SIMPLIFIED ANALYSIS OF PILED RAFT
FOUNDATIONS SUBJECTED TO ACTIVE
LOADING AND PASSIVE LOADING

Pastsakorn Kitiyodom
Research Associate, Kanazawa University

Tatsunori Matsumoto
Professor, Kanazawa University
REFERENCES


In practice, from an economic viewpoint, a foundation designer is most likely to consider first the use of a simple raft foundation to support a superstructure.

In the case where the use of a simple raft foundation is not sufficient, a fully piled foundation is employed.
In most conventional design, the foundation has been designed ignoring any contribution from the raft.

In the past few years, there has been an increasing recognition that the inclusion of the resistance of the raft in pile foundation design can lead to a considerable economy without compromising the safety or the performance of the foundation.
Considering current trends toward the limit state design or performance based design in the area of foundation engineering, precise estimation of deformation of a whole foundation and of stresses of its structural members is a vital issue in the framework of this new design criterion.

In the preliminary design stage, a number of alternative calculations are required.

“Hence a feasible but reliable deformation analysis method of piled raft foundations is sought for”

In addition, in some cases, the existing foundations may be also subjected to ground movements induced by nearby excavation operations, settling embankments, pile driving operations, tunnelling operations, moving slopes, or landslides.
Development of a feasible but reliable simplified analytical method for deformation analysis of piled raft foundations subjected to active loading (vertical, lateral and moment loads) and passive loading (ground movement).
Contents of Today Presentation

Part I: Development of PRAB

Part II: Verified the validity of PRAB through comparison analysis with three-dimensional FEM

Part III: Verified the applicability of PRAB through analyses of the centrifuge model test results

Part IV: Application of PRAB
Part I: Development of PRAB
Plate-beam-spring Modelling of Piled Raft

Soil: Springs at raft and pile nodes
Raft: Thin plate elements
Pile: Beam elements

\[ K_z^R = \frac{4G_s a}{1-\nu_s} \]
\[ K_x^R = K_y^R = \frac{32(1-\nu_s)G_s a}{7-8\nu_s} \]
\[ K_z^P = 2\pi G_s \Delta L / \ln(r_m / r_o) \]
\[ K_x^P = K_y^P = \zeta E_s \Delta L \]

\[ G_s, \nu_s \] Shear modulus, Poisson’s ratio of soil
\[ E_s \] Young’s modulus of soil
\[ a = b / \sqrt{\pi} \]
\[ r_m = 2.5L(1-\nu_s) \]
\[ \Delta L \] Pile element length
\[ r_o \] Pile radius
Plate-beam-spring Modelling of Piled Raft

Raft Vertical soil springs
\[ K_z^R = \frac{4G_s a}{1-\nu_s} \]

Raft Lateral soil springs
\[ K_x^R = K_y^R = \frac{32(1-\nu_s)G_s a}{7 - 8\nu_s} \]

Pile Vertical soil springs
\[ K_z^P = 2\pi G_s \Delta L / \ln(\frac{r_m}{r_o}) \]

Pile Lateral soil springs
\[ K_x^P = K_y^P = \zeta E_s \Delta L \]

\[ G_s, \nu_s \quad \text{Shear modulus, Poisson’s ratio of soil} \]
\[ E_s \quad \text{Young’s modulus of soil} \]
\[ a = b/\sqrt{\pi} \quad r_m = 2.5L(1-\nu_s) \]
\[ \Delta L \quad \text{Pile element length} \quad r_o \quad \text{Pile radius} \]
Incorporation of batter piles

\[ \gamma = \arccot h \]

\[
\begin{bmatrix}
\cos \gamma \cos \alpha & -\sin \alpha & \sin \gamma \cos \alpha \\
\cos \gamma \sin \alpha & \cos \alpha & \sin \gamma \sin \alpha \\
-\sin \gamma & 0 & \cos \gamma
\end{bmatrix}
\]

\[ 0^\circ \leq \alpha \leq 360^\circ \quad 0^\circ \leq \gamma \leq 90^\circ \]

\[
\{P\} = [T][K_p][T]^T \{w\}
\]

\[
\{P\} = [K_p^*]\{w\}
\]

\[
[K_s^*] = [R][K_s][R]^T
\]

Poulos & Madhav (1971)

- Soil springs are independent of rake angle
Structure-soil-structure Interaction

Total Stiffness Matrix of Piled Raft

\[
\begin{bmatrix}
\mathbf{K}_r
\end{bmatrix}\{w\} = \{F\} - \{P\}
\]

\[
\begin{bmatrix}
\mathbf{C} + \mathbf{K}_r + \mathbf{K}_p
\end{bmatrix}\{w\} = \begin{bmatrix}
\mathbf{K}
\end{bmatrix}\{w\} = \{F\}
\]

Diagonal coefficients of \([A]\)
Inverse of \([K_s^*]\)

Off-diagonal coefficients of \([A]\)
Based on Mindlin’s solutions

For instance, settlement of point 1

\[
w_i = \sum_{j=1}^{n} a_{ij} P_j
\]

\[
\{w\} = [A]\{P\}, \quad [C]\{w\} = \{P\}
\]
Multi-layer soil

Raft Vertical soil springs

\[ K_z^R = \frac{4\bar{G}a}{1-\nu_s} \left(1-\exp\left(-h/2a\right)\right) \]

Pile Vertical soil springs

\[ K_z^P = 2\pi G_s \Delta L / \ln(r_m / r_o) \]
\[ r_m = 2.5 \left[ \frac{(1-\nu_s)}{G_m L} \sum_{i=1}^{n} G_i L_i \left(1-\exp\left(-h/L_i\right)\right) \right]^{1/2} \frac{G_m}{G_b} \]

Raft lateral soil springs

\[ K_x^R = K_y^R = \frac{32(1-\nu_s)G_r a}{7-8\nu_s} \]

Pile lateral soil springs

\[ K_x^P = K_y^P = \frac{32(1-\nu_s)G_b r_o}{7-8\nu_s} \]
\[ K_x^P = K_y^P = \zeta E_s \Delta L \]

\( \bar{G} \)  Equivalent soil shear modulus
\( G_m \)  Maximum soil shear modulus
\( G_i \)  Soil shear modulus at element \( i \)
\( G_b \)  Soil shear modulus at pile base
\( G_r \)  Soil shear modulus at raft base
\( L_i \)  Length of element \( i \)
\( \Delta L \)  Pile element length
\( r_o \)  Pile radius
I is the vertical settlement influence factor which is given by Harr (1966).

Equivalent shear modulus, $\bar{G}$

\[
\frac{1}{\bar{E}_{s}} = \sum_{i=1}^{n} \frac{1}{E_i} \frac{\Delta I_i}{\Delta I_{total}}
\]

\[
\Delta I_i = I(z_{i}^{\text{top}}) - I(z_{i}^{\text{bottom}})
\]

\[
\Delta I_{total} = I(0) - I(h)
\]

\[
\bar{G} = \frac{\bar{E}_{s}}{2(1 + \nu_{s})}
\]
Average soil modulus

Average soil modulus is employed in the analysis to approximate for the interactions.

\[ E_{s(ij)} = \frac{\left( E_{s(i)} + E_{s(i+1)} \right) + \left( E_{s(j)} + E_{s(j+1)} \right)}{4} \]
Part II: Verified the validity of PRAB through comparison analysis with three-dimensional FEM
Comparison Analysis

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s/D$</td>
<td>$E_s$</td>
<td>$E_s$</td>
<td>$2E_s$</td>
<td>$4E_s$</td>
<td>$4E_s$</td>
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<tr>
<td>$L/D$</td>
<td>$E_s$</td>
<td>$2E_s$</td>
<td>$E_s$</td>
<td>$E_s$</td>
<td>$2E_s$</td>
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<tr>
<td>$h$</td>
<td>$E_s$</td>
<td>$4E_s$</td>
<td>$4E_s$</td>
<td>$2E_s$</td>
<td>$E_s$</td>
</tr>
</tbody>
</table>

$h = 2L, L/D = 25, s/D = 3.75, \nu_s = 0.3, E_p/E_s = 3000$
Three-dimensional FEM

\[ E_p = E_r = E_c = 30 \text{ GN/m}^2 \]
\[ \nu_p = \nu_r = \nu_c = 0.16 \]
\[ E_s = 30 \text{ MPa} \]
\[ \nu_s = 0.3 \]
\[ D = 1 \text{ m} \]
\[ K_{rs} = 10 \]
\[ V, H = 100 \text{ kN/m}^2 \]
\[ (900 \text{ kN}) \]
Comparison Analysis

<table>
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<tr>
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<td>$4E_s$</td>
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</table>

$h = 2L, L/D = 25, s/D = 3.75, \nu_s = 0.3, E_p/E_s = 3000$

![Diagram with dimensions and symbols]
Settlement of the pile

\[ I_{wV} = \frac{wE_s D}{V} \]

**Piled raft**

**Pile group**
Axial forces along pile

\[ C_{av} = \frac{A}{V} \]

Piled raft

Pile group
Lateral displacement of the pile

\[ I_{uH} = \frac{uE_s D}{H} \]

---

**Piled raft**

**Pile group**
Shear forces along piles

\[ C_{sH} = \frac{S}{H} \]

Piled raft

Pile group
**Bending moments along piles**

\[ C_{bh} = \frac{B}{HD} \]

![Graphs of bending moments along piles for Piled raft and Pile group](image)

- **Piled raft**
  - Cyclic bending moments
  - Depth from G.L. (m)

- **Pile group**
  - Cyclic bending moments
  - Depth from G.L. (m)
**Comparison Analysis**

<table>
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$h = 2L, L/D = 25, s/D = 3.75, \nu_s = 0.3, E_{p}/E_s = 3000$
Comparison of calculated results

Piled raft

Pile group
### Comparison Analysis

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$h = 2L$, $L/D = 25$, $s/D = 3.75$, $\nu_s = 0.3$, $E_p/E_s = 3000$
Comparison of calculated results

Piled raft

Settlement
Axial force
Lateral disp.
Shear force

PRAB
FEM

Pile group

Settlement
Axial force
Lateral disp.
Shear force

PRAB
FEM
### Comparison Analysis

#### Case 1 | Case 2 | Case 3 | Case 4 | Case 5
---|---|---|---|---
$E_s$ | $E_s$ | $2E_s$ | $4E_s$ | $4E_s$
$E_s$ | $2E_s$ | $E_s$ | $E_s$ | $2E_s$
$E_s$ | $4E_s$ | $4E_s$ | $2E_s$ | $E_s$

$h = 2L$, $L/D = 25$, $s/D = 3.75$, $\nu_s = 0.3$, $E_p/E_s = 3000$

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<td>$0.3L$</td>
<td>$0.4L$</td>
<td>$0.3L$</td>
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<tr>
<td>$H$</td>
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<td></td>
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<tr>
<td>$3.0$ m</td>
<td>$1.5$ m</td>
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<tr>
<td>$1.5$ m</td>
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<tr>
<td>$10.0$ m</td>
<td>$0.9$ m</td>
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<tr>
<td>$0.4$ m</td>
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</table>
Comparison of calculated results

Piled raft

Settlement
Axial force
Lateral disp.
Shear force

Pile group
### Case 2 Case 3 Case 4 Case 5

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>$E_s$</td>
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</table>

$h = 2L$, $L/D = 25$, $s/D = 3.75$, $\nu_s = 0.3$, $E_p/E_s = 3000$

![Diagram showing geometric relationships and material properties for different cases.](image)
Comparison of calculated results

“A simplified analysis method for piled raft foundation has been developed. The validity of the proposed method was verified”
Part III: Verified the applicability of PRAB through analyses of the centrifuge model test results
Horikoshi et al. (2003a) has conducted a series of static vertical loading tests and lateral loading tests on piled raft models. Much focus was placed on the load-displacement relationship and the load sharing between the piles and the raft. Effects of the rigidity at pile head connection on the piled raft behaviour were also examined in their work.

In order to investigate applicability of PRAB, analysis of these centrifuge model test results were carried out.
Rigid pile head connection

Raft connecting bolt

Pile 1
Pile 2
Pile 3
Pile 4

Model Raft

Loading direction

unit:mm

Embedded in raft

G.L.

strain gage

Aluminium Pipe
OD:10mm
ID:8mm

Bending + Axial strains
Bending strain only
Shear strain

after Horikoshi et al. (2003a)
Hinged pile head connection

Raft connecting bolt

Pile 1  Pile 2  Pile 3  Pile 4

Aluminium Pipe
OD:10mm
ID:8mm

Loading direction

unit:mm

Bending + Axial strain
Bending strain only
Shear strain

after Horikoshi et al. (2003a)
## Analysis conditions

<table>
<thead>
<tr>
<th></th>
<th>Loading direction</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Vertical loading</td>
<td>Lateral loading</td>
<td></td>
</tr>
<tr>
<td><strong>Pile</strong></td>
<td>Pile length = 170 mm</td>
<td>Pile length = 180 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Outer diameter = 10 mm, Inner diameter = 8 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Young’s modulus = 70.6 GN/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio = 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Raft</strong></td>
<td>Mass = 0.90 kg</td>
<td>Mass = 4.69 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width = 80 mm, Breadth = 80 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickness = 25 mm (substantially rigid)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Young’s modulus = 70.6 GN/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio = 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Soil</strong></td>
<td>Layer depth = 470 mm</td>
<td>Layer depth = 480 mm</td>
<td></td>
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<tr>
<td></td>
<td>Density = 1.52 t/m³, Internal friction angle = 35°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Void ratio = 0.76, Poisson’s ratio = 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Finite homogeneous layer</td>
<td></td>
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</tbody>
</table>
In order to take into account the non-linear response, the value of the uniform pile shaft resistance and the pile base bearing capacity were set as 100 kN/m² and 10000 kN/m², respectively.

- No failure occurred at the raft base.
Load-settlement relationship

![Graph showing load-settlement relationship with data points for measured and calculated vertical loads and settlements.](image-url)
Proportions of vertical loads carried by raft and piles

![Graph showing proportions of vertical loads carried by raft and piles.](image)
The analysis is conducted for only lateral loading stage. The vertical load carried by the raft before the lateral loading is taken into account as the initial condition and is assumed to distribute uniformly over the raft base.

In the estimation of the limit lateral pressure of the piles located just beneath the raft in cohesionless soils, the effect of the increase in the vertical stress of the soil due to the vertical load transferred through the raft should be taken into account.
Limit lateral pressure of the piles

Limit lateral pressure of pile \( p_u = K_p \sigma'_v \)

Effective stress \( \sigma'_v = \sigma'_{v0} + \Delta \sigma'_{v0}, \quad \sigma'_{v0} = \gamma_t H \)

Increase of stress due to overburden pressure

\[ \Delta \sigma'_{v0} = \frac{q_0 \times B \times L}{(B + z)(L + z)} \]

Rankine passive earth pressure coefficient

\[ K_p = \frac{1 + \sin \phi}{1 - \sin \phi} \]

Finite Homogeneous soil (bi-linear spring model)

- \( \phi = 35^\circ \)
- \( \gamma_t = 14.9 \text{ kN/m}^3 \)
- \( \mu = 0.42 \)
The calculated results that consider the effect of the increase in the soil stress beneath the raft overestimate the measured total lateral resistance, because of the overestimate of the lateral pile resistance.
The raft breadth is relatively narrow compared to the pile length. Hence the effect of the increase in the soil stress beneath the raft on the value of the limit lateral pressure of the pile is small.
Rigid pile head connection

- a) Consider increase in the soil stress beneath the raft

- b) No increase in the soil stress beneath the raft

Consequently, the calculated results which neglected the effect of the increase in the soil stress beneath the raft are closer to the measured values.

The analysis results hereafter were calculated using the limit soil pressure value without the effect of the increase in the soil stress beneath the raft.
The piles in the piled raft with the hinged pile head connection carry smaller amount of the lateral load than those in the piled raft with the rigid pile head connection, while the amount of the lateral load carried by the raft is almost the same.
“Even though the proposed method is *simple*, the method can be used with a *confidence* as a design tool for piled raft foundations”
Analyses of the static vertical and horizontal load test results of model pile group and model piled raft foundations with different pile head connection rigidities are carried out using a computer program PRAB (Piled Raft Analysis with Batter piles).

Good agreements between the calculated results and the experimental results will be demonstrated.
Analysis conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Pile length</td>
<td>600mm</td>
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<td>Outer diameter</td>
<td>40mm</td>
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<tr>
<td>Inner diameter</td>
<td>36mm</td>
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<tr>
<td>Young’s modulus</td>
<td>$7 \times 10^4$ kPa</td>
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<tr>
<td>Poisson’s ratio</td>
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</tr>
<tr>
<td>Raft Width</td>
<td>400mm</td>
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<tr>
<td>Breadth</td>
<td>400mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>40mm</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$1.93 \times 10^5$ kPa</td>
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<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Soil Layer depth</td>
<td>1000mm</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Dry Toyoura sand ($D_r = 80\%$)

Test set-up
Model foundations

Plan view

- N
- 400 (mm)
- 100 200 100
- P1
- P2
- P3
- P4
- S
- W 400 200 100
- S
- Model raft

Side view

- 40

Model raft

Model piles with different pile head connection conditions

- Shear strain gauge
- Axial strain gauge
- Aluminum pipe OD = 40 mm ID = 36 mm
- Top steel plate
- Top steel cap
- Rigid
- Semi-rigid
- Semi-hinged
- Hinged
- Connection bar

Dimensions:
- 95 mm
- 30.5 mm
- 10 mm
- 13 mm
**Hybrid analytical model**

Plate-beam-spring modelling of a piled raft

**Raft:** thin plates

**Piles:** elastic beams

**Soil:** interactive springs

### Model load test cases

<table>
<thead>
<tr>
<th>Test name</th>
<th>Type of foundation</th>
<th>Pile head condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1:Raft</td>
<td>Raft alone</td>
<td>—</td>
</tr>
<tr>
<td>Case2:PG-R</td>
<td>Pile group</td>
<td>Rigid</td>
</tr>
<tr>
<td>Case3:PG-H</td>
<td>Pile group</td>
<td>Hinged</td>
</tr>
<tr>
<td>Case4:PR-R</td>
<td>Piled raft</td>
<td>Rigid</td>
</tr>
<tr>
<td>Case5:PR-SR</td>
<td>Piled raft</td>
<td>Semi-rigid</td>
</tr>
<tr>
<td>Case6:PR-SH</td>
<td>Piled raft</td>
<td>Semi-hinged</td>
</tr>
<tr>
<td>Case7:PR-H</td>
<td>Piled raft</td>
<td>Hinged</td>
</tr>
</tbody>
</table>
Soil properties

Physical properties of Toyoura sand

\[ D_r = 80\% \]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum dry density, ( \rho_{d_{\text{max}}} )</td>
<td>1.621t/m³</td>
</tr>
<tr>
<td>Minimum dry density, ( \rho_{d_{\text{min}}} )</td>
<td>1.328t/m³</td>
</tr>
<tr>
<td>Density of soil particle, ( \rho_s )</td>
<td>2.637t/m³</td>
</tr>
<tr>
<td>Mean grain size, ( D_{50} )</td>
<td>0.17 mm</td>
</tr>
<tr>
<td>Internal friction angle, ( \phi' )</td>
<td>40 degrees</td>
</tr>
</tbody>
</table>

Confining pressure
- 245 kPa
- 196 kPa
- 147 kPa
- 98 kPa
- 49 kPa

\[ \phi' = 40^\circ \]

Deviator stress versus effective mean stress
Soil properties

Physical properties of Toyoura sand

\( D_r = 80\% \)

<table>
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<td>40 degrees</td>
</tr>
</tbody>
</table>

\[
G = G_{\text{ref}} \left( \frac{p}{p_{\text{ref}}} \right)^{0.5} \quad (1)
\]

\[
p = (1 + 2K_0) \cdot \sigma_v' / 3 \quad (2)
\]

\[
K_0 = 1 - \sin \phi'
\]

Shear modulus versus confining pressure
Resistance properties

Horizontal raft base resistance

\[ q_h = c + \mu_b \sigma_{vb}' \quad (c = 0, \mu_b = \tan \phi' = 0.84) \quad (4) \]

Vertical raft base resistance

\[ q_u = \alpha \cdot c \cdot N_c + \beta \cdot \gamma_1 \cdot B \cdot \eta \cdot N_\gamma + \gamma_2 \cdot D_f \cdot N_q \]

\[ (\alpha = 1.2, \beta = 0.3, N_c = 75.3, N_\gamma = 93.7 \text{ for } \phi' = 40^\circ) \quad (5) \]

Maximum shaft resistance of pile

\[ f_{\text{max}} = \mu \cdot \gamma \cdot z \cdot K_0 \quad (\mu = 0.84) \quad (6) \]

Maximum horizontal resistance of pile

\[ p_{\text{max}} = \alpha_p \cdot \gamma \cdot z \cdot K_p \quad (\alpha_p = 3.0) \quad (7) \]

\[ K_p = (1 + \sin \phi')/(1 - \sin \phi') \]

End-bearing capacity of pile

\[ R_p = q_c \cdot A_p \quad (q_c = 5000 \text{ kPa from CPT results}) \quad (9) \]
At the same vertical load, pile groups settle more than piled rafts.

The load-settlement curves are almost identical for the same type of foundation regardless of pile head connection rigidities.
Physical vs numerical Load—settlement relationship

Analysis results simulate the experimental results well.
At the initial stage of the vertical loading, only small vertical load is carried by the raft in the experimental results, due to the small stress level in the sand near the surface.

The proportions of the vertical load carried by the raft is about 0.35 for all types of pile head connection condition from the calculated results.

From the analyses, the rigidity of the pile head connection has little influence on the behavior of the pile foundation subjected to vertical load.
The initial horizontal stiffness is higher in the case of piled raft than that of corresponding pile group from both experimental and analysis results.

For the same type of foundation, the higher horizontal stiffness and horizontal resistance can be found in the foundation that has higher rigidity of pile head connection in both experimental and analysis results.
The piles in the piled raft with rigid pile head connection carry a high amount of the horizontal load in the initial stage from the analysis results.

From the analyses, the horizontal load carried by the raft for all cases are almost identical after the horizontal load reaches 2.5 kN.
The analysis results match well with the measured values for both piled rafts with rigid and hinged pile head connection conditions.
Part IV: Application of PRAB
A temporary road bridge having a span of 42.5 m and a width of 10 m was constructed over the existing Hokuriku railway line in 2002.

Pile foundations were employed for abutments of the bridge.

The bridge was used temporarily until the year of 2005.

The number of car traffics per day was about 2000, and about 200 trains passed under the bridge in a day.

Much attention was paid to the design of pile foundation and load distribution of the piles during the construction of the bridge.
Role of STATNAMIC test and PRAB

- STATNAMIC test was conducted on one of the constructed piles in an abutment to confirm the load-settlement relation.
- The piles in the abutment were instrumented with strain gauges to monitor the axial load of each pile throughout the construction steps of the superstructure.
- PRAB was employed to predict the load distribution and the settlements of the piles during the construction of the bridge, using the profile of the soil properties obtained from the wave matching analysis of the STATNAMIC test results.
The construction site was located next to the Hokuriku railway line.

The top soft clay with a thickness of 2.76 m was underlain by a relatively uniform sand layer of 18.95 m in thickness. A soft clay layer of 1.89 m thickness was intercalated between the sand layer and a hard gravel layer existing below a depth of 23.6 m.
A total of 20 piles were constructed for an abutment of the temporary bridge.
- The piles were bored concrete piles with H-shaped steel reinforcing bars.
- The H-shaped steel bars were extended to support the superstructure.
- Piles A, C and E were instrumented with strain gauges.
A total of 20 piles were constructed for an abutment of the temporary bridge. The piles were bored concrete piles with H-shaped steel reinforcing bars. The H-shaped steel bars were extended to support the superstructure. Piles A, C and E were instrumented with strain gauges.
Statnamic test
Measured signals

- Maximum applied load in the test was 2.2 MN.

Interpretations

Wave matching analysis
Wave matching analysis

- The one-dimensional stress–wave analysis was repeated using the measured $F_{\text{stn}}$ as the force boundary condition at the pile head, until a good matching between the calculated and the measured pile head displacements was obtained.
### Load distribution and settlement of piles

<table>
<thead>
<tr>
<th>Step</th>
<th>Load at the point (kN)</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>75.6</td>
<td>75.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(mount of 1st bridge girder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(mount of 2nd bridge girder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
<td>75.6</td>
</tr>
<tr>
<td></td>
<td>(mount of 3rd bridge girder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>158</td>
<td>168</td>
<td>176</td>
<td>190</td>
<td>208</td>
<td>266</td>
</tr>
<tr>
<td></td>
<td>(after completion of pavement and other facilities)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Load distribution and settlement of piles

<table>
<thead>
<tr>
<th>Step</th>
<th>Load at the point (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
</tr>
<tr>
<td>1</td>
<td>75.6</td>
</tr>
</tbody>
</table>
  (mount of 1st bridge girder)  
| 2    | 75.6 | 75.6 | 75.6 | 75.6 | 0 | 0 |
  (mount of 2nd bridge girder)  
| 3    | 75.6 | 75.6 | 75.6 | 75.6 | 75.6 | 75.6 |
  (mount of 3rd bridge girder)  
| 4    | 158 | 168 | 176 | 190 | 208 | 266 |
  (after completion of pavement and other facilities)
A group of five piles with a cap(raft) was modelled in the analysis.

The profiles of the soil shear modulus, the maximum shaft resistance, the base resistance obtained from the wave matching analysis were employed.
Step | Load at the point (kN) |  
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>1</td>
<td>75.6</td>
</tr>
</tbody>
</table>
(mount of 1st bridge girder)  
| 2   | 75.6 | 75.6 | 75.6 | 75.6 | 0   | 0   |  
(mount of 2nd bridge girder)  
| 3   | 75.6 | 75.6 | 75.6 | 75.6 | 75.6 | 75.6 |  
(mount of 3rd bridge girder)  
| 4   | 158  | 168  | 176  | 190  | 208  | 266  |  
(after completion of the bridge)
<table>
<thead>
<tr>
<th>Step</th>
<th>Load at the point (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>75.6 75.6 0 0 0 0 0</td>
</tr>
<tr>
<td></td>
<td>(mount of 1st bridge girder)</td>
</tr>
<tr>
<td>P2</td>
<td>75.6 75.6 75.6 75.6 0 0</td>
</tr>
<tr>
<td></td>
<td>(mount of 2nd bridge girder)</td>
</tr>
<tr>
<td>P3</td>
<td>75.6 75.6 75.6 75.6 75.6 75.6</td>
</tr>
<tr>
<td></td>
<td>(mount of 3rd bridge girder)</td>
</tr>
<tr>
<td>P4</td>
<td>158 168 176 190 208 266</td>
</tr>
<tr>
<td></td>
<td>(after completion of the bridge)</td>
</tr>
</tbody>
</table>

- **Pile A**: Limit settlement of 6.5 mm
- **Pile B**: Measured settlement < 2.5 mm (precision of track level = 2.5 mm)
“The load distribution and the settlements of the piles in the abutments calculated using PRAB match well with the field measurement values. Through the field measurements and the analyses, the safety of the pile foundation was confirmed.”

<table>
<thead>
<tr>
<th>Step</th>
<th>Load at the point (kN)</th>
<th>Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1  P2  P3  P4  P5  P6</td>
<td>Pile A</td>
</tr>
<tr>
<td>1</td>
<td>75.6 75.6 0 0 0 0</td>
<td>Limit settlement of 6.5 mm</td>
</tr>
<tr>
<td></td>
<td>(mount of 1st bridge girder)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>75.6 75.6 75.6 75.6 0 0</td>
<td>Measured settlement &lt; 2.5 mm (precision of track level = 2.5 mm)</td>
</tr>
<tr>
<td></td>
<td>(mount of 2nd bridge girder)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>75.6 75.6 75.6 75.6 75.6 75.6</td>
<td></td>
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<tr>
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<td>(mount of 3rd bridge girder)</td>
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<tr>
<td>4</td>
<td>158 168 176 190 208 266</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(after completion of the bridge)</td>
<td></td>
</tr>
</tbody>
</table>

Settlement
Concluding remarks

1. As a simplified method of numerical analysis for estimation of the deformation and load distribution of piled raft foundations subjected to active loading and passive loading, PRAB has been developed.

2. The validity and applicability of PRAB were verified through comparison with several published solutions, three-dimensional FEM and model test results.

3. Through the field measurements and the analyses using PRAB, the safety of the pile foundation of a bridge was confirmed.

4. A combination of field measurements with an appropriate deformation analysis of a whole pile foundation structure may lead to a rational reduction of the safety factor.

5. PRAB can be used with a confidence as a design tool for piled raft foundations.