3° C.F.P.B.
3° CONGRESO - SEMINARIO INTERNACIONAL
DE FUNDACIONES PROFUNDAS
DEL 27 AL 29 DE ABRIL DE 2017

SIMSG ISSMGE

DESIGN OPTIONS FOR PILED RAFTS
AN OVERVIEW

UNIVERSITÀ DEGLI STUDI DELLA CAMPANIA
LUIGI VANVITELLI
SCUOLA POLITECNICA E DELLE SCIENZE DI BASE
DIPARTIMENTO DI INGEGNERIA CIVILE
DESIGN EDILIZIA E AMBIENTE

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Scientific understanding proceeds by way of constructing and analysing models of the segments or aspects of reality under study. The purpose of these models is not to give a mirror image of reality, not to include all its elements in their exact sizes and proportions, but rather to single out and make available for intensive investigation those elements which are decisive.

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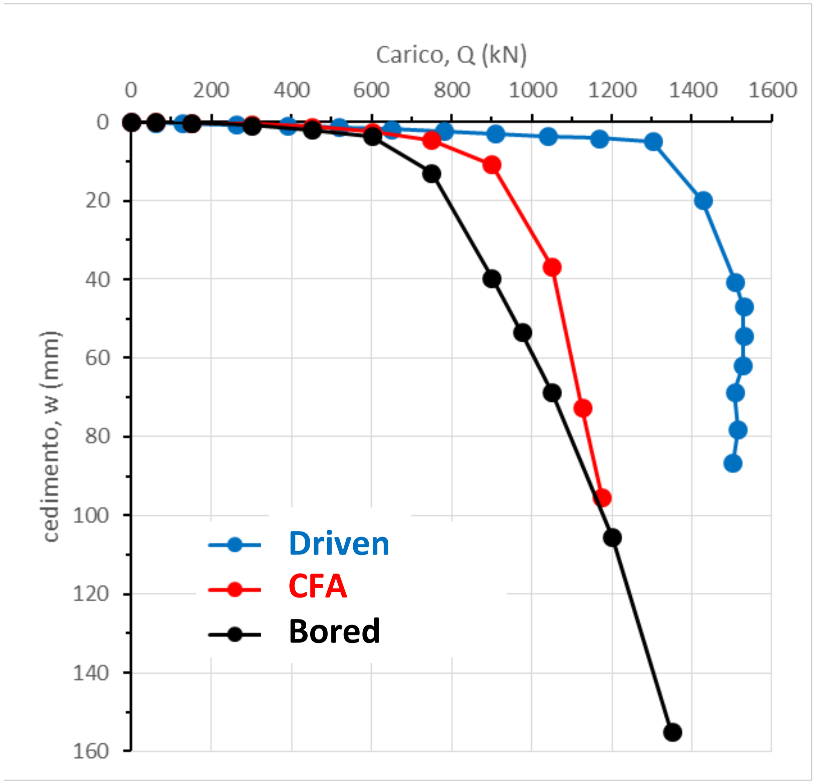
BARAN P.A., SWEEZY P.M. (1968)
Monopoly Capital: an essay on the American economic and social order.

The role played by pile technology ……

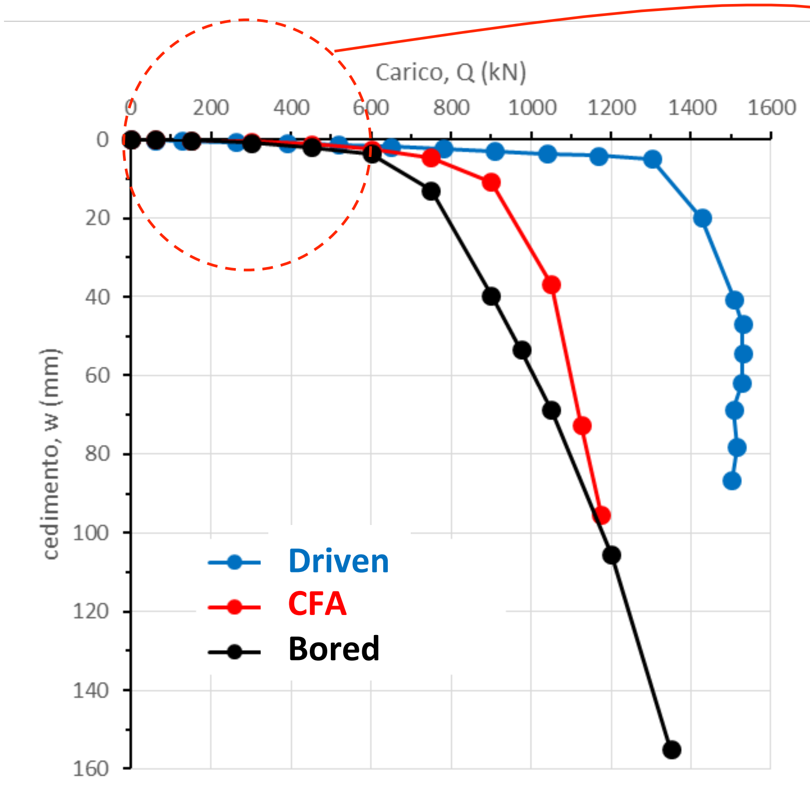
International Prediction Event – Portugal, ISC 2002



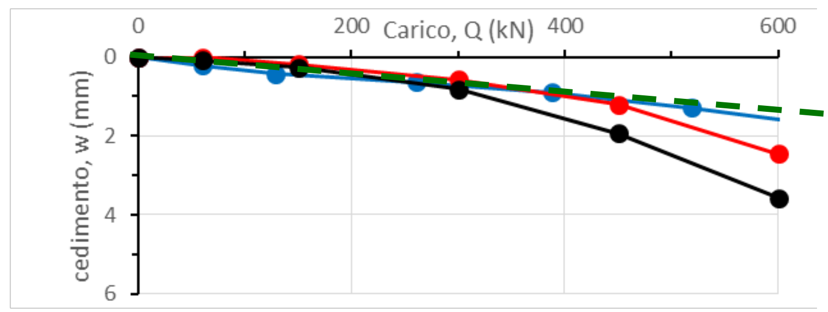
The shape of the curves are different pile by pile

The role played by pile technology ……

International Prediction Event – Portugal, ISC 2002

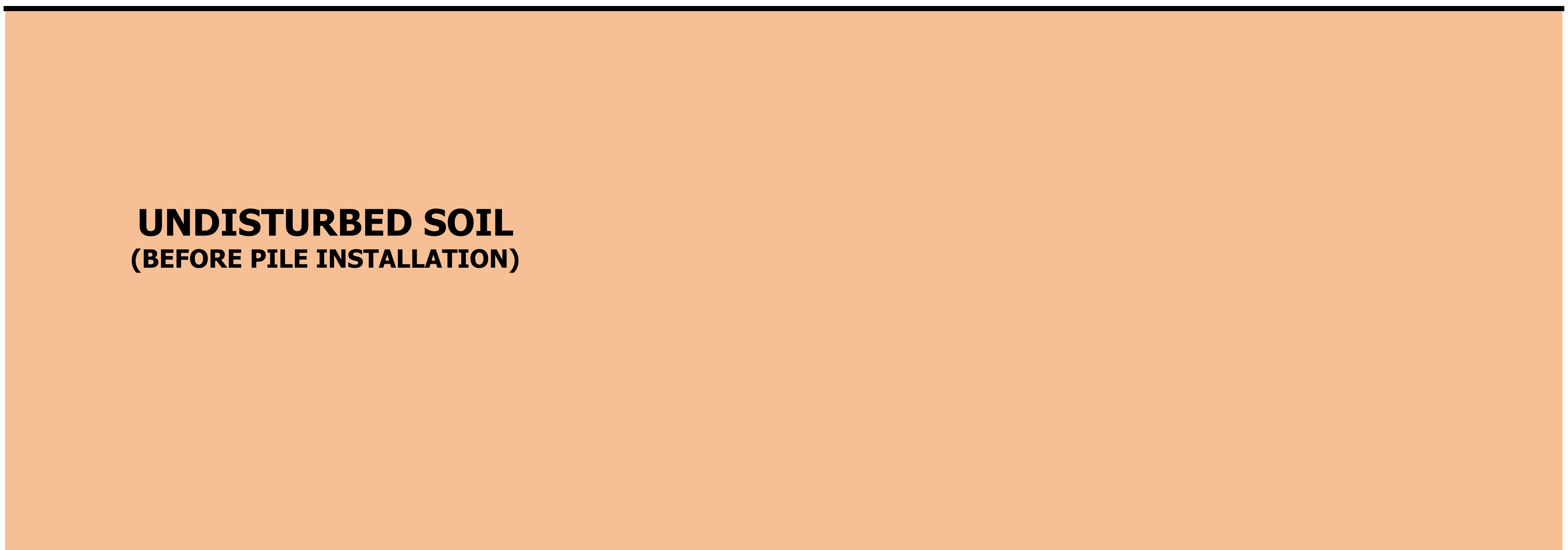


$K_{0,LT} = [dQ/dw]_{Q=0}$



The initial tangent is almost the same for any pile

SIMPLE EXPLANATION



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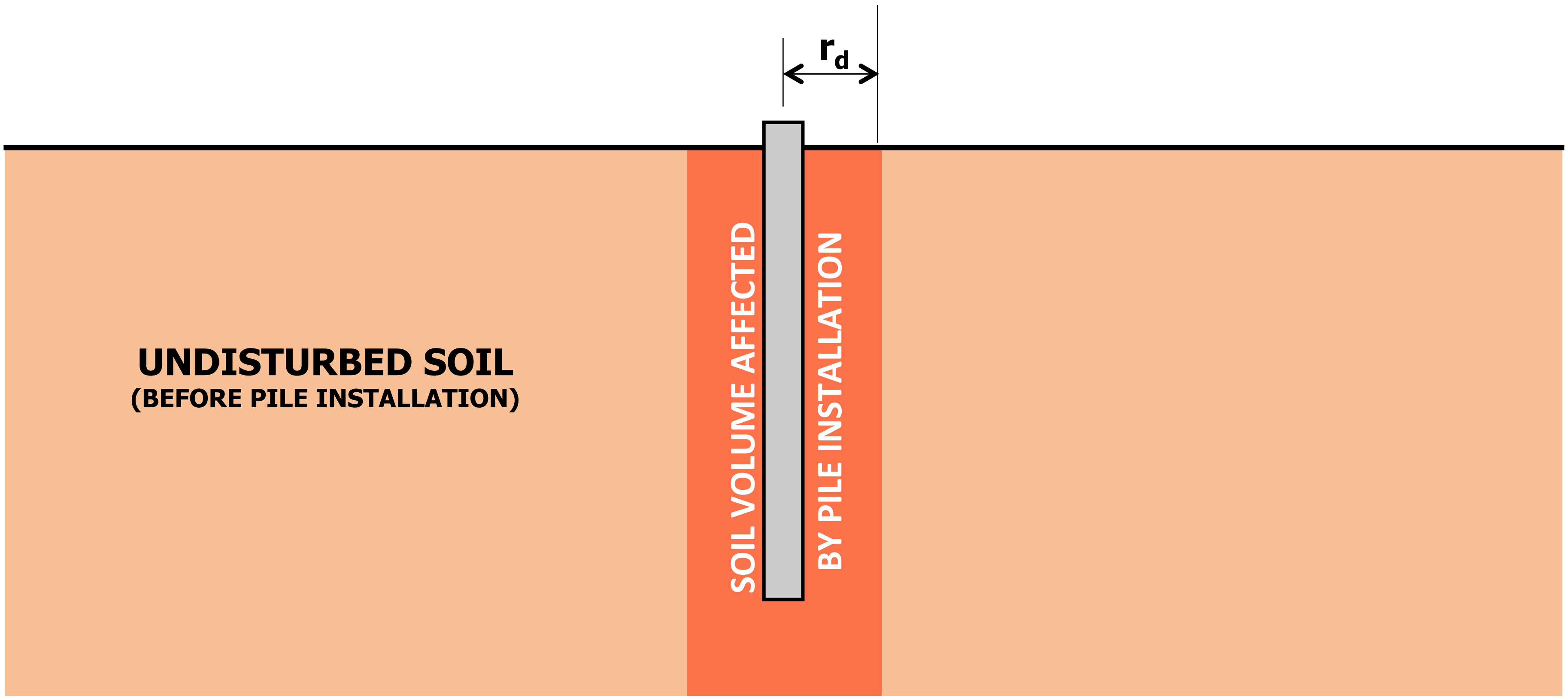

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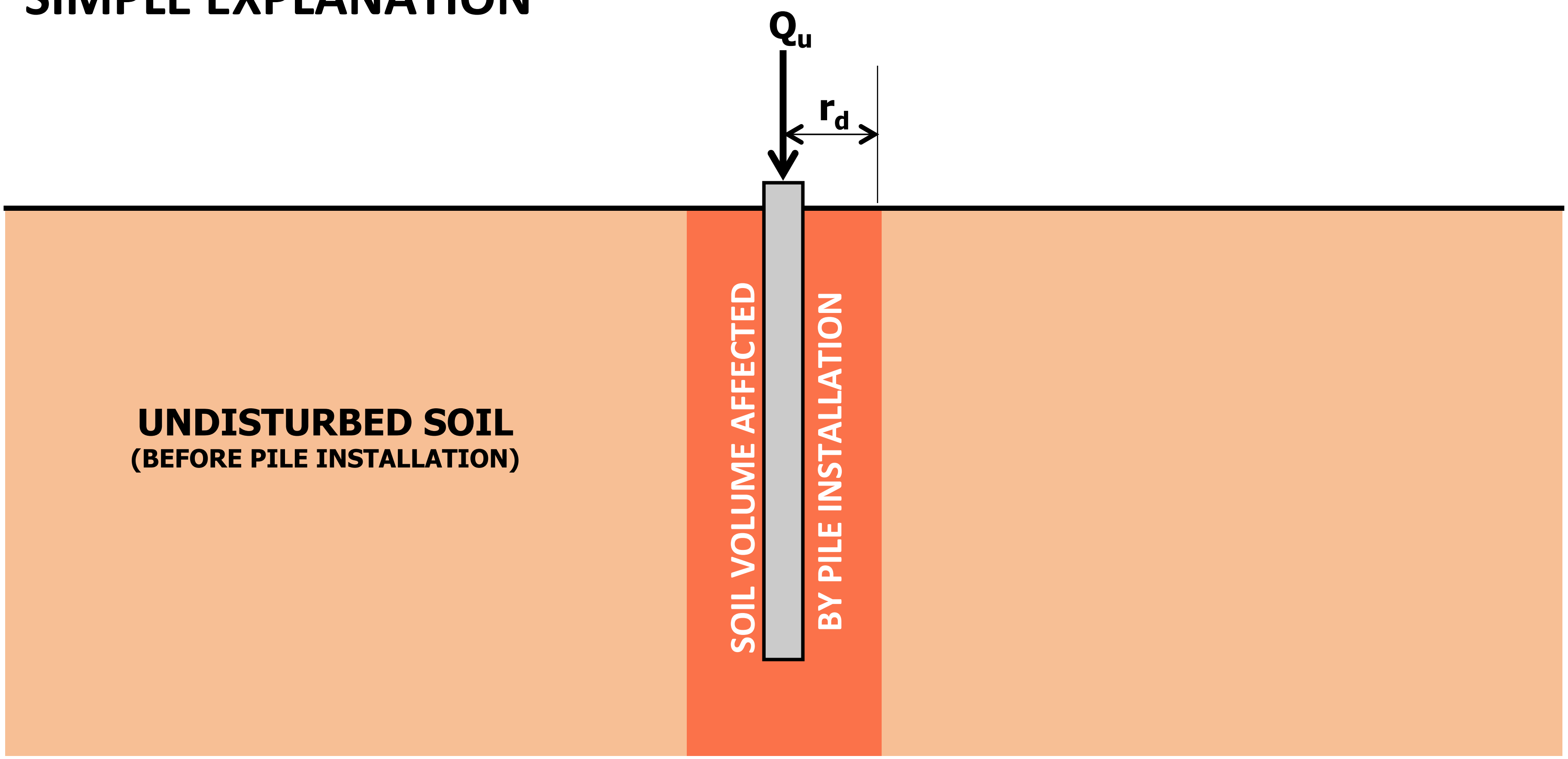
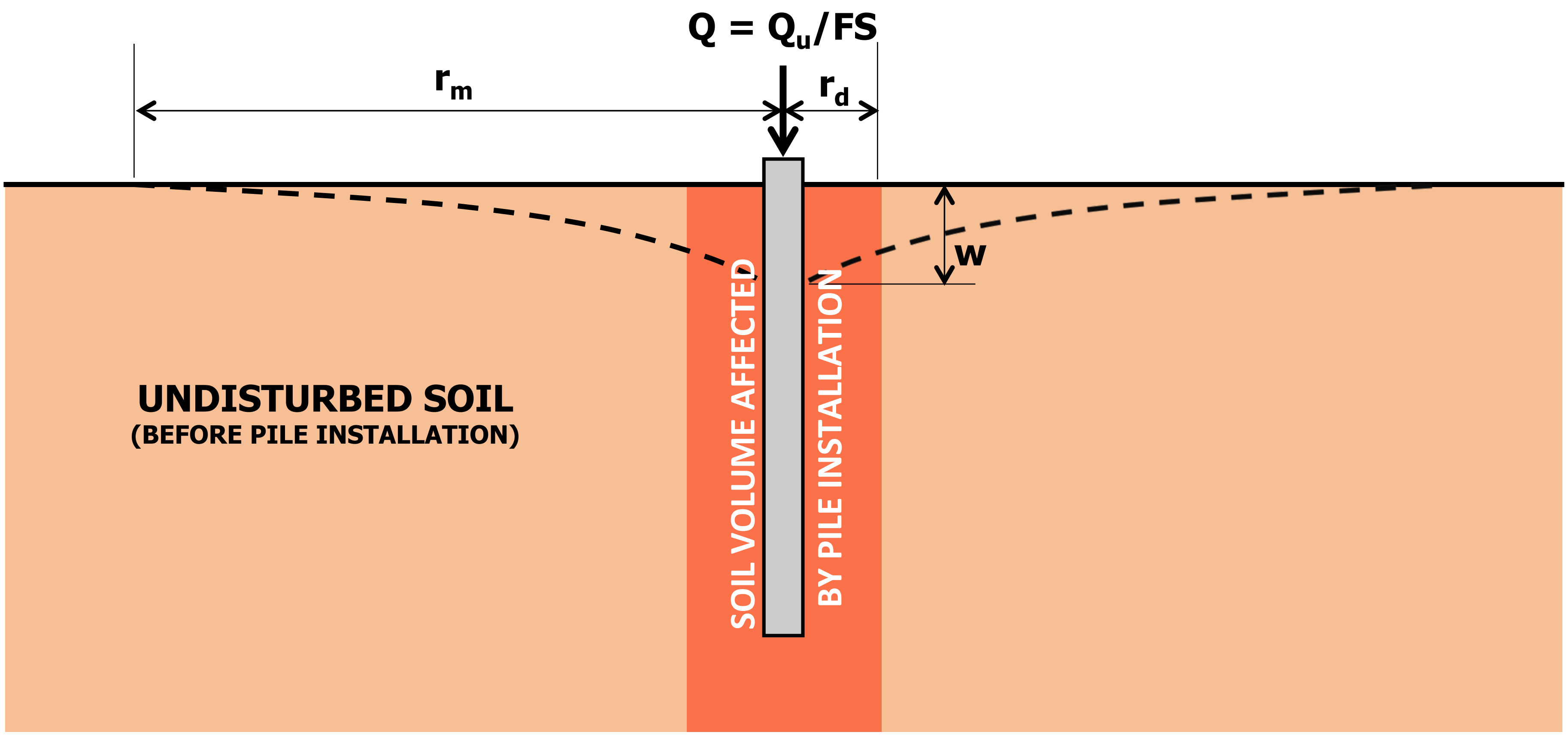


Failure develops in a thin soil cylinder within the affected one → great influence of the specific installation procedure

SIMPLE EXPLANATION



$$r_m = 2.5\cdot(1-\nu)\cdot L = (1.25\div 2.50)\cdot L$$

$$r_d = (1.25\div 2.5)\cdot d$$

$$r_m / r_d = (0.5\div 2)\cdot L/d \gg\gg 1$$

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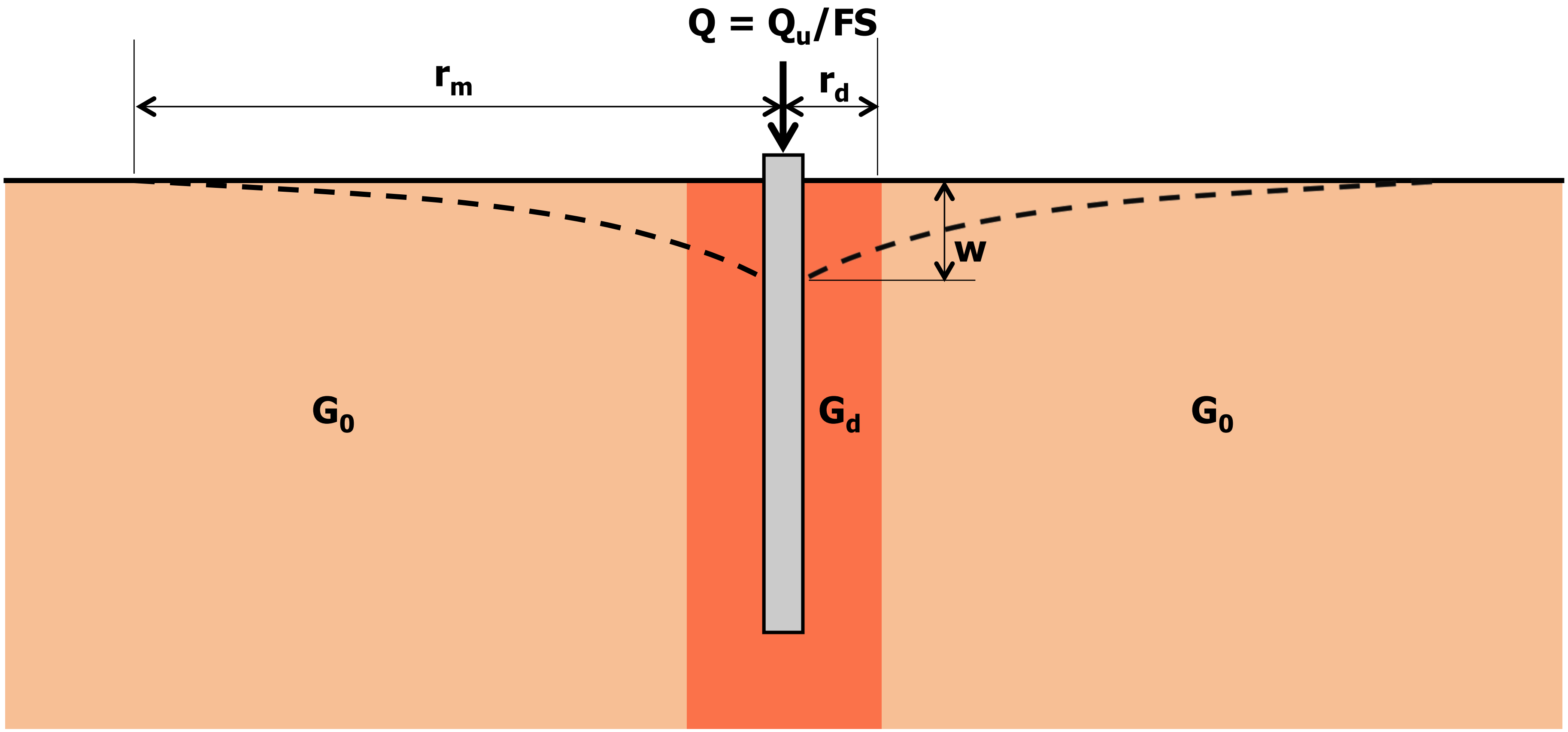

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ELASTIC THEORY, ALBEIT NOT ADEQUATE FOR PROBLEMS INVOLVING SOIL, IS A VERY SIMPLE TOOL TO DETECT MAIN ASPECTS

A simple formula for evaluating axial soil-pile stiffness K_0

Fleming et al., 2009: rigid pile embedded in an homogeneous elastic half-space

$$K_0 = 2 \cdot \pi \cdot G_0 \cdot L / \varsigma$$

$$\varsigma = \ln[5 \cdot (1-\nu) \cdot L/d] \rightarrow \text{for usual } L/d \text{ and } \nu \perp 3 \leq \varsigma \leq 5$$

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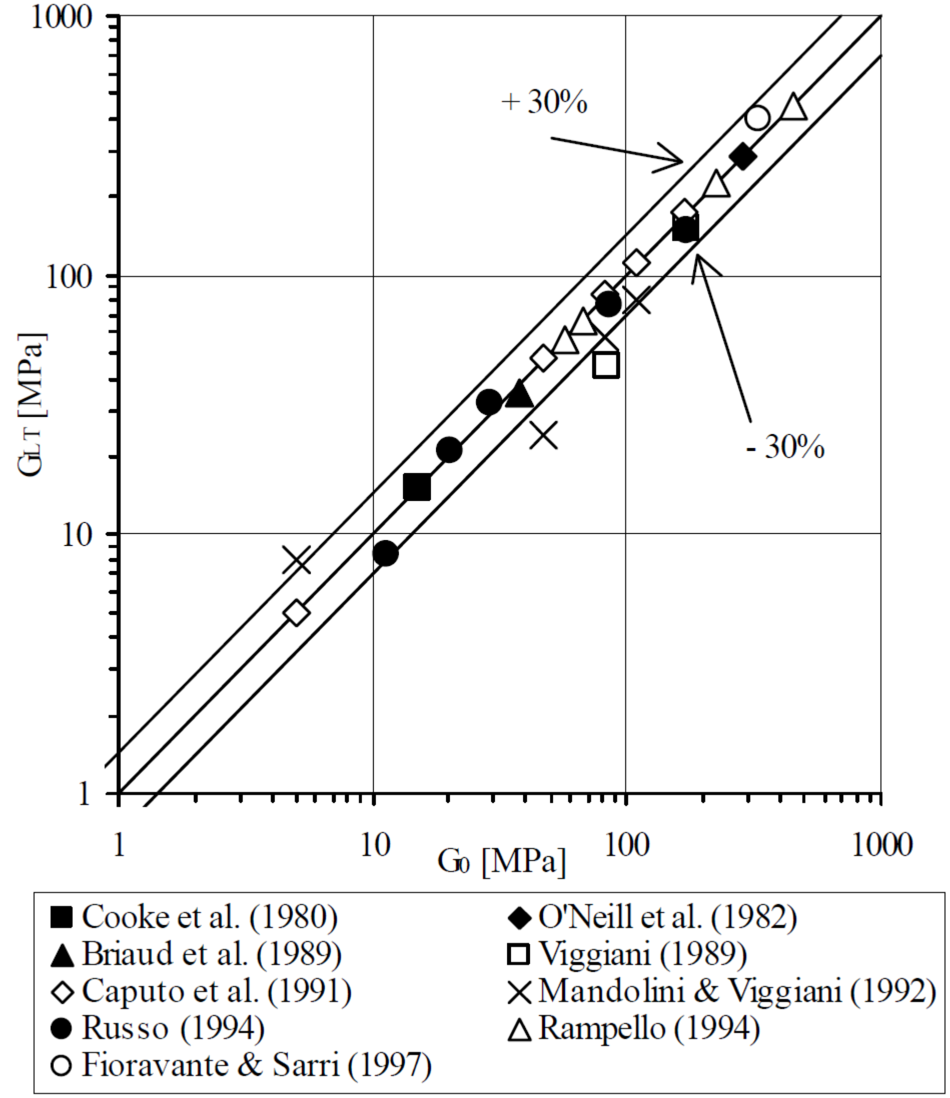
$$K_0 \sim 0.5 \cdot \pi \cdot G_0 \cdot L$$

$$G_{0,LT} \sim 2 \cdot K_{0,LT} / \pi \cdot L$$

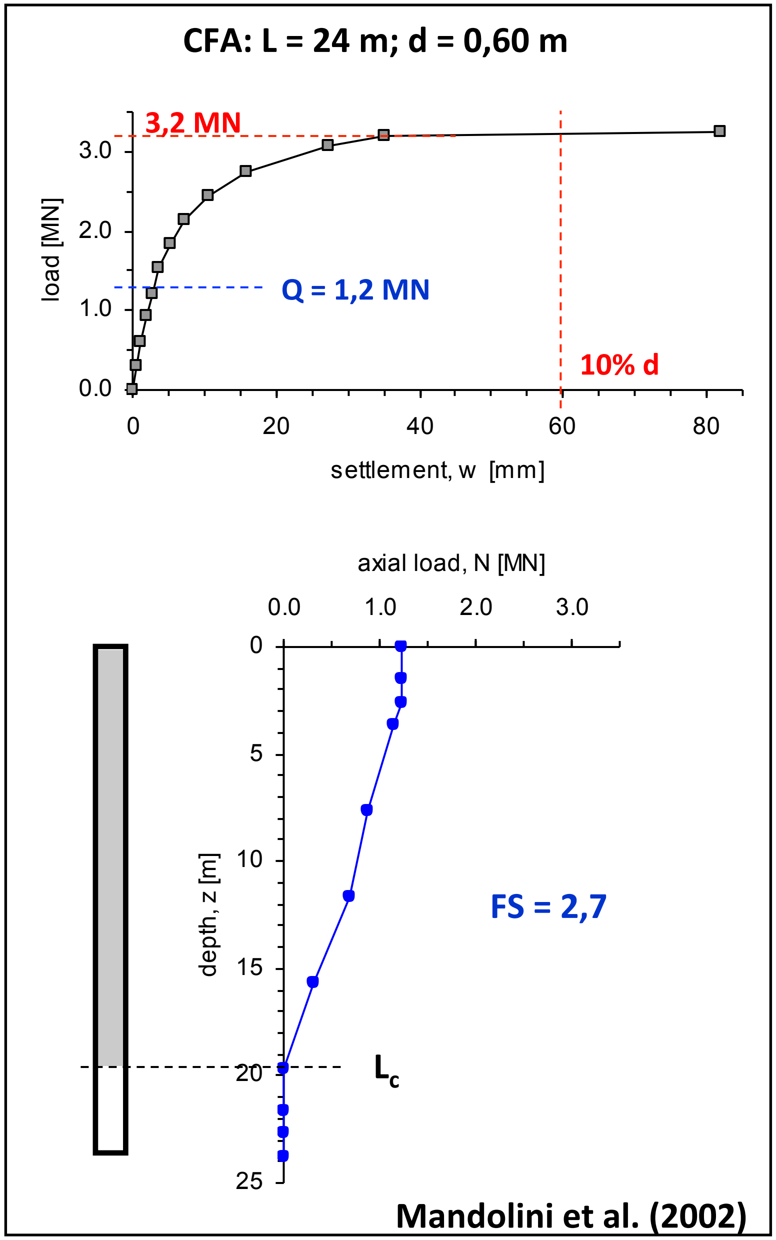
Mandolini & Viggiani (1997):
Settlement of piled foundations.
Geotéchnique, vol. 47(4)
Bishop Gold Medal Award by ICE, London, UK



Collected experimental evidence (Mandolini et al., 2005)

125 pile load tests on different piles (driven, screw, CFA, bored) in rather uniform subsoil conditions

$$L_c \sim 1.5 \cdot (E_p / G)^{0.5}$$



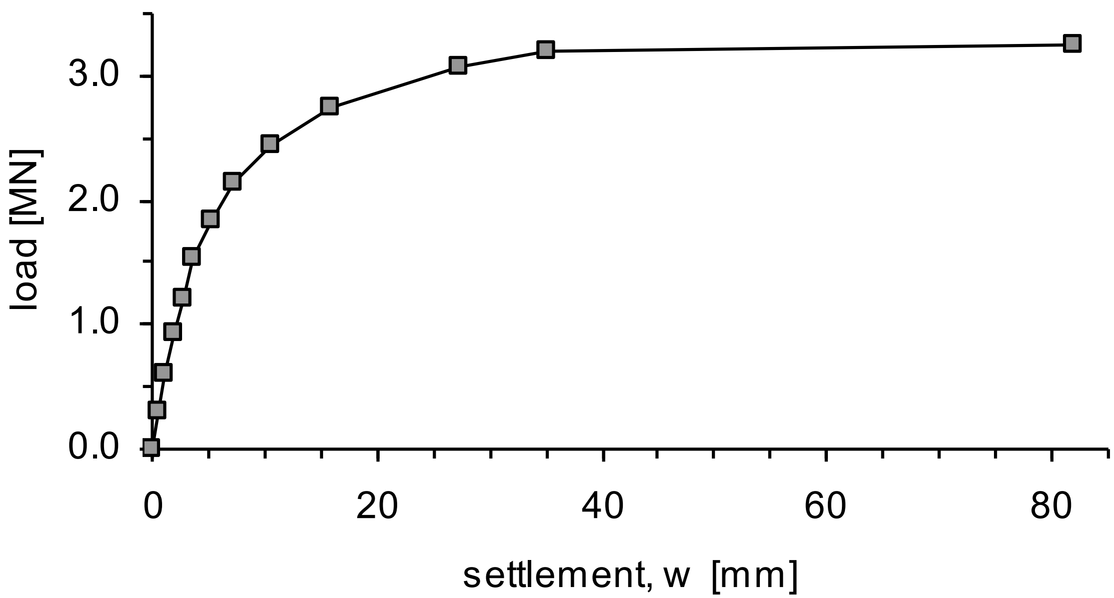
Collected experimental evidence (Mandolini et al., 2005)

d = 0.35 ÷ 2.00 m
L = 9.5 ÷ 42.0 m
L/d = 16 ÷ 61

$$RS_{av} = K_{0,meas.} / (EA/L_c)$$

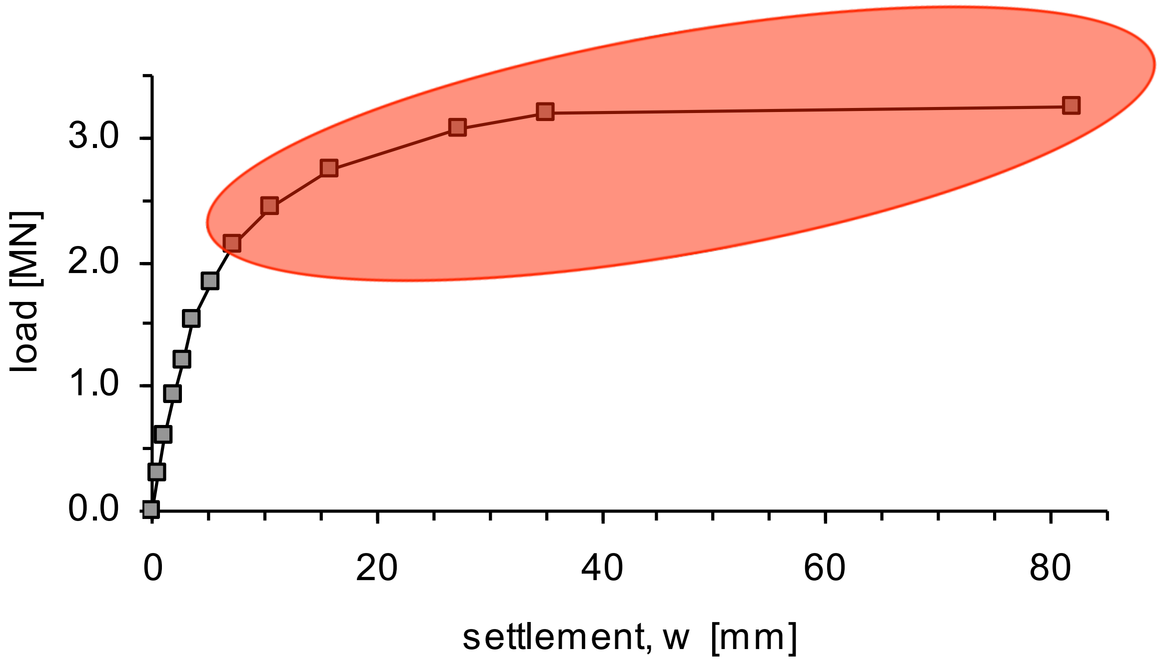
Pile type	$(RS)_{av}$	COV(RS)
Bored	1,46 (1)	0,28
CFA	1,44 (≈ 1)	0,46
Displacement	1,29 (≈ 0.9)	0,42

Summarizing:



Summarizing:

The pile response depends on the soil changes due to the specific pile installation procedure → great uncertainties



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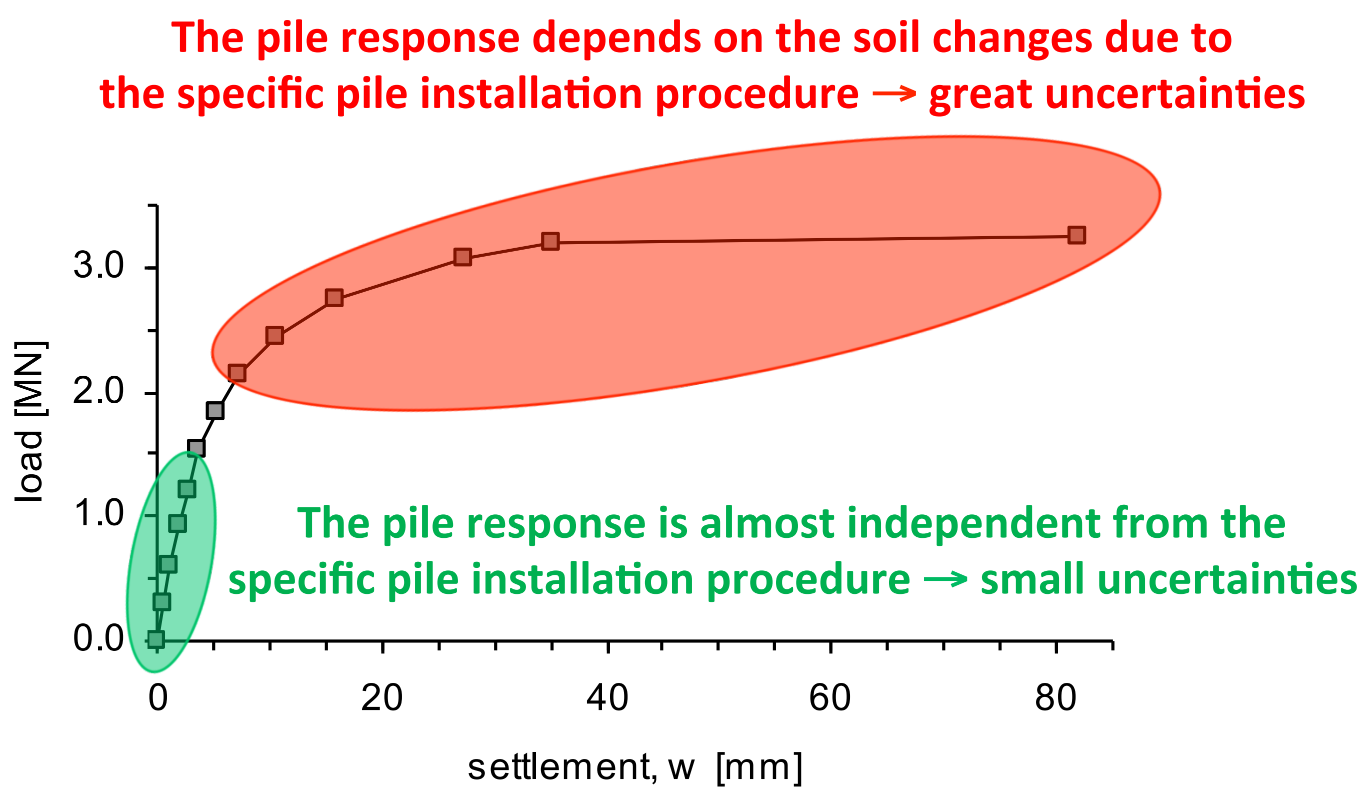

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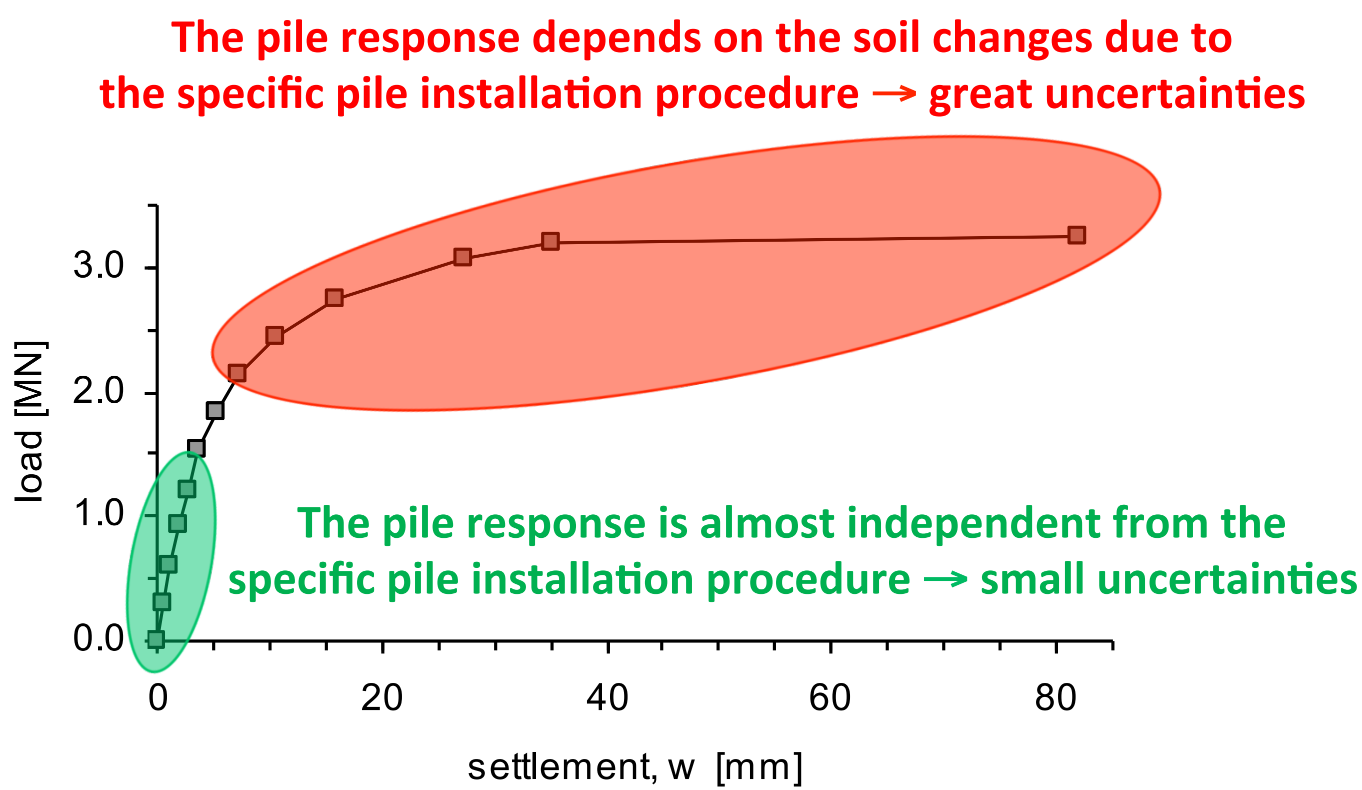

When dealing with piles, the more reliable design method is that of minimizing sensitivity to pile technology → stiffness and not capacity !!!

The only way to hopefully give a good answer is that of having a good question:

WHY PILES ARE NEEDED ?

ELASTIC THEORY, ALBEIT NOT ADEQUATE FOR PROBLEMS INVOLVING SOIL, IS A VERY SIMPLE TOOL TO DETECT MAIN ASPECTS

Average settlement of shallow foundation:

$$w = \frac{q \cdot B}{E} \cdot I = \frac{q_{lim} \cdot B}{FS \cdot E} \cdot I$$

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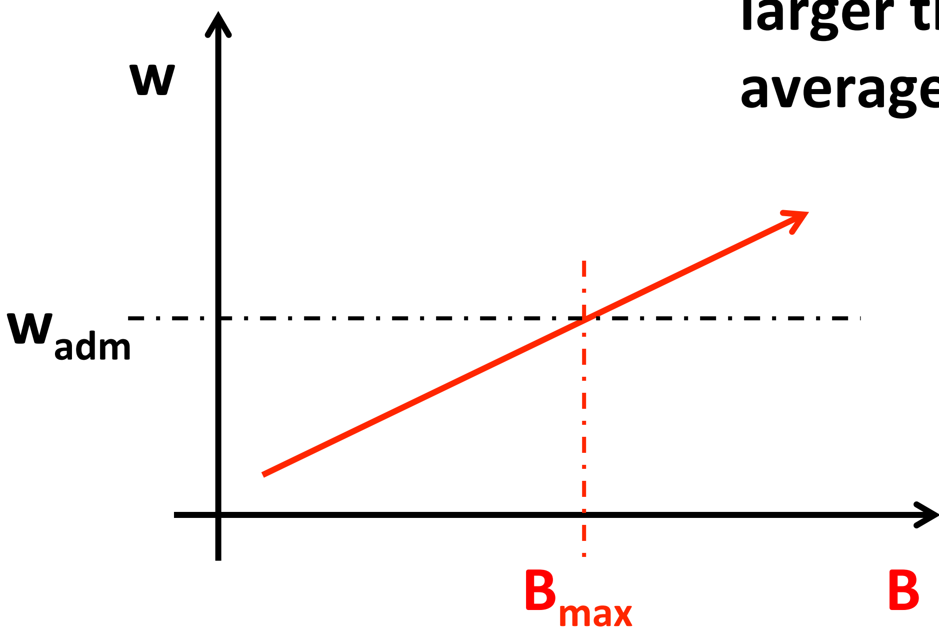

For a given soil stiffness and FS, foundation width should not be larger than B_{max} in order to limit average settlement.

Average settlement of shallow foundation:

$$w = q \cdot B / E \cdot I = q_{lim} \cdot B / FS \cdot E \cdot I$$

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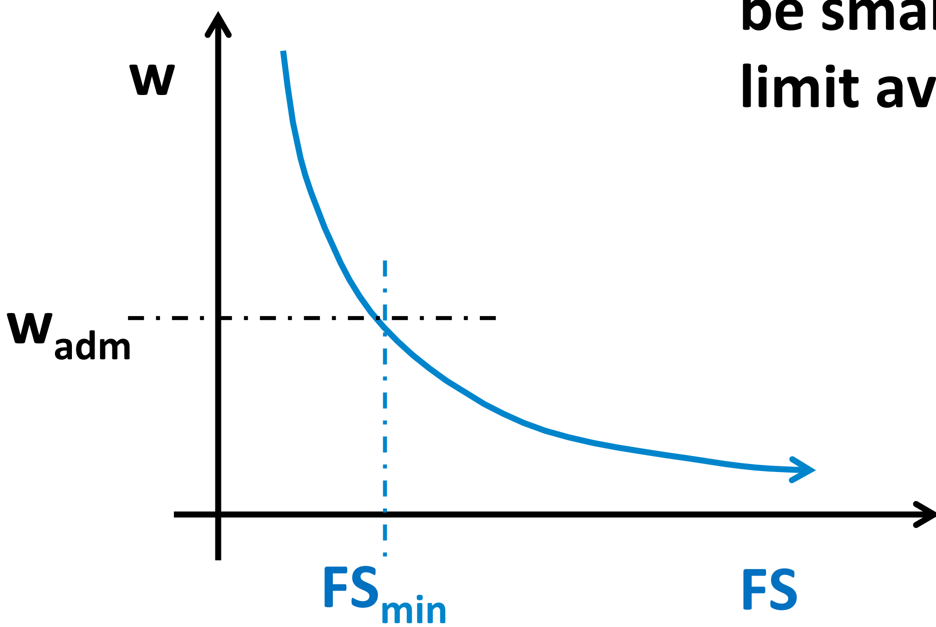

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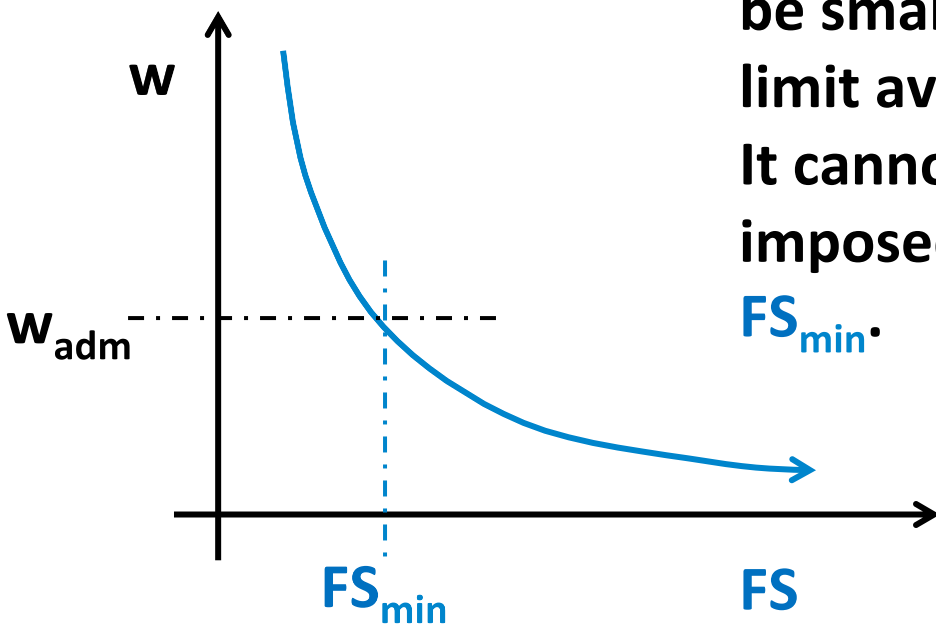
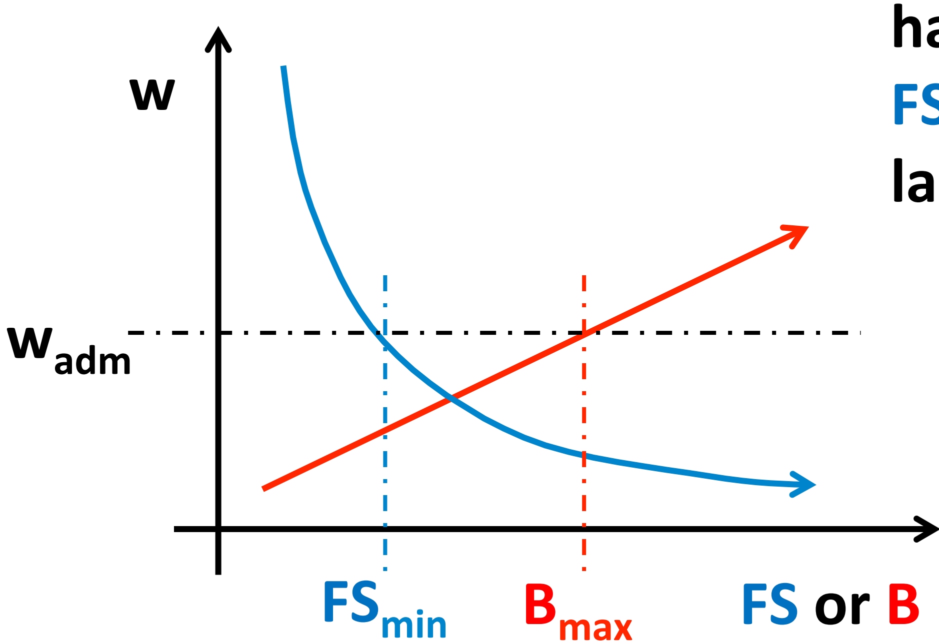


For a given soil stiffness and foundation width, FS should not be smaller than FS_{min} in order to limit average settlement.
It cannot be said that FS as imposed by Codes is larger FS_{min}.

Average settlement of shallow foundation:

$$w = q \cdot B/E \cdot I = q_{lim} \cdot B/FS \cdot E \cdot I$$



Large structures (large B) have typically larger FS (> FS_{min}) but could suffer large average settlement.

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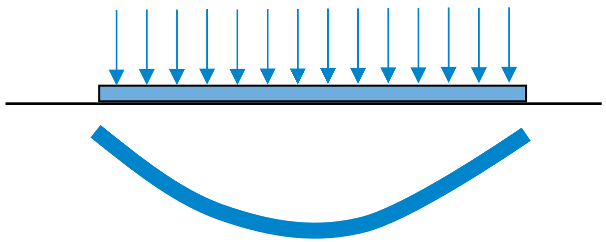
1. Piles can help in reducing average settlement

Large rafts have necessarily small raft-soil relative stiffness K_{rs} (expected dishing).



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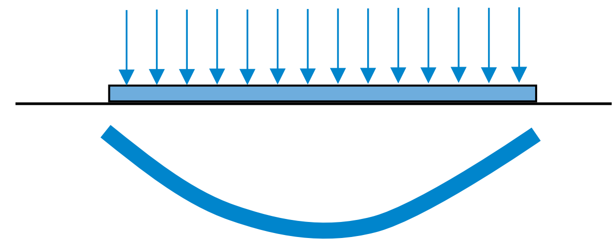

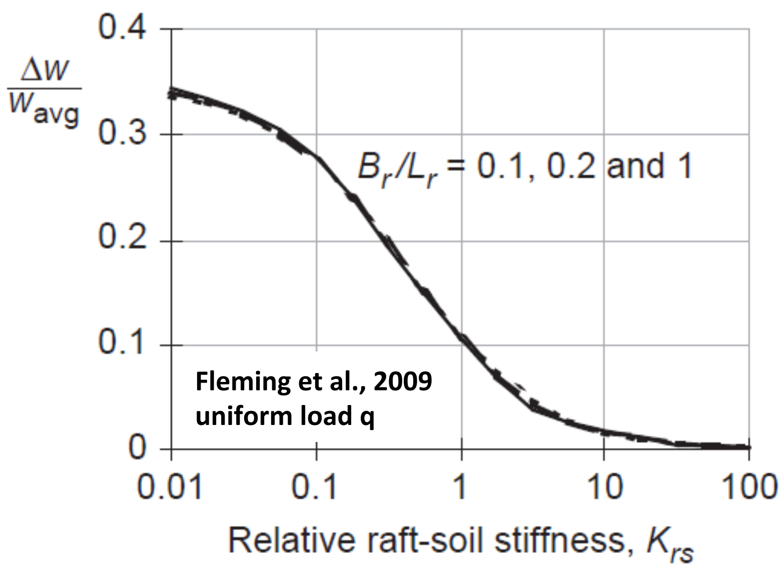

$$K_{rs} = 5.57 \frac{E_r}{E_s} \frac{1 - \nu_s^2}{1 - \nu_r^2} \left(\frac{B_r}{L_r} \right)^{0.5} \left(\frac{t_r}{L_r} \right)^3$$

For small values of K_{rs}, expected differential settlement can be ~ 1/3 of the expected average settlement of the unpiled raft (homogeneous soil conditions).

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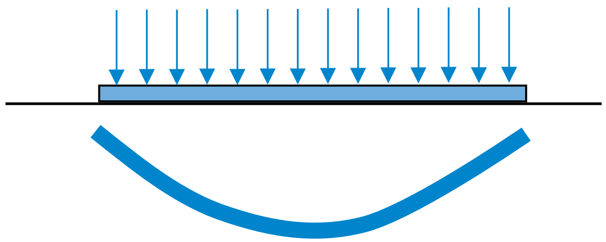

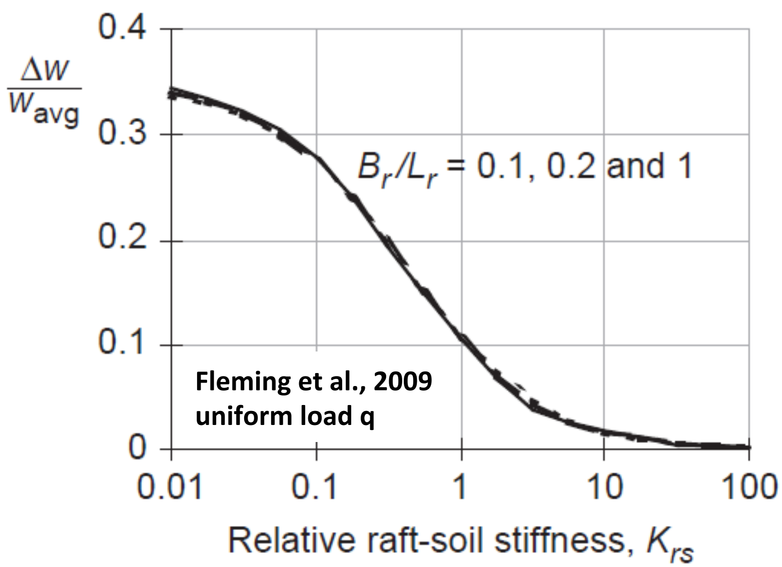

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Clearly, the larger the raft is, the thicker it should be.

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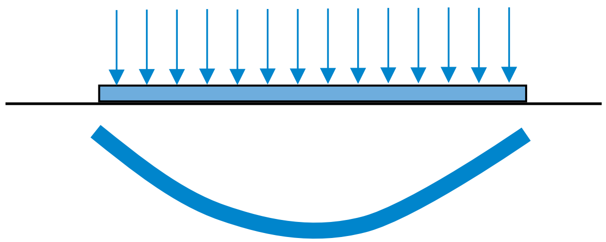
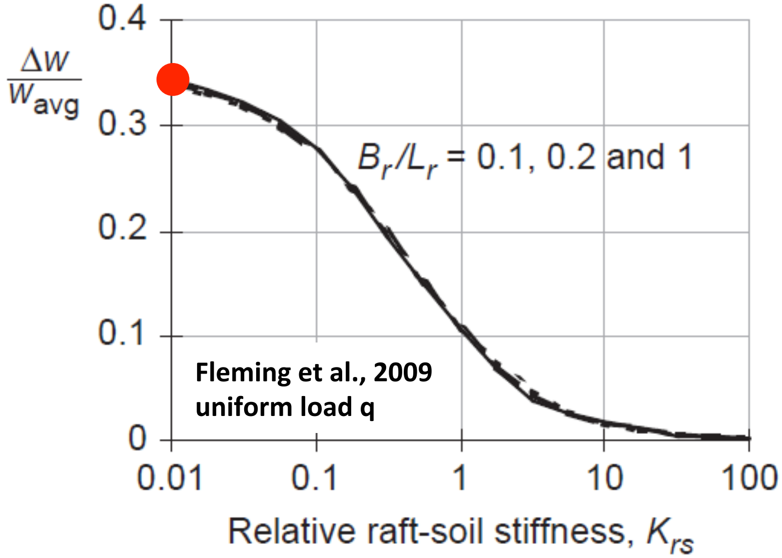


EXAMPLE

B_r = 50 m; L_r = 50 m; E_r/E_s = 250

ν_s = 0.30; ν_r = 0.15

$\Delta w/w_{avg}$ = 0.33 (K_{rs} = 0.01) → $t_r \sim$ 1 m



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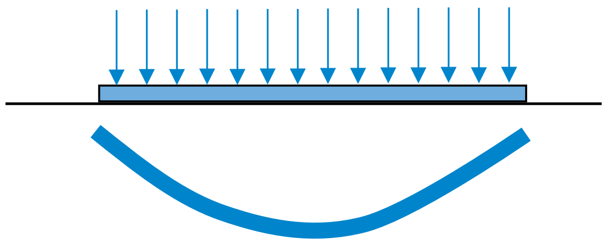

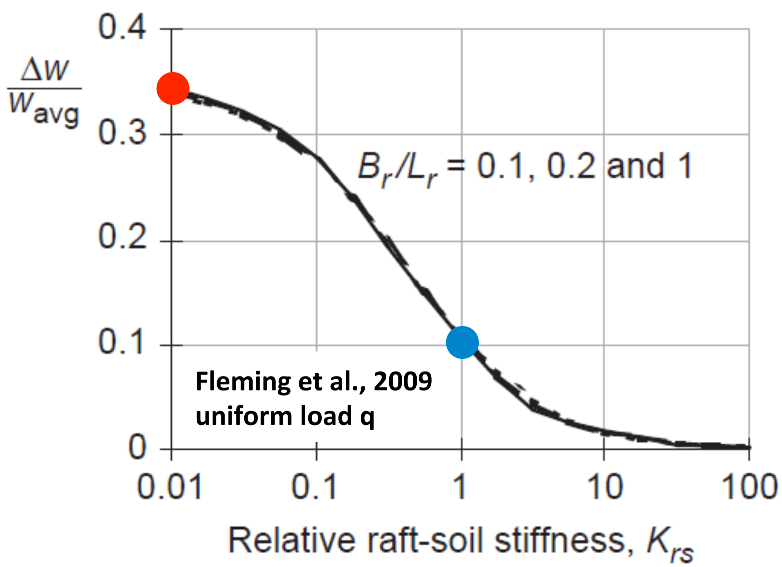

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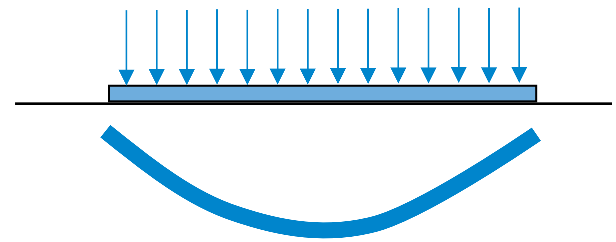

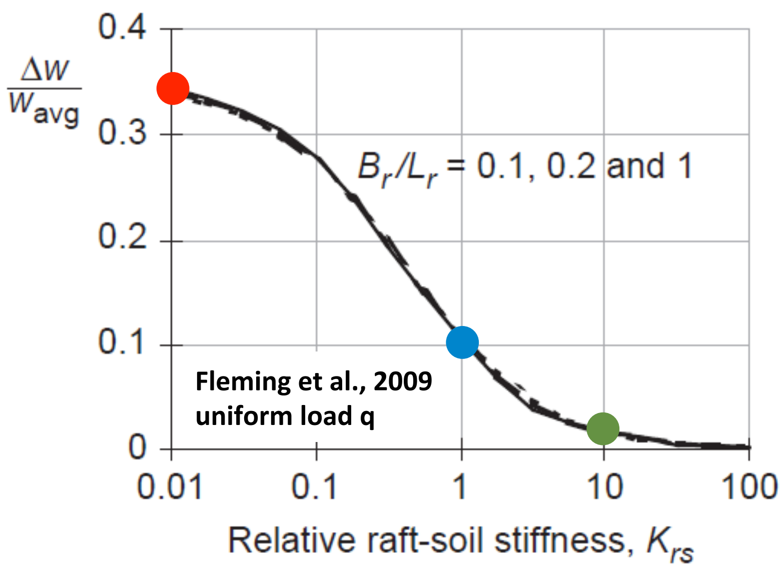

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$\Delta w/w_{avg} \sim$ 0 (K_{rs} = 10) → $t_r \sim$ 9.9 m

1. Piles can help in reducing average settlement
2. Piles can help in reducing differential settlement

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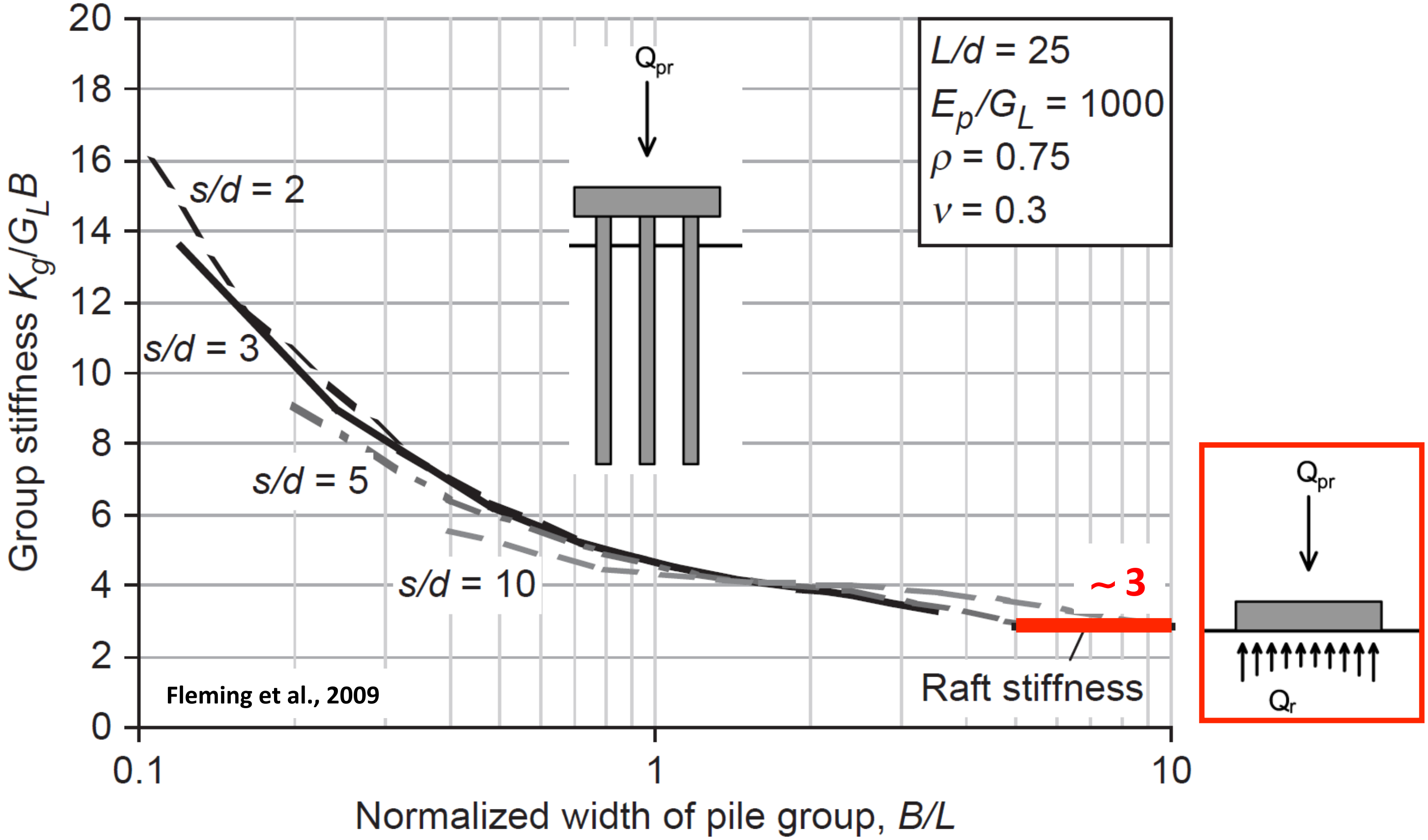
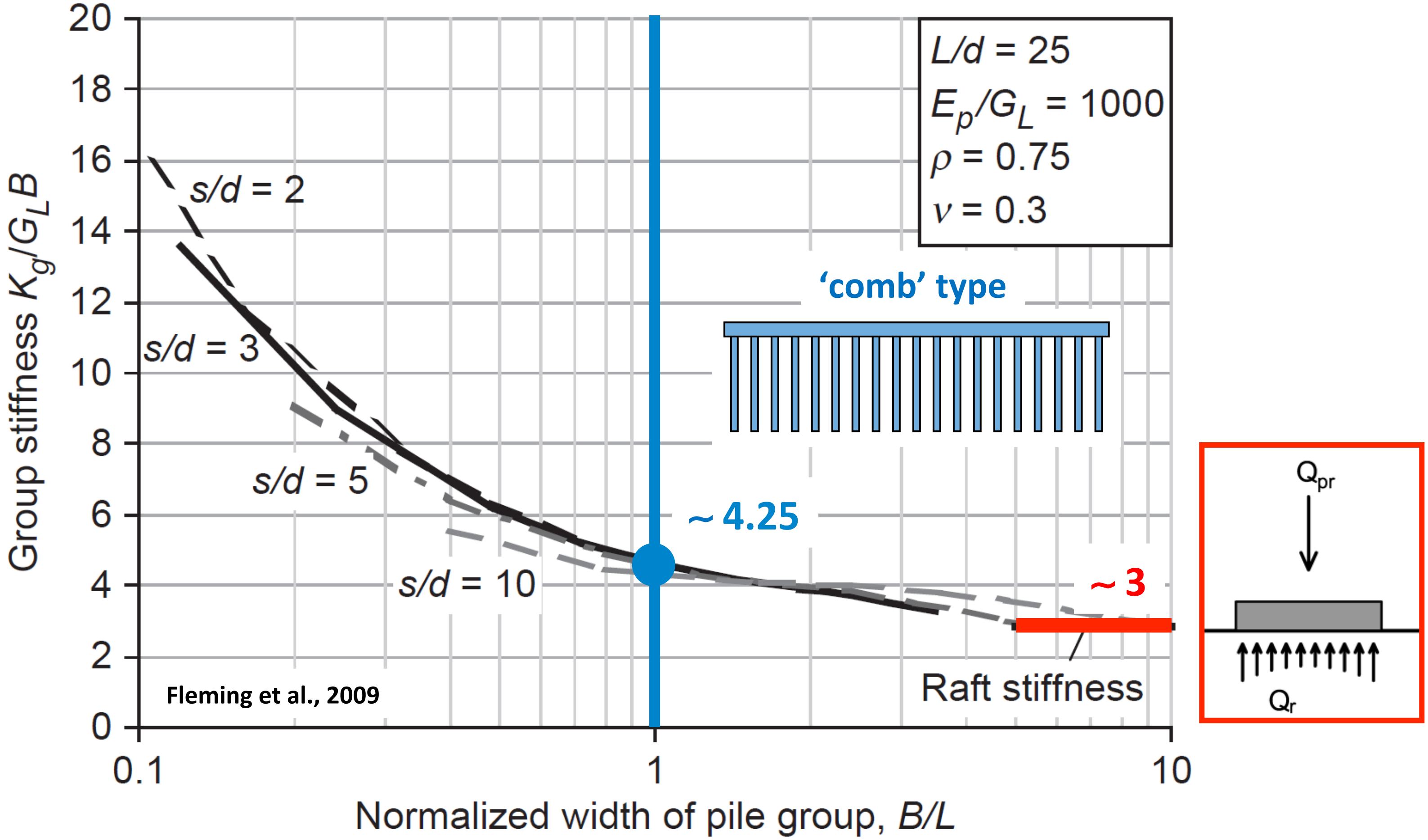
IS IT TRUE ?

$$K_{UR} = \frac{2 \cdot G \cdot B}{I \cdot (1-\nu)} \quad \rightarrow \text{square raft} \quad \frac{K_{UR}}{G \cdot B} = \frac{2}{0.946 \cdot (1-0.3)} \sim 3$$

Linear elastic solution for pile group stiffness



If the ratio B/L is large enough (say B/L > 1), adding piles is not very effective in increasing stiffness (4.25/3 ~ 1.4).



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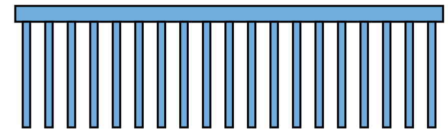
It is the case of large structures (large B): for practical pile length, it is often impossible to have B/L < 1.

‘comb’ type



EXAMPLE

B = 50 m
L = 50 m
d = 2 m
s = 8 m (4d)
N = 49 piles

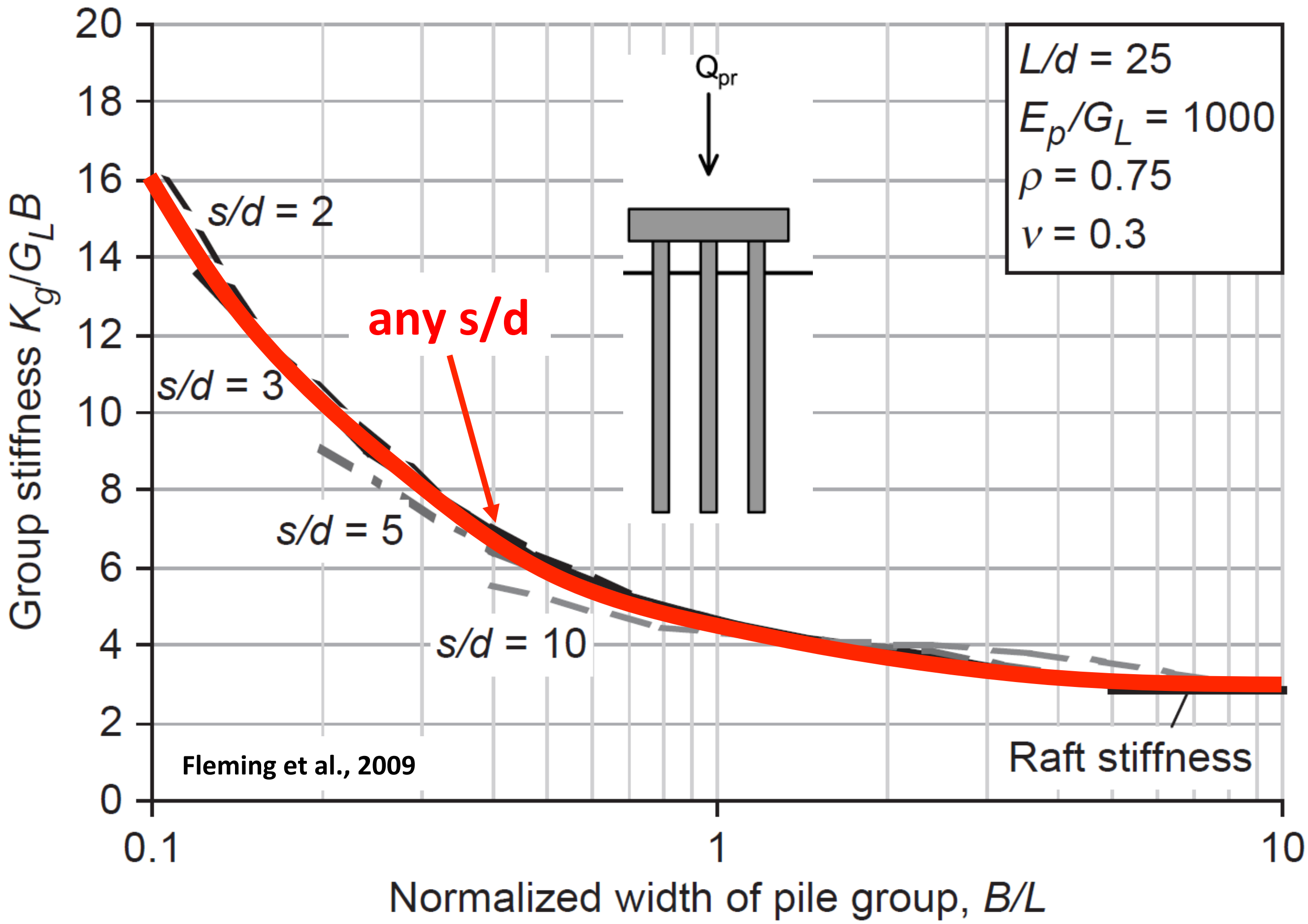
$$K_G / G \cdot B = 4,25$$

49 large diameter piles

(~ 2500 m total length, ~ 8000 m^3 concrete and soil removal, steel)

to reduce average settlement by 40% !!!!!

Due to the superimposition of curves for different spacing ratio s/d, the same pile group stiffness can be obtained with less but more spaced piles.



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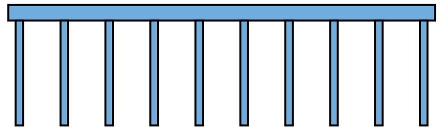
optimized 'comb' type



EXAMPLE

B = 50 m

L = 50 m

d = 2 m

s = 16 m (8d)

N = 16 piles

$$K_G / G \cdot B = 4{,}25$$

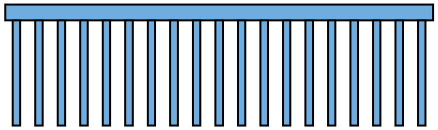
16 large diameter piles, but more spaced,

(~ 1/3 of the previous solution)

have the same effects!!!!!

Typically, a large raft has enough resistance; piles are hence needed only to reduce settlement.

'comb' type



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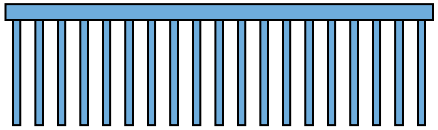
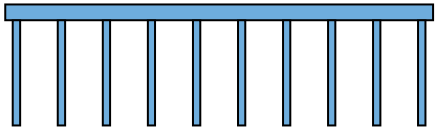


Due to practical problem, it is often impossible to have B/L < 1.
In these cases, piles can only slightly reduce average settlement (up to 40% in relatively homogeneous soil conditions). Optimized layouts should be pursued.



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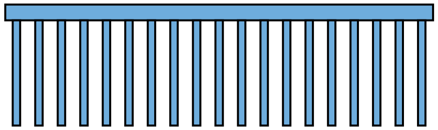
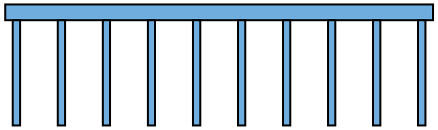
'comb' type



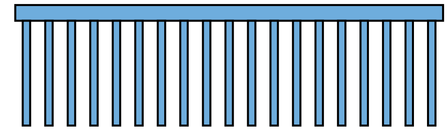
Due to practical problem, it is often impossible to have B/L < 1.
In these cases, piles can only slightly reduce average settlement (up to 40% in relatively homogeneous soil conditions). Optimized layouts should be pursued.

optimized 'comb' type



WARNING: If a reduction of 40% is not enough, adding piles do not help to satisfy that design requirement for which they have been considered.

‘comb’ type



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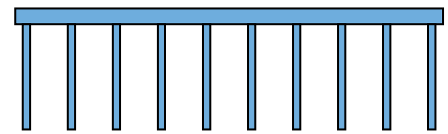

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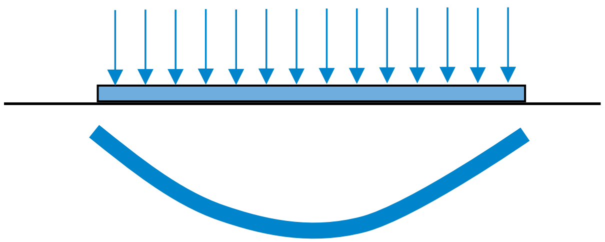
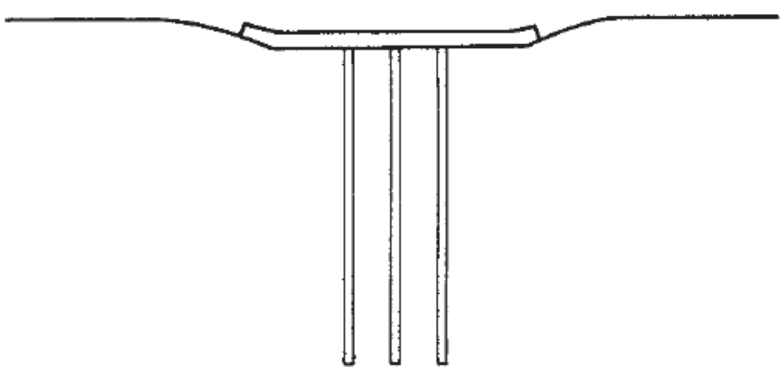
Piles strategically placed in order to reduce differential settlement.



(a) Dishing of unpiled raft



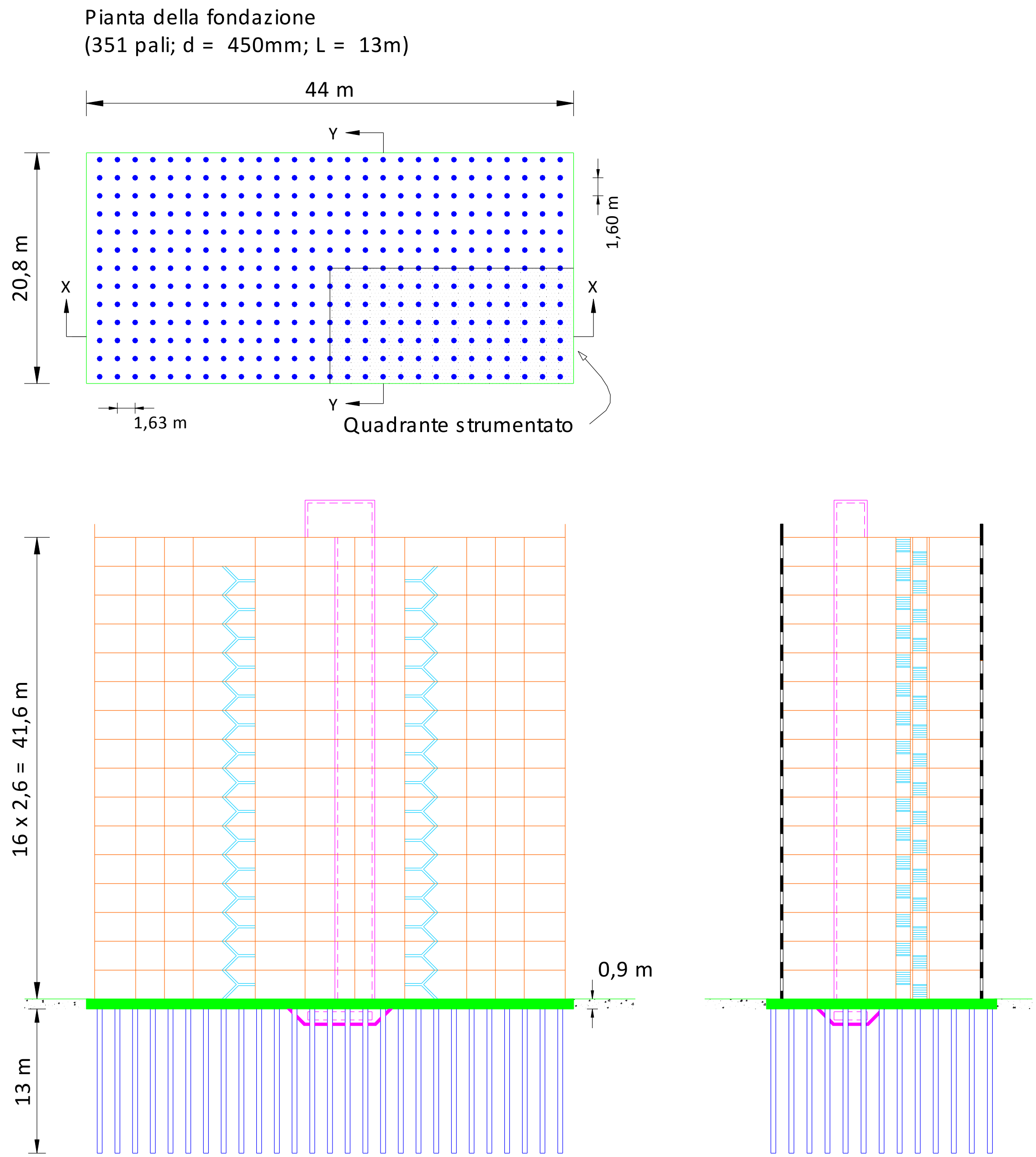
(b) Effect of differential settlement reducing piles

STONEBRIDGE PARK BUILDING (Cooke et al., 1980)

London clay:

$c_u \sim 100$ kPa

$G_0 = 21$ MPa



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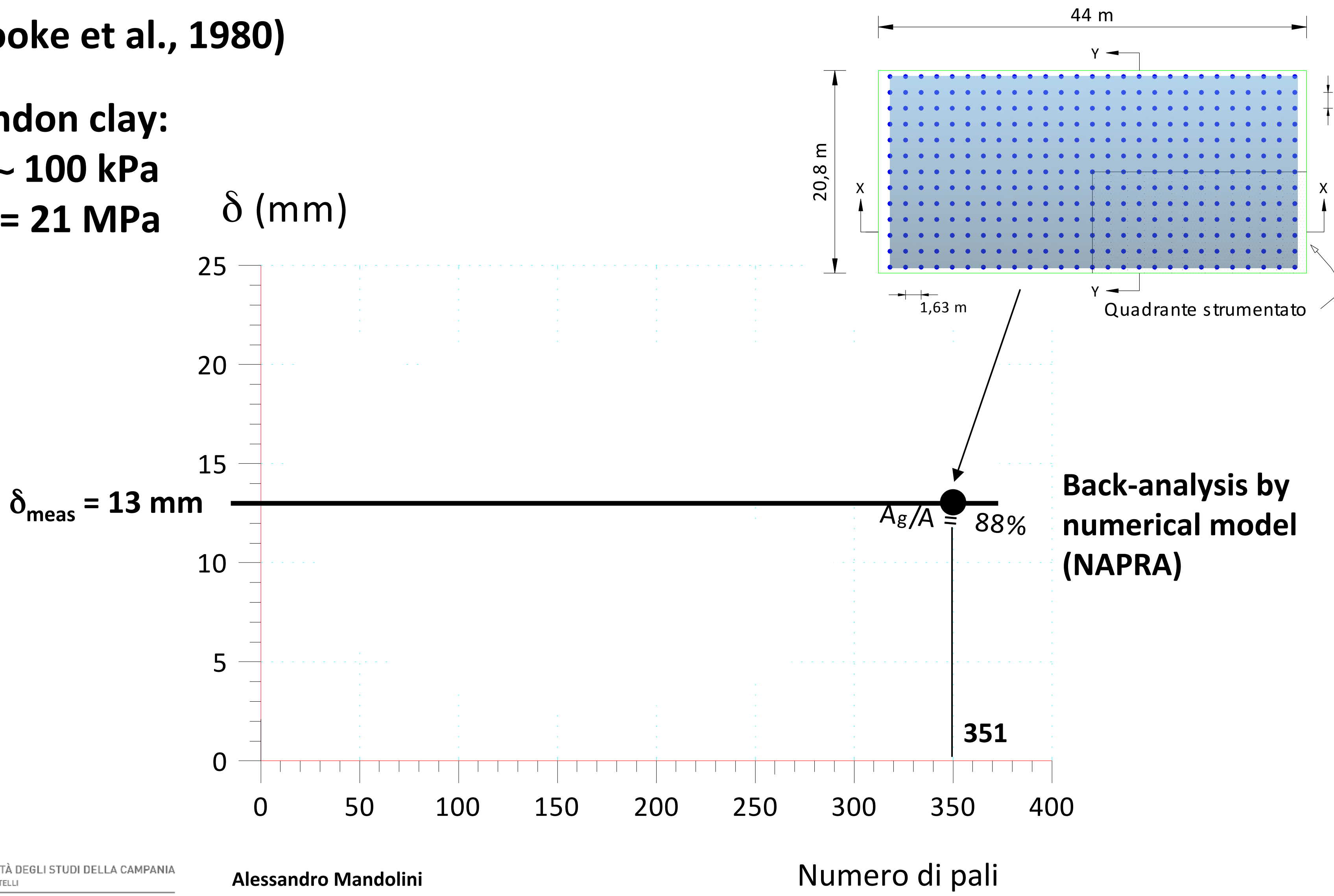

Back-analysis by numerical model (NAPRA)

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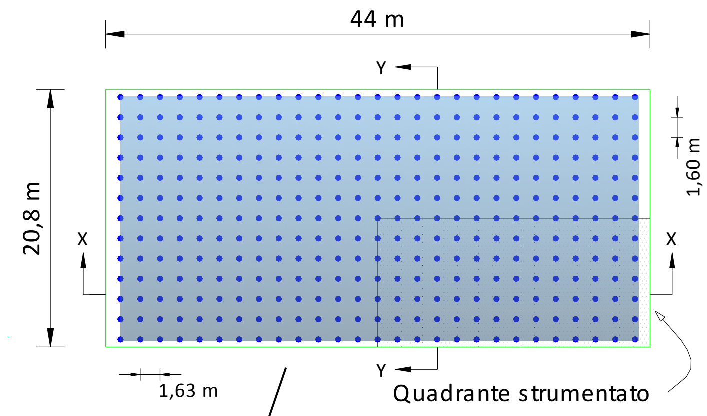

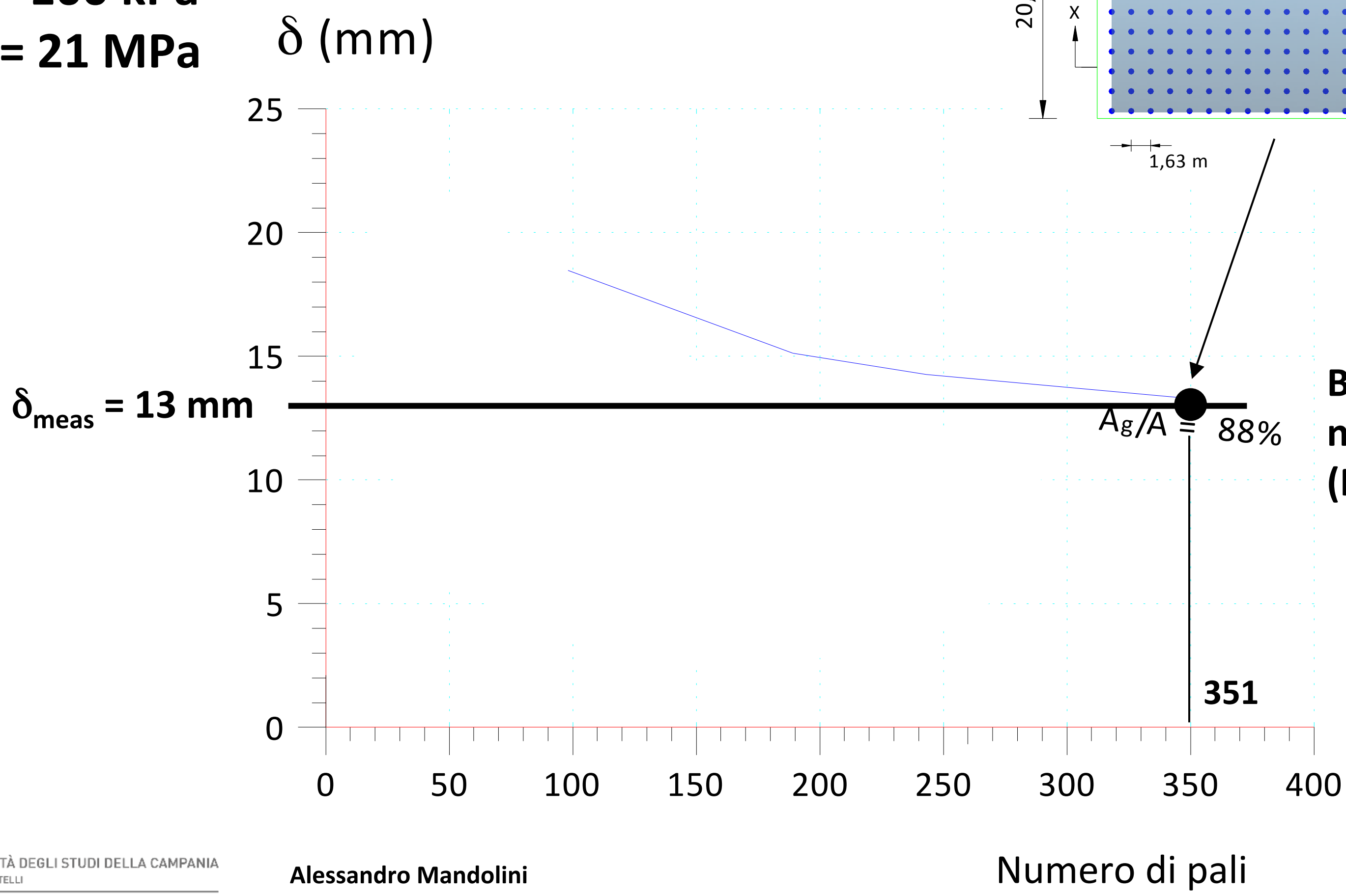

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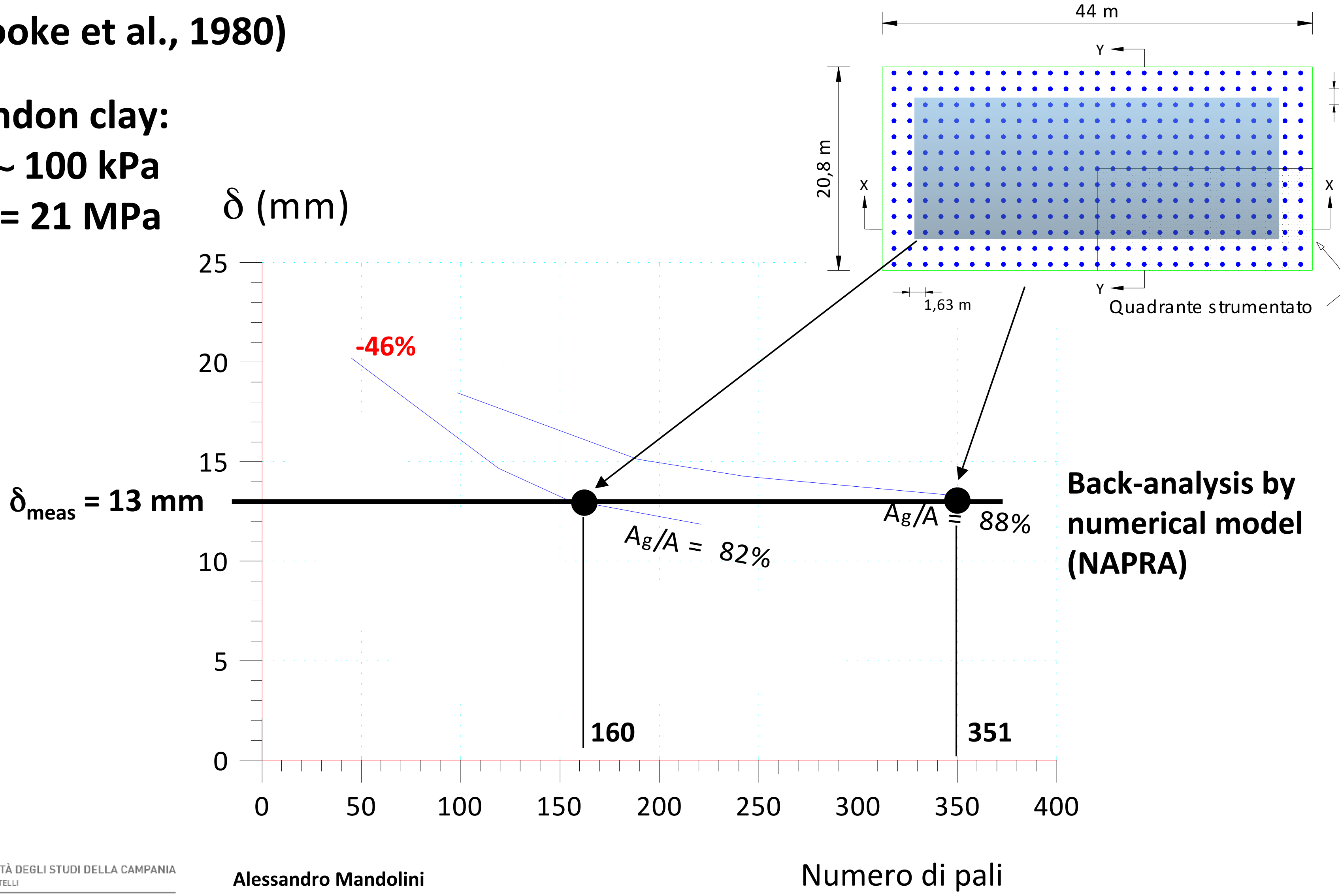

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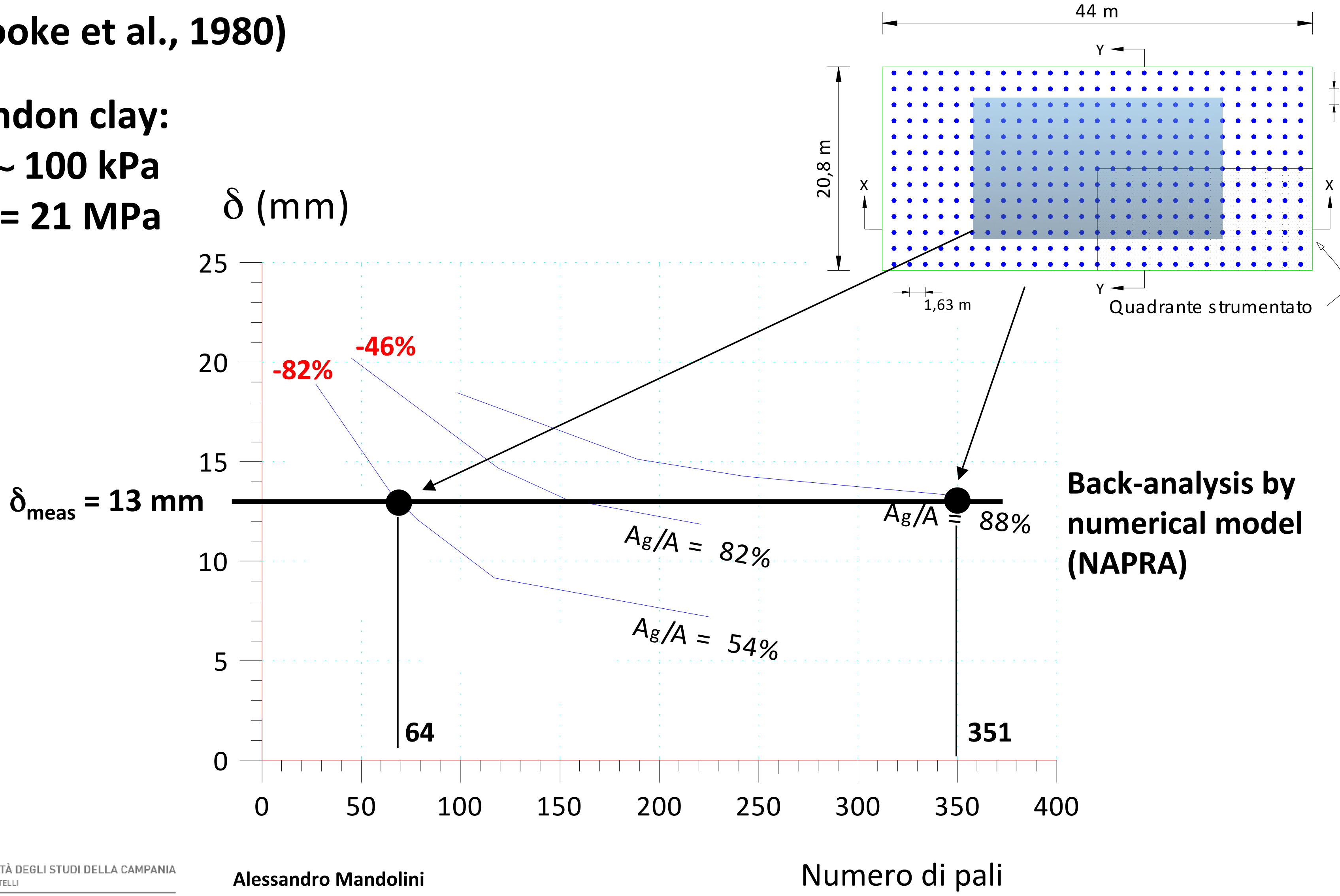

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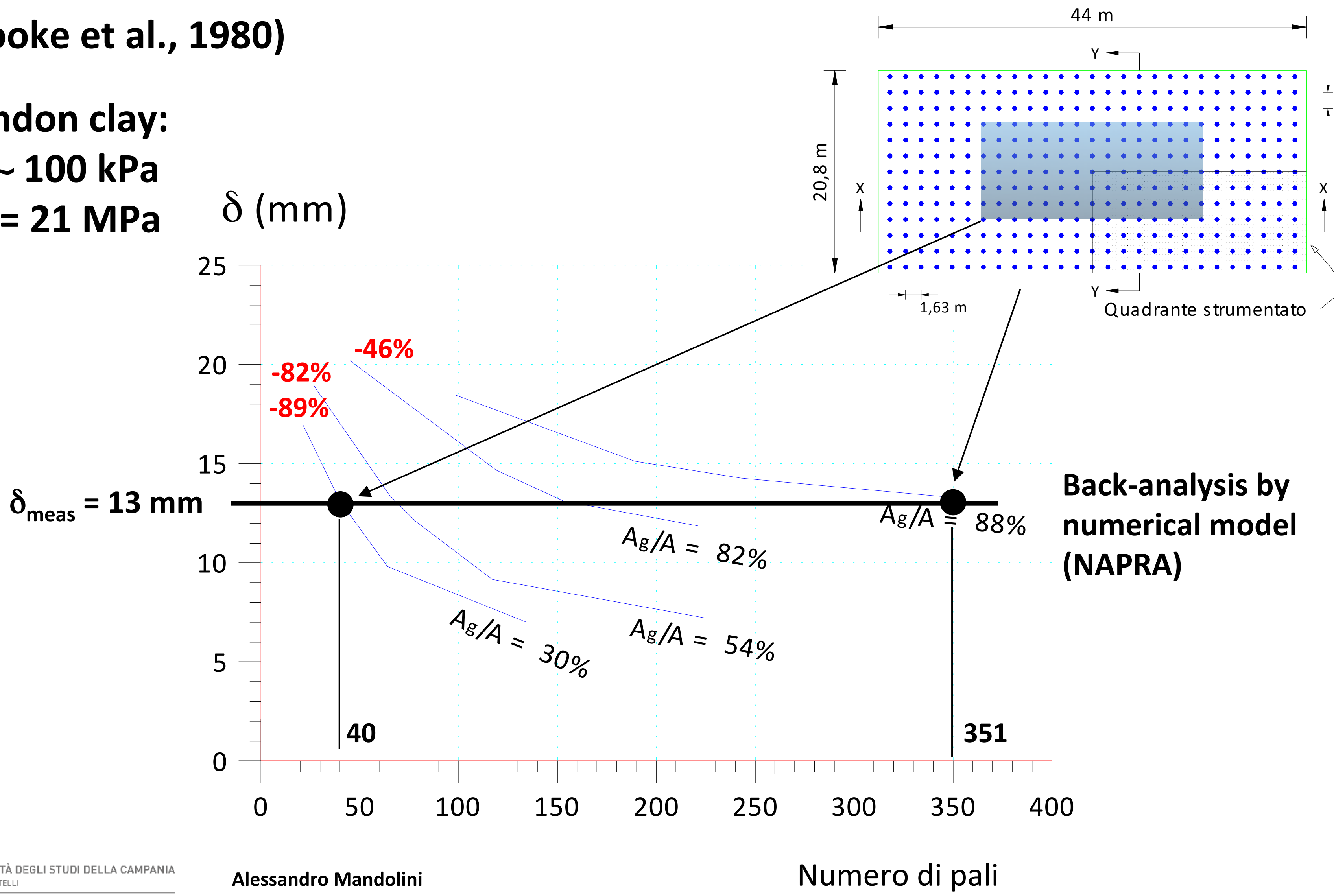
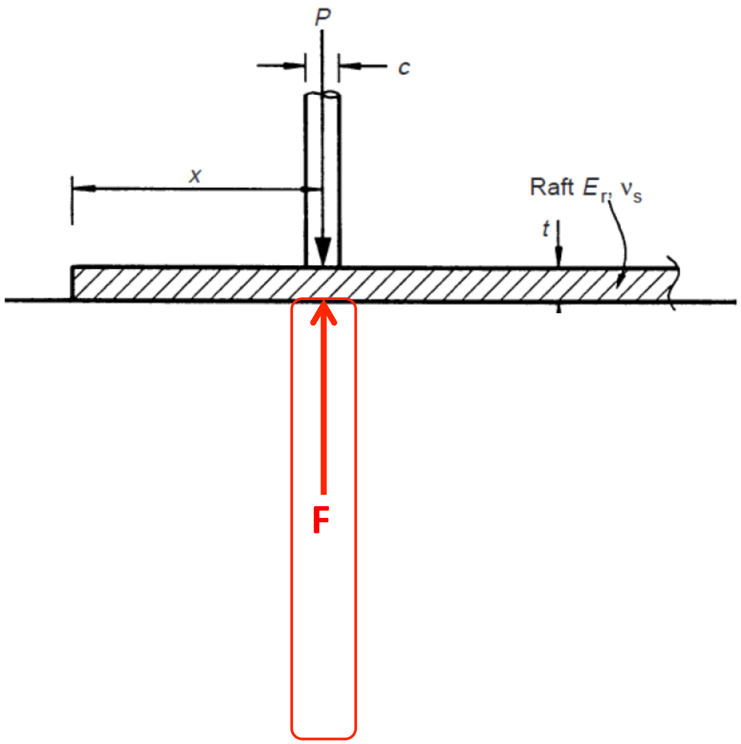


Back-analysis by numerical model (NAPRA)

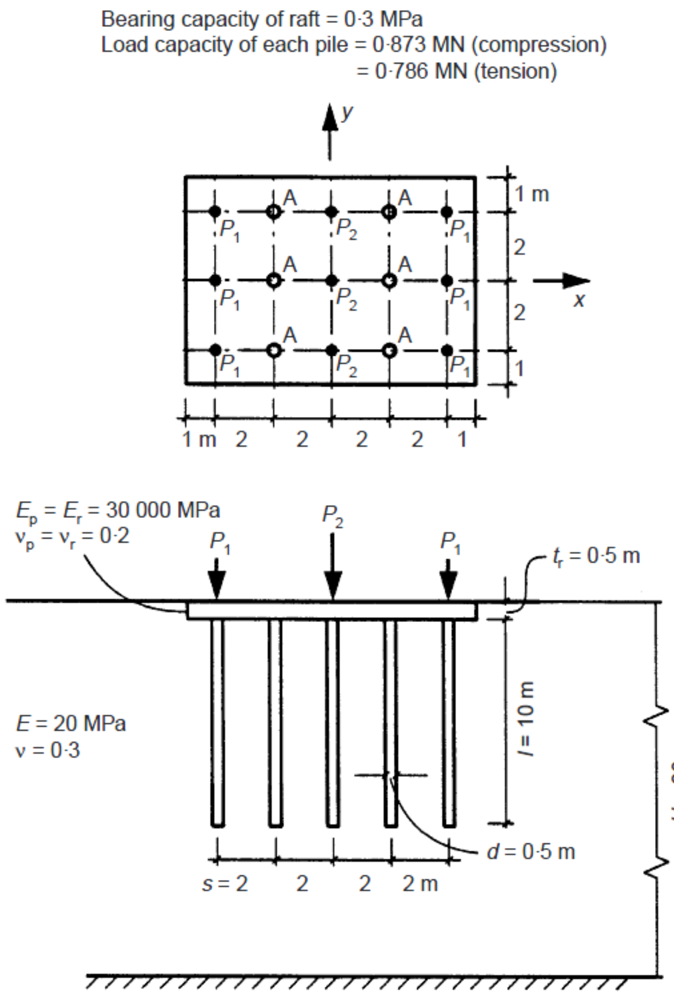
Reducing differential settlement: benefit on bending moment and shear forces in the raft



The concept

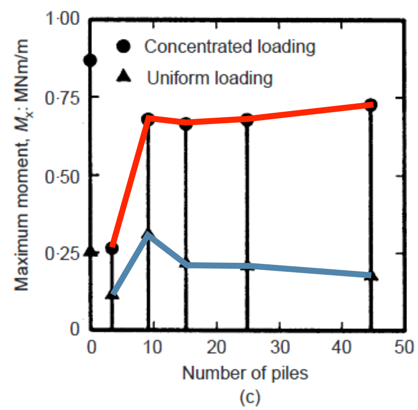
For given conditions, M and T will increase as P increases.
Piles placed just underneath the column and working at a load F will help to reduce the state of the stress into the raft at some distance x.

Reducing differential settlement: benefit on bending moment and shear forces in the raft



Theoretical example by Poulos (2001):

only 3 piles strategically located give the best performance in terms of bending moment M



~ 1/3 for concentrated loading
~ 1/2 for uniform loading

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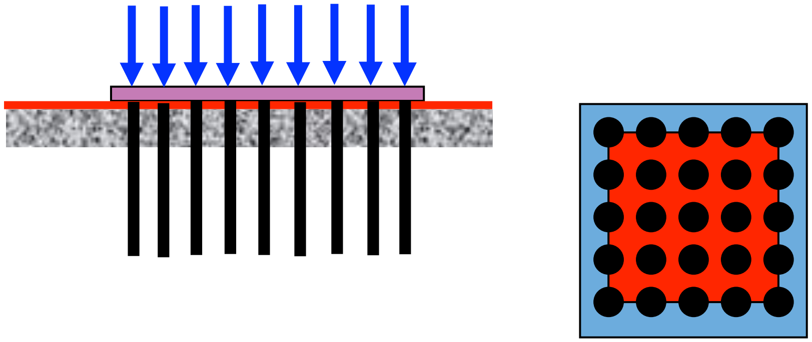
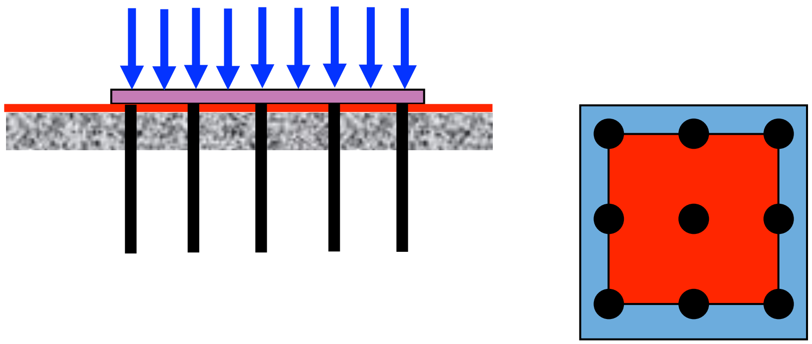
Different layouts for large piled rafts (B/L > 1)



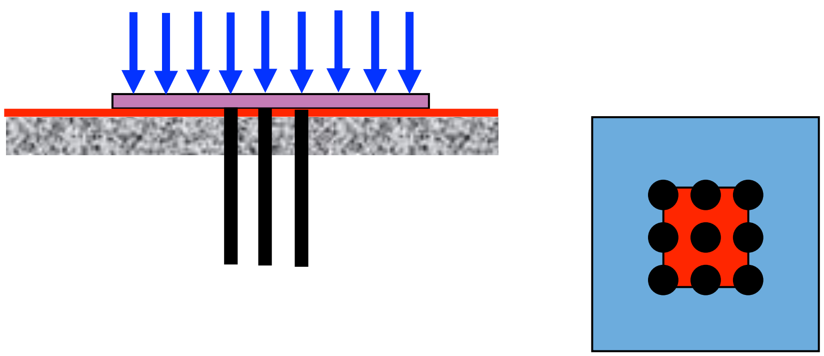
$A_G/A \rightarrow 1$
s/d small

CONVENTIONAL



$A_G/A \rightarrow 1$
s/d large

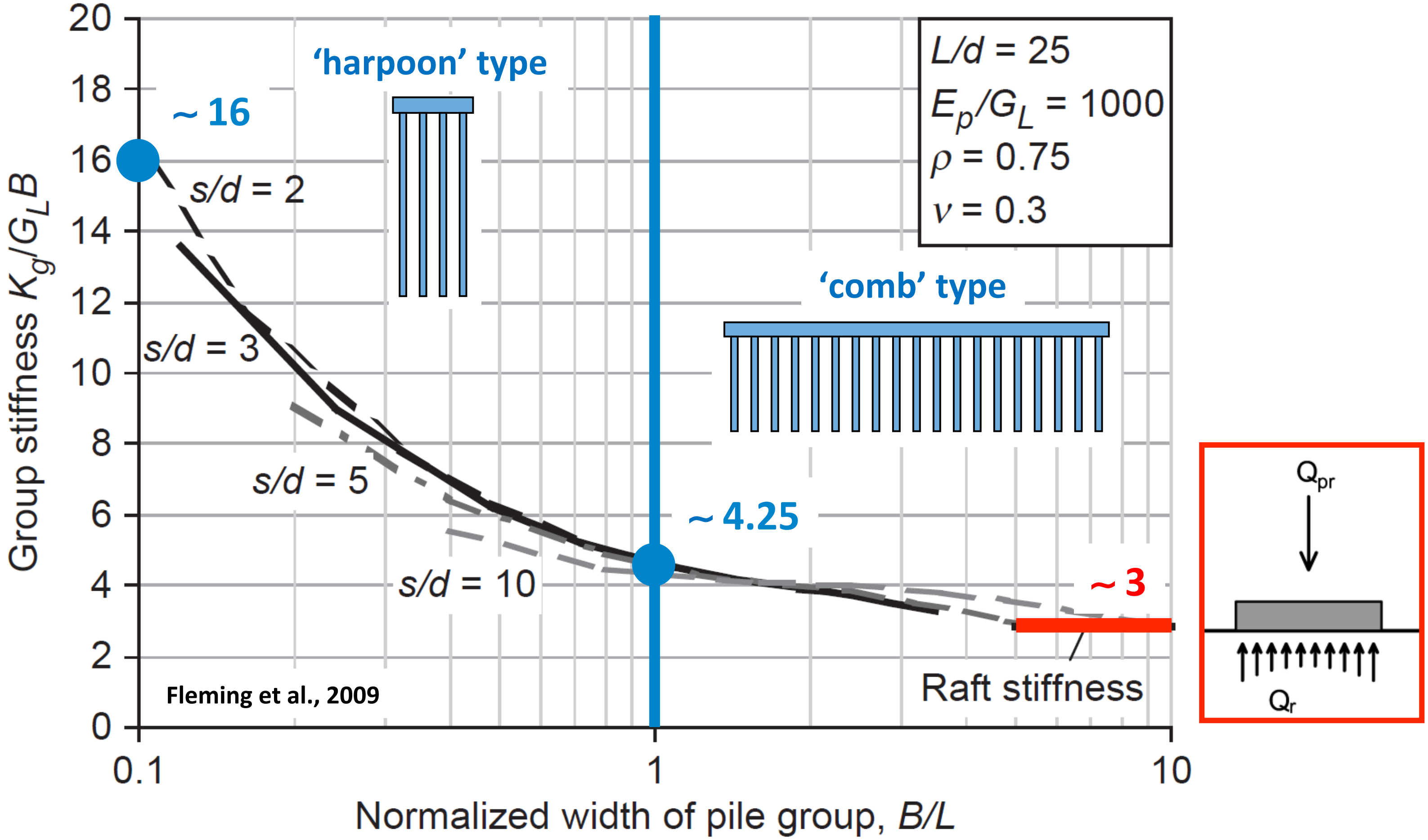
OPTIMIZED, but not necessarily effective



$A_G/A < 1$
s/d small

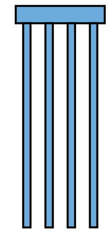
OPTIMIZED, effective for reducing Δw and M

If the ratio B/L is small enough (say B/L < 1), adding piles is more and more effective in increasing stiffness (16/3 ~ 5.3).



It is the case of small structures (small B) for which is relatively easy to have B/L < 1.

'harpoon' type



EXAMPLE

B = 10 m
L = 20 m
d = 0.5 m
s = 2 m (4d)
N = 25 piles

$$K_G / G \cdot B = 5.2$$

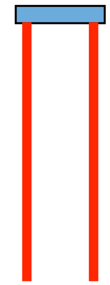
25 medium dia. piles

(total length 500 m)

to reduce average settlement by 70%

It is the case of small structures (small B) for which is relatively easy to have B/L < 1.

'harpoon' type



EXAMPLE

B = 10 m
L = 30 m
d = 0.5 m
s = 4 m (8d)
N = 9 piles

$$K_G / G \cdot B = 7.5$$

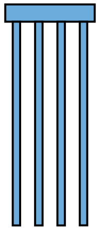
9 medium dia. piles, but more spaced and longer,

(total length ~ 1/2 of the previous solution)

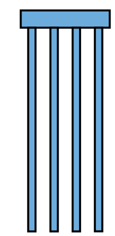
have the same effects!!!!!

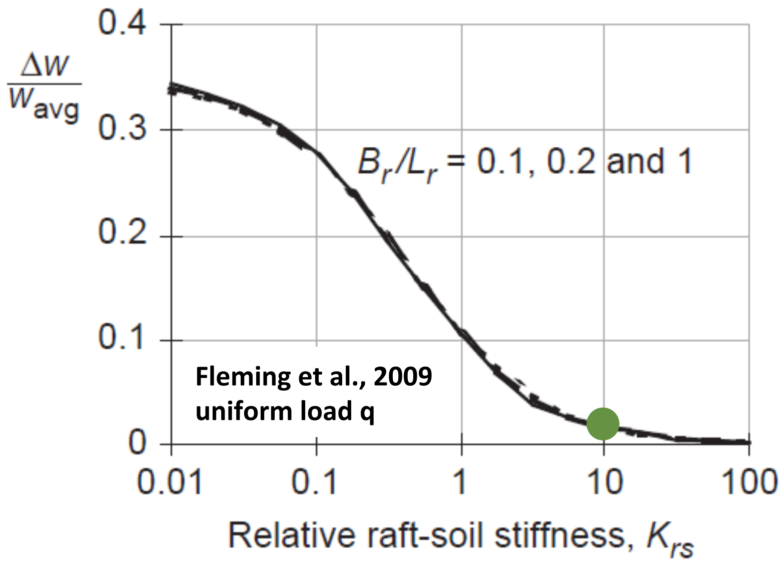
In the case of small structures (small B), piles can greatly help to reduce average settlement.

‘harpoon’ type



Differential settlement is not a major problem. If the case, it can be tackled by adopting reasonable raft thickness.





$$K_{rs} = 5.57 \frac{E_r}{E_s} \frac{1-\nu_s^2}{1-\nu_r^2} \left(\frac{B_r}{L_r}\right)^{0.5} \left(\frac{t_r}{L_r}\right)^3$$

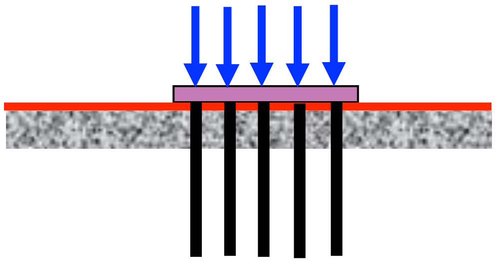
EXAMPLE

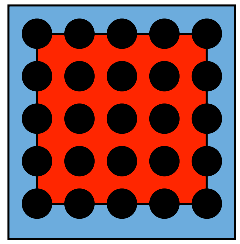
B_r = 10 m; L_r = 10 m; E_r/E_s = 250

ν_s = 0.30; ν_r = 0.15

$\Delta w/w_{avg} \sim 0$ (K_{rs} = 10) → $t_r \sim 2$ m

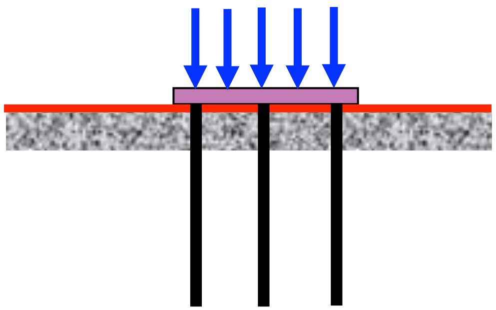
Different layouts for small piled rafts (B/L < 1)

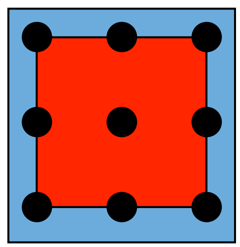




$A_G/A \rightarrow 1$
s/d small

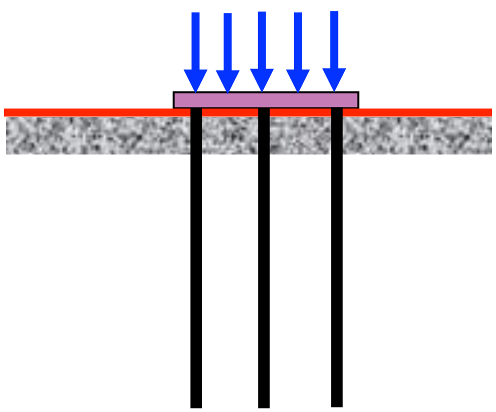
CONVENTIONAL

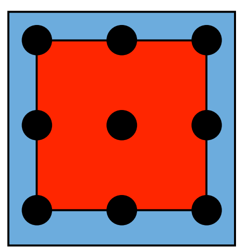




$A_G/A \rightarrow 1$
s/d large
B/L ~ 0.5÷0.7

OPTIMIZED, effective for reducing w





$A_G/A \rightarrow 1$
s/d large
B/L ~ 0.3÷0.4

OPTIMIZED, larger impact in reducing w

The decision of using piles can be also due to poor bearing capacity of the raft.

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$$q_{lim} = F_q \cdot N_q \cdot \sigma_{vD} + F_c \cdot N_c \cdot c + F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

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$$q_{lim} = \sout{F_q \cdot N_q \cdot \sigma_{vD}} + F_c \cdot N_c \cdot c + F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

For sake of simplicity, in the following the term related to foundation depth will be neglected.

$$q_{lim} = F_c \cdot N_c \cdot c + F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

In fine grained soils (clay, silty clay), undrained conditions are generally those governing bearing capacity problem:

$$q_{lim} \approx 6 \cdot c_u$$

In coarse grained soils (sand, gravel), only drained conditions have to be considered:

$$q_{lim} \approx F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

$$q_{lim} \approx 6 \cdot c_u$$

$$q_{lim} \approx F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

According to local Codes, maximum applied load is defined as:

$$q_{max} \approx \frac{6 \cdot c_u}{FS}$$

$$q_{lim} \approx \frac{F_\gamma \cdot N_\gamma \cdot \gamma \cdot B}{2 \cdot FS}$$

Assuming FS = 3, it is simple to demonstrate that:

in fine grained soils, it is possible to build structures corresponding to uniform loads ranging from few tens of kPa (n.c.) to few hundreds of kPa (o.c.).

$$q_{lim} \approx 6 \cdot c_u$$

$$q_{lim} \approx F_\gamma \cdot N_\gamma \cdot \gamma \cdot \frac{B}{2}$$

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Assuming FS = 3, it is simple to demonstrate that:

in coarse grained soils, it is possible to build structures corresponding to uniform loads ranging from few hundred of kPa (loose and n.c.) to few thousands of kPa (dense and o.c.).

The minimum factor of safety (FS = 3) is often, to not say very often, guaranteed

n.c. clay
few tens of meters

o.c clay
tens of meters

Loose n.c sand
few hundreds of meters

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Other benefit from adopting spaced piles ?

Two fundamental parameters:

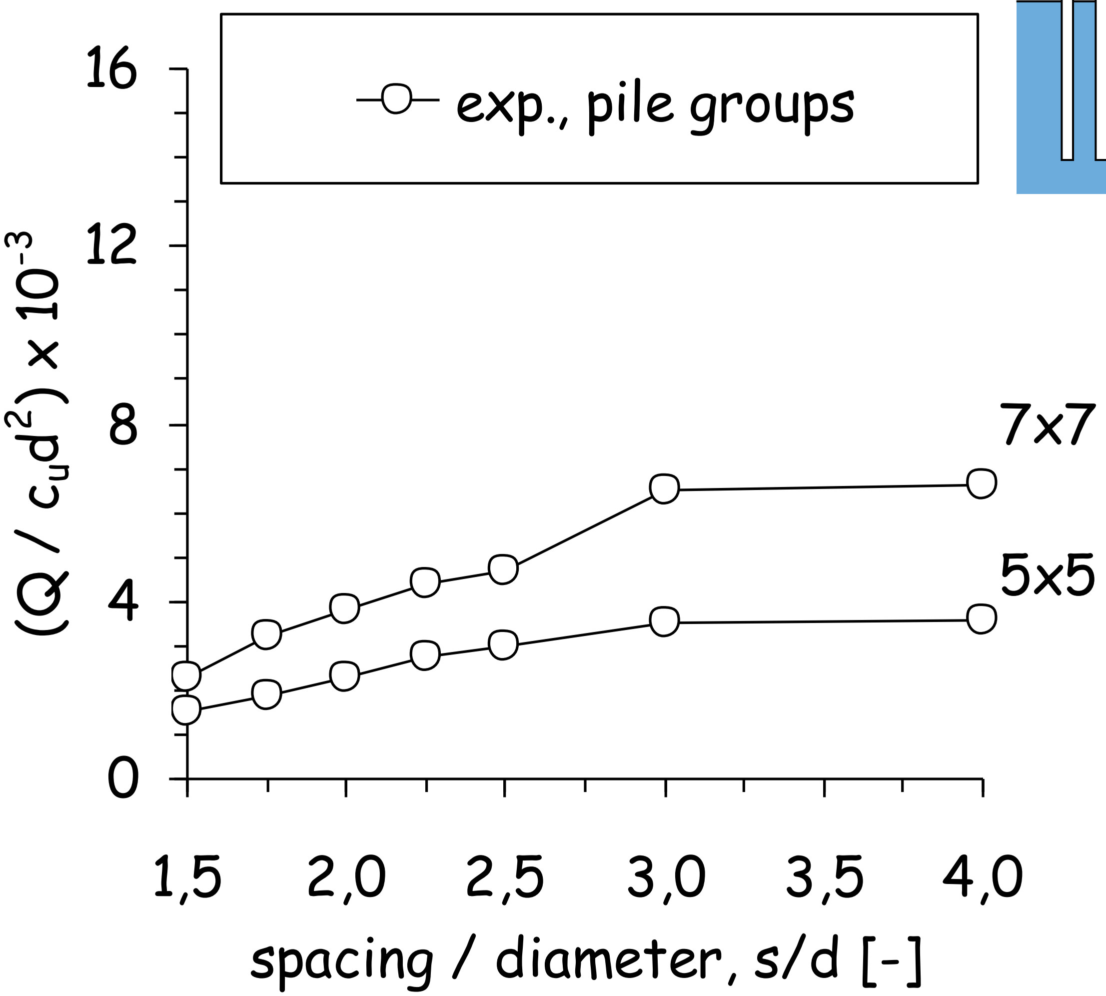
- **Pile group efficiency at failure** $\eta_{PG} = R_{PG} / R_S$

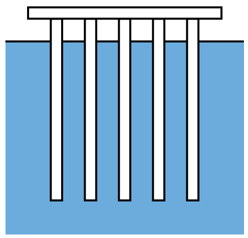
- **Piled raft efficiency at failure** $\beta_{PR} = R_{PR} / R_{PG}$

R_{PR} = piled raft resistance
R_{PG} = pile group resistance
R_S = single pile resistance

Cooke (1986): *Piled raft foundations on stiff clays—a contribution to design philosophy*
Géotechnique, vol. 36(2)

rem. London clay - 1-g lab model
$N = 3^2, 5^2, 7^2, 9^2$
L/d = 24, 48
s/d ≤ 4
w = 10%B





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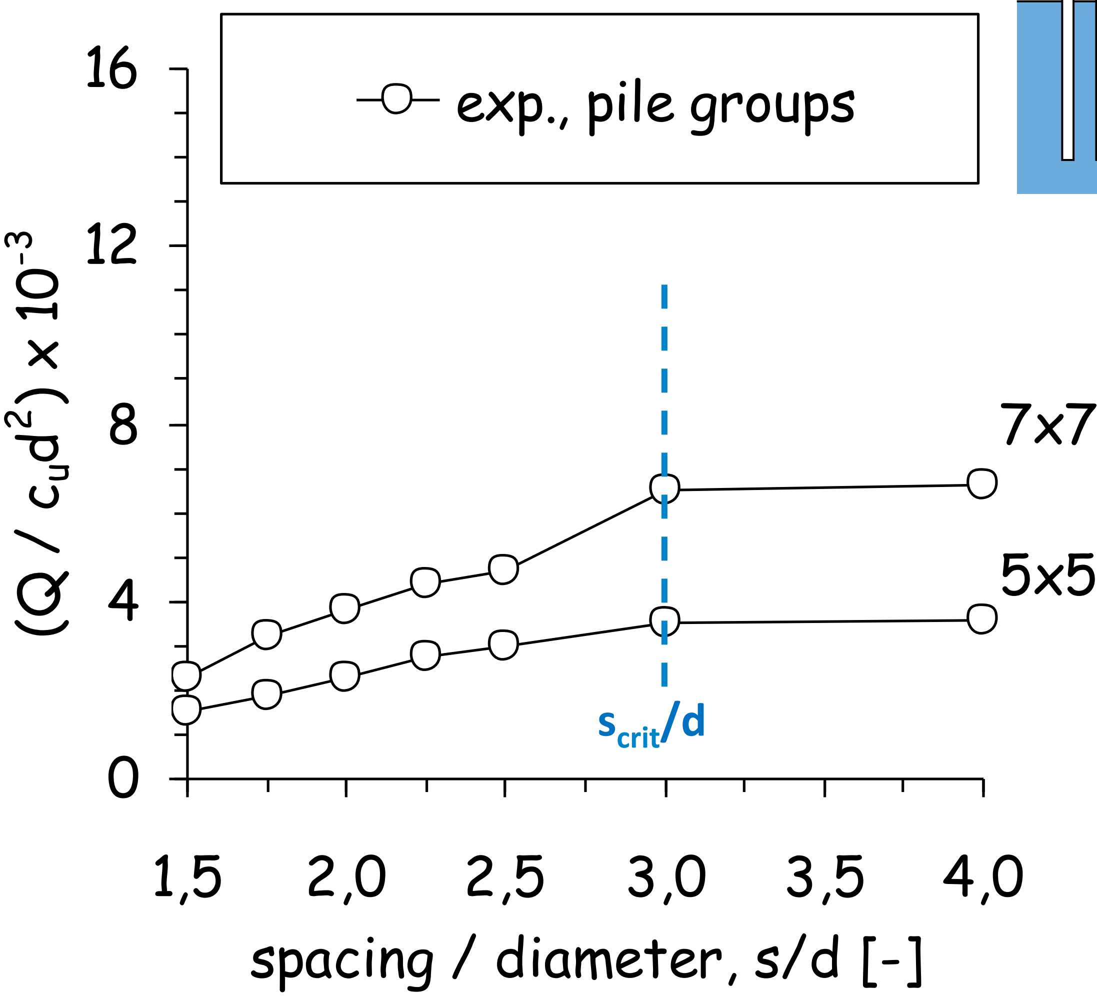

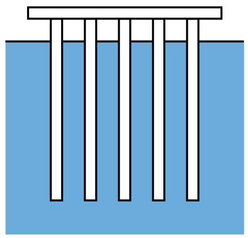

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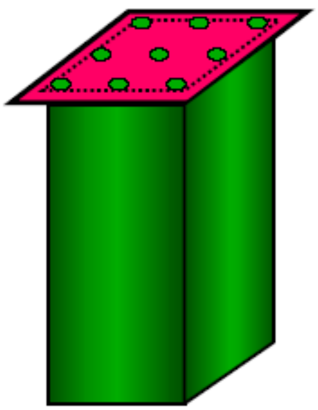

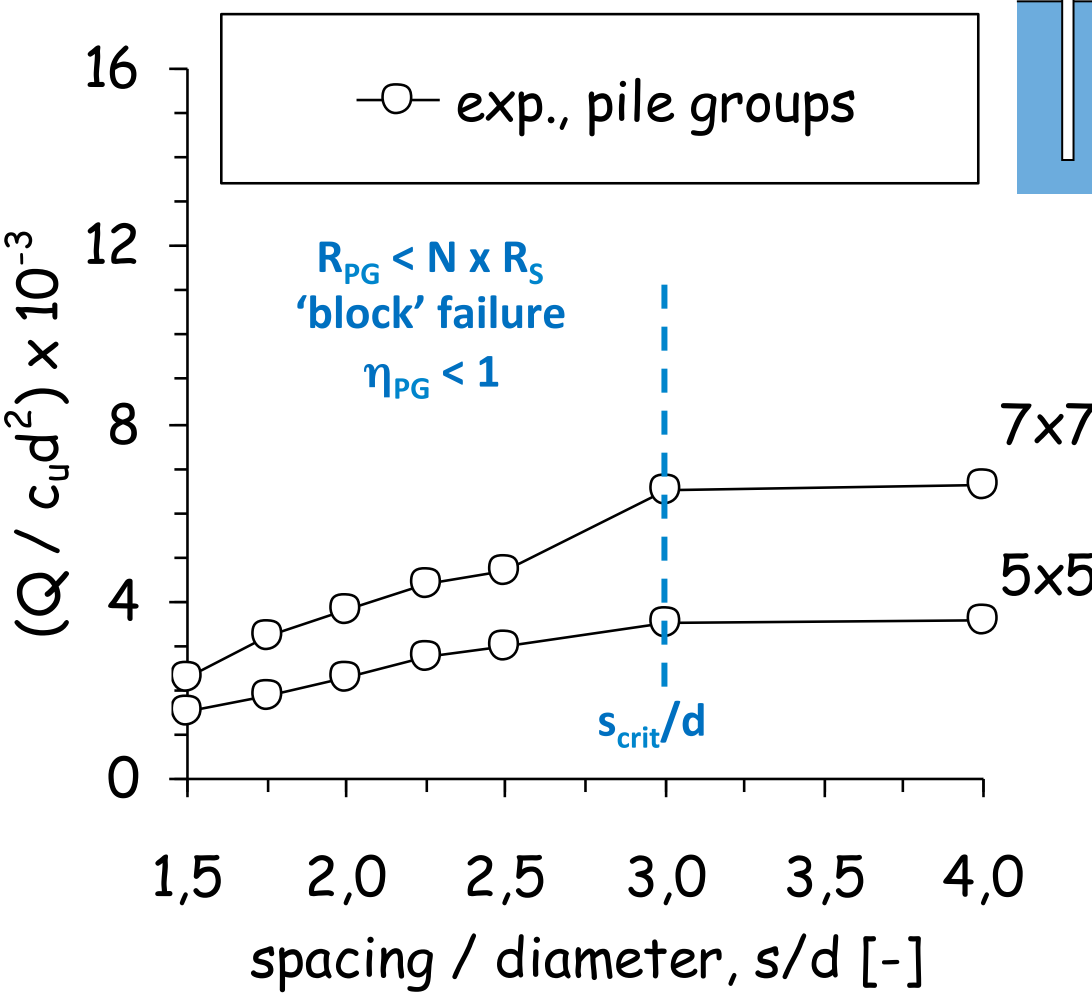

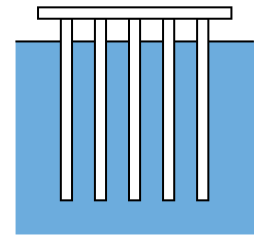

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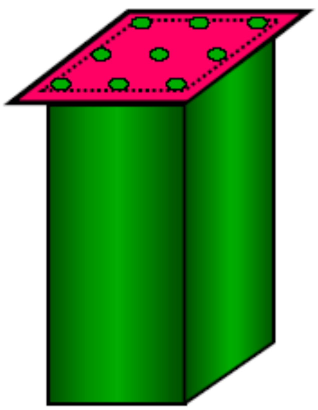

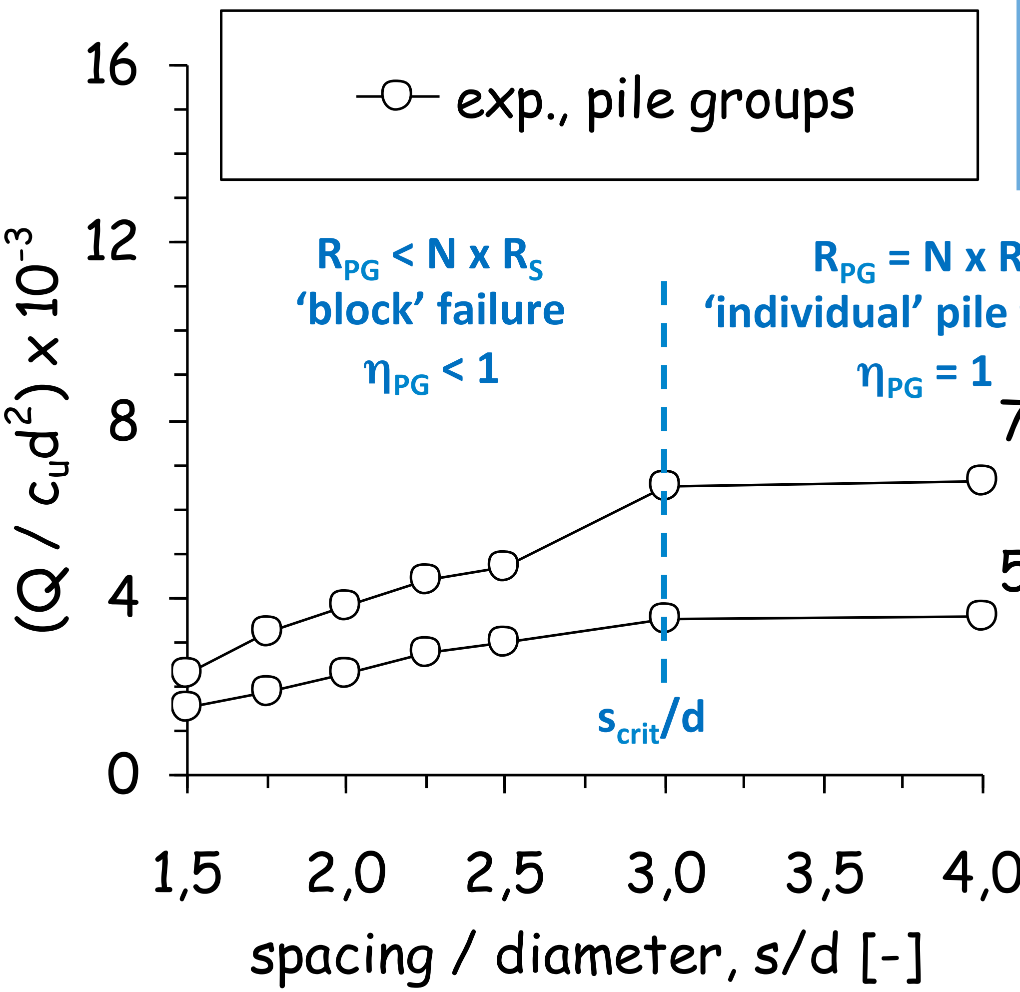

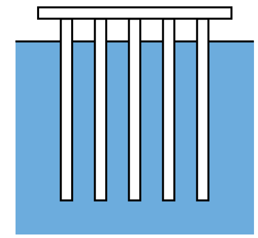

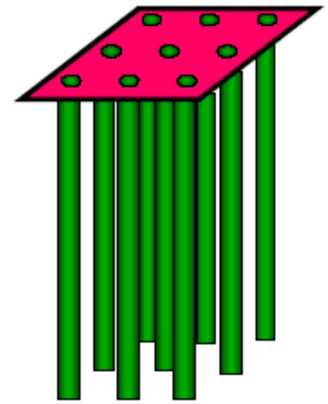

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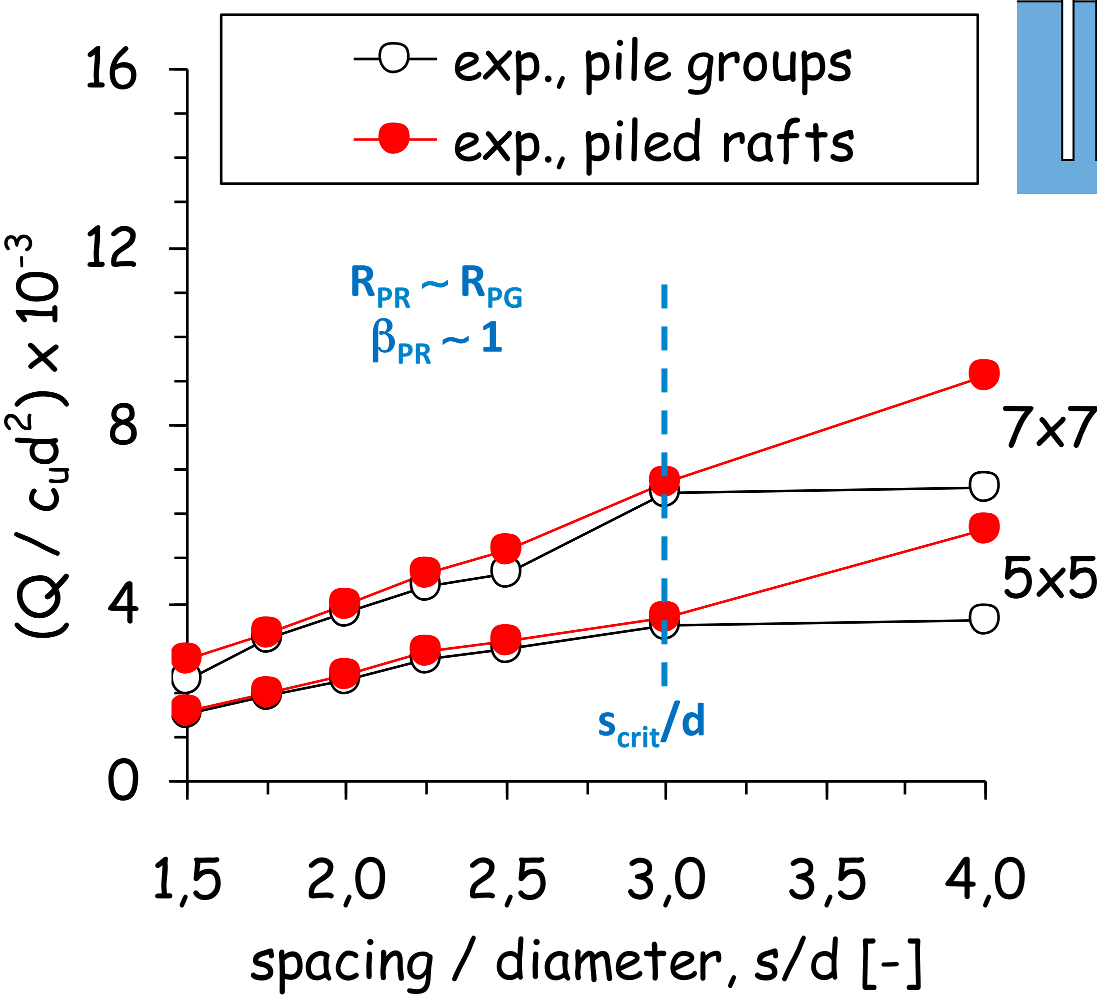

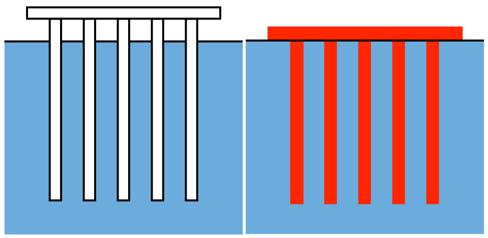

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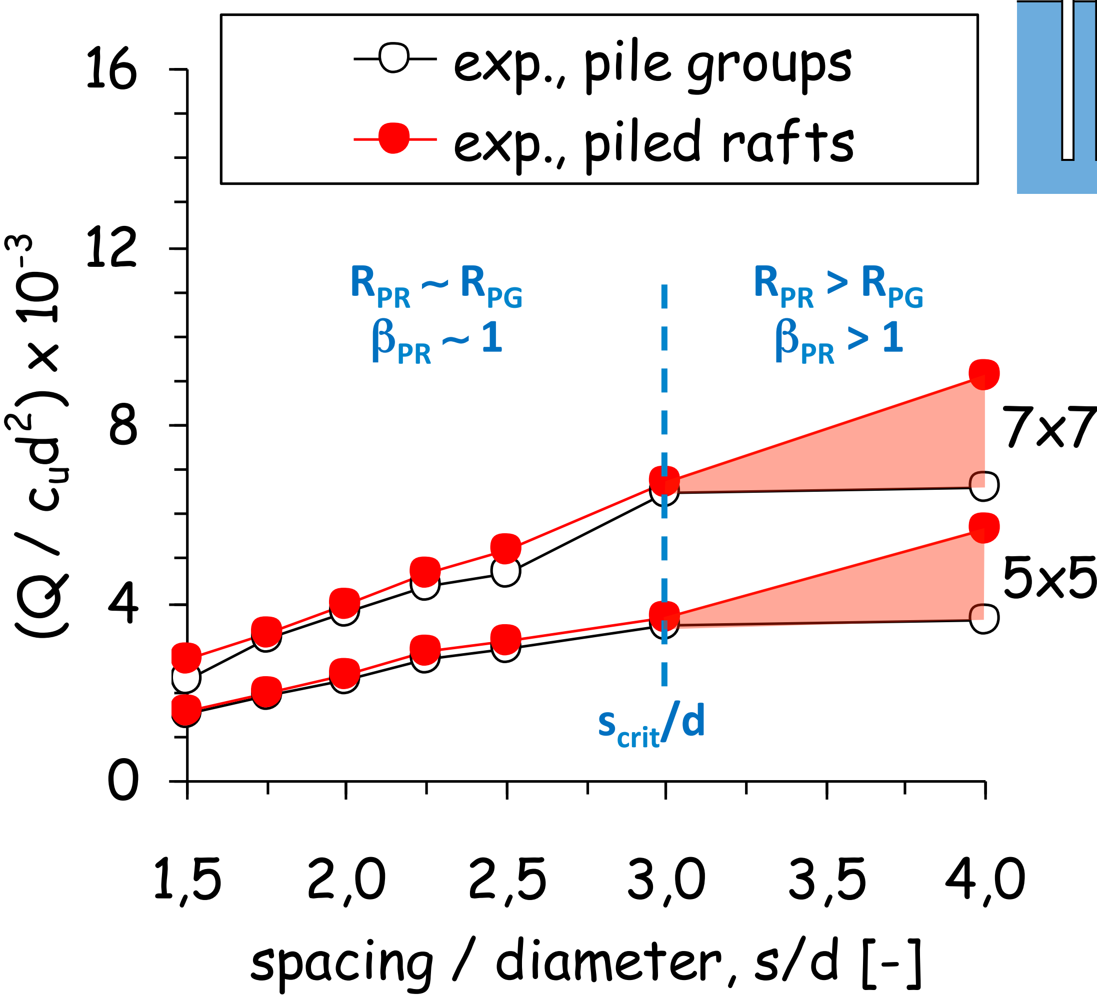
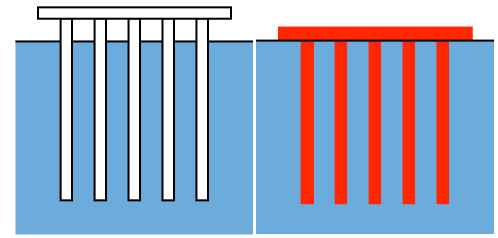
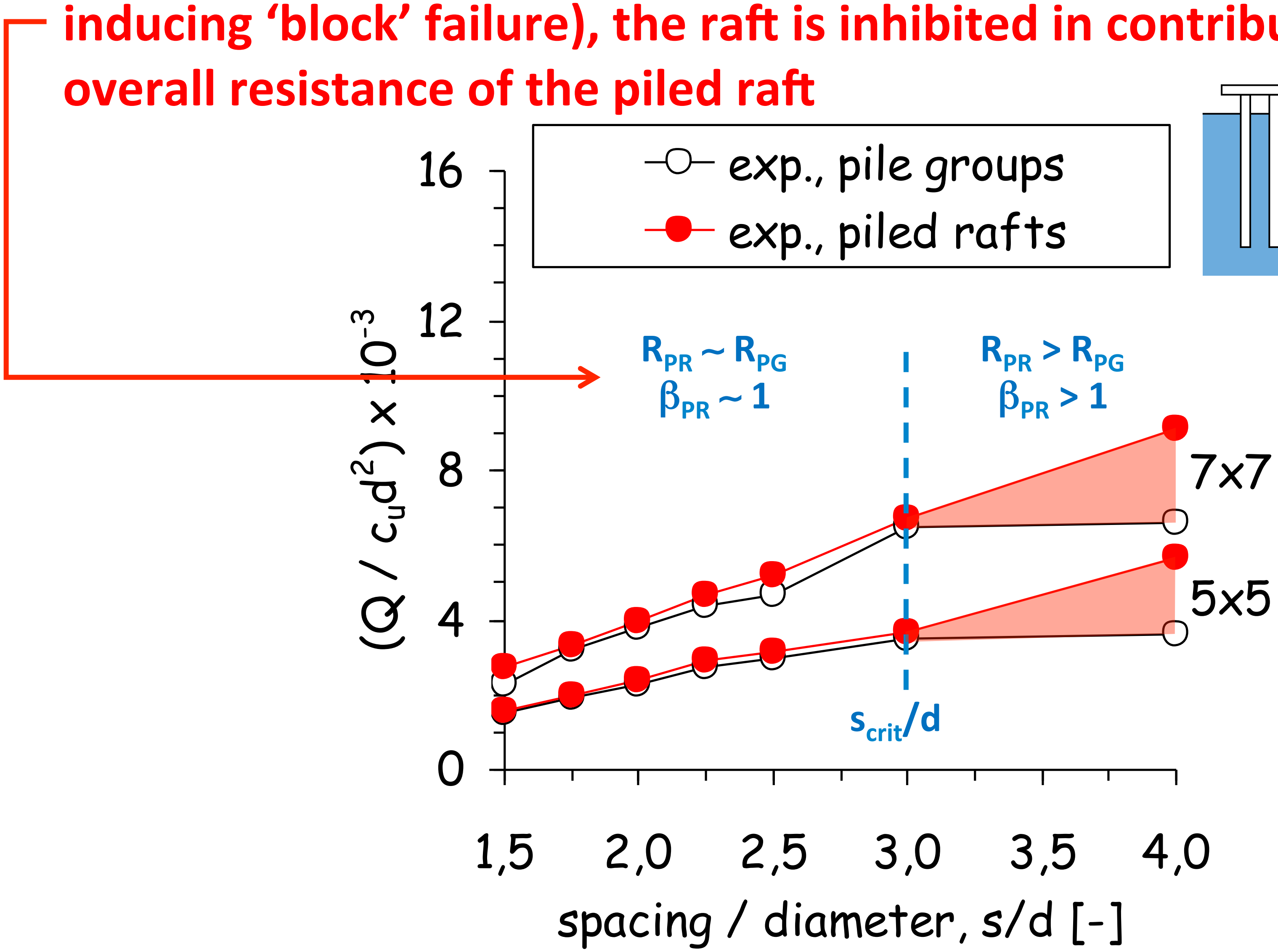
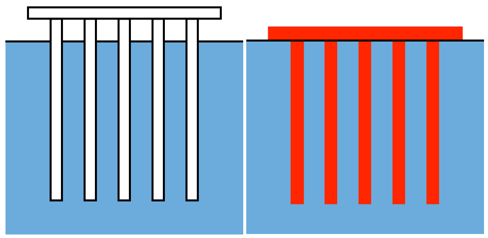




SHIELD EFFECT: For spacing <u>smaller</u> than some critical value (that inducing 'block' failure), the raft is inhibited in contributing to the overall resistance of the piled raft





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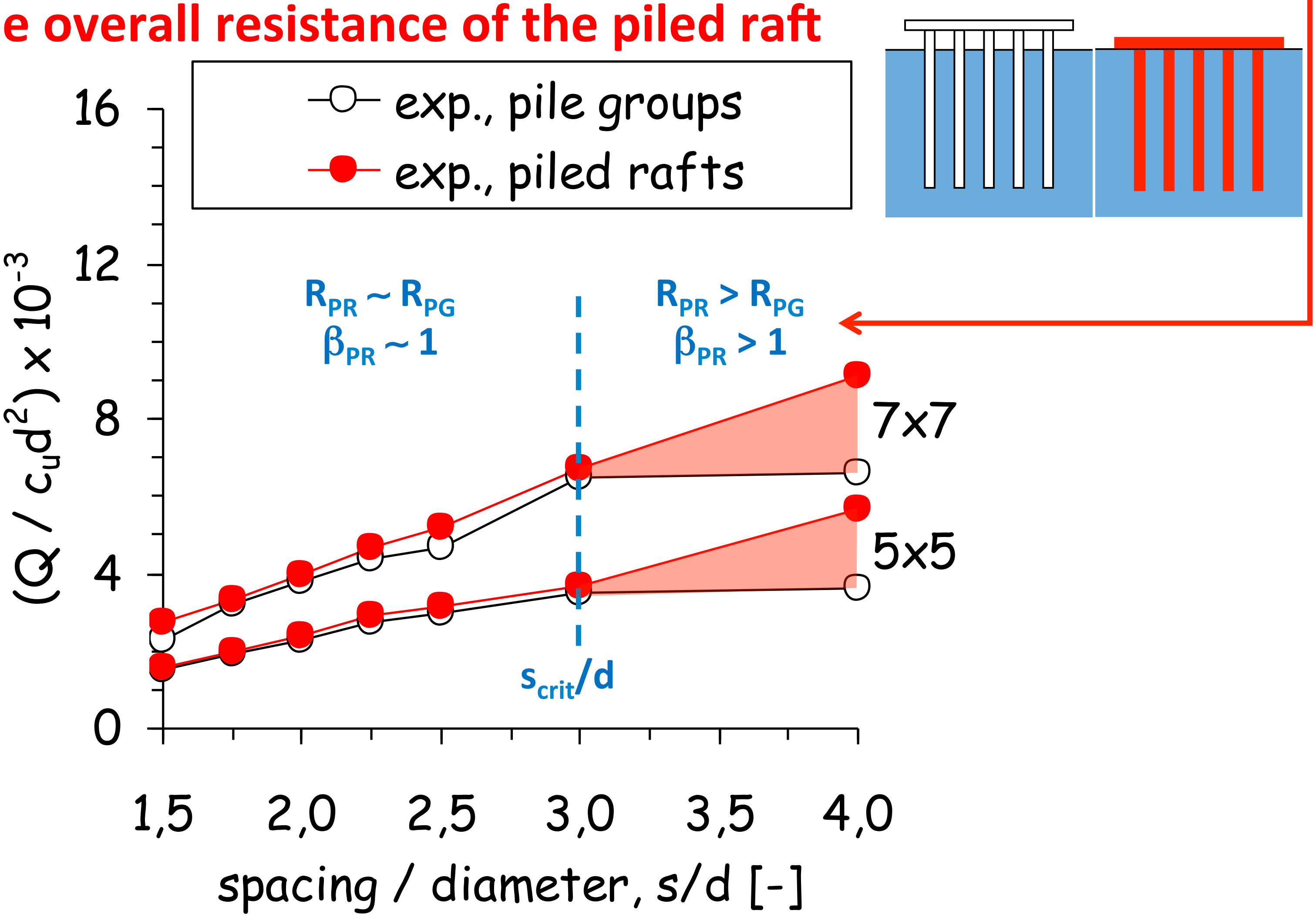
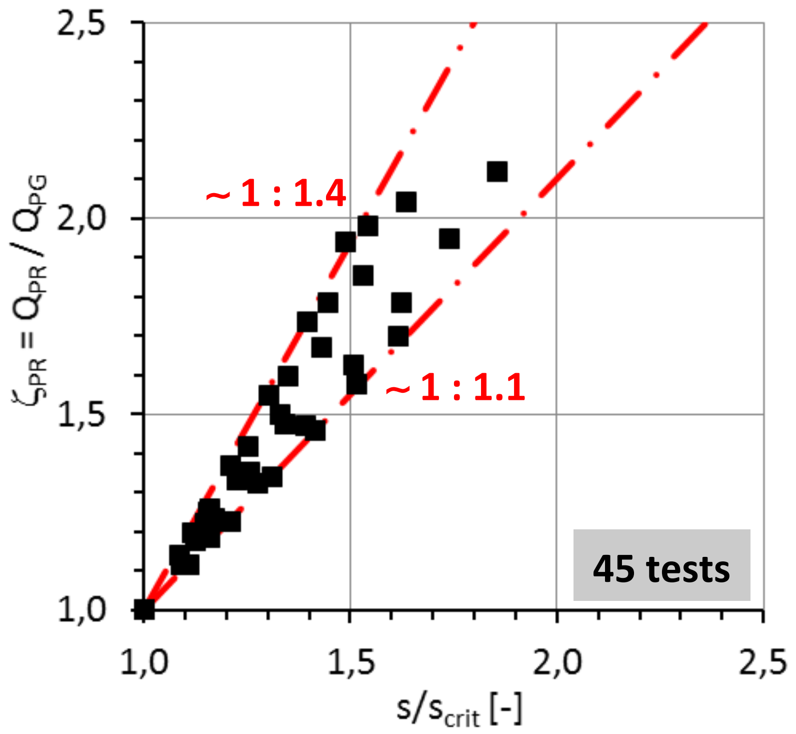
DESIGN EDILIZIA E AMBIENTE

RAFT ENHANCING PILE GROUP: For spacing larger than some critical value (that inducing 'block' failure), the raft cooperates with piles in increasing the overall resistance of the piled raft



Cooke (1986): ***Piled raft foundations on stiff clays—a contribution to design philosophy***
Géotechnique, vol. 36(2)



Piled raft resistance (R_{PR}) from 10% to 40% greater than that of Pile Group alone (R_{PG}), with pile spaced at $s \geq s_{crit}$, due to raft-soil contact.

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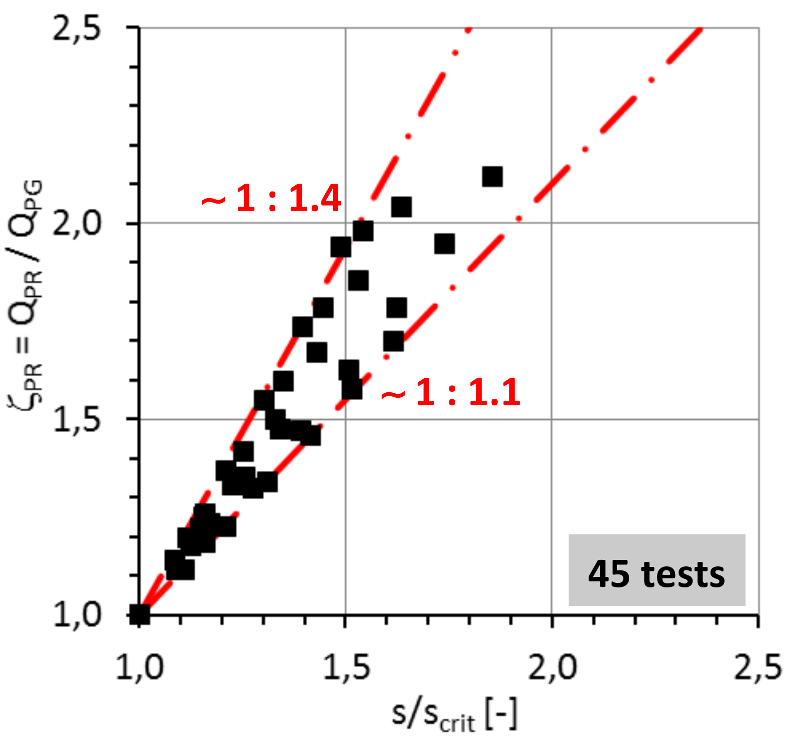
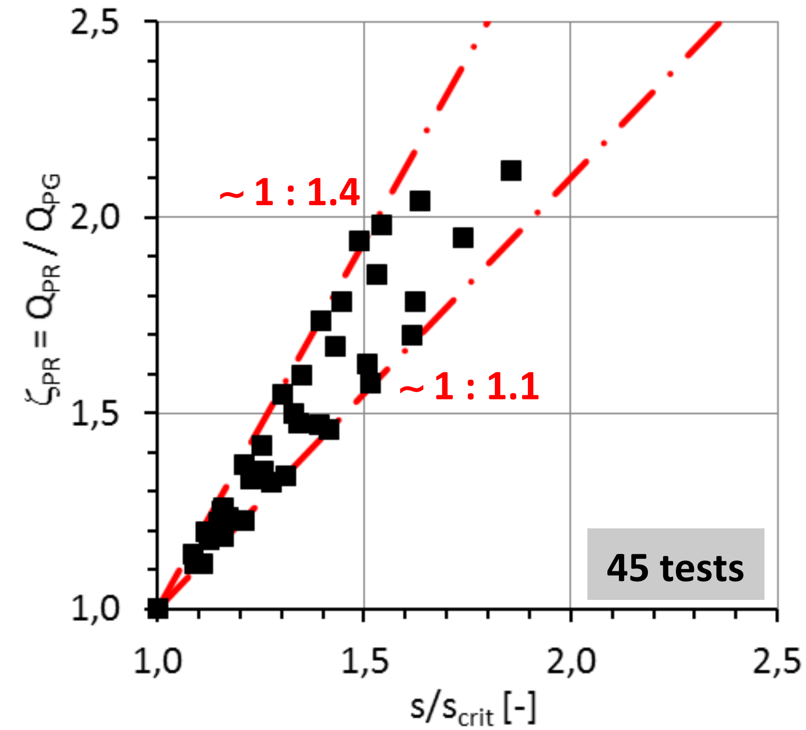


Piled raft resistance (R_{PR}) from 10% to 40% greater than that of Pile Group alone (R_{PG}), with pile spaced at $s \geq s_{crit}$, due to raft-soil contact.

Consequence on design: LESS PILES

SUMMARY

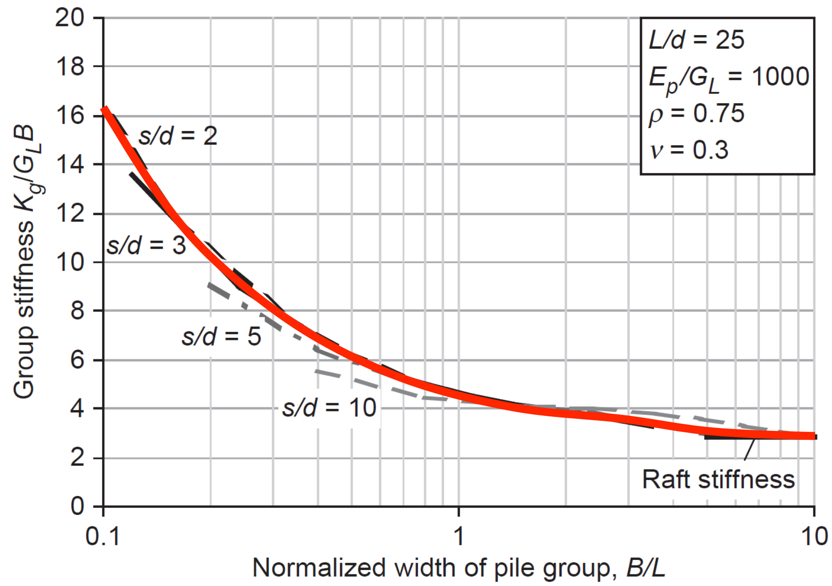
Piles should be installed at spacing s larger than critical value s_{crit} (preventing 'block' failure mode) in order to allow the raft to positively contribute to overall resistance of a piled raft (ζ_{PR} > 1).



SUMMARY

Piles should be installed at spacing s larger than critical value s_{crit} (preventing 'block' failure mode) in order to allow the raft to positively contribute to overall resistance of a piled raft ($\zeta_{PR} > 1$).

More spaced piles do not compromise the overall stiffness being the pile group stiffness almost constant for given s/d.



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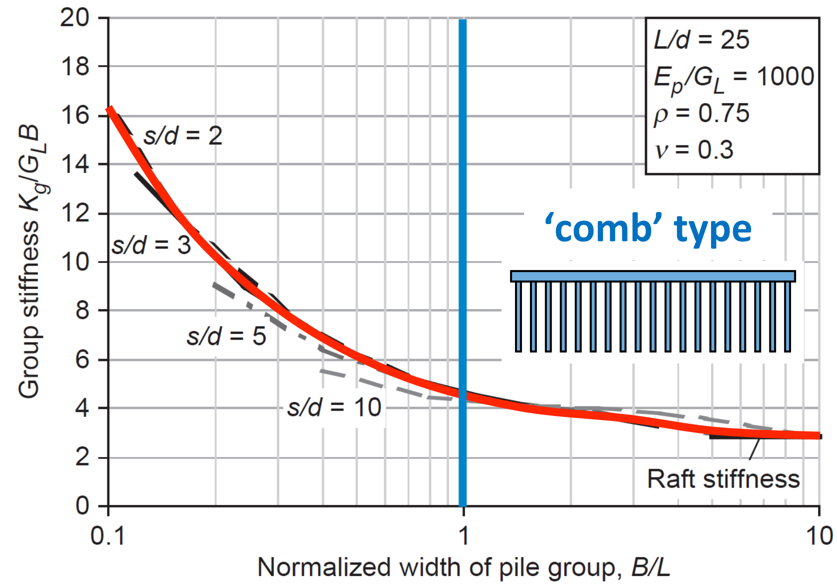
Piles should be installed at **spacing s larger than critical value s_{crit}** (preventing 'block' failure mode) in order to allow the raft to positively contribute to overall resistance of a piled raft ($\zeta_{PR} > 1$).

More spaced piles do not compromise the overall stiffness being the pile group stiffness almost constant for given s/d.

For <u>large raft</u> ('comb' type, B/L > 1), typically the unpiled raft has enough resistance. Adding **piles** is **not** very **effective to reduce average settlement**.



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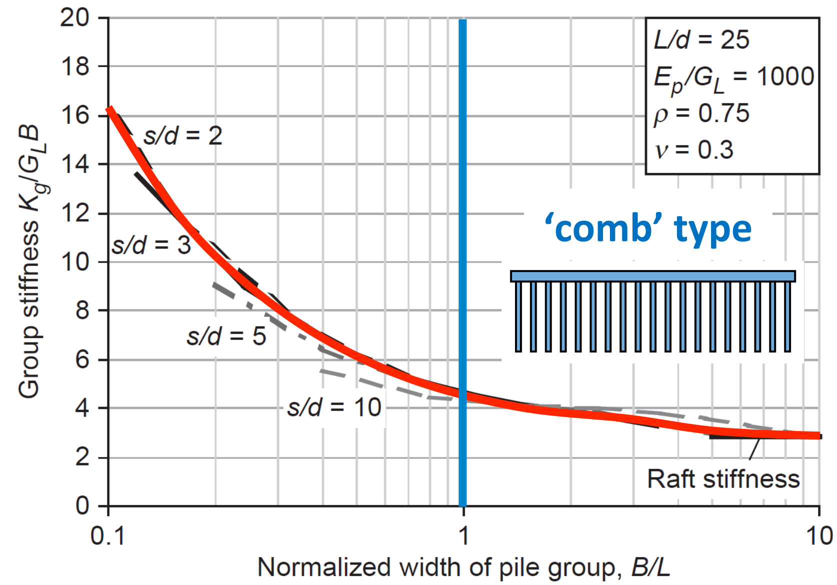
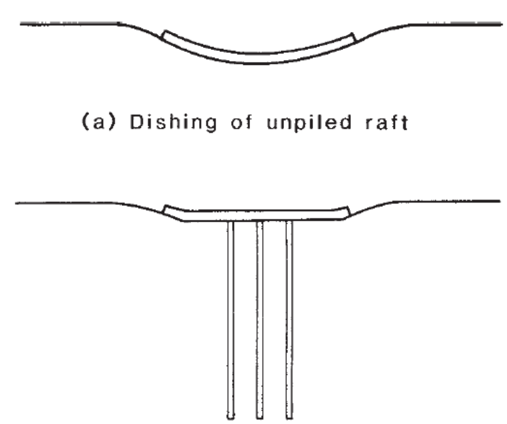
SUMMARY

Piles should be installed at spacing s larger than critical value s_{crit} (preventing 'block' failure mode) in order to allow the raft to positively contribute to overall resistance of a piled raft ($\zeta_{PR} > 1$).

More spaced piles do not compromise the overall stiffness being the pile group stiffness almost constant for given s/d.

For large raft ('comb' type, B/L > 1), typically the unpiled raft has enough resistance. Adding piles is not very effective to reduce average settlement.
If strategically placed below the raft, piles can greatly help to reduce differential settlement (DSBD), not practically achievable by increasing raft thickness.
Also bending moments and shear forces in the raft are reduced (RBD).





(a) Dishing of unpiled raft

(b) Effect of settlement reducing piles

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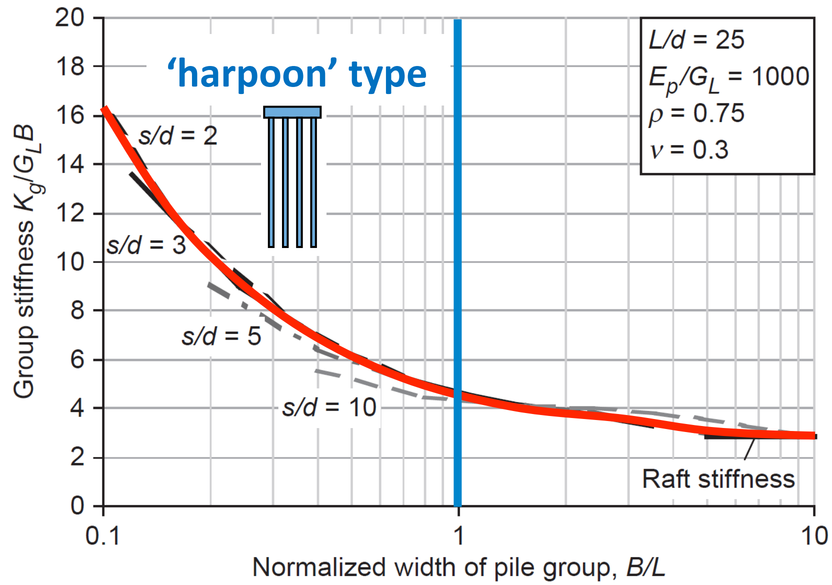
SUMMARY

Piles should be installed at spacing s larger than critical value s_{crit} (preventing 'block' failure mode) in order to allow the raft to positively contribute to overall resistance of a piled raft ($\zeta_{PR} > 1$).

More spaced piles do not compromise the overall stiffness being the pile group stiffness almost constant for given s/d.

For small raft ('harpoon' type, B/L < 1), the use of piles can derive from ULS problem. In these cases, piles adequately spaced can take advantage from the raft-soil contact to increase the overall resistance and to reduce average settlement (CSBD). The reduction of differential settlement can be easily obtained by increasing raft thickness within practical range.



‘CHEF RECIPE’ FOR AN OPTIMAL DESIGN APPROACH

‘CHEF RECIPE’ FOR AN OPTIMAL DESIGN APPROACH

PILES SHOULD BE AS LONG AND SPACED AS POSSIBLE AND STRATEGICALLY LOCATED WHERE LARGER SETTLEMENTS OF THE UNPILED RAFT ARE EXPECTED

Simple approach to static and seismic design of piled rafts

Mandolini, A [(1)], Di Laora, R.[(2)] and Iodice, C.[(3)]

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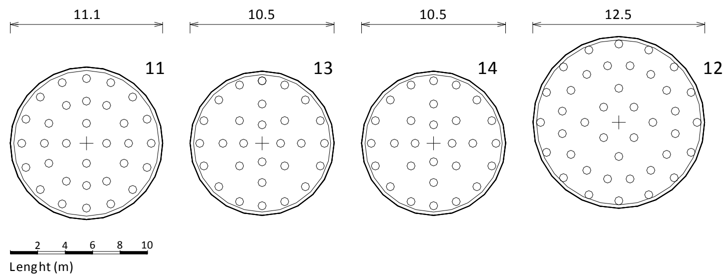
ABSTRACT. Current design of piled rafts often neglects a number of aspects well known in scientific literature, sometimes leading to increased costs without appreciable increase in performance. This work makes an attempt to partially fill this lack between State of Art and State of Practice; to this end, the paper briefly recalls available simple design methods regarding both geotechnical and seismic issues and proposes a novel simple procedure to estimate the load-settlement curve of a piled raft as well as the load sharing between piles and raft for vertical centered loads. The method has been validated through comparison with numerical and experimental data and applied to a case history; it will be shown that the proposed procedure, despite its simplicity, is able to account for the non-linearity in the soil behavior, the latter being responsible of progressive variation of the load sharing with increasing applied top load. Further, regarding seismic issues, simplified formulae from past works are recalled and discussed.

… a novel simple procedure to estimate the load-settlement curve of a piled raft as well as the load sharing between piles and raft for vertical centered loads.

Original CBD design: 128 piles



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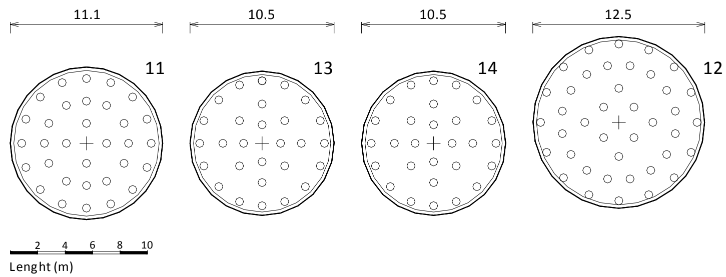
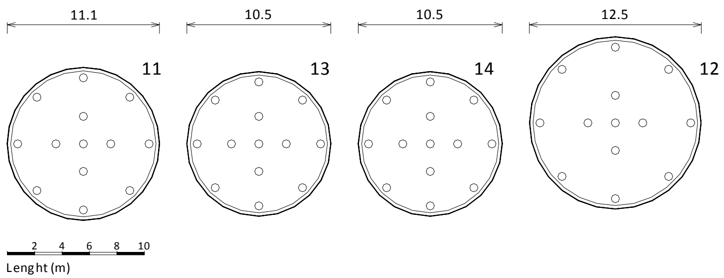


New SBD design: 52 piles



~ 60% less piles

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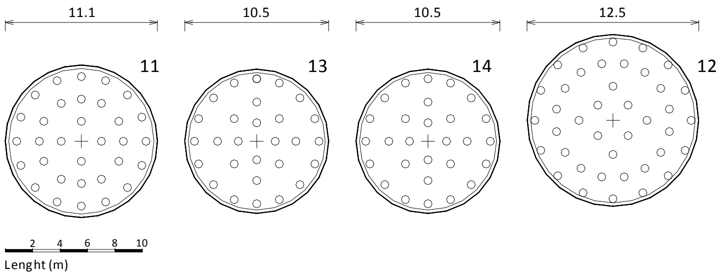

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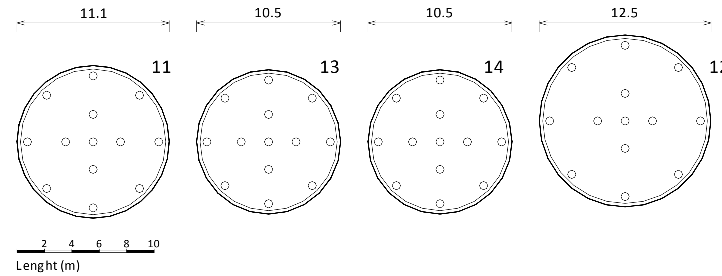

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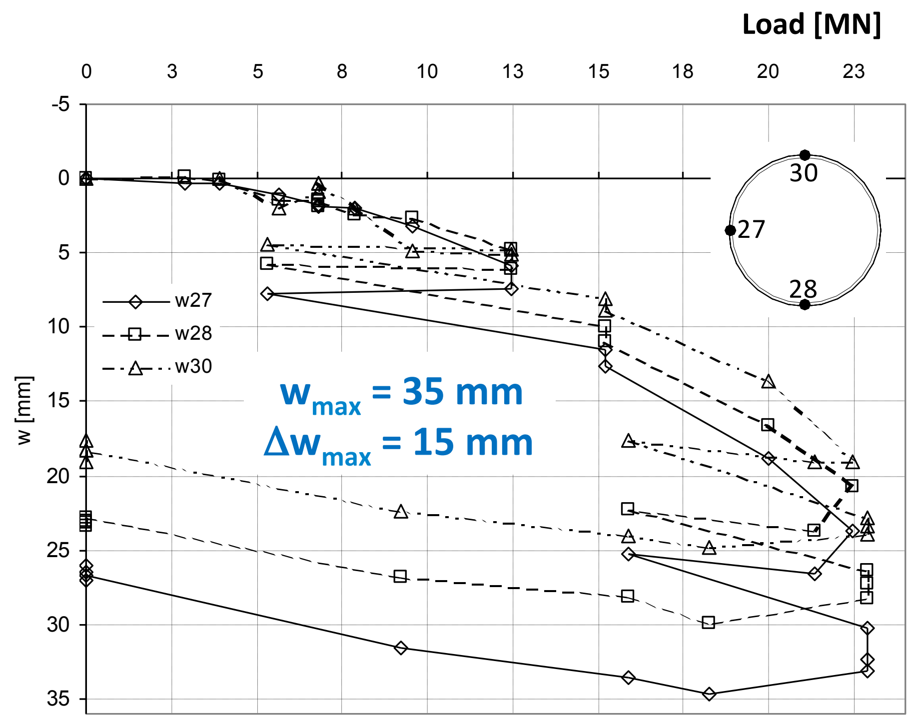
SATISFACTORY PERFORMANCE



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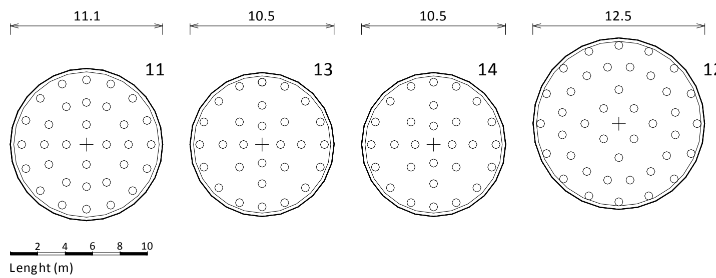

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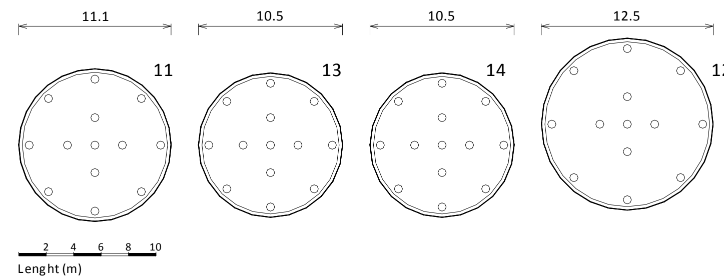

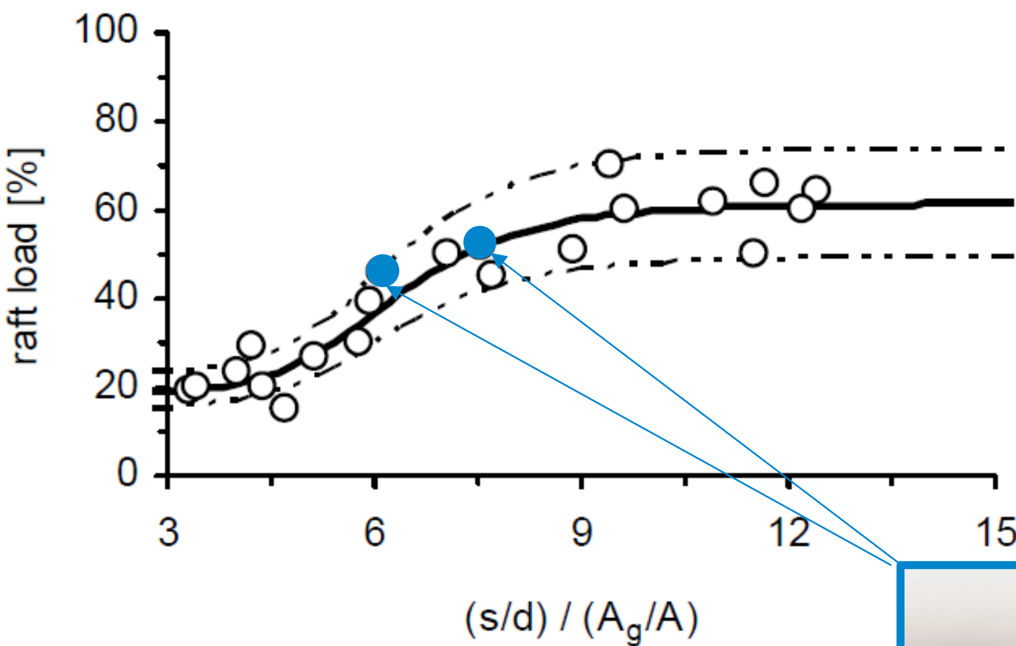

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NO OR LIMITED KNOWLEDGE OF THE SUBSOIL, NO RIGHT TO SPEAK (NOT ONLY OF PILED RAFT ……)

CONCLUDING REMARKS

- The **variety** of possible situation is such that any **generalisation** is **difficult**

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- The variety of possible situation is such that any generalisation is difficult
- Referring to simple and schematic situation helped to understand the great potential is now available for significant savings in the field of piled foundations
- The availability of simple and reliable methods of analysis makes possible and relatively easy the search for an optimum solution in each particular case

Nicht ist so praktisch wie eine gute theorie!

Kurt Lewin, 1946

"Nothing is more practical than a good theory"

Rainer, Mario, Alessandro & Bengt,

(known as The Fantastic Four)

at Mario's place

27/04/2015

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