Damage Factor of the School Building which Suffered the Damage on Pile Foundation

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***Abstract*— In this study, a school building damaged in the pile foundation in 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake was analyzed. The purpose of this study is to obtain the knowledge for making preventive measures against damage of the pile foundation by examining damage factors.**

An analysis object is a 3-story RC building with pile foundation. Pushover analysis was carried out. Superstructure model, substructure model and super-and-sub structure model were used for the analysis.

From the Comparison between the analysis result and actual damage, the following damage factors were obtained. Shear force of each pile is different depending on the location of the pile. Shear force of the pile under the shear walls is higher than others. Stress and deformation are concentrated at the upper part of the pile due to the characteristic of the ground surface.

Keywords*— *Pushover Analysis, Reinforced Concrete, 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake, Pile Foundation, Super-and-Sub Structure Model

I. INTRODUCTION

Many buildings were damaged in pile foundation in 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake as in [1]. In the Building Standard Law of Japan, the superstructure is obliged to design for large earthquakes, whereas the substructure is not obliged to design for large earthquakes in [2]. Even if the substructure fails, people's lives are saved. However, when substructure is damaged, it is difficult to use a building continuously. In particular, buildings used as place of refuge have to work after large earthquakes. Therefore, the substructure must be obliged to design for large earthquakes in the future.

In this study, a school building damaged in the pile foundation in 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake was analyzed. The purpose of this study is to obtain the knowledge for making preventive measures against damage of the pile foundation by examining damage factors. As shown in figure 1, plan and result of pushover analysis of superstructure model, substructure model and super-and-substructure model are described.

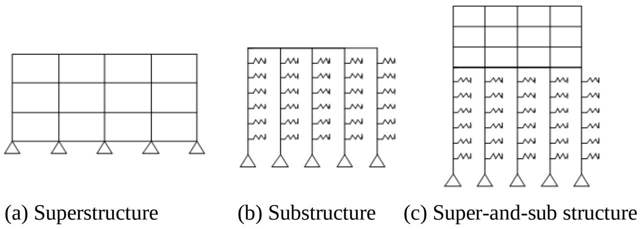


Fig. 1. *Analysis model*

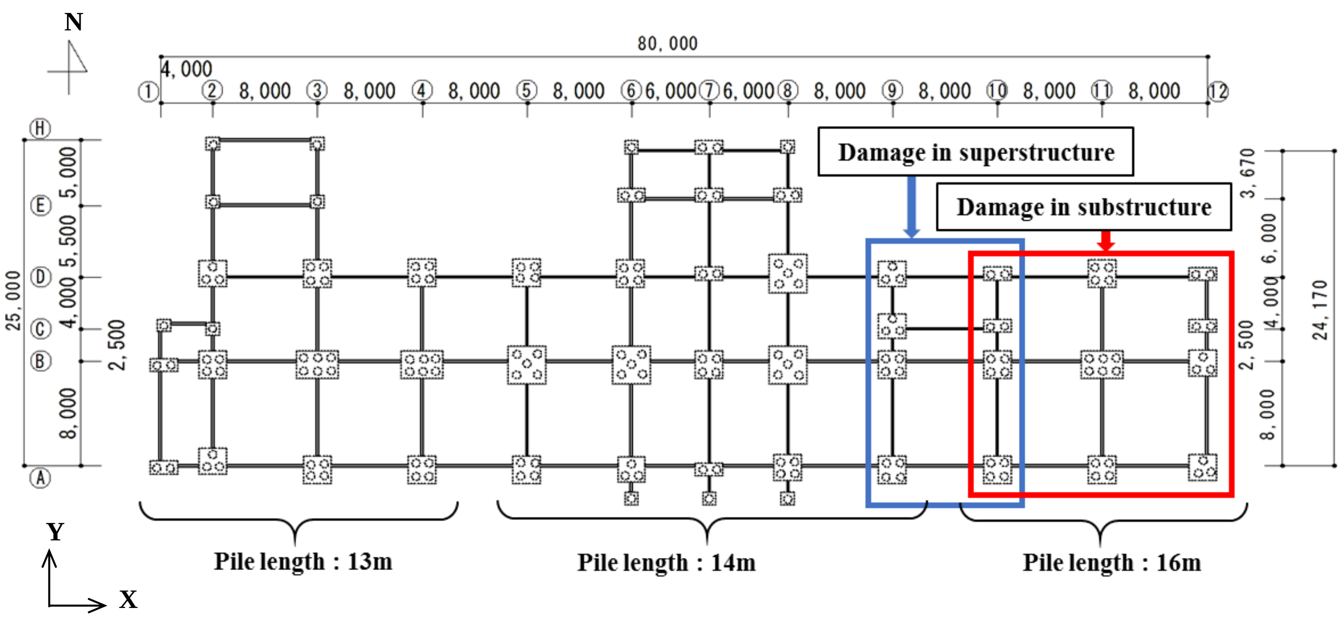
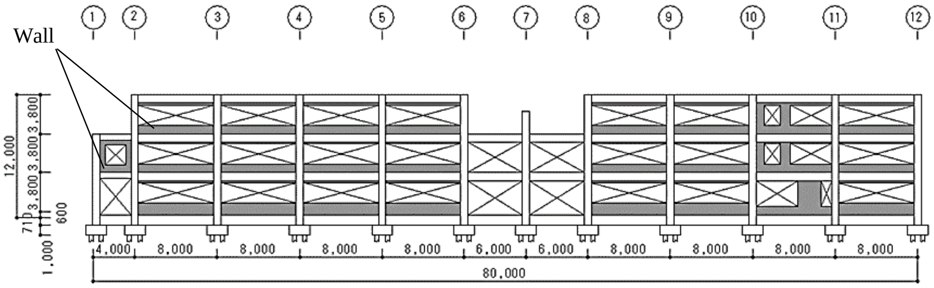
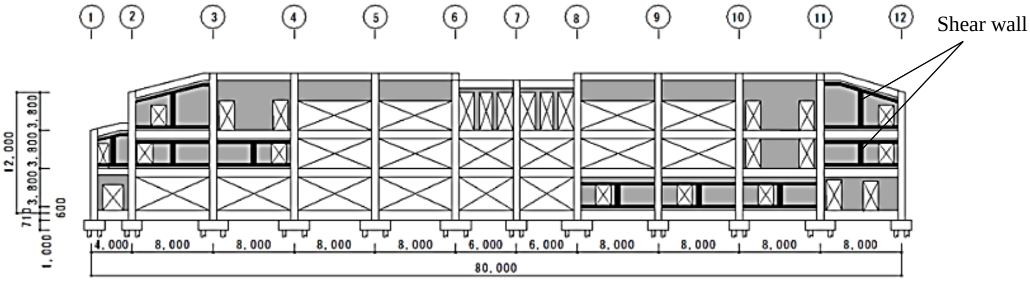


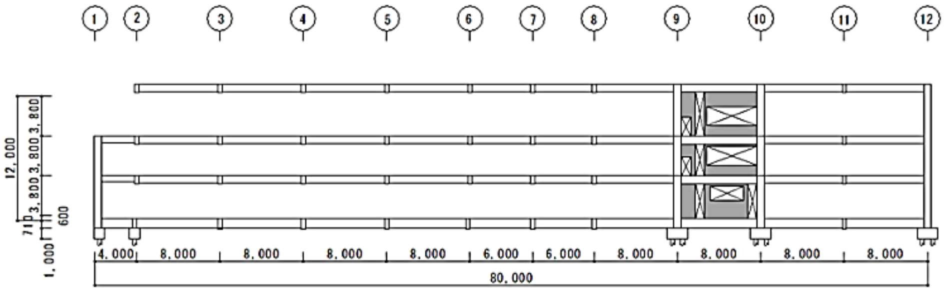
Fig. 2. *Pile foundation plan*



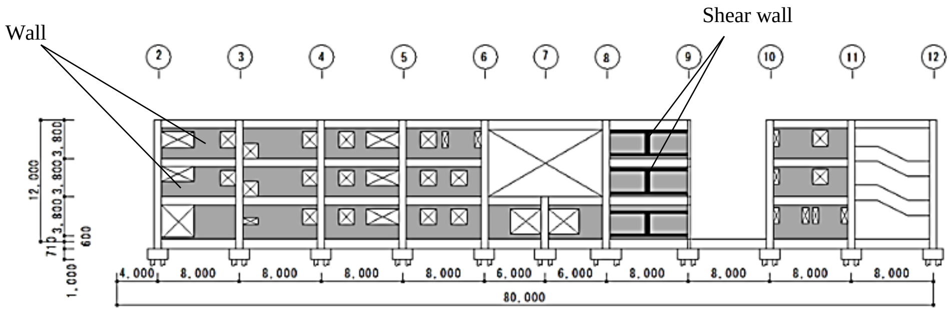
(a) Axis A



(b) Axis B



(c) Axis C



(d) Axis D

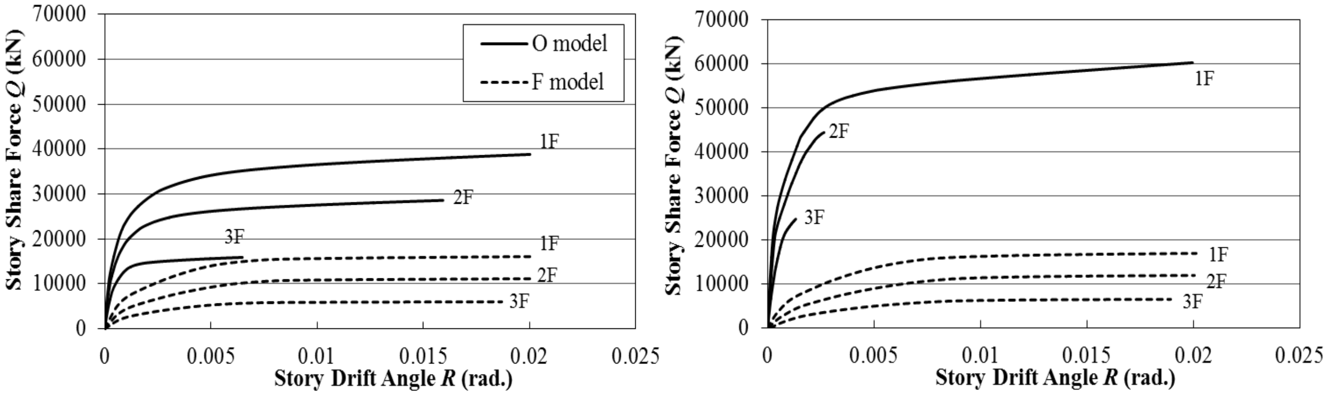
Fig. 3. *Framing elevation*

II. Overview of the Building

Figure 2 shows a pile foundation plan and figure 3 shows the framing elevation. An analysis object is a 3-story RC building with pile foundation. The building do not have basement floor. The building has the frame structure in X direction and the frame structure with shear walls in Y direction. The most of walls of the building have openings. The pile is PHC pile (B type) 400 φ is used for the piles. The length of piles of the building are 13 m (Axis 1 to 4), 14 m (Axis 5 to 9) and 16 m (Axis 10 to 12). The ground are classified into 3 strength class, from level 1 to level 3 in Japan. The building stands on the level 2 ground. Level 2 ground is classified as intermediate strength ground. The damage of the building in 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake are as follows. Slight cracks occurred in the columns and the walls at Axis 9-10 in the superstructure. On the other hand, compressive failure occurred in the pile head at Axis 10-12 in the substructure. Furthermore, the east side of the building (Axis 9 to 12) was sunk. Liquefaction was not observed.

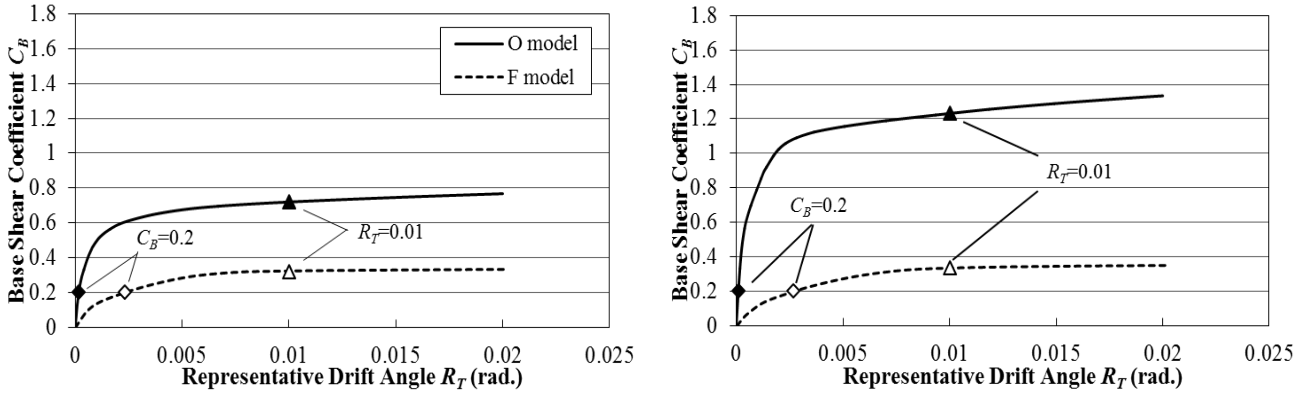
III. Superstructure Analysis

Analysis of superstructure was discussed in previous study as in [3]. In this chapter, analysis plan and result are described.



(a) X direction (b) Y direction

Fig. 4. *Shear force* (Q) *- story drift angle* (R) *relationship*



(a) X direction (b) Y direction

Fig. 5. *Base shear coefficient* (C_B) *- representative drift angle* (R_T) *relationship*

A. Analysis Plan

Frame model is used in the superstructure analysis. Frame model has the line member of columns and beams. The end spring model is applied to the beam members. The end spring model has the tri-linear skeleton curve which consider flexural cracking point and flexural yield point. The multi-spring model is applied to the column members. The shear walls are replaced with the line members and the end spring model is applied. Nonstructural walls are considered only their own weight. The other walls are replaced with the spandrel wall of the side beam and the hanging wall of the side beam, and the wing wall of the side columns. And they are considered as stiffness and strength of side beams and side columns. And the stiffness and strength of spandrel wall, hanging wall and wing wall are add to the stiffness and strength of beam and column. Since the slab is the dirt floor concrete structure, the second floor and the third floor are supposed to be rigid. The horizontal force distribution which is based on the Ai distribution as in [2] is used for the pushover analysis. The analysis is terminated when the maximum story drift angle reached 0.02 rad. Two analysis models, O model and F model, are constructed. No modification of the building is in O model, while all of the walls removed from the building in F model. For each model, 8cases of analysis are carried out the positive and negative loading are applied in X direction and Y direction There is almost same between positive and negative results. Therefore the result of the positive loading and 4 cases are shown.

B. Analysis Result

1) The story shear force (Q) - story drift angle (R) relationship: Figure 4 shows the story shear force (Q) - story drift angle (R) relationship. A solid line indicates O model, and a broken line indicates F model. In X direction, the story shear force of the first floor of O model is about 2.2 times larger than that of F model at R = 0.02 rad.. Because the building has many walls with openings in X direction. The strength of O model is much larger than that of F model which removed all the walls. Also, in Y direction, the story shear force of the first floor of O model is about 3.5 times larger than that of F model at R = 0.02 rad..

2) The base shear coefficient (C_B) - representative drift angle (R_T) relationship: Figure 5 shows the base shear coefficient (C_B) - representative drift angle (R_T) relationship. A solid line indicates O model, and a broken line indicates F model. The representative drift angle (R_T) is calculated by δ/h (where, δ means 3rd floor displacement, h means height from1st floor to 3rd floor). In X direction, the base shear coefficient of O model is about 2.2 times larger than that of F model at R_T = 0.01 rad.. Also, in Y direction, the base shear coefficient of the O model is about 3.7 times larger than that of F model at R_T = 0.01 rad..

3) Shear force acting on the pile head: Figure 6 and figure 7 shows the ratio of shear force acting on the pile head in X direction and Y direction, respectively. The ratio of shear

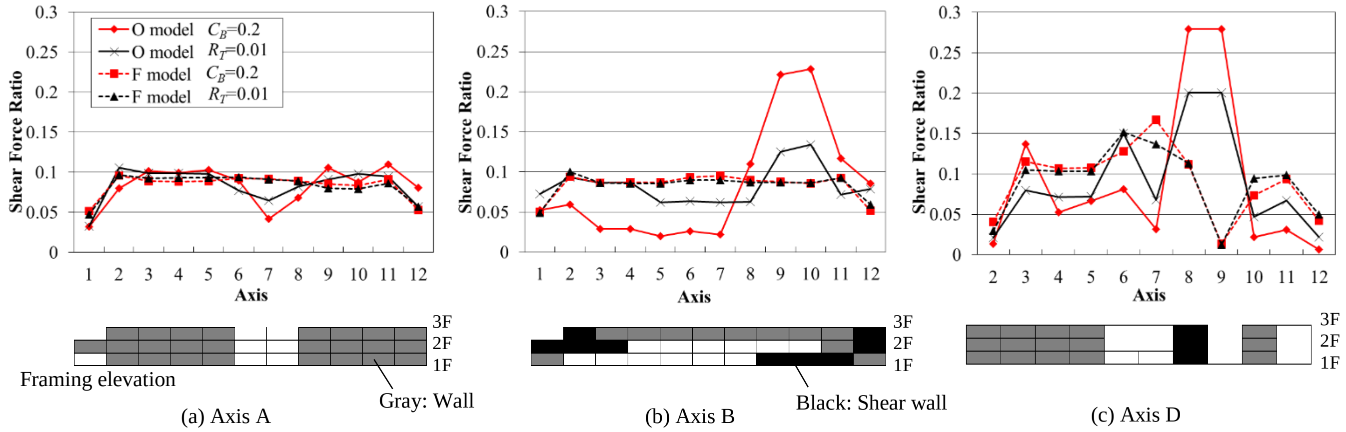


Fig. 6. *The ratio of shear force acting on the pile head* (*X direction*)

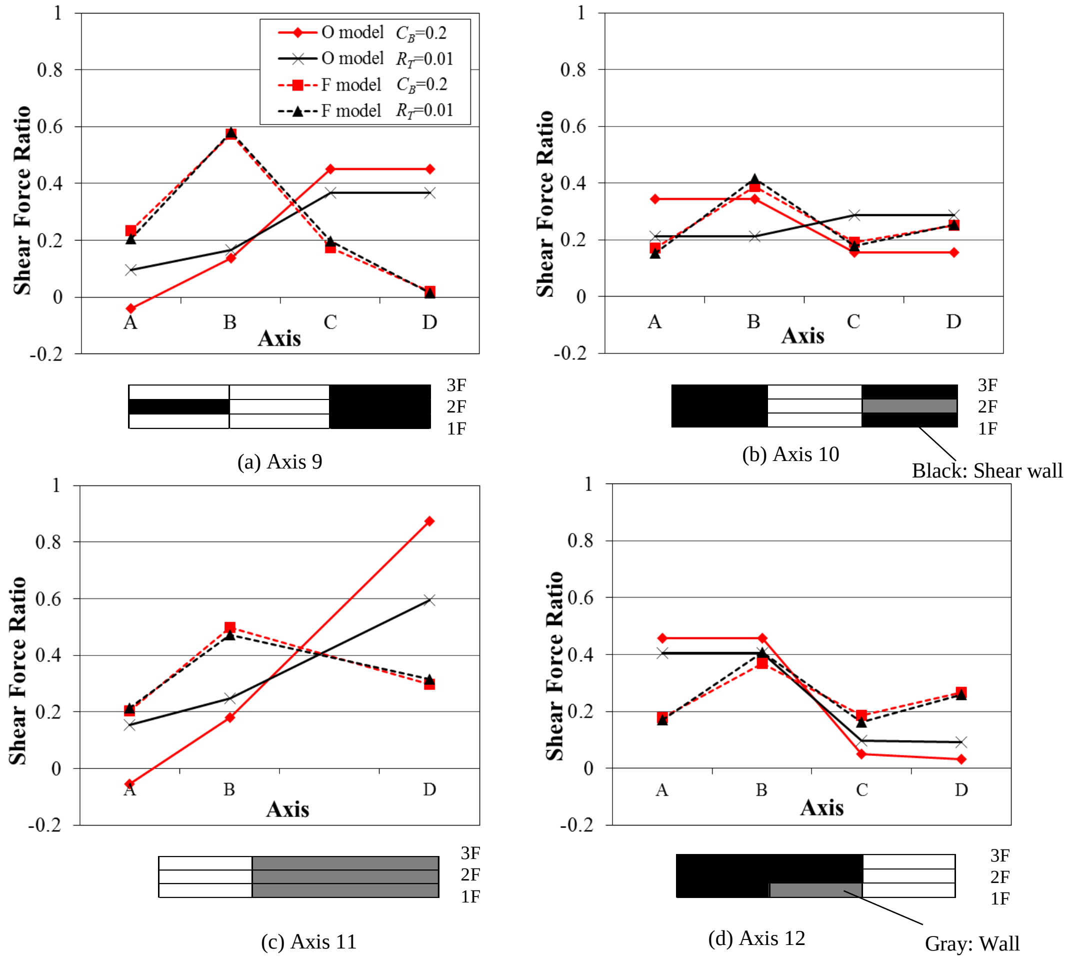


Fig. 7. *The ratio of shear force acting on the pile head* (*Y direction*)

force is obtained by dividing the shear force of each node by the total shear force of each axis. The shear force acting on the pile head is supposed as the horizontal reaction force of pin support of the superstructure and does not include the inertial force acting on the footing part. In X direction, O model has a tendency that the burden of shear force at the pile under the shear wall increases at C_B = 0.2. The burden of shear force on the east side of the building (Axis 8 to 11) is large. The result might displayed that the damage of the pile head occurred on the east side (9 to 12 streets) of the building.

IV. Substructure Analysis

A. Analysis Plan

In the substructure, pushover analysis of a single pile model is carried out and axial force and shear force acting from the superstructure are considered. Figure 8 shows soil boring log and figure 9 shows a single-pile model. From figure 8, it is understood that the ground surface portion is soft at A, B and C. Pile foundation is designed by method against moderate earthquake. A single pile model is used and it is divided into longitudinal elements of 100 cm length each.

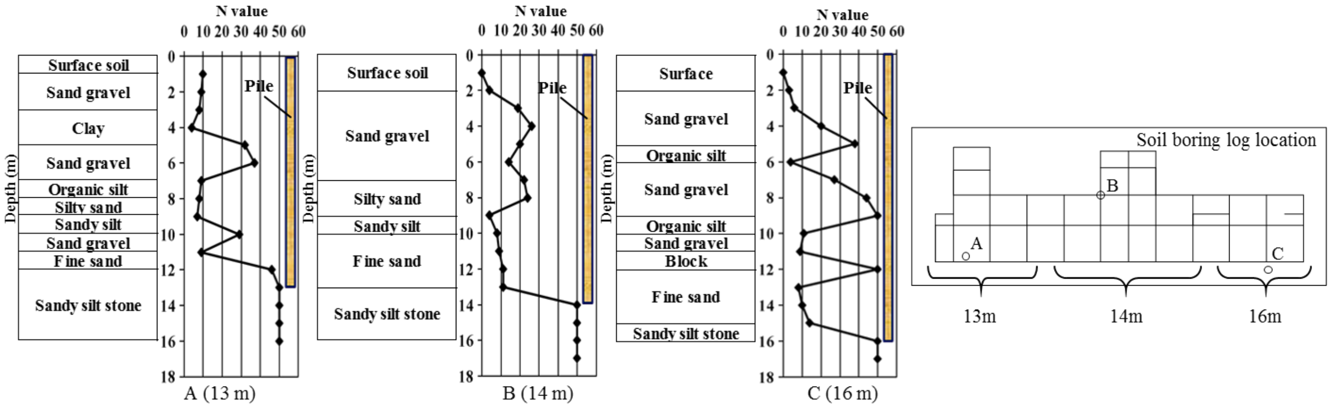


Fig. 8. *Soil boring log*

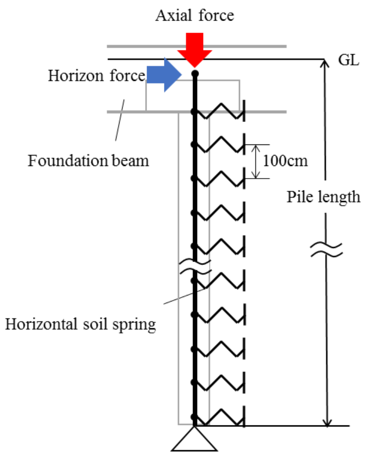


Fig. 9. *Single-pile model*

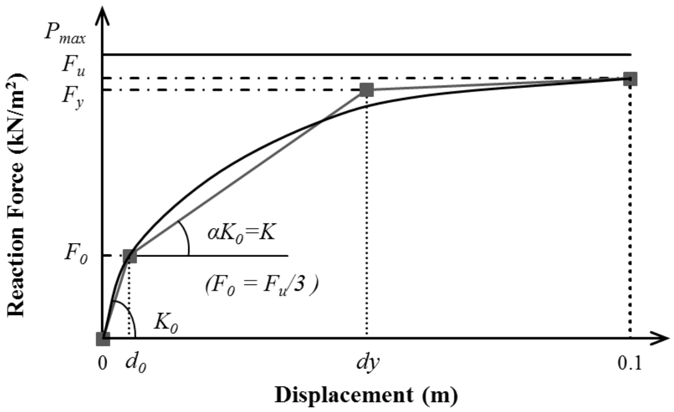


Fig. 10. *The skeleton curve of the horizontal soil spring*

The fiber model is applied to the pile cross section and the pile cross section was divided into 36 elements. Horizontal soil springs are attached to the node of the longitudinal element of the pile, and the pile end supported by pin. In this model, the pile length is defined as the length from the ground surface to the tip of the pile. Figure 10 shows the skeleton curve of the horizontal soil spring.

Horizontal soil springs are obtained by the following method as in [4].

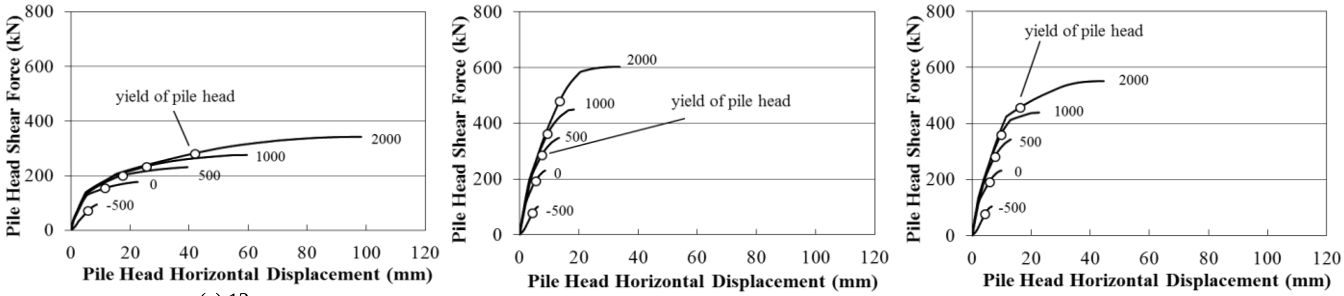
- Calculate the limit ground reaction force (P_{max}) in the horizontal direction.
- Draw a curve representing the horizontal ground reaction force (P) - horizontal displacement (d) relationship
- Suppose that the ground reaction force at $d = 0.1$ m is "F_u".
- Suppose that $F_u/3$ is the ground reaction force "F_c" of the first characteristic point.
- Set the stiffness after the second characteristic point to 1/1000 of the initial stiffness.
- Determine the second characteristic point when the area of skeleton curve equal to the area of the trilinear skeleton.
- Get the plastic ground reaction force from the ground reaction of the second characteristic point.

The ground constants used for the analysis are obtained from [5]. Three single pile models are constructed. These models have pile lengths of 13 m, 14m and 16 m. The procedure of the pushover analysis is as follows. Constant axial forces (-500 kN, 0 kN, 500 kN, 1000 kN, 2000 kN, positive means compression, negative means tension) are applied to each model. The horizontal force corresponding to the inertial force of the superstructure is applied to the foundation beam position. The analysis is terminated when the pile almost demonstrate the maximum yield strength.

B. Analysis Result

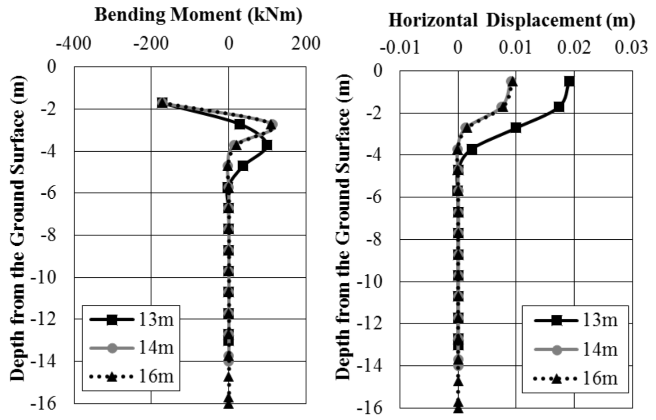
1) Pile head shear force - pile head horizontal displacement relationship: Figure 11 shows pile head shear force - pile head horizontal displacement relationship. The circle marks in the figure indicate the yield of the pile head. It is assumed that the pile head yielded when the outermost reinforcement bar of the pile head yielded. Comparison of pile head shear forces subject to axial force of 2000 kN is conducted. Maximum pile head shear force is about 350 kN for "13 m pile", about 600 kN for "14 m pile", about 550 kN for "16 m pile". The shear force of the pile head yield is about 300 kN for "13 m pile", about 500 kN for "14 m pile" and about 450 kN for "16 m pile". The shear force of the pile head for "16 m pile" is the smallest.

2) Distribution of bending moment and horizontal displacement of pile: Figure 12 shows Distribution of bending moment and horizontal displacement of pile (Axial force =500 kN). Figure 13 shows the distribution of the initial stiffness of the ground and the distribution of the plastic ground reaction force. Bending moment and horizontal displacement increase with larger compressive axial force.



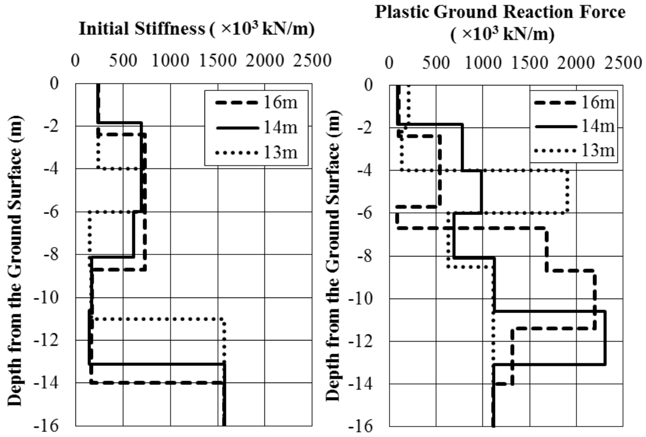
(a) 13m (b) 14m (c) 16m

Fig. 11. *Pile head shear force - pile head horizontal displacement relationship*



(a) Bending moment (b) Horizontal displacement

Fig. 12. *Distribution of bending moment and horizontal displacement of pile (Axial force =500 kN)*



(a) Initial stiffness (b) Plastic ground reaction force

Fig. 13. *Distribution of the initial stiffness of the ground and the distribution of the plastic ground reaction force*

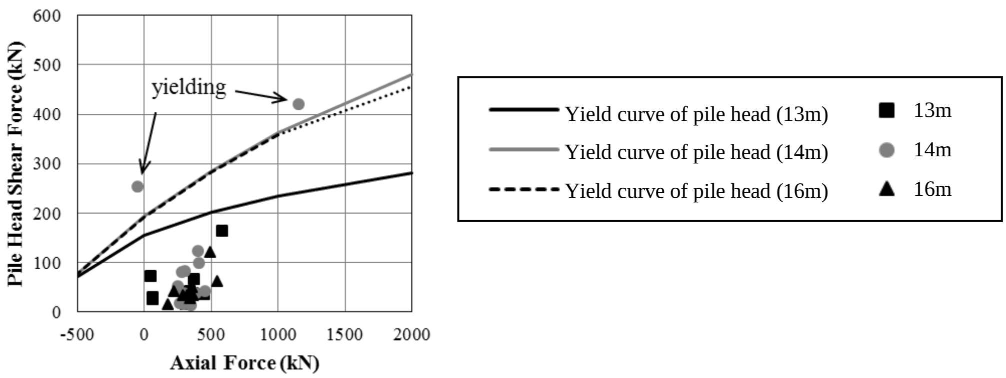


Fig. 14. *Shear force and axial force of pile head*

The bending moments of three piles are maximum at the point of nearly 4 m depth from the ground surface. The bending moment of "13 m pile" and "16 m pile" are almost 0 kN･m at the point of 6 m depth and more. The bending moment of "14 m pile" are almost 0 kN･m at the point of 5 m depth and more. In addition, horizontal displacement of each pile is nearly 0 m at the point of 5 m depth and more. As shown in figure 7, both the initial stiffness of the ground and plastic ground reaction force increases at the point of 4 m for "13 m pile" and that increases at the point of 2m for the other two piles. Therefore, the shear stiffness of the "13 m pile" is lower than that of the other two and the bending moment and the horizontal displacement distribute widely.

3) Pile head shear force - axial force relationship: Figure 14 shows the pile head shear force - axial force relationship. Lines in the figure indicate the yielding curve of the pile head, and dots in the figure indicate the result obtained by the superstructure analysis. Result of the superstructure analysis represents the pile head shear force and axial force acting on the single pile. Shear force corresponding to the seismic intensity 0.1 is added to the shear force of each pile considering the external force acting on the footing. The pile heads are yielded at the stress concentrated position (axis 8 and axis 9 on axis D) due to the influence of the shear walls. However the other pile head did not yield by the stress obtained from the superstructure analysis. It is thought that the influence of ground deformation was not consider in this substructure analysis and the possibility that stress obtained by the superstructure analysis was smaller than the stress in actual earthquake.

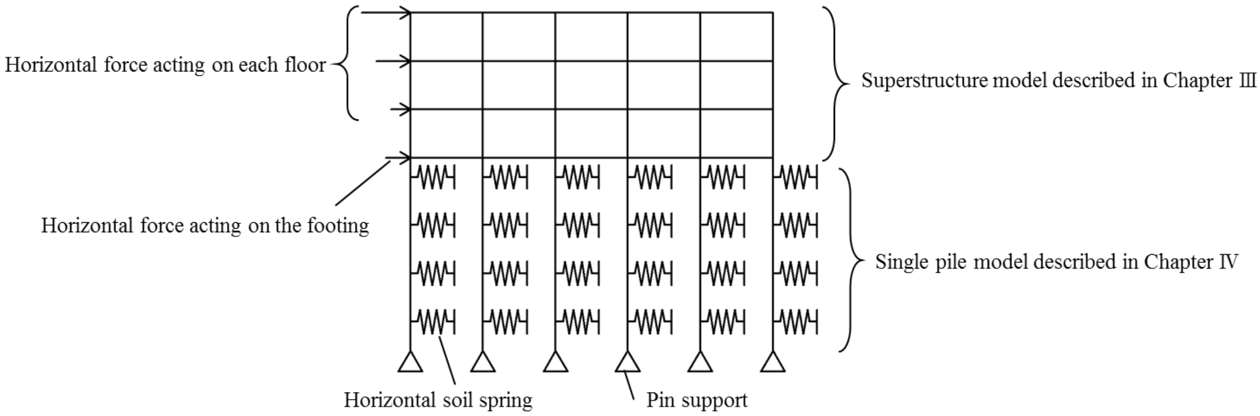


Fig. 15. *The outline of the super-and-sub structure model*

TABLE 1: *ANALYSIS CASE*

Model	Settings (1)	(2)	(3)	(4)	Commentary	X	Y
Io	-	-	-	-	Original model	✓	✓
I_{SM}	○	-	-	-	Supposed that there is no horizontal ground resistance of the ground surface	✓	
I_{SH}	-	○	-	-	Considering the accuracy of modeling the soil spring	✓	
I_{K2}	-	-	○	-	Considering the evaluation accuracy of the horizontal force acting on the footing	✓	
I_{K4}	-	-	-	○		✓	
I_{K2}'	○	○	○	-	Conbination of (1)、(2) and (3)	✓	
I_{K4}'	○	○	-	○	Conbination of (1)、(2) and (4)	✓	✓

*(1) The stiffness of the horizontal soil spring at the node under the pile head is almost zero
(2) Halving the stiffness and reaction force of horizontal soil spring
(3) Doubling horizontal force acting on the footing
(4) Quadrupling horizontal force acting on the footing

V. SUPER-AND-SUB STRUCTURE ANALYSIS

A. Analysis Plan

The super-and-sub structure model is constructed by combining the substructure model with the superstructure model. Figure 15 shows the outline of the super-and-sub structure model. Analysis is conducted for X direction and Y direction, and then the actual damage compared with the damage estimated by the analysis. The pushover analysis is carried out according to the analysis case shown in Table 1. Io model is the original model just combined superstructure model and substructure model used in chapter 3 and 4. In I_{SM} model, the stiffness of the horizontal soil spring at ground surface is set to almost zero to consider that N value of the ground surface is fairly small. In I_{SH} model, the stiffness and reaction force of the horizontal soil spring is set to half to consider the evaluation accuracy of the horizontal soil spring. In I_{K2} model and I_{K4} model, Seismic force acting on the footing are double and quadruple compared with Io model consider the evaluation accuracy of the seismic force acting on the footing. In I_{K2}' model, setting of Io model, I_{SM} model and I_{K2} model are applied simultaneously. In I_{K4}' model, setting of Io model, I_{SM} model and I_{K4} model are applied simultaneously. In X direction, analyses of all models are conducted. In Y direction, the analysis of Io model and analysis of I_{K4}' model which can simulate the actual damage situation well in X direction is conducted.

B. Analysis Result

1) The story share force (Q) - story drift angle (R) relationship: Figure 16 shows the story shear force (Q)-story drift angle (R) relationship. It is supposed that slight cracks occur in the building at C_B=0.2 in the analysis. It is assumed the actual damage of this building under the earthquake corresponds with the damage of analysis model at C_B = 0.2.

a) X direction: When the story drift angle of the first floor is about 0.003 radian. Because the pile head yielded and the unbalance force increased before yielding of the superstructure, the analysis was terminated. The story drift angle of each story in the superstructure at C_B = 0.2 are about 0.0005 radian.

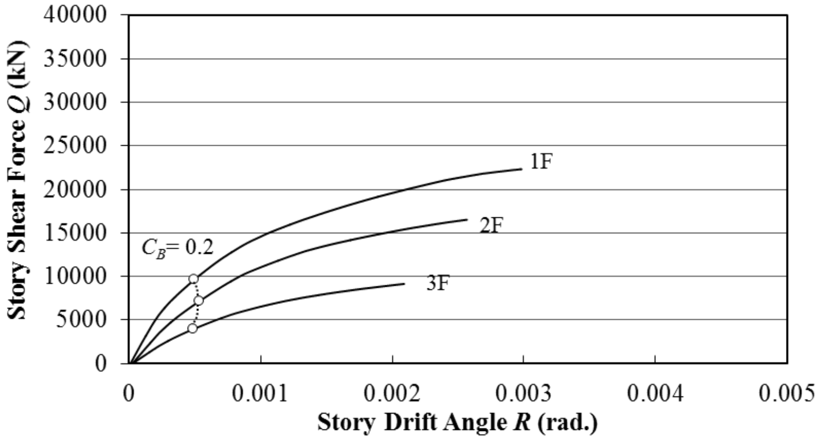
b) Y direction: The story drift angle of the first floor at C_B = 0.2 is about 0.00037 rad. However the story drift angle of the second floor and the third floor at C_B = 0.2 are about 0.0005 radian, it is same as X direction.

2) Burden ratio of pile head share force: Table 2 and Table 3 shows the burden ratio of pile head shear force at C_B = 0.2 of Io model. Bold letters indicate places where the burden ratio of pile head shear force is large.

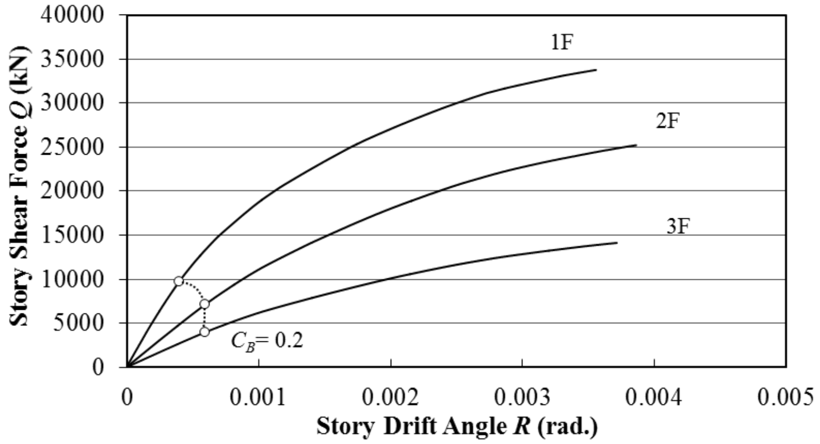
a) X direction: From the comparison of the burden ratio on each axis, burden ratio of axis B and D are large because the building has a lot of walls in axis B and D. From the comparison of the burden ratio on the pile length, burden ratio of "14 m pile" and "16 m pile" are relatively large.

b) Y direction: From the comparison of the burden ratio on the pile length, burden ratio of "13 m pile" and "14 m pile" are relatively large.

3) Comparison of pile head yield: Figure 17 shows the pile head yield place of Io model and I_{K4}' model. The circle mark indicates pile head yield place and the value of the yield



(a) X direction



(b) Y direction

Fig. 16. *The layer shear force (Q) – story drift angle (R) relationship (X direction)*

TABLE 2: *THE BURDEN RATIO OF THE PILE HEAD SHEAR FORCE*
(C_B=0.2, X direction)

Axis \ Axis	1	2	3	4	5	6	7	8	9	10	11	12	Total
H		0.006	0.006			0.008	0.008	0.008					0.037
E		0.006	0.006			0.009	0.009	0.009					0.039
D		0.016	0.026	0.023	**0.033**	**0.037**	0.028	**0.044**	**0.030**	0.019	0.028	0.015	0.299
C	0.003								0.025	0.024		0.005	0.057
B	0.011	0.015	0.024	0.024	0.029	**0.032**	**0.032**	**0.042**	**0.036**	**0.038**	**0.045**	0.027	0.355
A	0.011	0.014	0.017	0.016	0.021	0.019	0.020	0.018	0.018	0.018	0.018	0.014	0.205
Total	0.025	0.058	0.079	0.063	0.083	0.106	0.098	0.122	0.109	0.100	0.090	0.061	1.000

TABLE 3: *THE BURDEN RATIO OF THE PILE HEAD SHEAR FORCE*
(C_B=0.2, Y direction)

Axis \ Axis	1	2	3	4	5	6	7	8	9	10	11	12	Total
H		0.011	0.011			0.017	0.016	0.016					0.072
E		0.011	0.011			**0.026**	0.020	**0.024**					0.093
D		0.013	0.019	0.019	**0.023**	0.023	0.017	**0.053**	**0.024**	0.018	0.019	0.017	0.245
C	0.008								0.014	0.022		0.018	0.062
B	0.013	0.016	**0.025**	**0.024**	**0.056**	**0.055**	0.017	**0.053**	0.021	0.022	0.020	0.013	0.334
A	0.013	0.012	0.019	0.018	0.023	0.015	0.016	0.014	0.019	0.018	0.018	0.011	0.195
Total	0.035	0.064	0.085	0.060	0.101	0.136	0.086	0.160	0.077	0.080	0.056	0.059	1.000

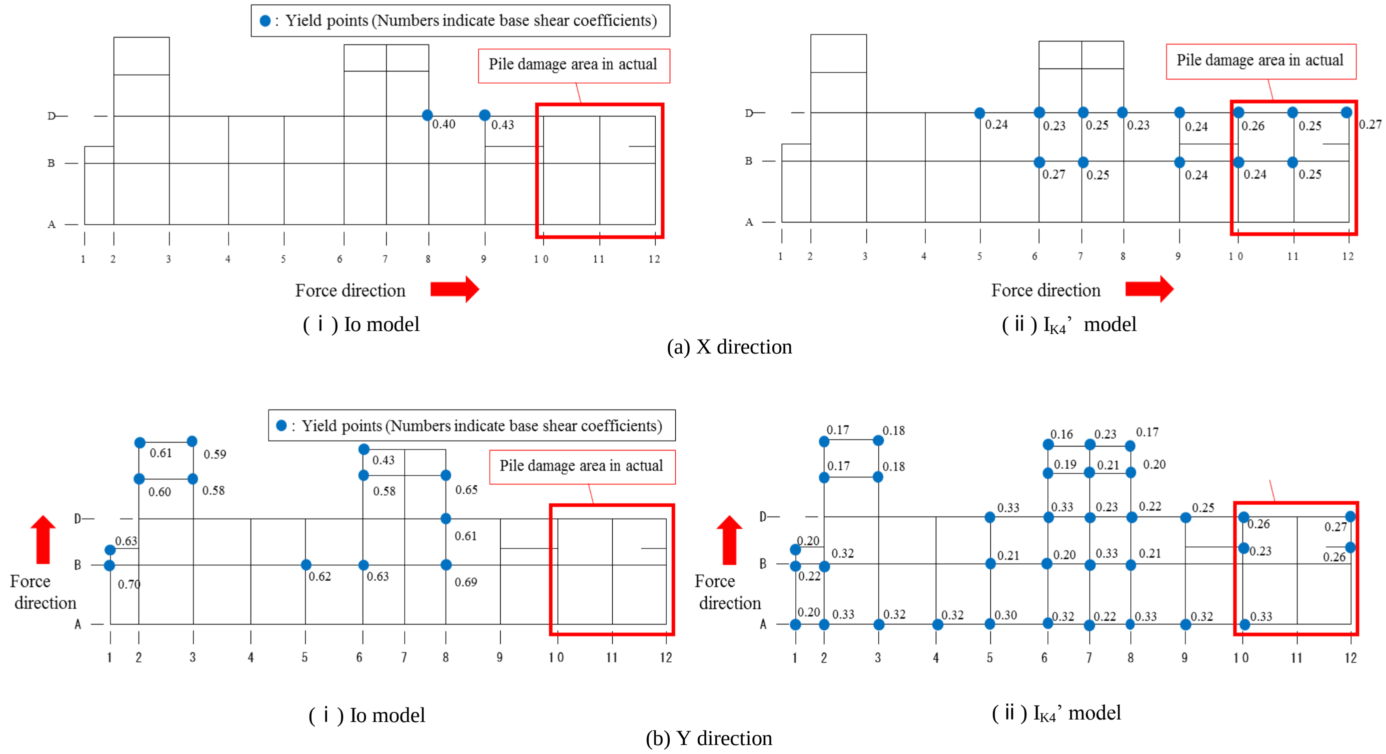


Fig.17. *The pile head yield point*

place indicates C_B when the yield occurred. It is assumed that the pile head yielded when the outermost reinforcement bar of the pile head yielded.

a) X direction: In Io model, the pile head yield at two places and that don't correspond with the actual damage places. I_{K4}' model result has some yielding place corresponding with the actual damage places on axis B and D. C_B are 0.23 to 0.27 in this case. Among the 7 cases, the I_{K4}' model can best simulate the actual damage of the pile foundation of the building.

b) Y direction: In Io model, the pile head does not yield at the actual damage places. In I_{K4}' model, about 70 % of the pile heads yielded and pile head yield even in places which has no damage in actual.

VI. Conclusion

A. Superstructure Analysis

The analyzed school building has high strength because the building has a lot of walls with openings. In X direction, the strength of O model is about 2.2 times larger than that of F model which all walls have been removed.

As a result of investigation of the shear force acting on the pile head, there is a tendency that the burden of shear force became larger due to the influence of the shear walls on the piles. The concentration of stress at the pile under the shear walls caused to the damage to the piles.

B. Substructure Analysis

Stress and deformation of the pile are concentrated in the range within 6 m from the pile head and the pile head shear force is greatly affected by the ground surface. The pile head yielded at the stress concentrated position due to the influence of the shear walls however the pile head did not yield at the other pile by the stress from the superstructure.

C. Super-and-sub Structure Analysis

It is assumed that external force acting this building as C_B=0.2 and an examination on the damage factor of this building was conducted. As a result, pile head yield point obtained by analysis rather corresponded to the damaged pile in actual. On the other hand, pile head yielded in the analysis at the no damaged pile in actual

The following damage factors can be mentioned by the super-and-sub structure model analysis.

- Stress concentration on the pile head due to shear walls
- The influence of ground surface on buildings is significant.
- The burden ratio of pile head shear force is different depending on the place.
- The building is significantly affected by the seismic motion in X direction.

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