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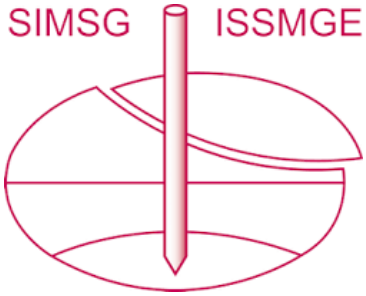

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Hydraulic model test on destabilization process of river bridge pier caused by local scours

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ABSTRACT

Local scour around the river bridge pier foundation during flood and heavy rains often causes critical tilting and settlement of the river bridge. In this study, therefore, a series of hydraulic model tests using middle size channels was performed, focusing on the destabilization of river bridge piers due to local scour. The subsoil reaction forces acting on the bottom surface of the pier model was measured at four positions, the horizontal displacement at the top of the pier and the natural frequencies of the pier model were measured during the tests. The experiments revealed that the natural frequency was the most sensitive index in detecting instability of the pier model due to local scour, among the horizontal displacement, ground reaction force distribution and natural frequency. Next, changes in the subsoil reaction forces distribution were detected, followed by changes in the horizontal displacement of the pier tops.

1. INTRODUCTION

In recent years, local scour has occurred on pier foundations of river bridges during heavy rains and river flooding, resulting in significant damage, such as bridge collapses and outflows (Enomoto et al, 2019, Takayanagi et al. 2019). This type of scour damage was previously common in the cases of old railway bridges, but recently it has been seen on well-maintained and managed roads, such as national and prefectural roads in Japan (Matsuda et al. 2019).

Figure 1 shows the piers of Kisegawa Ohashi Bridge (Prefectural Road 380) in Numazu City, Shizuoka Prefecture, which was damaged by heavy rains that have continued since July 2, 2021. The local scour of the pier foundation caused the pier to tilt toward the right bank and the girder to significantly subside in a V-shape. As seen in the photograph, there is a narrow space between the adjacent abutment and pier. The revetment was extended before the damage as the parapet of the old revetment could be seen on the inland side of the revetment on the right bank. The cause

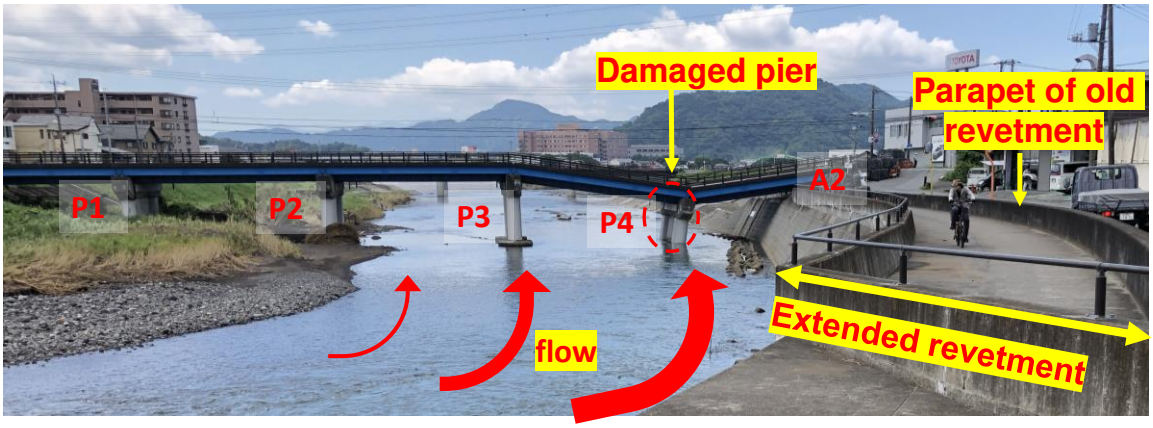

Figure 1 Damaged river bridge pier caused by scour (Kisegawa-bridge, 2021)

of the damage is believed to be a combination of two factors: the water level taking a while to reach its highest level (nearly the same as the highest recorded in 2007) and the pier being located on the outer edge of the curve where the flow speed is high. The narrow space at the outer edge may have caused the flow to contract, resulting in a higher flow speed than that at other piers. This high flow speed continuing for an extended period of time is thought to have greatly accelerated the local scour. In general, embedded depth of river bridge pier foundations are designed by considering the effects of local scour. However, the embedded depth of old river bridge may not be sufficient or may be inadequate due to constant riverbed degradation.

As illustrated in Figure 2, the damage to bridge piers caused by scour is a result of two complex phenomena: local scour of river bridge pier foundations and destabilization of bridge pier foundations. Traditional river engineering methods alone are not sufficient to fully understand these phenomena. Therefore, this study employs a combination of laboratory hydraulic model experiments and both conventional river engineering and geotechnical engineering perspectives and knowledge to gain insight into the occurrence and progression of scour. Additionally, the goal is to study the mechanism of destabilization of the bridge pier itself, which is crucial for proper maintenance and management.

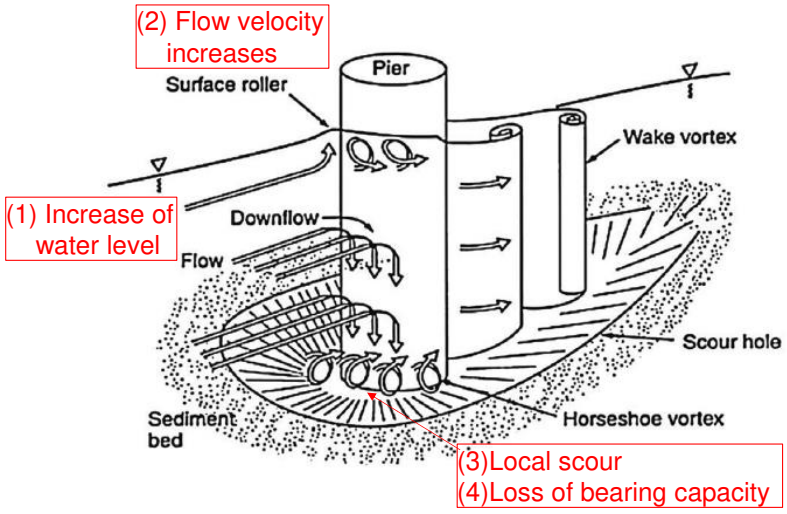

Figure 2 Destabilization of bridge pier caused by local scour (based on Melville and Coleman, 2000)

2.OVERVIEW OF EXPERIMENT

(1) Specifications of open channel and bridge pier

models, river bed ground materials

For the scour model experiment, a medium-sized open channel model with a length of 2.2 m, width of 0.6 m, and height of 0.4 m was utilized. The flow rate was adjustable using a pump, and the maximum water depth under the experimental conditions of this study was approximately 40 mm. The model experiment setup is outlined in Figure 3. The model scale was set to 1/30, and a direct foundation pier with a height of 7.5 m was used. The pier model was constructed of mortar and had an oval cross-section with a height of 250 mm, width of 70 mm, and length of 140 mm.

The ground material used in the model experiment was a full-scale replica of a typical river material with an average particle size (D_{50}) of approximately 25 mm. Silica sand No. 4 (D_{50}=0.72 mm), which is about 1/30 smaller than the actual riverbed material was used as the ground material in the model test. To investigate the impact of the particle size distribution of the riverbed material on the progression of local scour, some experiments were conducted using a ground material that was composed of a mix of silica sand No. 2 and No. 5 (as seen in Table 1).

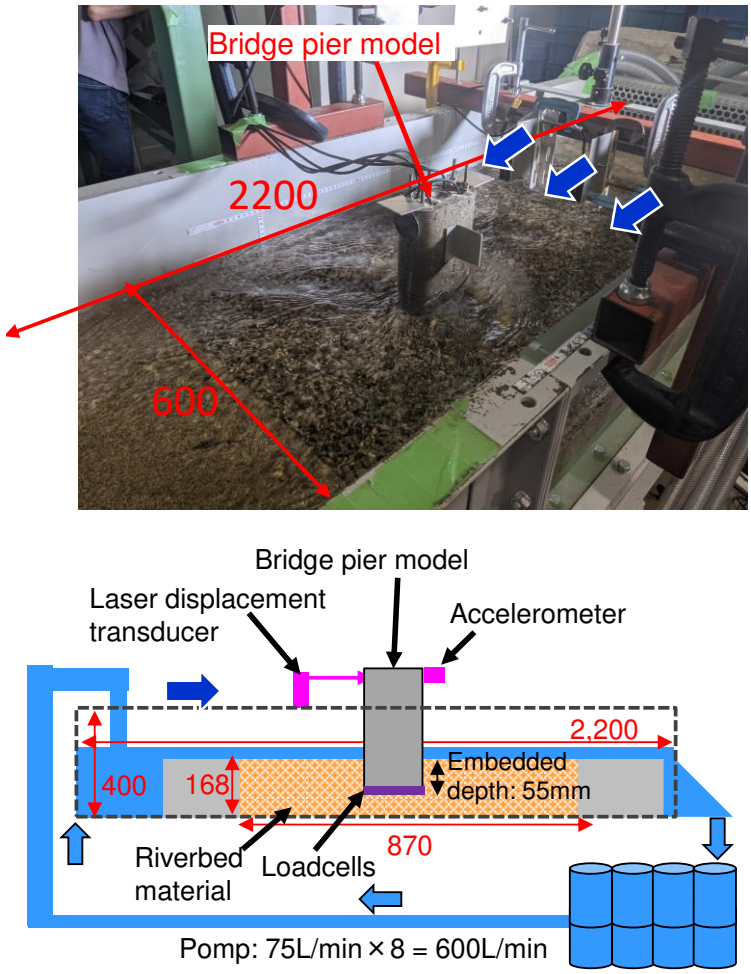

Figure 3 Overview of the model test

(2) Measurement of ground reaction force and horizontal displacement acting on bottom of pier

In order to measure the ground reaction force distribution, which changes as scour progresses, four loadcells were attached to the bottom of the pier model, as illustrated in Figure 4. The loadcells continuously recorded the force distribution over time. Additionally, the horizontal

Table 1 Dry density and mean diameters of bed material

Materials (Silica sand)	Dry density (D_r=79%) [g/cm^3]	Dry density (D_r=90%) [g/cm^3]	Mean diameter (D_{50}) [mm]
No.4	1.549	1.575	0.74
No.5	1.692	-	0.31
No.2 and No.4	1.679	-	1.3
No.2 and No.5	1.889	-	0.74

displacement of the upper end of the pier model was monitored using laser displacement transducers.

(3) Measurement of natural frequency of bridge pier

In this study, changes in the natural frequency of piers resulting from progressive scour were measured using impact vibration tests (percussion tests). This method is widely used as a non-destructive inspection method for railway river bridges in Japan (Shinoda et al. 2008). As the natural frequency decreases when local scour occurs around the pier foundation and the pier becomes unstable. However, the relationship between scour depth and decrease in natural frequency has not yet been quantitatively established. As a result, in practice, threshold values for determining the soundness of piers (i.e., foundation stability) are determined empirically. Therefore, in the model experiment of this study, impact vibration tests were conducted using the same method as the inspection of actual river bridges.

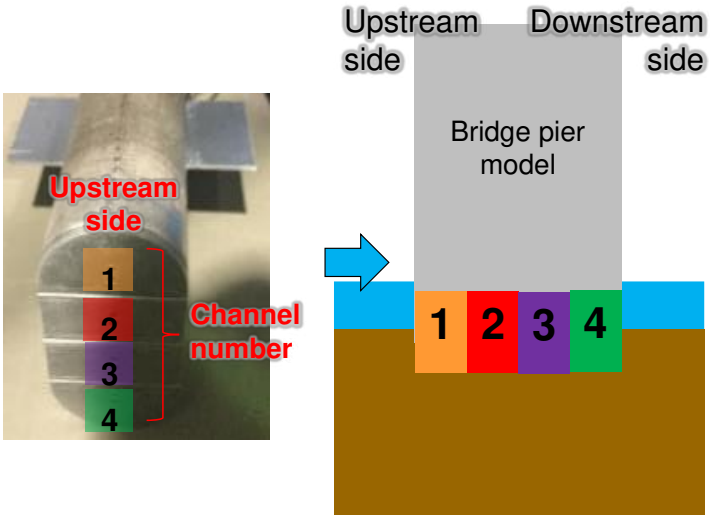

Figure 4 Four loadcells at the bottom of pier for the ground reaction force measurement

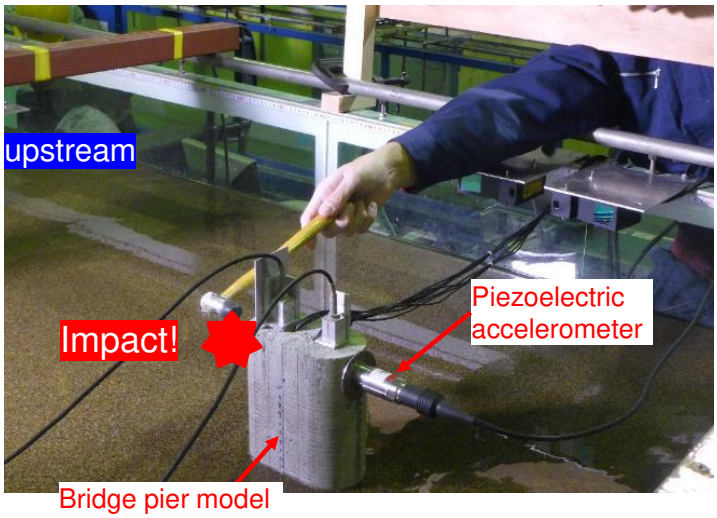

Figure 5 Impact vibration test (percussion test) for the natural frequency measurement

As shown in Figure 5, the upper end of the bridge pier model was struck with a small hammer and the response velocity during free vibration (approximately eight seconds) was measured by a piezoelectric accelerometer that was attached to the upper end of the pier model. Five small hammer impacts were repeated at each scour stage, and the measured response waveforms were superimposed and the natural frequency was calculated. It is possible that the fluid pressure near the pier may affect the measurement of the natural frequency, therefore after each flow rate stage was completed, a movable weir on the most downstream side of the water channel was raised while

the pump continued to operate, the water level was raised to a predetermined height (approximately 30 mm), and when the target value was reached, the water supply was stopped, and the natural frequency was measured in still water. Additionally, to avoid disturbing the scour shape, the movable weir was raised slowly to avoid reflected wave that generated by the operation of the weir.

The natural frequency was evaluated by identifying the frequency at which the amplitude was dominant and the phase was 0° or 180° from the Fourier amplitude spectrum and phase spectrum of the response velocity after the fast Fourier transform. The scour depth was measured along the pier by visually reading the measurement scale which was drawn every 5mm on the surface of the pier model. Since this visual measurement is made underwater, it is considered to have an accuracy of approximately 1 to 2 mm.

3. DESTABILIZATION OF BRIDGE PIERS

(1) Experimental conditions

Table 2 provides an overview of all the experiments conducted. Four types of riverbed materials were used: silica sand No. 4, silica sand No. 5, a mixture of silica sand No. 2 and No. 4, and a mixture of silica sand No. 2 and No. 5. The weight ratio (mixture) of the mixed sand of silica sand No. 2 and No. 4 was set to 37:63, to approximate the average grain size of this mixed sand (D_{50}=1.3mm) to the average grain size in the actual river that was being modeled. Additionally, the weight ratio of the mixed sand of silica sand No. 2 and No. 5 was set to 46:54, so that the average grain size of this mixed sand (D_{50}=0.74 mm) would be similar to silica sand No. 4 (D_{50}=0.74mm). The density of the riverbed material was also standardized to 79% of the relative density (D_r), but one experiment was conducted with a density of D_r=90% as a comparison. Additionally, the riverbed slope was standardized to 1/400. In the experiments, the riverbed model was made by manual compaction in the dry state and it was saturated under a low flow rate. After the completion of the saturation, the flow rate was gradually increased up to approximately 600 [L/min] by the pump, and the local scour around the pier progressed.

Table 2 Testing conditions for all experiments

	Material (silica sand)	Initial embedded depth [mm]	Relative density [%]	Initial resonance frequency [Hz]
Case8	No.4	65	79	34.3
Case10	No.4	60	79	42.8
Case11	No.4	60	90	44.9
Case12	No.5	60	79	43.6
Case13	No.5	100	79	54.1
Case14	No.2 and No.4	100	79	57.6
Case15	No.2 and No.5	100	79	57.1
Case16	No.2 and No.4	40	79	36.1
Case17	No.2 and No.5	50	79	40.6

(2) Change in Ground reaction force, pier displacement and natural frequency

Figures 6 and 7 depict the time histories of the response velocity and the Fourier amplitude spectrum when

the impact vibration test was conducted in Case 17 as examples. The Fourier amplitude spectrum was based on the average of the 5 impact loading tests.

Additionally, Figure 8 illustrates the measured ground reaction force, time history of the horizontal displacement measured at pier upper end, and natural frequency of the pier at each stage

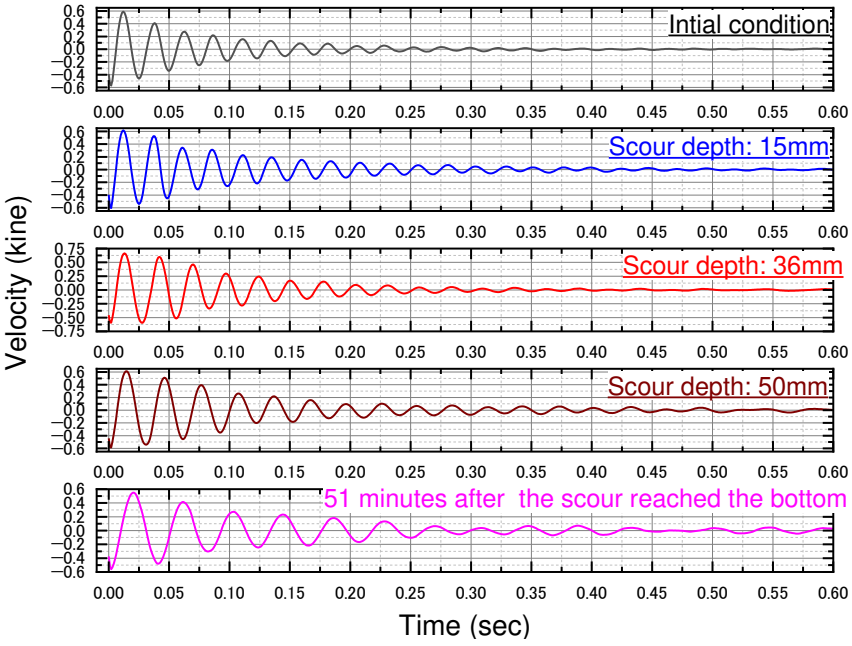

Figure 6 Response velocity of the pier model at different scour depth (measured by impact vibration tests)

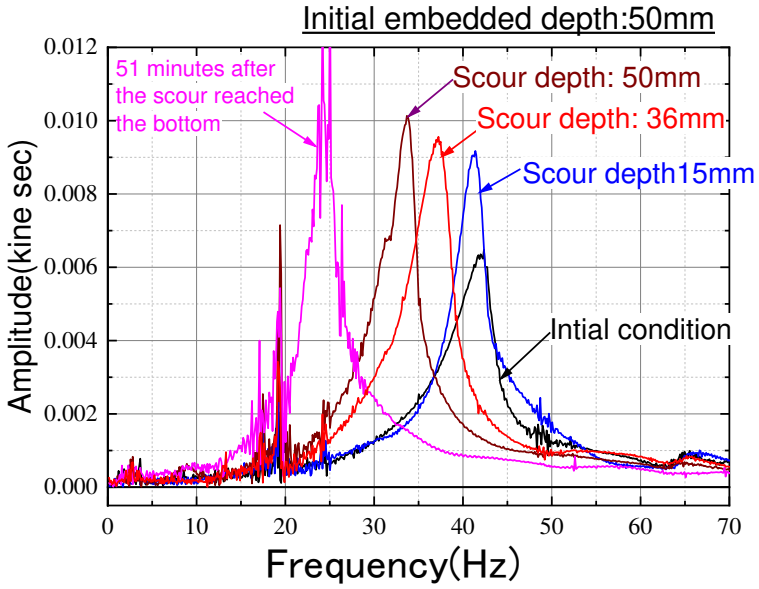

Figure 7 Fourier amplitude spectrum at different scour depth (measured by impact vibration tests, Case17)

of the experiment. In this experiment, the initial embedded depth of the pier model was 50 mm (Table 2). As shown in the pump flow rate and water depth in Figure 8, the flow rate was increased in stages by increasing the number of pumps in operation, resulting in progressive scour around the piers with each stage (as seen in Table 3).

As it can be seen from Figure 6, as scour progresses, the velocity response has a longer period and smaller damping, as evident in the Fourier amplitude spectrum shown in Figure 7.

Figure 8 and Table 3 reveal that while scour progresses gradually from the upstream tip to the side of the pier, the change in ground reaction force and pier displacement is minimal before 2,100 seconds when the pump flow reaches 600 L/min (maximum value). However, at this point, the natural frequency has already begun to gradually decrease (40.6 Hz→36.5 Hz). Furthermore, it can be observed that the ground reaction force begins to change significantly approximately 2,400 seconds, which was approximately 300 seconds after the pump flow rate reached 600 L/min (maximum value). Notably, the ground reaction force of loadcell No. 1 (most upstream side) and No. 4 (most downstream side) decreased, and conversely, the ground

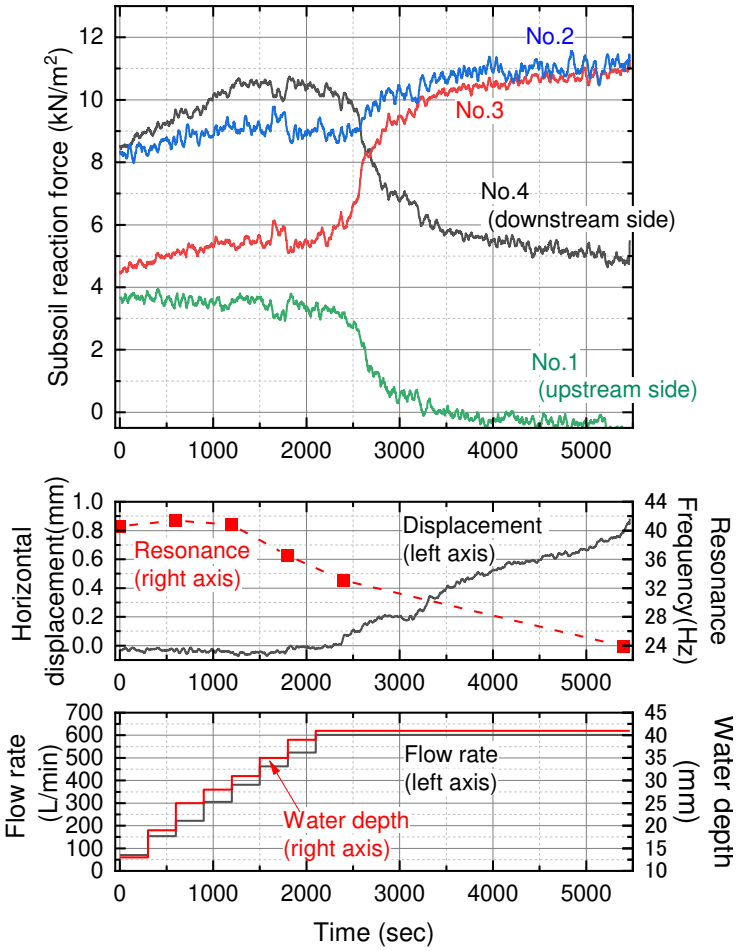

Figure 8 Time history of ground reaction force, horizontal displacement measured, natural frequency of the model pier and flow rate (Case 17)

Table 3 Scour depth around the bridge pier model at each stage (Case 17)

Time (sec)	Scour depth(mm)				Resonance frequency (Hz)
	Upstream tip	Left side	Right side	Down stream tip	
0	0	0	0	0	40.6
600	0	0	0	0	41.4
1200	15	3	5	1	40.8
1800	36	22	22	-4	36.5
2400	50	36	32	-9	33.1
5400	More than 50	43	35	5	23.9

*Scour depth is positive when sediment is scoured and negative when sediment is deposited.

reaction force at the center of the bottom (loadcells No. 2 and No. 3) increased. The scour depth on the upstream side of the pier exceeds the initial penetration depth (50 mm) at approximately 2,400 seconds (Table 3), indicating that the piers have transitioned to a state where they are supported mainly by the ground at the center of the bottom instead of the entire bottom. At this point, the natural frequency dropped to 33.1 Hz, which is 81% of the initial value.

Based on the experimental results, it can be inferred that the destabilization of bridge piers due to local scour is greatly influenced not only by the flow rate and water depth, but also by the duration of scour. Specifically, after 2,400 seconds when a constant pump flow rate was maintained, scour on the side of the pier further progressed (as seen in Table 3), accompanied by increased horizontal displacement and the ground reaction force on the most upstream side (loadcell No. 1) becoming almost zero approximately 4,000 seconds. As a result, the natural frequency decreased significantly from 33.1 Hz to 23.9 Hz.

This experimental result suggests that the destabilization of the bridge pier was first detected as a change in the natural frequency, and when the scour depth reached the initial embedded depth, the ground reaction force changed significantly, resulting in horizontal displacement. Although only the results of Case 17 are shown here, it was confirmed that this tendency did not depend on the type and density of the river bed material and the initial penetration depth of the piers.

(3) Relationship between scour depth and natural frequency

Figure 9 illustrates the relationship between the natural frequency normalized by the initial natural frequency, and the average scoured depth/initial embedded depth of the pier. The average

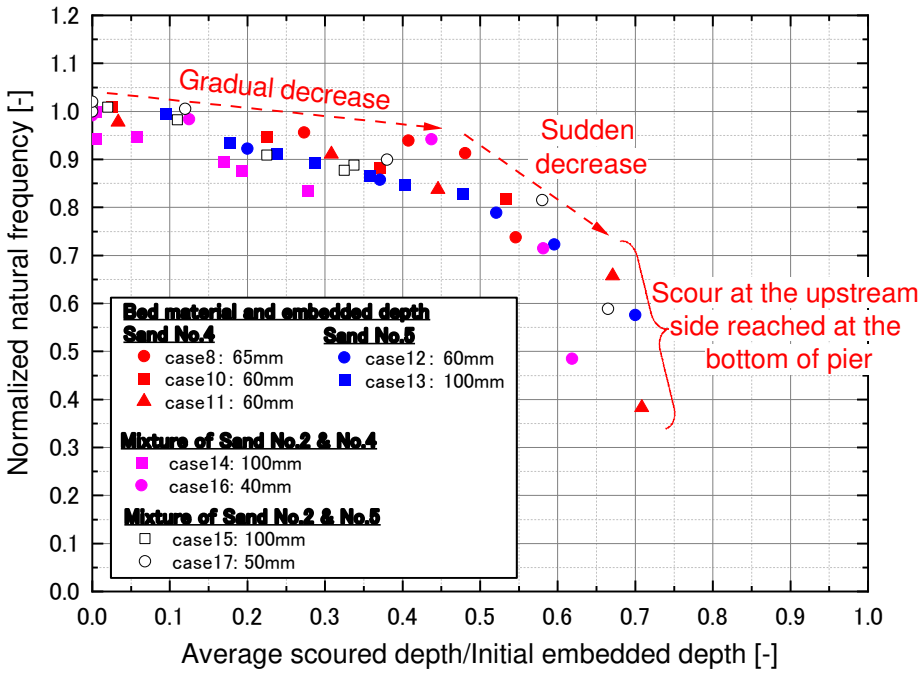

Figure 9 Relation between normalized natural frequency and embedded depth (measured by impact vibration tests, Case 17)

scour depth was measured at four locations around the pier model that was visually measured at each stage during the experiment (as seen in Table 3). From this figure, it can be observed that the natural frequency decreases as scour progresses in all experimental cases. During the initial stage of scour (i.e., average scoured depth increases to approximately 50% of initial embedded depth), the natural frequency decreased by approximately 20%, indicating a gradual decrease. This is because the local scour is limited to the side of the pier (particularly on the upstream side) and has not yet reached the bottom of the pier. In other words, it can be inferred that the natural frequency gradually decreased because the horizontal confining pressure of the ground acting on the pier decreased due to the scour around the pier.

The results of the experiment indicate that when local scour progressed further and the average scoured depth became 60% or less of the initial embedded depth, the natural frequency sharply dropped. This is likely because the local scour around the pier (particularly on the upstream side) reached the bottom of the pier model, reducing the effective width of the pier foundation, leading to rapid destabilization of the pier model. In the maintenance and management of railway river bridges in Japan, piers are considered to require special attention if the natural frequency of the bridge pier is 30% or more lower than the initial natural frequency. This 30% reduction threshold is based on previous experience, but it can be said to be generally appropriate based on this model experiment.

It can be seen from Figure 9 that the above-mentioned tendencies were consistent across all the experimental data obtained in this study and did not depend on the type and density of the riverbed material, nor on the initial embedded depth. In other words, under the conditions examined in this experiment, the natural frequency of the pier model is thought to be more affected by the constraint conditions of the pier model than by variations in the riverbed material.

4. CONCLUSION

In this study, a series of hydraulic model test on scour around the river bridge pier foundation was performed, and the following conclusions were drawn;

1. The sensitivity of detecting the destabilization of the pier model due to scour was highest when measuring the natural frequency of the pier, followed by the changes in ground reaction force distribution and then the changes in horizontal displacement at the top of the pier. This is because the natural frequency is immediately affected by the local scour of the side of the pier foundation, while changes in ground reaction force distribution and horizontal displacement are only observed when the scour reach to the ground beneath the foundation.
2. This study suggests that if deformation, such as residual displacement or subsidence at the top of the bridge, is observed during inspections after heavy rains, it may indicate that local scour has progressed significantly at the pier foundation.
3. The experimental results show that as the same flow rate is continued, local scour progresses over time, resulting in a decrease in the ground reaction force, an increase in the horizontal

displacement, and a decrease in the natural frequency. These phenomena suggest that the destabilization of bridge piers due to local scour is greatly affected by not only the maximum flow rate and water depth but also the duration of these condition.

4. The results also indicate that when the average scoured depth became 60% or less of the initial embedded depth, local scour of the ground immediately beneath the foundation begins, resulting in a decrease in the effective width of the bottom of the pier foundation and a rapid decrease in the natural frequency.

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