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Movement of Bridge Pier by Water Flow Under Flood Condition

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ABSTRACT

The foundation of bridge pier is scoured by water flow at the flood condition and this condition makes some changes on the support system of bridge foundation by soil mechanics. Namely some parts of soil foundation are scoured by water flow and the support force for bridge pier by this part is diminished at flood condition.
In this report, the authors show the results of model test on the vibration phenomenon by water flow under the flood condition to compare the feature of vibration between at flood condition and at non flood condition. The natural vibration of bridge pier is so different not only scored effects but also the surrounded water such as the frequency of locking motion of bridge pier becomes lower by added mass of water to compare the one at the non flood condition. Furthermore the vibration under the water flow shows some periodic motion combining the natural vibration motion of locking. The several results by different support condition of foundation are shown by changing the flow condition.

PREFACE

Bridge piers have potentially possibility that there happened harmful alteration such as inclination or settlement during flood time(J.Tanak et al, 2000). Main causes of those pier damages are considered by scour around the base due to strong stream flow. However, it is very difficult to evaluate the soundness of bridge pier, because nobody could confirm the base ground directly during flood. Because piers are normally supported by the rigid base ground, the change of supporting condition would affect to the vibration feature of the pier itself, that is, a dynamic characteristic(O. Suzuki et al, 2000).
Therefore, if supporting condition can be quantitatively observed by any measurement equipment, the running safety of the train on the railway bridges after and/or during the flood will be remarkably improved. However, few research papers treat the problem on the vibration properties of the bridge pier by flood condition especially related to the damage of pier. Therefore, we have performed fundamental hydraulic experiments to study the vibration of a cylindrical model pier supported by different steel springs.

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MODEL OF BRIDGE PIER

Bridge pier is usually constructed on hard ground basement or on the base which is supported on piles and is considered to be supported by elastic base such as locks and piles. As the ground materials around pier are removed by water flow at flood condition, the supported condition becomes to be changed and elastic supported system is also changed. The model bridge pier is made by spring supported system to be considered by similarity on field's pier and the change of basement by flood is adapted by the strength of spring plate. In model test, authors used two different plate spring and two different supporting length and also two different supporting systems such as four points support and three points support.

The vibration systems in model are three freedoms as vertical motion and rotation motion in two directions which are perpendicular to each other. And the vertical motion is very smaller than rotation motion by the deformation of plate springs, the analysis on model test data is mainly done to the rotational motion.

Model bridge piers are shown in figure 1 as four points support is the left hand side and three points support is right side, and dimensions of pier are as follows.

Height L is 30.7cm, diameter d is 8.8cm and distance of support by plate spring d1 is 5cm. Plate springs are used in two type as A (length is 103mm and width is 16mm) and B (length is 103mm and width is 26mm).

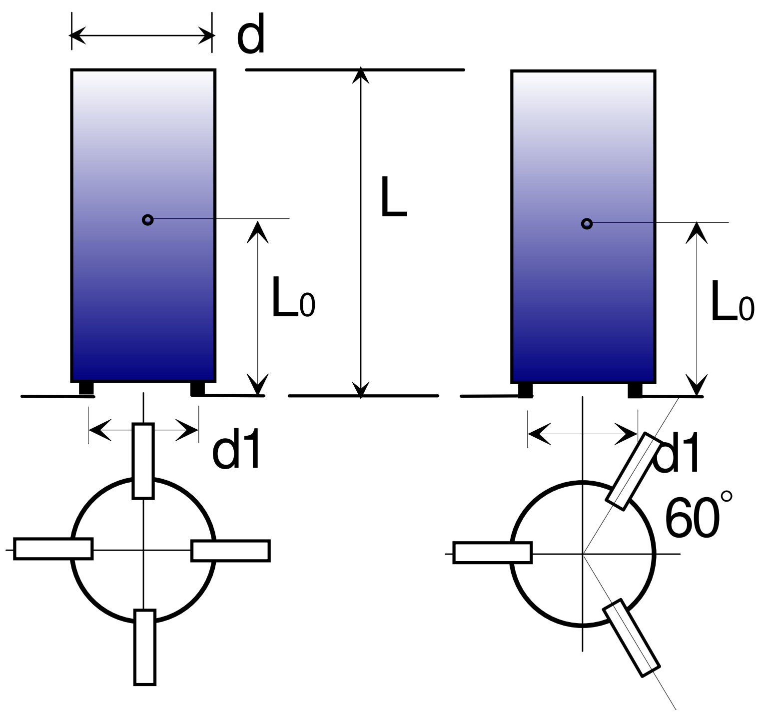


Fig.1 - Model Pier and Support System

THEORETICAL MODEL

As shown in figure 1, model piers are arranged two support systems as four points support and three points support, so the equations of motion must be made for these two support systems. When the pier moves in the water, it affects on the water movement and pier is also affected by velocity of water. Generally when the body makes accelerated motion in water, it must be considered added mass by surrounded water of body. This phenomenon is very familiar of hydrodynamic pressure on dam surface in reservoir at the earthquake conditions.

Coordinate system in model pier is shown in figure 2 for experimental model shown in figure 1. The equations for vibration is made under the water depth is h from the base of plate spring is fixed.

The rotational vibration in experimental model pier is larger than vertical movement, so the equation of vibration is shown only for rotational motions here.

At first added mass around the pier in water is written as equation (1) by distributed on pier surface with length dz.

$$dM_w = \rho C_w A dz \qquad \cdots\cdots(1)$$

Here C_w is coefficient of added mass, A is horizontal section of pier and ρ is density of water. So the moment of inertia I_w by this added mass at origin o is derived as equation (2).

$$I_w = \int_0^h z^2 dM_w = \int_0^h \rho C_w A z^2 dz = \rho C_w A \frac{h^3}{3} \qquad \cdots\cdots(2)$$

And moment of inertia by mass of pier is given as equation (3) when the mass of pier is M and its gravity center is laying at height L_0 from the base of plate spring.

$$I = M L_0^{\,2} \qquad \cdots\cdots(3)$$

For four points support system, plate springs are arranged with two different stiffness for x and y directions respectively. But in three point support system, it is arranged with same stiffness at three points.

The basic equations of vibration for model pier are shown from equation (4) to (6).

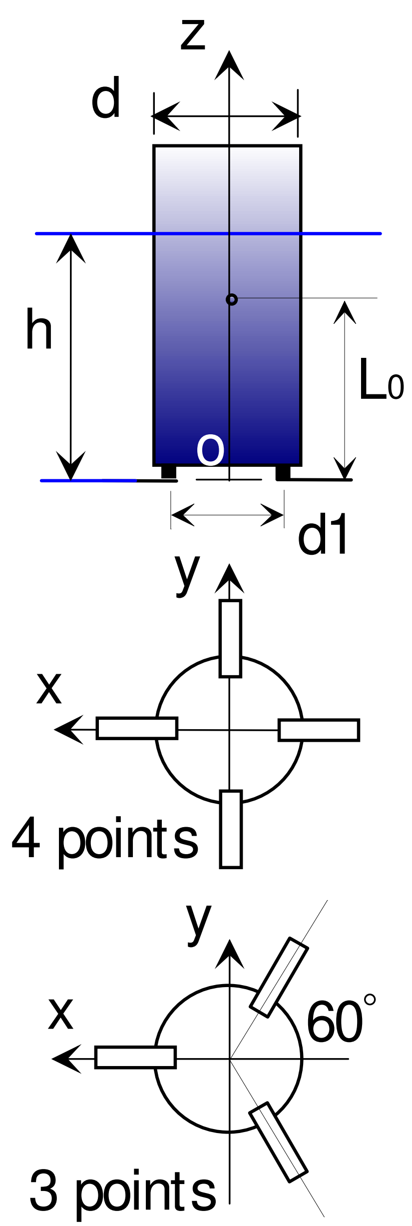


Fig.2 - Coordinate System

For four points support system, equation (4) and (5) are given for rotational motion of x and y direction.

$$\left(M L_0^{\,2} + \rho C_w A \frac{h^3}{3} \right) \frac{d^2\theta_x}{dt^2} + R_{2x} \frac{d\theta_x}{dt} + 2k \left(\frac{d_1}{2} \right)^2 \theta_x = F_{\theta_x} \qquad \cdots\cdots(4)$$

$$\left(M L_0^{\,2} + \rho C_w A \frac{h^3}{3} \right) \frac{d^2\theta_y}{dt^2} + R_{2y} \frac{d\theta_y}{dt} + 2k \left(\frac{d_1}{2} \right)^2 \theta_y = F_{\theta_y} \qquad \cdots\cdots(5)$$

Here θ_x and θ_y are movement of angle for direction x and y respectively at origin o and $F\theta_x$ and $F\theta_y$ are external force for each directions. For three points support system, equation (6) gives basic vibration equation for ax and y directions in same expression.

$$\left(M L_0^{\ 2} + \rho C_w A \frac{h^3}{3}\right)\frac{d^2\theta}{d t^2} + R\frac{d\theta}{d t} + \frac{3k}{2}\left(\frac{d_1}{2}\right)^2 \theta = F_\theta \qquad \cdots\cdots(6)$$

In these equations, R, R_x and R_y are damping constants for vibration in each direction. When the external force does not act on the pier, these equations show the natural damping conditions. Natural frequencies for these equations are written as equation (7) and (8).

$$f = \frac{1}{2\pi}\frac{d_1}{2L_0}\sqrt{\frac{2k_i}{M}}\frac{1}{\sqrt{1+\frac{\rho C_w A h}{3M}\left(\frac{h}{L_0}\right)^2}}, \quad i = x, y \qquad \cdots\cdots(7)$$

$$f = \frac{1}{2\pi}\frac{d_1}{2L_0}\sqrt{\frac{3k_i}{2M}}\frac{1}{\sqrt{1+\frac{\rho C_w A h}{3M}\left(\frac{h}{L_0}\right)^2}} \qquad \cdots\cdots(8)$$

It is very interesting that the effect of water depth on natural frequency is given by three power term of h. This means that pier under flood condition has decreasing of natural frequency in three power term of h and has some difficulty for the response of pressure change by water flow under the flood.

EXPERIMENTAL RESULTS

Experiments in model pier are made two types such as using the vibration table and using water flow channel. Test by vibration table has done by model pier is fixed in the box that supporting spring plate are arranged and this box is placed in water tank.

Fig.3 - Pier Box

Fig.4 - Four Point Plate Spring

The figure 3 and 4 are shown pier box and four points plate spring with pier model and vibration table and water tank which placed on vibration table are shown in figure 5 and 6.

Pier box as shown figure 3 is fixed in the water tank when vibration in water is measured.

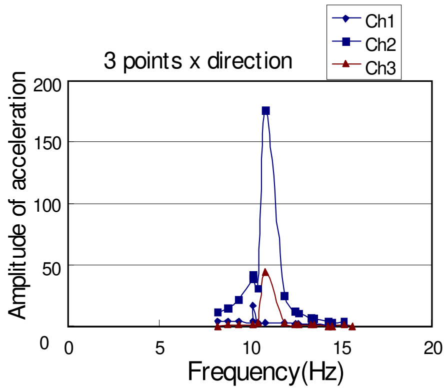
Fig.5 - Vibration Table

Fig.6 - Water Tank

Test by Vibration Table

Vibration table can be operated continuously to be varied frequency from 5 Hz to 20 Hz in 10 minuets intervals under constant output power. Movement of pier is measured at three points by accelerometer which are attached on the top of pier for x and y directions and base at vibration table for x direction. Data are collected by data logar which can take the data in 0.01 second intervals and treated by Excel Soft in personal computer.
Experiment has been done both in air and in water by using two type spring plates under four and three supporting system. Here the typical results by test are shown.

1) Three points support system
The natural frequency for x and y directions are same in theoretical analysis and this is confirmed by experimental test as follows. Response curves in frequency and amplitude of acceleration are shown in figure 7 and 8 for x and y direction in air and the peak value of channel 2 has almost same value in these two graphs as 11.1Hz and 10.9Hz. The difference of these is only 0.2Hz and 2% of value. This result shows good relations for theoretical analysis. But when the amplitude becomes larger for vibration direction, the motion of perpendicular direction for this also becomes larger. This feature is different from the response of four points support system, because an irregularity in fixed point of spring may affect on this motion.



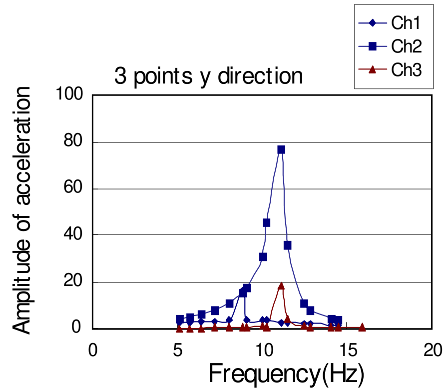
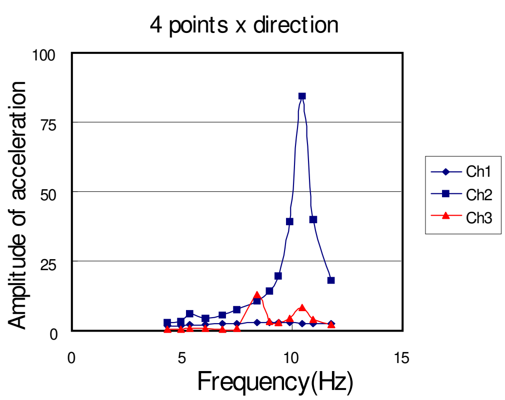


Fig.7 - Three Points x Direction

Fig.8 - Three Points y Direction

2) Four point support system

Response curves in four points support system are shown in figures 9 and 10 in the case that the stiffness supporting plate is different as the one of x direction is stronger than y direction. The natural frequencies for x and y directions are10.5 and 8.25 Hz respectively can be found as peak point in figure 9 and 10.



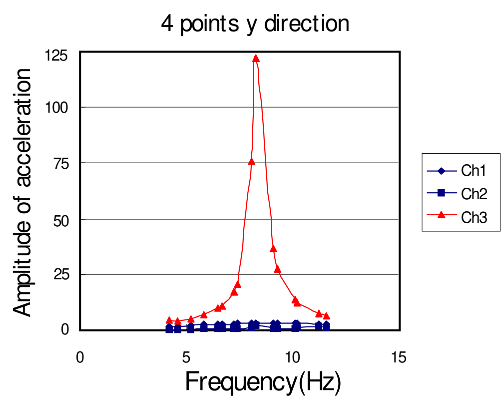


Fig.9 - Four Points x Direction

Fig.10 - Four Points y Direction

In these graphs there is a difference in figure 9 compared to figure 10 as that response of y direction arises at natural frequency of y direction and also at natural frequency of x direction. In the case of weak spring constant, motion can occur easily by some irregular support conditions same as three point support system.

3) Response in water

The response in water for four point support is shown as an example and analysis on this result is treated with the data of test in water flow channel. When water depth is changed from 0 to 19cm in step 10, 15 and 19 cm, natural frequency is decreasing and its results are shown in figure 11.

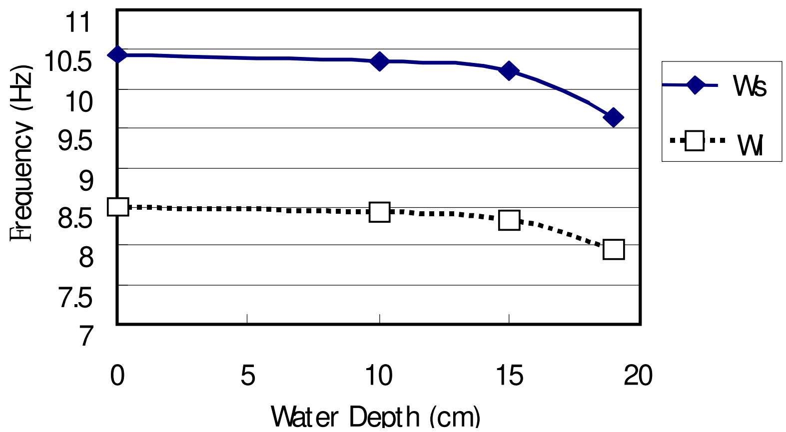


Fig.11 - Frequency Change with Water Depth

Frequency is decreasing about 10% from in air to 19cm water depth in figure 11, and this feature has good correlations to the theoretical analysis.

Test in Water Flow Channel

In water channel, two type data are collected as natural frequency by damping vibration and vibration in flow. In this report, authors focus on the variation of natural vibration in water especially, so the data on how the natural frequency in the water is changed is summarized in this chapter.
The test has been done in several cases combining the stiffness of plate spring, mass of bridge pier with sand or without sand and water depth. The typical record of damping vibration is shown in figure 12; the natural frequency and damping ratio are calculated from this record.

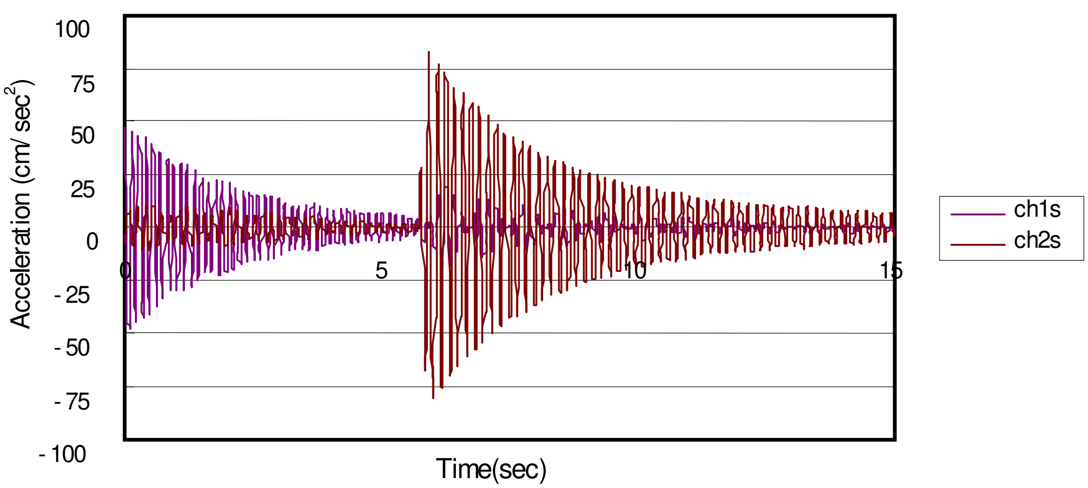


Fig.12 - Damping Vibration in Water Flow Channel

In this figure, channel 1 shows the vibration of x direction and channel 2 shows the one of y directions. They show very fine damping vibration curves. From these observation data, natural frequency and damping ratio are collected in two direction x and y which are flow direction and perpendicular direction of flow and those values are different with the amount of water depth.

1) Spring constant

Spring constant can be derived from the data in air by using data of mass and inertia of pier from three points support and four points support conditions and the results are 1800 N/cm in long span and 2600 N/cm in short span fixed case in both support systems with B type plate (width is 26mm). A type spring plate has 1650 N/cm and 890 N/cm for short and log span fixed case respectively.

2) Natural frequency in water flow and added inertia in water flow

Experiments in flow are carried in variation of mass of pier and stiffness of spring constant as shown in Table 1.

Table 1 - Cases in Water Flow

Case	Spring type	Mass g	X N/cm	Y N/cm
N	B	1220	1800	2600
S	B	3000	1800	2600
F	B	3000	2600	1800
A	A	1220	1650	890
B	A	3000	1650	890
C	A	3000	890	1650

Experimental data in these cases gives many results on natural frequency and damping ratio. The main interest is the variation of natural frequency by water depth changes and an example of case N is shown in figure 13.

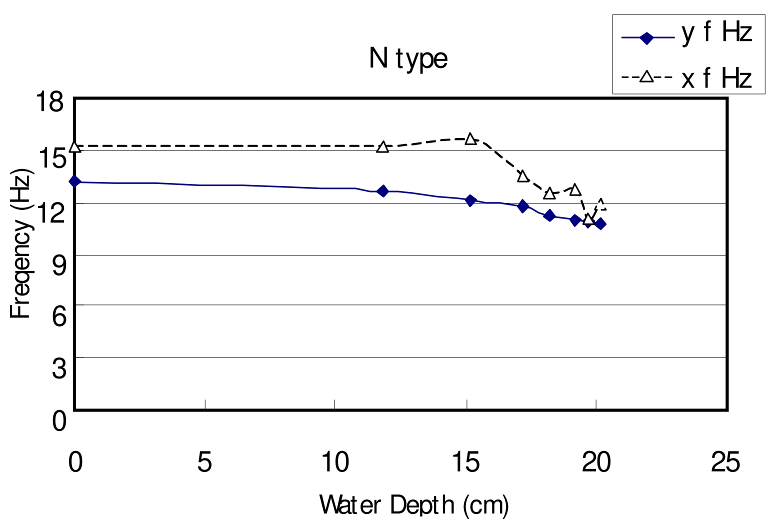


Fig.13 - Natural Frequency in Water Flow

As shown in figure 13, natural frequency decreases with the water depth is increasing, this means that the inertia of pier must be increased because the spring constant does not changed. This change is derived from the term in equation (7).

$$dM = \frac{\rho C_w A h}{3}\left(\frac{h}{L_0}\right)^2 \qquad \cdots\cdots(9)$$

The value of dM can be calculated from data by using the equation (7) and after that, the evaluation for equation (9) has been done. An example of the relation between natural frequency and added mass is shown in figure 14 as the case A.

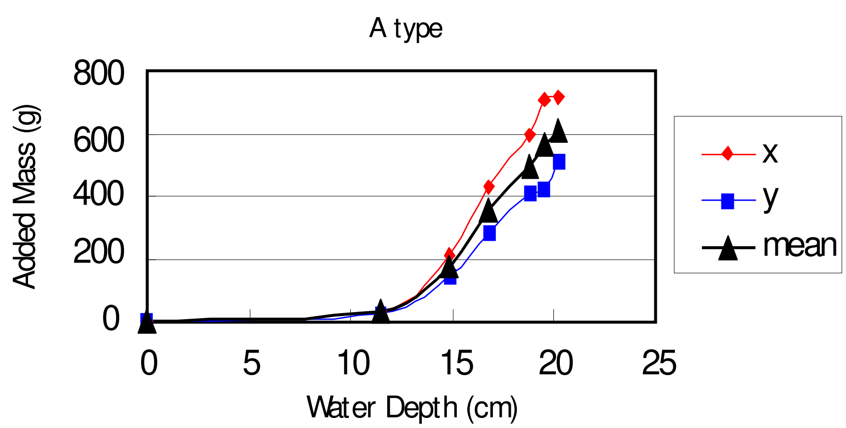


Fig.14 - Added Mass Inertia in Water Flow

Inertia by added mass is increasing great with water depth is increasing as shown in figure 14 and the values of x and y direction are different is different. These features can be seen in the cases A, B and C without the cases N, S and F. This main difference may be a stiffness of plate spring in this stage.

3) Consideration on added inertia

There is a difference in added inertia between cases N, S and F and cases A, B and C as mentioned above, such the value of dM has a difference of value in directions X and Y in cases A, B and C. But it is almost same value in cases N, S and F. This relation is clearly understood in figures 16 and 17 as there can be seen two different area in cases A, B and C. In these graphs, the most fitted line is drawn by calculating the value C_w in equation (9) from the data. The value of C_w is shown in table 2 with the value of spring constant k.

Table 2 - Value of C_w

Case	k N/cm	Cw
N,F,S	2700	1.591
N,F,S	1800	1.568
A,B,C hard	1650	1.109
A,B,C soft	890	0.8112

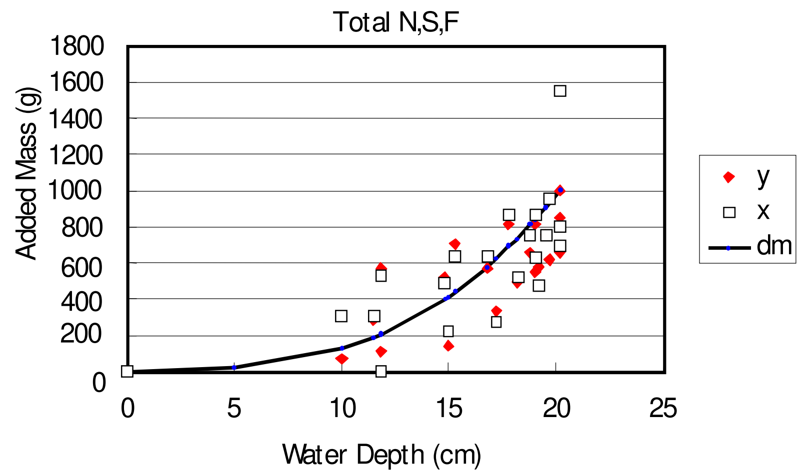


Fig. 15 - Cases N, S and F

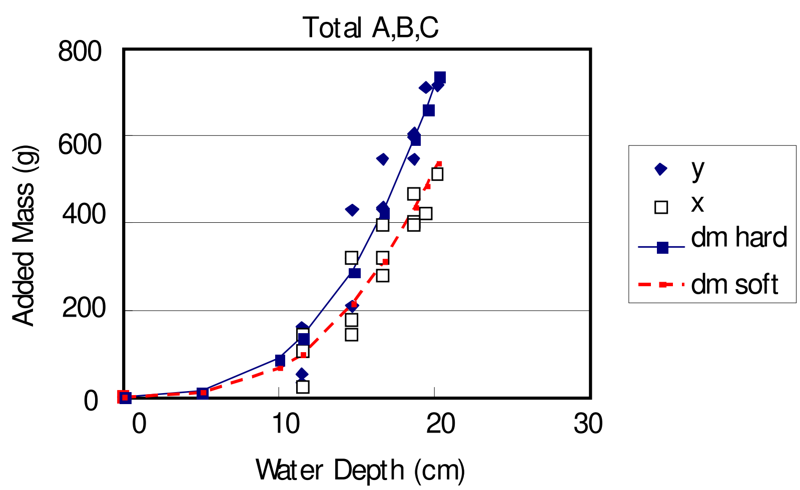


Fig. 16 - Cases A, B and C

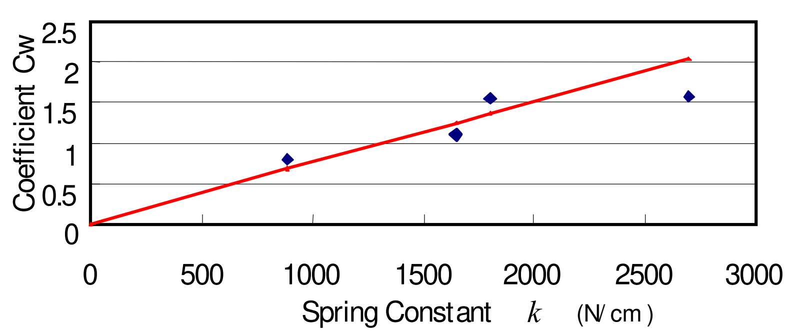


Fig. 17 - Relation between C_w and k

The value of C_w is not constant in all cases but it is related to the spring constant as it becomes greater with the spring constant as shown in table 2 and figure 17. It is not clear why it becomes greater in this stage, it must be made to be clear in next model test.

4) Damping ratio in water flow

There can be seen a difference in damping ratio with the difference of direction as flow direction or perpendicular direction of flow. The typical example is case C as shown in figure 18.

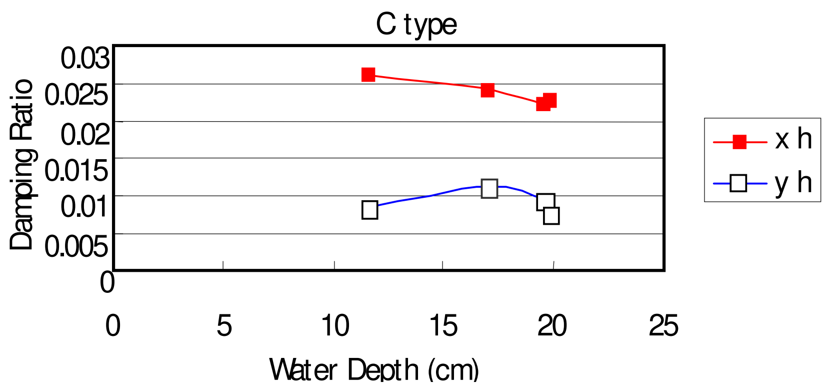


Fig.18 - Damping Ratio in Case C

Direction x in this figure is corresponding to water flow direction and y is perpendicular direction of flow. The value of y direction has 1/2.5 of value of x direction and this shows the possibility of continuous vibration by water flow. This point also gives the interests on vibration of pier under the flood conditions.

CONCLUSION

The model test of bridge pier related to the flood condition has developed without the similarity between fields bridge pier, but the very interesting results can be derived on the added inertia under the water. It has three power terms of water depth h and has good correlations between theoretical analysis and the results from model test.

There remains many interesting problems in this phenomenon such as the relations to water velocity and flow pattern around the pier and the similitude the phenomenon to fields bridge pier especially under the flood condition. This research work is two years program between JR and Toyo University from 2001 to 2002. These remained problems are studying in model test and theoretical analysis in this year.

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