New foundations in Japan and recent pile researches in Kyoto University

Kyoto University    Makoto Kimura
kimura.makoto.8r@kyoto-u.ac.jp

Niigata EQ of 1964

Collapse of the building due to liquefaction
Japanese design ideas of road bridge foundations

New pile foundation in Japan

Investigation of mechanical behavior of pile group
Seismic design for pier and foundation

Basic idea for seismic design

Earthquake force for design
\∧
Horizontal bearing capacity on pier
\∧
Horizontal bearing capacity on foundation

No foundation failure
Needs of seismic reinforcement for existing foundations

- Reinforcement for existing foundations

After Kobe earthquake

- Earthquake force for design
- Increase
- Stiffness of pier
- Reinforcement of pier
- Horizontal bearing capacity on foundation
- Reinforcement of foundation

Pandora’s box

Advancement of numerical method

Combined calculation for upper structure and foundation
Needs of seismic reinforcement for existing foundations
Plastic deformation caused by the earthquake disaster

The Southern Hyogo prefecture EQ in 1995

Cracks generated in piles

The 2011 off the Pacific coast of Tohoku EQ

Damage to the pile in the soft ground and liquefied ground

Cumulative No. of pile damage found by the bore-hole camera investigation

Based on the reports of restoration for foundation structures of Kobe line #3 by Hanshin Expressway
Why do we design a footing?
Offshore pile foundations for roads

- **Jacket steel pile foundation with inclined piles**

- Not so heavy

**Diagram labels:**
- Jacket leg
- Steel pile
- Ballast tank
- Soft soil layer
- Stuff substratum
- Jacket structure
- Pier
Inertial force

Type A

Type B

Axial force distribution

Axial force (MN)

TypeA : Analysis (at 6.61s)
TypeA : Test (at 6.30s)
TypeB : Analysis (at 6.59s)
TypeB : Test (at 6.17s)
Pile foundation

Caisson foundation

Remarks: C.G.: Center of gravity
RESPONSE FOR ACCELERATION AND DISPLACEMENT

**Acceleration**

- **Upper structure**
- **Foundation**

**Displacement**

- **Upper structure**
- **Foundation**
Shaking table test and numerical simulation on seismic performance of a bridge column integrated by multiple steel pipes with directly-connected piles

Koichi Isobe (Hokkaido University)
H. Sugiyama, M. Shinohara, H. Kobayashi (Hanshin Expressway)
Y. Sawamura, Y. Mitsuyoshi, M. Kimura (Kyoto University)
Development of “Integrated column by multiple steel pipes” (2004)

- A bridge column integrated by 4 steel pipes and multiple shear panels interconnecting the pipes has been proposed.
- It is designed based on damage control concept, in which the vertical load is supported by the steel pipes and the lateral load is adjunctively supported by shear links.
- Shear panels are made of low yield stress steel and have hysteretic energy dissipation properties.
- It intends to lead seismic damage into shear panels and enables early recovery by replacing only panels.
Development of “Integrated column by multiple steel pipes” (2004)

- Budget-pleasing prefabricated material (ready-made spiral steel pipes) are used.
- Anchor frame is NOT necessary unlike a conventional steel pier structure.
- Reduce 30% of construction cost
- Reduce construction time
- Rapid transportation open

NO Anchor frame
## Cost analysis

<table>
<thead>
<tr>
<th>Pile group</th>
<th>Integrated column by multiple steel pipes</th>
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<tbody>
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<table>
<thead>
<tr>
<th>建物構体</th>
<th>鋼製構体</th>
<th>鋼管集成構体</th>
<th>鋼管集成構体</th>
<th>建物構体</th>
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</thead>
<tbody>
<tr>
<td>塔吊打設 (φ 1500 × 3本)</td>
<td>ケーブル基盤 (φ 600)</td>
<td>塔吊打設 (φ 1500 × 3本)</td>
<td>ケーブル基盤 (φ 600)</td>
<td>塔吊打設 (φ 1500 × 3本)</td>
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<tr>
<td>86,300 (千円)</td>
<td>86,300 (千円)</td>
<td>64,000 (千円)</td>
<td>64,000 (千円)</td>
<td>47,556 (千円)</td>
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<td>基礎工</td>
<td>基礎工</td>
<td>基礎工</td>
<td>基礎工</td>
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<td>40,030 (千円)</td>
<td>62,230 (千円)</td>
<td>40,030 (千円)</td>
<td>62,230 (千円)</td>
<td>34,660 (千円)</td>
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<tr>
<td>合計</td>
<td>128,830 (千円)</td>
<td>149,130 (千円)</td>
<td>104,030 (千円)</td>
<td>126,330 (千円)</td>
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<td>比率</td>
<td>(1.00)</td>
<td>(1.00)</td>
<td>(0.82)</td>
<td>(1.00)</td>
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<td>比率</td>
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<td>註</td>
<td>(柱-鉄設製費は除く)</td>
<td>(柱-鉄設製費は除く)</td>
<td>(柱-鉄設製費は除く)</td>
<td>(柱-鉄設製費は除く)</td>
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</table>

1.00  1.18  0.82  1.00  0.65
Introduction

Proposal of “Steel pipe pile foundation” for integrated column

- Each pipe of the column is supported by a directly connected steel pile without a footing
- Maybe rational & reasonable foundation structure for “A bridge column integrated column by multiple steel pipes”
- Not impair the ability of the integrated column structure
- Reduce inertia force and sectional force at the connected area between piles and column
- Reduce the cost of footing and the number of piles
- Can employ the pile foundation in narrow construction conditions
Purpose of Study

- **Shaking table test and Numerical simulation**
  - To compare the both seismic performance (footing type vs footing-less type)
    - Axial force acting at pile heads
    - Lateral displacement at a pier top and pile heads
    - Cross sectional force acting in a bridge column and piles
  - To confirm the yield order of the member for the proposed structure
  - To check the behavior of the proposed structure in liquefiable sand
  - To identify the structural issues of the proposed type
  - To cross-check analytical model by simulating the model tests
Outline of Shaking table test

Shaking table and Large-scale rigid box with tempered glass

- Public Works Research Institute in Tsukuba
- Large-scale 3-dimensional shaking table
- Table size: 8m x 8m
- Box size: 4m (W) x 1m (L) x 2m (H)
- See the ground through the tempered glass
Outline of Shaking table test

- Detail of the model used in the tests

<table>
<thead>
<tr>
<th>Member</th>
<th>Material</th>
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<tbody>
<tr>
<td>Steel pipe</td>
<td>STK400</td>
</tr>
<tr>
<td>Shear panel</td>
<td>LY225</td>
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<tr>
<td>Underground beam</td>
<td>SS400</td>
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</table>

Footing type | Footing-less
Outline of Shaking table test

Footing type

Footing-less type
Results of Shaking table test  Dry sand

Response acceleration vs lateral displacement @ pier top

- The stiffness of Case-1-F (D-F) is bigger than that of Case-1-S (D-S).
- Case-1-F yields at earlier stage than Case-1-S.
- Response acceleration and lateral displacement for Case-1-F increase rapidly and brittle deformation is observed.
Results of Shaking table test

Strain on the structure at Step 3

Strain on the structure at Step 3
## Results of Shaking table test

### Damage process of the member

<table>
<thead>
<tr>
<th>加振No. (最大入力加速度)</th>
<th>上段</th>
<th>中段</th>
<th>下段</th>
<th>柱</th>
<th>杭</th>
<th>上段</th>
<th>中段</th>
<th>下段</th>
<th>地中梁</th>
<th>鋼管</th>
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<td>(a)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>(a)</td>
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<tr>
<td>第2加振 (1.0 m/sec²)</td>
<td>(b)</td>
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<tr>
<td>第3加振 (1.5 m/sec²)</td>
<td>(c)</td>
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<tr>
<td>第4加振 (2.0 m/sec²)</td>
<td>せん断パネル</td>
<td>柱・杭 (鋼管)</td>
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</tr>
<tr>
<td>第5加振 (2.5 m/sec²)</td>
<td>☐ 弹性</td>
<td>☐ 弹性</td>
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<td>第6加振 (3.0 m/sec²)</td>
<td>☐ 塑性</td>
<td>☐ 塑性</td>
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<td>第7加振 (3.5 m/sec²)</td>
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<td>☐ 塑性の可能性あり</td>
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<td></td>
<td></td>
<td></td>
<td>(b)</td>
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<tr>
<td>第8加振 (5.0 m/sec²)</td>
<td>☐ 面外変形</td>
<td>☐ 塑性の可能性あり</td>
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- The proposed substructure (Case-1-S) have advantages of strain reduction of column by strain decentralization at footing point.
- It has high seismic performance and high toughness if the conditions are right in view of the fact that the main member (columns and piles) holds a large residual strength after yielding of the shear panels.
Summary for model tests

- Based on the fact that the main members such as the columns and piles yield after the shear panels (secondary member) yield, the proposed structure has a damage control performance by energy absorption due to plastic deformation of the shear panels.

- In particular, S-type has high seismic performance because the main member (columns and piles) holds a large residual strength even after yielding of the shear panels.
My new pile foundations
5.2 LNG receiving terminal and LNG tank

LNG tank need enough stability even if earthquake

Double-walled metal tank

45,000 m³

Group pile foundation
(496 of steel pipe pile)

⇒ can be used for loading test

⇒ demolished after 40 years service

48 m

25 m

Colunnar section

N value

0 20 40

Unit: m

14 m

18 m

Support layer φ 0.4

G.L. 14.0

LNG tank

LNG receiving terminal
5.3 Experimental condition

- 3 × 1 group pile specimen
- 7 × 9 group pile specimen
- Reaction piles
- Strain gauge, Displacement transducer, Inclinometer
- Loading direction
- 18 m
- 5,000 kN jack
- Steel pipe pile
- Protective concrete
- LNG tank
- 496 of steel pipe pile

Demolished after 40 years service

Load (kN) vs. Time (Hour)

⇒ Prediction FEM analysis to decide max. load
5.3 Experimental conditions

Unidirectional multiple-cycle multiple-step loading (6 cycle)

Max. load is decided to 30,000 kN

⇒ How to decide max. load?

It is very difficult to calculate the load to see ultimate behavior of 63 of group pile foundation

3D elasto-plastic FEM analysis
= Simulating group pile effect elast-plastic approximate solution
⇒ Conducted prediction analysis to decide max. load
5.4 Prediction analysis condition

Prediction analysis by 3 dimensional elasto-plastic FEM

Analysis area

Beam (Bilinear)

Solid element
1/10 EI of real pile

Pile: Hybrid model (Bilinear)

Ground: Subloading $t_{ij}$ model
5.4 Prediction analysis model

Pile group effect depend on $L/d$

Only beam element model overestimate pile spacing $L$
and pile group effect is misestimated.
5.5 Results ~Load-displacement~

Even high load, remain stiffness ⇒ not reasonable

Actually, ultimate load was lower (25400 kN) ⇒ ductile deformation over yield load in design

Simulate accurately at initial phase but not after yield
5.5 Results ~deformation of group pile~

- The front pile
  - Loading direction
- The second pile

2.2° 1.8° 1.7° 1.6°
Front Back
-1.4 m
-2.4 m
-2.9 m
-3.4 m
-3.6 m
-3.8 m
-3.9 m

Position of the maximum bending moment from FEM result
3.0° 4.1° 3.0° 1.5° 1.5° 1.5° 1.5°

8,000 kN applied

25,400 kN applied
5.5 Results ~Load share of each pile~

Middle or back pile share small load

According to increase of load load share decrease

Large group pile effect generate in spite of $L/d = 5$

$\Rightarrow$ over 0.9 load share

$3 \times 1$ group pile $L/d = 5$

Specific to large scale group pile