Piled Raft Foundations

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What is Piled Raft?

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Horikoshi, K. and Yamashita, K. (2000): Estimation of load deformation behaviour of pile foundations subjected to vertical loading, Chapter 4: Analytical methods for estimating load deformation relation of pile group and piled raft (Part 3), ditto, 48(2): 47-52 (in Japanese).

What's piled raft ?

Design targets of a pile foundation

Q1: How many piles are required to carry the weight of the superstructure safely ? (Capacity Based Design)

Q2: How many piles are required to reduce the settlements to an acceptable level ? (Settlement Based Design)

The answers to the above two questions are often very different.

Q3: Over which region of the raft should the piles be installed to minimise the differential settlement ?

Establishment of a new design framework is necessary.

Piled raft may be an effective foundation type to accommodate these design targets.

What's piled raft ?

Design Concept

Alternative design philosophies

Three different design philosophies with respect to piled rafts (Randolph 1994):

"Conventional approach", in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity.

"Creep Piling", in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80 % of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the preconsolidation pressure of the soil.
(portion of load exceeding the pre-consolidation pressure of the ground is supported by the piles)

"Differential settlement control", in which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement.

What's piled raft ?

Design Concept

Alternative design philosophies

Three different design philosophies with respect to piled rafts (Randolph 1994):

"Conventional approach".

"Differential settlement control"

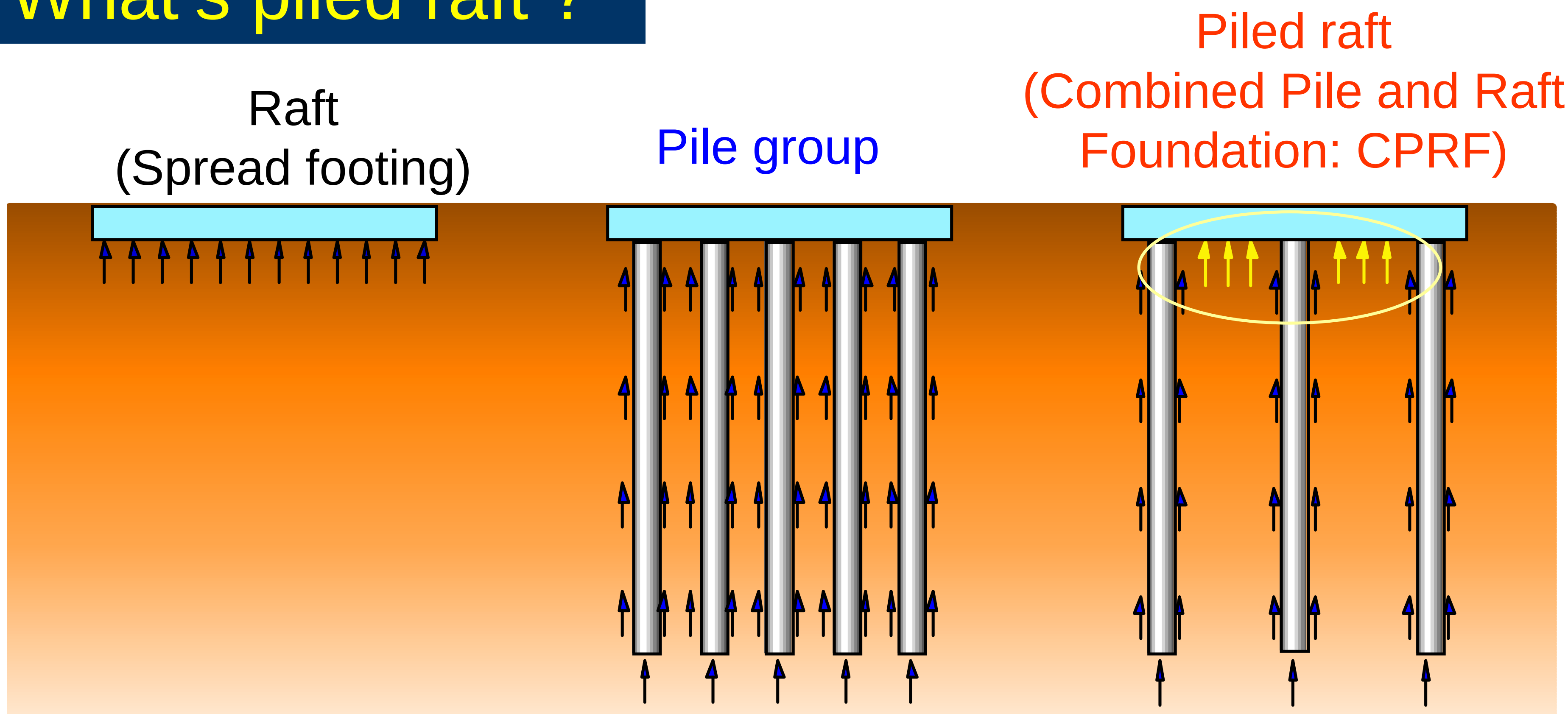
"Creep Piling" in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80 % of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the preconsolidation pressure of the soil.

"A more extreme version of Creep Piling", in which the full load capacity is utilized, i.e. some or all of the piles operate at 100% of their ultimate load capacity.

→ the concept of using piles primarily as settlement reducers.

→ the piles contribute to increasing the ultimate load capacity of the entire foundation system.

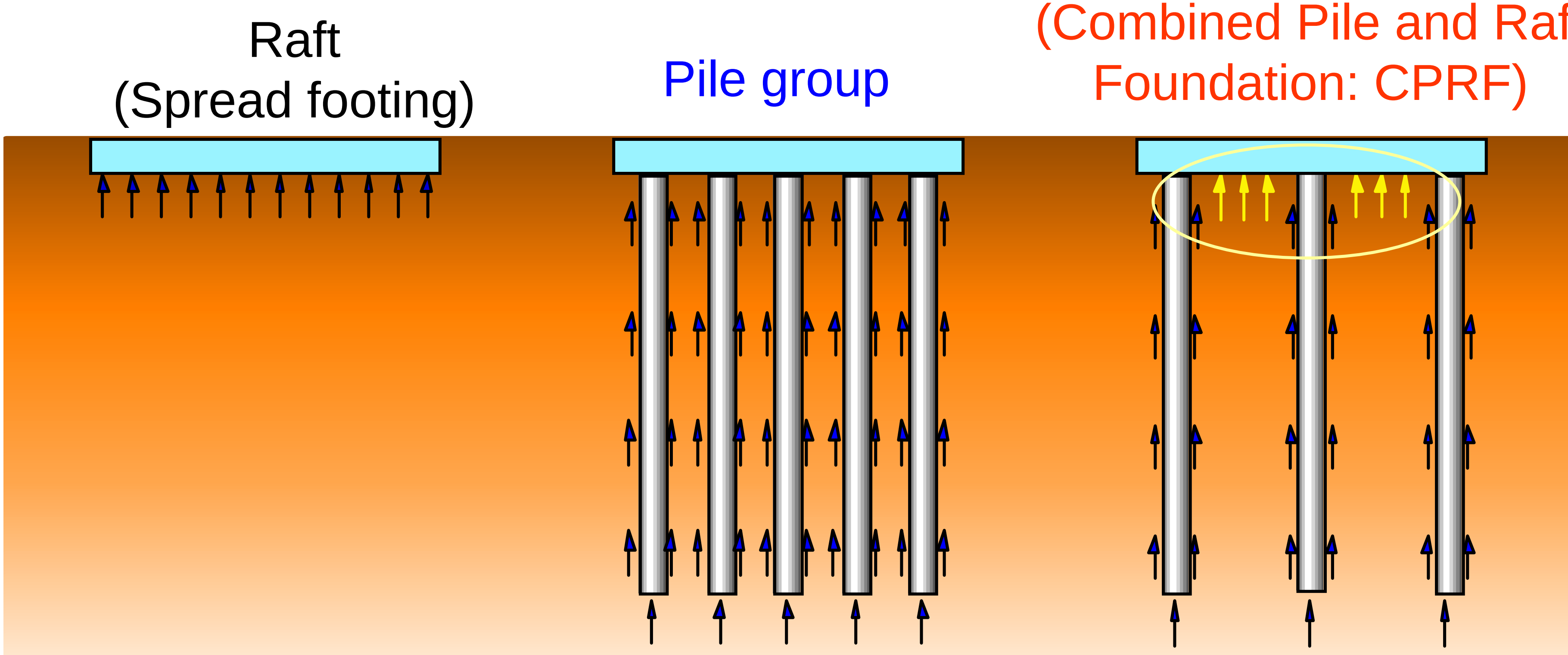
What's piled raft ?



Raft foundation:

All the vertical load is supported by the raft contact pressure.

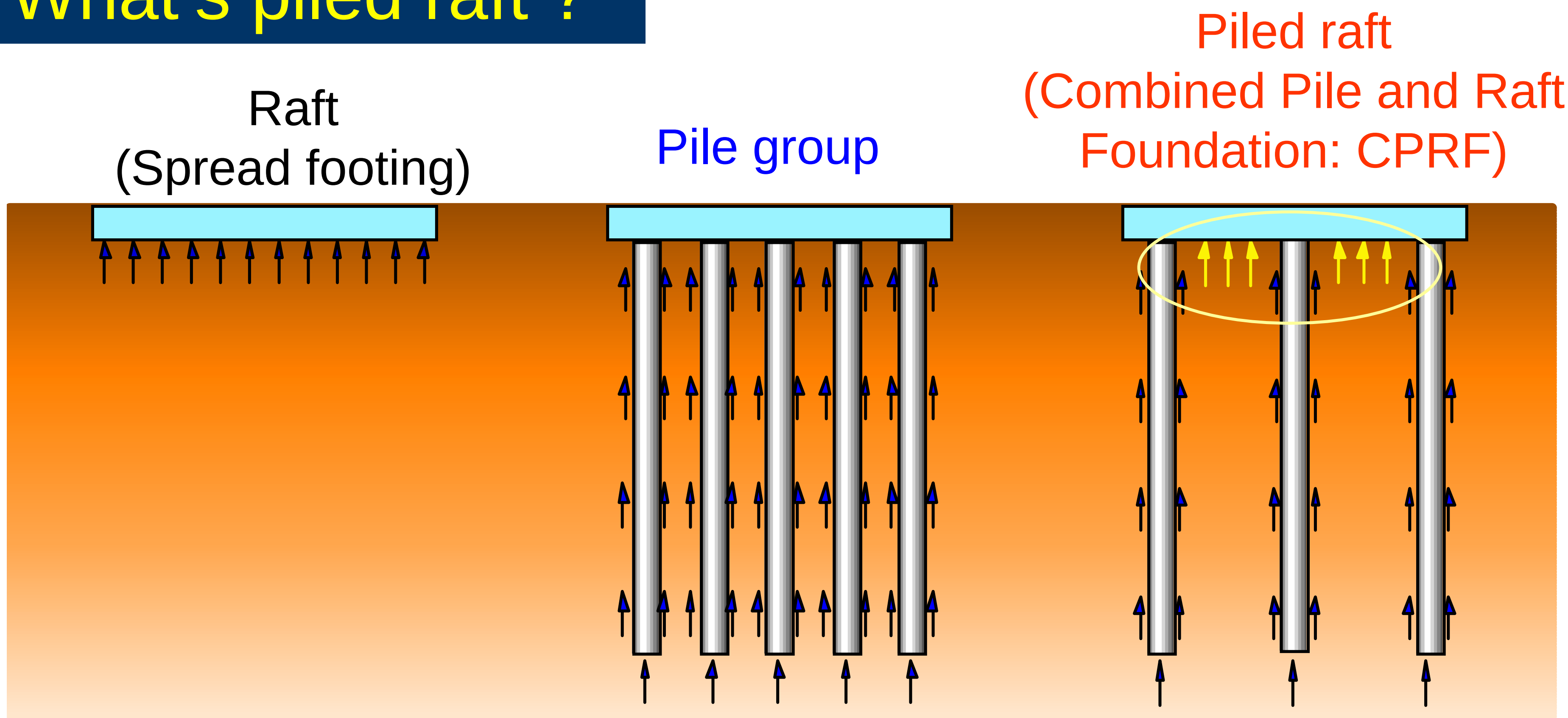
What's piled raft ?



Pile group (conventional design):

All the vertical load is assumed to be supported by the piles alone

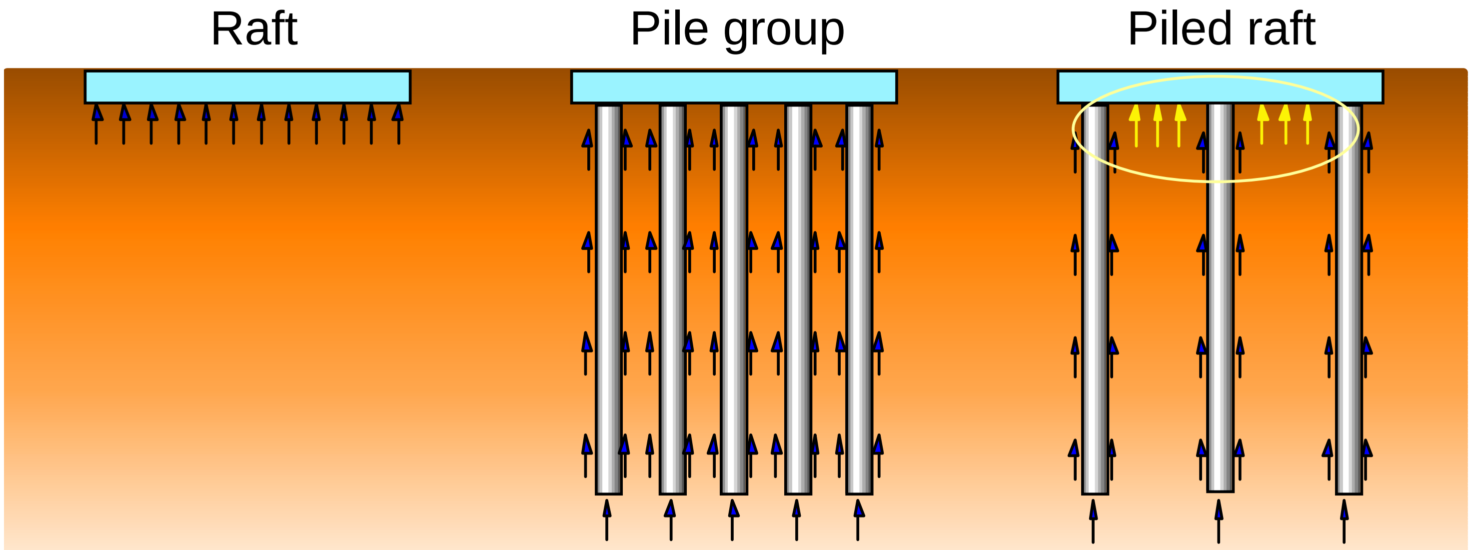
What's piled raft ?



Piled raft:

The load transferred to soil through the raft is effectively considered in design.

What's piled raft ?



Key features of piled raft design subjected to vertical load alone

1. Friction piles are used as settlement reducers.
2. Number piles is reduced, compared to design of pile group.
3. As the pile spacing is large, much load is transferred to the soil through the raft base.
4. Each pile is loaded close to its ultimate capacity.

   Hence, consideration of non-linear pile settlement behavior is very important.
5. Designers need to estimate the settlement more accurately.

   In the settlement estimation, interactions between the raft, piles, and soil need to be considered.

What's piled raft ?

Comparison with conventional pile design of pile group

Piled Raft : **Economy and safety to settlement**

Competent soil exists beneath the raft ===> Bearing capacity: OK

But settlement (especially differential settlement) exceeds an acceptable level.

Generally, it is decided to increase the raft thickness or to install piles beneath the raft.

Pile Group :

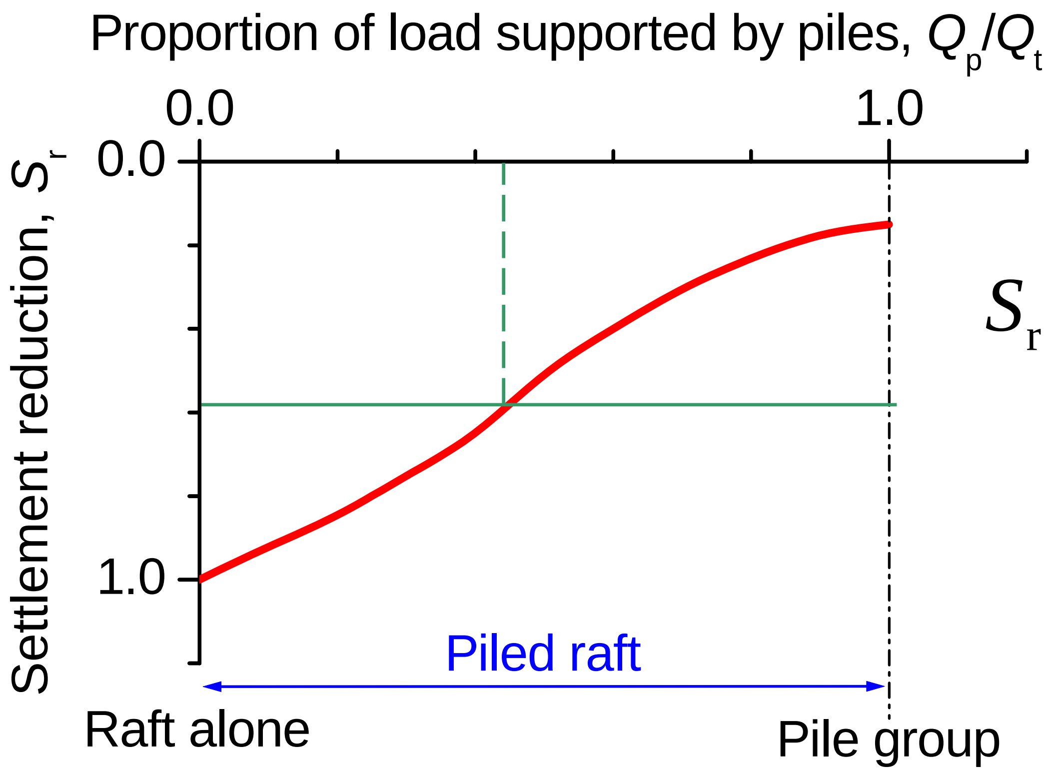
All the load is assumed to be carried by piles alone, in spite of the fact that some portions of load are transferred to soil through the raft.

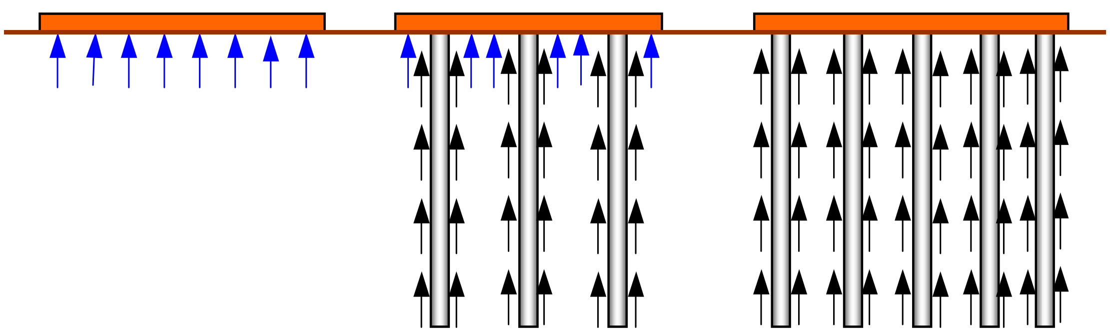
→ The number of piles is generally large.
The safety factor of about 2 - 3 is generally employed.

→ The settlement of pile group is automatically very small.
Engineers do not have to care the settlement.

What's piled raft ?

Piles as settlement reducers in piled raft





Q_t = total vertical load

Q_p = load carried by piles

$$S_r = \frac{\text{Settlement of foundation}}{\text{Settlement of raft alone}}$$

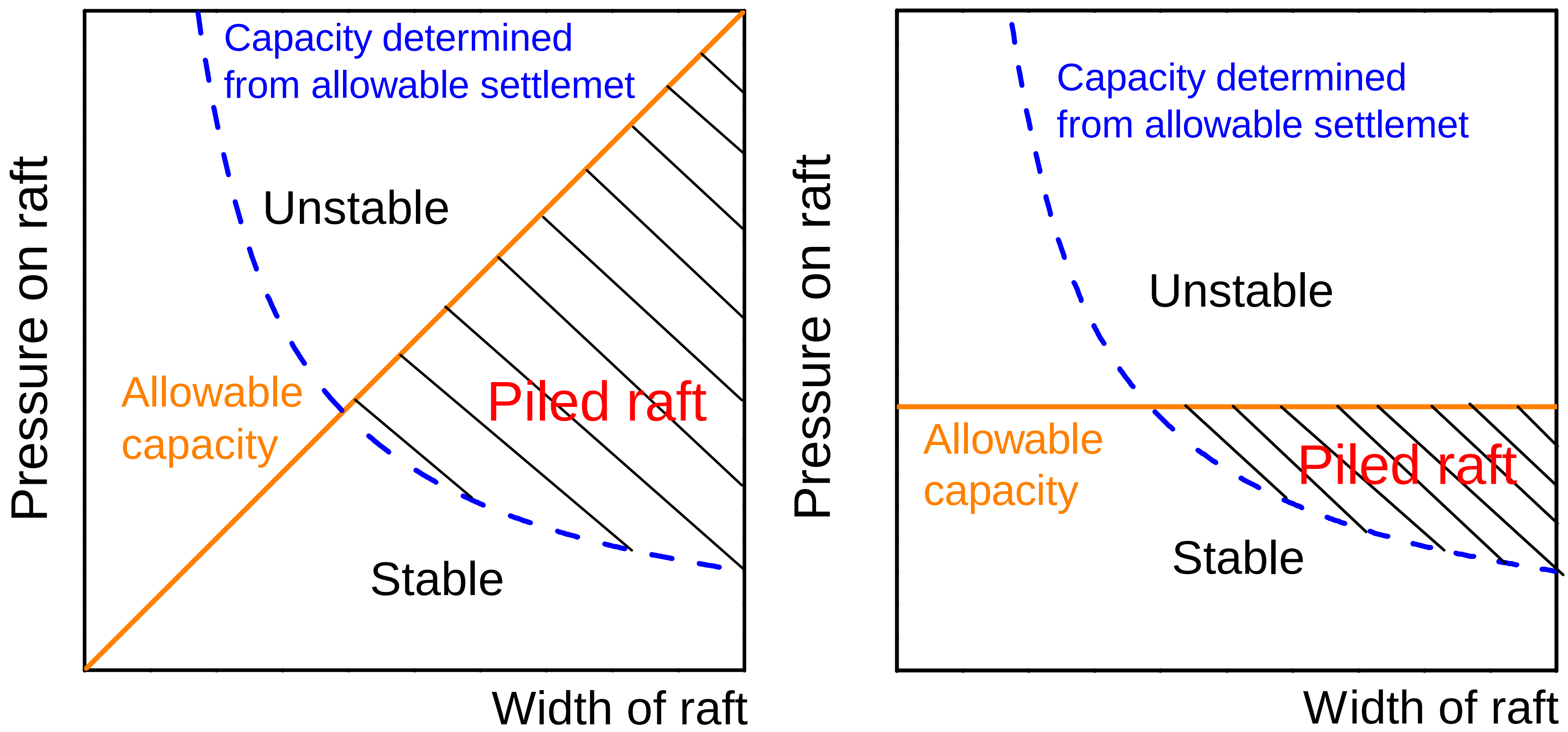
How many piles are required?

Allowable settlement

Designers need to estimate the settlement and the proportion of load carried by the piles accurately.

What's piled raft ?

Effective application of piled raft (Kakurai, 1998)

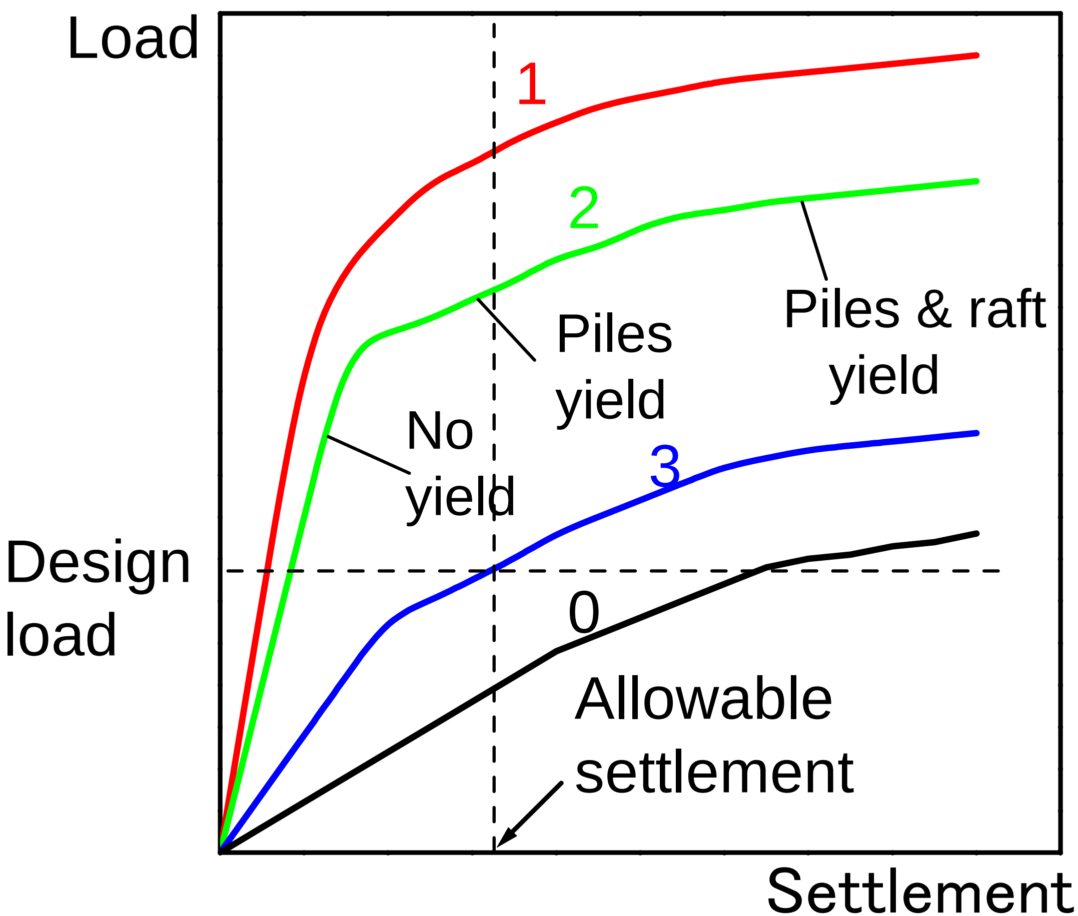


(a) Sandy ground

(b) Clayey ground

What's piled raft ?

Load-settlement curves of piled rafts according to various design philosophies (Poulos, 2001)



Curve 0:
raft only (settlement excessive)

Curve 1:
raft with piles designed for conventional safety factor

Curve 2:
raft with piles designed for lower safety factor

Curve 3:
raft with piles designed for full utilization of capacity

What's piled raft ?

Merits of piled raft over raft (spread) foundation

1. Reduction of average settlement and differential settlements.
2. Reduction of tilting of foundation due to eccentric load and unexpected variation of properties of surface soil.
3. Reduction of stresses in foundation beam or foundation slab.
4. Increase in safety margin of whole foundation structure against bearing failure.

Soil conditions inadequate for piled raft

1. Surface layer of soft clay or loose sand
2. Existence of a high compressible soil layer in the ground
3. Consolidating ground
4. Existence of an expansive soil layer in the ground

History of piled raft

First application of piled raft design:

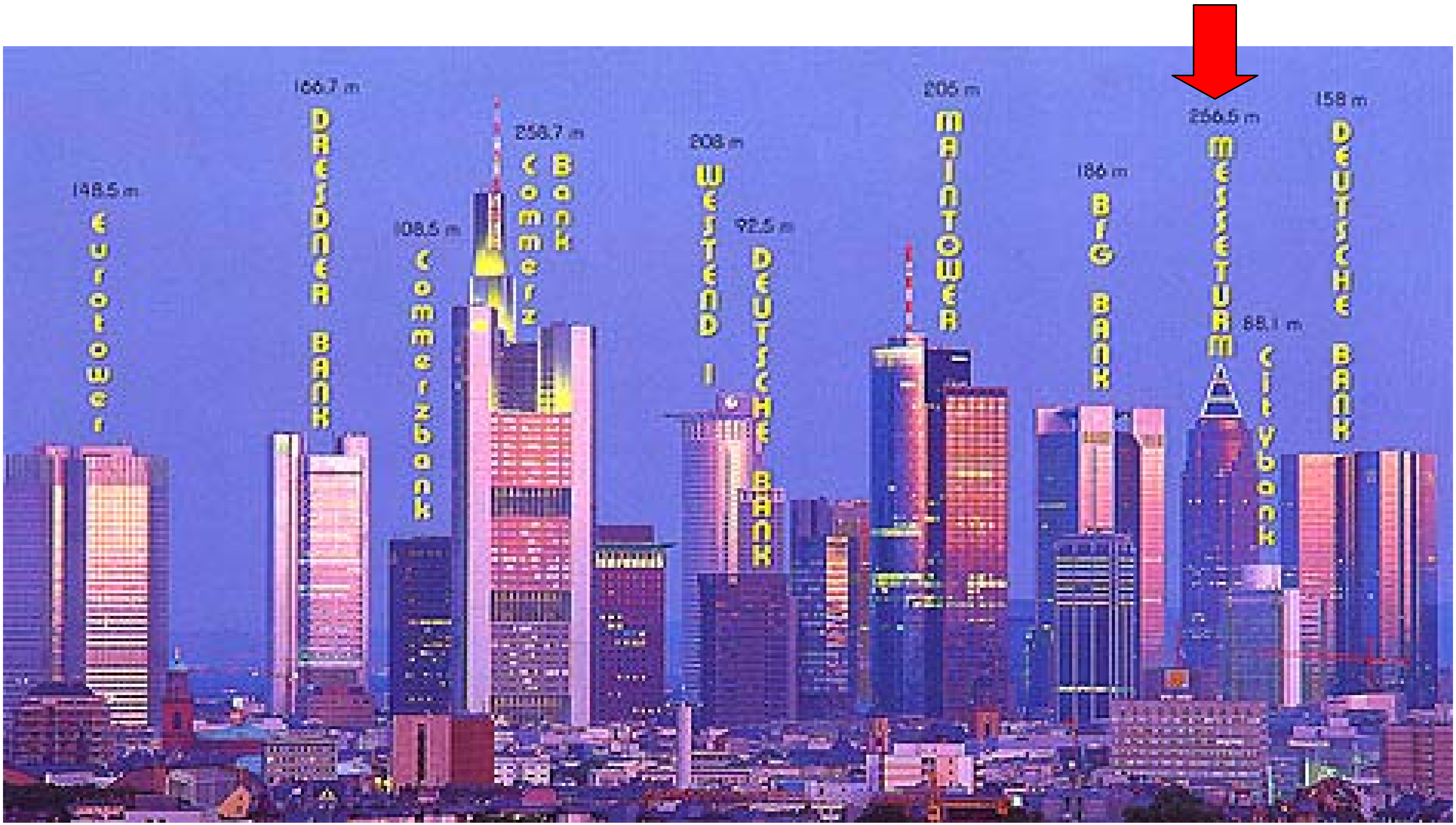
Foundation for a high-rise building in Mexico City. (Zeevaert, 1957)

In Japan, piled rafts were first used in 1980s by Takenaka Corporation. Thereafter, application of piled rafts to building foundations is extending increasingly.

Piled rafts have been used for foundations of many buildings in Germany since 1980s.

Piled raft for high-rise building

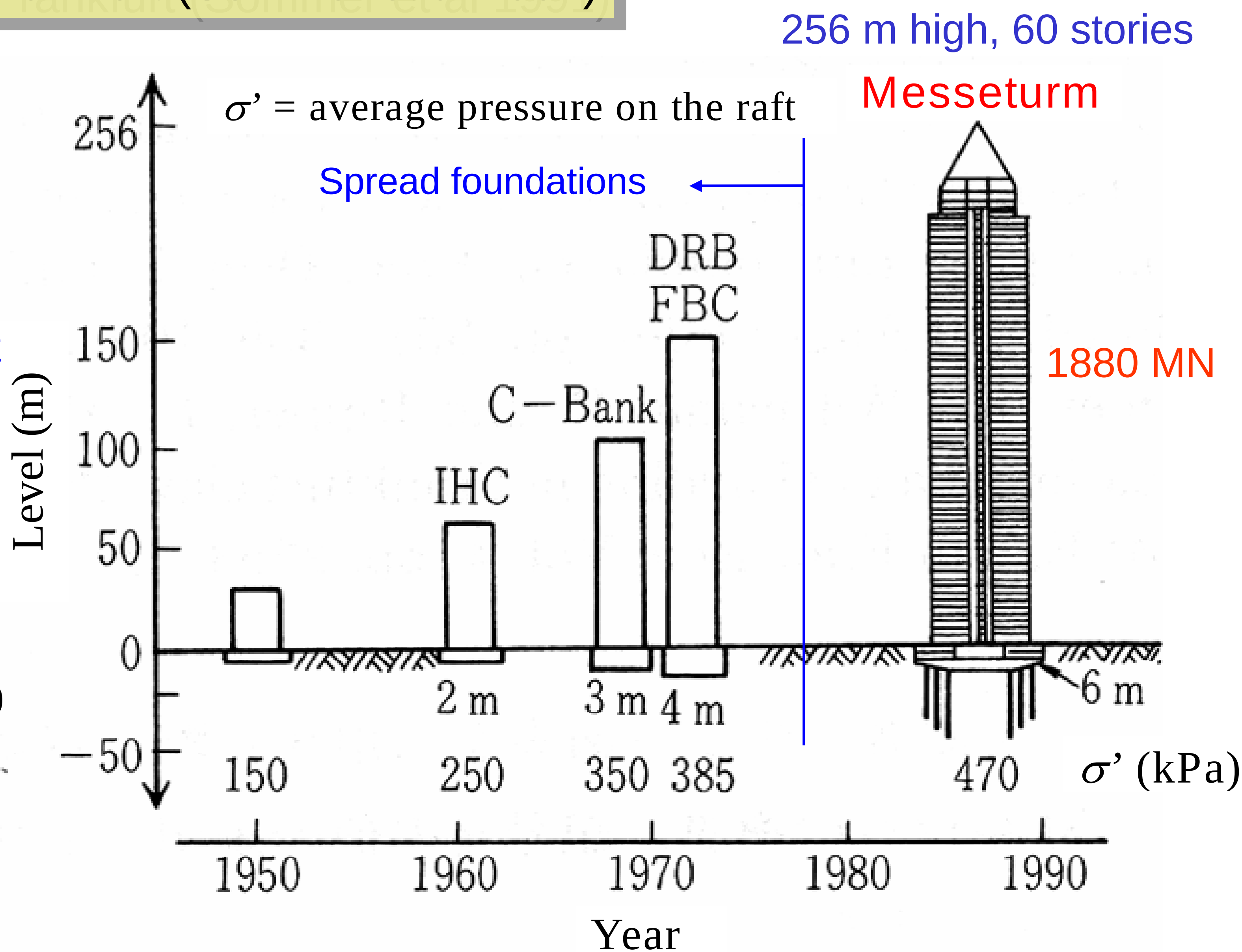
Messeturm in Frankfurt
256 m high, 60 stories



Piled raft for high-rise building

Messeturm in Frankfurt (Sommer et al 1991)

Differential settlement = 20% of the average settlement for raft foundations.

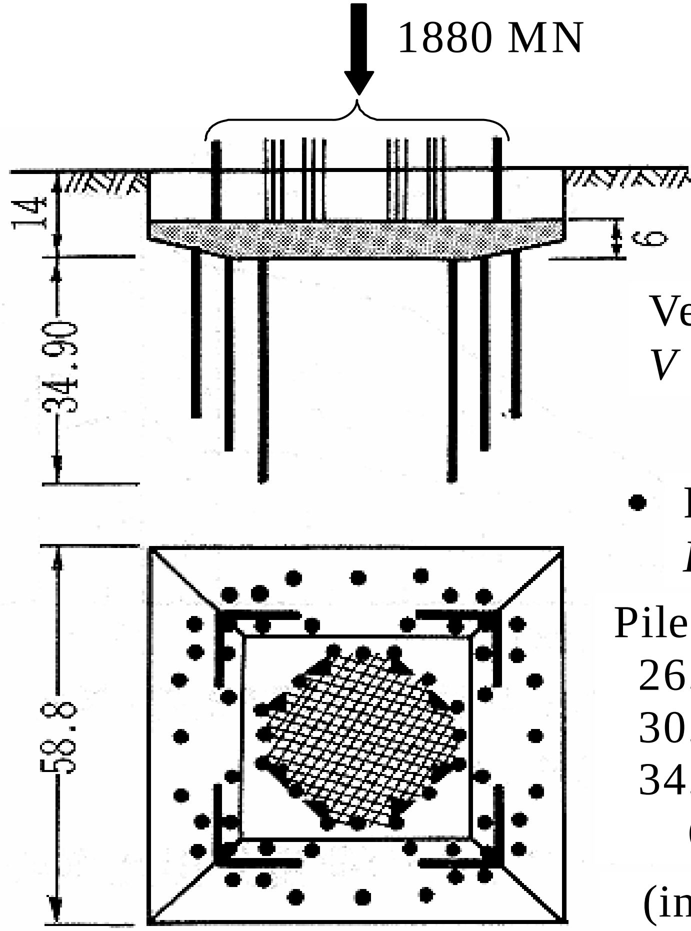


Messeturm

Settlement of 300 to 400 mm, if raft foundation was emplyed.

Piled raft for high-rise building

Messeturm in Frankfurt



Vertical load
V = 1880 MN

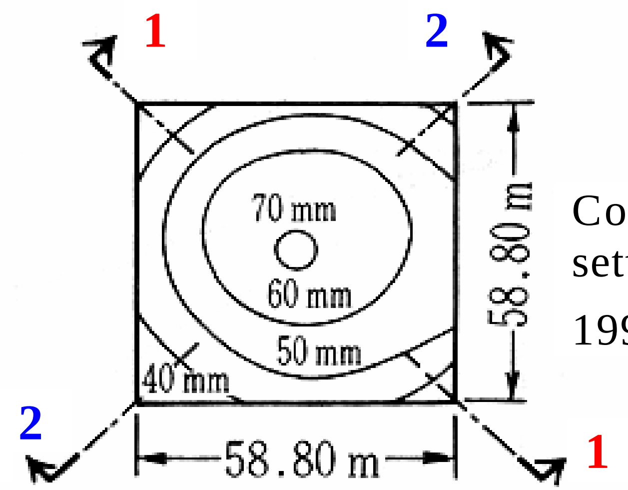
• Pile locations
D = 1.3 m

Pile lengths
26.9 m : 28 piles
30.9 m : 20 piles
34.9 m : 16 piles
64 piles in total

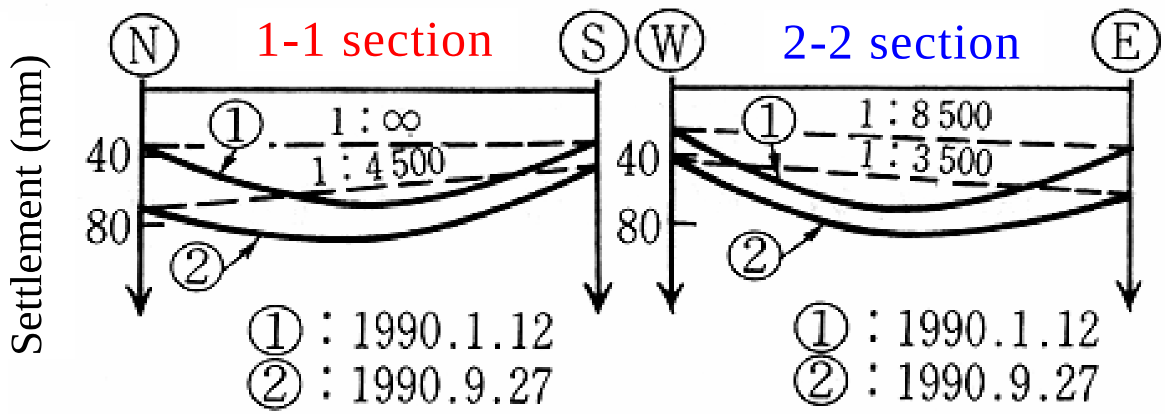
(in m)

Av. settlement = 70 mm

Dif. settlement = 30 mm



Contour of settlements
1990.1.12



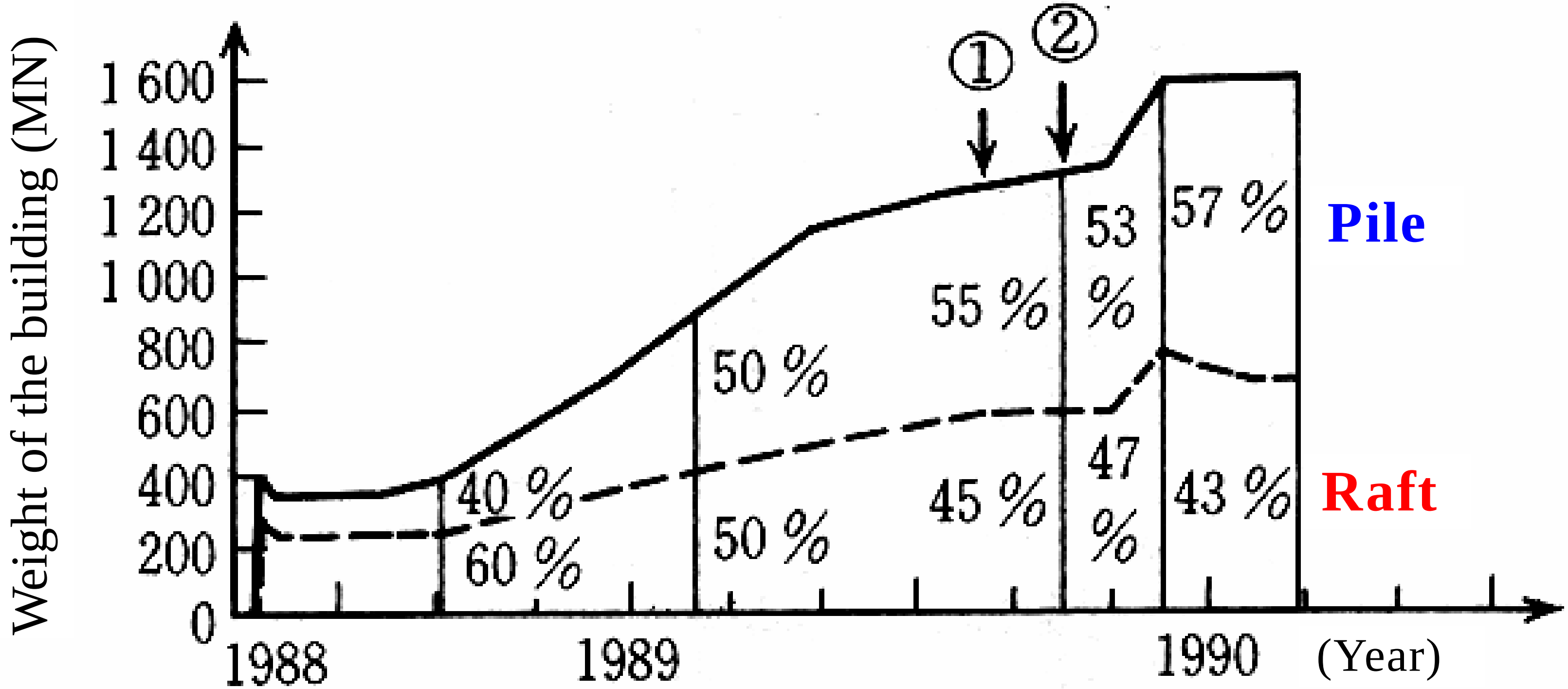
Raft:

Thickness = 6 m

Level of raft = 14 m below G.L.

Piled raft for high-rise building

Messeturm in Frankfurt



① Start of lowering of water table for construction of U bahn

② Completion of construction of the building structure

Design philosophies of piled raft

What's piled raft ?

1. Pile group with large pile spacing
   Expect of raft resistance by increasing pile spacing largely.

2. Creep pile
   Piles are installed beneath the raft so that the raft base pressure becomes less than the pre-consolidation pressure of the ground. (portion of load exceeding the pre-consolidation pressure is supported by the piles)

3. Differential settlement control
   Optimum arrangement of piles to obtain minimum differential settlement.

Methods for estimating settlement of piled raft foundation

1. Simple methods
2. Approximate computer-based methods
3. More rigorous computer-based methods (BEM, FEM)

Concept of stiffness (= load / settlement) is important.

Analysis Methods of Single Piles and Pile Groups

1. Simple methods

(1) Equivalent raft method (Tomlinson 1986)

(2) Equivalent pier method
(Davis & Poulos 1972, Poulos & Davis 1980)

(3) Method using settlement ratio of single pile to pile group
(Butterfield & Douglas 1981)

2. Detailed methods

(1) Load transfer method (*t* - *z* method)

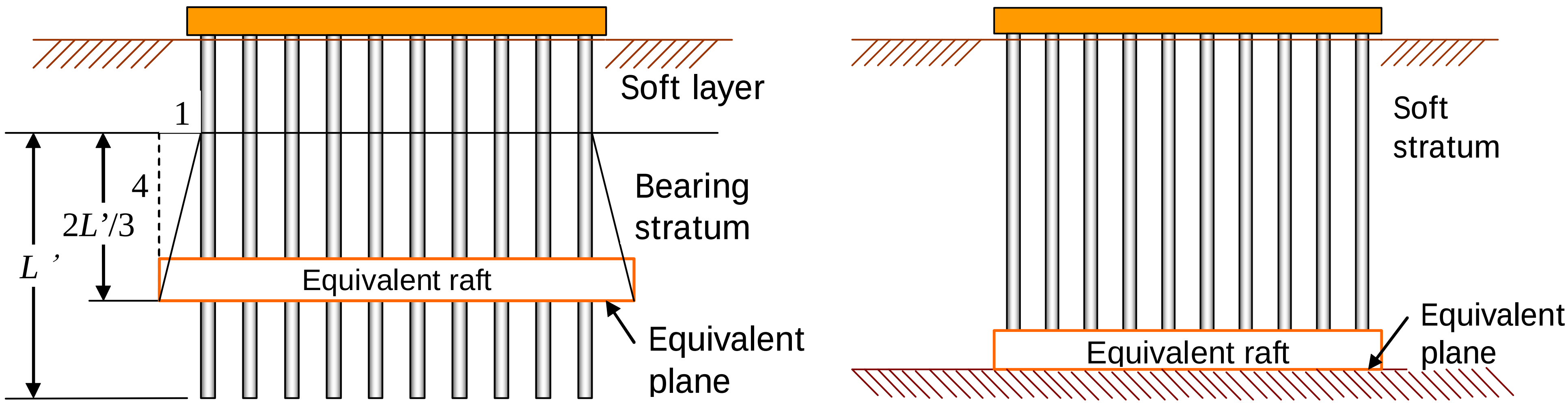
(2) BEM

(3) FEM (1-dimensional, 2-dimensional and 3-dimensional)

Analysis Methods of Single Piles and Pile Groups

1. Simple methods (1) Equivalent raft method (Tomlinson 1986)

Applied to the case that area of pile group is relatively larger than pile length



(a) Primarily friction piles (b) Primarily end-bearing piles

Size of equivalent raft:

A load-spread of 1 in 4 is generally assumed in order to evaluate the size of the equivalent raft.

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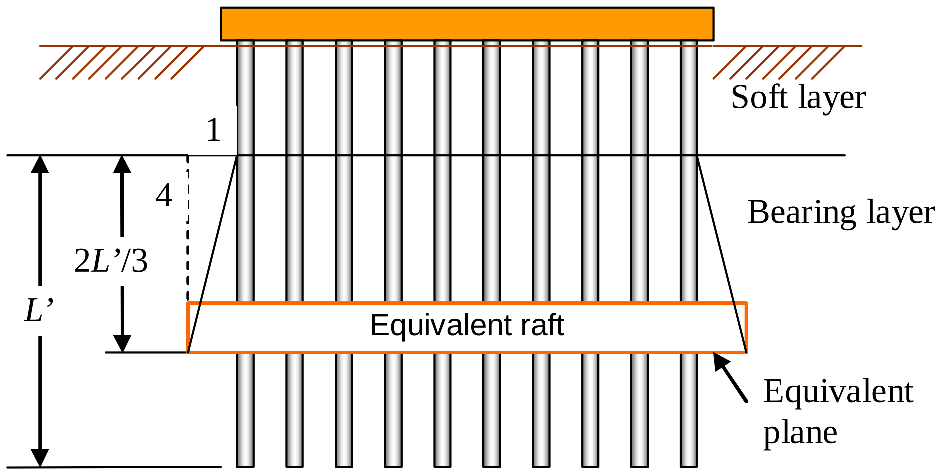
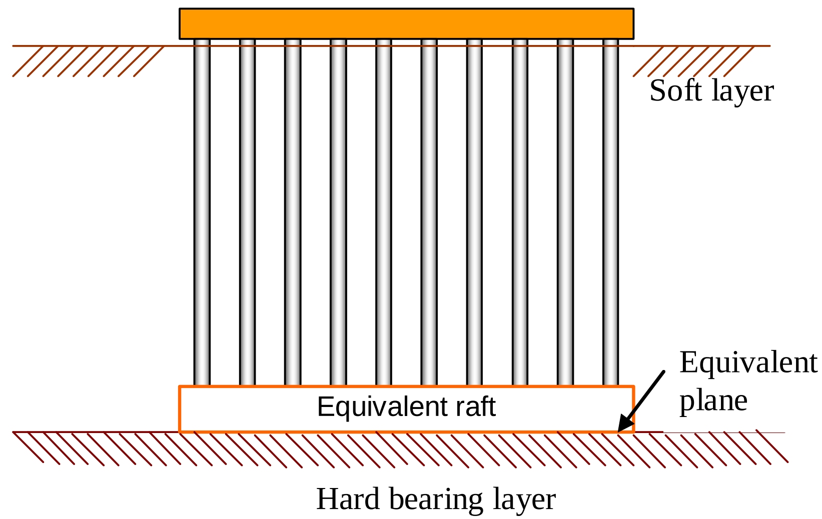
1. Simple methods (1) Equivalent raft method (Tomlinson 1986)

Applied to the case that area of pile group is relatively larger than pile length



(a) Primarily friction piles



(b) Primarily end-bearing piles

$$w_{avg} = w_{raft} + \Delta w$$

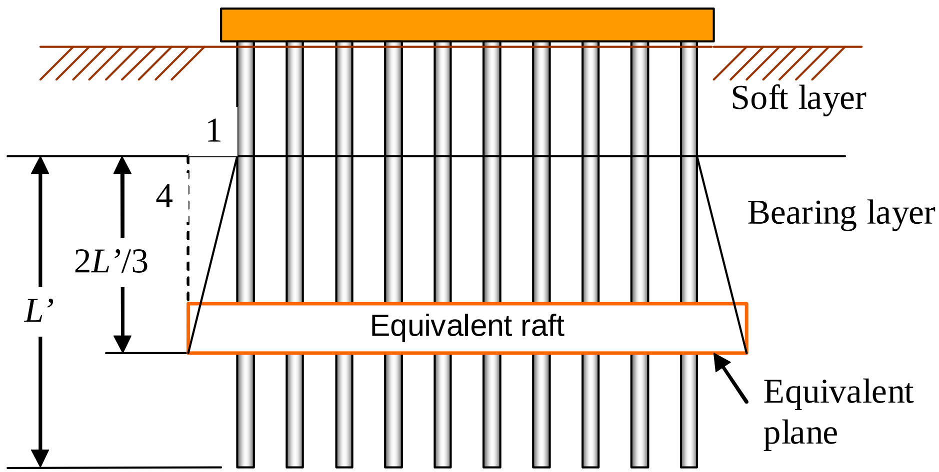
w_{avg} : average settlement of pile group

w_{raft} : settlement of equivalent raft

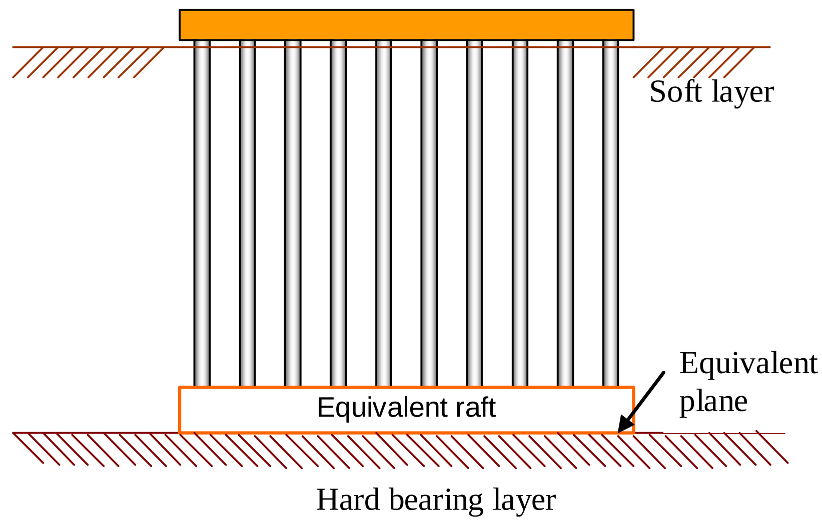
Δw : elastic compression of free standing pile section above the equivalent raft

Analysis Methods of Single Piles and Pile Groups

1. Simple methods (1) Equivalent raft method (Tomlinson 1986)



(a) Friction piles



(b) End-bearing piles

$$w_{avg} = w_{raft} + \Delta w$$

$$w_{raft} = F_D q \sum_{i=1}^{n} \left(\frac{I_\varepsilon}{E_s} \right) h_i$$

The raft settlement, w_{raft}, is evaluated by integrating the vertical strains, allowing for variations in soil modulus and correcting for the raft embedment below the ground surface using the solutions of Fox (1948).

The raft embedment is taken as that below the top of the main bearing stratum.

Analysis Methods of Single Piles and Pile Groups

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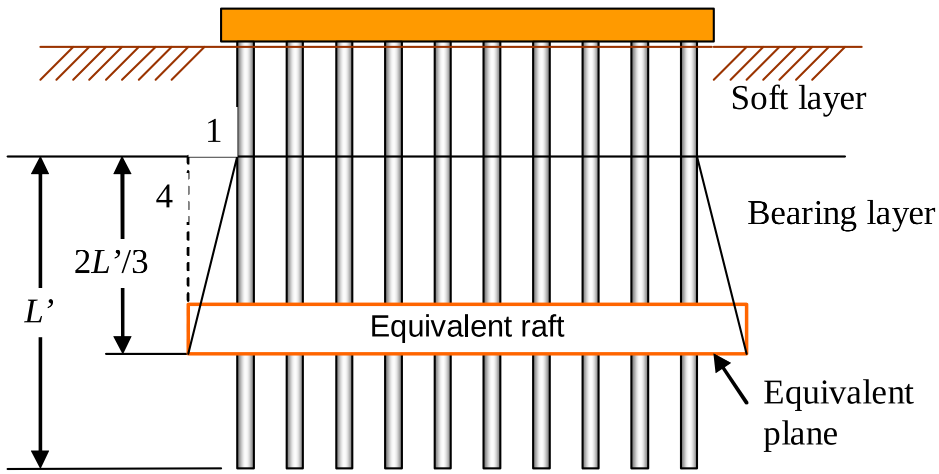
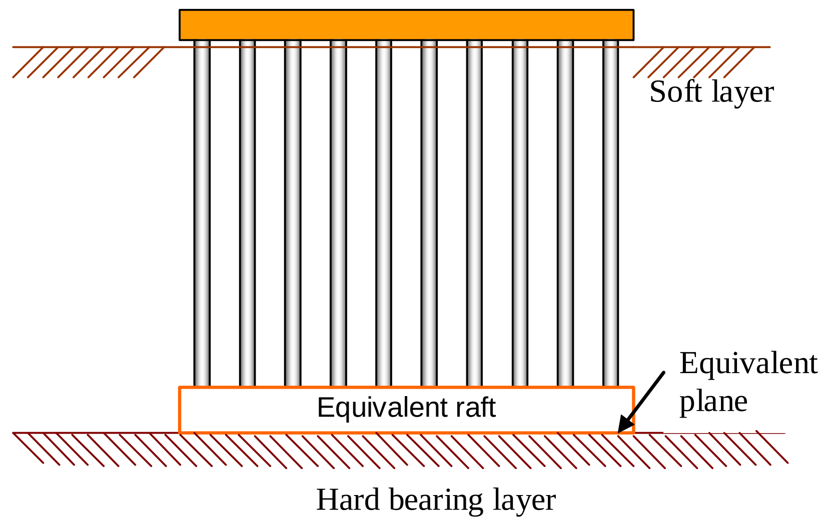


(a) Friction piles



(b) End-bearing piles

$$w_{avg} = w_{raft} + \Delta w$$

$$w_{raft} = F_D q \sum_{i=1}^{n} \left(\frac{I_\varepsilon}{E_s} \right)_i h_i$$

q = average pressure applied to raft

I_ε = influencel factor from which vertical strain is calculated

$(E_s)_i$ = Young's modulus for the i^{th} layer

h_i = thickness for the i^{th} layer

F_D = correction factor (Fox, 1948)

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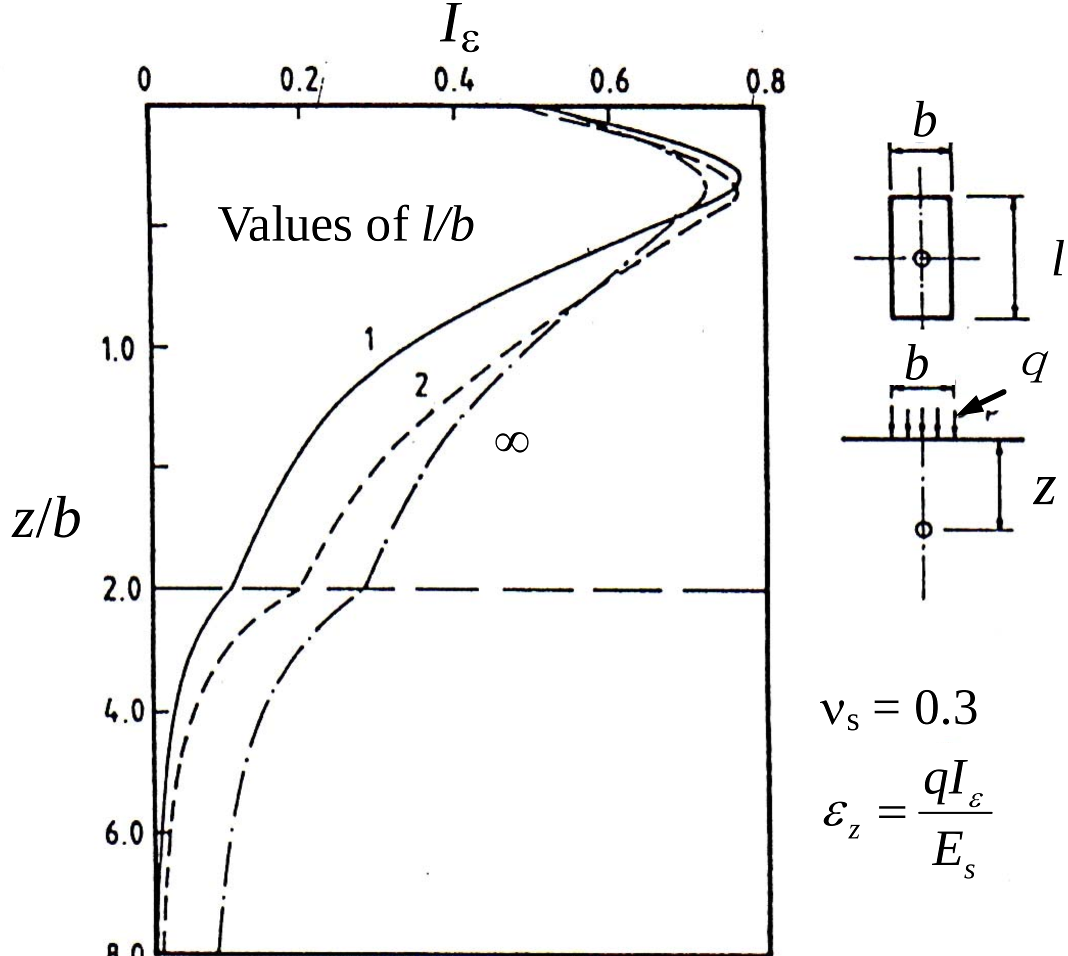

Influence factor for vertical strain (Poulos, 1993)

Analysis Methods of Single Piles and Pile Groups

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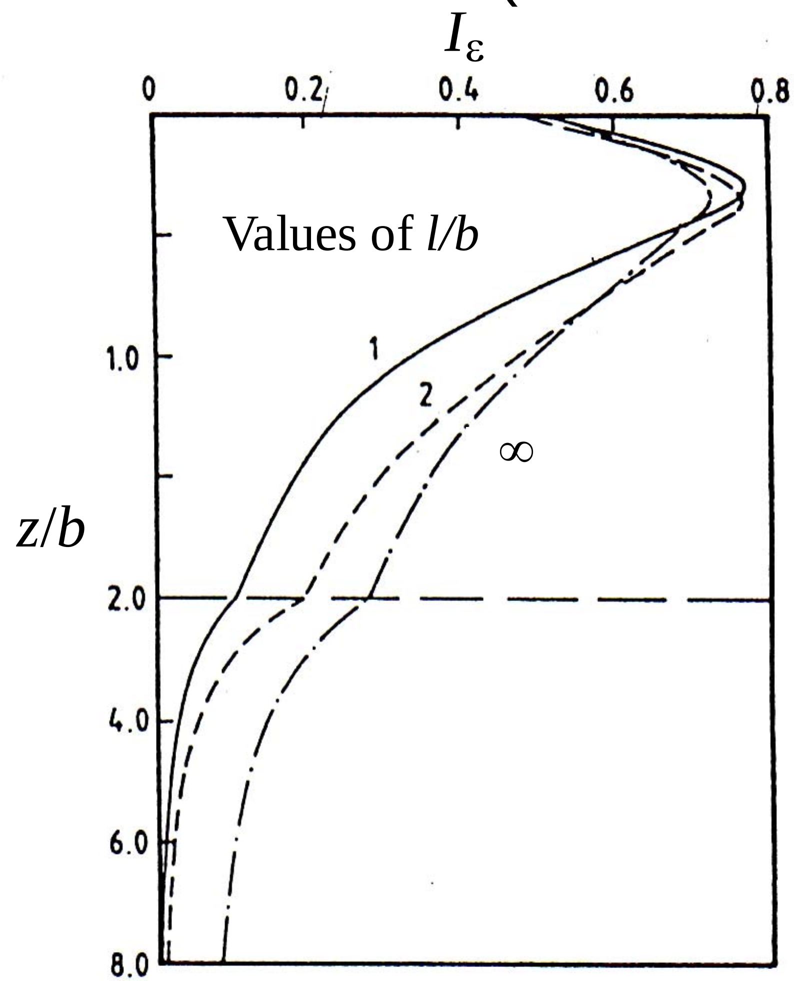
$$w_{avg} = w_{raft} + \Delta w$$

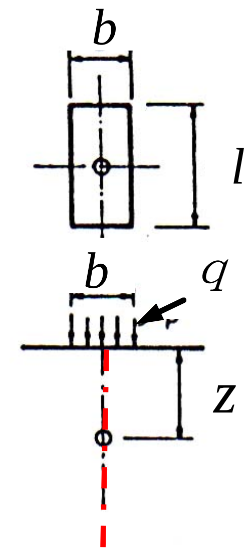
$$w_{raft} = F_D q \sum_{i=1}^{n} \left(\frac{I_\varepsilon}{E_s} \right)_i h_i$$

The influence factors are for the centre-line of a rectangular raft where the vertical strain becomes the largest.

⇩

In order to obtain the average raft settlement, the settlement calculated from the equation should be reduced by approximately 20 %.





$\nu_s = 0.3$

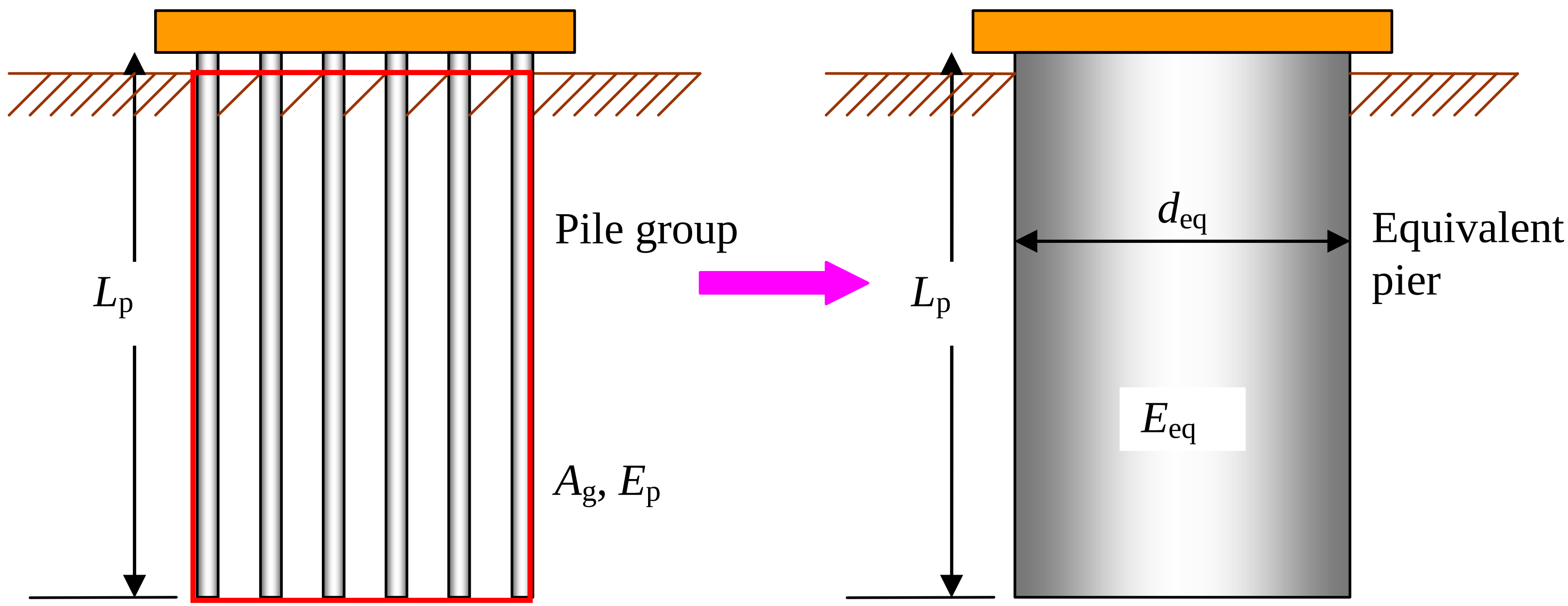
$$\varepsilon_z = \frac{q I_\varepsilon}{E_s}$$

Influence factor for vertical strain (Poulos, 1993)

Analysis Methods of Single Piles and Pile Groups

1. Simple methods (2) Equivalent pier method (Poulos & Davis 1980)

Applied to the case that area of pile group is relatively smaller than pile length



The methods considers the region of soil in which the piles are embedded as an equivalent continuum.

the pile group ⇒ an equivalent pier

→ Estimation of settlement using equations for a single pile

Analysis Methods of Single Piles and Pile Groups

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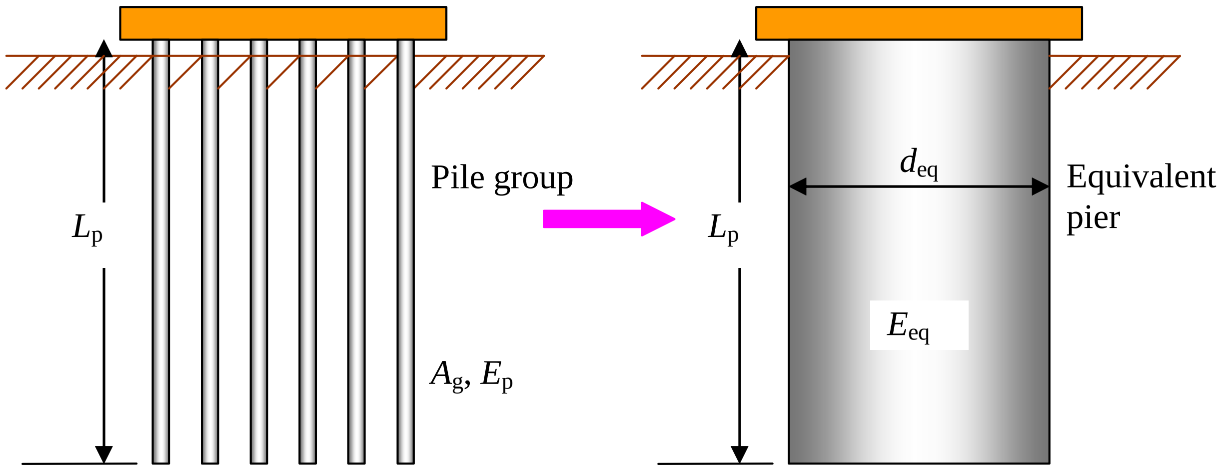
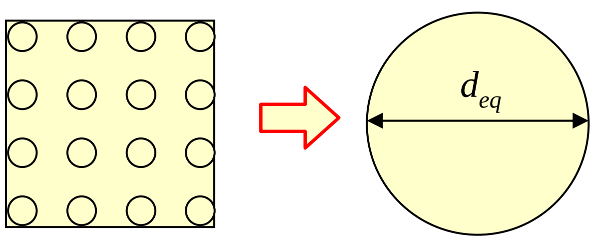


Young's modulus of equivalent pier:

$$E_{eq} = E_s + (E_p - E_s)\frac{A_{tp}}{A_g}$$

E_{eq}: Young's modulus of equivalent pier
E_s: Young's modulus of soil
E_p: Young's modulus of pile
A_{tp}: Total of cross-sectional area of individual piles
A_g: Cross-sectional area of block



Area of block = Area of equivalent pier

$$d_{eq} = \sqrt{\frac{4}{\pi}}\sqrt{A_g} = 1.13\sqrt{A_g}$$

→ Estimation of settlement using equation for a single pile

Analysis Methods of Single Piles and Pile Groups

1. Simple methods (2) Equivalent pier method

Estimation of pile head stiffness for a single pile (Randolph & Wroth 1978)

$$\frac{P_t}{G_L r_p w_t} = \frac{\dfrac{4\eta}{(1-\nu_s)\xi} + \rho \dfrac{2\pi}{\zeta} \dfrac{\tanh \mu L}{\mu L} \dfrac{L}{r_p}}{1 + \dfrac{1}{\pi\lambda} \dfrac{4\eta}{(1-\nu_s)\xi} \dfrac{\tanh \mu L}{\mu L} \dfrac{L}{r_p}}$$

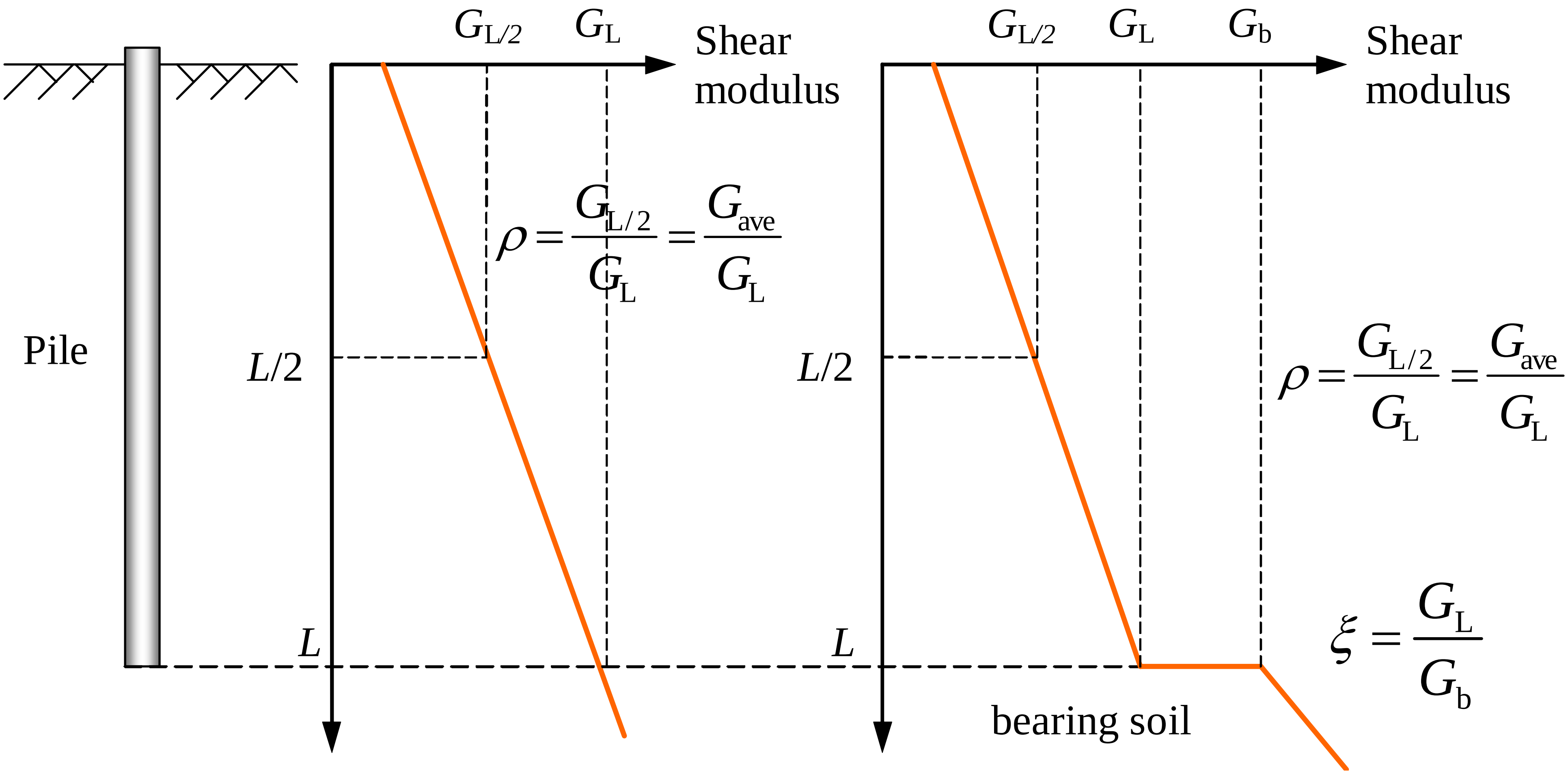
P_t: Load on pile top
w_t: Pile head settlement
r_p: Pile radius
L_p : Pile length
G_L: Shear modulus of soil at the pile toe

$\eta = r_b/r_p$ Ratio of radius of pile shaft and radius of pile base (r_b : radius of pile base)
ν_s Poisson's ratio of soil
$\xi = G_L/G_b$ Ratio of shear modus of soil at the pile toe to bearing soil
$\rho = G_{ave}/G_L$ Coefficient of change in shear modulus of soil with depth
(G_{ave} : average of Young's modulus of soil down the pile)
$\lambda = E_p/G_L$ Relative stiffness of soil and pile
$\mu L = \sqrt{2/\zeta\lambda}(L/r_p)$
$\zeta = \ln(r_m/r_p)$
$r_m = 2.5\rho(1-\nu_s)L$

For piles of lower aspect ratio

$$\zeta = \ln\left[5 + 2.5(1-\nu_s)L_p/r_p\right]$$

(Randolph 1994)



(a) Friction pile (b) End-bearing pile

Analysis Methods of Single Piles and Pile Groups

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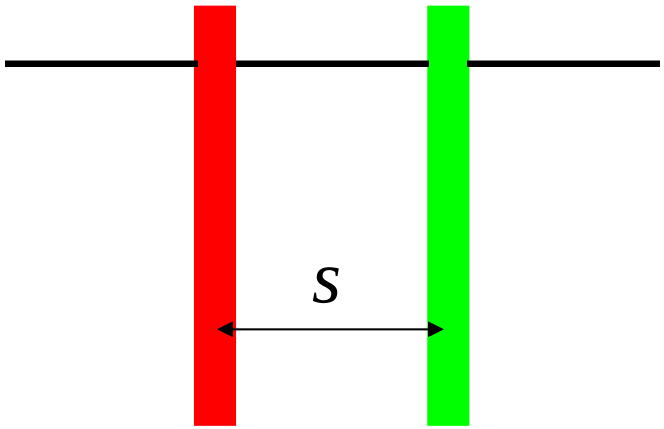
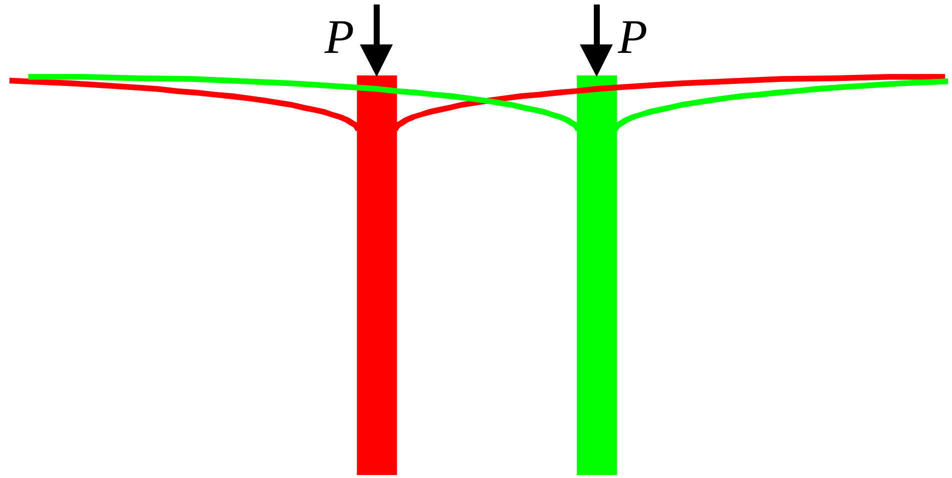
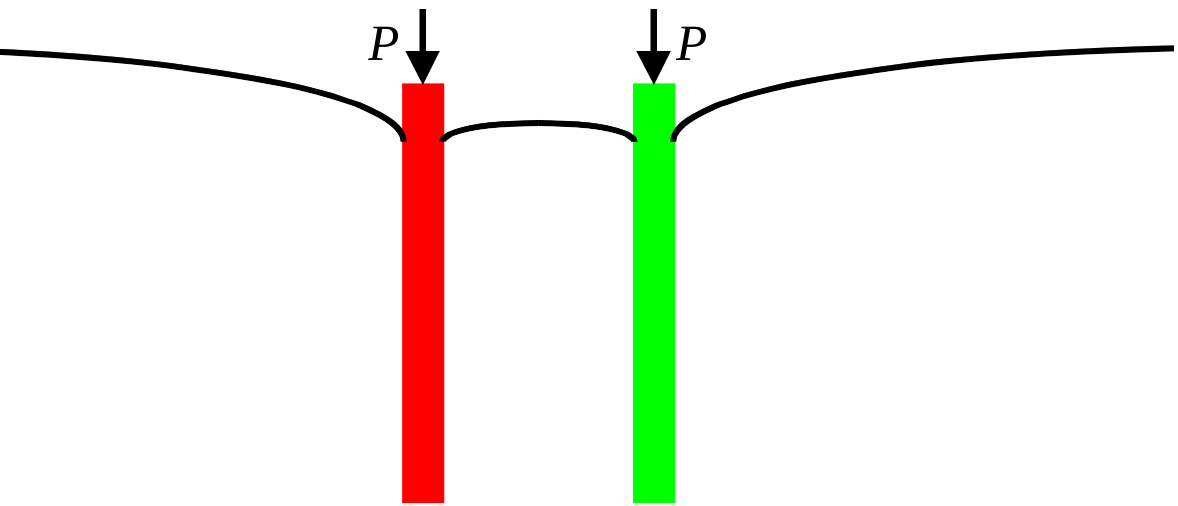
Proportion of load reaching the pile base, P_b/P_t (Randolph & Wroth 1978)

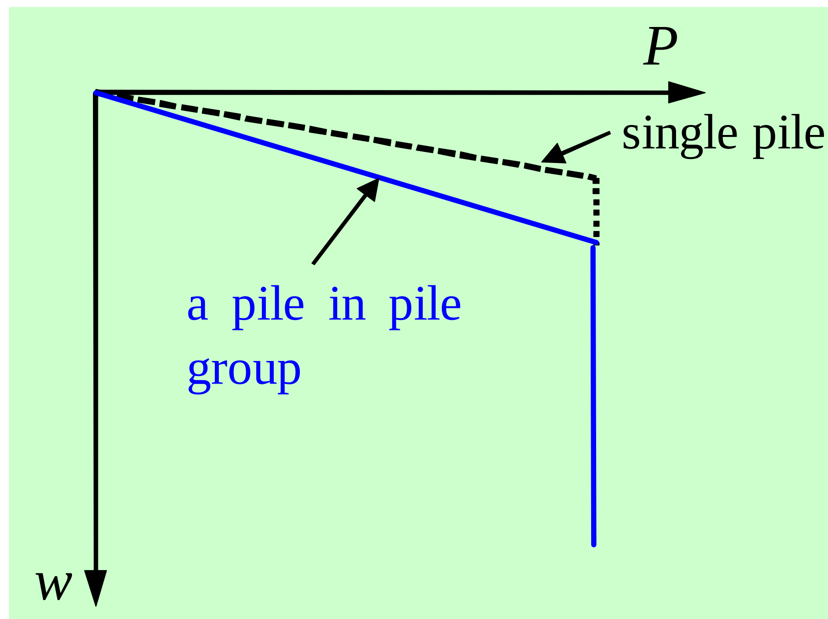
$$\frac{P_b}{P_t} = \frac{\dfrac{4\eta}{(1-\nu_s)\xi} \dfrac{1}{\cosh \mu L}}{\dfrac{4\eta}{(1-\nu_s)\xi} + \rho \dfrac{2\pi}{\zeta} \dfrac{\tanh \mu L}{\mu L} \dfrac{L}{r_p}}$$

Interaction effects between piles

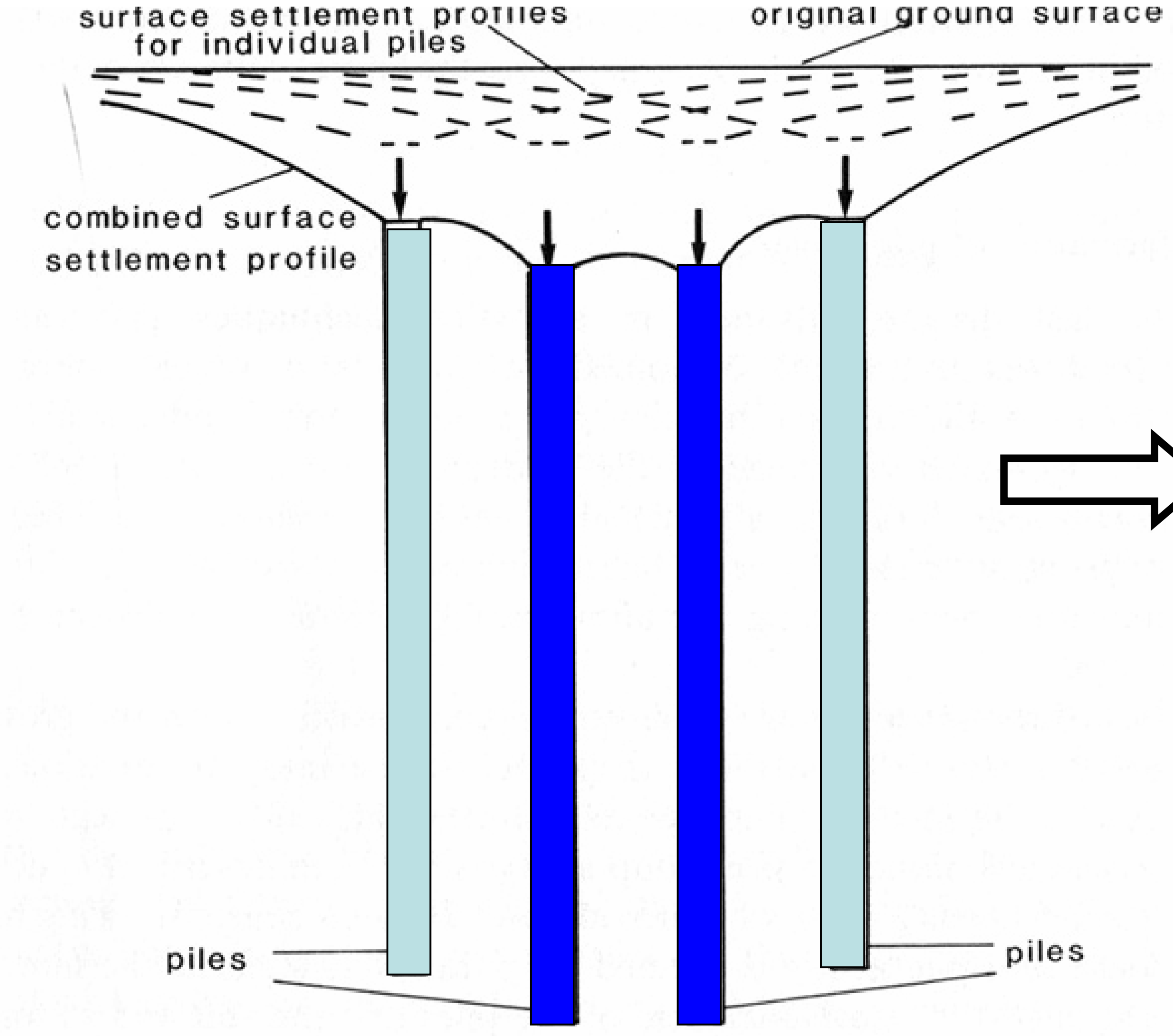








Interaction effects between piles



Superposition of settlement for group of piles

Importance of consideration of interaction effects.

Analysis Methods of Single Piles and Pile Groups

1. Simple methods

(3) Method using settlement ratio of single pile to pile group (Butterfield & Douglas 1981)

Group Settlement Ratio: $R_s = \dfrac{nk_1}{K}$

n : number of piles
k_1 : Pile head stiffness of a single pile
K : Pile head stiffness of pile group

$$K = \frac{nk_1}{R_s} = \eta n k_1, \qquad \eta = \frac{1}{R_s}$$

η : group efficiency

$$\eta < 1.0$$

$\eta = n^{-e}$ (an approximation) $\quad K = n^{-e} n k_1 = n^{(1-e)} k_1$

e = 0.3 to 0.5 for friction piles
$e \geq 0.6$ for end-bearing piles

(based on elastic analyses) (Fleming et al, 1992)

The value of *e* depends on various factors.

aspect ratio of the pile, relative stiffness of soil and pile, pile spacing, uniformity of the ground, Poisson's ratio of the soil

Analysis Methods of Single Piles and Pile Groups

1. Simple methods

Advantages

- feasible to handle
- adequate for preliminary design
- adequate for parametric study

Disadvantages

- average settlement alone is estimated
- forces in individual piles cannot be estimated
- difficult to estimate non-linear behaviour

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(3) Method using settlement ratio of single pile to pile group
(Butterfield & Douglas 1981)

2. Detailed methods

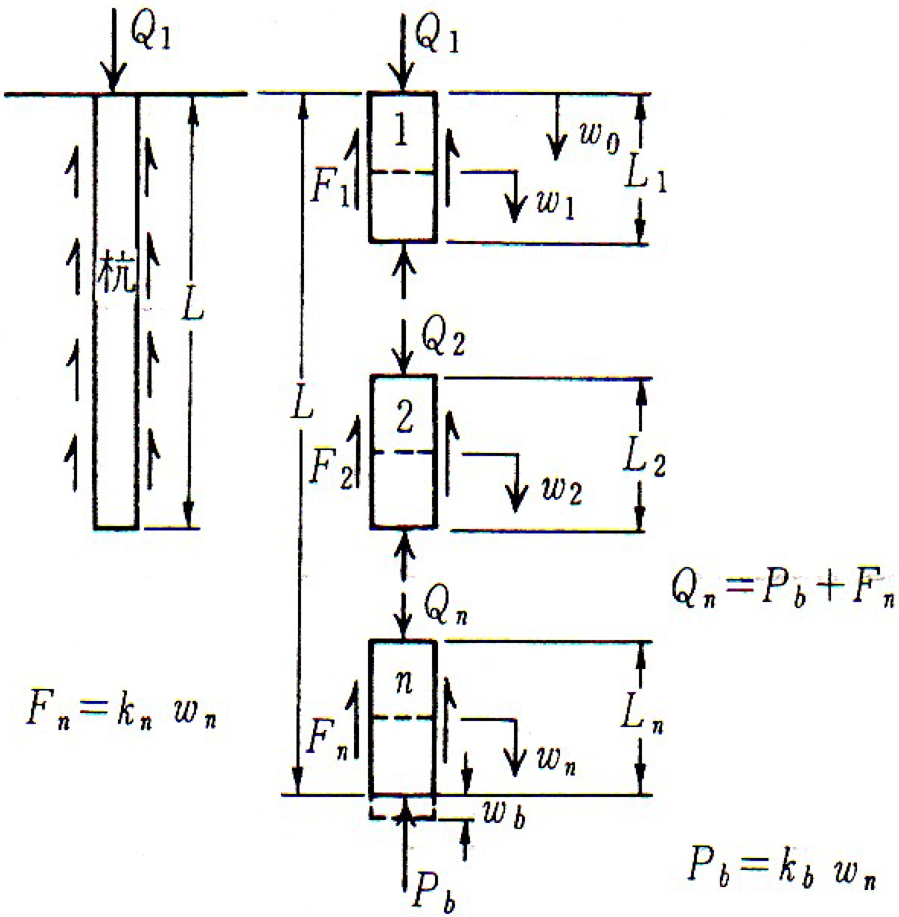
(1) Load transfer method (*t* - *z* method)

(2) BEM

(3) FEM (1-dimensional, 2-dimensional and 3-dimensional)

Analysis Methods ofr Single Piles and Pile Group

2. Detail methods (1) Load transfer method (Coyle & Reese 1966)



Shaft resistance $\tau = kw$

Force equilibrium $EA\dfrac{dw}{dz} - kwU = 0$

τ: shaft resistance
k: coefficient of subgrade reaction
w: pile settlement
E: Young's modulus of pile
A: Cross-sectional area of pile
U: Circumferential length of pile

Calculation is iterated with assumed pile displacements and coefficients of subgrade reaction.

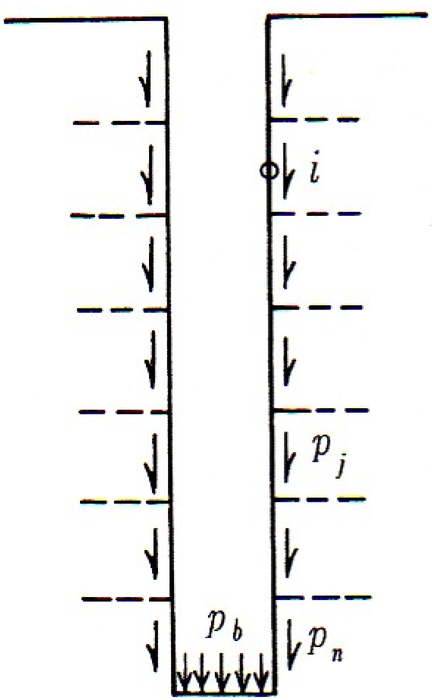
This method is capable to deal with multi layered ground.

This method could not be applied to pile group, because influence of neibouring piles (interaction) is not considered.

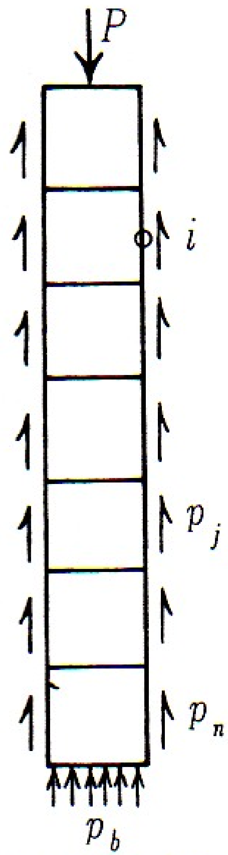
Analysis Methods for Single Piles and Pile Groups

2. Detail methods (2) BEM: Boundary Element Method

(D' Appolonia & Romualdi 1963, Poulos & Davis 1980)



Stresses acting on ground

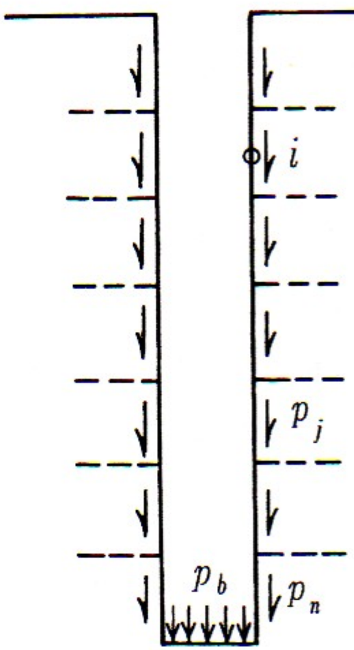


Stresses acting on pile

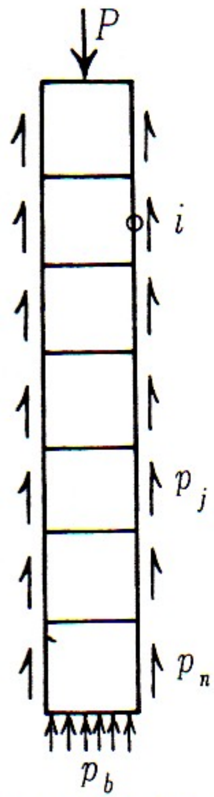
- The most rigorous treatment of piles and pile groups.
- Full interface between soil and pile is divided into elements.
- The Mindlin’s solution is used to relate the displacement of each element to the traction on each element.
- Corresponding equations are written for the structural response of the pile, using FDM or FEM.
- The two sets of equations, together with overall equilibrium, allow the unknown tractions to be found.
- Hence, the stiffness and load distribution throughout the foundation are evaluated.

Analysis Methods for Single Piles and Pile Groups

2. Detail methods (2) BEM: Boundary Element Method



Stresses acting on ground



Stresses acting on pile

Limitations:

- The ground is basically treated as a homogeneous linear elastic continuum, because the Mindlin's solution is used to estimate interaction (influence) factors.
- The computational resources required to perform the ideal analysis become excessive, in practice.

Simplification in analysis of pile group:

Combination of a load transfer approach to quantify the relationship between local traction and displacement along each pile, together with the elastic solution of MIndlin to calculate additional displacement due to the tractions acting on the elements of all other pile elements.

Analysis Methods for Single Piles and Pile Groups

2. Detail methods (2) BEM (Boundary Element Method)

Method using interaction factor (Poulos & Davis, 1980)

Settlement of pile *k* in pile group

$$w_k = w_1 \sum_{j=1}^{n} \alpha_{kj} P_j$$

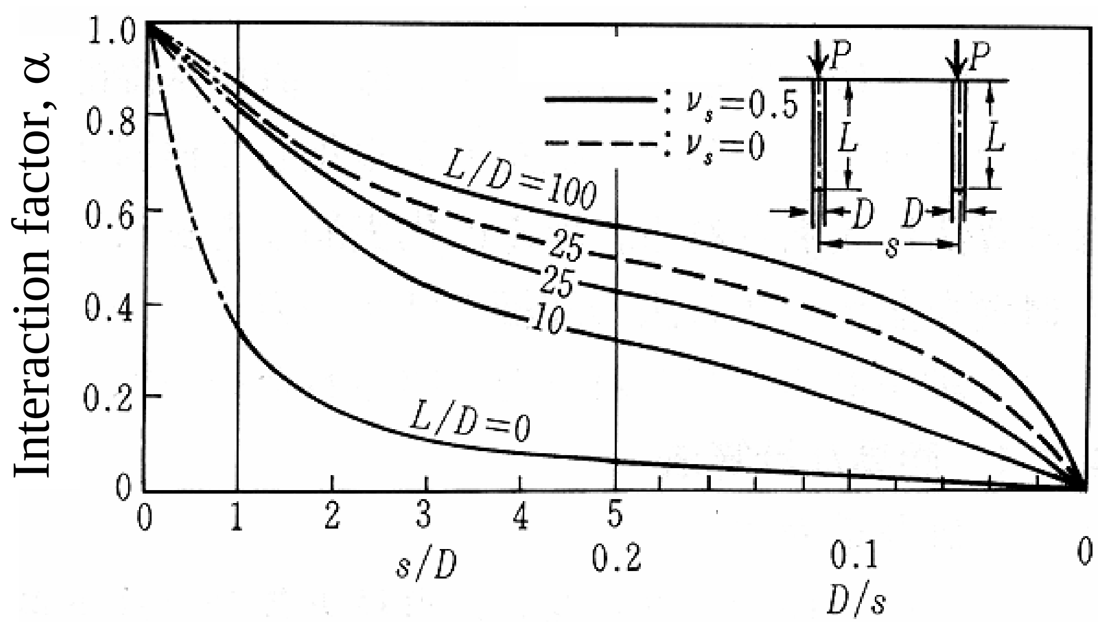
w_1 : Settlement of single pile due to unit load

α_{kj} : Interaction factor between pile k and pile j

P_j : Load on pile j

n : Number of piles in group

Interactions between all piles in pile group are considered.

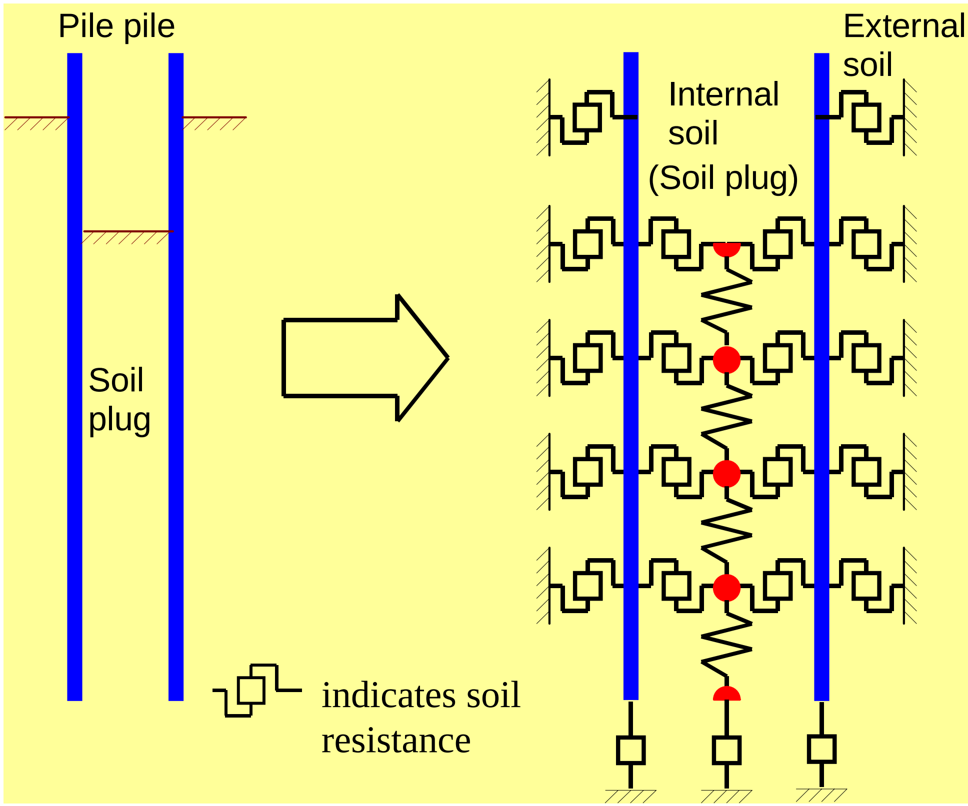


$$\alpha = \frac{\text{Settlement due to neibouring pile}}{\text{Settlement due to its own load}}$$

Analysis Methods for Single Piles and Pile Groups

2. Detail methods (3) FEM: Finite Element Method

One-dimensional modelling for single pile



One-dimensional modelling of an open-ended pipe pile
(Matsumoto & Takei 1991)

Pile:
one-dimensional elastic continuum

Outer soil:
(non-linear) spring and slider in series connected to pile nodes

Inner soil (soil plug):
one-dimensional elastic continuum connected to pile nodes

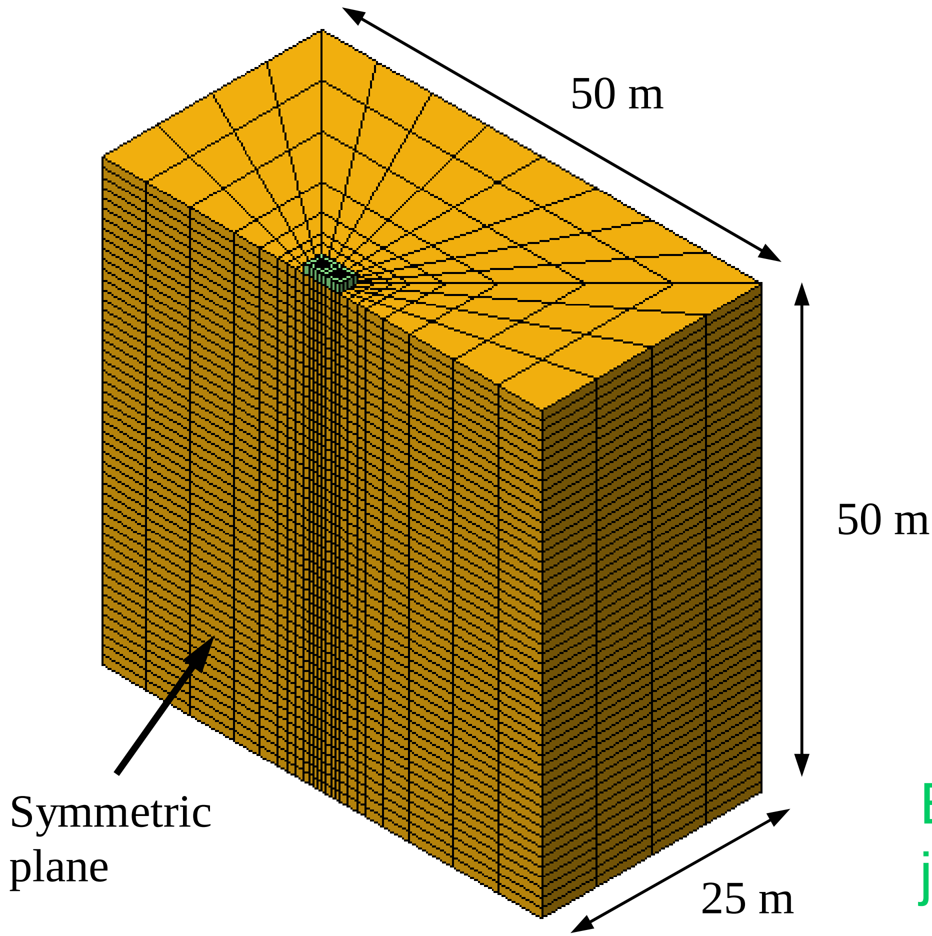
Values of soil springs and sliders must be prescribed explicitly.

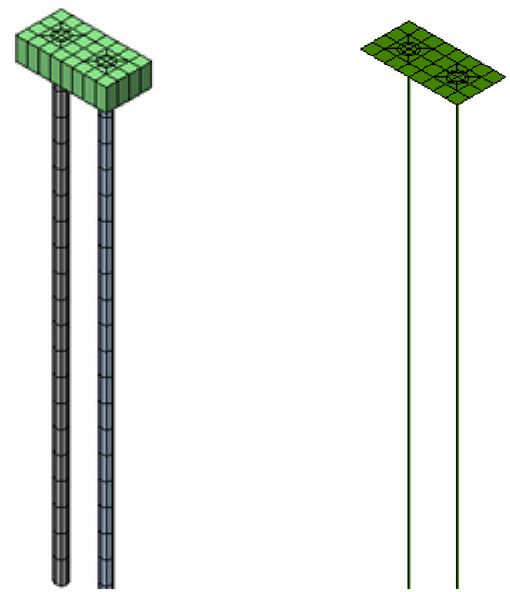
Analysis Methods for Single Piles and Pile Group

2. Detail methods

(3) FEM: Finite Element Method

Three dimensional modellling





Rigorous analysis method

- Complicated soil conditions
- Complicated boundary conditions
- Non-linear behaviour of soil
- Applicable to dynamic analysis

Estimation of initial stress conditions just after pile installation is difficult.

Summary of Lecture 1

Design concept of pile raft

- Conventional approach
- Creep piling
- Differential settlement control

Difference between design concepts of pile group and pile raft

Effective application of pile raft

Analysis methods of single piles and pile groups

- Simple methods
- Detailed methods