Analysis Methods of Piled Raft Foundations

REFERENCES

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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).

Analysis Methods of Piled Raft Foundations

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.

"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.

Analysis Methods of Piled Raft Foundations

Design Concept | Alternative design philosophies

Two classes of piled raft foundations (De Sanctis et al 2001, Viggiani 2001):

1. "Small" piled rafts, where the primary reason for adding the piles is to increase the factor of safety (this typically involves rafts with widths between 5 and 15 m).

   Conventional philosophy

2. "Large" piled rafts, whose bearing capacity is sufficient to carry the applied load with a reasonable safety margin.

   In such cases, the width of the raft is larger in comparison with the length of the piles (typically, the width of the raft exceeds the length of the piles).

   Creep piling philosophy

Analysis Methods of Piled Raft Foundations

Design Concept | Design issues

1. Ultimate load capacity for vertical, lateral and moment loadings
2. Maximum settlement
3. Differential settlement
4. Raft moments and shears for the structural design of the raft
5. Pile loads and moments for the structural design of the piles

Emphasis has been placed on the bearing capacity and settlement under vertical loads.

In some cases, the foundation requirements may be governed by the horizontal and overturning moments by wind loading, seismic loading, rather than the vertical dead and live loads.

Analysis Methods of Piled Raft Foundations

Classification of methods of analysis (Poulos, 1997, 2001)

1. Simplified calculation methods

(1) Poulos-Davis-Randolph (PDR) Method

(2) Burland's Approach (Burland 1995)

2. Approximate computer-based methods

(1) Strip on Springs Approach (Poulos, 1991)

(2) Plate on Springs Approach (Poulos, 1994)

(3) Methods combining boundary element for the piles and finite element analysis for the raft.
(Clancy & Randolph 1993, Kitiyodom & Matsumoto 2003, 2004)

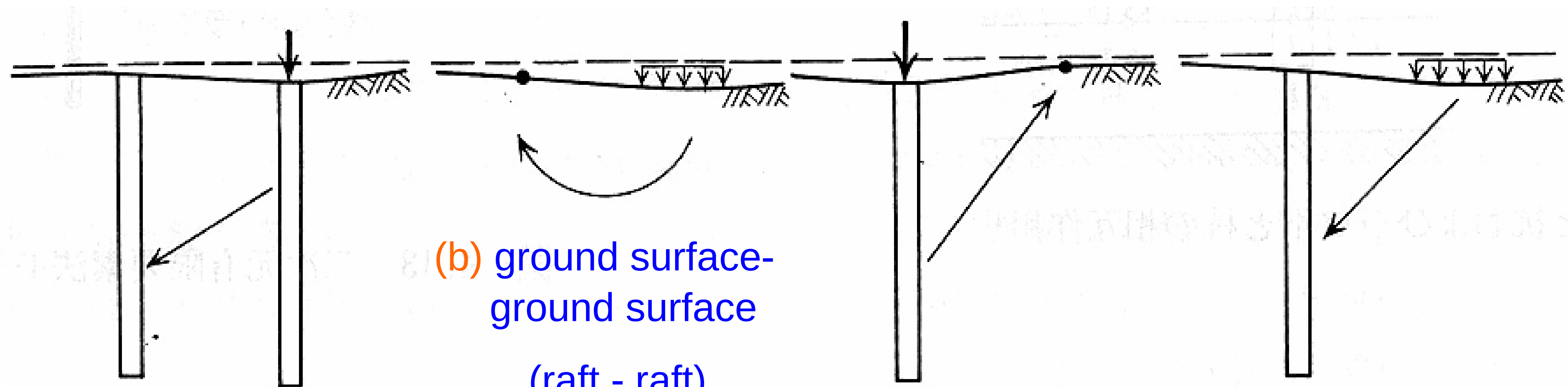
3. More rigorous computer-based methods

(1) BEM

(2) FEM (two-dimensional and three-dimensional)

Analysis Methods of Piled Raft Foundations

Importance of consideration of four interactions



(b) ground surface-
ground surface

(raft - raft)

(a) pile - pile

(c) pile - ground surface
(pile - raft)

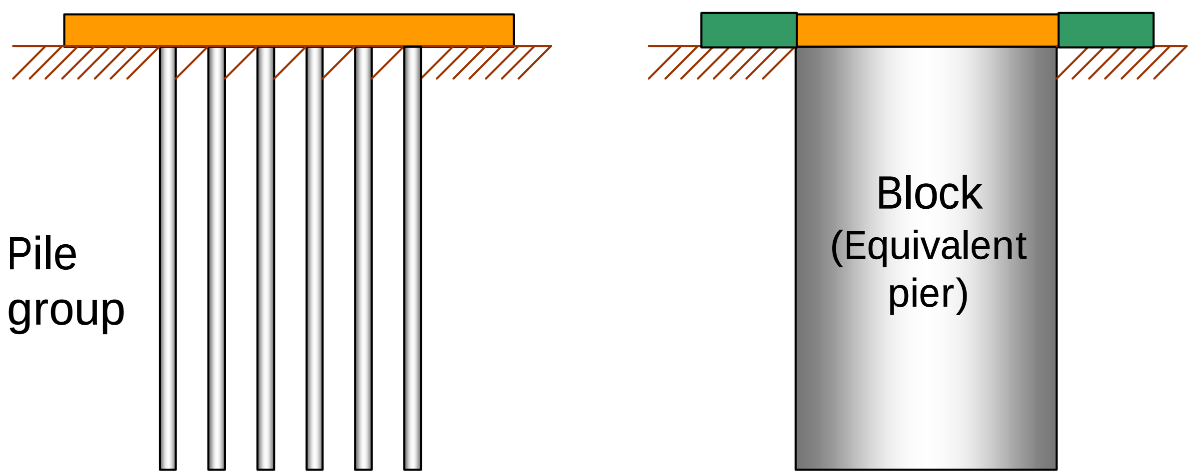
(d) ground surface - pile
(raft - pile)

Analysis Methods of Piled Raft Foundations

1. Simplified methods

For assessing vertical bearing capacity of a piled raft using simple approaches, the ultimate load capacity can generally be taken as the lesser of

- The sum of the ultimate capacities of the raft plus all the piles
- The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

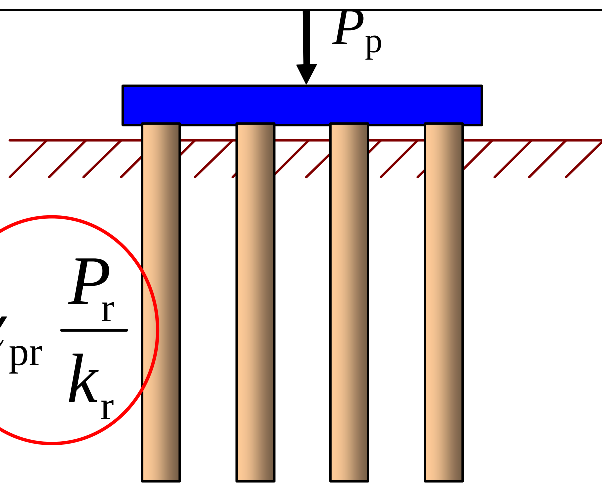


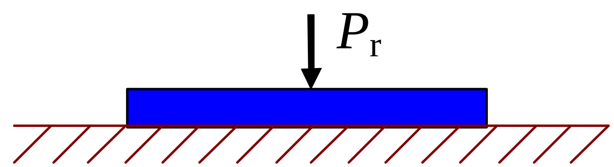
Analysis Methods of Piled Raft Foundations

1. Simplified methods (1) Poulos-Davis-Randolph (PDR) Method

$$\begin{Bmatrix} w_p \\ w_r \end{Bmatrix} = \begin{bmatrix} 1/k_p & \alpha_{pr}/k_r \\ \alpha_{rp}/k_p & 1/k_r \end{bmatrix} \begin{Bmatrix} P_p \\ P_r \end{Bmatrix}$$

- w_p : Settlement of pile group
- w_r : Settlement of raft
- k_p : Settlement stiffness of pile group
- k_r : Settlement stiffness of raft
- α_{pr} : Interaction factor for pile group settlement due to load on raft
- α_{rp}: Interaction factor for raft settlement due to load on pile group





$$w_p = \frac{P_p}{k_p} + \alpha_{pr}\frac{P_r}{k_r}$$

$$w_r = \frac{P_r}{k_r} + \alpha_{rp}\frac{P_p}{k_p}$$

1. Simplified methods (1) Poulos-Davis-Randolph (PDR) Method

Assumptions:

(1) Settlements of pile group and raft are equal in piled raft ($w_p = w_r$).

(2) $\alpha_{pr}/k_r = \alpha_{rp}/k_p$ from the reciprocal problem.

$$\begin{Bmatrix} w_p \\ w_r \end{Bmatrix} = \begin{bmatrix} 1/k_p & \alpha_{pr}/k_r \\ \alpha_{rp}/k_p & 1/k_r \end{bmatrix} \begin{Bmatrix} P_p \\ P_r \end{Bmatrix}$$

Stiffness of piled raft

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{k_p + k_r(1 - 2\alpha_{rp})}{1 - (k_r/k_p)\alpha_{rp}^2}$$

Proportion of the total applied load carried by the raft

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{(1 - \alpha_{rp})k_r}{k_p + (1 - 2\alpha_{rp})k_r}$$

Assumptions:

(1) Settlements of pile group and raft are equal in piled raft ($w_p = w_r$).

(2) $\alpha_{pr}/k_r = \alpha_{rp}/k_p$ from the reciprocal problem.

Stiffness of piled raft

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{k_p + k_r(1 - 2\alpha_{rp})}{1 - (k_r / k_p)\alpha_{rp}^2}$$

Proportion of the total applied load carried by the raft

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{(1-\alpha_{rp})k_r}{k_p + (1-2\alpha_{rp})k_r}$$

k_p: Settlement stiffness of pile group

Equivalent raft method, Equivalent pier method,
Rigorous methods (BEM, FEM, etc.)

k_r: (Average) Settlement stiffness of raft

Average settlement stiffness of raft does not depend on the bending rigidity of the raft.

e.c. $$w_{ave} = \frac{P_r(1-\nu_s)}{4G_s a_{eq}}$$

Analysis Methods of Piled Raft Foundations

1. Simplified methods (1) Poulos-Davis-Randolph (PDR) Method

Stiffness of piled raft

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{k_p + k_r(1 - 2\alpha_{rp})}{1 - (k_r / k_p)\alpha_{rp}^2}$$

Proportion of the total applied load carried by the raft

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{(1 - \alpha_{rp})k_r}{k_p + (1 - 2\alpha_{rp})k_r}$$

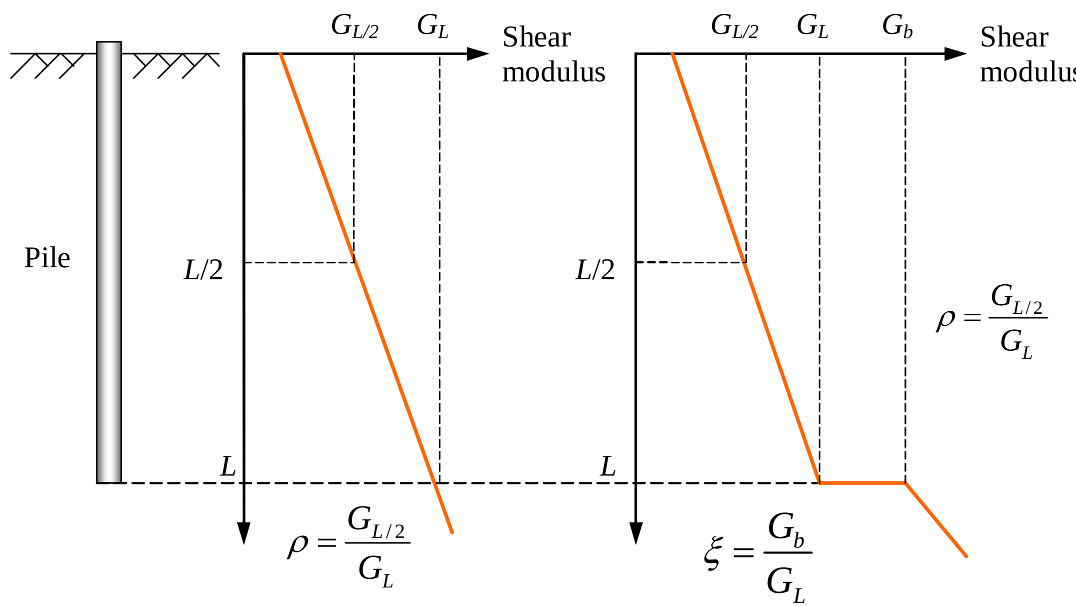
Raft-pile interaction factor, α_{rp}

$$\alpha_{rp} = 1 - \frac{\ln(r_r / r_p)}{\zeta}$$

$$\zeta = \ln(r_m / r_p)$$

r_p = radius of equivalent pier

$$r_m = \{0.25 + \xi[2.5\rho(1-\nu) - 0.25]\}L$$



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

Analysis Methods of Piled Raft Foundations

1. Simplified methods (1) Poulos-Davis-Randolph (PDR) Method

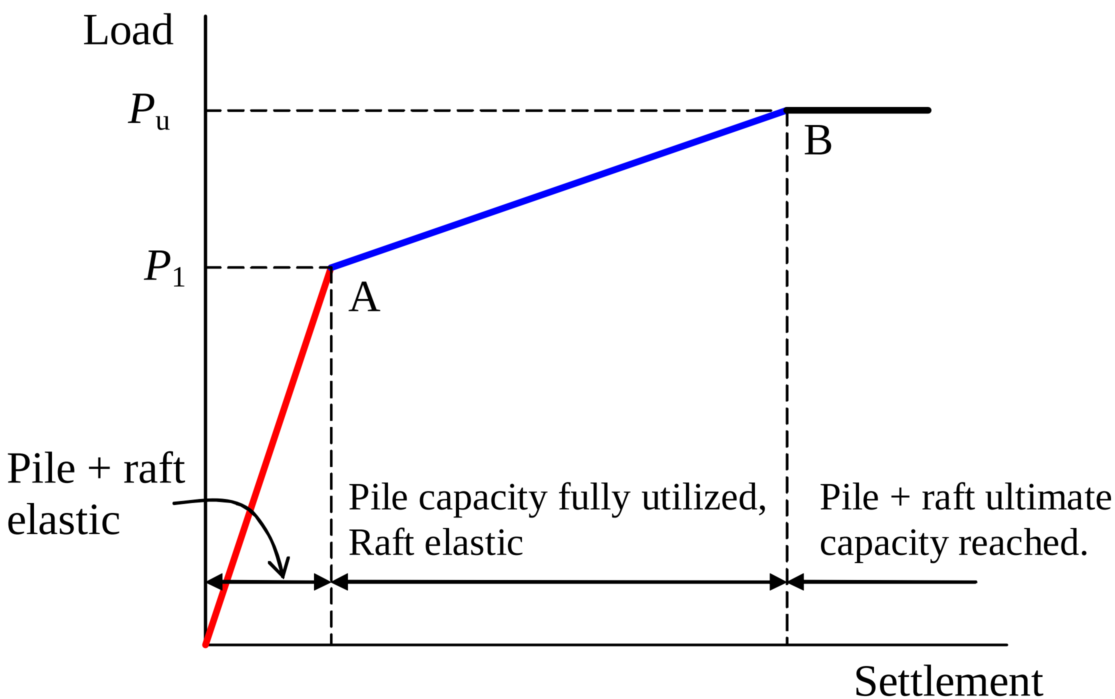
Stiffness of piled raft

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{k_p + k_r\left(1 - 2\alpha_{rp}\right)}{1 - \left(k_r / k_p\right)\ \alpha_{rp}^2}$$

Proportion of the total applied load carried by the raft

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{(1-\alpha_{rp})k_r}{k_p + (1-2\alpha_{rp})k_r} = X$$

Simplified load-settlement curve for preliminary analysis



Total applied load, P_1, at which the pile capacity reached:

$P_1 = P_{up}/(1-X)$

P_{up} = ultimate load capacity of the piles in the group

Analysis Methods of Piled Raft Foundations

1. Simplified methods (2) Burland's approach

The piles are designed to act as settlement reducers and to develop their full geotechnical capacity at the design load.

Simplified process of design

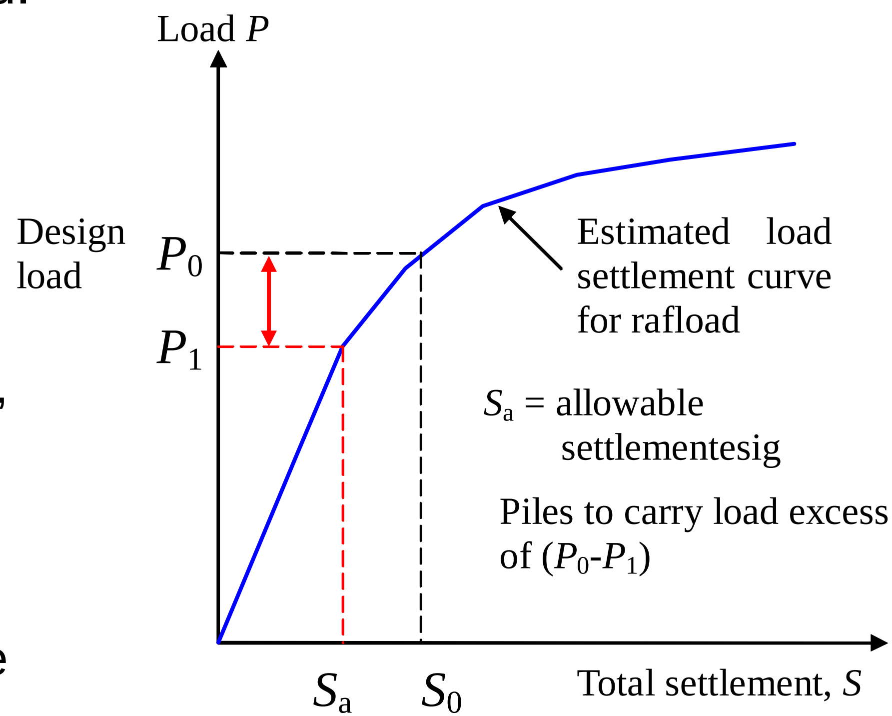
1. Estimate the total long-term load-settlement relationship for the raft without piles.

   Design load P_0 gives a total settlement S_0.

2. Assess an acceptable design settlement S_a, which should include a margin of safety.

   P_1 is the load capacity by the raft alone, corresponding to S_a.

3. The load excess, $P_0 - P_1$, is assumed to be carried by settlement-reducing piles.



The shaft resistance of these piles will be fully mobilized (no factor of safety is applied).

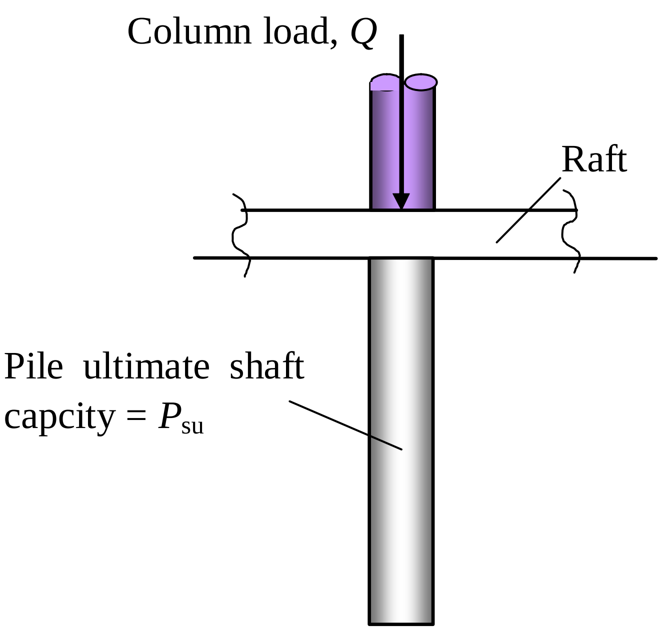
However, Burland suggests that a "mobilization factor" of 0.9 be applied to the "conservative best estimate" of ultimate pile shaft capacity, P_{su}.

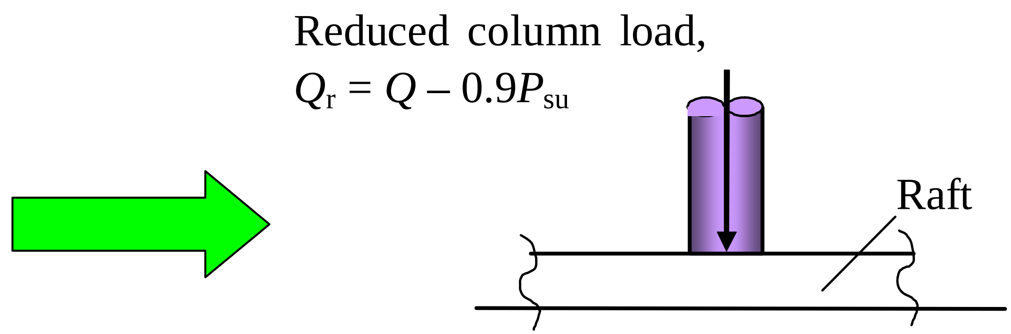
Analysis Methods of Piled Raft Foundations

1. Simplified methods (2) Burland's approach

Design process

1. Estimate the total load-term load-settlement relationship for the raft without piles.
2. Assess an acceptable design settlement S_d, which should include a margin of safety.
3. The load excess $P_0 - P_1$ is assumed to be carried by settlement-reducing piles.
4. If the piles are located below columns which carry a load in excess of P_{su}, the piled raft may be analysed as a raft on which reduced column loads act.





5. The bending moments in the raft can then be obtained by analysing the piled raft as a raft subjected to the reduced load, Q_r.

Analysis Methods of Piled Raft Foundations

1. Simplified methods (2) Burland's approach

Design process

1. Estimate the total load-term load-settlement relationship for the raft without piles.
2. Assess an acceptable design settlement, S_d, which should include a margin of safety.
3. The load excess $P0 - P1$ is assumed to be carried by settlement-reducing piles.
4. If the piles are located below columns which carry a load in excess of P_{su}, the piled raft may be analysed as a raft on which reduced column loads act.
5. The bending moments in the raft can then be obtained by analysing the piled raft as a raft subjected to the reduced load, Q_r.

The process for estimating the settlement of the piled raft is not explicitly set out.

Approximate approach by Randolph:

$$S_{pr} = S_r \times \frac{k_r}{k_{pr}}$$

S_{pr} = Settlement of piled raft
S_r = Settlement of raft
k_r = Stiffness of raft
k_{pr} = Stiffness of piled raft

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{k_p + k_r\left(1 - 2\alpha_{rp}\right)}{1 - \left(k_r / k_p\right)\ \alpha_{rp}^2}$$

Analysis Methods of Piled Raft Foundations

1. Simplified methods

Advantages

- feasible with a calculator
- adequate in the preliminary design stage

Limitations

- adequate for only simple configuration of raft and piles
  (square or rectangular raft with uniformly distributed piles subjected to uniform vertical loads)
- cannot treat eccentric vertical loads
- cannot estimate differential settlements
- cannot estimate bending moments and shears in raft
- cannot estimate axial forces and bending moments of individual piles

Analysis Methods fo Piled Raft Foundations

2. Approximate computer-based methods

(1) Strip on Springs Approach (Poulos 1991)

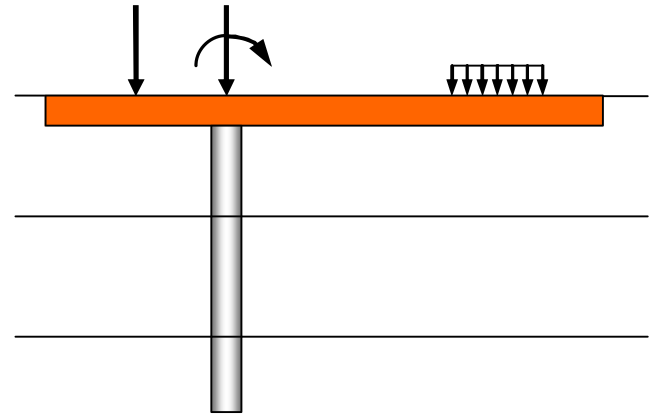
(2) Plate on Springs Approach (Poulos 1994)

(3) Hybrid Method: Combination of FEM and the theory of elasticity
(Clancy & Randolph 1993, Kitiyodom & Matsumoto 2003, 2004)

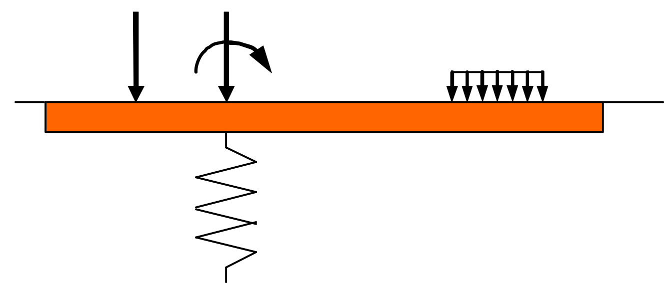
Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods
(1) Strip on Springs Approach (Poulos 1991)

1. A section of the raft is represented by a strip, and the supporting piles by springs.



(a) Actual pile



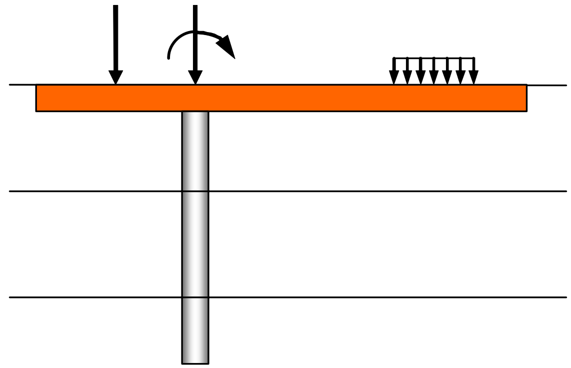
(b) Pile representation

Analysis Methods for Piled Raft Foundations

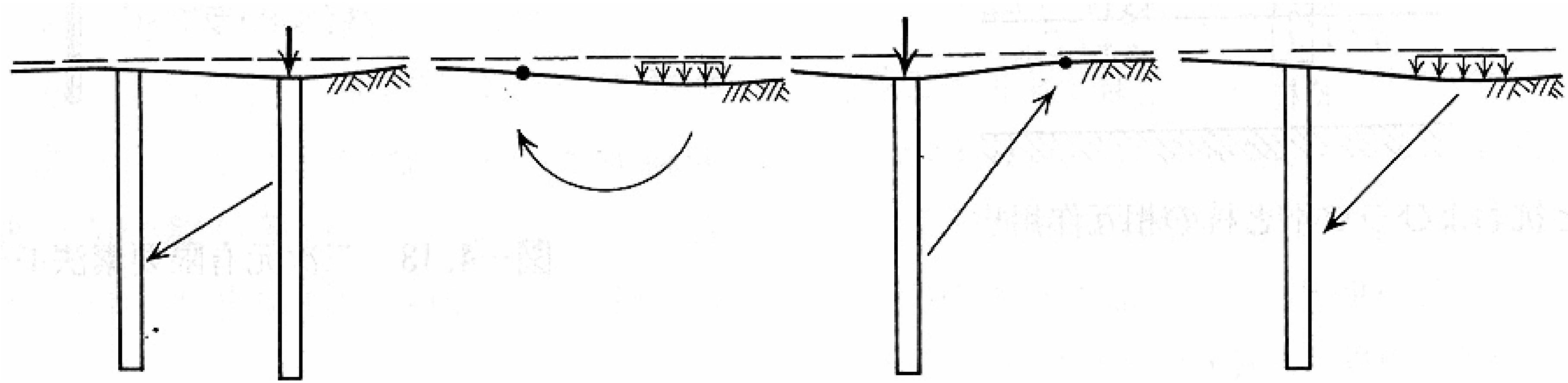
2. Approximate computer-based methods
(1) Strip on Springs Approach (Poulos 1991)

1. A section of the raft is represented by a strip, and the supporting piles by springs.

2. Approximate allowance is made for all four components of interactions (pile-pile elements, raft-raft, pile-raft and raft-pile) are taken into account.



(a) Actual pile

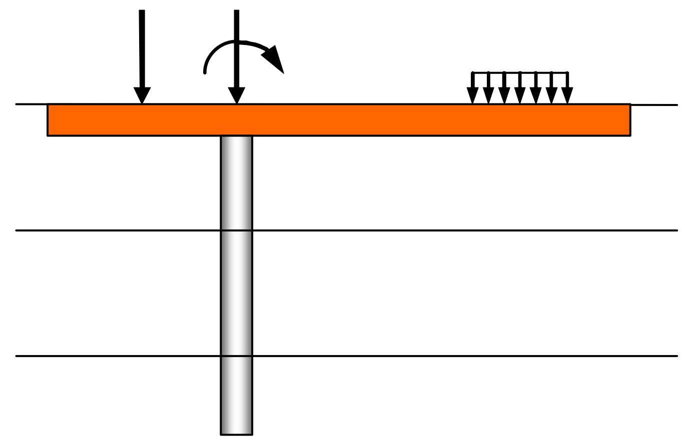


(a) pile - pile (b) raft - raft (c) pile - raft (d) raft - pile

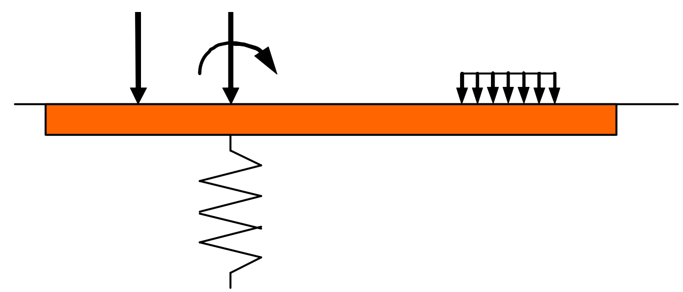
Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods
(1) Strip on Springs Approach (Poulos 1991)

1. A section of the raft is represented by a strip, and the supporting piles by springs.
2. Approximate allowance is made for all four components of interactions (pile-pile elements, raft-raft, pile-raft and raft-pile) are taken into account.
3. The effects of the raft outside the strip section are taken into account by computing the free-filed soil settlements due to these parts.
4. The strip section is analysed to obtain the settlements and moments due to the applied loading on the strip section and the soil settlements due to the sections outside the strip.



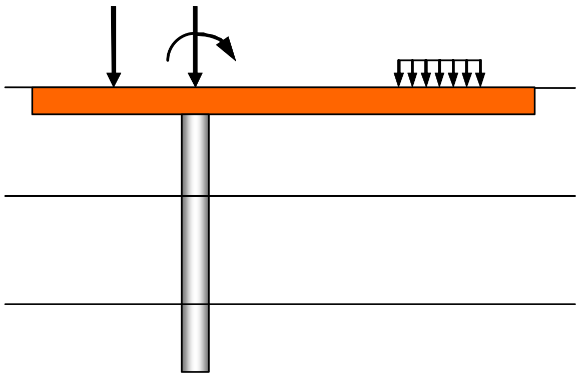
(a) Actual pile



(b) Pile representation

Analysis Methods for Piled Raft Foundations

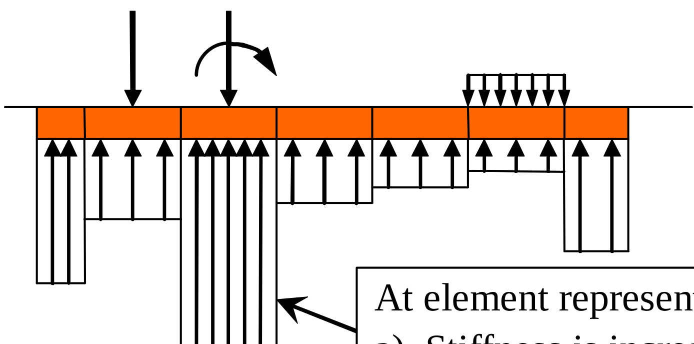
2. Approximate computer-based methods (1) Strip on Springs Approach: GASP



The method has been implemented into a computer program GASP (Geotechnical Analysis of Strip with Piles).

Soil non-linearity is taken into account in GASP by

- limiting the strip-soil contact pressures to not exceed the bearing capacity or the raft uplift capacity, and
- limiting the pile loads to not exceed the compressive and uplift capacities of the piles.



At element representing pile:

a) Stiffness is increased

b) Pile force is "smeared" over element

c) Limiting compressive and tensile pile-soil stresses are computed from compressive and tensile capacity of pile respectively

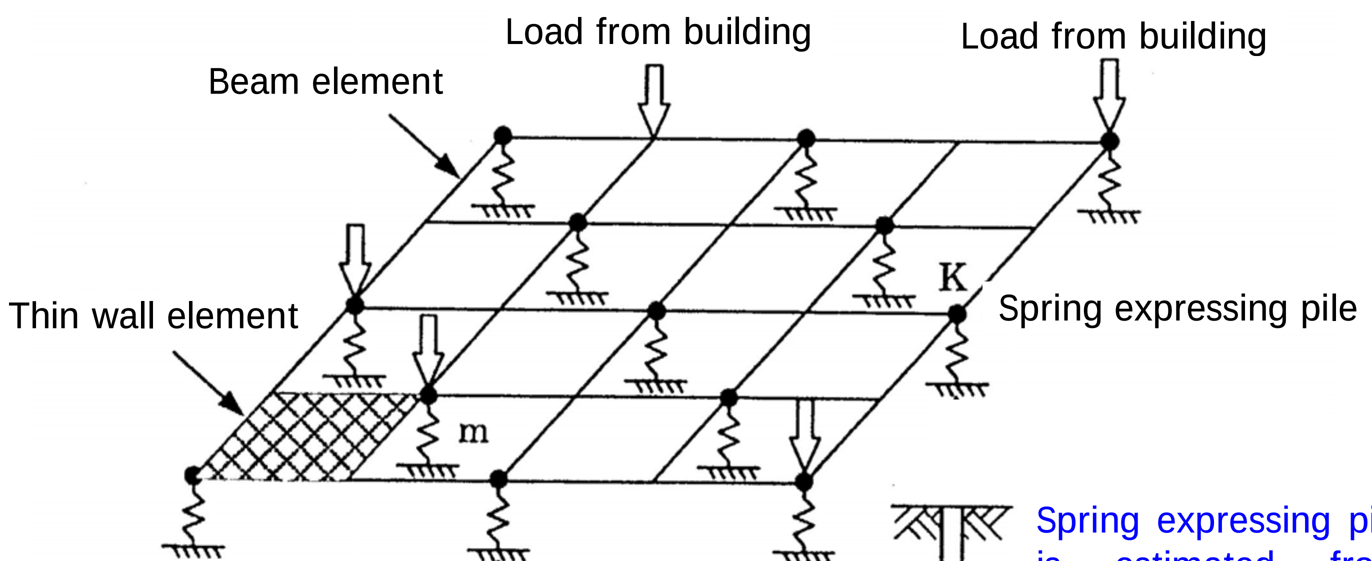
Analysis Methods for Piled Raft Foundations

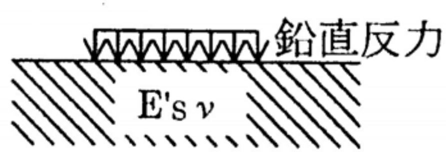
2. Approximate computer-based methods (2) Plate on Springs Approach

Modelling

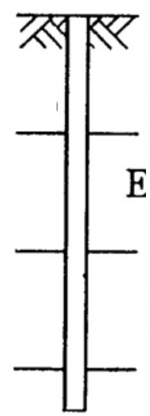
Raft: an elastic plate, Soil: an elastic continuum

Piles: interactive springs





Spring at node without pile is estimated from analysis of plate on the ground



Spring expressing pile is estimated from single pile analysis or from pile load test

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods (2) Plate on Springs Approach

Modelling

Raft: an elastic plate, Soil: an elastic continuum

Piles: interactive springs

In a computer program GARP: Geotechnical Analysis of Raft with Piles (Poulos 1994, Sales et al 2000),

- finite difference method or finite element method for the plate
- various interactions via approximate elastic solutions

  - layering of the soil profile
  - the effects of piles reaching their ultimate capacity (both in compression and tension)
  - the development of bearing capacity failure below the raft
  - the presence of free-field soil settlements acting on the foundation system

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods (2) Plate on Springs Approach

Russo and Viggiani (1997), Russo (1998) proposed an approach similar to GARP.

Non-linear behaviour of the piles is considered via the assumption of a hyperbolic load-settlement curve for single piles:

$$w_k = w_1 \sum \alpha_{kj} P_j$$

w_k : Settlement of node k
w_1 : Settlement of that node due to unit load
α_{kj} : Interaction factor between node k and node j ($\alpha_{kj} = 1$ when $k = j$)
P_j : Load on node j

$$\alpha_{kk} = 1/\left(1 - P_k / P_{k,\lim}\right)$$

for hyperbolic load-settlement curve for a node of single pile

$P_{k,\,\lim}$: Apparent limit load capacity of a single pile when assuming hyperbolic load-settlement curve of the pile

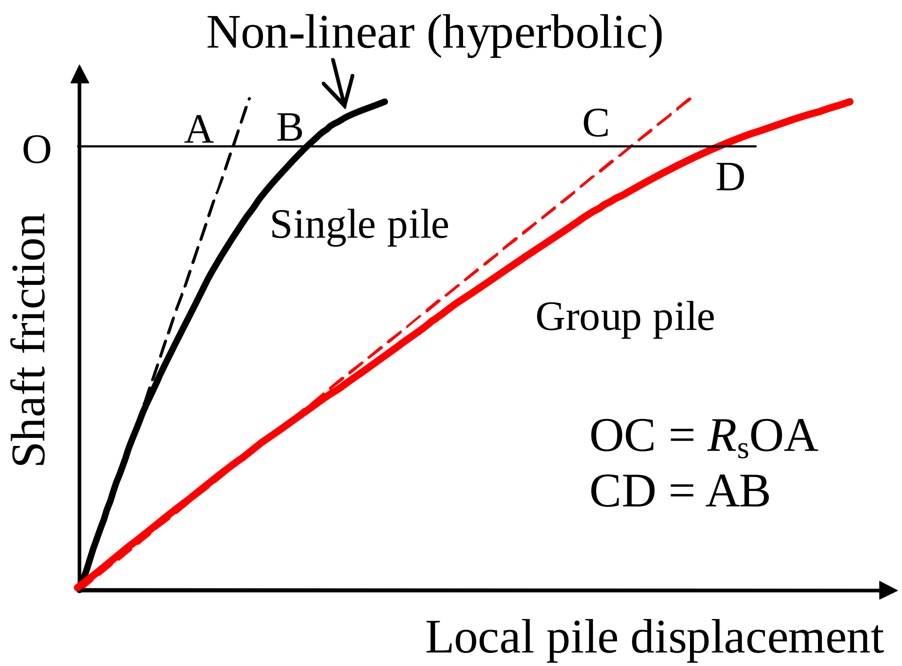
Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods (2) Plate on Springs Approach

Russo and Viggiani (1997), and Russo (1998)

Pile - pile interaction is applied only to the elastic component of the pile settlement.

Non-linear component of settlement of a pile is assumed to arise only from loading on that particular pile.



Calculation of interaction with non-linear load transfer curves

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods
   (1) Strip on Springs Approach
   (2) Plate on Springs Approach

Advantages

- Load-settlement curve at the pile head obtained from the load test can be readily utilized in the analysis.
- Calculation time is less.

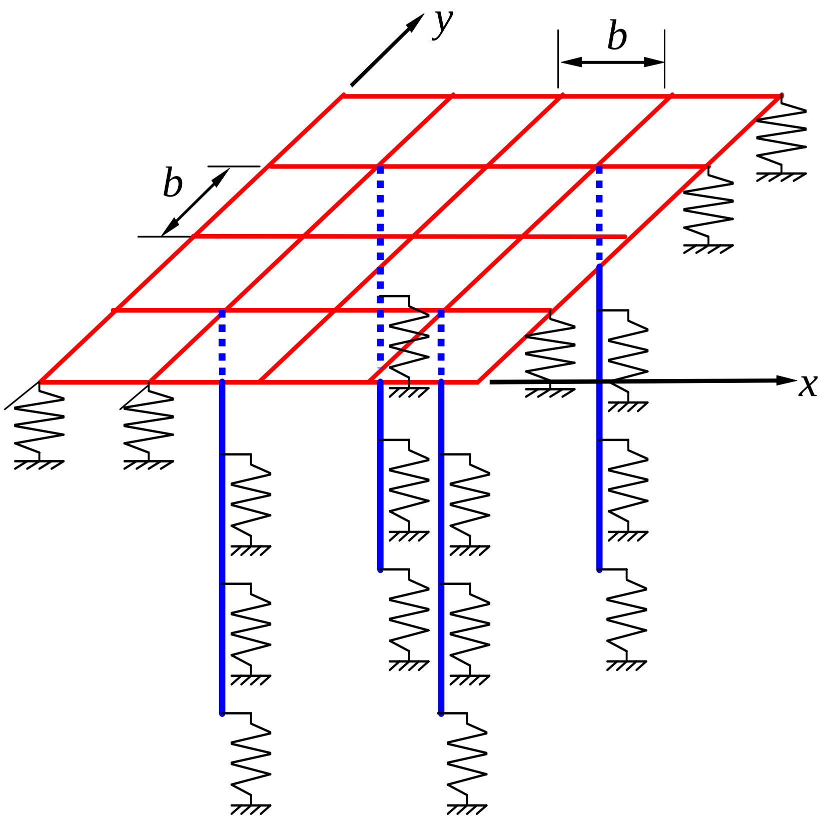
Limitations

- Distributions of axial forces and shaft resistance down the piles cannot be estimated.
- Interaction factors between springs representing piles are estimated in approximated manner.
  (one spring is used for representing each pile)

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity



Hybrid numerical model of piled raft

(Clancy & Randolph 1993)

Raft : Plate elements (FEM)

Piles : One-dimensional elements (FEM)

Soil : Interactive springs connected to pile nodes and raft nodes

Deformations of the raft and the piles are computed by finite element analysis.

Interactions between all nodes are taken into account based on the Mindlin's first solution.

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity

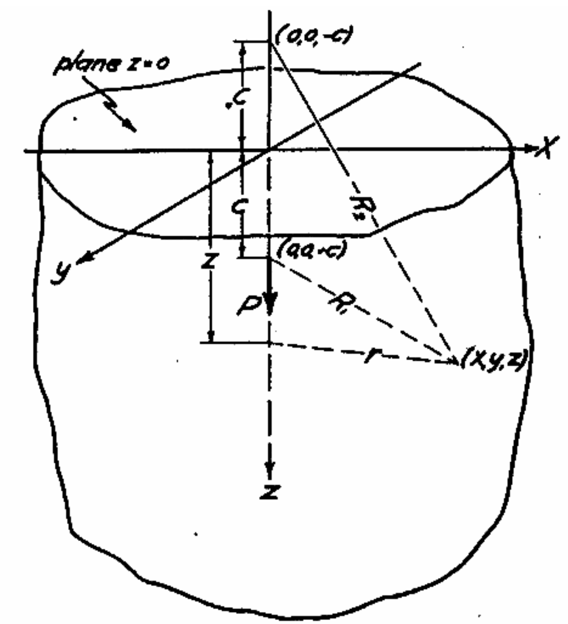
Interactions between soil springs at all nodes are taken into account based on the Mindlin's first solution.

$$w_i = \sum_{j=1}^{n} \alpha_{ij} P_j$$

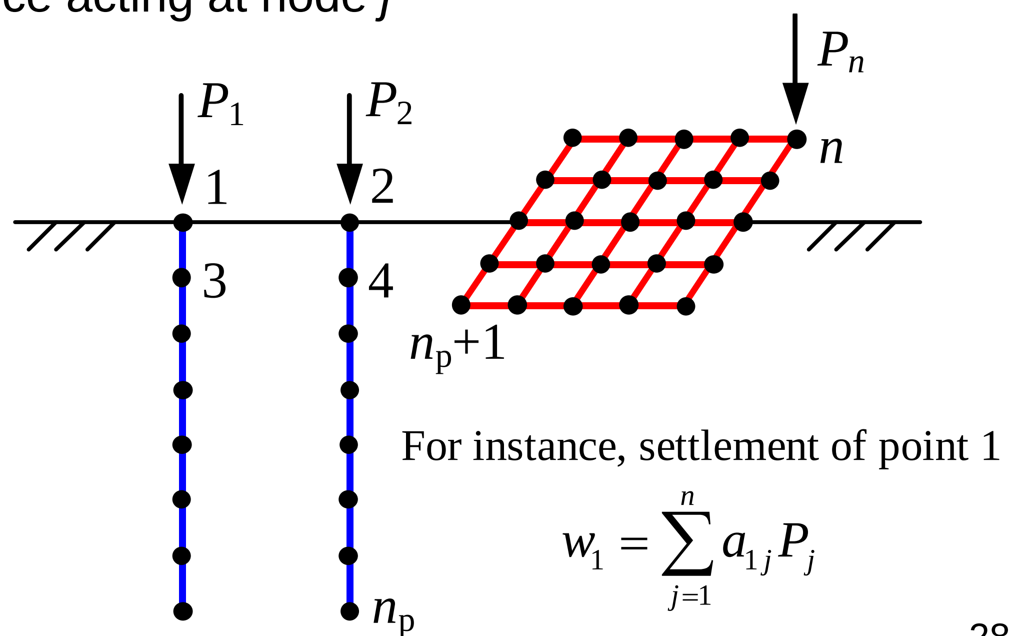
w_i = Settlement of node *i*

α_{ij} = Soil flexibility coefficient denoting settlement at node *i* due to a unit load acting at node *j*

P_j = Force acting at node *j*



The first Mindlin's problem



Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity

With a hybrid method in which only vertical interactive soil springs are incorporated,

Advantages

- Bending moments in the raft can be estimated.
- Distributions of axial forces and soil resistance in individual piles can be estimated.

Limitations

- Basically, Mindlin's solutions are applicable to a uniform elastic ground.

Ta & Small (1996) proposed Finite Layer Method to calculate deformation of a piled raft in multi-layered ground.

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity

For a hybrid method in which only vertical interactive soil springs are incorporated,

Limitations

- Bending moments and shear forces in the piles cannot be estimated.
- The method is not applied to piled rafts subjected to horizontal load, because the horizontal soil resistance is not implemented.
- Even for piled rafts subjected to vertical loading, accuracy of the calculation results are higher for piled rafts having symmetrical configuration and symmetrical vertical loads.
- Even if a piled raft is subjected to vertical loads alone, bending moments of piles and horizontal displacements occur.
- Even if a piled raft is subjected to horizontal loads alone, axial forces of piles and vertical displacements occur.

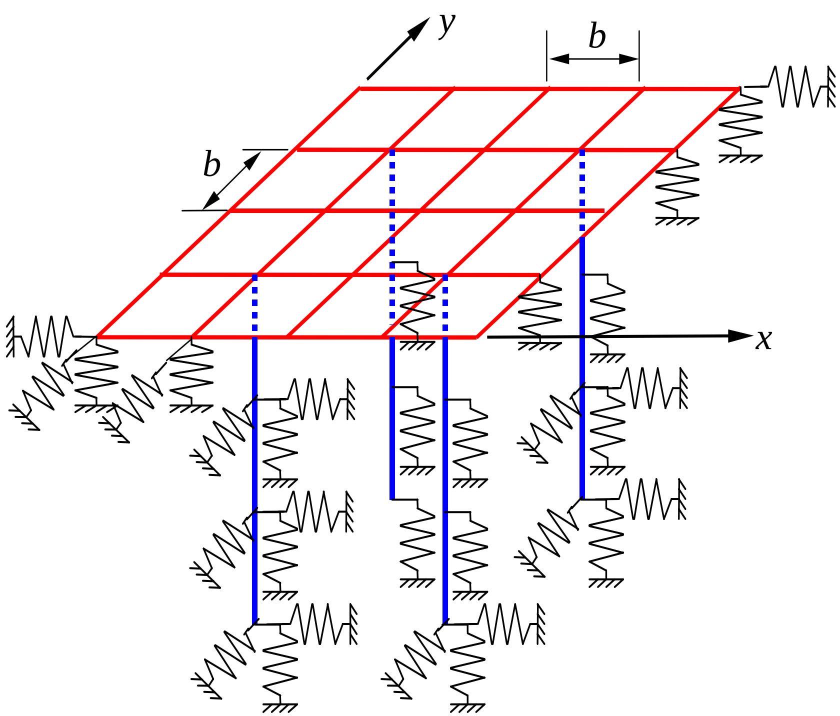
Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity

Simplified three-dimensional deformation analysis of piled rafts

Kitiyodom & Matsumoto (2003, 2004) developed a computer program PRAB (Piled Raft Analysis with Batter piles), based on a hybrid modelling, for three-dimensional deformation analysis of piled raft subjected to general loading.



Raft : Plate elements (FEM)

Piles : Beam elements (FEM)

Soil : Interactive springs connected to pile nodes and raft node

Three interactive soil springs are connected to each pile or raft node:

- one spring in vertical (*z*) direction
- two springs in horizontal (*x* and *y*) directions

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

(3) Hybrid Methods: Combination of FEM and the theory of elasticity

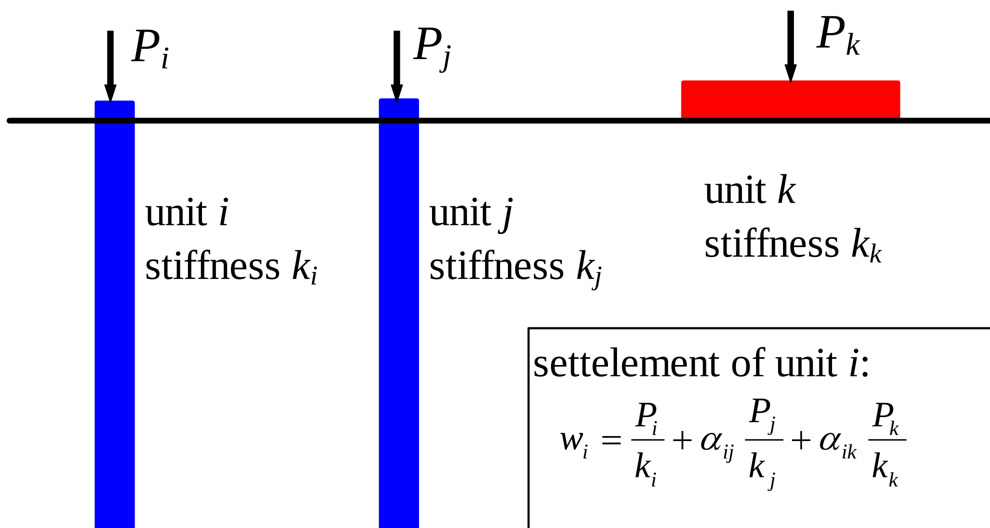
Simplified three-dimensional deformation analysis of piled rafts (PRAB)

- Three components of force acting on each node are considered.

  force in the vertical (*z*) direction, two forces in the horizontal (*x* and *y*) directions

- Interactions between nodes are fully allowed for.

  pile node-pile node, raft node-raft node, raft node-pile node, pile node-raft node for vertical and horizontal forces.

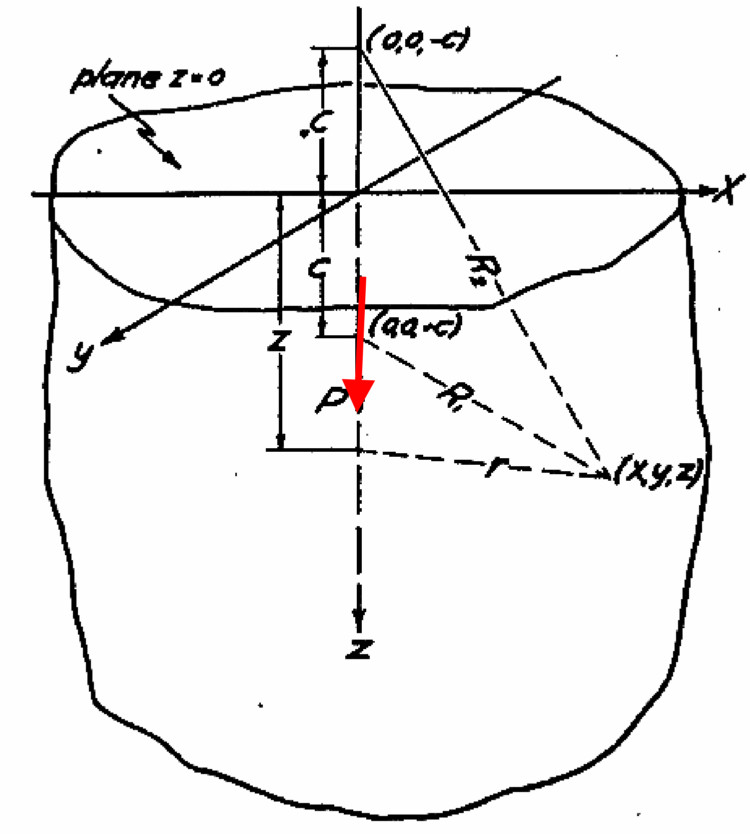


settelement of unit i:

$$w_i = \frac{P_i}{k_i} + \alpha_{ij}\frac{P_j}{k_j} + \alpha_{ik}\frac{P_k}{k_k}$$

Simplified three-dimensional deformation analysis of piled rafts

Mindlin's Solution for Vertical Point Load



Vertical displacement

$$w=\frac{Pr}{16\pi G(1-\nu)}\left[\frac{3-4\nu}{R_1}+\frac{8(1-\nu)^2-(3-4\nu)}{R_2}\right.$$

$$\left.+\frac{(z-c)^2}{R_1^3}+\frac{(3-4\nu)(z+c)^2-2cz}{R_2^3}+\frac{6cz(z+c)^2}{R_2^5}\right]$$

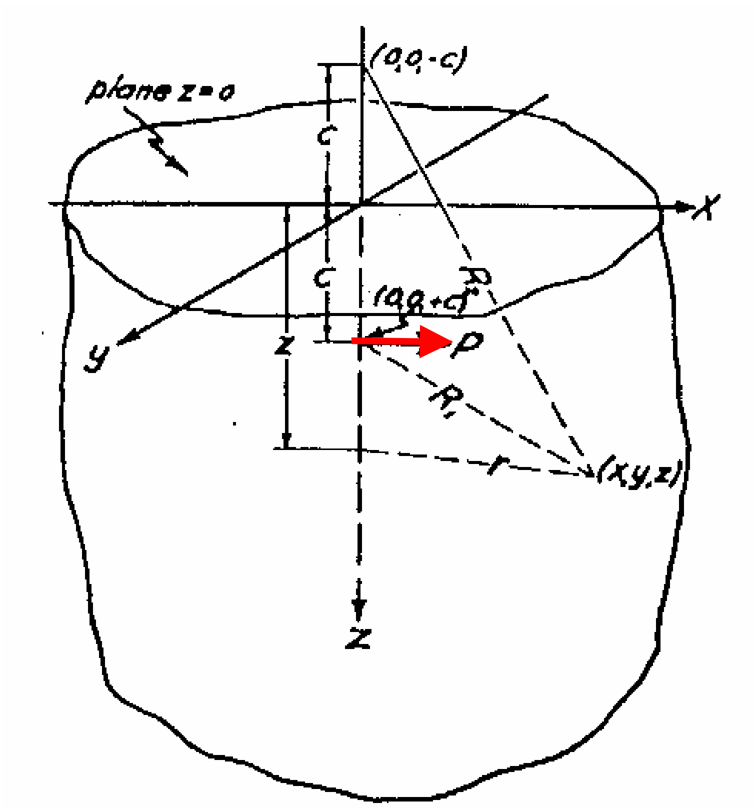
Lateral (radial) displacement

$$U=\frac{Pr}{16\pi G(1-\nu)}\left[\frac{z-c}{R_1^3}+\frac{(3-4\nu)(z-c)}{R_2^3}\right.$$

$$\left.+\frac{4(1-\nu)(1-2\nu)}{R_2(R_2+z+c)}+\frac{6cz(z+c)}{R_2^5}\right]$$

Simplified three-dimensional deformation analysis of piled rafts

Mindlin's Solution for Horizontal Point Load



Horizontal displacement in *x*-direction

$$u = \frac{Pr}{16\pi G(1-\nu)}\left[\frac{3-4\nu}{R_1} + \frac{1}{R_2} + \frac{x^2}{R_1^3} + \frac{(3-4\nu)x^2}{R_2^3} + \frac{2cz}{R_2^3}\left(1-\frac{3x^2}{R_2^2}\right) + \frac{4(1\text{-}\nu)(1\text{-}2\nu)}{R_2+z+c}\left(1-\frac{x^2}{R_2(R_2+z+c)}\right)\right]$$

Horizontal displacement in *y*-direction

$$v = \frac{Pxy}{16\pi G(1-\nu)}\left[\left[\frac{1}{R_1^3} + \frac{3-4\nu}{R_2{}^2} - \frac{6cz}{R_2{}^5} - \frac{4(1-\nu)(1-2\nu)}{R_2(R_2+z+c)^2}\right]\right]$$

Vertical Displacement

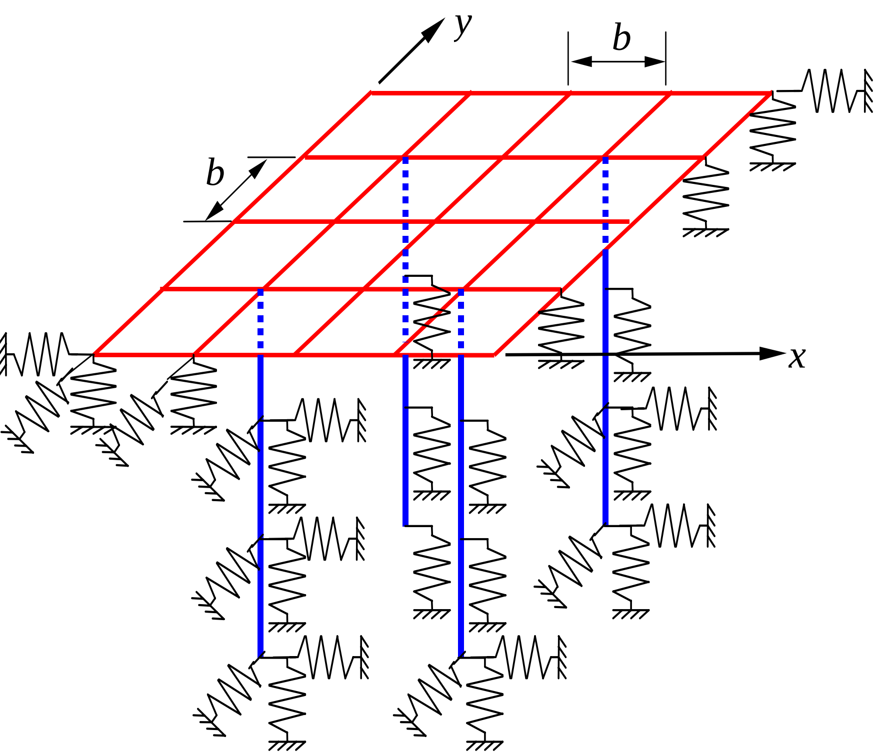
$$w = \frac{Px}{16\pi G(1-\nu)}\left[\frac{z-c}{R_1{}^3} + \frac{(3-4\nu)(z-c)}{R_2{}^3} - \frac{6cz(z+c)}{R_2^5} + \frac{4(1-\nu)(1-2\nu)}{R_2(R_2+z+c)}\right]$$

Analysis Methods for Piled Raft Foundations

2. Approximate computer-based methods

Simplified three-dimensional deformation analysis of piled rafts, PRAB

Effects of multi-layered ground are approximately taken into account.



PRAB is capable for calculating three dimensional deformation of single piles, pile group and piled rafts subjected to general loadings (combination of vertical loads, horizontal loads and overturning moments).

Bending moments in the raft

Mobilisations of the raft base contact pressures

Distributions of axial forces, bending moments and shear forces in individual piles

Mobilisations of shaft resistance and end-bearing resistance in individual piles

Analysis Methods for Piled Raft Foundations

3. More rigorous computer-based methods

(1) Boundary Element Method

- Applicable to only a uniform elastic ground.
- It is rather difficult to treat non-linearity and failure of soil.

(2) Finite Element Method

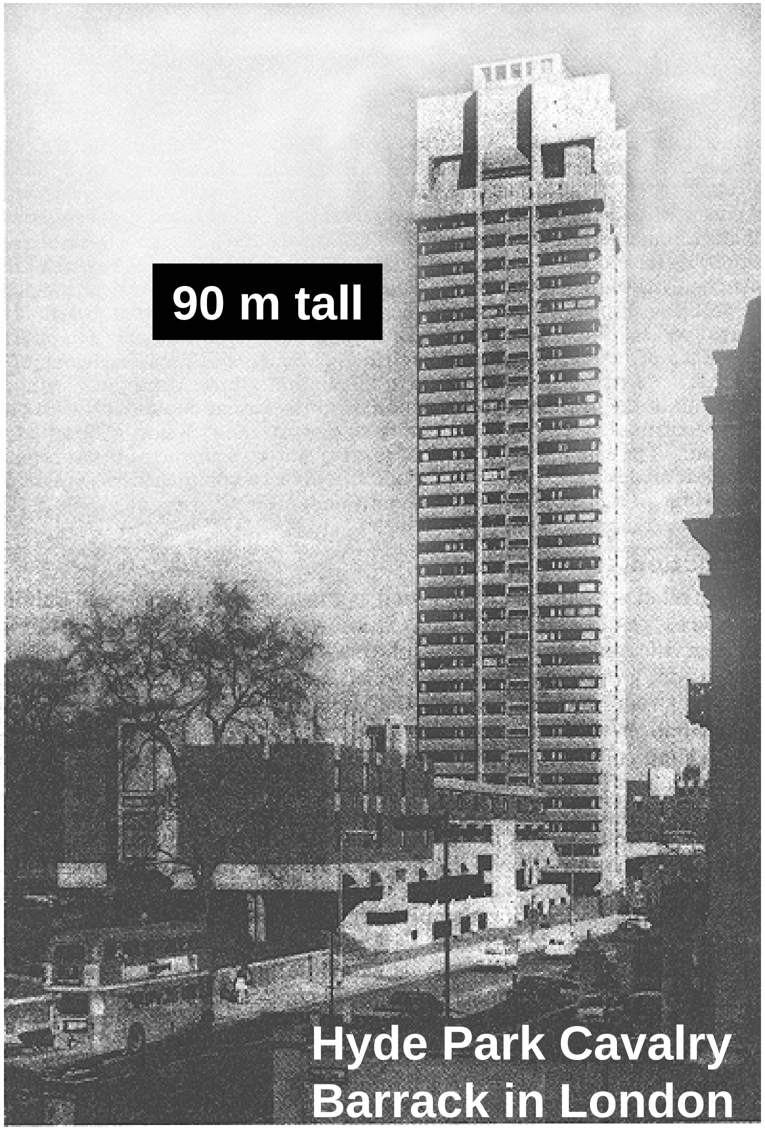
Two-dimensional FEM and Three-dimensional FEM

Most rigorous analysis method

- Complicated soil conditions
- Complicated boundary conditions
- Non-linear behaviour of soil

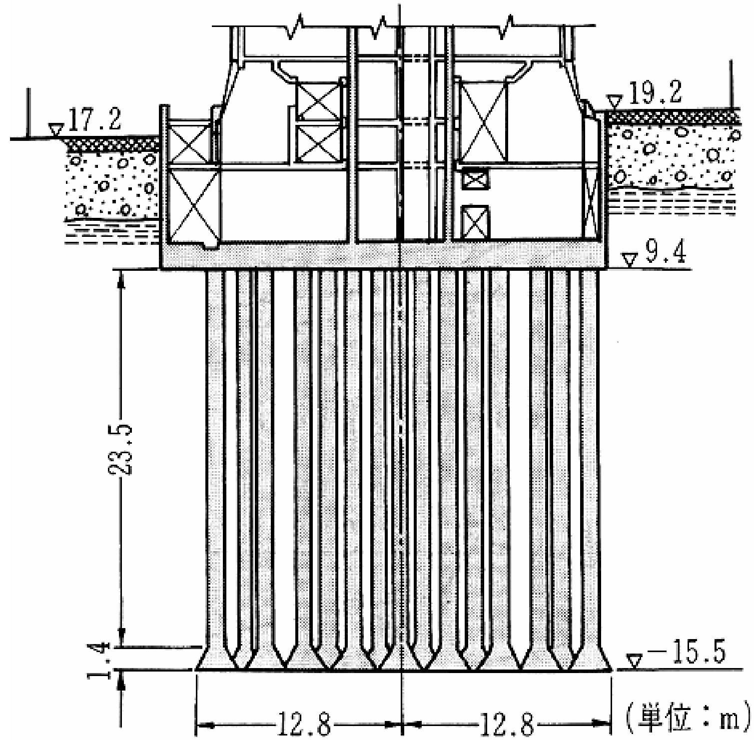
Analysis Methods for Piled Raft Foundations

Application of two-dimensional FEM (Hooper 1973)



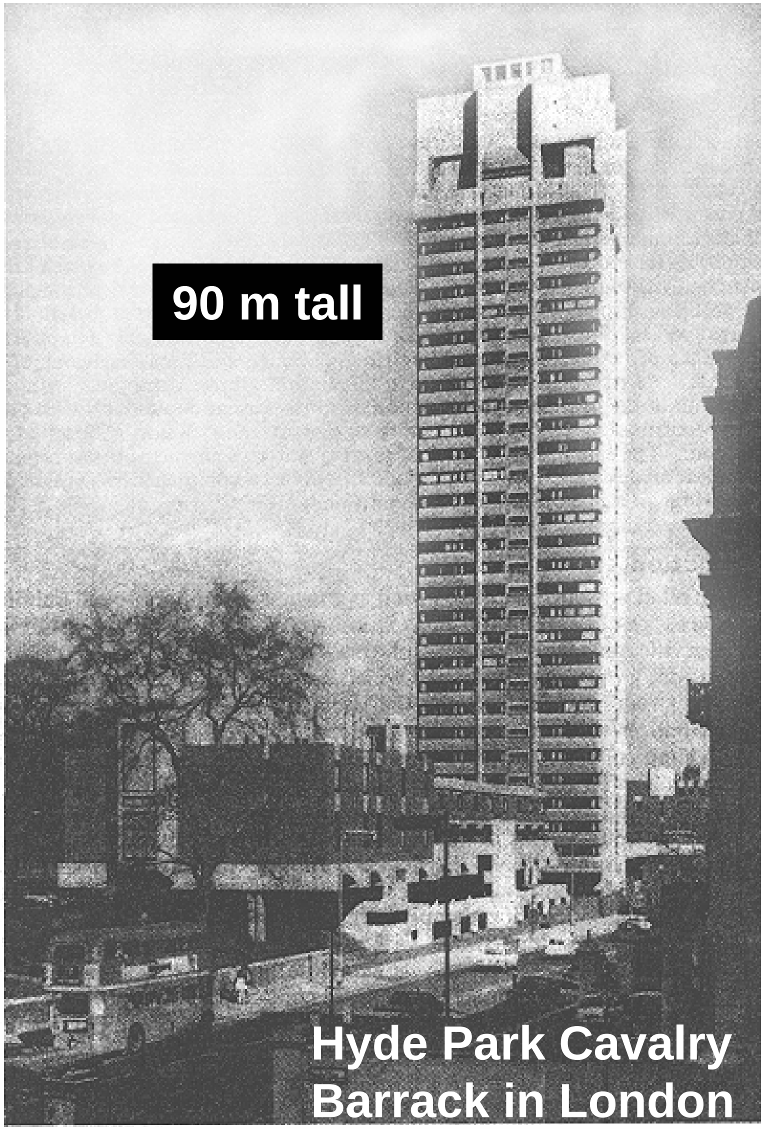
Number piles = 51
Pile diameter = 0.91 m (2.4 m at base)
Pile length = 24.8 m

Depth of raft = 9 m
Thickness of raft = 1.52 m



Analysis Methods for Piled Raft Foundations

Application of two-dimensional FEM



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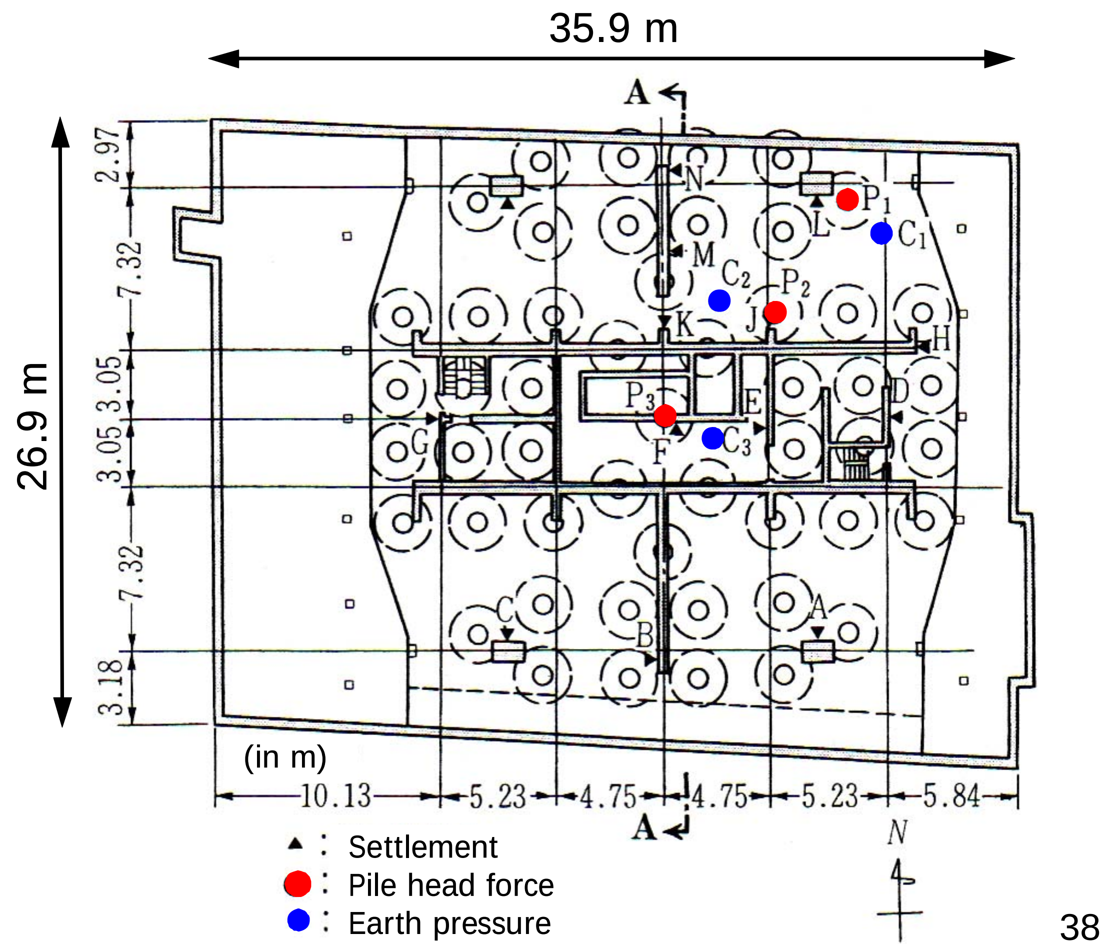
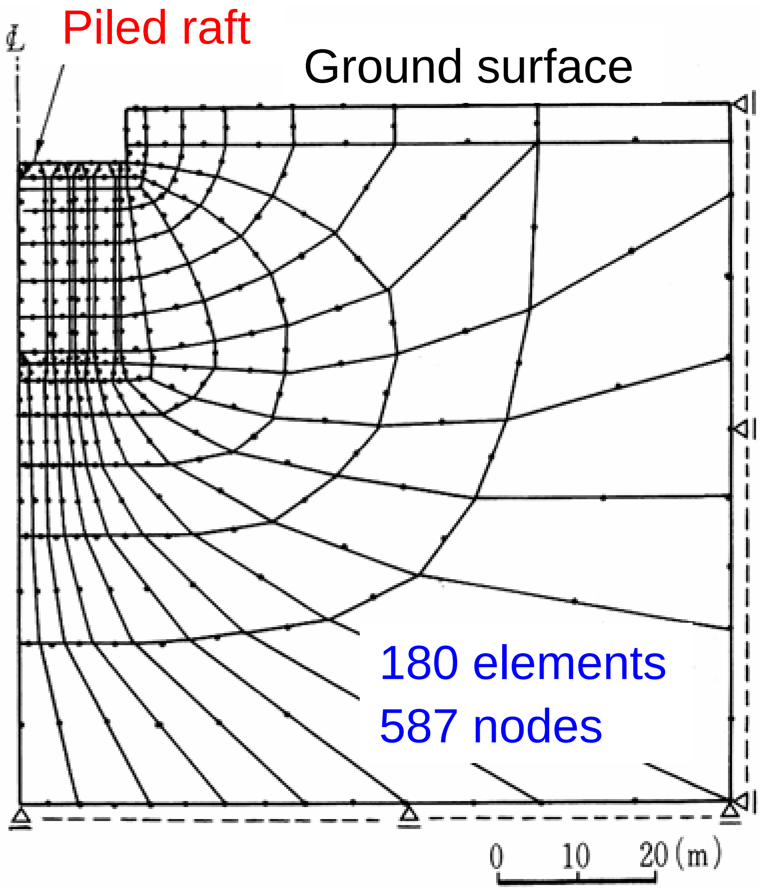


Analysis Methods for Piled Raft Foundations

Application of two-dimensional FEM (Hooper 1973)



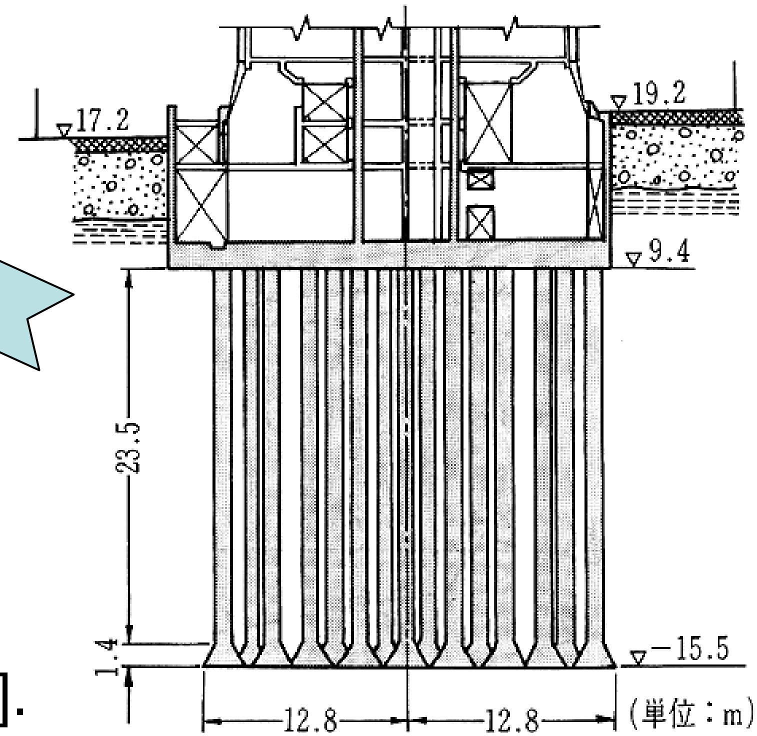
Axi-symmetric modelling

Piles were modelled as a ring wall.

Gibson ground [E = 10 + 5.2z (MPa)].

Pile diameter = 0.91 m
Pile length = 24.8 m
Number piles = 51

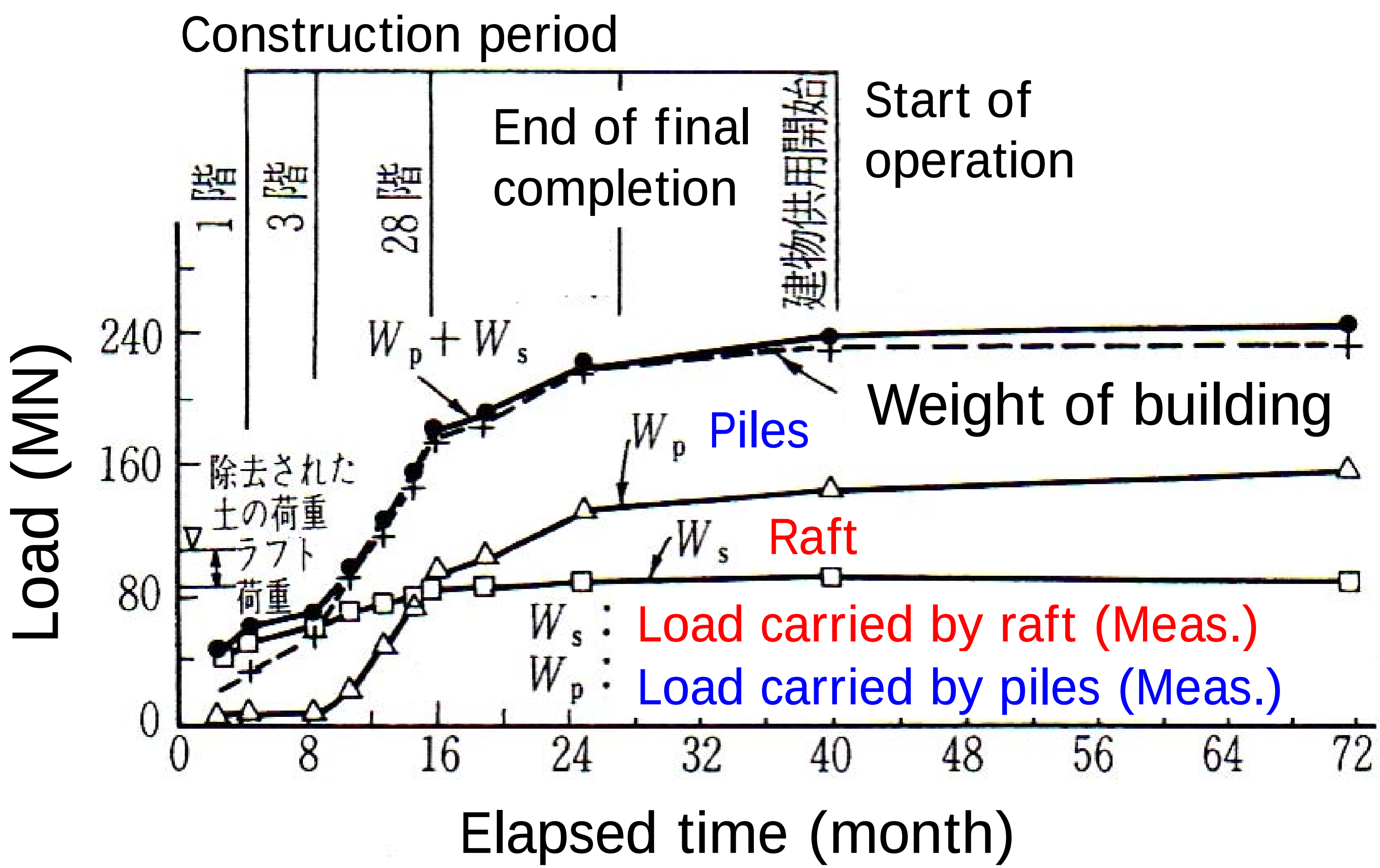
Depth of raft = 9 m
Thickness of raft = 1.52 m



Analysis Methods for Piled Raft Foundations

Application of two-dimensional FEM (Hooper 1973)

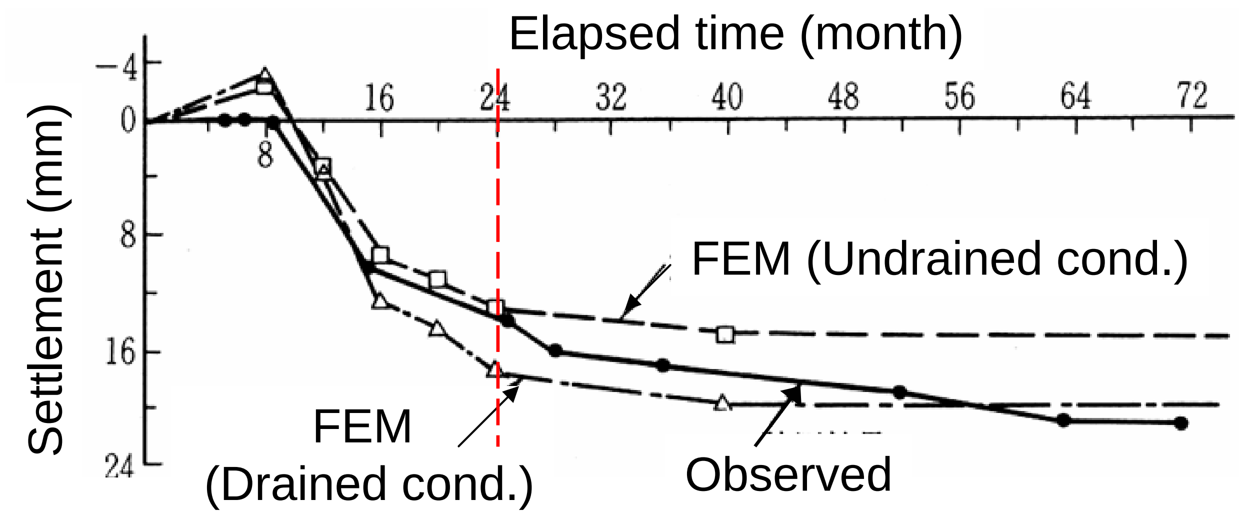
Measured changes in loads with elapsed time



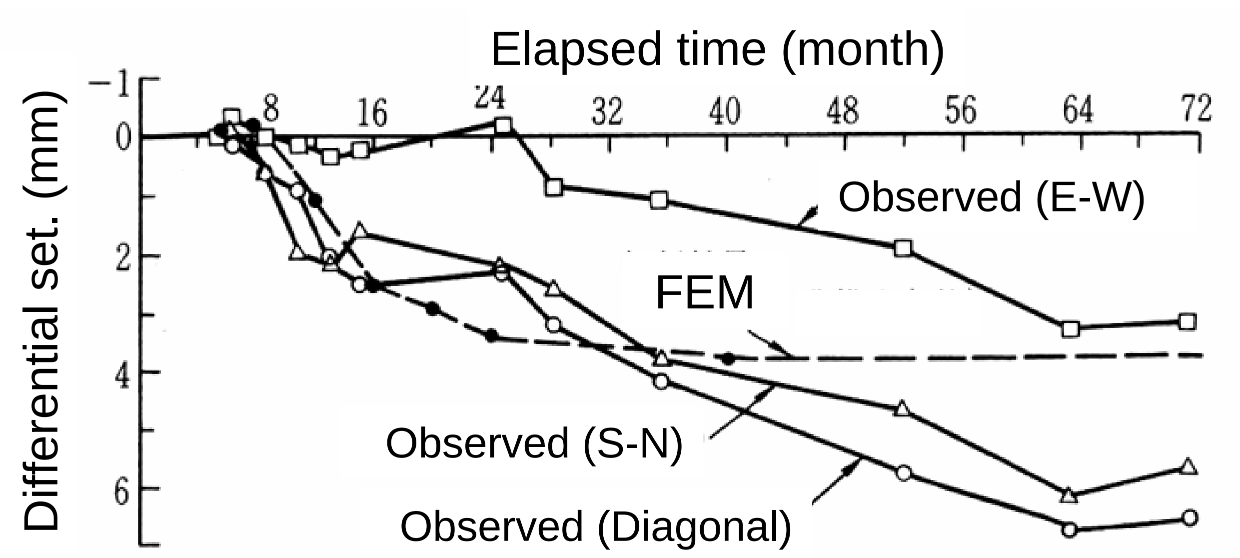
Analysis Methods for Piled Raft Foundations

Application of two-dimensional FEM (Hooper 1973)

Average settlement



Differential settlement



Analysis Methods for Piled Raft Foundations

Limitations of two-dimensional FEM analyses

Various assumptions have to be made:

- Row of the piles is modelled by a plate or a ring wall.
  - Equivalent Young's modulus of pile element?
  - Equivalent bending rigidity of pile element?
  - Equivalent axial rigidity of pile element?
  - Estimation of the shaft resistance of the pile?
  - Which direction of the foundation is of major concern?

Forces induced in individual piles cannot be estimated.

Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

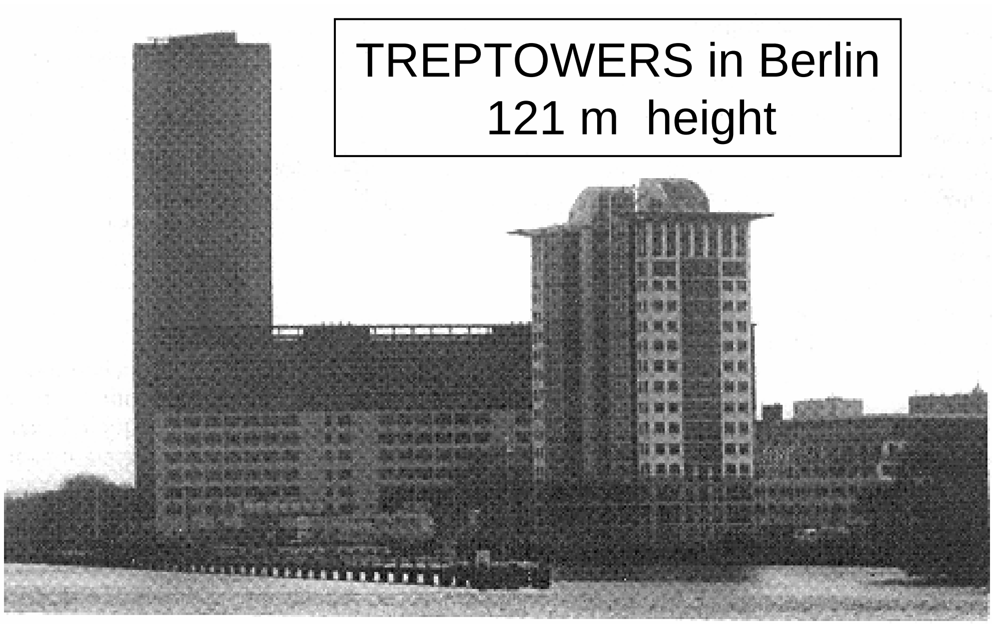
Surface layer: Reclaimed soil

Dense sand layer (Berlin sand) below the surface layer to a depth of 40 m.

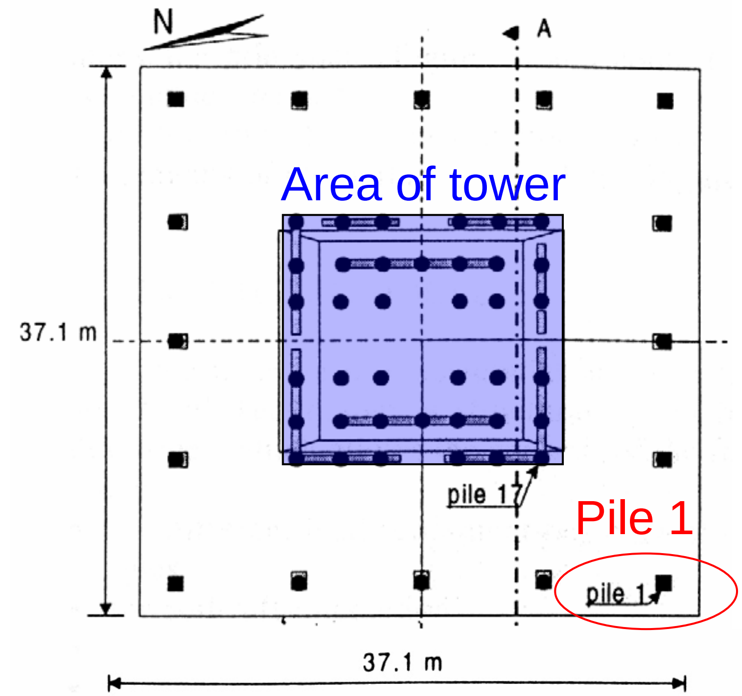
54 cast in-situ concrete piles

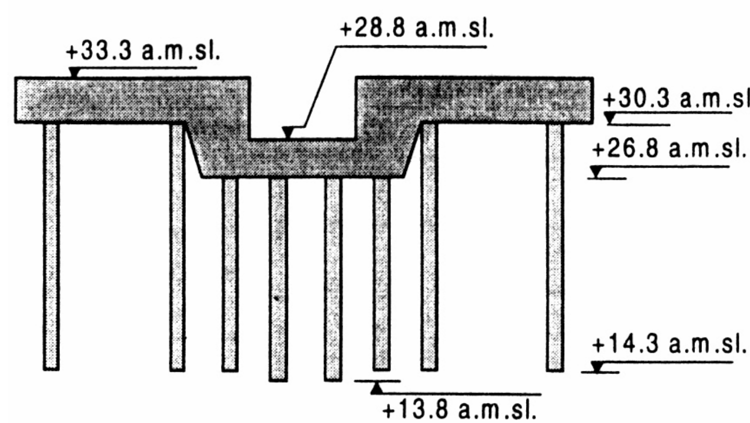
Pile diameter = 0.88 m

Pile lengths = 12.5 -16.0 m



TREPTOWERS in Berlin
121 m height

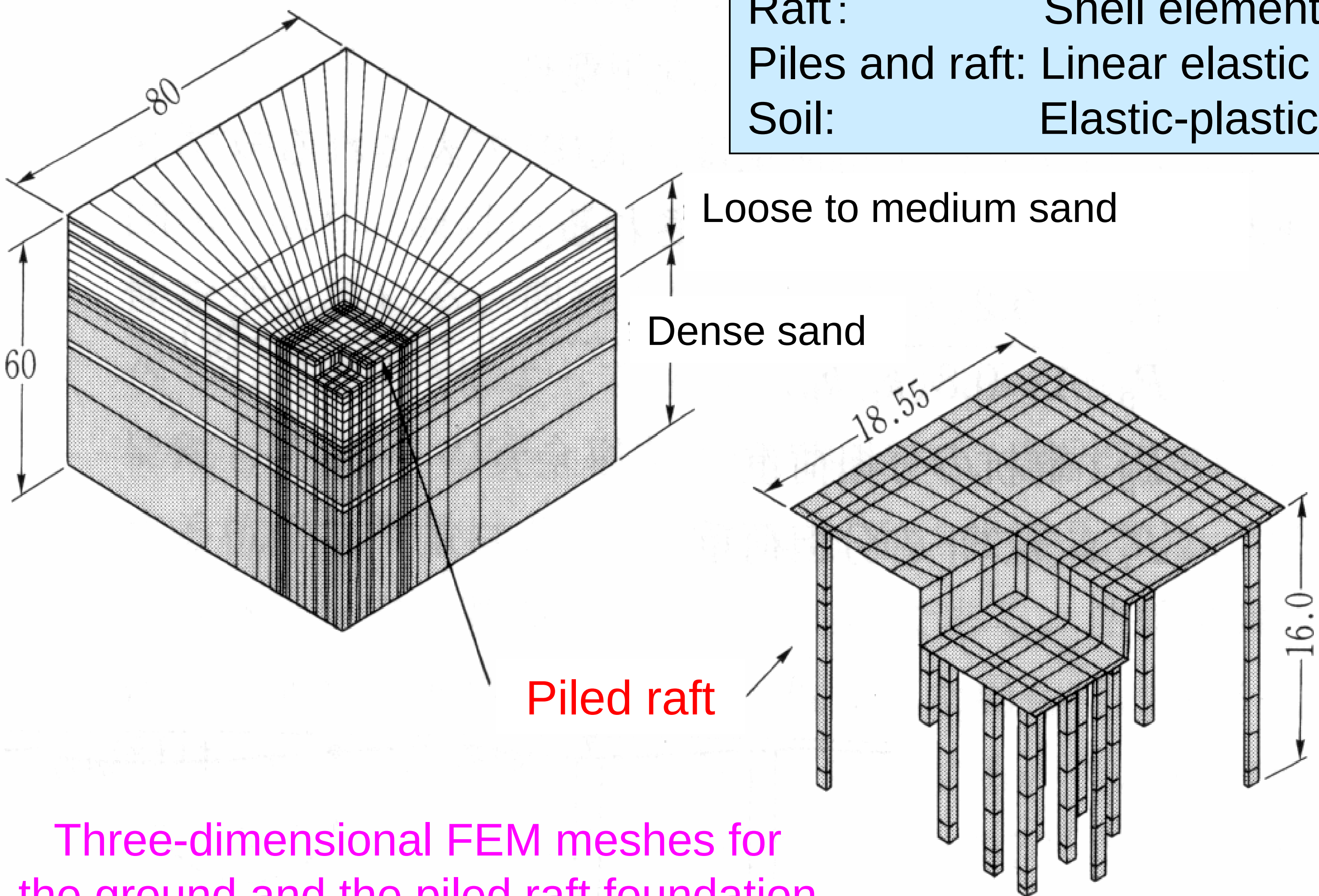




Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

Raft:	Shell elements
Piles and raft:	Linear elastic materials
Soil:	Elastic-plastic material

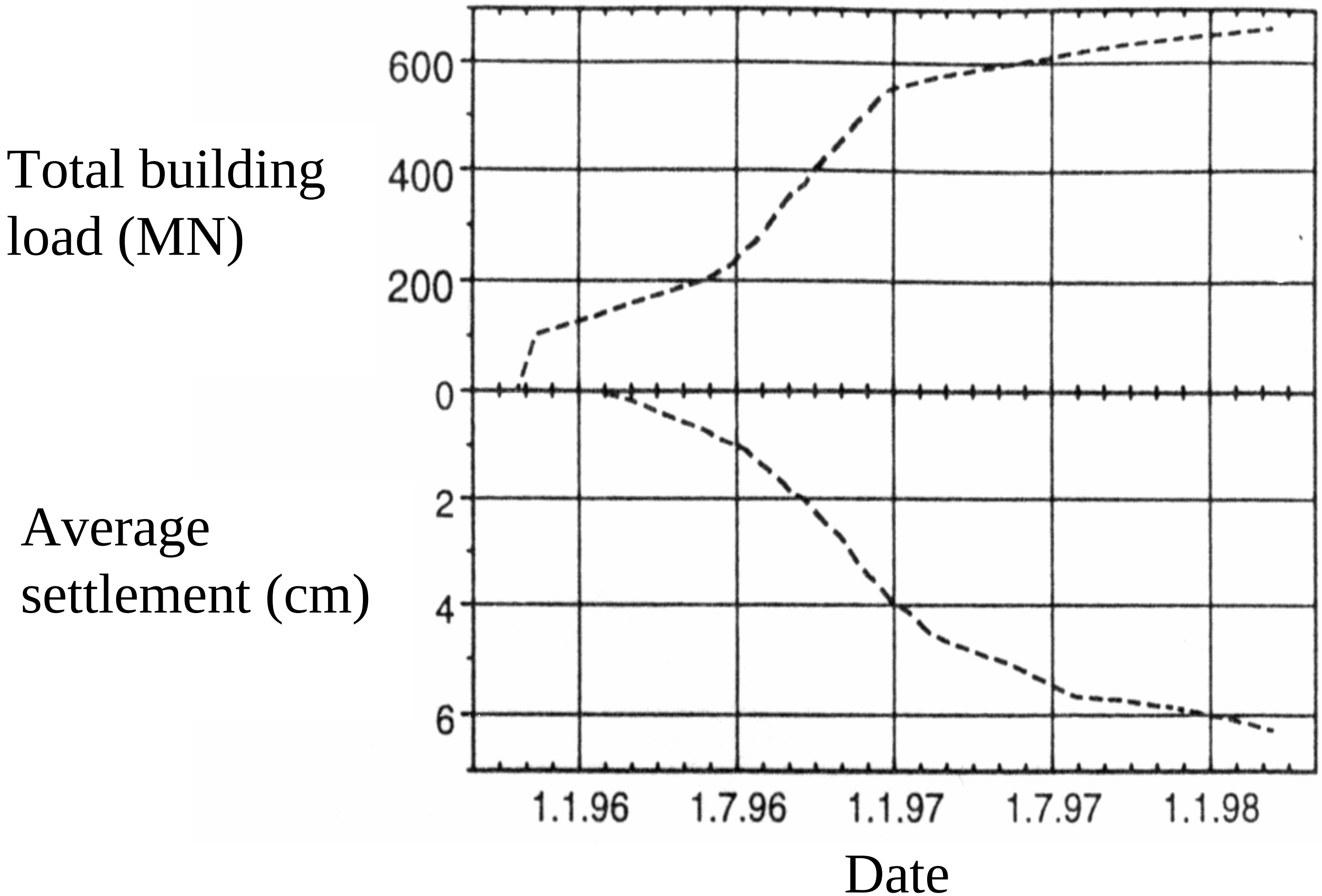


Three-dimensional FEM meshes for the ground and the piled raft foundation

Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

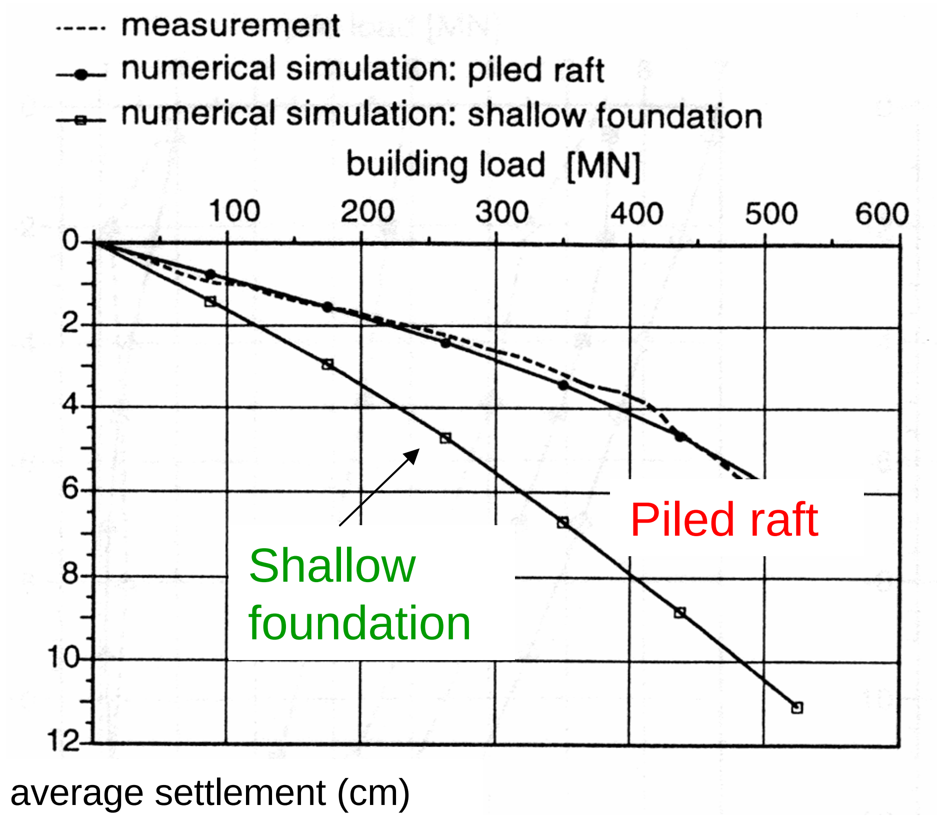
Observed performance

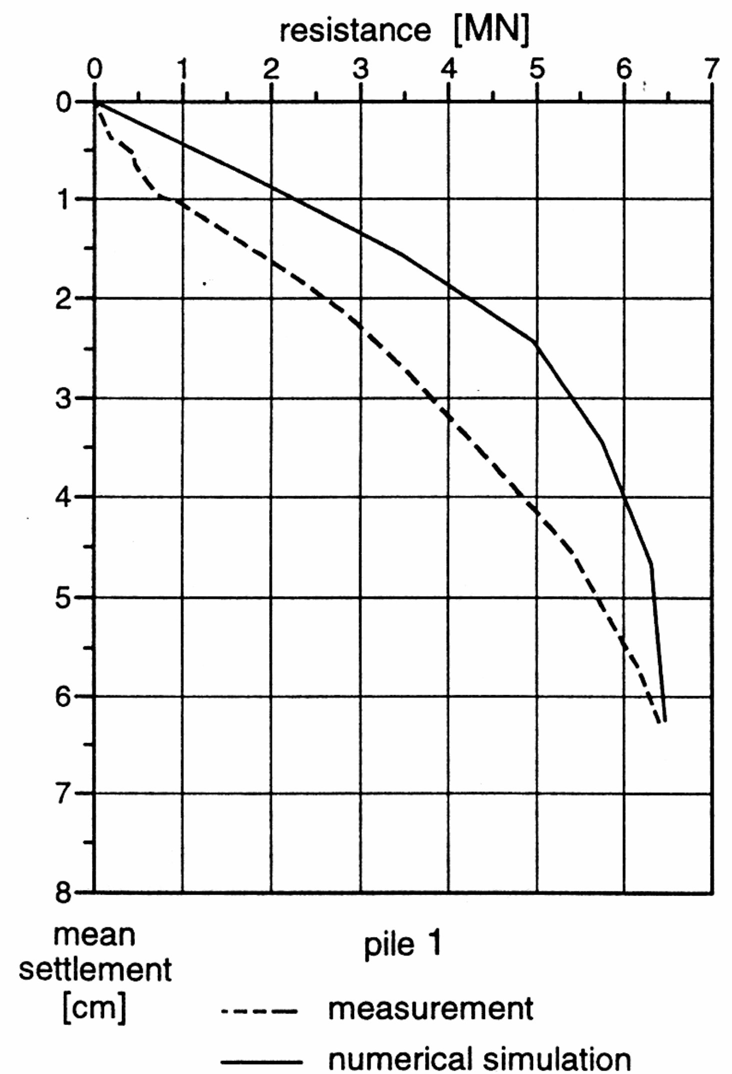


Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

Measured and numerical performance



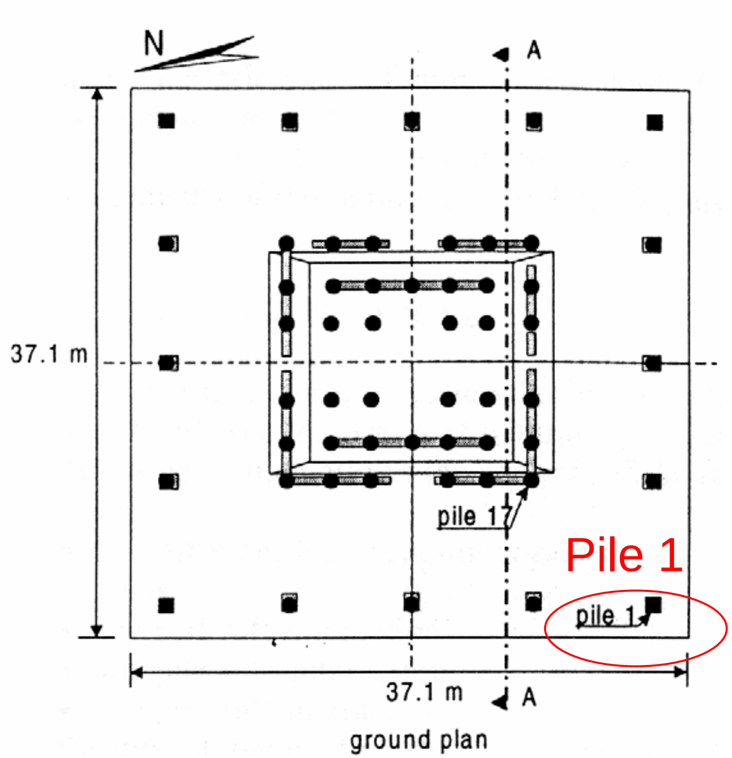


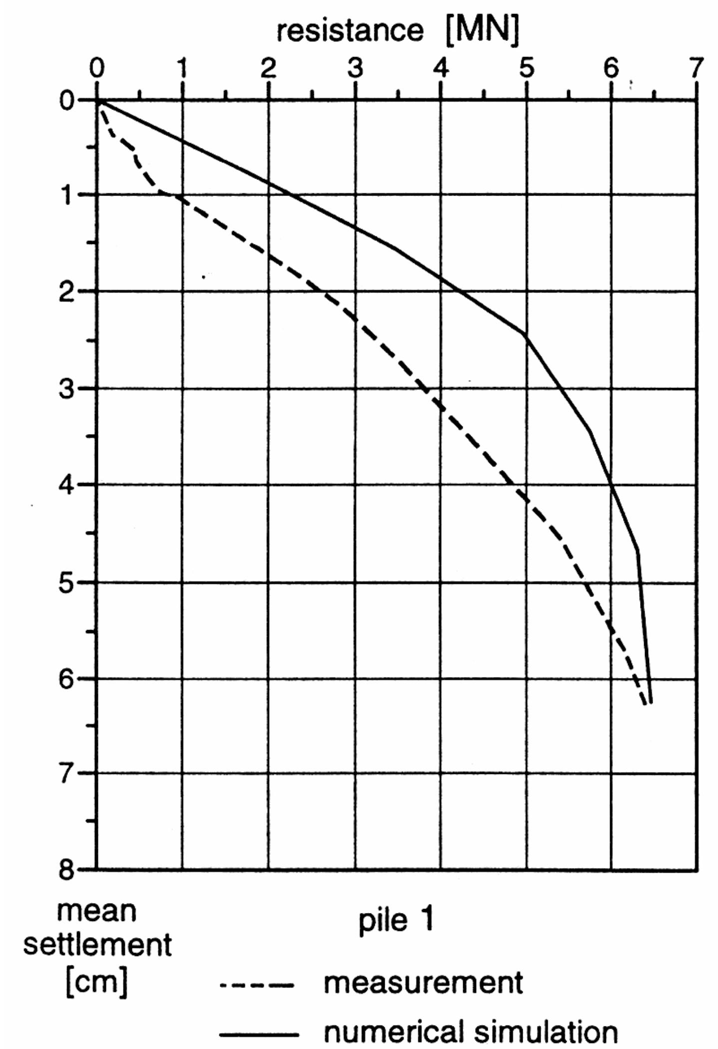
Average settlement of the piled raft is 53% of that of the shallow foundation.

Piles carry 65% of the total load.

Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

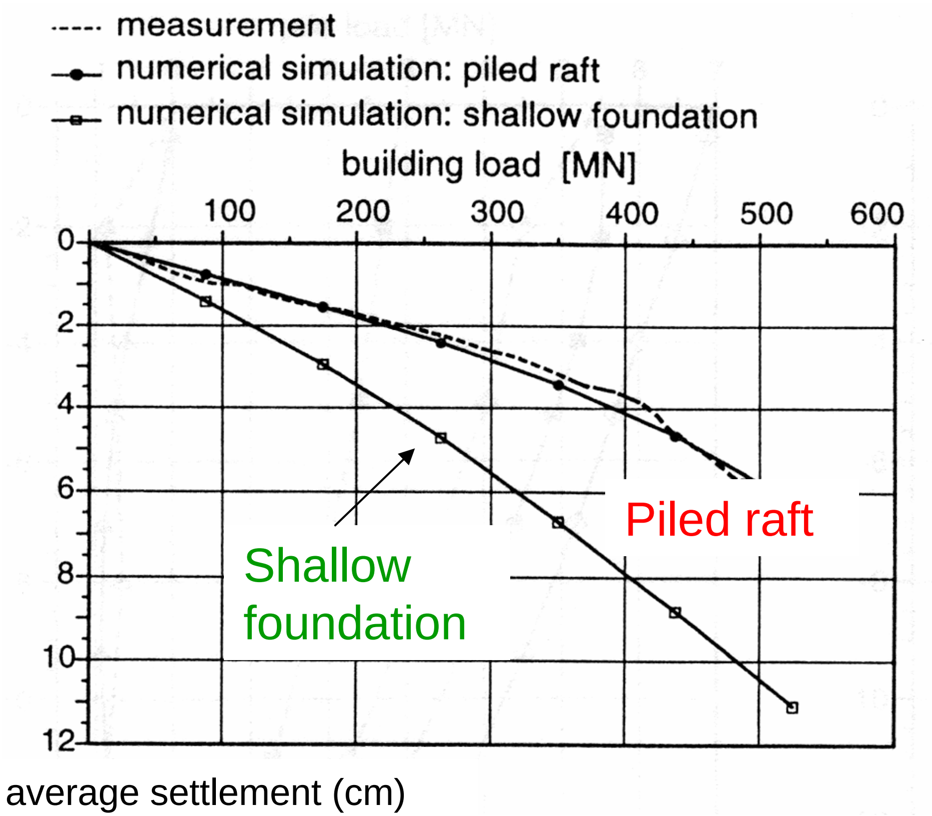


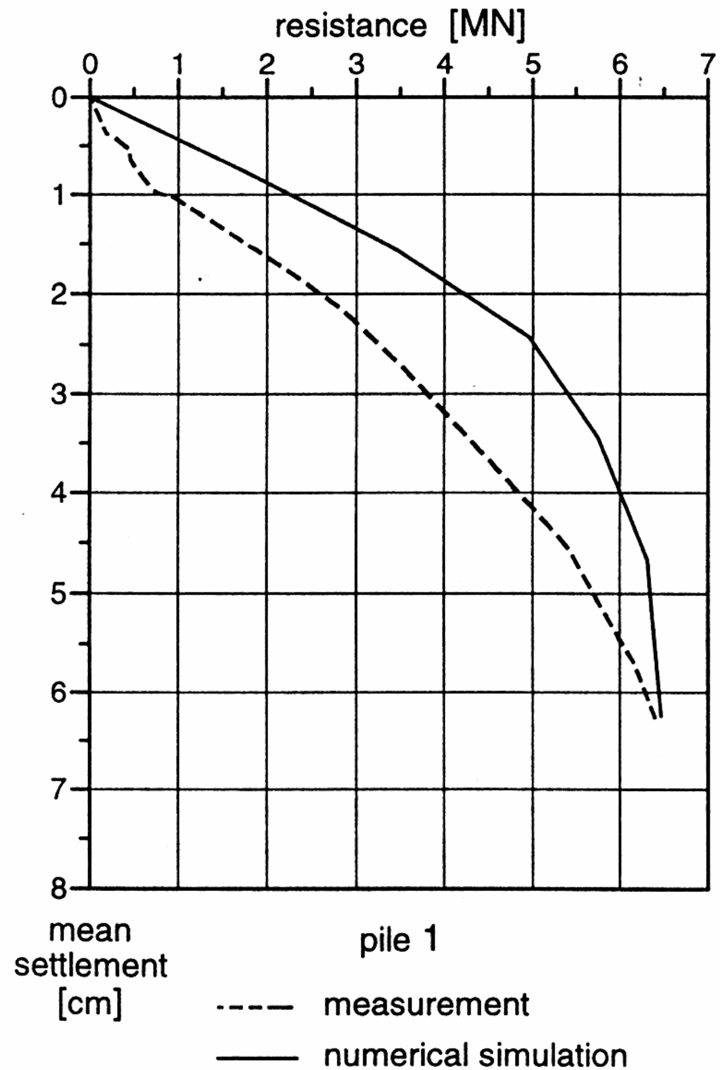


Analysis Methods for Piled Raft Foundations

Application of three-dimensional FEM (Kazenbach et al 1998)

Measured and numerical performance





Average settlement of the piled raft is 53% of that of the shallow foundation.

Piles carry 65% of the total load.

Summary of Lecture 3

Design concepts of piled rafts

Design issues of piled rafts

Methods of analysis of piled raft

1. Simplified calculation methods
   (1) Poulos-Davis-Randolph (PDR) Method
   (2) Burland's Approach (Burland 1995)

2. Approximate computer-based methods
   (1) Strip on Springs Approach (Poulos, 1991)
   (2) Plate on Springs Approach (Poulos, 1994)
   (3) Methods combining boundary element for the piles and finite element analysis for the raft.

3. More rigorous computer-based methods
   (1) BEM
   (2) FEM (two-dimensional and three-dimensional)