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A STUDY ON DAMAGE DETECTION METHOD FOR EXISTING PILES AFTER EARTHQUAKE

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SUMMARY

In this paper, a non-destructive damage evaluation procedure is presented, which aims at detecting early or fatal cracks in existing piles after severe earthquakes. The bending motion of a target pile excited by an impulsive load, which is induced by hammering at the ground surface nearly, is measured at the top to obtain the dynamic compliance of the pile in one direction. Numerical simulations and experiments show that evaluating the dynamic compliance in every direction can suggest the severity of the cracks as well as their location and orientation.

INTRODUCTION

After Miyagiken-oki Earthquake in 1978, the damage of existing piles, which supported a building, became a big problem. Also, in case of the Great Hanshin Earthquake in 1995, the damaged existing plies of public buildings presented a serious problem to reconstruct the buildings after an earthquake [1], [2]. During earthquake, soil is deformed and then buildings cause sway-rocking motion. Therefore, when the piles cause the severe bending motion, these are damaged. The damage of buildings is detected by visual inspection by experts, however the damage of piles is not detected, because piles are buried in soil. Piles must to be dug up to detect damage of them. In the reconstruction after the earthquake, damage piles must be assessed as their viability for future use. After the Great Hanshin Earthquake, a shock was given to the head of the pile vertically, and the reflection of the wave motion was measured. However, the trial to investigate damage from the measured value did no show good results. Since a crack of pile due to damage is usually closed, the shock from the head of the pile does not show appropriate wave motion impedance and a reflected wave does not contain information on the damage in the pile properly.

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In this study, the authors have been proposing a new damage detection system of existing piles. The bending motion of a target pile excited by an impulsive load, which is induced by hammering at the ground surface nearly, is measured at the top to obtain the dynamic compliance of the pile in one direction. Numerical simulations by FEM analysis and experiments show that evaluating the dynamic compliance in every direction can suggest the severity of the cracks as well as their location and orientation. We examine the validity of the proposed system.

OUTLINE OF DAMAGE DETECTION PROCEDURE FOR EXISTING PILES

The proposed method consists of the following steps:(1) and (2)

(1) The search of the presence of the crack and the orientation of the crack.
A buried pile with a crack is shown in Figure 1. As shown in this figure, we define the orientation, which a crack is appearing in the pile, as the direction at 0° and define a right angle direction with it as the direction at 90°. Taking the position excited by an impulsive load; that is the position of weight drop, as 0°, 90° and 180°, respectively, we measure the peak angular velocity and the peak displacement of the top of a pile in each location. If the pile has a crack, then the peak angular velocity and the peak displacement change by the orientation of the crack in each location. When the orientation of the crack is 0°, the peak angular velocity is expected to be minimum. Because the vibration energy of the soil pressure caused by shock wave of an impulsive load is not transmitted to the pile for the presence of crack.

(2) The search of the crack depth and the crack location
As mentioned in the former section, the vibration energy of the soil pressure is not transmitted to the crack and then the peak angular velocity at the top of pile is expected to be small in proportion to the crack depth. Since the elastic restraint becomes large in proportion to upper weight in the soil, the pile with a crack in deeper location is affected by the vibration energy of the soil pressure strongly. A pile becomes a hinge-shaped at the location of crack according to the crack depth and then rigid motion occurs at this location. Therefore, the displacement at the top of a pile increases in proportion to the crack depth.
So, if the agreement between numerical simulations and experiments with a small-scale model can be obtained, the proposed system is applied to the damage detection of piles.

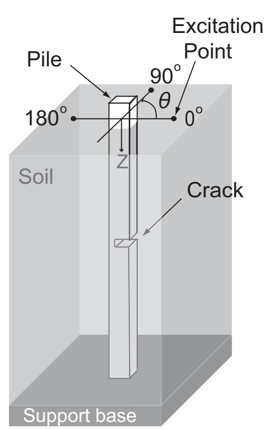

Figure 1: Pile buried with a crack

NUMERICAL SIMULATIONS BY FEM ANALYSIS

In this study, in order to investigate the motion of pile by the difference in the crack depth and the crack location, pile models with various types of cracks are used. The geometry of cracks is shown in the Figure 2.The crack location is a distance in the Z direction from the ground surface. The crack depth U is the depth in the horizontal direction from the surface of the pile. The crack width W is the height in the Z direction of a crack. The specifications of location, depth and width of crack on a pile are shown in Table 1. Numerical simulations using 6 pile models with cracks and a pile model with no crack were carried out.

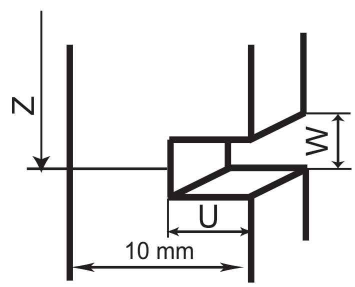

Figure 2: Focused crack

Table 1: Geometry of cracks

Crack position Z(mm)	100	100	300	300	500	500
Crack depth U(mm)	4	8	4	8	4	8
Crack width W(mm)	2	2	2	2	2	2

Numerical simulations were carried out by ANSYS [3]; that is analytical software of the finite element method. The FEM model is shown in the Figure 3. The pile model used with numerical simulations has the form of a rectangular solid. The size of a pile is $10mm \times 10mm \times 800mm$. The FEM model by rotating only a pile is used instead of changing the location of an impulsive load (weight drop). To understand from Figure 4, the inside of a crack is assumed to be hollow. This assumption is closer to the real conditions in case of a crack in the actual pile, because the soil is not perfectly filled up in the crack. Tetrahedrons and hexahedrons were used for the element division of FEM model. As for the pile model, one side of an element is maximum 20mm. As for the soil model, one side of an element is maximum 35mm. As the boundary condition, the pile is perfectly fixed by rigid support base. Because the actual pile is supported by deeper base in the soil. Boundary conditions of FEM model are shown in the Table 2. The law of similarity is not specially taken into consideration because the purpose of this study is that an experiment corresponds with the simulation. Dry sand was used as the soil model and a steel material was used as the pile model. Material property is shown in the Table 3. An impulsive surface load of 75000 [N/m^2] for only 0.0001s-0.0041s is added on the ground surface to excite the bending motion of a pile. The distance between the position of load and a pile is 200mm. Calculation time is 0-0.01s. Sampling frequency is 10kHz. Modal damping was taken into consideration for FEM model.

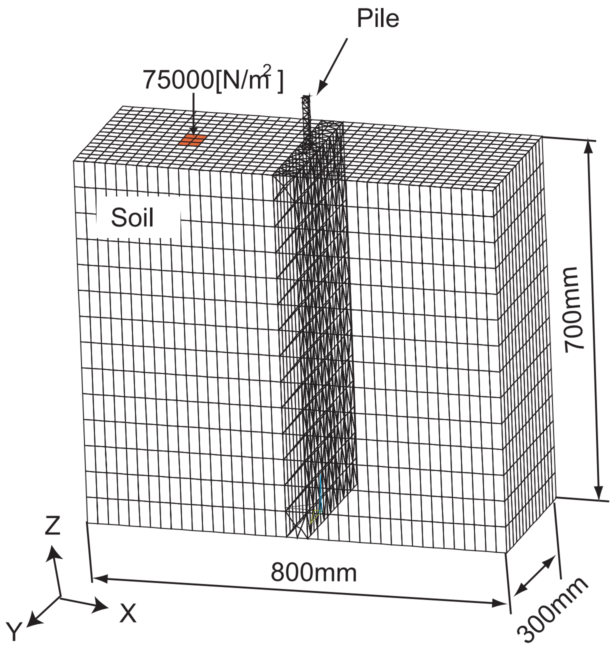

Figure 3: FEM model

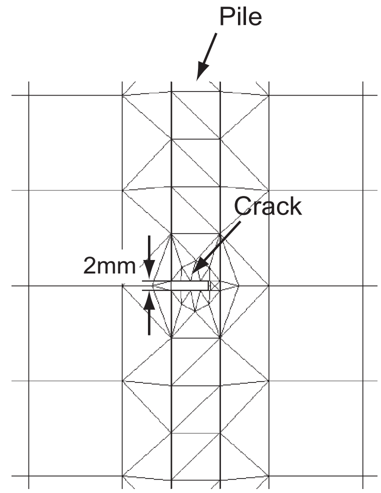

Figure 4: Focused crack

Table 2: Boundary conditions of FEM model

Area	Restraint
X area	Displacement in the X direction Rotation about Y-axis Rotation about Z-axis
Y area	Displacement in the Y direction Rotation about X-axis Rotation about Z-axis
Z area (base)	Displacement in the Z direction Rotation about X-axis Rotation about Y-axis
Base of pile	All displacement and rotation

Table 3: Material properties

	Soil	Pile
Young's modulus E [N/m^2]	3.96×10^{7}	2.05×10^{11}
Poisson's ratio ν	0.25	0.3
Density ρ [kg/m^3]	1.55×10^{3}	7.8×10^{3}

RESULTS OF NUMERICAL SIMULATIONS

(1) The search of the presence of crack and the orientation of crack

The results of the FEM analysis in case of the crack location Z= 300mm and the crack depth U= 8mm are shown in the Figure 5. This figure shows the peak angular velocity at the top of pile for the location of load, θ. From this figure, it is clear that the peak angular velocity for θ=0° becomes smaller than that for θ=90° . The presence of the crack and a crack orientation can be detected in this result.

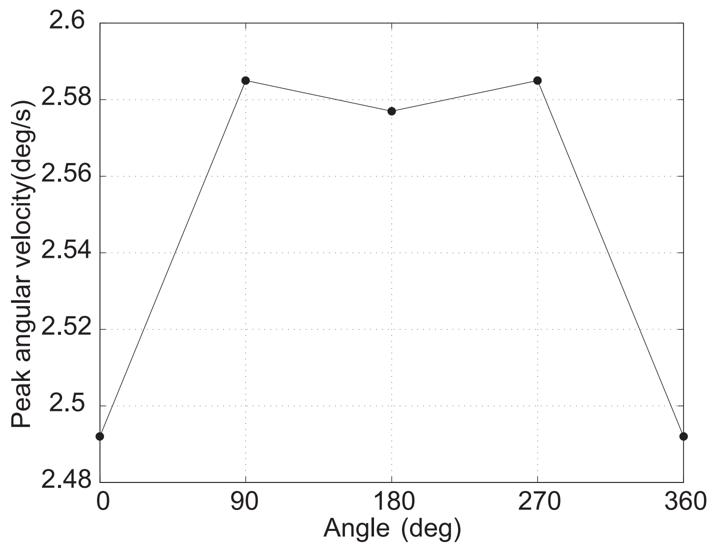

Figure 5: Peak values of angular velocity versus direction θ falling weight (Z=300mm, U=4mm)

(2) Stiffness in 90° direction for the crack

A problem is that data on the pile with no crack do not exist in case of existing piles. So we use data on the pile with a crack in 90° direction as the data on the pile with no crack. In order to confirm that the data on the pile with no crack correspond to the data in 90° direction for the crack, the stiffness of pile in 90° direction for the crack is examined. The method to obtain Stiffness of Pile is shown in the Figure 6. Under the condition of no soil, when the static load P is added to the top of pile in 0° direction and 90° direction, respectively, the relation between the displacement x of the top of pile and stiffness k of pile is given by.

$$k = \frac{P}{x} \tag{1}$$

The ratio k/k' with stiffness k of the pile with a crack in 0° direction or 90° direction and stiffness k' of the pile with no crack is calculated. Stiffness ratio k/k' is shown in Figure 7. In this figure, as crack depth increases, stiffness ratio k/k' in 0° direction decreases. On the other hand, as crack depth increases, stiffness ratio in 90° direction is almost constant. Stiffness in 90° direction of the pile with a crack is the same as stiffness of the pile with no crack consequently. From this result, when there are no data on the pile with no crack, the data on the pile with a crack in 90° direction can be utilized as the data on the pile with no crack.

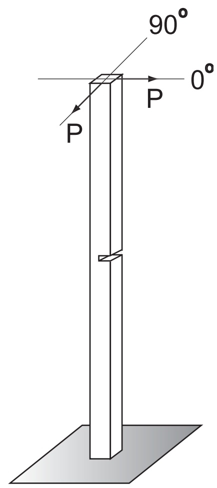

Figure 6: Method to obtain stiffness of pile

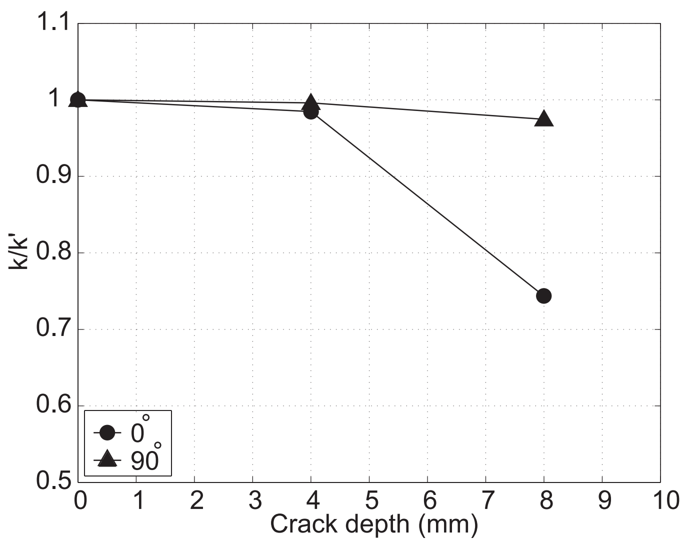

Figure 7: Stiffness ratio (Z=300mm)

(3) Evaluation of calculated data at the top of pile

As shown in Figure 3, an impulsive load is added to the position at the distance 200 mm from a pile. The propagated wave motion through the soil causes the bending motion of a pile. Then the angular velocity and displacement at the top of pile are calculated. By using the data on the pile with a crack in 90° direction as the data on the pile with no crack, a crack location and crack depth are estimated. Peak angular velocity and peak acceleration at the top of pile in each crack location are shown in the Figure 8, Figure 9. For example in a crack location Z= 500mm, as crack depth increases, peak angular velocity at the top of pile decrease. On the other hand, peak acceleration is almost constant. On the contrary, in a crack location Z= 100mm, as crack depth increases, peak acceleration at the top of pile increases and peak angular velocity is almost constant. By comparing both changes of peak angular velocity and peak acceleration, a crack location and crack depth are estimated.

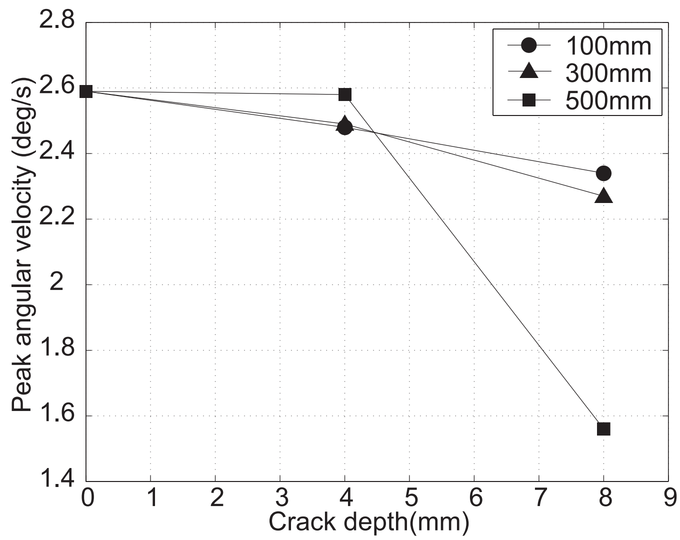

Figure 8: Peak values of angular velocity at top of pile

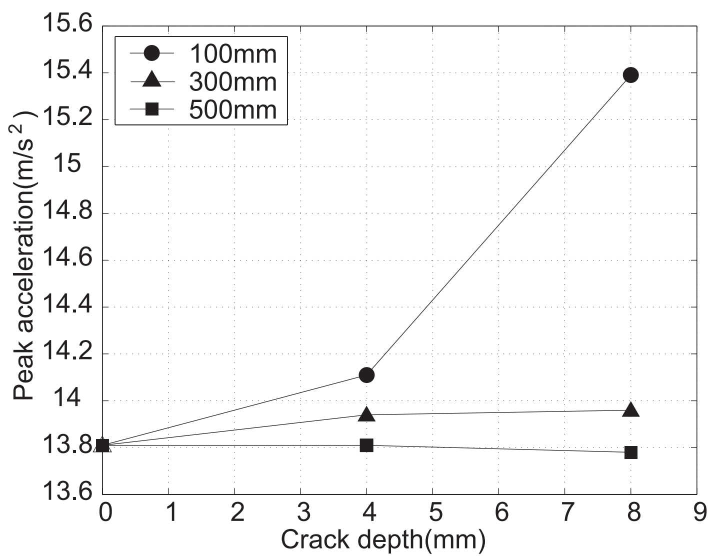

Figure 9: Peak values of acceleration at top of pile

EXPERIMENTS

Method of Experiment

The experimental setup as large as FEM model in the simulation is used, because the purpose of this study is that a result of simulation corresponds to a result of an experiment. The experimental setup is shown in Figure 10. The width of the sand box (in Y direction in the FEM model) is 300mm. In this experimental setup, however, the influence of the wave motion reflection by the wall of the sand box cannot be neglected. Plywood board with 15mm thick is used as the wall that is the boundary of the sand box. Therefore the boundary of the sand box is not the boundary with no degree of freedom in vertical direction with the wall like the simulation perfectly. The bottom part of the pile is completely fixed with the steel supports and the bolts. We installed the plywood stick with a cone-shaped weight on the side of the sand box by a hinge to add an impulsive load to the soil. It became possible that the same load was added to the same position by dropping this plywood stick from the fixed angle. For measurement, the angular velocity sensor and accelerometer are installed at the top of pile model.

The pile model used in the experiment is the rectangular steel whose size is $10mm \times 10mm \times 800mm$. Kinds of the pile are 6 pile models with cracks and a pile model with no crack. Geometry of cracks in piles is shown in Table 4. Material properties of the pile model and soil model are shown in Table 5. Material properties of the soil were decided from the result of the experiment.

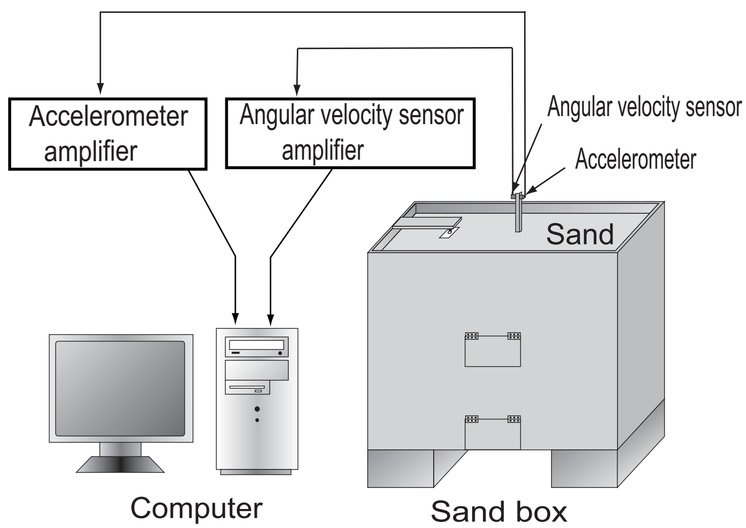

Figure 10: Experimental setup

Table 4: Geometry of cracks

Crack position Z(mm)	100	100	300	300	500	500
Crack depth U(mm)	4	8	4	8	4	8
Crack width W(mm)	2	2	2	2	2	2

Table 5: Material properties

Pile	
Material	$SS400$ (Steel)
Density	7.8×10^3 (Kg/m^3)

Soil	
Material	Natural sand number 5 (Dry)
Density	1.55×10^3 (Kg/m^3)

RESULTS OF EXPERIMENT

(1) The search of the presence of the crack and the orientation of the crack

Peak angular velocity measured at the top of pile in each location of impulsive load is shown in Figure 11. The results obtained from this figure agree with the FEM analysis results in Figure 5. Therefore, the validity of this proposed detection system of crack was confirmed in not only the simulation but also the experiment.

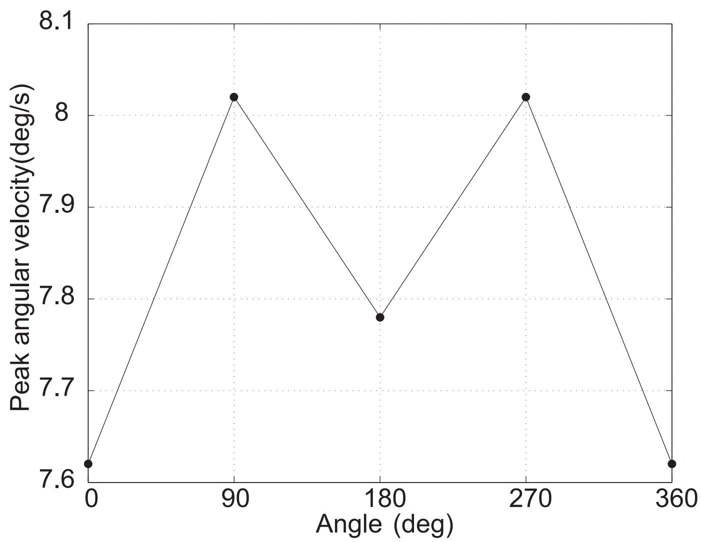

Figure 11: Peak values of angular velocity versus direction θ falling weight (Z=300mm,U=4mm)

(2) Evaluation of measured data on pile

Peak angular velocity and peak displacement measured at the top of pile in each crack location are shown in the Figure 12, Figure 13. In comparison with the FEM analysis results in Figure 8, Figure 9, peak angular velocity of crack location Z= 100mm increase greatly as crack depth increases. Peak acceleration of crack location Z= 300mm, 500mm is a little different from the results of FEM analysis. But, the tendency of a result of an experiment almost corresponds to a result of FEM analysis. It can be clear that these results show the agreement between the simulation and the experiment.

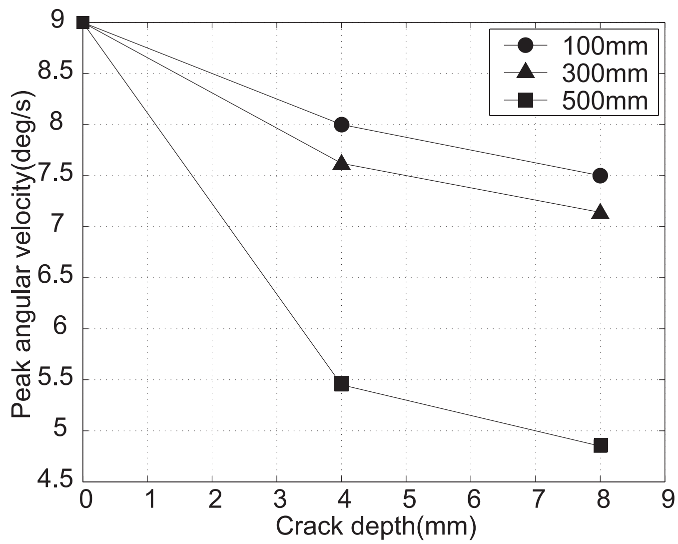

Figure 12: Peak values of angular velocity at top of pile

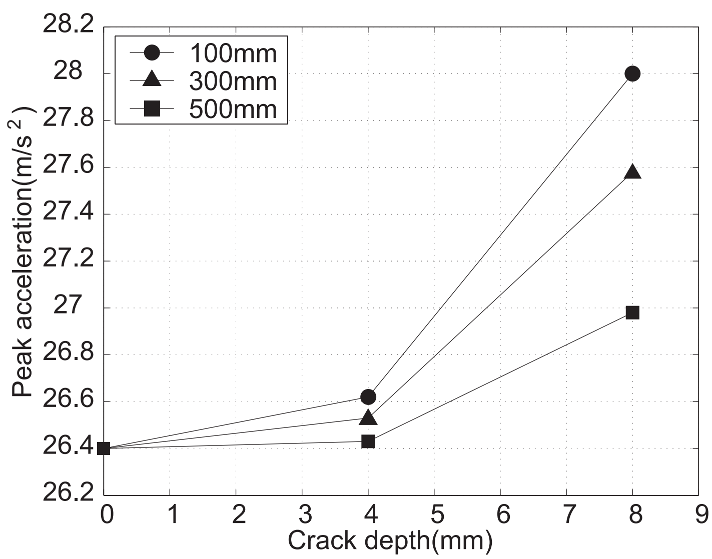

Figure 13: Peak values of acceleration at top of pile

CONCLUSIONS

In this study, the detection system of the crack in the existing pile is proposed. The wave motion propagated through the soil causes the bending motion of a pile. Namely, the position excited by an impulsive load (weight drop) is changed respectively with 0° ,90° and 180° , we measure the peak angular velocity and the peak acceleration of the top of a pile in each position and the presence of the crack and orientation of the crack are estimated from those values. By using data on the pile with a crack in 90° direction as the data on the pile with no crack, the crack location and the crack depth are also estimated. The results of experiment almost agree with the simulation results using FEM analysis. Therefore, it is confirmed that the proposed system can be applied to the actual pile. Finally the flowchart to detect the crack is shown in the Figure 14.

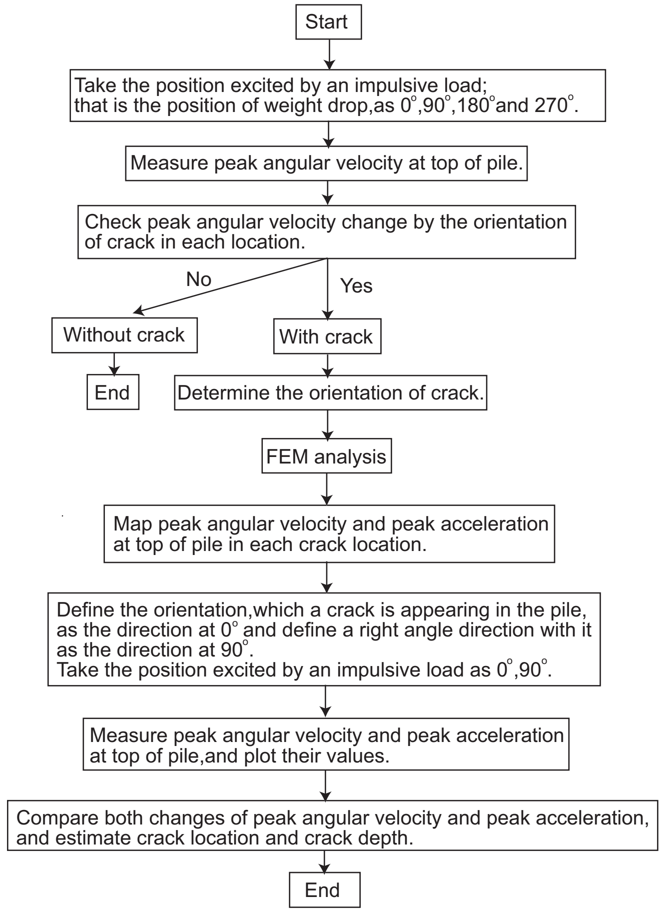

Figure 14: Flowchart of damage detection method

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