STUDY ON
HOW TO CONSIDER PILE FOUNDATION PERFORMANCE WHEN SETTING SEISMIC PERFORMANCE OF BUILDING

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In this paper, I discuss how to consider the seismic performance of pile foundation when setting the seismic performance of building.

1. Look back on past earthquake damage of pile foundation in Japan and follow the revision process of related regulations

2. Outline the current state of seismic design of piles against large Earthquake
   * Building Low not require. for pile foundation.
   * Government /Local Administrative Agency : require it with the target seismic performance of Important bldgs.: without repairing or not requiring major repair

3. From the lessen of recent Large earthquake, once the pile is damaged, there are many difficulties in restoring it, so we recognize that there are many cases where buildings are disassembled even if the superstructure is not damaged.

4. My personal opinion; Based on the perspective of property protection and function maintenance after large Earthq., it is necessary to set the target seismic performance of the building comprehensively by combining seismic performance of the superstructure and the pile foundation, and it is important to explain this setting result to the owner and to get his agreement.

5. Newly developed pile system is presented. this pile is strengthened seismic performance and can be continuously used also after large earthquake.
The author expects specially a comment about the current situation of your country to this subject. How is the Seismic design of pile foundation performed??

Supplement:
Structural design system in Japan under the Building Standard Law:
Buildings of a certain size or larger more must be designed by the 1st class Kenchiku-shi (mean registered architect or building engineer).
In addition, if the structural engineer has not passed the Structural Design Examination for the 1st class Structural design engineer (Kouzou-sekkei 1st class Kenchiku-shi), it is necessary to undergo design review by them.
So, We don't have Geotechnical Engineer license system to design building foundations.
How about in your country? SE or GE, who design foundation?
Introduction
In the Japanese seismic codes, the design for the superstructure is specified against two stages of seismic forces. Taking the design route such as the most general allowable stress design as an example, we design by allowable stress method in the 1st phase design for the medium earthquake, and in the 2nd phase design for the large earthquake, make the horizontal holding capacity of the building more than the necessary holding horizontal strength. On the other hand, the 1st phase seismic design of foundation introduced as a legal requirement in 2000
1. Past Seismic Damage of Pile in Japan and Changes in Related Regulations and Guideline

1.1 Legalization of Seismic Design (1st Phase) of Pile Foundation.

Table 1 Major earthquakes caused pile damage in JAPAN and its effect to design practice

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Major events</th>
<th>Affect to design practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964 Nigata (M7.5)</td>
<td>Liquefaction damage enormous. Settlement/inclination; buildings,</td>
<td>1974 (AIJ std. revised),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simplified liquefaction assessment</td>
</tr>
<tr>
<td>1968 tokachi-oki (M7.9)</td>
<td>Serious damage / collapse of RC buildings, Pile damages reported</td>
<td>1981 (Bldg-Law) New seismic design code introduced</td>
</tr>
<tr>
<td>1978 miyagikenn -oki (M7.4)</td>
<td>RC Buildings Damage, PC Pile damages focused</td>
<td>1984 (Bldg-Recm) Pile aseismic design (1st phase) recommended</td>
</tr>
<tr>
<td>1995 Hyogokenn -nambu (M7.2)</td>
<td>Building collapsed serious, damage to various piles reported</td>
<td>1988 (AIJ std. revised) liquefaction assessment (EI-method). Pile aseismic design (2nd)</td>
</tr>
<tr>
<td>2011 Higashi-nihon (M9.0)</td>
<td>Tsunami damage was enormous PC,PHC piles damages reported</td>
<td>2001 (Bldg-Law revised) Seismic design (1st) for pile required (AIJ std. revised) liquefaction assessment modified, Pile aseismic design (2nd)</td>
</tr>
</tbody>
</table>

Notes: AIJ std.; Architectural Institute of JAPAN design standard / recommendation, Bldg-Law; Building Law, Bldg-Recm; Recommendation

- Seismic design against the large earthquake (so called “Shin-taishin:New seismic design regulation ⇒ 2nd phase seismic design”) for superstructure introduced in 1982.
  On the other hand, Seismic design for pile foundations, (only the 1st phase, against medium earthquake) was introduced in The Bldg-Law in 2000.
- It is considered that requiring the seismic design of 2nd phase for the pile foundation deviates from a policy of minimum legislation aiming at human life protection.
1964 Niigata (M7.5) ⇒ Liquefaction damage enormous,

Fig 1 Earthquake Damage Case of Pile Foundation Building
(a) Niigata 1964 Source: (a); Kawamura et al. (1985),

- More than 300 buildings were settled and incline damaged due to liquefaction.
- Some of damaged pile foundation building used for more than 20 years after restoring settlement and inclination without noticing.
- RC 5F apartment with spread foundation layered sideways, but gradually tilted after the shake finished. no human life has been lost.
1.2 Summary of Foundation Damage in the Hyogo ken Yanbu earthquake 1995

◇ Regional distribution of damage caused by piles spreads widely: reclaimed land areas, soft ground areas along coast-line, hilly areas and alluvial topography areas.
◇ Many damage cases of cast-in-place concrete piles which had not been reported so far have also collected. *Bored pile (precast pile): d46+b75=121 (72%), Cast-in-place pile: 35 (20%)
◇ Survey by the Kinki branch of AIJ: 168 cases of pile foundation damage were collected. The damage status (Figure 1 (d)): pile head, over 40%, pile body under the ground; 10%.
⇒ Study on pile design considering the influence of the ground displacement

Fig 1 Earthquake Damage Case of Pile Foundation Building ((c) Pile damage pattern observed

Fig 1(d) Pile damage location (for each pile type)
1.3 Remarkable damage of pile foundation building.

School building built across the landfill part created by pond reclaiming and natural ground.

Source: (a); Kawamura et al. (1985), (b); Nishida et al. (1997)

1st floor columns on the natural ground side were collapsed and 2nd floor fallen down. Researchers point out that the possibility of damaging the pile foundation can cause damage to buildings related to human lives. ⇒ In 1985 Mexico, Building collapsed due to pile destroyed, the human life was spoiled.
## 2. Current Status of Seismic Design of Pile Foundation in Japan

### Table 2 Outline of Pile Foundation design Standards (Seismic design) in Japan

<table>
<thead>
<tr>
<th>Name of Text</th>
<th>(1) Building Standard Law Including relevant enforcement orders &amp; notification</th>
<th>(2) General seismic planning standard for government facility (By Government Buildings Department, Ministry of I.T.)</th>
<th>(3) Recommendation for design of building foundation (By Architectural Institute of Japan: AIJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
<td>Laws and regulations</td>
<td>Specification for design ordering</td>
<td>Recommended guidelines of academic organizations</td>
</tr>
<tr>
<td>Target building</td>
<td>All buildings requiring application for building confirmation</td>
<td>Public facility</td>
<td>General building</td>
</tr>
</tbody>
</table>

#### Seismic design 1st phase (Moderate earthquake)
- It may be described as a shake of about 80 gal in surface acceleration
- Required performance: No damage

| 1) Design method: Allowable stress design |
| 2) Design horizontal force: \( P_{hp} = P_{h0} * (1-\alpha) \) (T1) |
| \( \alpha \): embedding effect (Max. 0.7) |
| \( P_{h0} = P_{h0} + k \cdot Wg \) (T2) |
| \( P_{h0} \): horizontal shear force of the lowest story |
| \( k \): seismic coefficient of basement |
| (0.1 to 0.05 depending on the basement depth) |
| \( Wg \): weight of basement |
| \( P_{ho} = Z - Co \cdot Ws \) (T3) |
| \( Z \): zoning factor |
| \( Co \): Standard shear coefficient (\( \approx 0.2 \)) |
| \( Ws \): weight of superstructure |

**Required performance:** Secure functionality without repairing after severe earthquake

**Can be achieved in this way?**

#### Seismic design 2nd phase (Severe earthquake)
- described as a shake of about 250 gal in surface acceleration
- Required performance: life safety/
- Collapse prevention of superstructure

<table>
<thead>
<tr>
<th>Not required</th>
</tr>
</thead>
<tbody>
<tr>
<td>* except for the slender building which tower ratio would be ( H/B &gt; 4 ), (required to verify the bearing capacity of pile)</td>
</tr>
<tr>
<td>* building height exceeding 60m &amp; isolated structure; requested by the Design Review Committee</td>
</tr>
</tbody>
</table>

**Required by the following condition**

- a) Category 1&2
- b) Height over 31m
- c) Soft surface ground

**Required**

1) Design method: Capacity design
- Horizontal holding capacity
2) Design horizontal force Horizontal capacity of piles foundation \( \geq \) Required capacity of superstructure
3) Design method: Elasto-Plastic Stress Analysis (Push over analysis, etc.)

**Can be achieved in this way?**
(0.0 \leq y \leq 0.1) \quad K_H = 3.16 \cdot k_{h0} \cdot B \cdot H \quad (1) \\
(0.0 \leq y \leq 0.1) \quad K_H = k_{h0} \cdot B \cdot H \quad (1a) \\
(0.1 \leq y) \quad K_H = k_{h0} \cdot y^{-1/2} \cdot B \cdot H \quad (2) \\
K_{h0} = \alpha \cdot \xi \cdot E_0 \cdot B^{-3/4} \quad (3)

Remark: In practice, the expression (1a) is often used instead of the expression (1).

$K_H$ : horizontal springs \( (\text{kN/m}) \), \( y \) : horizontal displacement \( (\text{m}) \)

$k_{h0}$ : coefficient of lateral subgrade reaction \( (\text{kN/m}^2) \)

$k_{h0} \cdot y \leq P_y \cdot P_y$ : Plastic horizontal ground reaction force (see Fig.2)

$B$ : pile diameter \( (\text{m}) \), $H$ : spring interval \( (\text{m}) \), $E_p I_p$ : Flexural rigidity of pile

$\alpha$ : constant according to the evaluation method of $E_0$ \( (\text{m}^{-1}) \)

$\xi$ : pile group coefficient (simple pile foundation to $\xi = 1.0$)

$E_0$ : modulus of deformation of the ground \( (\text{kN/m}^2) \)

1) borehole horizontal loading test (pressurerometer test etc.) : $\alpha = 80$
2) unconfined or triaxial compression test : $\alpha = 80$
3) $E_0 = 700 \text{N}$. ($N$ value of SPT) sand; $\alpha = 80$, clay; $\alpha = 60$

Fig 2  Seismic design model of pile foundation common in practice (leftmost above), the top next; right figure analysis result of P - Y relationship of whole pile, leftmost down; model example of flexural stiffness and subgrade reaction of each pile

Fig 3  Plastic horizontal subgrade reaction force; $P_y$.

Fig 4  Pile-ground model for evaluating the influence of ground displacement in addition to the inertial force of the superstructure. (AIJ (2001))
3. Concept of Target Performance of Pile Foundation

3.1 Difficulty of Restoration of Damaged Pile Foundation

◇ As far as looking back on our past experiences of earthquake damage, it is very unlikely that damage to the pile would cause the building to collapse and endanger human life.  
⇒ When the required performance of the building would be “protection of human life” against large earthquake, there may be no necessity of taking into consideration the seismic performance of pile foundation to the seismic performance of building.

→ We are only having been blessed with the fortune until now?

◇ On the other hand, from the viewpoint of conservation of property, prompt restart of use after the earthquake, and ensuring continuous usability, the seismic design of pile aimed at reducing or preventing damage of pile foundation is significant. And we should always think together with the target performance of the superstructure and foundation.

◇ The important point is that the degree of difficulty of the reinforcement and repair technique of the pile foundation and the cost associated with it are far more enormous than the superstructure.

◇ There is a technical limit to the detection of damage in the underground, even if reinforcement or repair is done, the risk of being damaged again remains. Even though the damage of the superstructure is minor, it is estimated that there are many cases where the building is dismantled due to the damage of the foundation.

◇ The construction method and related data is not sufficient to select whether to repair the foundation of the damaged pile or to dismantle the building. The further research and development are expected very much.
3.2 Survey on Recovery of Damaged Pile Foundation

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(a) Hyogo ken nanbu Erthq. (1995.1.17)

Fig 5 Dismantled / restoration investigation of pile foundation damaged building

- In the year after the earthquake 1995.1.17 occurred, 141 cases of pile foundation damage were collected and 65 cases (46%) answered that restoration work would be carried out, including during on study. ⇒ dismantled is 34 cases (24%), *
- Earthq.2010. recovery ;9 cases(20%) vs. disassembly ;28(60% )
- From the lesson of Earthq.1995, the engineers recognized: the reinforcement of the pile foundation is expensive, it is difficult to reinforce the underground part of pile body and also the risk of damage again after the reinforcement will be not solved.
- Is it possible to guess that the above-mentioned recognition affected the increase in the ratio of demolition?.

(b) Higashi nihon Erthq. (2011.3.11)
3.3 Accountability of Target Performance of Pile Foundation

- It is dangerous to repair and reuse damaged piles unless it is clear that there is no possibility of damage other than the pile head and the underground soundness is guaranteed.

In other words, it is difficult to respond to the request of the builder as maintaining function and resumption of use at an early stage on the conditions which permitted some degree of damage (shear failure and bending crush) to the pile foundation.

Considering that the selection method of seismic performance of pile foundation against large earthquake is not sufficiently clarified, I think that it is important to explain to the builder and form consensus with the builder is very important about the setting of the target performance of the pile foundation which must be performed by the structural designer's own judgment.

- Fig. 6 is an attempt to classify the damage pattern of the pile foundation at the time of the earthquake according to the degree of damage and apply it to the required performance of the assumed building and use it for grading the target performance. (KOBAYASHI (1997))

- A viewpoint to evaluate comprehensive performance by combining the superstructure and the foundation will be further necessary.

- In addition, a research and technical development for reparability (maintain a repairable damage condition) of pile foundation related to damage B (limit of property preservation) shown in the figure is necessary.
Fig 6 Relationship between damage statuses of pile foundation (EQ 95.1.17) and required performance of building (Translation of Kobayashi (2001) in Japanese at the author's responsibility)

More research and technical development for reparable (maintain a repairable damage condition) of pile foundation is necessary.
4. Example of Pile with Enhanced Seismic Performance

4.1 Outline of SPHC Pile

**SPHC pile Specification:**

- **Type of pile:** Prestressed High-Strength Pile (PHC) Covered by Steel Pipe to use as Top Pile as the left
- **Diameter (D):** φ400 ~ φ1300mm
- **Length (L):** 4 ~ 15m (L':3.5 - 14.5m)
- **Steel pile:** SKK & STK 400, 490, ts=4.5 - 22mm σy;235,325 N/mm²
- **Adapted PHC Pile:** φ300 ~ φ1200mm (D-100mm)
  - Prestressed Glade -A, B, C (σPc:4, 8, 10N/mm²)
- **Concrete Strength Fc:** 85, 105, 123N/mm²
- **Grout material:** Cement milk water cement ratio W/C 60%, σc: 27N/mm²

**Fig 6(a) Conceptual diagram**

**Fig 6(b) Full view**
4.2 Seismic performance data-1:

- Structural performance of this pile has been certified by a third party judgment agency

1. **Calculation method** of allowable $M_a$, $Q_a$
   Ultimate Strength $M_u$, $Q_u$

2. **Plastic deformation ability**: $4 \times \phi_y$

$\phi_y$: Curvature to which a steel pipe reaches yield stress.

Design $M$-$N$ correlation diagram with The test load

M-$\phi$ diagram (design & Test)
4.2 Seismic performance data - 2

Fig 6(c) Bending test (M-Φ) SPHC-pile (500φ)

Tensile load N = 500 kN = 1/2 of

※ N = 1000 kN; 2/3 Tu of PHC 400φ (grade C)

Fig 6(d) Status of internal PHC pile after test

After the force test, the steel pipe was peeled off and the damaged state of the inner PHC pile body was confirmed, but only a minute hair crack was observed, and almost no damage occurred.

Test pile: SPHC pile, SteelPipe 500φ, SKK490, ts = 6 mm
PHC pile 400φ (grade C)

Design N-M correlation diagram with the test load
It is said that it can be used continuously after a major earthquake.

Although the target performance of damage prevention has been replaced by verification of the short-term allowable stress degree so far, the damage avoidance limit, (damage limit) can be set for this SPHC pile.

It becomes possible to execute the design based on the new performance limit.

Fig7.(e) SPHC pile Assumed seismic performance

Fig7.(f) PHC pile(connecting below) Assumed seismic performance
5. Conclusion

My personal opinion on the target performance of pile foundation against a major earthquake is presented. As follows.

− When the target performance of a building is protection of “human life”, there may be no necessity of taking the performance of the pile foundation into consideration. It could be negligible to take into count of performance of Pile foundation, Although it is a limitation based on the past experience.

− When the target performance of a building would be “maintain function or resume to use at an early stage “, the performance of the pile foundation against large earthquake should be considered.

− More research and technical development for reparability (maintain a repairable damage condition) of pile foundation is necessary

− Structural engineers should enforce the explanation to the builder about how to set the target performance of the pile foundation so as to satisfy the required seismic performance of the building as with the superstructure.
Appendix: Outline of Two Major Piling Construction Method in Japan

The two major construction methods of pile foundation in Japan:

- **Pre-bored with enlarged base method** for precast concrete piles. (Fig 8(a))
- **the earth drill bottom-enlarged method** for cast-in-place concrete pile (Fig 8(b))

In both methods, to obtain a large vertical bearing capacity,

*the number of constructions/year (roughly); Cast-in-place:1,500 / Bored precast pile: 4,000

(a) **Pre-bored with enlarged base method** (precast concrete pile)

Using precast pile: **PHC** (Prestressed High Strength concrete pile),
**SC** (Steel Composite Concrete Pile), etc.
- Max Diameter 1300mm
- Max bottom bearing Capacity: Ra: 19MPa
- Concrete strength: Fc105,123 N/mm²

*It is mostly adopted in a middle-scale buildings. Since it is factory production, the quality of concrete is stable.
*PHC pile is deficient in ductility by pre-stressing

Fig 8. Construction procedure of two major piling method, part of pile specification
(Pre-bored with enlarged base method for precast concrete piles.)
(b) the earth drill bottom-enlarged method

(cast-in-place concrete pile (Fig 8(b))

Max Diameter 4400mm
Max bottom bearing Capacity: Ra: 43 MPa
Concrete strength: Fc60 N/mm²

*Since large bearing capacity is expectable, it is adopted mostly in high rise buildings.
*In many cases, the digging ground is industrial waste and reservation of the disposal ground poses a problem.
Thank you very much for your attention