma_{jg}}{\Gamma_V \cdot \Gamma_G \cdot \gamma_w} = 1.5$
- · - $k_s \cdot \tan \phi'_a \cdot \frac{\gamma'_s}{\Gamma_V \cdot \Gamma_R \cdot \gamma_w} = 0.25$ △ $\frac{\gamma_{jg}}{\Gamma_V \cdot \Gamma_G \cdot \gamma_w} = 1.8$

UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

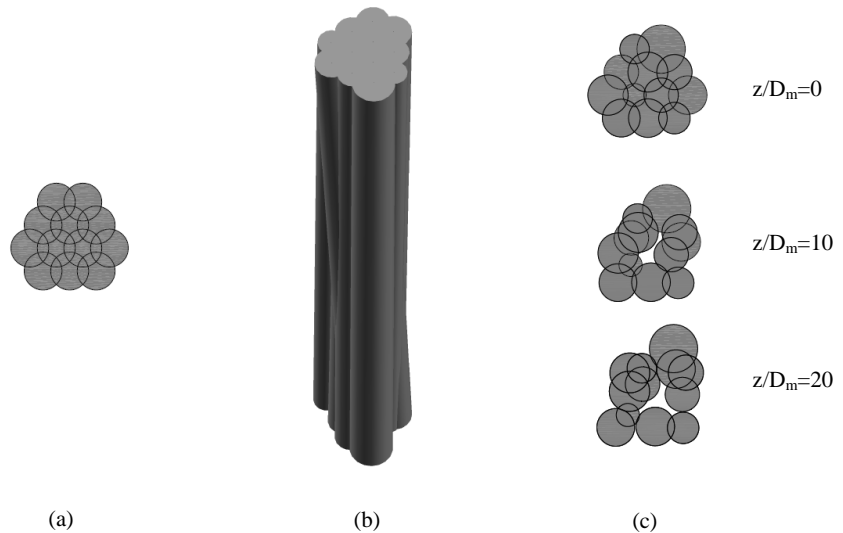
Problema idraulico: è necessaria l'impermeabilità?

Se ci sono difetti può succedere che passi acqua. Il che non è necessariamente un problema, se la portata entrante è gestibile in cantiere. Bisogna stimare la portata entrante nel caso in cui ci sia qualche "buco". Questo può essere fatto con la relazione:

$$Q = k \cdot j \cdot (1 - F_{\min}(z)) \cdot A_p$$

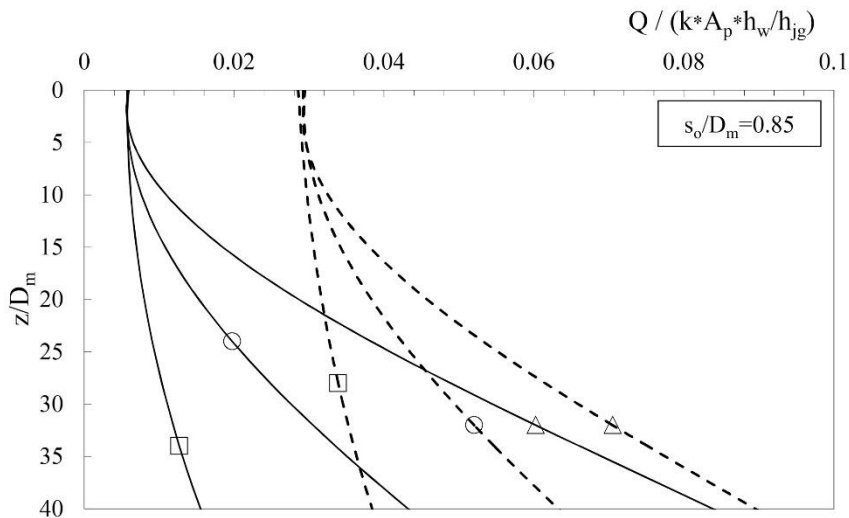
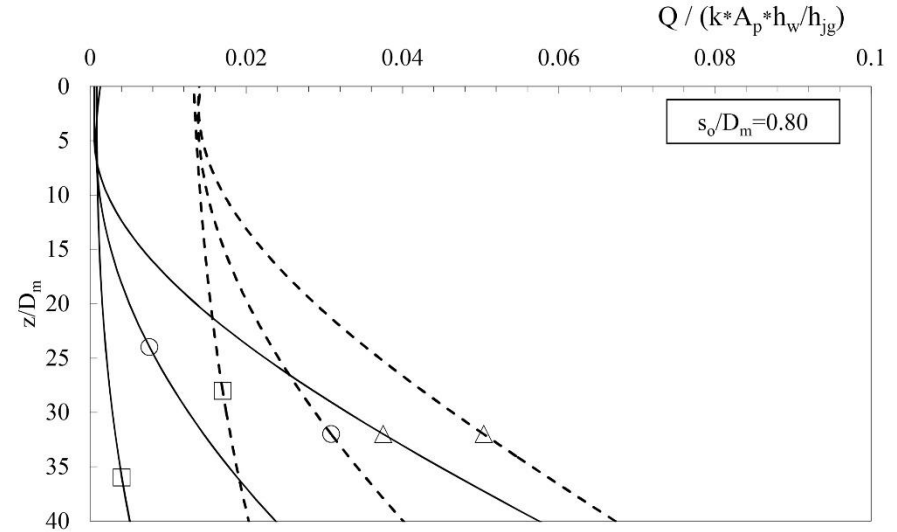
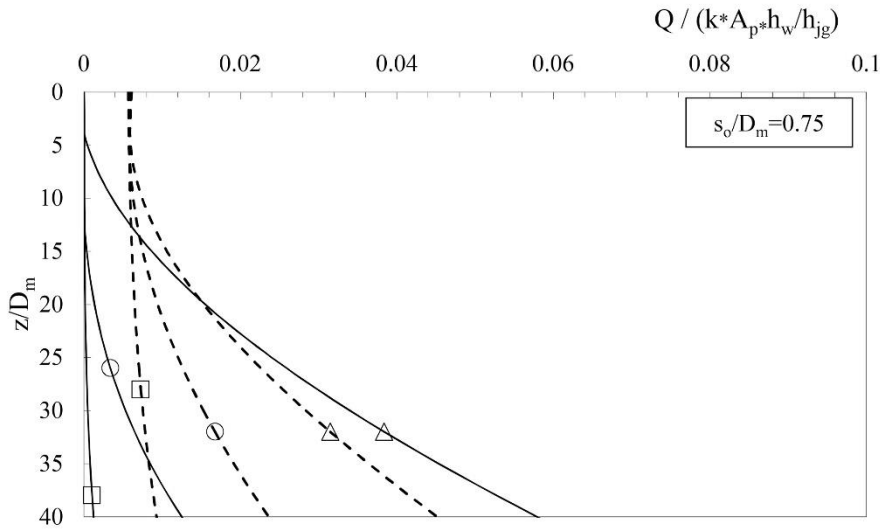
In cui $F_{\min}(z)$ è il fattore di riempimento alla profondità dell'estradosso della parte di tampone trattata, e k è il coefficiente di permeabilità del terreno.

La funzione F può essere calcolata con la procedura Monte Carlo e associata ad un livello di rischio e a valori dei parametri statistici per il diametro e la posizione delle colonne, nonché a valori del rapporto tra interasse e diametro delle colonne in superficie (s_o/D_m). Qui a fianco l'esempio per un gruppo di 12 colonne

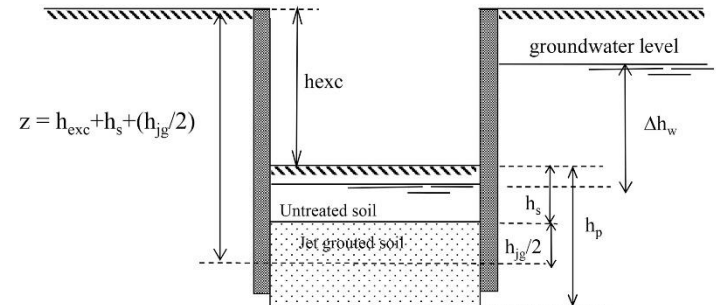


UN ESEMPIO: IL PROGETTO DEL TAMPONE DI FONDO

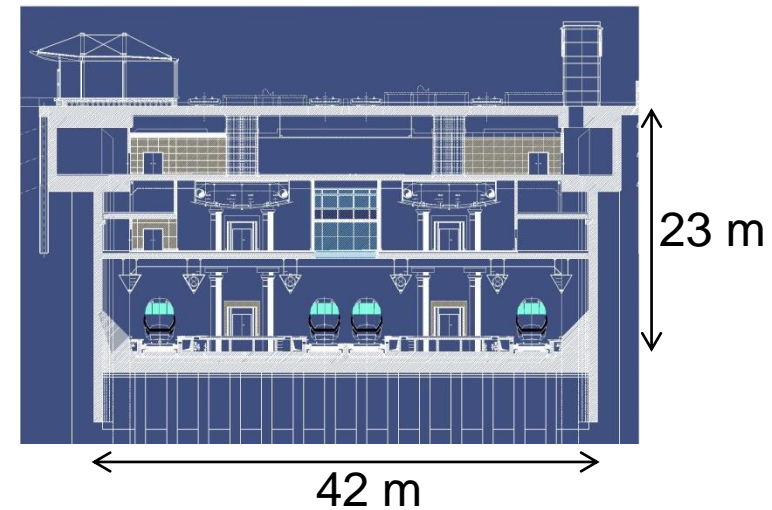
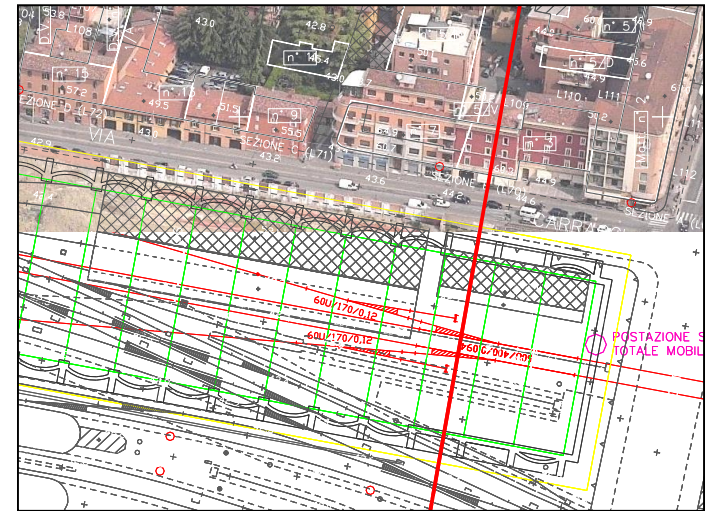
Problema idraulico: è necessaria l'impermeabilità?



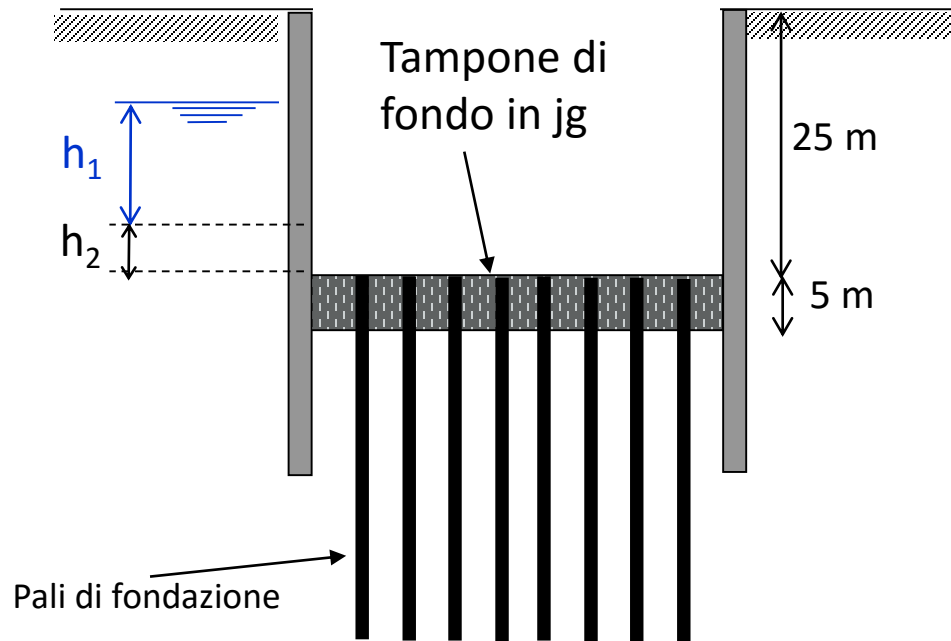
CV(D)	DS(β) ($^\circ$)
0.1	□ 0.1
0.2	○ 0.2
	△ 0.3



Il caso di un grande tampone di fondo



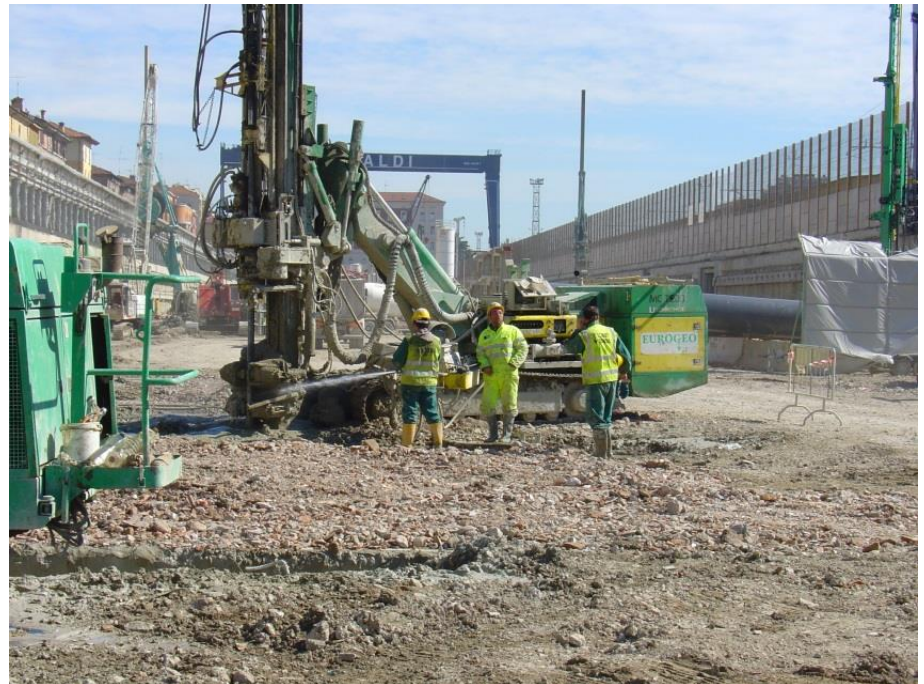
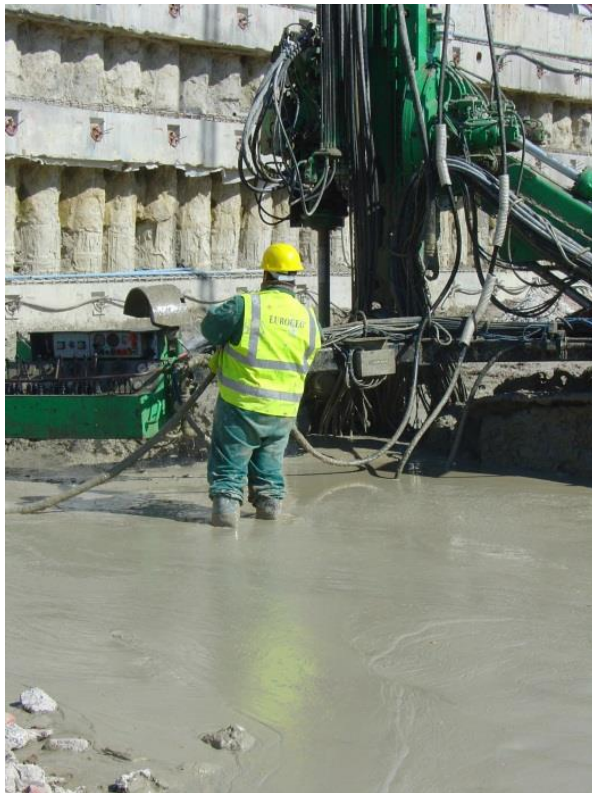
Il caso di un grande tampone di fondo



SCELTE DI PROGETTO

I pali (concepiti come fondazioni delle strutture da realizzarsi) dovevano aiutare il tampone contro la sottospinta

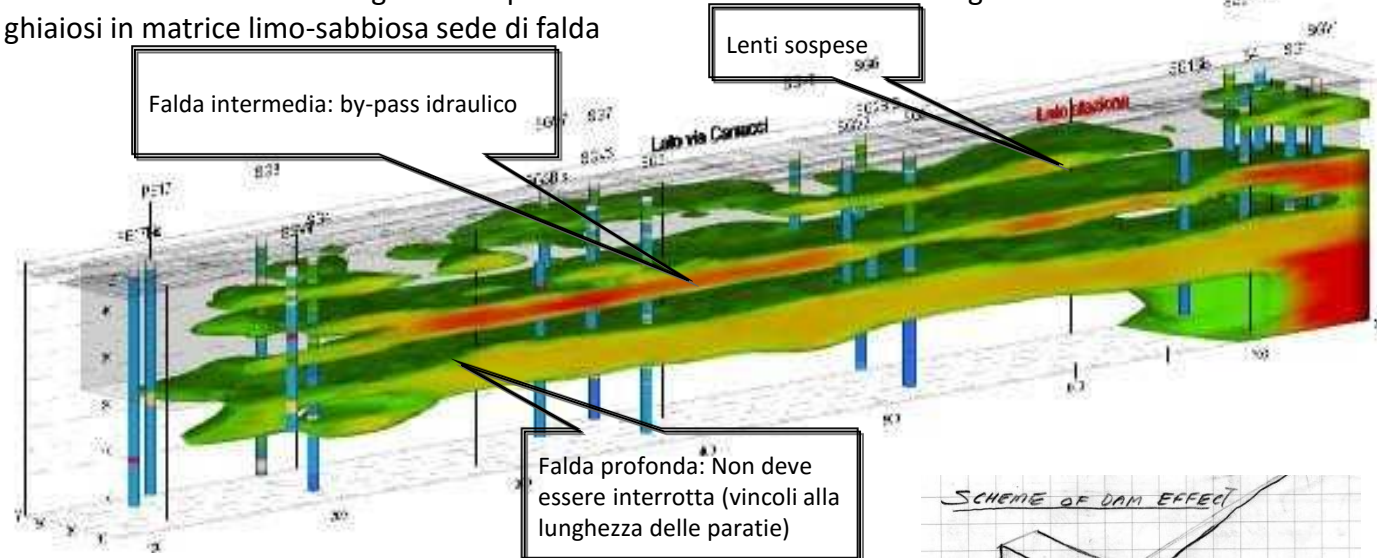
Il caso di un grande tampone di fondo



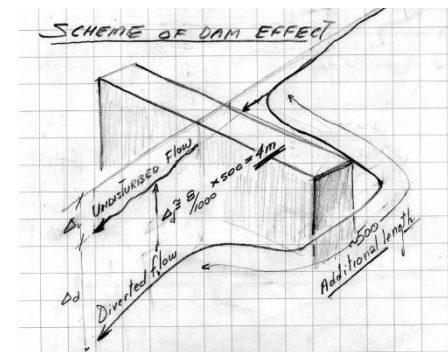
Il caso di un grande tampone di fondo

Il complesso contesto geotecnico e idrogeologico

Prevalenza di terreni limo-argillosi con presenza di livelli e strati di terreno granulare sabbioso-limosi e ghiaiosi in matrice limo-sabbiosa sede di falda

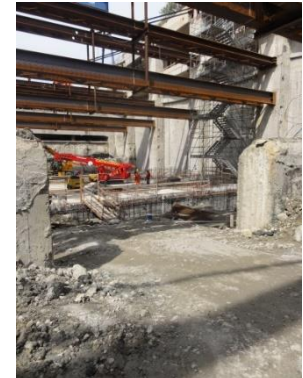


- Lenti superficiali all'interno dei depositi limoso-argillosi.
- Falda intermedia, sabbie limose e sabbie ghiaiose, con livelli piezometrici elevati, (tra $\cong 5.5$ e 11 m).
- Falda profonda, (alternanze di sabbie limose, limi sabbiosi e argille limose)
- Acquifero principale profondo (corpi sabbioso-ghiaiosi)
Riserva idrica Non deve essere interferita



Il caso di un grande tampone di fondo

Alla fine tutto è andato talmente bene da potere effettuare anche visite con gli studenti!



Interventi di rinforzo:

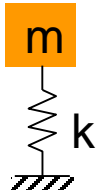
SOFT GROUTING

Summary of presentation

1. Introduction (some basic definitions – only 2 slides!)
2. The problem and the proposed mitigation solution
3. Materials to be adopted
4. Numerical analyses
5. Centrifuge and in situ testing
6. Conclusions?

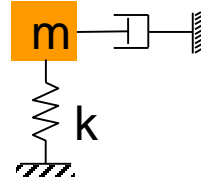
RESPONSE OF A SINGLE DEGREE OF FREEDOM (SDOF) SYSTEM

Natural frequency



Undamped
(no energy dissipation)

$$f = \frac{1}{2\pi} \cdot \left(\frac{k}{m} \right)^{0.5}$$



Damped
(with energy dissipation)

ξ = damping ratio

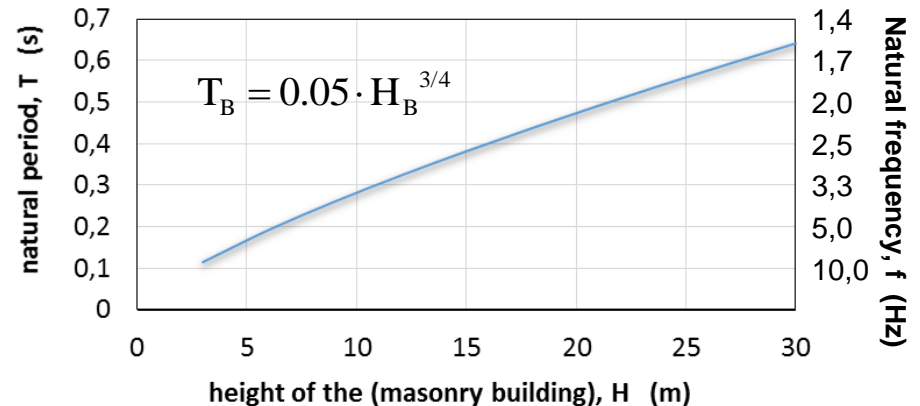
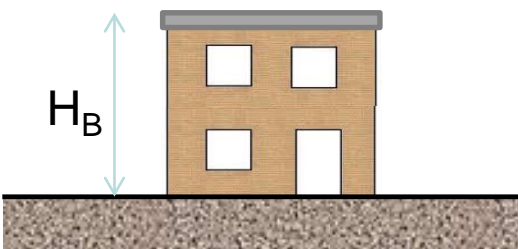
$$f = \frac{1}{2\pi} \cdot \left(\frac{k}{m} \right)^{0.5} (1 - \xi^2)^{0.5}$$

Natural period

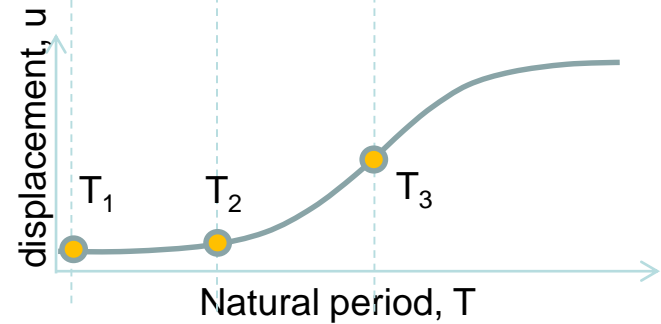
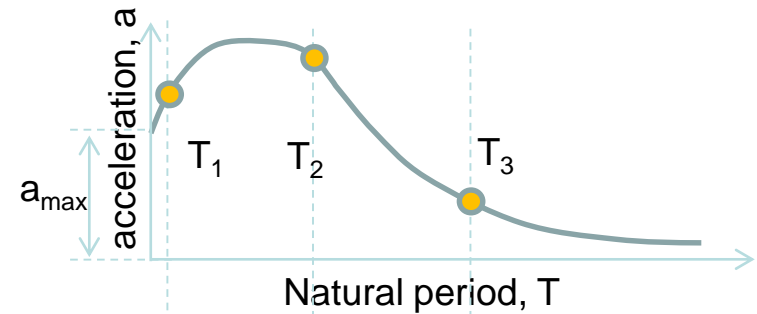
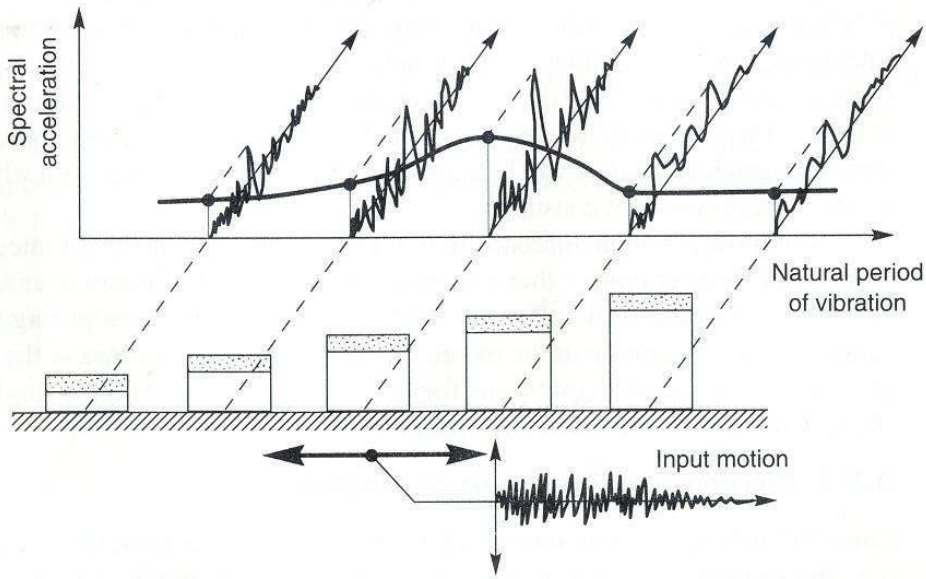
$$T = \frac{1}{f} = \frac{2\pi}{\left(\frac{k}{m} \right)^{0.5}}$$

$$T = \frac{1}{f} = \frac{2\pi}{\left[\frac{k}{m} \cdot (1 - \xi^2) \right]^{0.5}}$$

The natural period T_B (sec) of a masonry building of height H_B (m) can be estimated in a simplified way



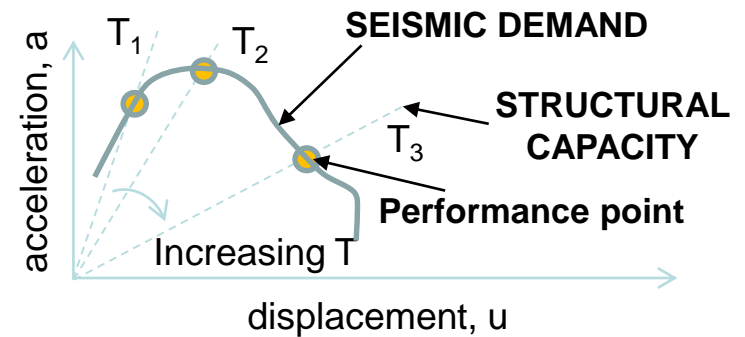
Response spectra (a, v, u) $f(\xi)$



Synthetic parameter

response Spectrum
Intensity (Housner, 1959)

$$SI = \int_{0.1s}^{2.5s} S_v(\xi = 0.05, T) dT$$



EARTHQUAKES AND EXISTING BUILDINGS

The impact of earthquakes on old structures is often dramatic because:

- it usually causes most of the casualties
- relevant historical buildings may be severely damaged



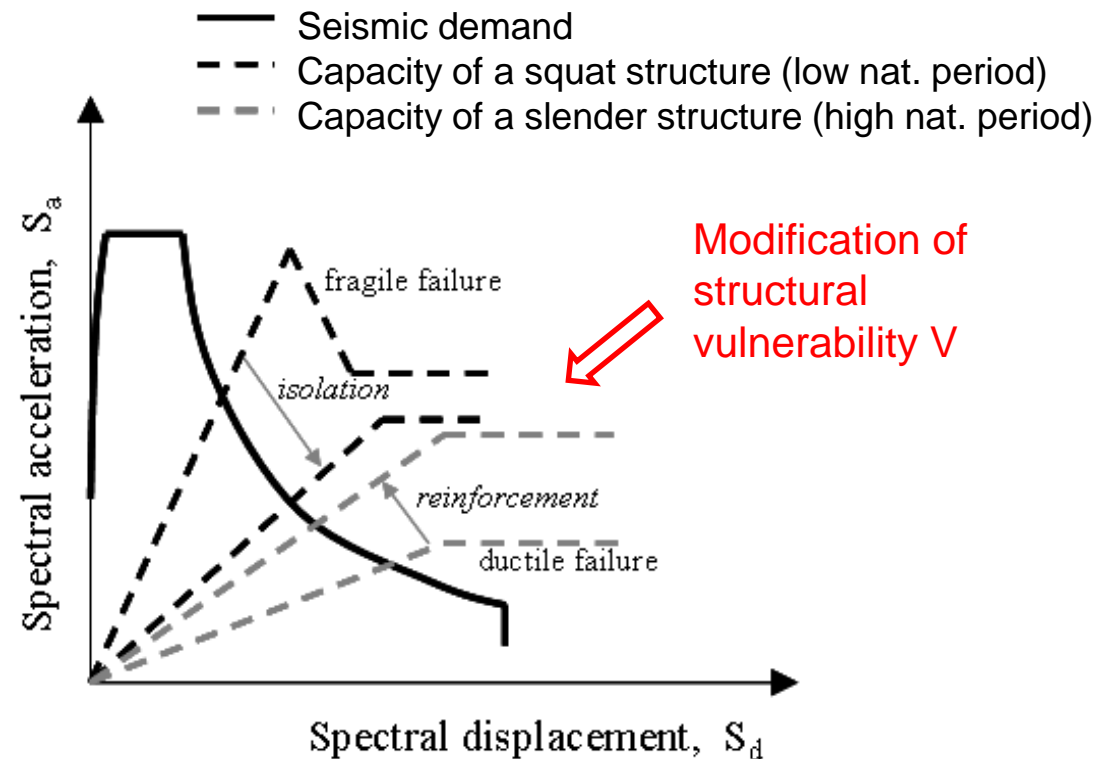
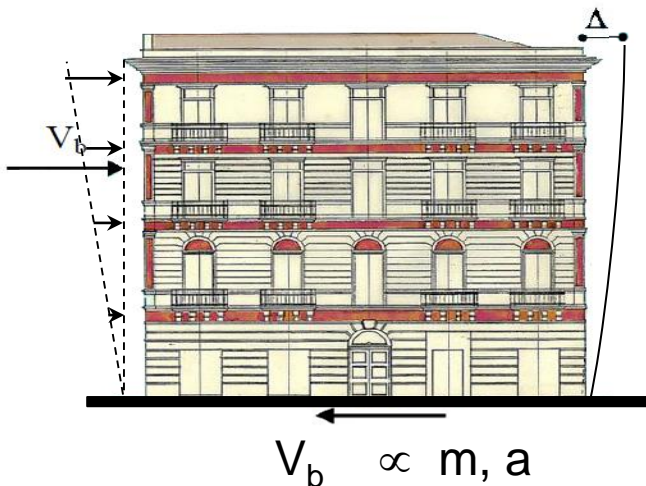
Images from the recent earthquake in Emilia Romagna ($M_w=5.86$, Italy 2012)

CLASSICAL MITIGATION SOLUTIONS

$$R = H \cdot V \cdot E$$

The foremost solution to tackle seismic risk **R** for existing structures is structural retrofitting, i.e. the use of structural or ground modifications aimed at reducing the vulnerability **V**

Typical retrofitting procedures tend to modify the capacity curve to meet the seismic demand with the needed safety factor



PROBLEMS IN USING CLASSICAL MITIGATION SOLUTIONS

- not always effective
- usually expensive
- possible lack of respect of the architectural integrity of the building to be protected



Cathedral of Saint Francis of Assisi (Italy)

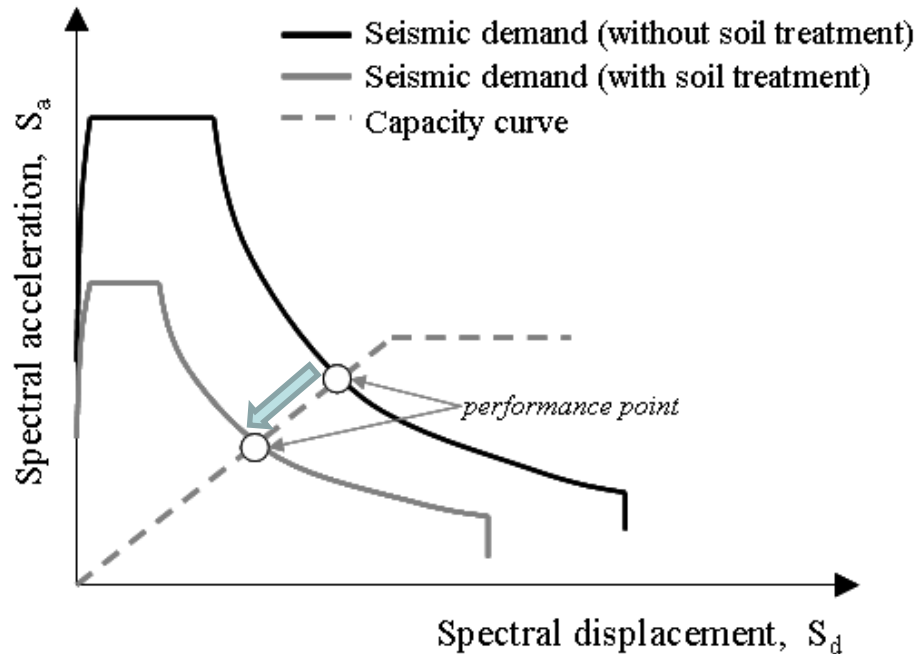


- **Need of new (and possibly less expensive) solutions**
- **Respect of historical and architectural integrity**

DO WE HAVE ANY ALTERNATIVE?

$$R = H \cdot V \cdot E$$

We may try to modify seismic amplification in the upper most part of the subsoil reducing the seismic acceleration, thus mitigating the seismic risk **R** via a reduction of the hazard **H**

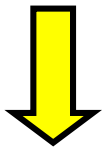


“Geotechnical” way to look at the problem (modification of soil behaviour)

HOW CAN WE DO THAT?



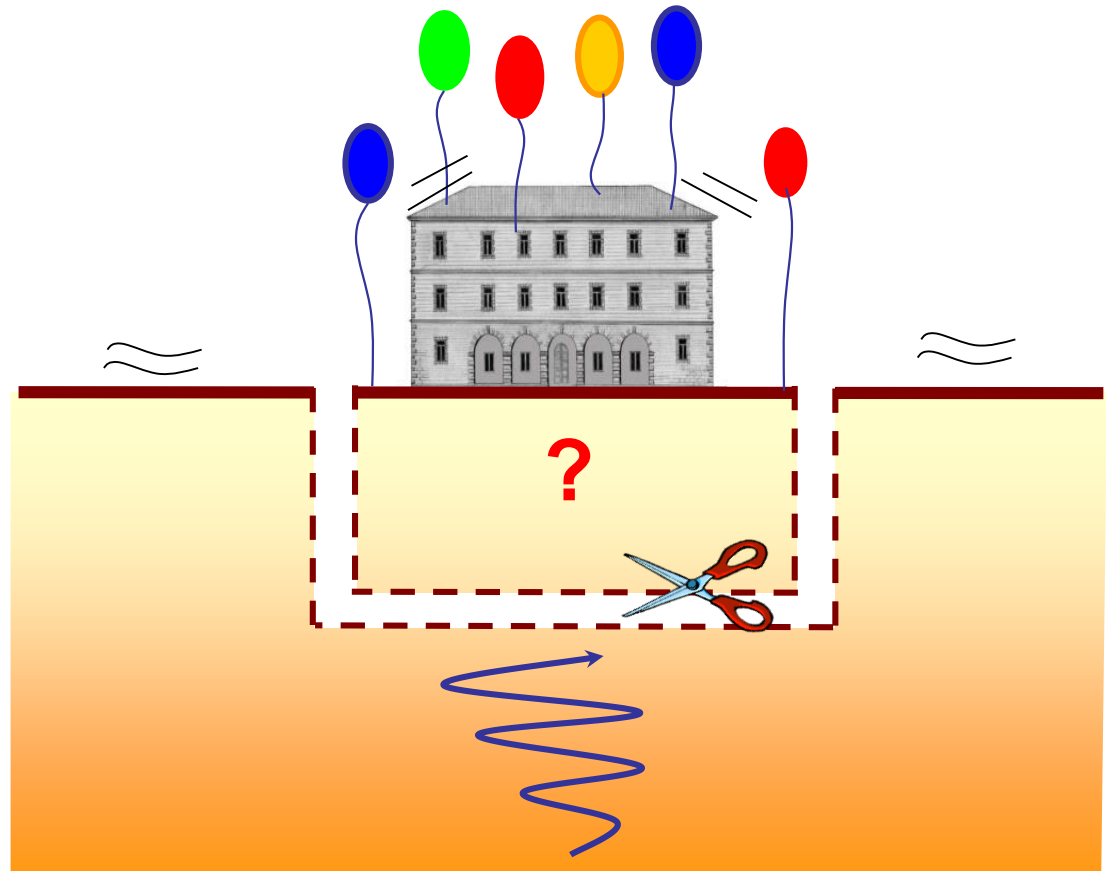
The ideal solution would be a complete disconnection from the shaking subsoil !



Are we able to do it?



Site seismic amplification depends on stratigraphy, which (at least in principle) can be artificially (and locally) modified

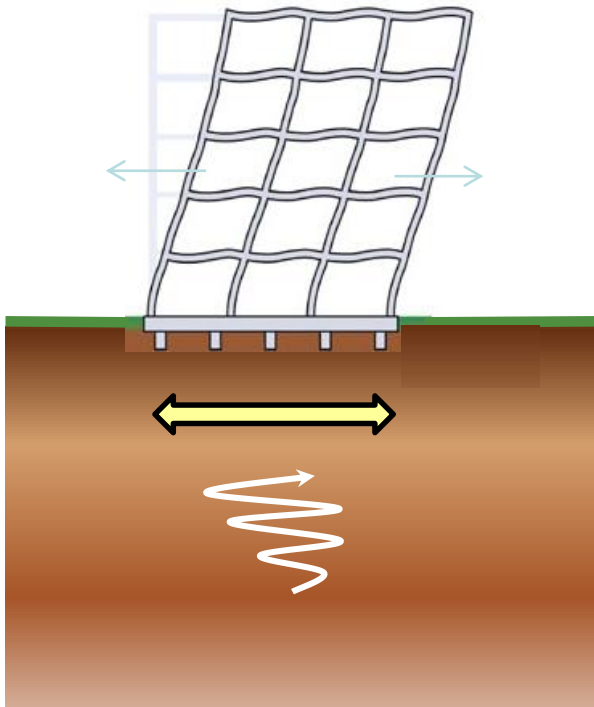


GROUND MODIFICATION

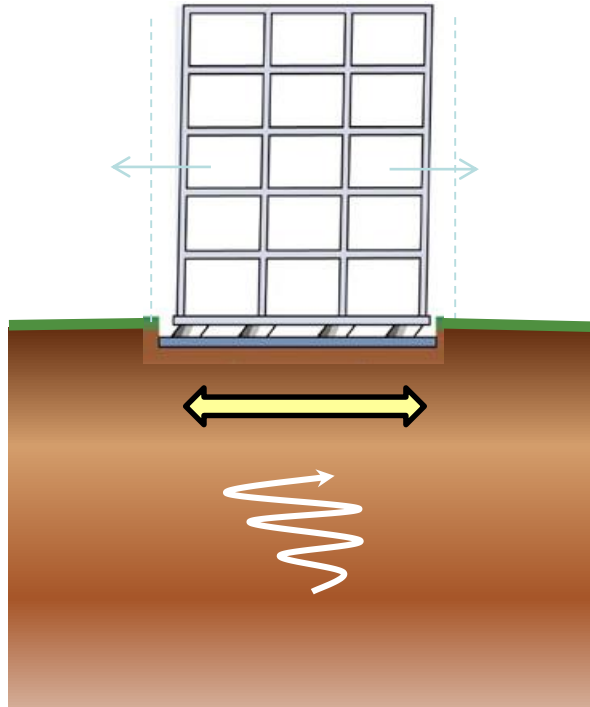
The simplest solution is to insert a thin stratum of 'soft' grouted soil.

HOW CAN WE DO THAT?

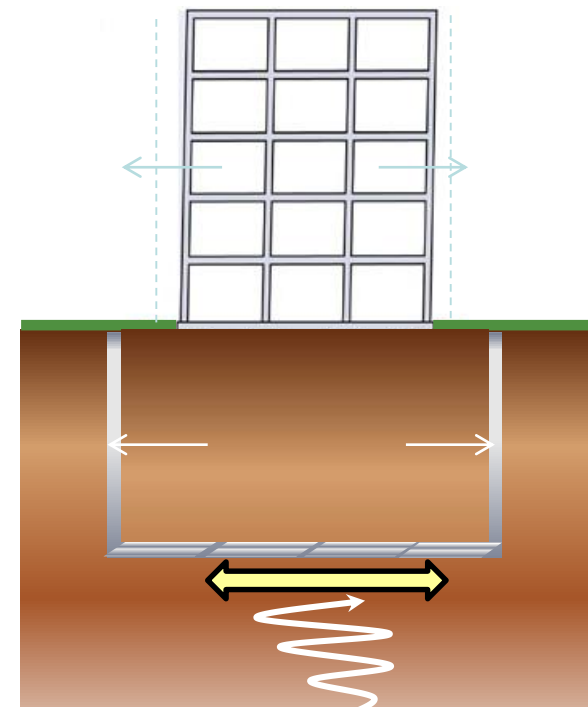
Unprotected building



Structural isolation



Geotechnical isolation



“Structural” way to look at the problem (modification of structural behaviour)



- Reduction of base shear stiffness
- Increase of damping

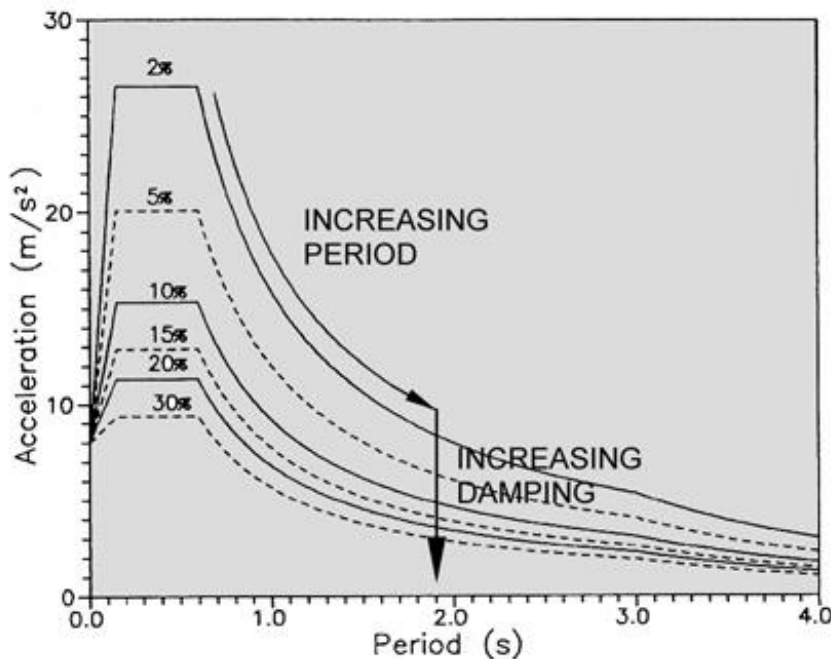
- Reduction of base shear stiffness
- Increase of mass
- Increase of damping

$$R = H \cdot V \cdot E$$

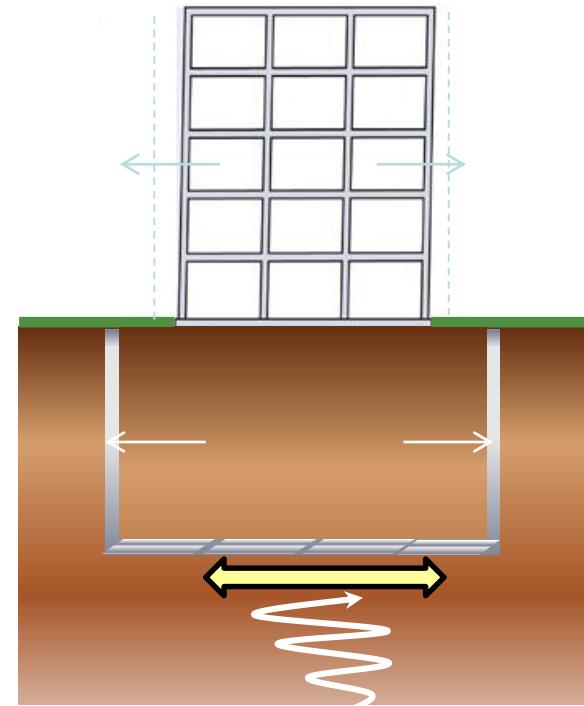
HOW CAN WE DO THAT?

$$R = H \cdot V \cdot E$$

$$T = \frac{1}{f} = \frac{2\pi}{\left[\frac{k}{m} \cdot (1 - \xi^2)\right]^{0.5}}$$



Geotechnical isolation



- Reduction of base shear stiffness
- Increase of mass
- Increase of damping

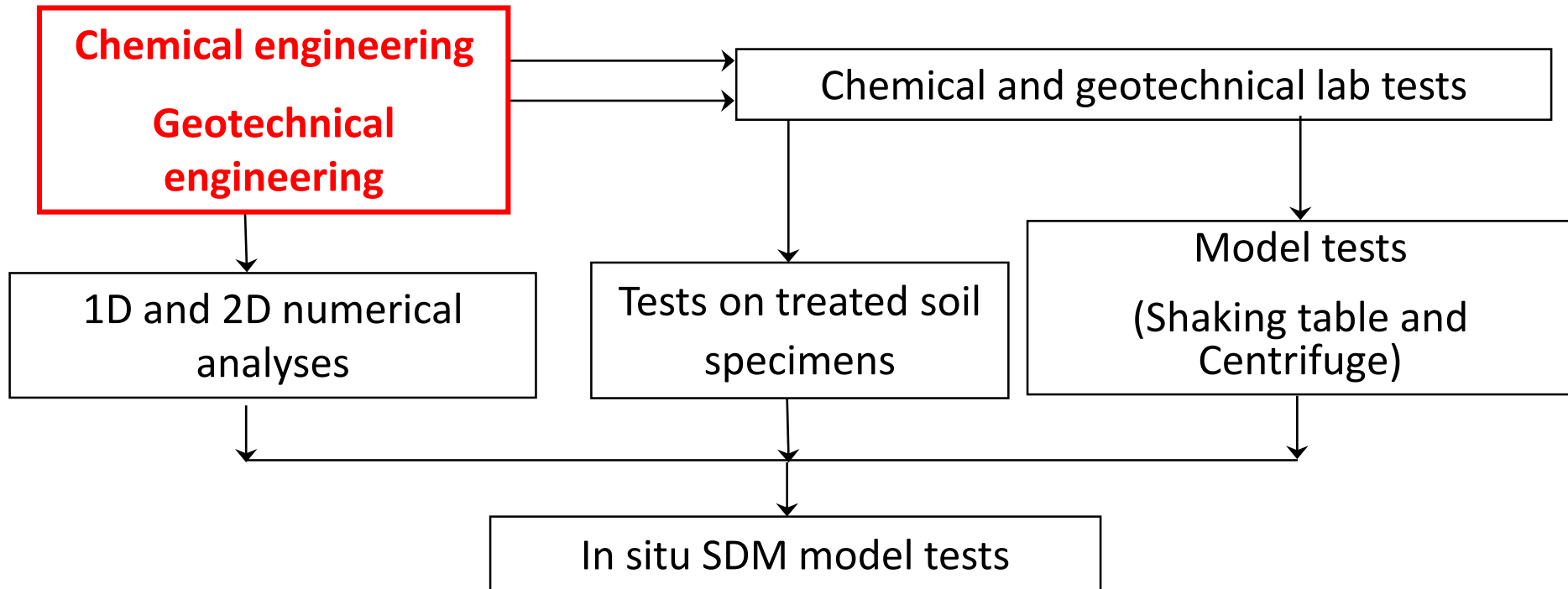
NEW GROUND MODIFICATION APPROACH



Research program under course

WORK IN PROGRESS!

The final goal of this research program is to find a technically feasible solution, going from the modeling stage to the application procedure



MATERIALS FOR THE SOFT GROUTING

Materials having low shear strength and stiffness are being tested, like:

- Viscous fluids (to be placed in situ in rubber “balloons”)
- Water absorbing powders, that in principle can be mixed with the insitu soil in desired percentages

Hydrophilic Polymers (*Super Absorbing Polymers – SAP*)



Dry state:

- Powder Form
- Tunable grain size

Swelling



They absorb water
(up to 200 times their original weight)



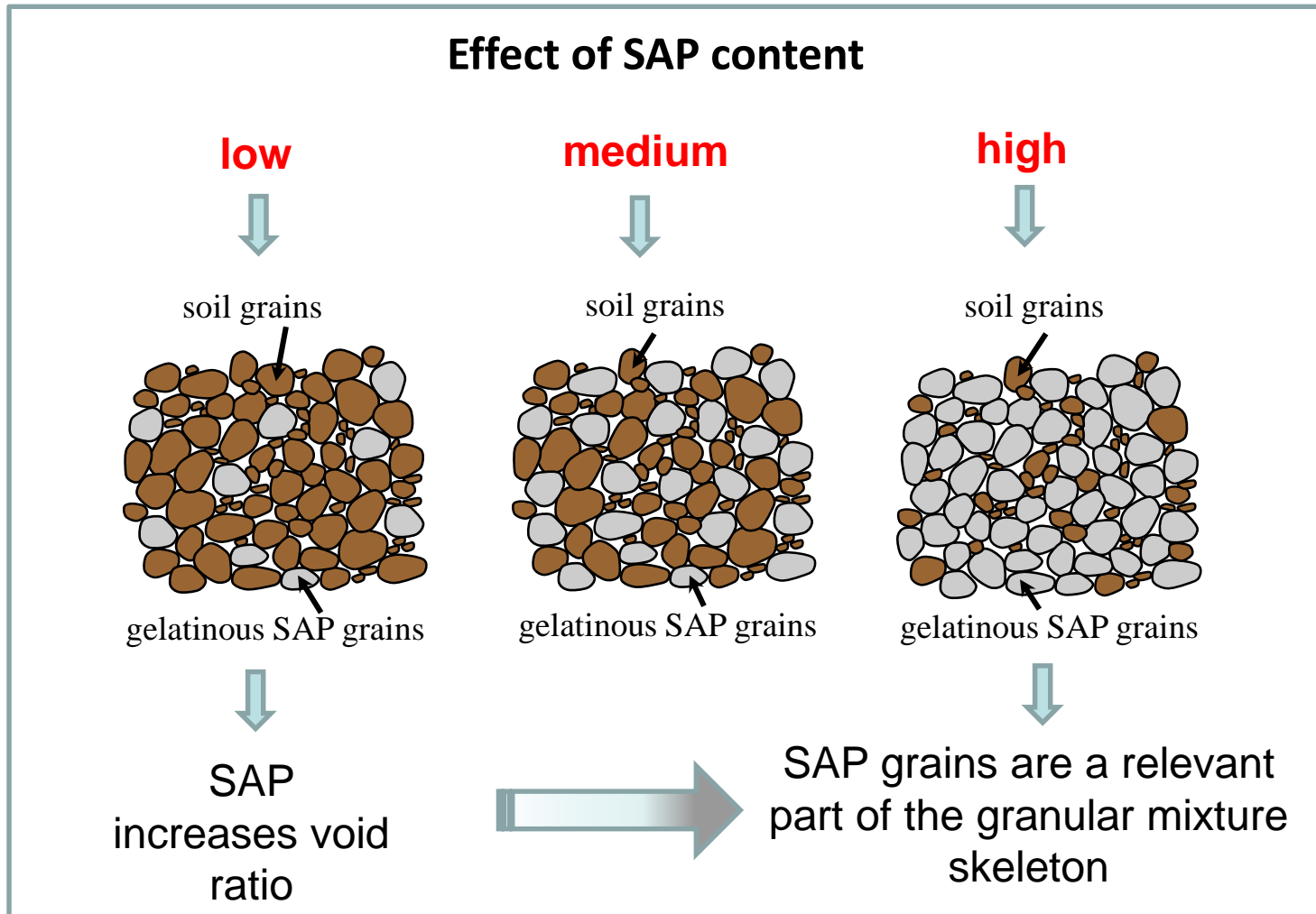
Swelled state:

- Crosslinked gel
- Water like density

Swelling ratio and rate, as well as the capacity of retaining bonded water, depend on polymers chemistry, powder grading, solution ionic strength. **They can be tuned.**

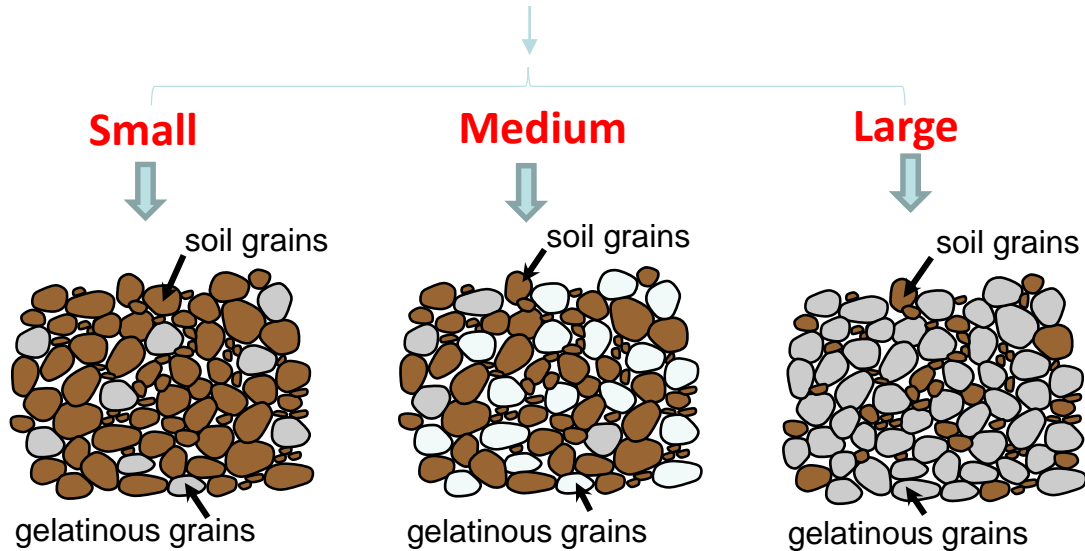
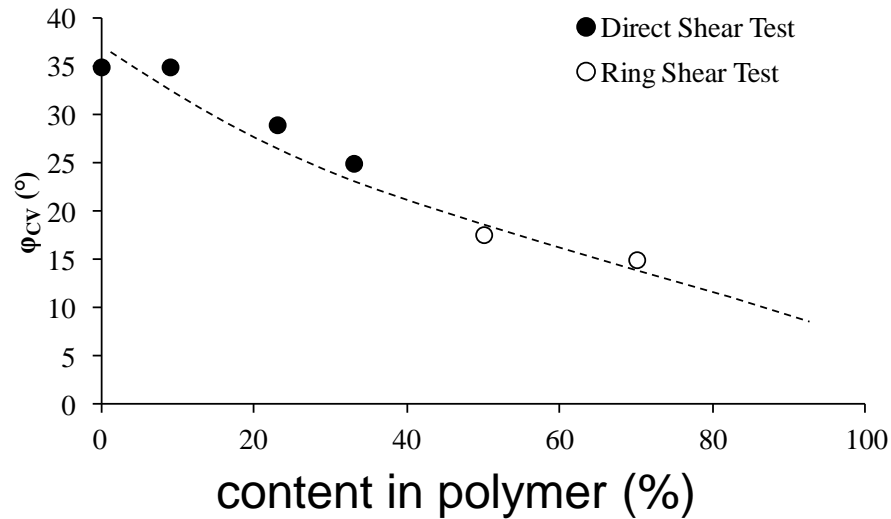
MATERIALS FOR THE SOFT GROUTING

Hydrophilic Polymers (Super Absorbing Polymers – SAP)



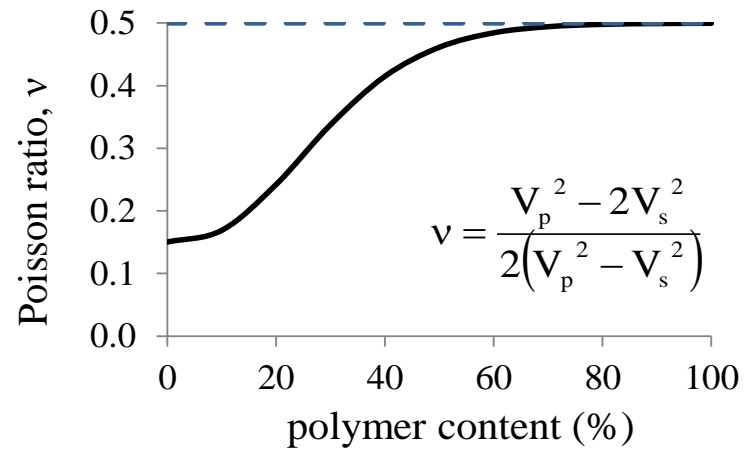
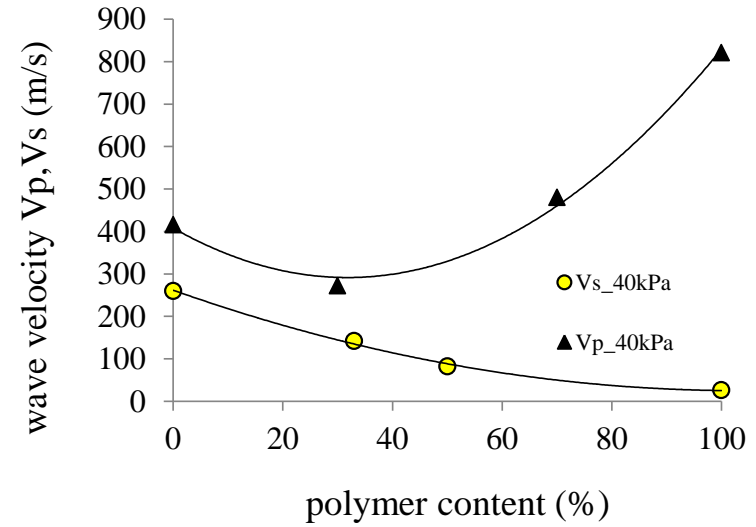
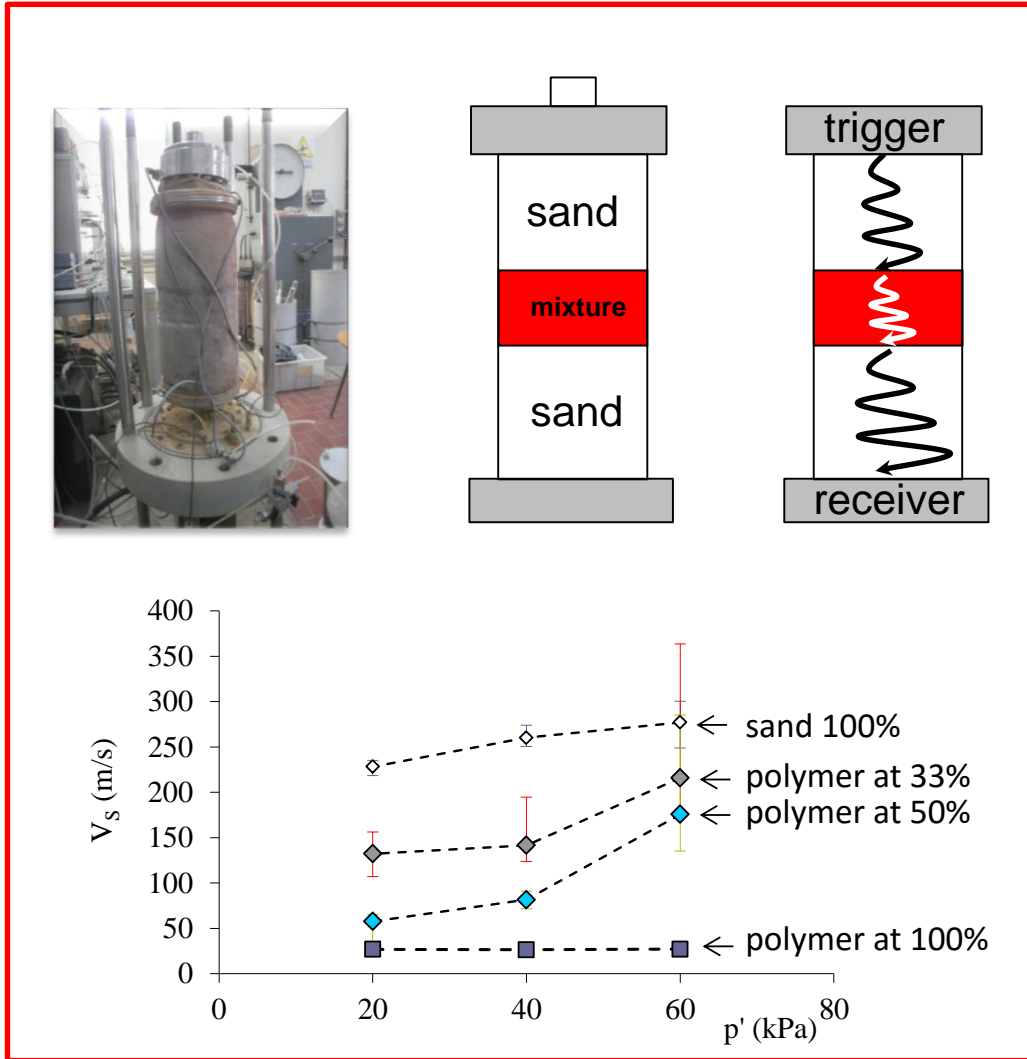
HYDROPHILIC POLYMER (SAP) – lab testing

Shear strength of a sand-SAP mixture



HYDROPHILIC POLYMER (SAP) – lab testing

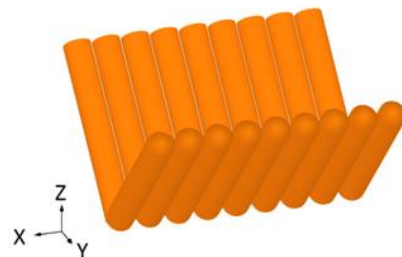
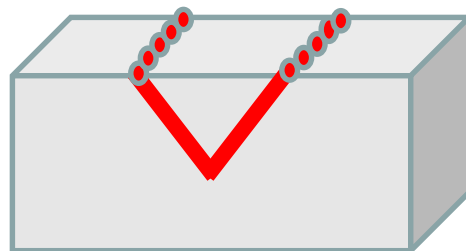
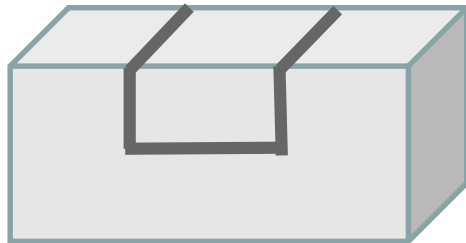
Shear and volumetric stiffness of a sand-SAP mixture



Minimum value (for 100% polymer) $\Rightarrow V_s=26.5 \text{ m/s} \Rightarrow G_0=0.7 \text{ MPa} \quad (\rho=1020 \text{ kg/m}^3)$

NUMERICAL ANALYSES

Analyzed schemes



Tools

- FLAC 7
- PLAXIS 2D

Models

- Elastic
- Elastic - perfectly plastic
- Non linearly elastic – plastic with strain hardening

Seismic inputs

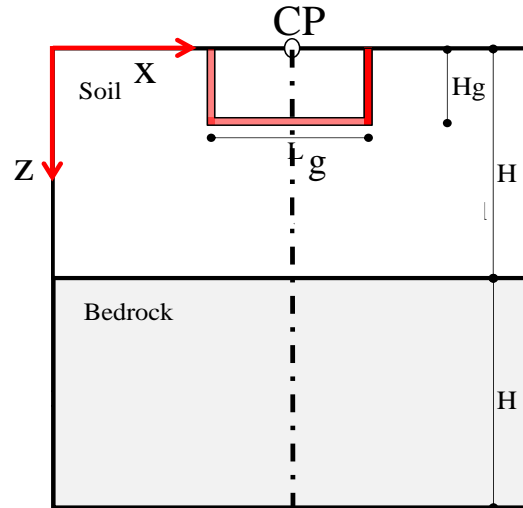
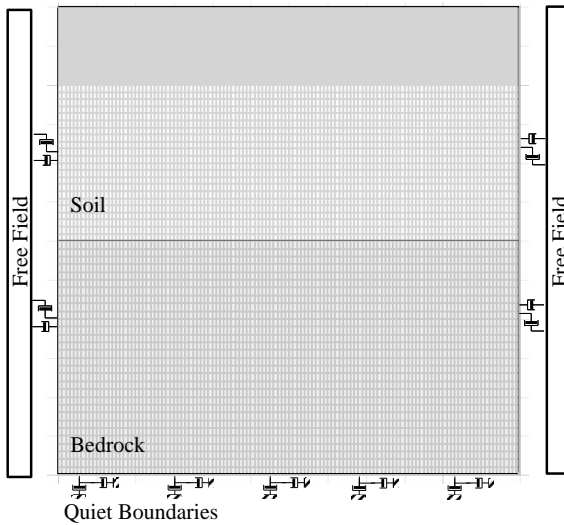
- Ricker wavelets (f_{char} , a_{max})

Parametric investigation

- Geometrical characteristics
- Mechanical parameters

NUMERICAL ANALYSES

FLAC 7

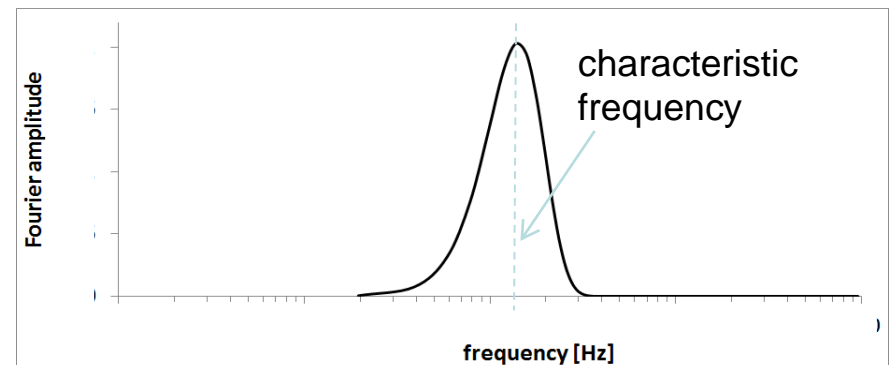
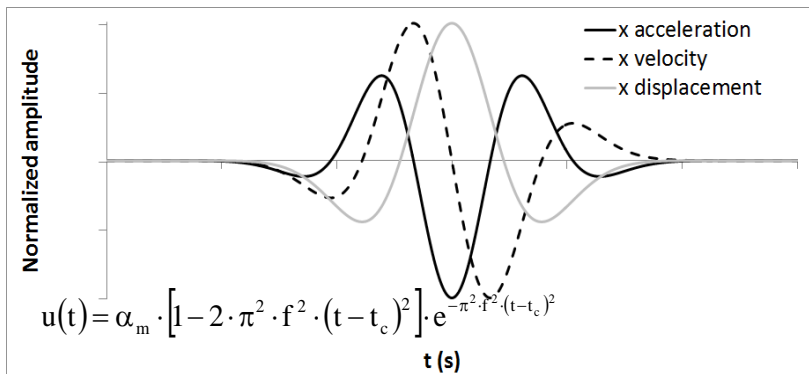


Soil layer natural frequency

$$f_n = \frac{(2 \cdot n - 1) \cdot V_s}{4 \cdot H} \quad n = 1$$

$$H_s = 60 \text{ m} \quad V_{s,s} = 300 \text{ m/s} \quad \Rightarrow \quad f_n = 1,07 \text{ Hz} \quad T_n = 0,93 \text{ s}$$

Seismic input: Ricker Wavelets



- Characteristic frequencies (and amplitudes) of Ricker wavelets used for each model: **0.5Hz, 1Hz, 2Hz, 5Hz** ($a_{\max} = 0.05g, 0.5 g$)

NUMERICAL ANALYSES

FLAC 7

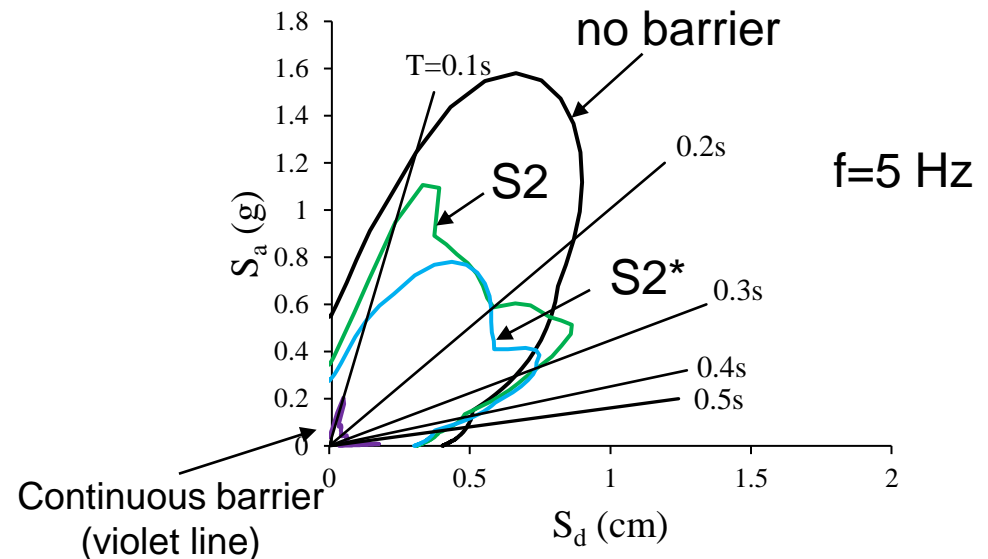
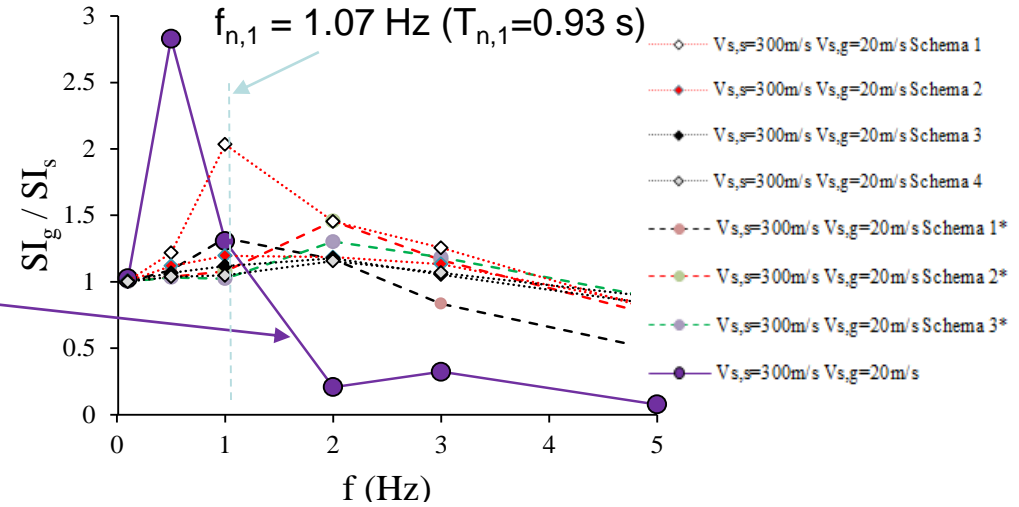
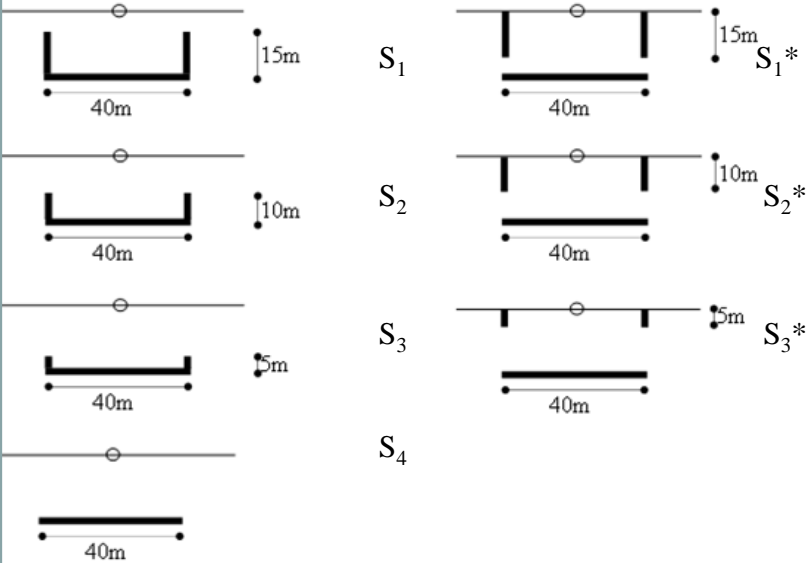
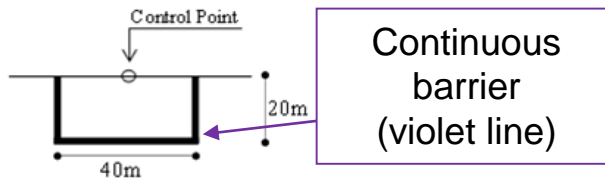


Do we need a continuous barrier?

→ Uni

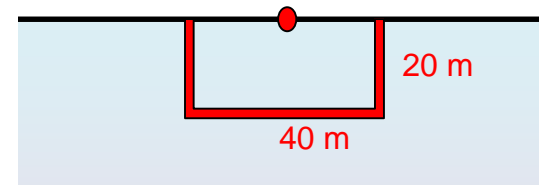
Elastic analyses

($V_{s,s}=300\text{m/s}$ $V_{s,g}=20\text{m/s}$ $H_g=20\text{m}$)



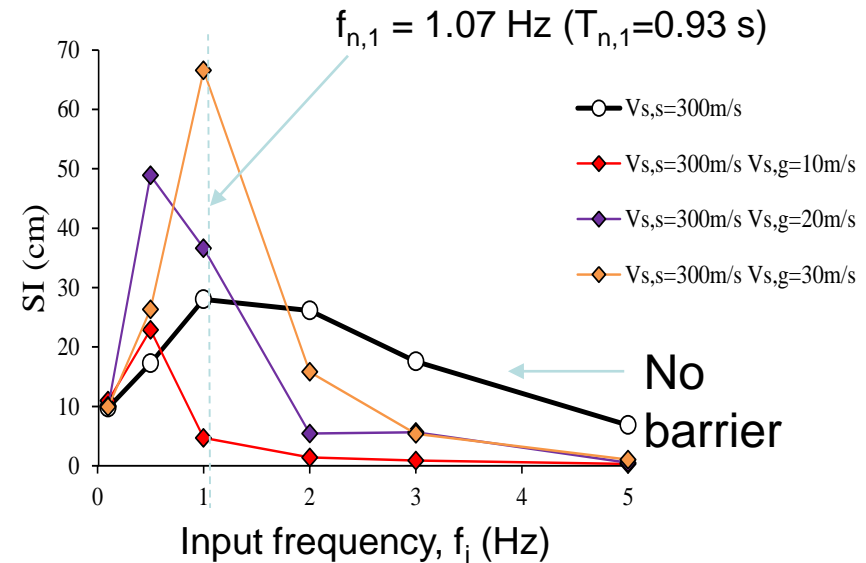
NUMERICAL ANALYSES

FLAC 7 – elastic analyses



Effect of dynamic impedance ratio α

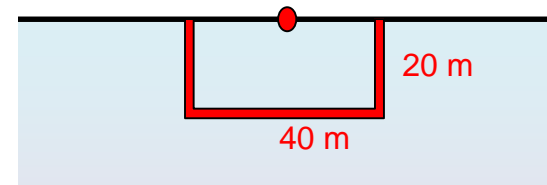
Soil		Grouted layers		Impedance ratio
$V_{s,s}$ (m/s)	ρ (kg/m ³)	$V_{s,g}$ (m/s)	ρ (kg/m ³)	$\alpha = \frac{\rho_s \cdot V_{s,s}}{\rho_g \cdot V_{s,g}}$
300	2040	10	1020	60
		20		30
		30		20



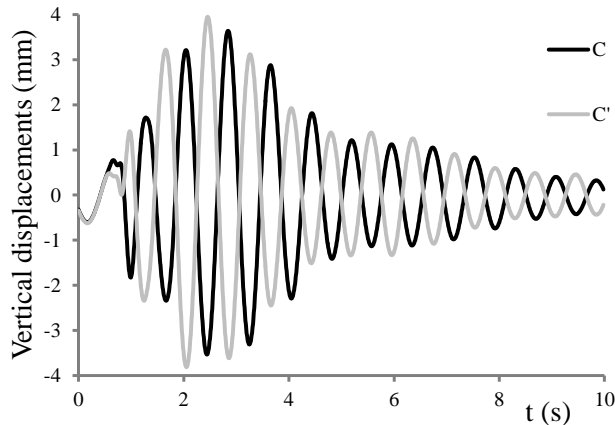
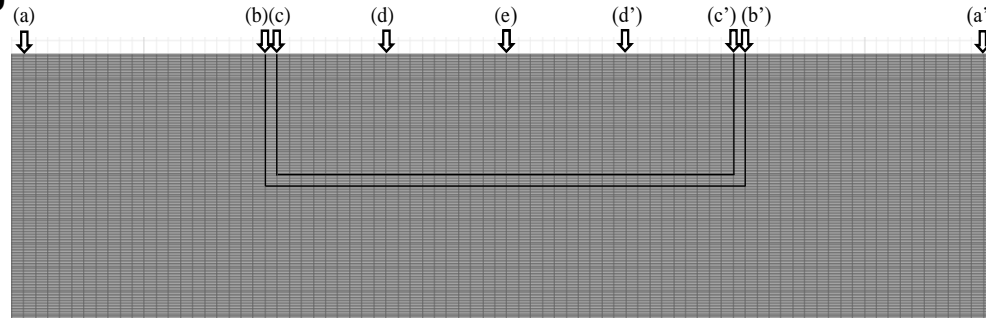
- If the soil behaves elastically, the barrier can be detrimental for low input frequencies
- Increasing the impedance ratio α reduces the amplification and shifts the natural frequency to lower values

NUMERICAL ANALYSES

FLAC 7 – elastic analyses



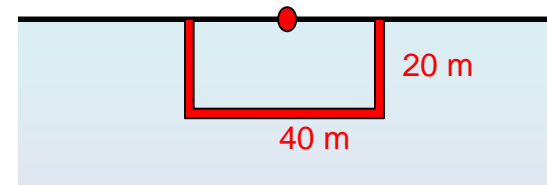
Evidence of
«rocking»



- Because of the very low shear stiffness of the grouted layer, deformations concentrate there and the bounded mass «swings» with extremely small deformations

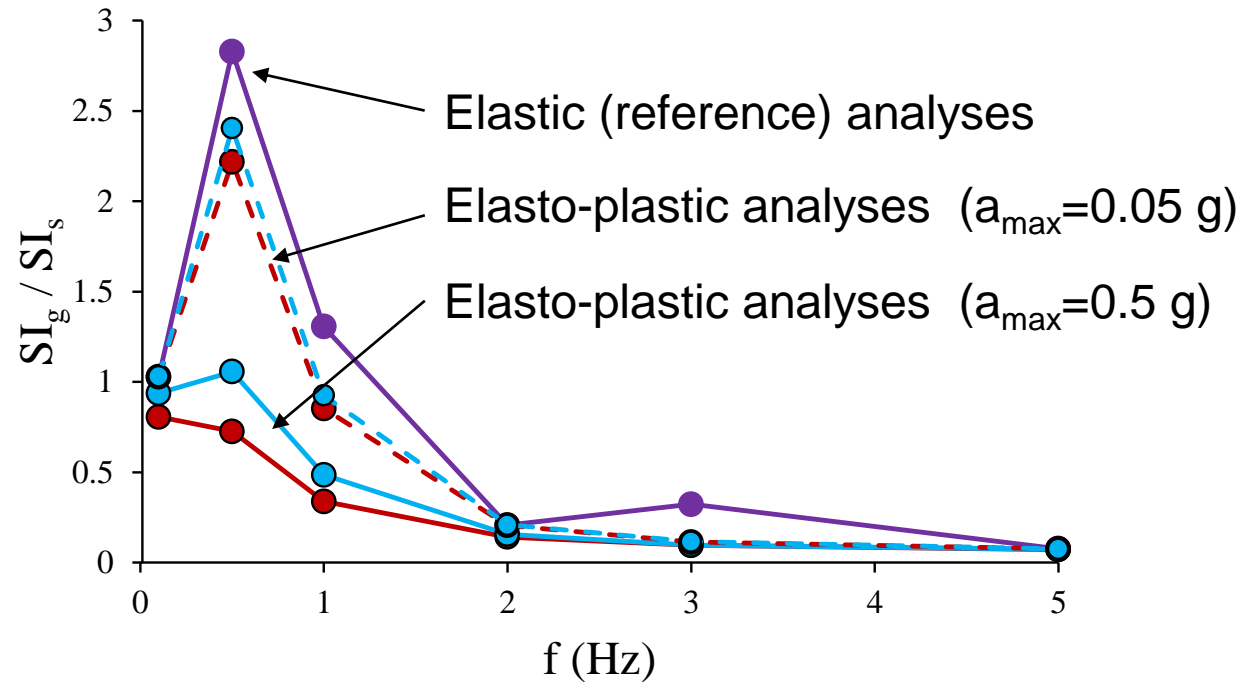
NUMERICAL ANALYSES

FLAC 7 – elasto-plastic analyses



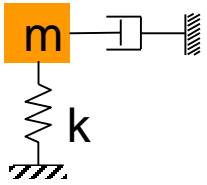
Blue dots: $\varphi_g=15^\circ$

Red dots: $\varphi_g=5^\circ$

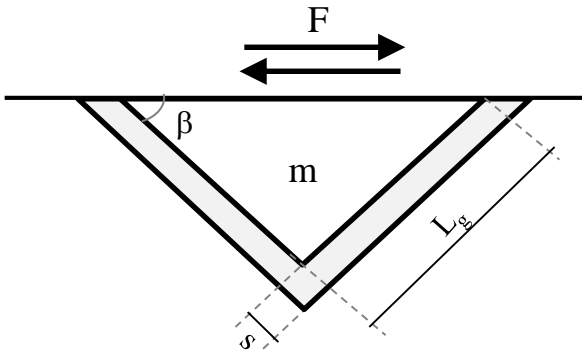
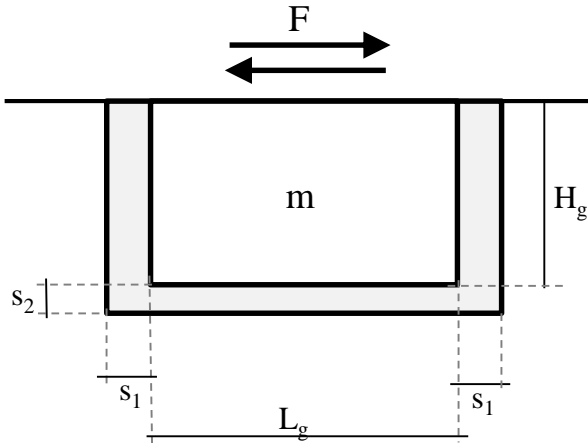


- Yielding and localized failure within the base grouted layer has a positive effect on the attenuation of lower frequencies.
- The barrier is more effective on strong seismic inputs.
- There is no need to have extremely low values of the shear strength.

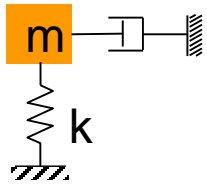
EQUIVALENT SDOF SYSTEM



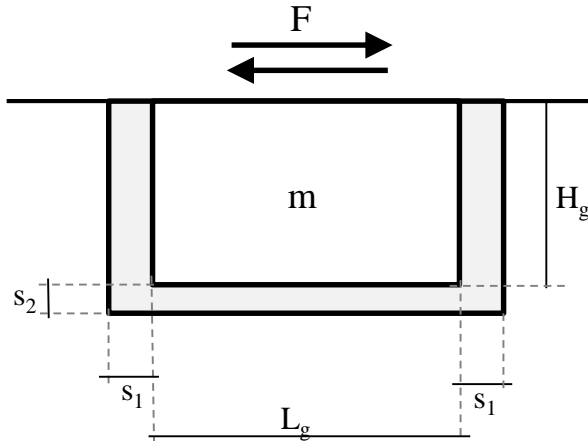
$$f = \frac{1}{2\pi} \cdot \left(\frac{k}{m} \right)^{0.5} (1 - \xi^2)^{0.5}$$



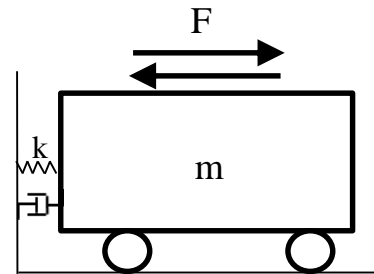
EQUIVALENT SDOF SYSTEM



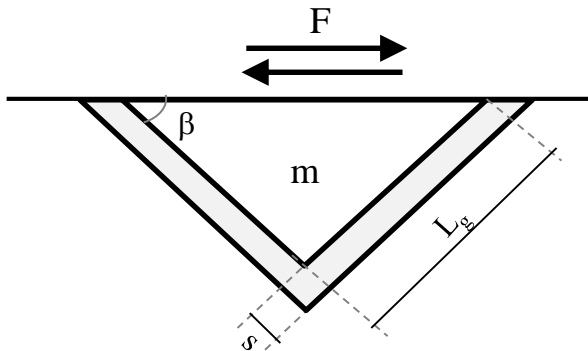
$$f = \frac{1}{2\pi} \cdot \left(\frac{k}{m} \right)^{0.5} (1 - \xi^2)^{0.5}$$



$$\Rightarrow f = \frac{1}{2\pi} \cdot \left[\frac{1 - \xi^2}{\rho} \left(\frac{2 \cdot E_g}{S_1 \cdot L_g} + \frac{G_g}{S_2 \cdot H_g} \right) \right]^{0.5}$$



$$m = \rho \cdot (\text{Soil Volume})$$

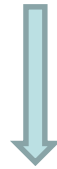
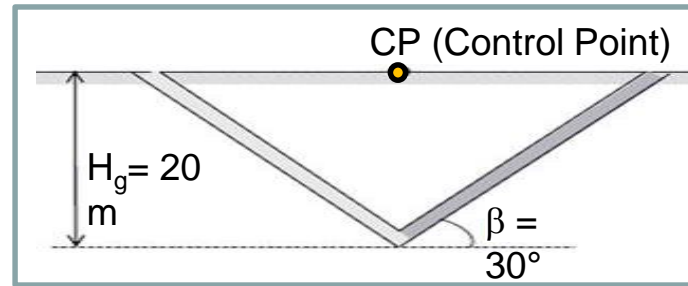
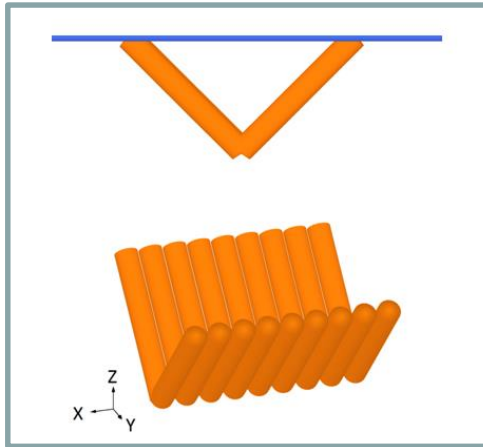


$$\Rightarrow f = \frac{1}{2\pi} \left\{ \left(\frac{1 - \xi^2}{\rho \cdot L_g} \right)^2 \cdot \left[\left(\frac{2 \cdot E_g}{S} \right)^2 \cdot \frac{1}{(\cos \beta)^2} + \left(\frac{G_g}{S} \right)^2 \cdot \frac{1}{(\sin \beta)^2} \right] \right\}^{0.25}$$

For low values of E_g and G_g , as well as for a large isolated soil mass (m), f is much lower than the first natural frequency of the free field soil layer

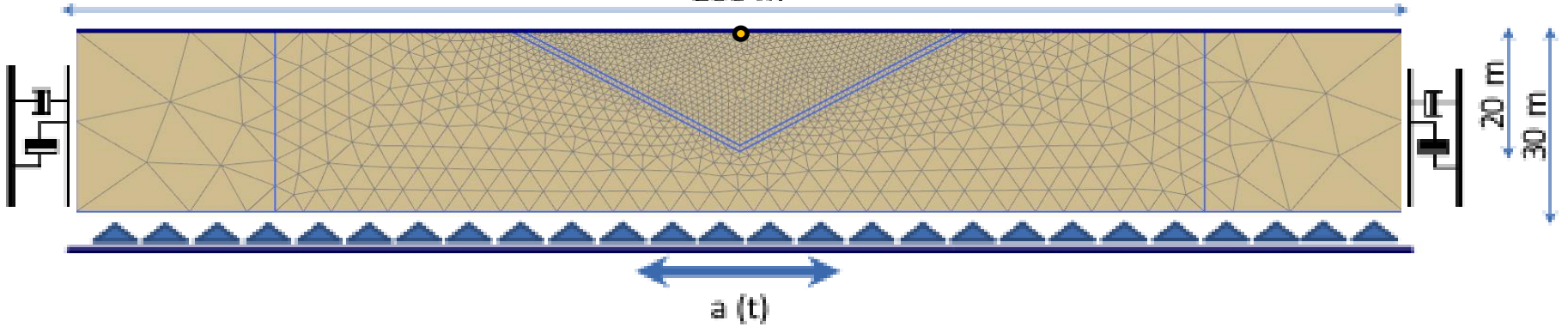
NUMERICAL ANALYSES

PLAXIS 2D

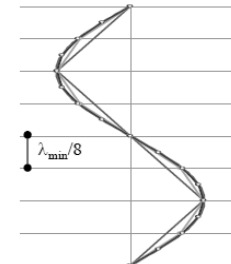


MESH

200 m

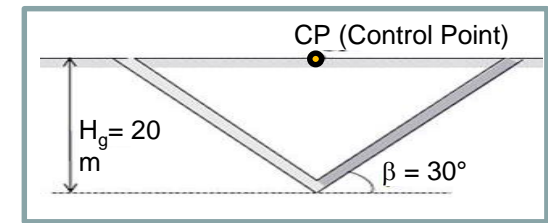


$$\lambda_{\min} = \frac{V_s}{f_{\max}}$$

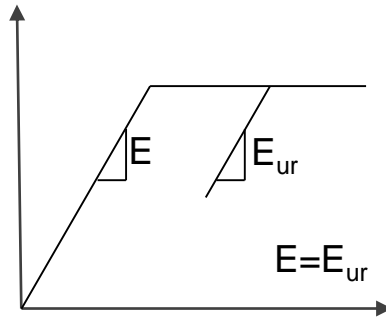


NUMERICAL ANALYSES

PLAXIS 2D models

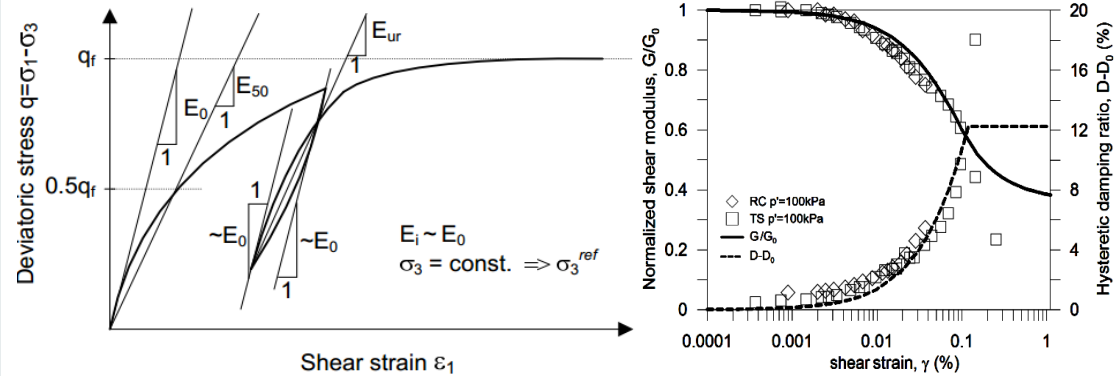


Soft barrier: «Mohr-Coulomb»



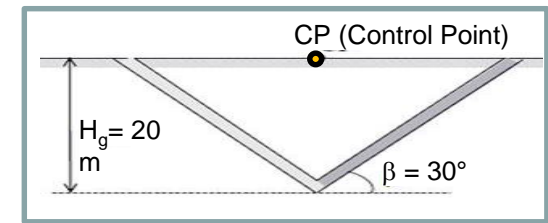
parameter	value
V_{st} (m/s)	20
ρ_t (kg/m ³)	1000
G_t (MPa)	0.4
ν_t	0.45
ϕ_t (°)	15
ψ_t (°)	0

Sand: Hardening Soil Small Strain



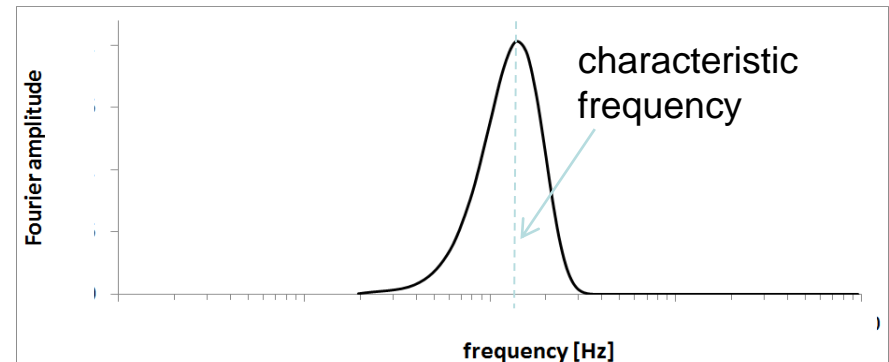
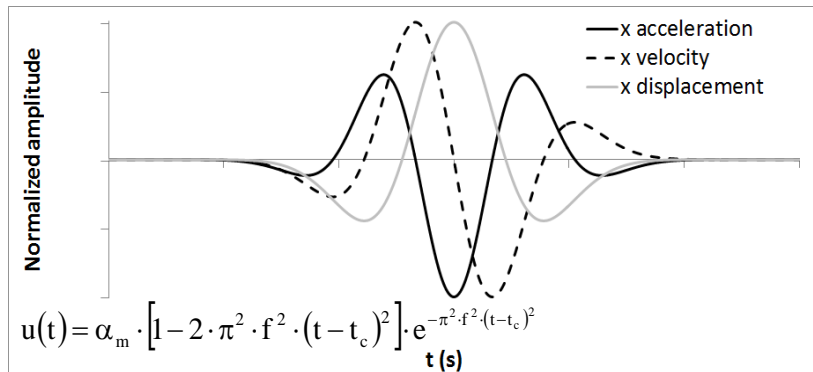
parameter	sand		
	(S1)	(S2)	(S3)
γ (kN/m ³)	14.5	15.0	15.5
$E_{50,ref}$ (MPa)	9.3	18.6	18.6
$E_{oed,ref}$ (MPa)	10.2	20.5	20.5
$E_{ur,ref}$ (MPa)	31.1	62.2	124.3
$G_{0,ref}$ (MPa)	36.3	72.7	145.4
ν_{ur}		0.2	
m		0.4	
$\gamma_{0.7}$		$5.8 \cdot 10^{-4}$	
$\gamma_{cut-off}$		$10.1 \cdot 10^{-4}$	
ϕ_{pk} (°)		38.6	
ψ_{pk} (°)		8.2	
c' (kPa)		0.01	

NUMERICAL ANALYSES PLAXIS 2D



Label	Description	Dynamic impedance ratio, $\alpha = \eta_s / \eta_t$
S1_NO	No treatment in sand S1	-
S1_V	Sand S1 with soft V-shaped caisson	11
S2_NO	No treatment in sand S2	-
S2_V	Sand S2 with soft V-shaped caisson	15
S3_NO	No treatment in sand S3	-
S3_V	Sand S3 with soft V-shaped caisson	22

Seismic input: Ricker Wavelets

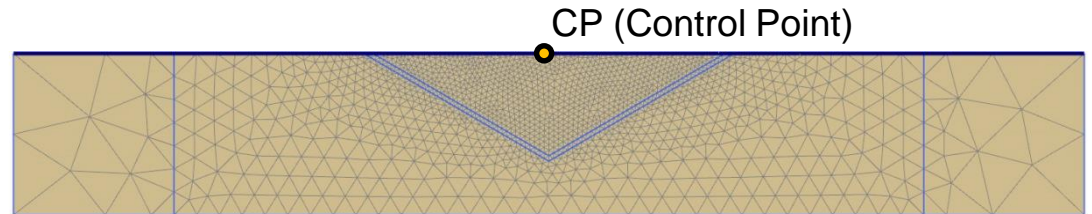
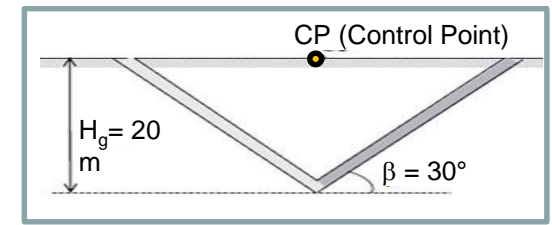


- Characteristic frequencies (and amplitudes) of Ricker wavelets used for each model: **0.5Hz, 1Hz, 2Hz, 5Hz** ($a_{\max} = 0.05g, 0.5g$)

NUMERICAL ANALYSES

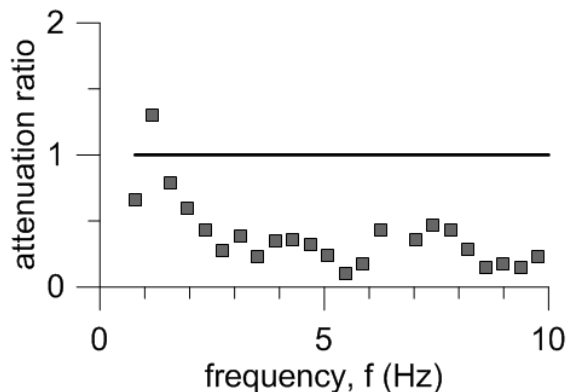
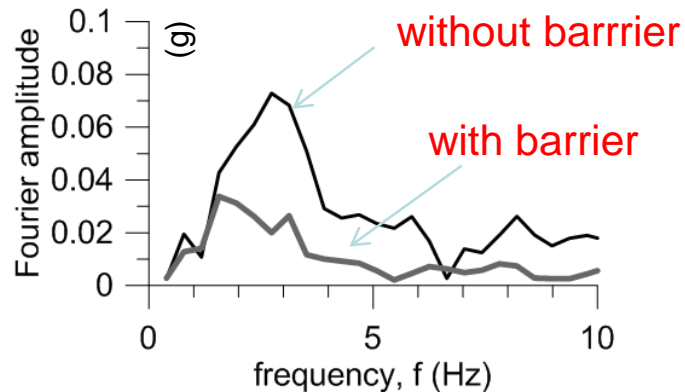
PLAXIS 2D

SOME RESULTS



Model S2, Ricker wavelet: $f=2$ Hz

(Interpretation in terms of acceleration in



The soft barrier can be very efficient!



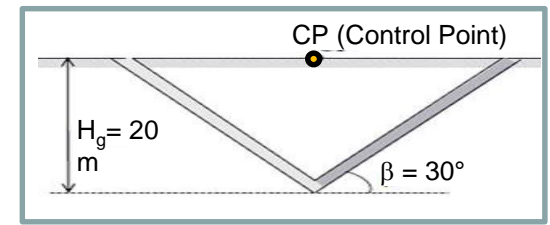
The efficiency of the caisson improves by:

- increasing the dynamic impedance ratio α ;
- reducing the shear stiffness of the soft barrier;
- taking into account soil and barrier elasto-plastic behaviour

NUMERICAL ANALYSES

PLAXIS 2D

SUMMING UP THE RESULTS



response Spectrum Intensity (Housner, 1959)

$$SI = \int_{0.1s}^{2.5s} S_v(\xi = 0.05, T) dT$$

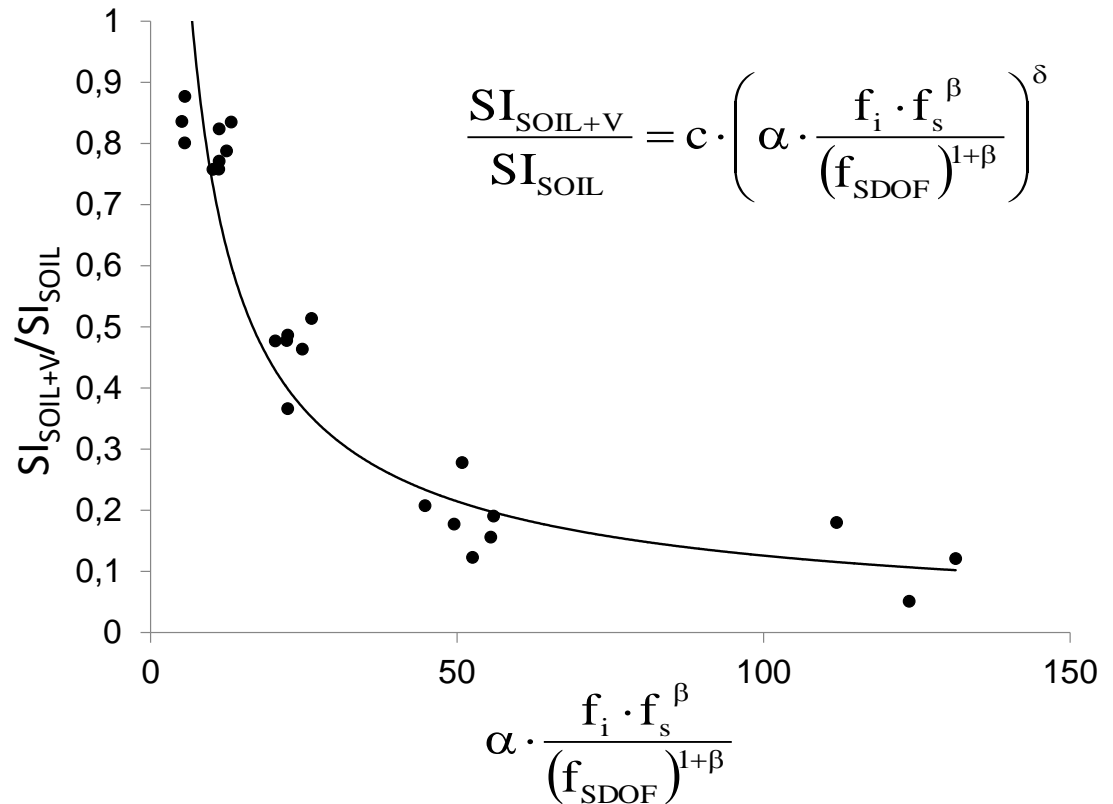
A possible interpretation

$$\frac{SI_{SOIL+V}}{SI_{SOIL}} = f\left(\alpha, \frac{f_i}{f_{SDOF}}, \frac{f_s}{f_{SDOF}}\right)$$

f_i : characteristic input frequency

f_s : natural frequency of the soil layer ($f_s(S1)=1.3$ Hz, $f_s(S2)=1.8$ Hz, $f_s(S3)=2.6$ Hz)

$\alpha = \eta_s / \eta_t$: impedance ratio between SDM and natural soil

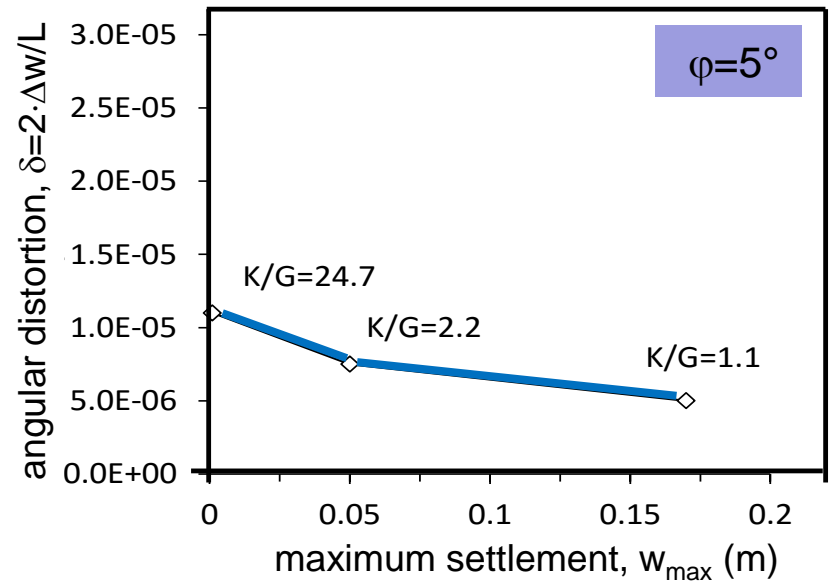
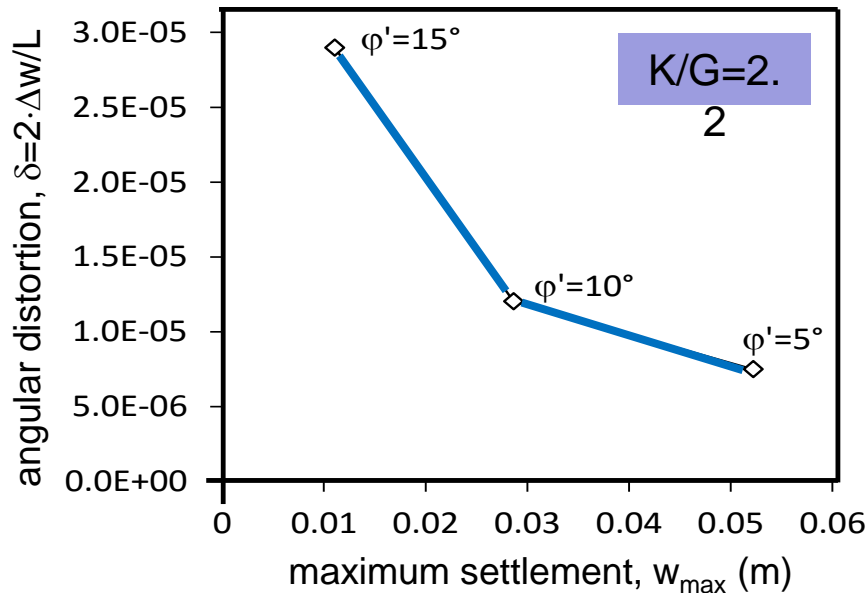
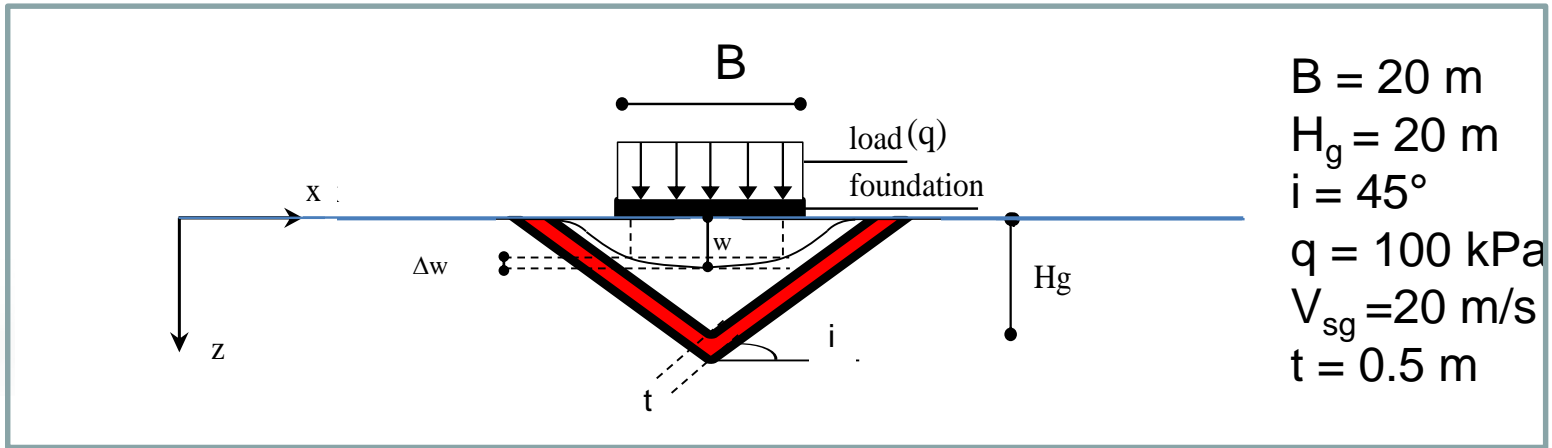


It seems possible to have a general interpretation of the overall results using the equivalent SDOF concept

NUMERICAL ANALYSES

PLAXIS 2D

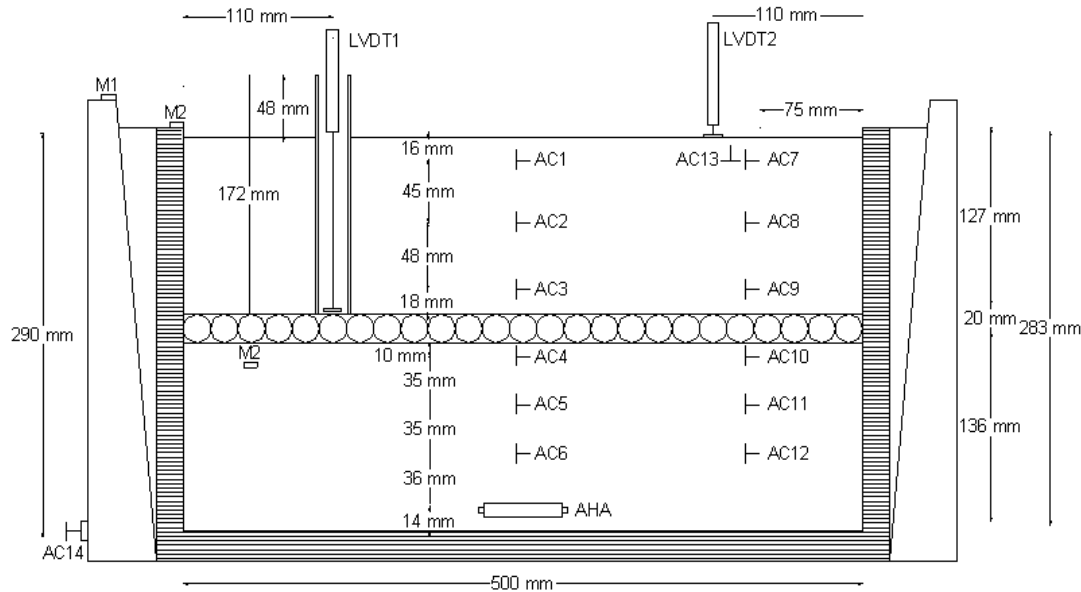
ARE WE CAUSING ANY STATIC PROBLEM?



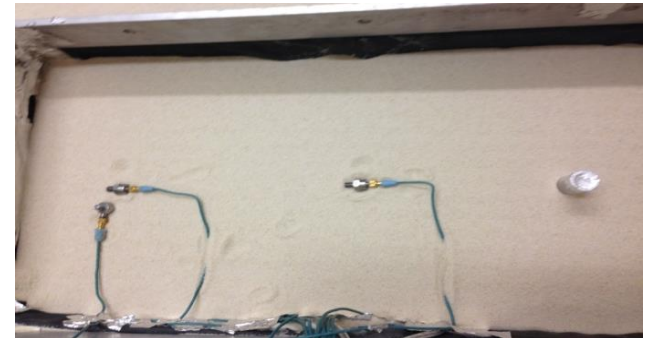
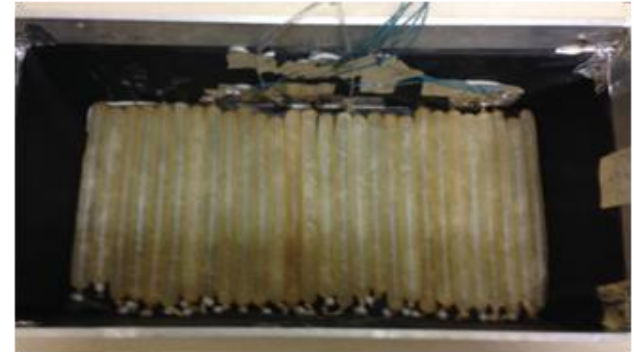
CENTRIFUGE TESTING

Schofield Center – Cambridge (UK)

Horizontal soft barrier



AC: Piezoelectric Accelerometer
M: Microelectromechanical System Accelerometer
LVDT: Linear Variable Differential Transformer
AHA: Airhammer Piezoelectric Accelerometer

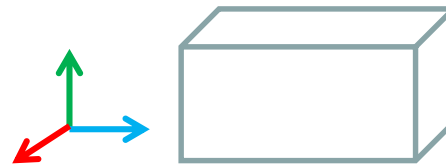


Dimensions

Model

Prototype (80g)

500 mm x 250 mm x 300 mm
m x 24 m

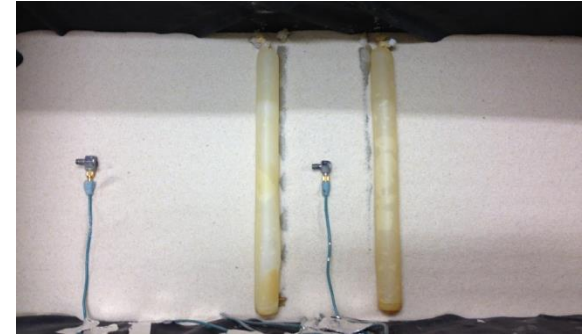
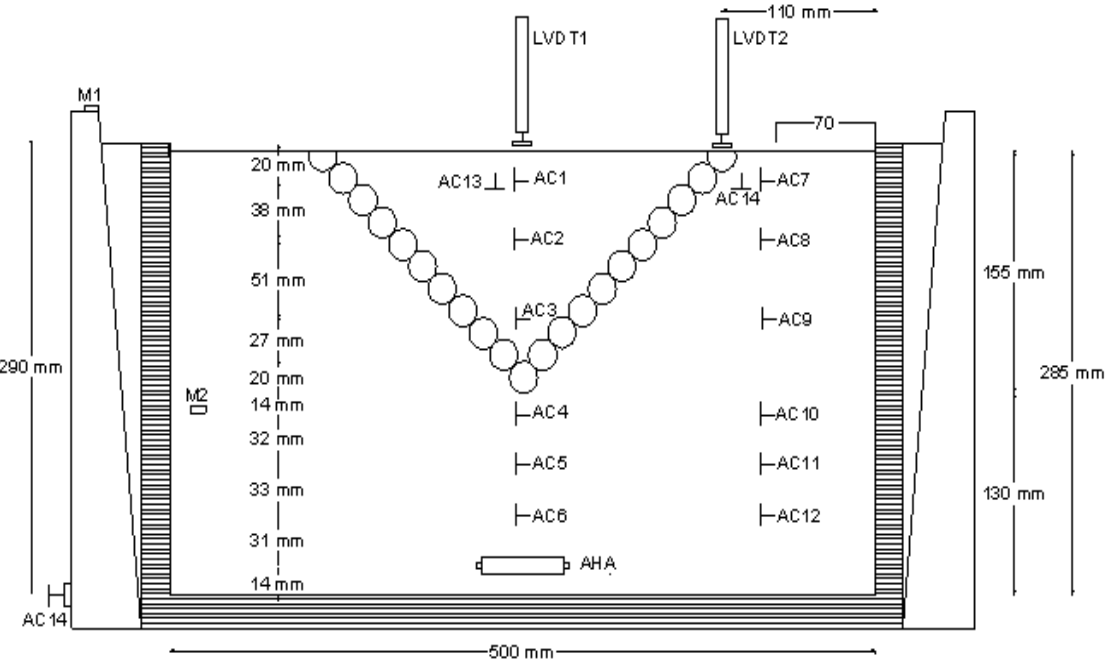


40 m x 20

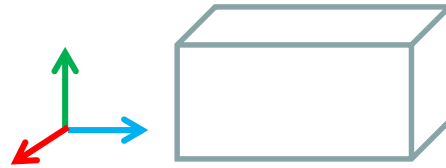
CENTRIFUGE TESTING

Schofield Center – Cambridge (UK)

V-shaped soft barrier



Dimensions



Model

Prototype (80g)

500 mm x 250 mm x 300 mm
m x 24 m

40 m x 20

CENTRIFUGE TESTING

Schofield Center – Cambridge (UK)

Materials and testing programme

- Hostun Sand HN31 $Dr=85\%$ (Flavigny, 1990)
- Super Absorbent Polymer (SAP)

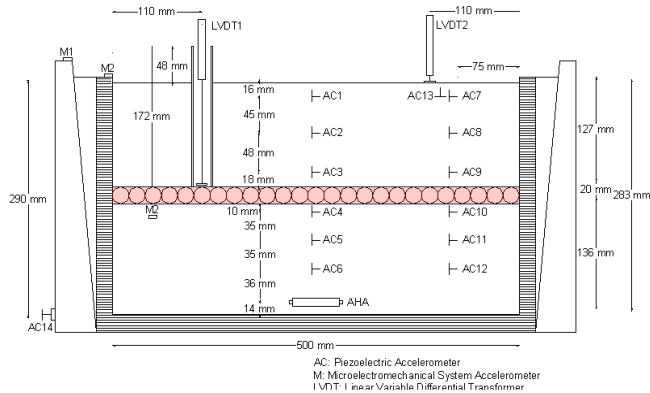
Horizontal barrier					
Gravity level (g)	Input	Frequency (Hz)		Amplitude (g)	
		Model	Prototype	Model	Prototype
50g	EQ1	50	1.00	4.63	0.09
	EQ2	30	0.60	0.60	0.01
80g	EQ3	50	0.63	2.61	0.05
	EQ4	50	0.63	9.82	0.12
	EQ5	30	0.38	1.89	0.75
	EQ6	60	0.75	0.68	0.01
	EQ7	60	0.75	16.61	0.33
	EQ8	30	0.38	4.49	0.06

V Barrier					
Gravity level (g)	Input	Frequency (Hz)		Amplitude (g)	
		Model	Prototype	Model	Prototype
80g	EQ1	50	0.63	7.22	0.09
	EQ2	50	0.63	13.50	0.17
	EQ3	30	0.38	1.34	0.02
	EQ4	60	0.75	13.20	0.17
	EQ5	60	0.75	19.10	0.24
	EQ6	30	0.38	4.85	0.06
50g	EQ7	50	1.00	9.15	0.18
	EQ8	30	0.60	0.89	0.01

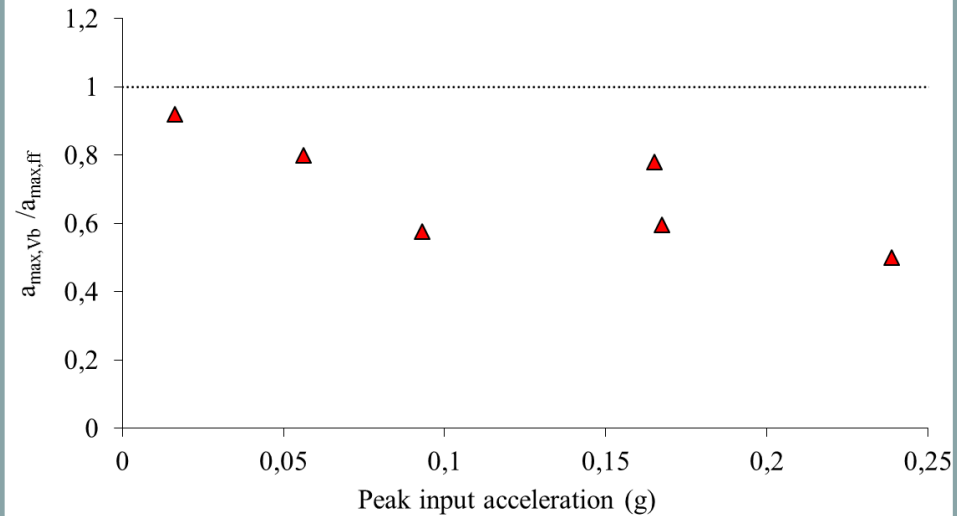
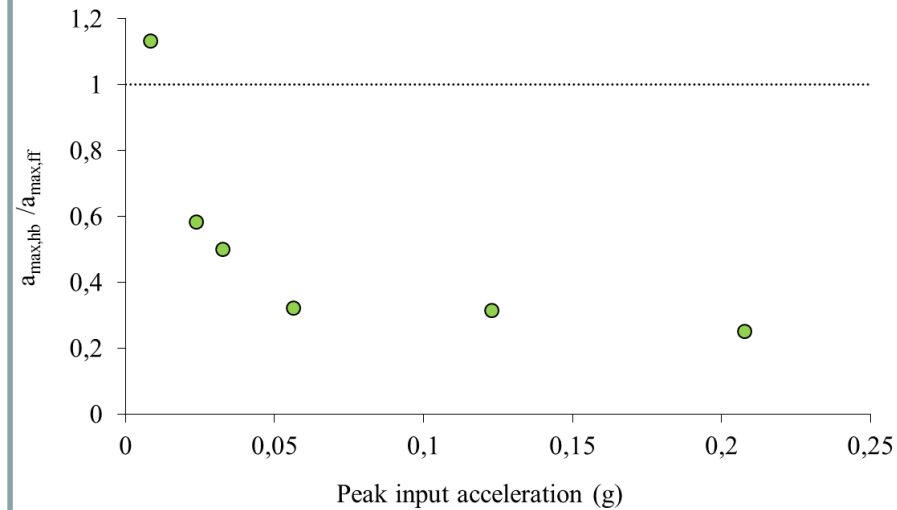
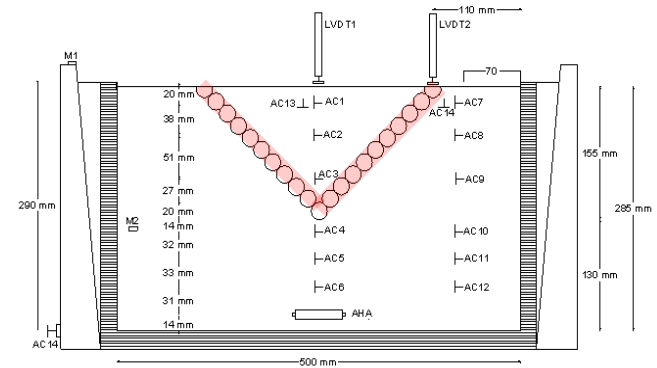
CENTRIFUGE TESTING

Schofield Center – Cambridge (UK)

Horizontal barrier



V-shaped barrier



- The increase in peak input acceleration makes the barrier more effective (because of yielding)

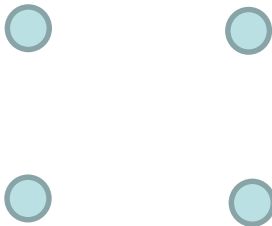
IN SITU TESTING



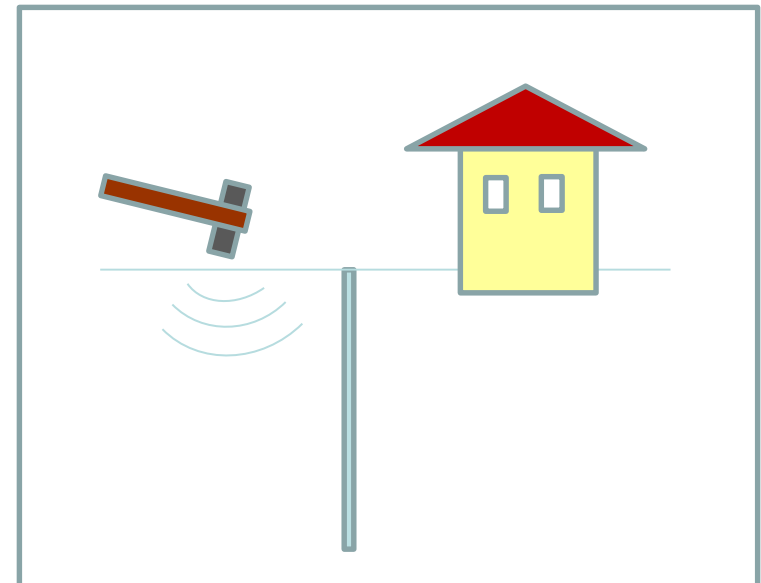
Two field trials programmed:

- A - Single columns with different grouts (under course)
- B - Linear barrier and dynamic testing with a given grout (to be started soon)

Field trial A

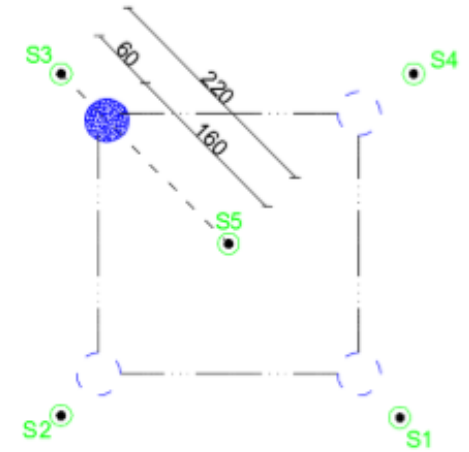
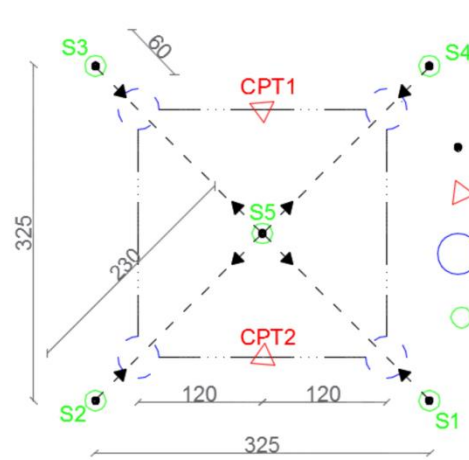


Field trial B

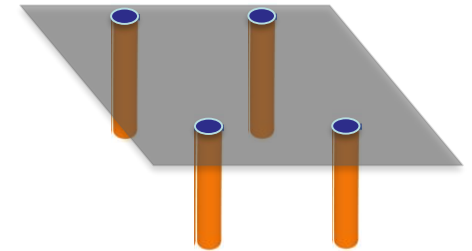


IN SITU TESTING

Field trial A



- Drillings with SPT
- CPT
- Cross Hole tests
- Inclinometers



Cross Hole tests have allowed to measure the shear wave velocity of the material within the columns (SAP):

$$V_{s,SAP}=26,8 \text{ m/s}$$

Perfectly consistent with laboratory findings!



PRELIMINARY CONCLUSIONS ON THIS VERY INNOVATIVE GROUND MODIFICATION TECHNOLOGY

- ✓ Super absorbing polymers seem suited to create soft barriers with tuned stiffness and shear strength. They will last longer under ground water table.
- ✓ Because of the reduction of the natural frequency of the isolated soil mass, the soft barrier is suited for protecting structures having higher natural frequencies (i.e. squat buildings).
- ✓ Interestingly, the stronger the seismic input the better the isolation performance.
- ✓ The rectangular barrier is less feasible than the V shaped one. However, it can reduce static problems to a minimum by having horizontal and vertical barriers of different volumetric stiffness.

CONCLUSIONI GENERALI

Dobbiamo preoccuparci dell'uso crescente dei progressi tecnologici?
Sono una reale innovazione nella progettazione geotecnica?

La classicità



A. Palladio, Villa Almerico Capra Valmarana,
Vicenza 1566

L'innovazione?

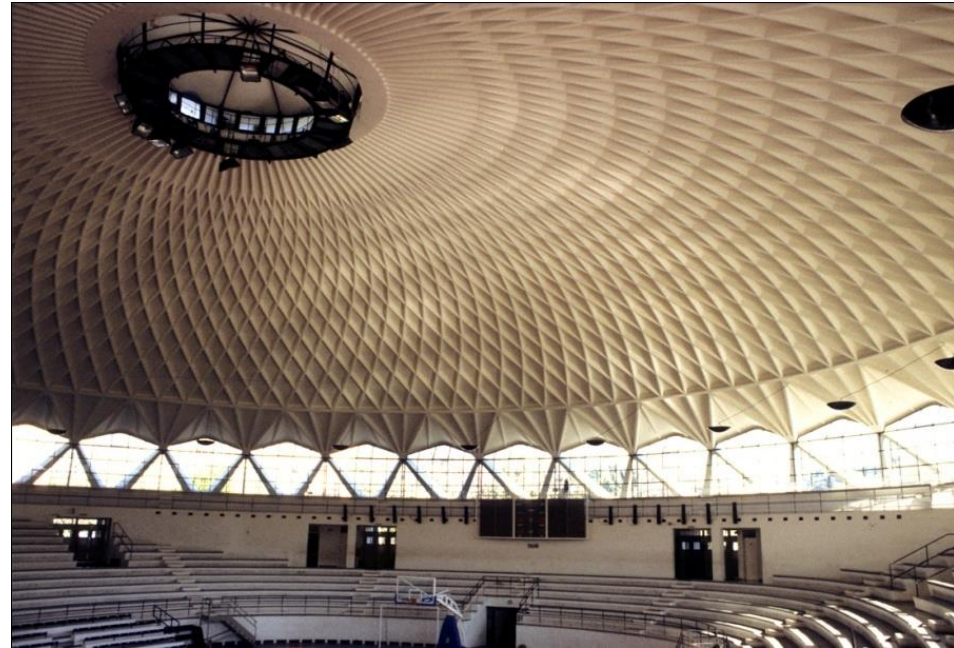


anonimi (purtroppo!)

CONCLUSIONI GENERALI

L'innovazione!

Z. Hadid, MAXXI, Roma 2006



P. L. Nervi, Palazzetto dello sport,
Roma 1958

CONCLUSIONI GENERALI

Il problema non è la tecnologia ma l'uso che se ne fa.
L'innovazione pretende CONOSCENZA e COSCIENZA



A. Siza, Padiglione del Portogallo per l'EXPO, Lisbona 1998