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

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Abstract

In this paper, we discuss how to consider the seismic performance of pile foundation when setting the seismic performance of building.First of all, we look back on past earthquake damage of pile foundation in Japan and follow the revision process of related regulations such as building standard law and guidelines that occurred as a result. After that, we will outline the current state of seismic design of piles.

Next, 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 upper structure is not damaged. Although some of researchers and designers have complained about the need to consider large earthquake in seismic design of piles, this is not introduced in the law standard at present, and only when it is executed by voluntary judgment of building owner and structural engineer. Therefore, we mention that it is hard to say that the pile design considering the large earthquake is spreading.

Finally, concluding my personal opinion as follows. Based on the perspective of property protection and function maintenance after the disaster, it is necessary to set the target seismic performance of the building comprehensively by combining seismic performance of the supper structure and the pile foundation, and it is important to explain this setting result to the owner and to get his agreement. Additionally, an example of a construction method that answered reinforcement of seismic performance of ready-made concrete pile foundation, which is one of the issues, was presented.

Introduction

In the Japanese seismic codes, the design for the supper structure 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, with regard to the foundation design, the 1st phase seismic design finally regarded as a legal requirement by the amendment of the law in 2000 and it has reached the present.

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 briefly describe about the past major earthquakes affecting the seismic design of pile foundation, the remarkable seismic event, the revision of law and guideline due to the influence of the seismic damage.

- In the Niigata earthquake of 1964, massive liquefaction damage occurred, and more than 300 buildings were settled and incline damaged. RC walled apartment with spread foundation layered sideways, but gradually tilted after the shake finished, almost no damage to the structure of the building, no human life has been lost.
- Some of the damaged pile foundation buildings were used for more than 20 years after restoring settlement and inclination, and it was found that they were suffering serious damage at the

underground during rebuilding work. Fig. 1 (a) is an example of this. It is suggested that even if pile foundation undergoes major damage, there is a low possibility of damaging the human life, and the underground damage of the pile is likely to be overlooked.

- The damage of pile foundation was noticed since the 1978 Miyagi-oki earthquake. Examination of digging of the head of the pile was conducted, and restoration and reinforcement of pile was also carried out. Prior to that, in the Tokachi - Oki Earthquake of 1968, a lot of serious damage occurred in the RC building, which in turn triggered a major revision of the seismic law in 1981. This is the so-

Table 1. Major Earthquakes Caused Pile Damage in JAPAN and its Effect to Design Practice

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

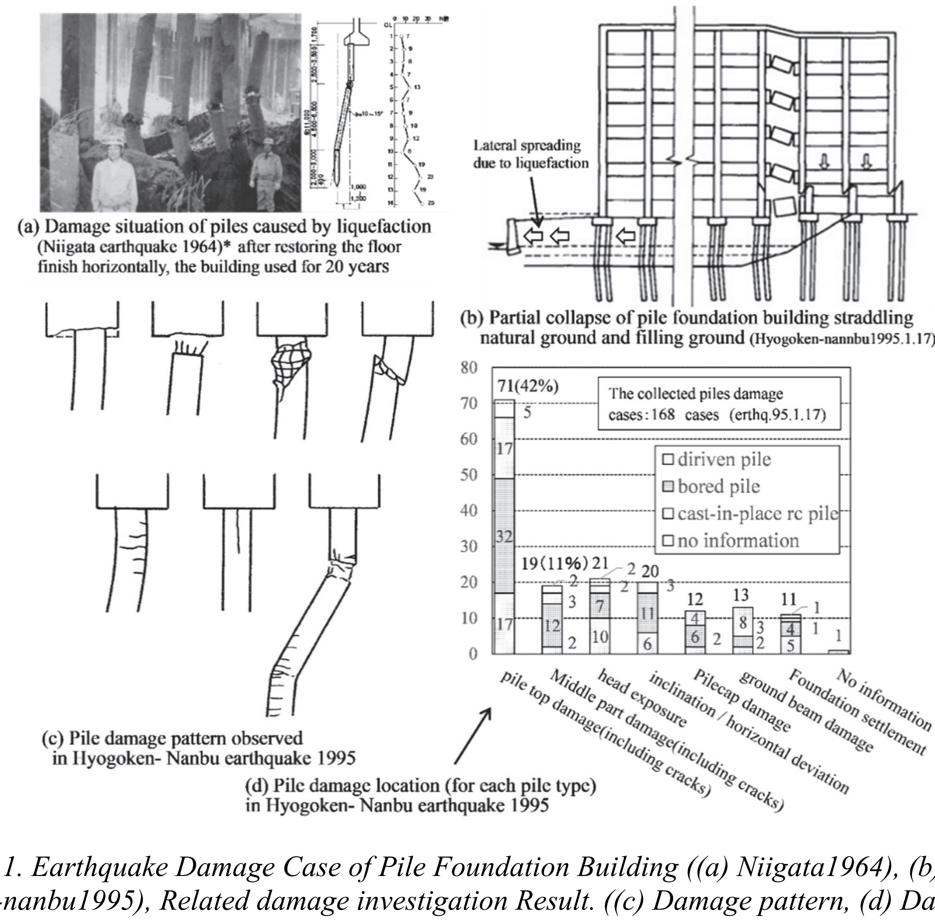


Figure 1. Earthquake Damage Case of Pile Foundation Building ((a) Niigata1964), (b) Hyogo-ken-nanbu1995), Related damage investigation Result. ((c) Damage pattern, (d) Damage Position, (d) Survey of damage position of pile.
Source :(a); Kawamura.et al. (1985), (b); Nishida. et al. (1997)

called "new seismic design method (Shin-Tai-shin)", the 2nd Phase seismic design has been introduced for supper structure, and it has reached today.

- The 1995 Hyogo ken Nanbu Earthquake occurred during this period, and even if unprecedented damage mainly occurred in the old standard building, the new earthquake-resistant design method was judged to be effective. It was the first time in history that pile foundation damages of more than 100 buildings were reported.
- Next, I will touch on the transition of the basic structural design guidelines (originally design standards) of the Japanese Architectural Institute of Japan. In the 1974 revised edition, a simple liquefaction assessment method based on N value is posted as research results after the Niigata earthquake. In addition, as a method for evaluating the horizontal resistance of a pile, the formula of Y.L.Chang by the elastic bearing beam theory and the method of B.B.Broms as the ultimate horizontal bearing capacity equation were described. After the subsequent revision, in the current 2001 edition, the analysis method considering in nonlinearity of the ground and the pile, the evaluation method of the relevant ground constant, etc. are shown as verification of the ultimate limit state. The outline is described in the next section.

1.2 Summary of Foundation Damage in the Hyogo Ken Nanbu Earthquake

- Regional distribution of damage caused by piles spreads to reclaimed land areas with large influence of lateral spreading due to liquefaction and soft ground areas along coastline as well as hilly areas and alluvial topography areas which the support layer is sallow. In addition, many cases of damage to in-place concrete piles which had not been reported so far have also occurred. Figure 1 (c) depicts the damage pattern in reference to each report.
- In the survey of earthquake damage carried out by the Kinki branch of the Institute of Architecture, 168 cases of pile foundation damage were collected. Figure 1 (d) shows the classification result of the damage status by pile type based on this investigation result. It is noteworthy that the damage of the pile head (including cracks) exceeds 40% of the total, but the damage of the pile body under the ground is also confirmed by about 10%.
- Regarding the damage of the underground, it was considered that the influence of ground response due to the earthquake, in addition to the influence of ground displacement due to lateral spreading in liquefaction. Based on this result, the study of the design method considering the influence of the ground displacement was also started.

1.3 Remarkable Damage of Pile Foundation Building. Fig.1 (2) is a case of a five-story school building built across the landfill part created by pond reclaiming and natural ground. At the time of the earthquake, the old pond sedimentary layer of the landfill part liquefied and laterally moved, the pile on the landfill side was damaged and inconsistent settlement occurred. It is explained that this caused the earthquake force to concentrate on the first floor columns on the natural ground side and columns were collapsed and 2nd floor fallen down. It was fortunate that the students have not come to school yet because of the early morning. Researchers point out that the possibility of damaging the pile foundation can cause damage to buildings related to human lives.

In the 1985 Mexico earthquake, it is reported that in reality the pile was destroyed and the building collapsed, the victims went out. I think that it is too optimistic to think that no serious situation will occur in the future because damage related to human life has not occurred in the past

2. Current Status of Seismic Design of Pile Foundation in Japan

2.1 In Case of General Private Building. The (1) column in Table 2 is an outline of seismic regulations of pile foundations for general buildings. No damage to medium earthquake is required performance, and it is secured by allowable unit stress method design. The design horizontal force at that time is evaluated from the equation (T1) to the equation (T3) in the column (1). Seismic force of the base part is evaluated by seismic intensity K and added to shear force of the lowermost floor of the supper structure to be the designed horizontal force of the pile. In addition, the reduction factor α is adopted as rooting effect of the underground part.

In Fig. 2, as a general stress analysis model, a superstructure separated type multilayer ground-pile model is shown. The horizontal spring of the ground is obtained by the equations (1) to (3) based on the coefficient of lateral subgrade reaction kh0, and consideration is given to the nonlinearity of the ground reaction force. However, in the allowable stress design of the 1st phase design, in the case where the horizontal displacement does not greatly exceed 1 cm, there are many cases where the linear spring analysis is adopted by the equation (1a). Although the 2nd phase design is not a legal requirement, it is actually required in buildings that require a review by the Evaluation Committee such as over 60 m high high-rise buildings and base-isolated buildings. In such case, the basic guidelines of AIJ are utilized.

2.2 In Case of the Building of Government and Local Administrative Agency. It is as described in the middle column (2) in Table 2, and the importance coefficient I = 1.5 to 1.0 is introduced for the design seismic force. 2nd phase seismic design of pile foundation is also required for category-1and category-2 buildings of high importance. In this case, the 2nd design seismic force of the foundation is calculated by multiplying the 1st design force by the ratio of the required horizontal holding force of the supper

Table 2. Outline of Pile Foundation Design Standards (Seismic Design) in Japan

Name of Text	(1)Building Standard Law Including relevant enforcement orders & notification	(2)General seismic planning standard for government facility (By Government Buildings Department, Ministry of LIT)	(3)Recommendation for design of building foundation (By Architectural institute of Japan: AIJ)
Characteristic	Laws and regulations	Specification for design ordering	Recommended guidelines of academic organizations
Target building	All buildings requiring application for building confirmation	Public facility	General building
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: $P_{hp}=P_h*(1-α)$ (T1) α: embedding effect (Max.0.7) $P_h=P_{h0}+k*Wg$ (T2) P_{h0}:horizontal shear force of the lowest story k:seiseimic coefficient of basement (0.1 to 0.05 depending on the basement depth H) Wg:Weight ofbasement $P_{ho}=Z*Co*Ws$ (T3) Z:zoning factor Co: Standard shear coefficient (=0.2) Ws:weight of superstructure	1) : same as the left 2)Design horizontal force: $P_{hp}'=P_{hp}*I$ (T1a) *consider the importance factor(I) in the expression on the left category1:I=1.5 category2:I=1.25 category3:I=1.0 category1: Disaster Command Center＆ Disaster base medical / Firefighting facility etc. * Required performance: Secure functionality without repairing after severe earthquake	1)Design method: resembling the limit state design(LRFD) the damage limit design of this Recommendation corresponds to the seismic phase-1 2)Design horizontal force: design load of seismic phase-1 is applicable 3) Details of design: Explanation on evaluation method of ground resistance and elasto-plastic properties of pile body
Seismic design2nd phase (severe earthquake) described as a shake of about 250gal in surface acceleration Required performance: life safety/ Collapse prevention of superstructure	Not required * except for the the slender building which tower ratio would be H/B>4, (required to verify the bearing capacity of pile) * building height exceeding 60 m & isolated structure: requested by the Design Review Committee	Required by the followin condition a) Category1&2 b) Height over 31m c) Soft surface ground 1) Design method: Capacity design (Horizontal holding capacity) 2) Design horizontal force Horizontal capacity of piles foundation ≧Required capacity of superstructure 3)General analysis method: Push over analysis	Required 1) Design method: Capacity design 2) Design horizontal- force Not clear Designer should set by himself 3)Design method: Elasto-Plastic Stress Analysis (Push over analysis,etc.)

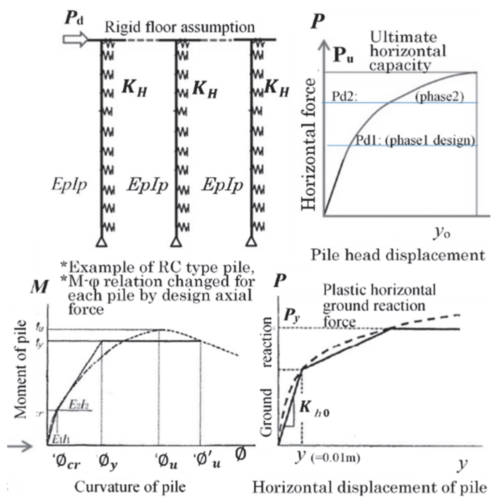
structure of 1st floor and its 1st design horizontal force. It is explained that the required performance of category-1and category-2 can be used without repairing or even requiring major repair even after a large earthquake which is assumed in 2nd phase seismic design.

2.3 Method of AIJ Foundation Design Guidelines. Although it is a guideline for the LRFD design system, it is not used for practical. However, an evaluation method of ultimate horizontal strength of pile foundation is shown, and as shown in Fig.3, the calculation method of the plastic lateral subgrade reaction force is also described, it is used as a reference material.

The evaluation method based on the response displacement method as shown in Fig. 4 is also shown for the influence evaluation of the response displacement of the ground which was one of the subject in the Hyogo ken Nanbu earthquake. This guideline is planned to be revised in 2019, and the method of evaluating the ultimate strength of the pile foundation is also aimed largely.

3. Concept of Target Performance of Pile Foundation

3.1 Difficulty of Restoration of Damaged Pile Foundation As far as looking back on past experiences of earthquake damage, it is very unlikely that damage to the pile will cause the building to collapse and endanger human life at risk. Therefore, in order to satisfy the "protection of human life" as the required performance of the building, the condition for setting the target performance to the pile foundation is limited to the very special case.



$(0.0 \le y \le 0.1)$ $\quad K_H = 3.16 \cdot k_{h0} \cdot B \cdot H$ (1)

$(0.0 \le y \le 0.1)$ $\quad K_H = k_{h0} \cdot B \cdot H$ (1a)

$(0.1 \le y)$ $\quad K_H = k_{h0} \cdot y^{-1/2} \cdot B \cdot H$ (2)

$K_{h0} = \alpha \cdot \xi \cdot E_0 \cdot B^{-3/4}$ (3)

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

K_H : horizontal springs (kN/m), y : horizontal displacement (m)

k_{h0} : coefficient of lateral subgrade reaction (kN/m^3)

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

B : pile diameter(m) , H : spring interval(m), E_pI_p: Flexural rigidity of pile

α : constant according to the evaluation method of E_0 (m^{-1})

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

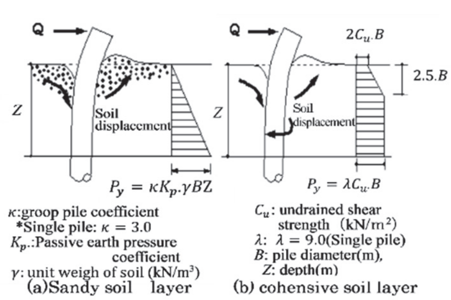
E_0 : modulus of deformation of the ground (kN/m^2)

1) borehole horizontal loading test (pressuremeter test etc.) : $\alpha = 80$

2) unconfined or triaxial compression test : $\alpha = 80$

3) $E_0 = 700N$, (N value of SPT) sand; $\alpha = 80$,clay; $\alpha = 60$

Figure 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.



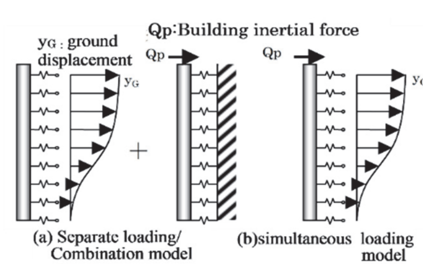


Figure 3. Plastic horizontal subgrade reaction force; Py. Fig 4 Pile-ground model for evaluating the influence of ground displacement in addition to the inertial force of the superstructure. (AIJ (2001).

Meanwhile, from the viewpoint of conservation of property, prompt restart of use after the earthquake, and ensuring continuous usability, the seismic design aimed at reducing damage or preventing damage to the pile foundation is significant, and we should always think together with the target performance of the supper structure 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.

In addition, as mentioned above, there is a technical limit to the detection of damage in the underground, even if reinforcement or repair is done, the risk of the damage again remains. Even though the damage of the supper structure is minor, it is estimated that there are many cases where the building is dismantled due to the damage of the foundation. Unfortunately, it is hard to find technical solution method and construction data for choosing whether to repair the foundation of the damaged pile or to dismantle the building, and we must expect future research and development.

In the next section, we will introduce the contents of the pile foundation restoration survey conducted after the Hyogo ken Nanbu Earthquake, etc. for reference.

3.2 Survey on Recovery of Damaged Pile Foundation Fig. 5(a) shows the results of the survey carried out by the AIJ Kansai branch after the Hyogo ken Nanbu earthquake1995. In the year after the earthquake 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.

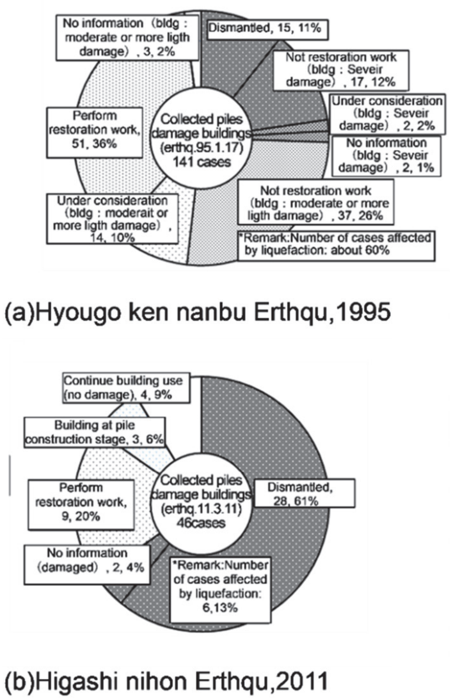


Figure 5. Dismantled / restoration investigation of pile foundation damaged building (EQ1995&2011).

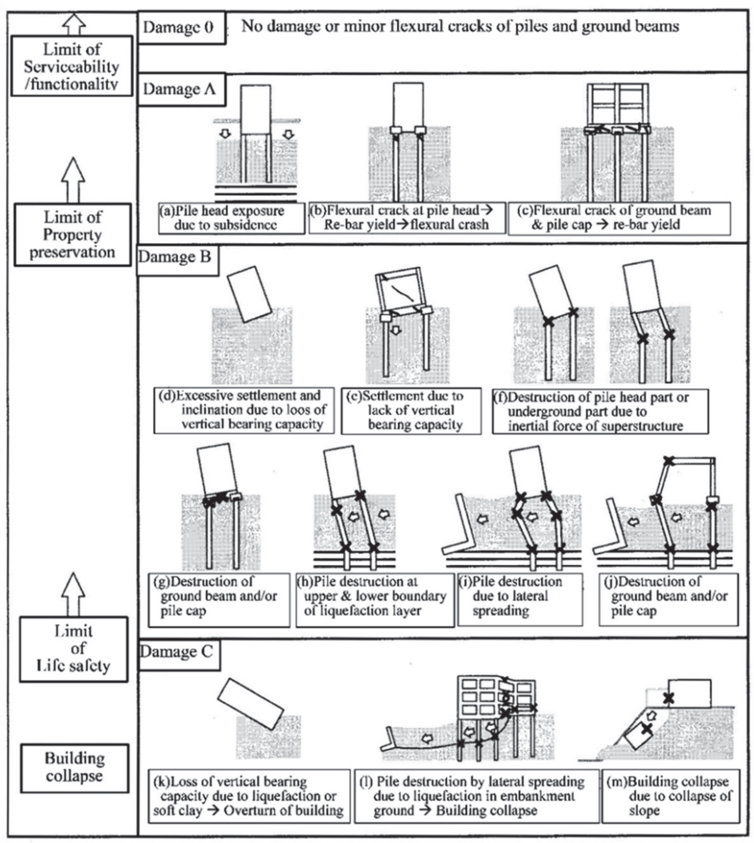


Figure 6. Relationship between damage statuses of pile foundation (EQ 95.1.17) and required performance of building. (Translation of Kobayashi (2001) in Japanese at the author's responsibility.)

On the contrary, dismantled is 34 cases, if predicting disassembly real number by adding answers such as not being restored by wrecking. In addition, in the subsequent Inoue et al. (1997) summary, 227 cases of foundation damage were collected and 129 cases of pile foundation were reported. As for the restoration contents, it is understood that it is limited to the correction of the subsidence, the inclination and the restoration and reinforcement of the pile head.

Fig. 5(b) shows the results of a survey of damage caused by pile foundations in the 2010 East Japan Great Earthquake. Although the number of damaged buildings by this earthquake is overwhelmingly small, it is difficult to compare, but in the number of damaged cases occurred in the pile, the recovery is 9 cases and the disassembly is cases more than 60% from 28 cases. Understanding the difficulty of comparing both results, I tried to boldly examine this difference. It is hard to say that the breakthrough epoch-making reinforcement technology was developed in the past 15 years. As a lesson from the case of the Hyogo ken Nambe Earthquake, the engineers recognized the reinforcement of the pile foundation to be expensive, the reinforcement difficult except for the pile head, and also the remaining risk of the damage after the reinforcement. It is estimated that the above has influenced the difference.

3.3 Accountability of Target Performance of Pile Foundation It is dangerous to repair and reuse affected 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 owner as maintaining function and resumption of use at an early stage with permits 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 major 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 supper structure and the foundation will be further necessary. In addition, as a research subject, further investigation on repairability of pile foundation related to damage B (limit of land conservation) shown in the figure is necessary.

4. Example of Pile Construction Method with Enhanced Seismic Performance

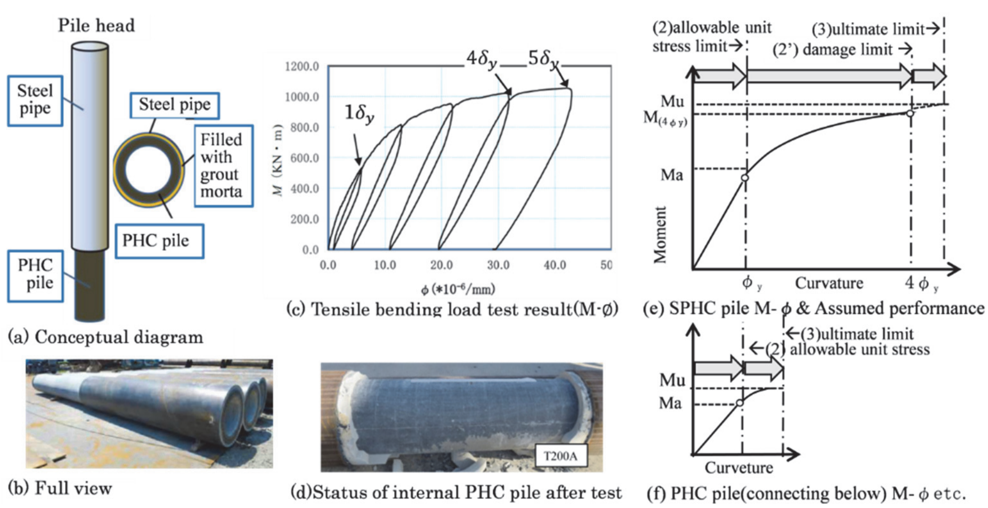


Fig 7. Outline of SPHC pile, its loading test result, seismic performance, (Kakurai(2014,2017))

The outline of the SPHC pile is shown in Fig. Cover the PHC pile with a steel pipe and fill it with grout to manufacture it. Used as the top position pile of ready-made pile foundation. Regarding deformation performance, it has been certified by a third party judgment agency that it has been verified by the axial force bending load test that it has a stable capacity holding ability up to a curvature four times the yield point curvature. It is an extremely effective pile for quake resistant secondary design of piles. Moreover, 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. 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 can be set for this pile, and it becomes possible to execute the design based on the new performance limit. Figures 7 (c) and (f) show the difference in seismic performance with PHC pile.

5. Conclusion

I mentioned my personal opinion on the target performance of pile foundation against a major earthquake. Finally, I would like to appeal to the structural engineer on the enforcement of 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 supper structure.

Appendix Outline of Two Major Piling Construction Method in Japan

The two major construction methods of pile foundation in Japan are the earth drill bottom-enlarged method for cast-in-place RC pile (Fig8(b))and pre-bored with emlargd base method for ready-made concrete piles.(Fig8(a)) In both methods, to obtain a large vertical bearing capacity, the pile diameter of tip is enlarged or the excavation diameter of the tip is increased. Because of the maximum tip pile diameter is 4.8 m, the former method is suitable for high-rise building.and latter method have 1.3 m as max.daimeter and which is widely used for midle and low-rise building. In the seismic performance, the former is regarded as dominant. It is roughly estimated that the number of constructions per year is 1,500 for the former and 4000 for the latter.

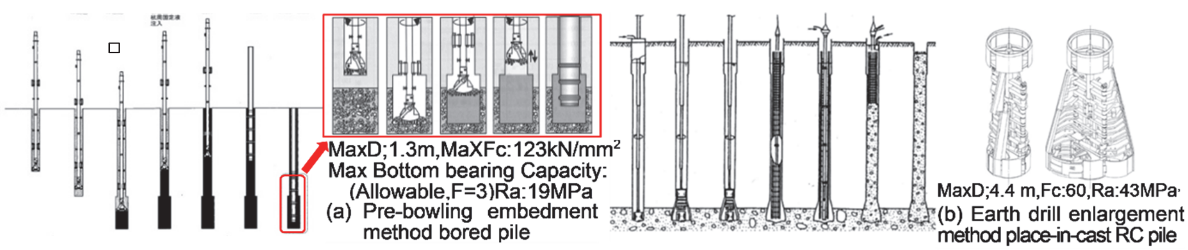


Fig 8. Construction procedure of two major piling method, part of pile specification

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