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EVALUATION OF LATERAL RESISTANCE OF DAMAGED PILE BASED ON FULL SCALE LATERAL LOAD TEST

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Abstract

Existing piles can be used when a building is being rebuilt as these piles can reduce construction costs and wastes. Prior to their reuse, the appropriateness of the existing piles is inspected for reuse. In general, only piles judged to be fine are reused. Reusing damaged piles as well as fine piles can be useful for designing. This paper describes a method for evaluating the lateral resistance of damaged piles. The major findings obtained are summarized as follows: i) It is important to evaluate the lateral resistance of the damaged pile so as to consider the decrease in the elastic modulus of the pile and the hinge action of the flexural yielding part of the pile. ii) When the elastic modulus of the damaged part of the pile is about half of that of the fine part, the pile damage has little effect on the lateral resistance of the pile despite the location of the damage. iii) When the location of the damage is below $2.1/\beta$, the lateral resistance of the damaged pile is roughly equivalent to that of the fine pile despite the extent of the damage.

Keywords: Full-scale lateral load test; Pile damage; Lateral resistance; Existing pile

1. Introduction

Existing piles can be used when a building is being rebuilt as these piles can reduce construction costs and wastes. Prior to their reuse, the appropriateness of the existing piles is inspected for reuse by using the pile integrity test (PIT). In general, only piles judged to be fine are reused. Reusing the piles with cracks (i.e. damaged piles) as well as fine piles can be useful for designing buildings, but there are not enough studies on the lateral resistance of damaged piles. Therefore, this paper describes a method for evaluating the lateral resistance of damaged piles.

First, the piles were subjected to bend tests to confirm the depth (i.e. distance from pile head) and extent (i.e. width of cracks) of the damage. After the bend tests, the piles were driven into the soil by the pre-boring method with cement milk. Then the full-scale lateral load tests were conducted to investigate the characteristics of the lateral resistance of the damaged piles. The results indicate that the lateral resistance of damaged piles can be equivalent to that of the fine piles depending on the depth and extent of damage (Section 2). Next, the test results were roughly simulated by using a beam-spring model to determine the effect of pile damage (Section 3). Finally, by means of the analytical models, parametric studies were conducted to quantitatively evaluate the effect of the depth and extent of damage on the lateral resistance of damaged piles (Section 4).

2. Lateral Load Test

2.1 Preparation of Damaged Pile

Prior to the lateral load tests, the bend tests were conducted to prepare the damage piles. The pile specifications are shown in Table 1. The bend tests were conducted based on JIS A 5373 [1]. Considering the characteristic length of pile ($1/\beta$), the depth of cracks was determined. $1/\beta$ represents the vertical range of soil under the ground surface, which has great influence on the lateral resistance of piles [2]. Here, $1/\beta$ is 2.0m calculated from the properties of soil and pile when the pile head displacement is 1cm. As shown in Table 1 and Photo. 1, the depths of cracks are 2 types: i) The cracks are at pile head (0~2m depth from pile head) and the effect on lateral resistance can be great, ii) The cracks are in the middle of pile (3~4m depth from pile head) and the effect on lateral resistance can be small. The widths of cracks are 2 types: i) The pile has slight cracks which are hard to watch, ii) The pile has severe cracks which are easy to watch.

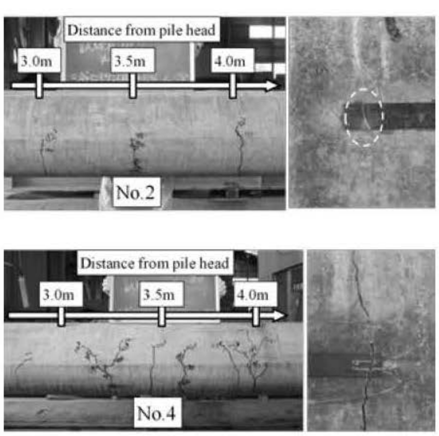
2.2 Method of Lateral Load Test

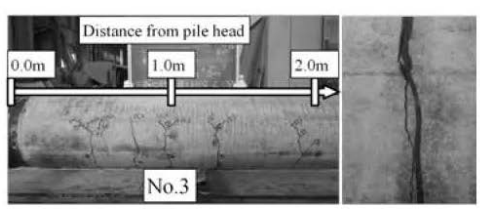
The lateral load tests were conducted based on JGS 1810-2010 [3]. The piles arrangement is shown in Fig. 1. After the bend tests, the piles were driven into the soil by the pre-boring method with cement milk. In order to avoid the effect of a reaction pile neighboring on the lateral resistance of a test pile, the piles were fully spaced and the spacing was 3m. The sides of piles that the cracks were occurred by the bend tests were arranged to the east. The pile heads were 500mm above the ground surface and the ground surface was flat. Soil layers and *N* values are shown in Fig. 2. The surface layers of soil (GL0~-7m) mainly consist of Kanto loam (*N*=2~4), and the bearing layer (GL-7m~) consists of gravel.

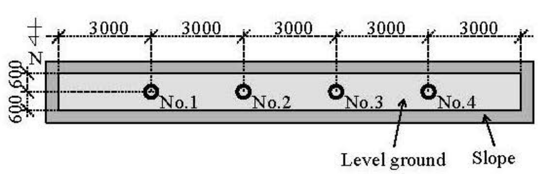
Test cases are shown in Table 2, and load equipment is shown in Figs. 3, 4. In case 1, No.1 and No.2 piles were loaded each other. In case 2, No.3 pile was loaded using No.1 and No.2 piles as reaction piles. Case 3 was the same case as case 2. The test pile heads were pinned. Here, the pile head load is the jack load, pile head displacement is the displacement of the loading point, and pile head rotation angle is calculated from the difference of the displacement between the loading point and the upper point (loading point+500mm).

Table 1 – Pile specifications

Pile number	No.1	No.2	No.3	No.4
Pile type	PHC	PHC	PHC	PHC
Diameter and thickness (mm)	ϕ400_t65	ϕ400_t65	ϕ400_t65	ϕ400_t65
Length (m)	7	7	7	7
Initial elastic modulus E ($\times 10^7$ kN/m^2)	5.88	5.88	5.88	5.88
Elastic modulus at maximum load E' ($\times 10^7$ kN/m^2)	-	3.35	1.01	1.05
Moment of inertia of area I (cm^4)	101821	101821	101821	101821
Cracking moment M_{cr} (kN*m)	56	56	56	56
Ultimate moment M_u (kN*m)	92	92	92	92
Depth of cracks	-	Middle	Pile head	Middle
Width of cracks (mm)	-	0.025	0.5	0.7







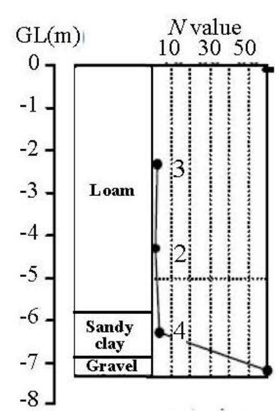


Photo. 1 – Pile damage

Fig. 1 – Pile arrangement

Fig. 2 – Soil layers and *N* values

Table 2 – Test cases

Case	Case1	Case2	Case3
Test piles	No.1, No.2	No.3	No.4
Reaction piles	–	No.1, No.2	No.2, No.3

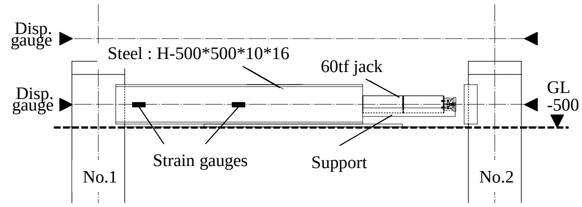


Fig. 3 – Case1 equipment

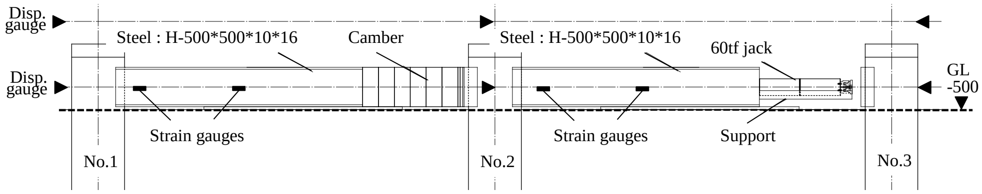


Fig. 4 – Case2 equipment

2.3 Lateral Resistance of Slightly Damaged Pile

The secant stiffness at pile head of slightly damaged pile (No.2) is shown Fig. 5. The stiffness is the secant stiffness at the peak load of each loading cycle calculated from pile head load-displacement curve. The result of fine pile (No.1) is also shown for comparison. Here, $1/\beta$ (explained in section 2.1) of No.1 is 1.94m and the damaged part of No.2 is in the middle of pile (3~4m depth from pile head). The stiffness of No.2 decreases with the displacement increasing. While the displacement is small, the stiffness of No.2 is roughly equivalent to that of No.1. This is because while the displacement is small, most of the subgrade reaction are loaded onto the part of pile near the pile head, and the part of No.2 is as roughly fine as that of No.1. Although the middle of No.2 pile is damaged, the stiffness of No.2 is still roughly equivalent to that of No.1 at large displacement. There can be two reasons: i) The slightly damage of pile has almost no effect on the lateral resistance of pile. ii) Little subgrade reaction is loaded onto the damaged middle part of pile at large displacement. In the following Section 3, this is examined again by analytical study.

2.4 Lateral Resistance of Severely Damaged Pile

The secant stiffness at pile head of severely damaged piles (No.3, 4) is shown Fig. 6. The stiffness of No.3 decreases with the displacement increasing, and it is smaller than that of No.1. This is because while $1/\beta$ of No.1 is 1.94m, the damaged part of No.3 is at pile head (0~2m depth from pile head) and the stiffness of the part could be smaller than that of the fine part. In order to examine the result more, the decrease in the stiffness is focused. The elastic modulus *E'* of No.3 at maximum load is 1.01×10^7kN/m^2 calculated from the bend test and it is smaller than the initial elastic modulus *E* (see Table 1). Fig. 7 shows the pile head load-displacement curve calculated from *Chang*'s equation [2] using the decreased *E'* of No.3. To calculate the curve, the coefficient of horizontal subgrade reaction k_h of No.1 is used. Fig. 7 indicates that while using the decreased elastic modulus *E'* leads to the displacement increasing, the calculated displacement using *Chang*'s equation (k_h of No.1, *E'* of No.3) is smaller than the test result of No.3. This is because No.3 pile was flexural yielded by the bend test and the yielded part of the pile could act like a hinge which helps the displacement to increase more.

According to Fig. 6, the stiffness of No.4 decreases with the displacement increasing. While the displacement is small, the stiffness of No.4 is roughly equivalent to that of No.1. This is because while $1/\beta$ of No.1 is 1.94m, the damaged part of No.4 is in the middle of pile (3~4m depth from pile head) and the stiffness of the part could not decrease. With the displacement increasing, $1/\beta$ of No.4 could become deeper toward the damaged part. However, the stiffness of No.4 does not differ from that of No.1 at large displacement despite the pile damage same as No.3. The result indicates that under this soil condition, little subgrade reaction is loaded onto the damaged middle part of pile at large displacement.

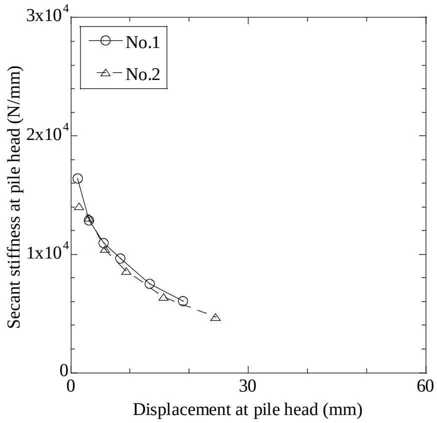


Fig. 5 – Lateral resistance of slightly damaged pile (No.2)

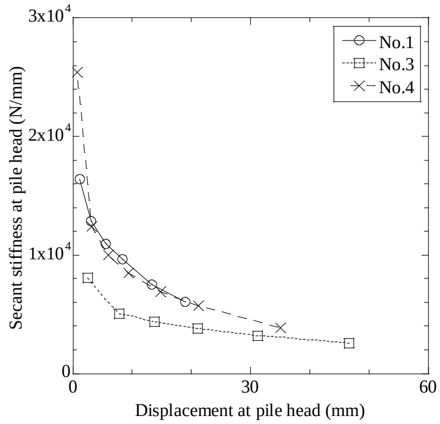


Fig. 6 – Lateral resistance of severely damaged piles (No.3, 4)

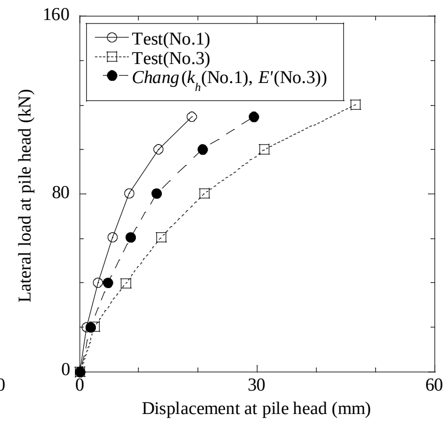


Fig. 7 – Effect of decrease in elastic modulus

3. Analytical Study

In Section 2, the test results indicate that depending on the depth and extent of damage, the lateral resistance of damaged piles can be equivalent to that of fine piles. It is useful for reusing damaged piles to quantitatively evaluate the lateral resistance of the piles in correspondence with the depth and extent of the damage. Prior to the quantitative evaluation with parametric studies, this Section 3 describes the analytical model which can simulate the test results. Following the investigation of the test results (see section 2.3), the effect of slightly damage of pile is examined by the analytical studies.

3.1 Method of Analyses

Direct iterative method [2)] is the convergence calculation method for a pile loaded laterally in the multilayered soil. In this method, the pile is modelled as non-linear beam elements and the horizontal subgrade reaction is modelled as non-linear spring elements. The pile's bending rigidity EI is the secant stiffness of the bending moment-curvature curve (M-ϕ curve). The soil's coefficient of horizontal subgrade reaction k_h is the secant stiffness of the subgrade reaction-displacement curve (P-y curve). Analytical models are shown in Fig. 8. According to the test condition, the pile head is above the ground surface and both pile head and pile end are pinned. The pile is surrounded by Kanto loam from pile head to pile end. The initial elastic modulus E of pile is based on the test results (see Table 1). The M-ϕ curve of pile is modelled as Tri-linear curve based on the test result of No.4 (see Fig. 9).

The uniaxial compressive strength q_u and the deformation coefficient E_{50} of Kanto loam are shown in Table 3. E_{50} is the secant stiffness at half of q_u in the stress-strain curve. According to the AIJ recommendation [2], soil springs have the standard coefficient of horizontal subgrade reaction k_{h0} and the *Broms'* ultimate subgrade reaction P_y (see equations (1)-(3)). Here, α=80, E_0=E_{50}, C_u=q_u/2, μ=1.4, λ=9.0. (α: constant for each evaluation method, E_0: initial deformation coefficient, B: pile diameter, z: depth under the ground, γ: unit weight of soil, C_u: undrained shear strength, μ and λ: coefficient that takes group pile effects into account)

$$k_{h0} = \alpha \times E_0 \times B^{-3/4} \tag{1}$$

$$[Z/B<2.5] \quad \frac{P_y}{\gamma B} = 2\left(1+\mu\frac{z}{B}\right)\frac{C_u}{\gamma B} \tag{2}$$

$$[Z/B>2.5] \quad \frac{P_y}{\gamma B} = \lambda\frac{C_u}{\gamma B} \tag{3}$$

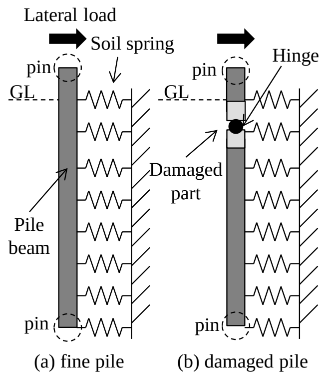


Fig. 8 – Analytical models

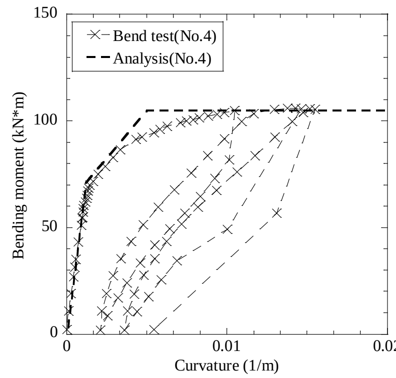


Fig. 9 – M-ϕ curve for analyses

Table 3 – Material properties of soil

GL(m)	q_u (kN/m^2)	E_{50} (kN/m^2)
0~-3	88.0	4300
-3~-5	78.3	3900
-5~-7	82.8	4300

3.2 Analytical modeling of Damaged Part of Pile

The test results indicate that the lateral resistance of damaged pile depends on the decrease in the elastic modulus of pile and the act like a hinge of flexural yielding part of pile. Therefore, the analytical model of damaged pile (Fig. 8b) has the damaged part with a decreased elastic modulus and a hinge. The decreased elastic modulus E' is calculated from the bend tests (see Table 4). The hinge has the decreased moment of inertia of area I' calculated from equations (4)-(7) (see Fig. 10). The initial elastic modulus E is that of No.1 calculated from the bend test (E=5.88×10^{7}kN/m^2).

Fig. 11 shows the moment of inertia of area I'-crack ratio curve calculated from equations (4)-(7). (D=400mm, d=270mm). The crack ratio is calculated from previous α, and I' is standardized by I of fine part. With the crack ratio increasing, the central axis becomes away from the X-axis and I' becomes smaller. In the following analyses, I'/I=0.00871 because the three-quarters of circumference of No.3 was cracked in the tests.

$$A = \iint r dr d\theta = \frac{\alpha}{4}\left(D^2 - d^2\right),\ \left\{\frac{d}{2} \le r \le \frac{D}{2}, -\alpha \le \theta \le \alpha\right\} \tag{4}$$

$$S = \iint y r dr d\theta = \frac{1}{12}\sin\alpha\left(D^3 - d^3\right) \tag{5}$$

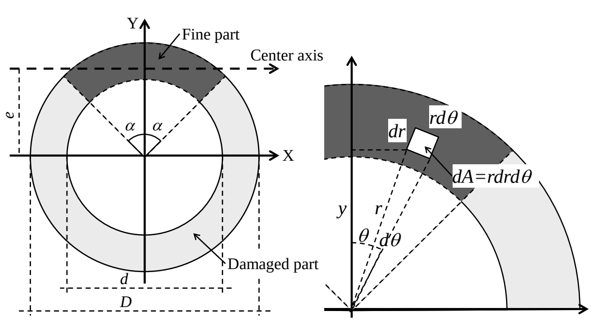
$$e = \frac{S}{A} = \frac{\sin\alpha\left(D^3 - d^3\right)}{3\alpha\left(D^2 - d^2\right)} \tag{6}$$

$$I' = \iint (y-e)^2 r dr d\theta = \frac{1}{64}(\alpha + \sin\alpha\cos\alpha)\left(D^4 - d^4\right) - \frac{\sin^2\alpha\left(D^3 - d^3\right)^2}{36\alpha\left(D^2 - d^2\right)} \tag{7}$$

(A: cross-sectional area, S: statical moment of area, e: distance between central axis and X-axis, α: the angle that represents the rate of fine cross-section), D: outer pile diameter, d: inner pile diameter)

Table 4 – Material properties of pile

Pile number	No.3	No.4
Damaged part	0.5~1.8m deep under pile head	2.7~4.3m deep under pile head
Hinge depth (m)	0.5~1.8	3.2~4.0
Damaged part E' ($\times 10^7$ kN/m^2)	1.01	1.05



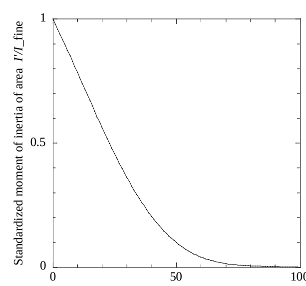


Fig. 10 – Method for calculating moment of inertia of area I' Fig. 11 – Moment of inertia of area I'

3.3 Simulation Analyses of Lateral Load Test

Fig. 12 shows the lateral resistance of fine piles calculated from analyses; pile head load-displacement curves and pile head load-rotation angle curves. The test result of fine pile (No.1) is also shown for comparison. The analytical results indicate that it is necessary for properly evaluation of the lateral resistance of pile to consider the non-linear characteristics of pile (M-ϕ curve).

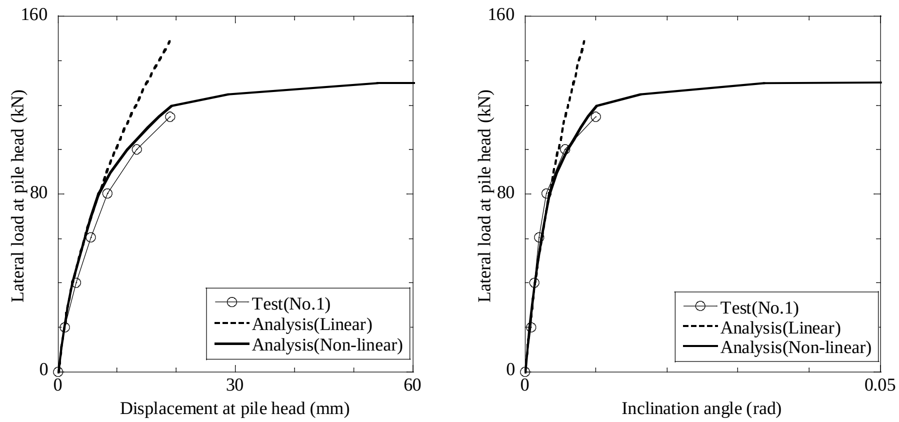
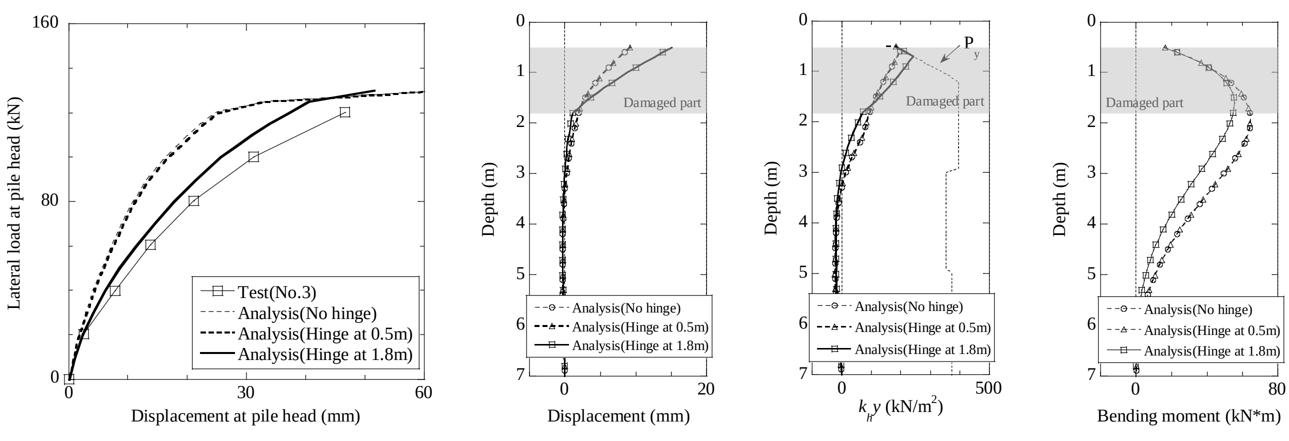


Fig. 12 – Lateral resistance of fine piles calculated from analyses (No.1)

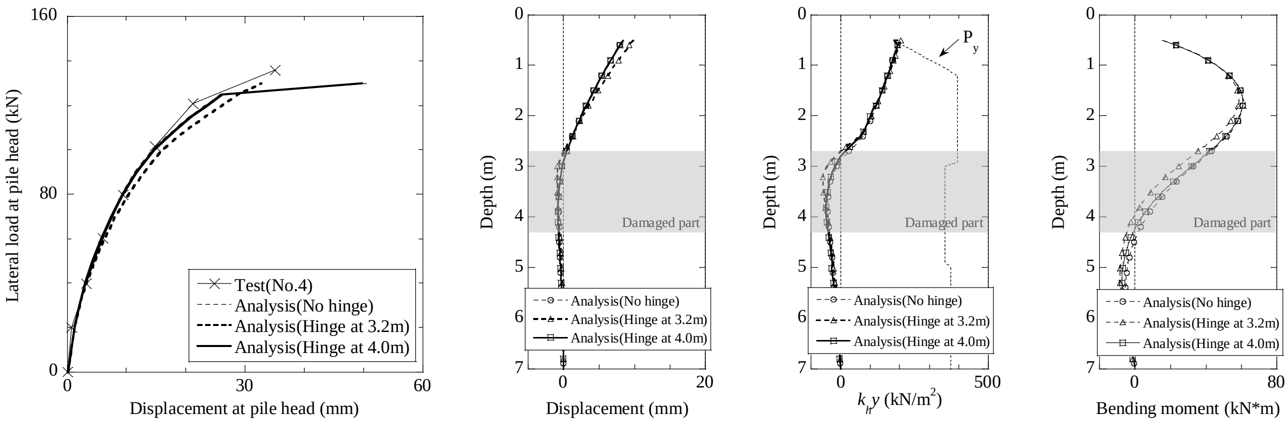
Fig. 13 shows the lateral resistance and distributions of piles damaged at pile head calculated from analyses; pile head load-displacement curves and distributions of pile displacement, horizontal subgrade reaction and pile bending moment when the pile head load is 80kN (i.e. the bending moment of fine pile reaches the test-observed cracking moment). The test result of damaged pile (No.3) and the analytical result of damaged pile with no-hinge are also shown for comparison. Fig. 18a indicates that the hinge is effective on properly evaluation of the lateral resistance of damaged pile. While the more precisely simulation of the test results need more advanced analyses such as FEM, the proposed analytical model is considered to be generally appropriate. Figs. 13b, c indicate that while the hinge is located at 1.8m depth, most of the subgrade reaction becomes loaded onto the part of the pile above the damaged part. Therefore, the pile deformation increases sharply above the damaged part.



(a) Pile head load-displacement curves (b) Displacement (c) Subgrade reaction (d) Bending moment

Fig. 13 – Lateral resistance and distributions of piles damaged at pile head calculated from analyses (No.3)

Fig. 14 shows the lateral resistance and distributions of piles damaged in the middle calculated from analyses. The test result of damaged pile (No.4) and the analytical result of damaged pile with no-hinge are also shown for comparison. Unlike the pile damaged at pile head (see Fig. 13), the lateral resistance of piles damaged in the middle does not differ from analytical model to analytical model. This is because according to Fig. 14c, the effect of the damaged part on the subgrade reaction is limited around the damaged part, and most of the subgrade reaction is loaded onto the part of the pile above the damaged part. As described in Section 2, under this soil condition, the shallow range of soil under the ground surface has great influence on the lateral resistance of pile at large displacement. Although No.4 pile has the damaged part in the middle, the part of the pile near pile head is fine.

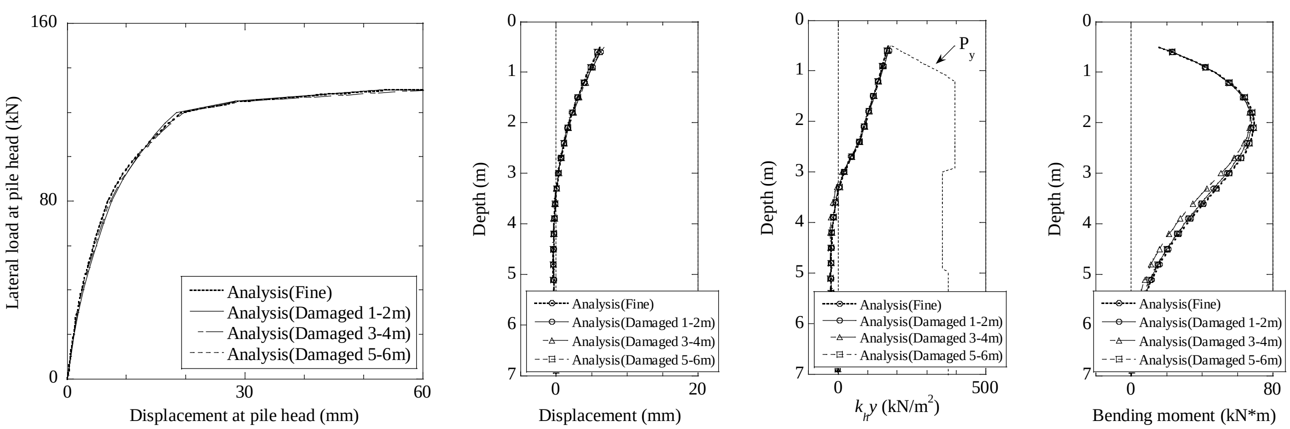


(a) Pile head load-displacement curves (b) Displacement (c) Subgrade reaction (d) Bending moment

Fig. 14 – Lateral resistance and distributions of piles damaged in the middle calculated from analyses (No.4)

3.4 Effect of Slightly Damage on Lateral Resistance of Pile

Fig. 15 shows the lateral resistance and distributions of slightly damaged pile calculated from analyses. The analytical result of fine pile is also shown for comparison. The locations of damaged part of pile are 3 types: Distance from the pile head is 1~2m, 3~4m, 5~6m. The elastic modulus of the damaged part is that of No.2 calculated from the bend test (E'=3.35×10^{7}kN/m^2). The damaged part has no hinge because the crack of No.2 was closed by pre-stress. Fig. 15a indicates that the slightly damage of piles have little effect on the lateral resistance of the piles despite the locations of the damage. This is because when the pile damage is slight, the distribution of subgrade reaction of the damaged pile is roughly equivalent to that of the fine pile (see Fig. 15c). Therefore, the slightly damaged pile is just as deformed as the fine pile and its lateral resistance is roughly equivalent to that of the fine pile.



(a) Pile head load-displacement curves (b) Displacement (c) Subgrade reaction (d) Bending moment

Fig. 15 – Lateral resistance and distributions of slightly damaged piles calculated from analyses

4. Quantitative Evaluation of Lateral Resistance of Damaged Pile

By means of the analytical models described in Section 3, parametric studies are conducted to quantitatively evaluate the effect of the depth and extent of damage on the lateral resistance of damaged pile. This paper adopts secant stiffness at 1cm of the pile head displacement, which is calculated from the pile head load-displacement curve, as an index which represents the lateral resistance of the pile.

4.1 Method of Parametric Study

In order to study simply, a pile head is under the ground surface and the pile is surrounded by uniform Kanto loam from the pile head to the pile end (q_u=88kN/m^2, E_{50}=4300kN/m^2). In the tests described in Section 2, the effect of pile damage on the lateral resistance could be evaluated small because the rigidity of pile is relatively smaller than that of soil. To properly evaluate the effect of pile damage without the magnitude relation between the rigidities of pile and soil, the pile diameter is 4 types: 300, 400, 600, 800mm. The range of damaged part of pile is 1m and the damaged part is located from the pile head to the pile end. The hinge is located among the damaged part: top, middle, bottom of the part. The extent of the pile damage is 3 types: i) The pile is slightly damaged with *E'* of No.2 at test-observed cracking moment and no-hinge, ii) The pile is moderately damaged with *E'* of No.3 at designed ultimate moment and the hinge has *I'* at 40% of crack ratio, iii) The pile is severely damaged with *E'* of No.3 at test-observed ultimate moment and the hinge has *I'* at 75% of crack ratio.

4.2 Quantitative Evaluation

Fig. 16 shows the secant stiffness at pile head of damaged piles calculated from parametric studies. The results are classified according to the depth and extent of the pile damage. The stiffness of the vertical axis is standardized by the stiffness of fine pile. The damage location of the horizontal axis is standardized by $1/\beta$ of fine pile, which is calculated from the coefficient of horizontal subgrade reaction k_h at 1cm of the pile head displacement. The test results and the logarithmic curves of the analytical results are also shown.

When the elastic modulus of the damaged part of pile is about half of that of the fine part (*E'/E*=1/2), the pile damage has little effect on the lateral resistance of the pile despite the location of the damage. This is because, as shown in Fig. 15c, the slightly damage of the pile has little effect to the distribution of subgrade reaction. When the elastic modulus of the damaged part of pile is about one sixth of that of the fine part (*E'/E*=1/6), the pile head displacement increases nearing the location of the damage to its pile head. This is because, as shown in Fig. 13c, the damaged part acts like a hinge and most of the subgrade reaction becomes loaded onto the part of the pile above the damaged part. Therefore, the pile deformation increases sharply above the damaged part. On the other hand, when the location of the damage is below $2.1/\beta$, the lateral resistance of the damaged pile is roughly equivalent to that of the fine pile despite the extent of the damage.

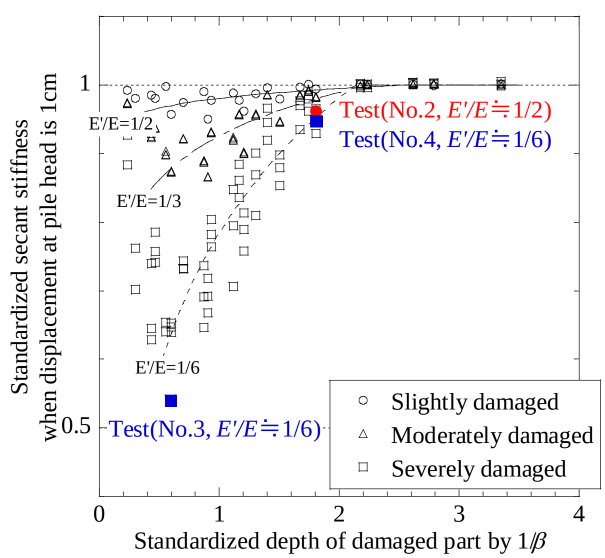


Fig. 16 – Evaluation of lateral resistance of damaged piles according to depth and extent of damage

5. Conclusion

The major findings obtained from tests and analyses are summarized as follows:

1) It is important to evaluate the lateral resistance of the damaged pile so as to consider the decrease in the elastic modulus of the pile and the hinge action of the flexural yielding part of the pile.
2) When the elastic modulus of the damaged part of the pile is about half of that of the fine part (E'/E=1/2), the pile damage has little effect on the lateral resistance of the pile despite the location of the damage. This is because when the pile damage is slight, the distribution of subgrade reaction of the damaged pile is roughly equivalent to that of the fine pile. Therefore, the slightly damaged pile is just as deformed as the fine pile and its lateral resistance is roughly equivalent to that of the fine pile.
3) When the elastic modulus of the damaged part of the pile is about one-sixth of that of the fine part (E'/E=1/6), the pile head displacement increases near the location of the damage to its pile head. This is because when the location is nearer to its pile head, the damaged part acts as a hinge, and most of the subgrade reaction becomes loaded onto the part of the pile above the damaged part. Therefore, the pile deformation increases sharply above the damaged part. The analyses results indicate that when the location of the damage is above $2.1/\beta$, a sharp deformation of the pile occurs.
4) On the other hand, when the location of the damage is below $2.1/\beta$, the lateral resistance of the damaged pile is roughly equivalent to that of the fine pile despite the extent of the damage. This is because the effect of the damaged part on the subgrade reaction is limited around the damaged part. Therefore, the damaged part has little effect on most of the subgrade reaction loaded to the pile head.

6. References

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