Calculation Method of Hydrodynamic Pressure in Seismic Response Analysis of Gates

by

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ABSTRACT

In order to maintain dam storage functions, it is essential to guarantee the safety of the dam body and appurtenant structures which are use to control the flow of water from the dam reservoir, i.e. gates and so on.

This report describes a study on basic characteristics of hydrodynamic pressure acting on gates during an earthquake based on numerical analysis that considered vibration of dam bodies and gates, and based on its results, proposes a method of calculating hydrodynamic pressure during an earthquake in the seismic performance evaluation analysis of gates.

KEYWORDS: Gates, Hydrodynamic Pressure, Guideline, Seismic Performance Evaluation,

1. INTRODUCTION

The Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes (Draft) [1] (Below "The Guideline") issued by the Ministry of Land, Infrastructure and Transport in March of 2005 stipulates two requirements concerning seismic performance that a dam must ensure under level-2 earthquake motions: "It shall maintain its water storage function," and, "damage caused shall be within a repairable range." In order to maintain dam storage functions, it is essential to guarantee the safety of the dam body and other parts of its structure including gates. So the Guideline divides the objects for a evaluation into dam body (body of the dam and parts of the foundation in contact with the dam body) and appurtenant structures etc. (structures and systems of various kinds that are installed on or around the dam body to maintain the functions of the dam) and stipulates the fundamental concepts of the evaluation methods for each.

When an actual seismic performance evaluation is done, gates of discharge systems are generally selected as appurtenant structures etc., which needed to maintain the dam's water storage function. Gates include those installed on the dam crest, those installed at high elevations inside the dam body and there are several types of gates, so the evaluation analysis method for gates is studied considering the characteristics of each gate. Gates, even those installed in dam bodies, generate vibrations separate from those of the dam body, so the analysis model used must be one capable of correctly representing the vibration properties of the gate itself. And hydrodynamic pressure from the reservoir during an earthquake acts on the gates in the same way it acts on the dam body. Because the self-weight of a gate is low, the hydrodynamic pressure acting on a gate from the reservoir has a greater impact on the dynamic behavior of structures than that acting on the dam body. Many research activities concerning hydrodynamic pressure during an earthquake that is generated by vibration of the dam body have been reported [2], but there have been little studies of hydrodynamic pressure accompanying the vibration of gates.

This report describes a study of basic characteristics of hydrodynamic pressure acting on gates during an earthquake based on numerical analysis that considered vibration of dam bodies and gates, and based on its results, proposes a method of calculating hydrodynamic pressure during an earthquake in the seismic performance evaluation analysis of gates.

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2. CONCEPT OF SEISMIC PERFORMANCE EVALUATION OF GATES

The Guideline provision regarding appurtenant structures that have been selected for evaluation stipulates that, "It shall be confirmed that even if the appurtenant structures etc. are damaged, the water storage function of the dam will be maintained by seismic response analysis or other appropriate method performed according to the functions and structural properties of the appurtenant structures etc."

It is technologically possible to analyze a dam body and to simultaneously model and perform seismic response analysis of its gates. But an example of an FEM model of the dam body and an example of an FEM model of a radial gate are shown on the left side and right side respectively of Fig. 1, and in order to appropriately represent the vibration properties of a gate, it must be modeled with elements with much more precise dimensions than those of the dam body. So practically, the seismic response analysis of the dam body and the gate should be done separately. In this case, first the seismic response analysis of the dam body is done, then the response acceleration is calculated at the locations where the gate is installed (for example, the location of the trunnion if it is a radial gate installed in the dam body and the location of the rollers if it is a roller gate). The response acceleration can be handled as input earthquake motion for the seismic response analysis of the gate. It is evaluated by obtaining the stress or deformation produced in each member of the gate by seismic response analysis. The seismic response analysis must consider the gate's self weight and the hydrostatic pressure as the static load, and must also appropriately consider the inertia of the gate itself and the impact of the hydrodynamic pressure acting on the gate during an earthquake.

3. OUTLINE OF STUDY OF HYDRODYNAMIC PRESSURE ACTING ON GATES

3.1 Hydrodynamic Pressure in Present Design Method in Japan

Under the present design method in Japan [3], the gate is designed considering the static seismic load (inertia) that is represented by the design seismic coefficient in the same way as in the design of the dam body, and the hydrodynamic pressure that is calculated using Westergaard's hydrodynamic pressure equation [4] that is shown in equation (1).

$$p_d = 0.875 W_o \cdot k\sqrt{H \cdot h} \quad \cdots\cdots\cdots\cdots \quad (1)$$

Where:

p_d : Hydrodynamic pressure (kN/ m^2)

W_o : Unit weight of the water (kN/m^3)

k : Design seismic coefficient

H : Depth from the reservoir water surface to the foundation (m)

h : Depth from the reservoir water surface to the point of action of hydrodynamic pressure.

But Westergaard's hydrodynamic pressure equation is an equation induced by hypothesizing that the dam body is a rigid body. Observations of dam behaviors during earthquake have revealed that in fact, the higher on the dam body, the larger the vibrations produced. Applying Westergaard's equation to evaluate the hydrodynamic pressure on a gate is equivalent to assuming a situation in which the gate vibrates the same way as the dam body or ignoring the impact of the vibration of the gate itself.

3.2 Concept of Hydrodynamic Pressure on a Dam Body in Seismic Response Analysis

Studies of hydrodynamic pressure acting on dam bodies during earthquakes generally treat the stored water as a compressible (non-cohesive) fluid body. When the compressibility of stored water is considered, the hydrodynamic pressure is affected by the frequency of the input earthquake motion, causing the resonance phenomenon under certain frequencies. But if the energy absorption at the bottom of the reservoir is also considered, the resonance phenomenon becomes gentler [5] and the actual earthquake motion includes a variety of frequency components, so the resonance phenomenon in reservoir water is not remarkable. So even if it is handled as a non-compressible (non-cohesive) fluid body, analysis that is approximate but provides adequate precision can be performed. The hydrodynamic pressure equation and solution that

Westergaard studied obtains hydrodynamic pressure in a case where originally it is treated as a compressive non-cohesive fluid body, but the so-called Westergaard's hydrodynamic pressure equation that is regularly used for dam design represents the distribution of hydrodynamic pressure in a case where the frequency of the input earthquake motion is fixed at about 4/3Hz, and can be almost approximated by the hydrodynamic pressure distribution obtained assuming a non-compressive fluid body in a case of rigid body vibration of the dam body.

And when performing non-linear analysis to consider damage to the dam body [6] in particular, the modeling of the reservoir should be as simple as possible for the sake of more efficient calculation. For this reason, dynamic analysis of dam bodies is even now conducted while considering the hydrodynamic pressure during an earthquake based on Westergaard's hydrodynamic equation.

3.3 Study Based on Numerical Experiments Concerning Hydrodynamic Pressure Acting on Gates

The following two points should be considered to study hydrodynamic pressure acting on a gate compared with that on a dam body.

- Hydrodynamic pressure at the gate location, that is not the sum of all hydrodynamic pressure acting on the overall dam body
- Impact for hydrodynamic pressure by the occurrence of the vibration in the gate along with the vibration of the dam body

The above two points were studied separately in this report.

In Chapter Four, first the relationship of the form of vibration of the dam body with the distribution of hydrodynamic pressure is studied. The hydrodynamic pressure in gate parts is affected by vibration of dam near the gate location along with the vibration of the entire dam body, and clarifying the degree of this impact is the object of this study. The study was performed for input motion of a sinusoidal wave.

Chapter Five is a study of the characteristics of the hydrodynamic pressure acting on the gate in a case where vibration unrelated to the dam body vibration is generated in the gate. In this study, the vibration of the gate under an actual earthquake motion is studied along with vibration with a sinusoidal wave.

4. RELATIONSHIP OF DAM BODY ACCELERATION DISTRIBUTION WITH HYDRODYNAMIC PRESSURE DISTRIBUTION ACTING ON DAM BODY

4.1 Outline

Stored water is modeled as a non-compressive (non-cohesive) fluid body to study the relationship of the acceleration distribution of the fluid body with the hydrodynamic pressure that acts on the dam body.

In a case where Westergaard's hydrodynamic pressure equation is used to calculate the hydrodynamic pressure, the local hydrodynamic pressure (hydrodynamic pressure at the gate location) is calculated by considering only vibration at this location (vibration at the location of the gate).

So when the stored water is assumed to be a non-compressive fluid body, the hydrodynamic pressure distribution produced by vibration of the dam body is calculated at the same time as the hydrodynamic pressure based on Westergaard's hydrodynamic pressure equation and the results of the two calculations are compared.

4.2 Analysis Conditions

The objects of the analysis are the dam body and the reservoir as shown in Fig. 2. But an actual analysis considers only the vibration on the upstream side of the dam body without modeling the dam body itself, and inputs the acceleration value to the reservoir. In a case where the stored water is assumed to be a non-compressive fluid body, there is no frequency dependency on the hydrodynamic pressure during an earthquake and there is no phase difference with the input earthquake motion frequency, so the hydrodynamic pressure results are represented by the maximum amplitude of the hydrodynamic pressure. And the upstream surface of the dam body is divided into 20 equal parts to obtain the hydrodynamic pressure at 21 nodes.

In the analysis, the hydrodynamic pressure matrix is calculated based on finite element analysis of the reservoir model assuming it is non-compressive, and then it multiplies this matrix by the acceleration distribution vector on the upstream surface of the dam body to obtain the hydrodynamic pressure during an earthquake that acts on the upstream surface of the dam body. In this paper, this method is called "case considering the overall dam body response." The method of calculating the hydrodynamic pressure based on Westergaard's hydrodynamic pressure equation is called "case where only the local dam body response is considered" in this paper.

4.3 Analysis Results

4.3.1 Results of Calculation of Hydrodynamic Pressure Distribution

(1) Hydrodynamic pressure during an earthquake in a case of rigid vibration of a dam body.

Figure 3 shows the hydrodynamic pressure amplitude distribution acting on the upstream surface of a dam body in a case where the same horizontal vibration (acceleration amplitude of $1m/sec^2$) occurs on the entire upstream surface of a dam body. It shows that the value considering only local dam body response is slightly higher than the value considering the entire dam body response at the top and in the bottom of the dam body, but overall, their form is almost identical.

(2) Hydrodynamic pressure during an earthquake in a case where vibration equivalent to the characteristic vibration shape of the dam body occurs

Figures 4 to 7 show the hydrodynamic pressure amplitude distribution acting on the upstream surface of the dam body in a case where the upstream surface of the dam body is vibrating horizontally (crest acceleration amplitude of $1m/sec^2$) based on the acceleration distribution of the 1st, 2nd, 4th and 5th order shapes of the characteristic vibration modes of the dam body. The 3rd vibration shape is generally excited by the vertical earthquake motion, so it is not considered.

Looking at the hydrodynamic pressure distribution shape equivalent to the 1st mode shape reveals that the value considering only local dam body response is larger at the top and inversely it is smaller near the bottom than the value considering the overall dam body response. But no large difference is found with the overall values. Looking at the hydrodynamic pressure distribution shape equivalent to the 2nd mode shape reveals that the value considering only local dam body response is generally larger than the value considering the overall dam body response. The hydrodynamic pressure equivalent to the 4th order and 5th order mode shape reveals the same tendency, and as the order advances, this tendency becomes greater. This means that in the case of vibration in which the low order vibration of the dam body is dominant, even if the hydrodynamic pressure during an earthquake is calculated considering only local dam body response, it seems to be possible to evaluate it with a certain degree of accuracy, but it can be stated that in a case where it is necessary to focus on the high order vibration of the dam body, it is not appropriate to evaluate the hydrodynamic pressure considering only local dam body response.

4.3.2. Comparison of Maximum Value and Total Forces of Hydrodynamic Pressure

Table 1 summarizes the maximum absolute value and the sum of the horizontal forces produced by the hydrodynamic pressure in all cases studied in the previous part of this report. The table shows that there is little difference between the totals of the horizontal forces considering the entire dam body response and considering only the local dam body response. The local maximum value shows that it is over-estimated based on the concept of considering only local dam body response. This occurs because the higher order the vibration of the dam body, the more remarkable this tendency.

4.4 Summary

The above study has revealed the following facts.

In the case of vibration with the low order vibration of the dam body dominant, it is possible to evaluate the hydrodynamic pressure during an earthquake considering even only the local dam body response, but when it is necessary to focus on the high order vibration of the dam body, considering only local dam body response may result in excessive hydrodynamic pressure, so it is necessary to evaluate the hydrodynamic pressure considering the overall dam body response.

5. HYDRODYNAMIC PRESSURE DURING AN EARTHQUAKE CONSIDERING CHARACTERISTIC VIBRATION OF A GATE

5.1 Outline

So the hydrodynamic pressure during an earthquake in a case where a gate produces local characteristic vibration that differs from that of the dam body is studied. This study was divided into the following two parts.

a. Study of hydrodynamic pressure in a case where the gate produces sinusoidal wave vibration

b. Study of hydrodynamic pressure in a case where simulated earthquake response of the gate is produced

This study was an analysis performed considering the dam body to be a rigid body and under the hypothesis that the gate produces vibration different from that of the dam body. Regarding a), as in Chapter Four, it was hypothesized that the stored water is non-compressive fluid body, but regarding b), the characteristics of hydrodynamic pressures of both a non-compressive fluid body and a compressive fluid body were studied.

5.2 Study for Sinusoidal Wave Vibration

5.2.1 Analysis Conditions

Analysis conditions are same as Chapter 4.

5.2.2 Analysis results

Figure 8 is the hydrodynamic pressure amplitude in a case where only one point at a medium elevation on the dam body vibrates horizontally with acceleration amplitude of $1m/sec^2$. The figure shows that the hydrodynamic pressure considering only the local dam body response is much larger than the value that considers the overall dam body response. This occurs because in the actual phenomenon, vibration at a certain point affects hydrodynamic pressure acting on other points.

Although it is not shown here, an analysis performed separately has shown that as in the case where vibration occurs only in the upper part of the dam body or at a low elevation, considering only the local dam body response evaluates the hydrodynamic pressure higher than in a case where the entire dam body response is considered.

Table 2 shows the maximum absolute value and the sum of the horizontal forces. The table shows that there is little difference between the totals of the horizontal forces considering the entire dam body response and considering only the local dam body response. But, the maximum value could be over-estimated based on the concept of considering only local dam body response.

5.3 Study for Earthquake Response Vibration (Case of Non-compressive Fluid Body)

5.3.1 Analysis Conditions

Results of dynamic analysis of the separately executed dam body and conduit gate are used to calculate the hydrodynamic pressure acting on the gate during an earthquake by the overall dam body vibration and by the relative gate vibration different from the overall dam body vibration. The hydrodynamic pressure was obtained using the hydrodynamic pressure matrix that hypothesizes a non-compressive fluid body by a method considering the overall dam body response and by a method considering only local dam body response based on Westergaard's added mass (Westergaard's hydrodynamic pressure equation).

The response acceleration at the gate location was obtained from the dynamic time history analysis for the dam model with a height of 67m, with a maximum input acceleration of 851gal. The location of a gate is 23m form the foundation. And, that response acceleration was used as an input motion for the gate structural model, the response acceleration of the gate was calculated.

Figure 9 shows the dam body response acceleration at the location of the gate pin, in other words the input earthquake motion to the pin in the earthquake response analysis of the gate that was obtained based on the results of the dynamic analysis of the dam body.

In this study, the dam body was vibrated rigidly at the acceleration shown in Fig. 9. Figure 10 shows the acceleration time history of the gate vibrations corresponding to the dam body. This is average horizontal acceleration of the upstream surface of the gate, and it is a value obtained by subtracting the overall dam body vibration from the vibration acceleration of the gate. The maximum acceleration of the relative gate vibration is about four times the maximum acceleration of the dam body vibration. Figure 11 shows the response spectrum of the acceleration time histories in Fig. 9 and Fig. 10. Those spectra were normalized by the maximum acceleration of each acceleration time histories. From this figure, it is shown that the vibration of gates has smaller component in low frequency range than that of the overall dam body vibration.

Figure 12 is a schematic diagram of the positions of the dam body and the gate hypothesized for this study. Here the gate is hypothesized, but the gate structure itself is not modeled. It is assumed that the gate location conforms to the front surface of the dam body without considering the conduit pipe at the front surface of the gate.

The acceleration distribution of the overall dam body and the corresponding hydrodynamic pressure distribution are shown in Fig. 13, and the relative gate acceleration and the corresponding hydrodynamic pressure are shown in Fig. 14. Assuming that the gate is small as compared with a height of the dam, the gate vibration was caused to correspond to the vibration at one node.

5.3.2 Analysis Results

Figures 15 to 17 show the hydrodynamic pressure time history at nodes corresponding to the gate under the overall dam body vibration shown in Fig. 9 and the relative gate vibration shown in Fig. 10. Figure 15 shows the hydrodynamic pressure under the overall dam vibration, Figure 16 shows the hydrodynamic pressure under the relative gate vibration, and Fig. 17 shows the hydrodynamic pressure under the combined gate vibrations (overall dam body vibration + relative gate vibration), showing values calculated (1) considering the overall dam body response and (2) considering only the local dam body response. Figure 15 shows that hydrodynamic pressure values under the overall dam body vibration were little different when obtained by the two methods (1) and (2). But Fig. 16 shows that the hydrodynamic pressure under the relative gate vibration that was obtained by method (2) was a very high value, and that it is difficult to calculate the local hydrodynamic pressure by considering only the local dam body response by ignoring the overall dam body response. And Fig. 15(a) and Fig. 16(a) show that the hydrodynamic pressure under the relative gate vibration based on method (1) is much lower than the hydrodynamic pressure under the overall dam body vibration. Comparing Fig. 15(a) to Fig. 17(a) shows that the hydrodynamic pressure on the gate under the combined vibration is almost equal to the hydrodynamic pressure under overall dam body vibration.

The above findings show that to calculate the hydrodynamic pressure acting on a gate during an earthquake when performing earthquake response analysis of a gate, it is possible to calculate the hydrodynamic pressure considering overall dam body response while ignoring the relative gate vibration.

5.4 Studies for the Earthquake Response Vibration (Case of Compressive Fluid Body)

5.4.1 Analysis Conditions

This part of the report explains the properties of the hydrodynamic pressure acting on a gate during an earthquake for a case where the entire dam body undergoes rigid body vibration and for a case where only the gate vibrates, while considering the stored water to be a compressive fluid body.

The object of the analysis consists of the dam body and the reservoir water that are shown schematically in Fig. 18. The analysis model was modeled two dimensionally.

The material physical properties analyzed are shown in Table 3. The material physical property of the reservoir bottom is almost equivalent to the acoustic impedance ratio β= 5. The acoustic impedance ratio indicates the reflectivity of the reservoir bottom, is generally between β = 1 to 5, and the smaller the value of β, the lower the reflexivity of the reservoir bottom, with β = 5 correspondent to hard rock.

The boundary conditions are, on the reservoir far side, a cohesive boundary that approximately represents limitless surroundings, while the water surface boundary of the reservoir is a free water surface condition.

Linear dynamic analysis is performed based on the frequency response analysis method and the maximum frequency considered in analysis is 20Hz. Figure 19 shows excitation points for a case where only the gate is vibrated and a case where the entire dam body is rigidly vibrated.

5.4.2 Analysis Results

Figure 20 shows the hydrodynamic pressure time history under the overall dam vibration, and Fig. 21 shows the hydrodynamic pressure time history under the relative gate vibration. Figure 22 shows the total hydrodynamic pressure under the combined vibration. From Fig. 20 and Fig. 22, it is revealed that the hydrodynamic pressure can be evaluated considering only the overall dam vibration, that is to say, ignoring the relative gate vibration even if the compressibility of the stored water is considered.

Figure 23 shows that the hydrodynamic pressure acting on the gate in a case where the compressibility of the stored water was considered and in a case where ignoring the compressibility of the stored water. From this figure, there are not so large differences in the overall wave forms and the maximum value for the non-compressive water is larger than that for the compressive water. This fact indicates the treatment of the stored water as non-compressive body is good and rational assumption to calculate the hydrodynamic pressure acting on a gate.

6. CONCLUSIONS

The following summarizes the results of a study of hydrodynamic pressure acting on dam bodies and on gates during an earthquake performed by numerical analysis of the vibration of dam bodies and gates.

1) In the case of vibration with low order vibration of a dam body dominant, the hydrodynamic pressure can be evaluated by considering even only the local dam body response.

2) In a case where it is necessary to focus on high order vibration of a dam body, or under local vibration such as vibration of a gate, if hydrodynamic pressure is evaluated considering only local dam body response, the hydrodynamic pressure is over-evaluated.

3) The hydrodynamic pressure on a gate produced by the relative gate vibration is smaller than that by overall vibration of the dam body.

According to the above findings, regarding the hydrodynamic pressure acting on a gate during an earthquake, the hydrodynamic pressure acting on the upstream surface of a dam body is calculated by a method that considers the overall dam body response but does not consider the characteristic vibration on a gate itself, and the hydrodynamic pressure at the gate location obtained from this result can be considered to be the hydrodynamic pressure acting on the gate. When the dynamic analysis of the gate is performed separately from the dam body analysis, the time history of the hydrodynamic pressure obtained by the above concept can be applied as the external force on the gate.

For this study, the hydrodynamic pressure for the overall dam body response was obtained using a hydrodynamic pressure matrix, but if the hydrodynamic pressure is obtained through dynamic analysis of the dam body based on a method that considers the overall response of the dam body, it is possible to do so applying this to the dynamic analysis of the gate as it is, regardless of whether it is considered to be a non-compressive fluid body or a compressive fluid body.

7. REFERENCES

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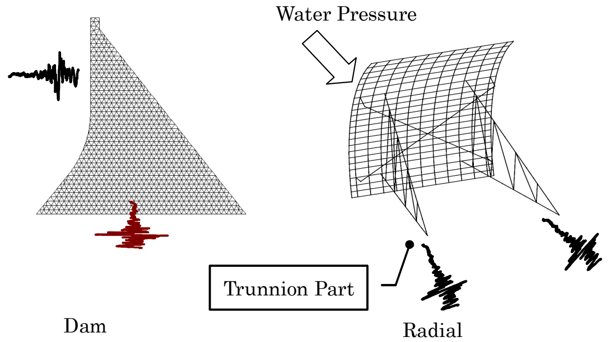


Fig. 1 Example of an Analysis Model of a Gate (Radial Gate)

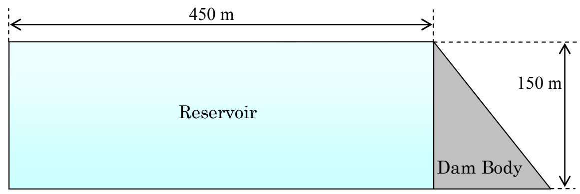
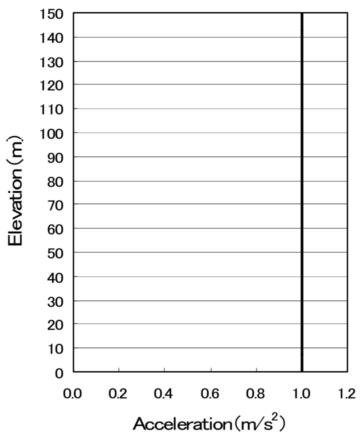
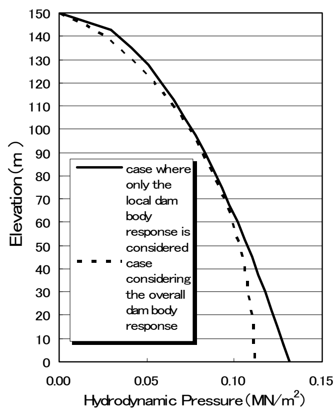


Fig. 2 Objects of the Analysis

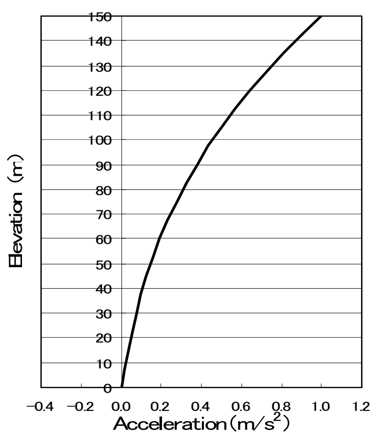


(a) Acceleration distribution

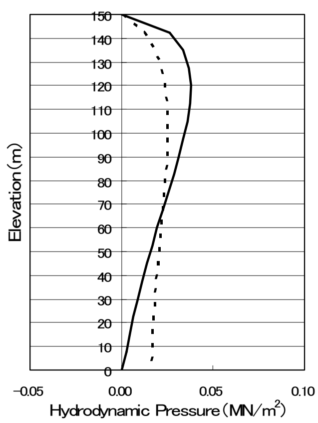


(b) Hydrodynamic pressure distribution

Fig. 3 Case of Uniform Rigid Vibration of the Dam Body

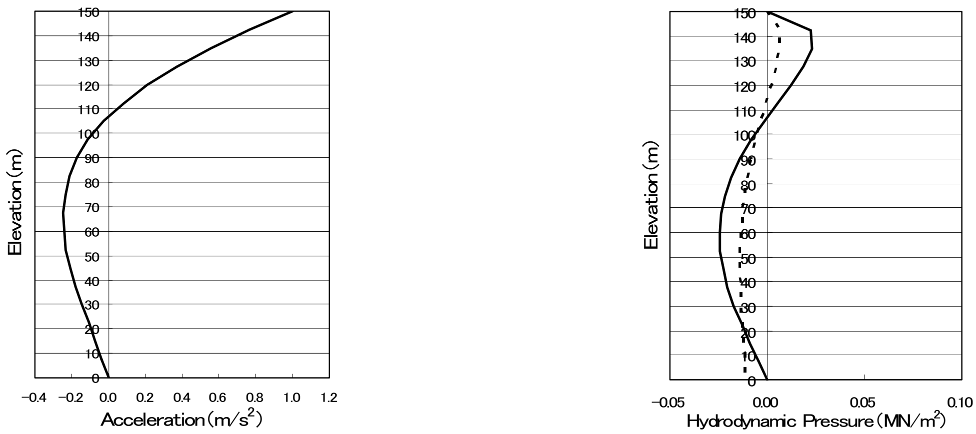


(a) Acceleration distribution



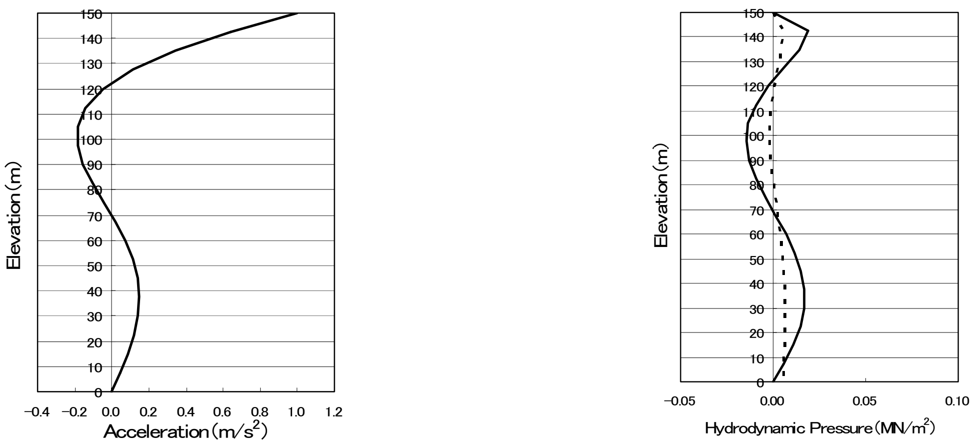
(b) Hydrodynamic pressure distribution

Fig. 4 Case of 1st Mode Vibration Shape of the Dam Body



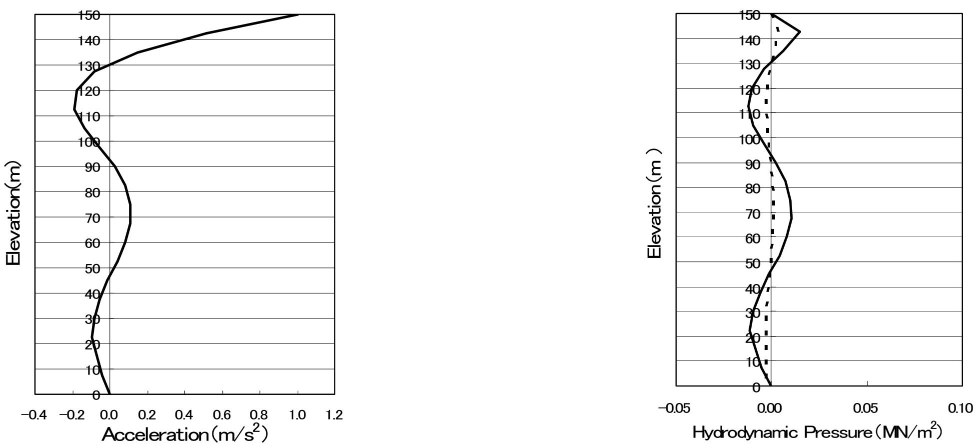
(a) Acceleration distribution (b) Hydrodynamic pressure distribution

Fig. 5 Case of 2nd Mode Vibration Shape of the Dam Body



(a) Acceleration distribution (b) Hydrodynamic pressure distribution

Fig. 6 Case of 4th Mode Vibration Shape of the Dam Body

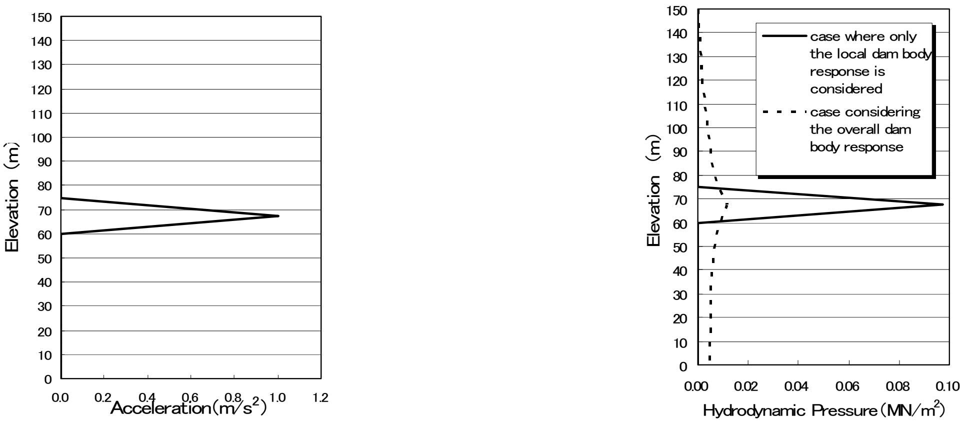


(a) Acceleration distribution (b) Hydrodynamic pressure distribution

Fig. 7 Case of 5th Mode Vibration Shape of the Dam Body

Table 1 Comparison of Maximum value and Horizontal Total Forces of Hydrodynamic Pressure Acting on the Upstream Side of the Dam Body

Case	Considering overall dam body response (A)		Considering only local dam body response (B)		B / A	
	Max. value	Total force	Max. value	Total force	Max. value	Total force
Uniform rigid body vibration	0.111	12.19	0.131	13.08	1.18	1.07
1st mode vibration shape	0.025	3.04	0.038	3.26	1.50	1.07
2nd mode vibration shape	-0.014	-1.09	-0.025	-1.07	1.76	0.98
4th mode vibration shape	0.006	0.46	0.019	0.55	3.20	1.20
5th mode vibration shape	-0.003	-0.13	0.015	-0.14	-5.39	1.14



(a) Acceleration distribution (b) Hydrodynamic pressure distribution

Fig. 8 Case of Vibration of one Point at Medium Elevation

Table 2 Comparison of Maximum value and Horizontal Total Forces of Hydrodynamic Pressure Acting on the Upstream Side of the Dam Body

Case	Considering overall dam body response (A)		Considering only local dam body response (B)		B / A	
	Max. value	Total force	Max. value	Total force	Max. value	Total force
One point vibration at a medium elevation	0.012	0.72	0.097	0.73	8.36	1.02

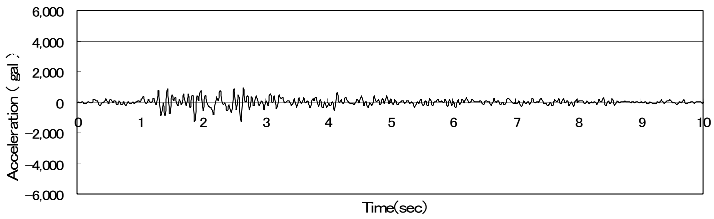


Fig. 9 Acceleration Time History of the Overall Dam Body Vibration

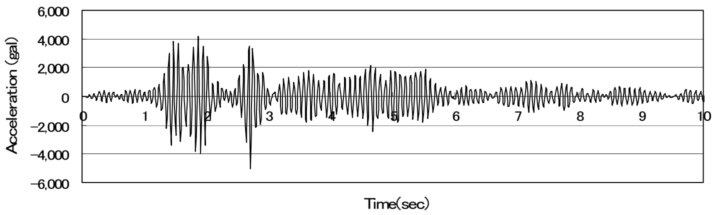


Fig. 10 Acceleration Time History of Relative Vibration of Gate

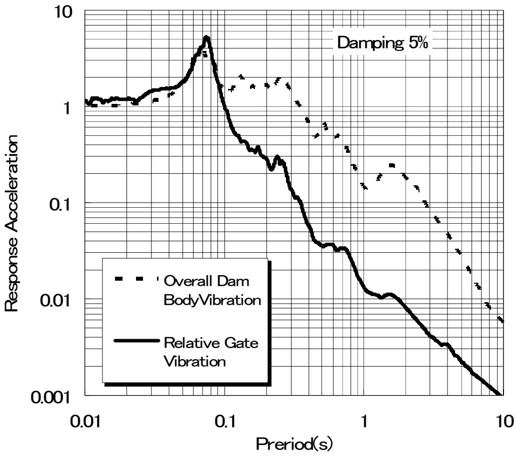


Fig.11 Normalized Response Spectrum of Acceleration

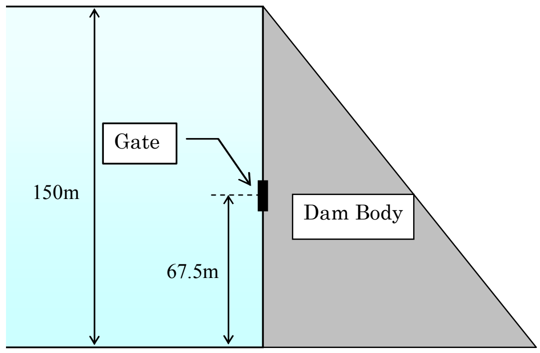
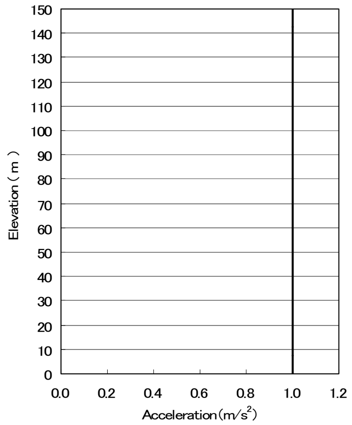
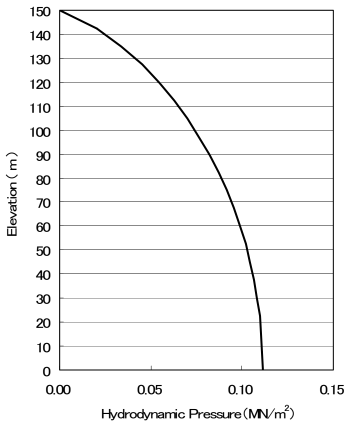


Fig. 12 Schematic Figure of the Dam Body and Gate Locations

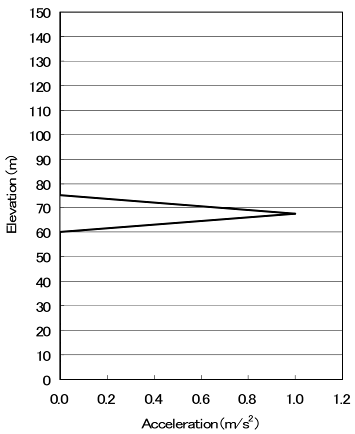


(a) Acceleration distribution

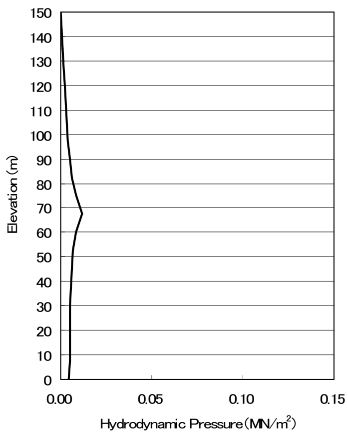


(b) Hydrodynamic pressure distribution

Fig. 13 Overall Dam Body Vibration Distribution and Corresponding Hydrodynamic Pressure Distribution

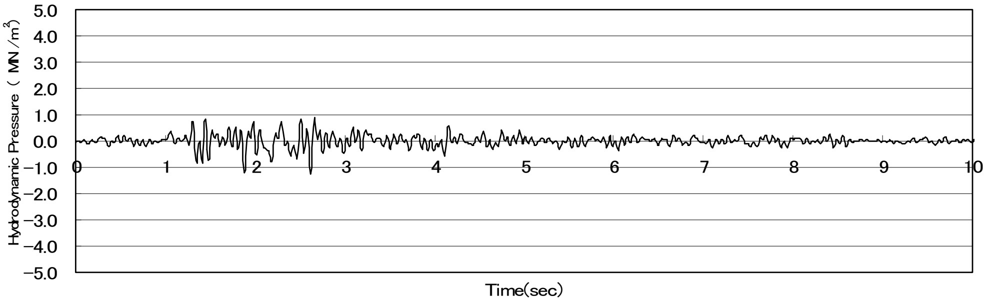


(a) Acceleration distribution

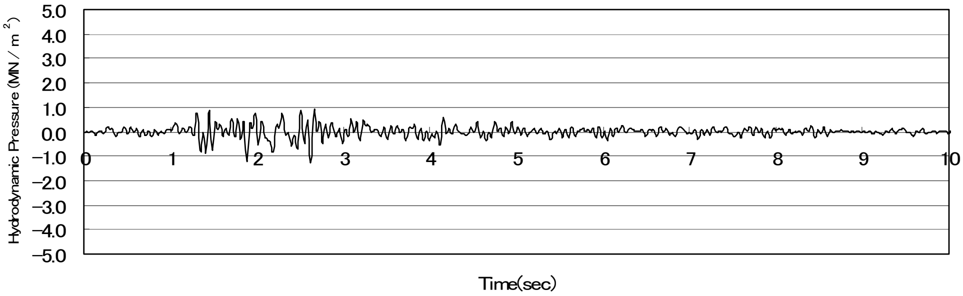


(b) Hydrodynamic pressure distribution

Fig. 14 Relative Gate Vibration Distribution and Corresponding Hydrodynamic Pressure Distribution

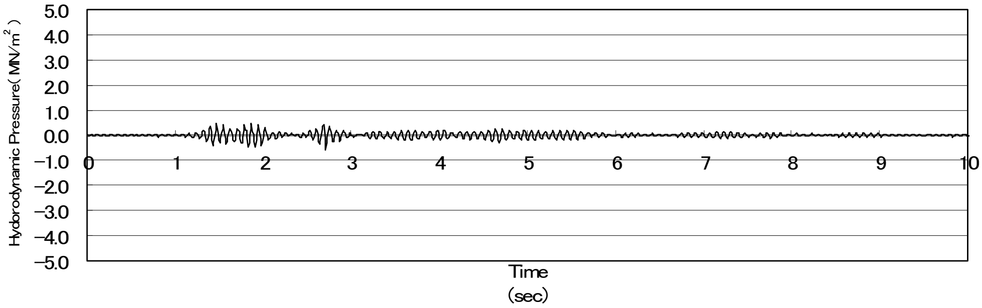


(a) Case considering the overall dam body response

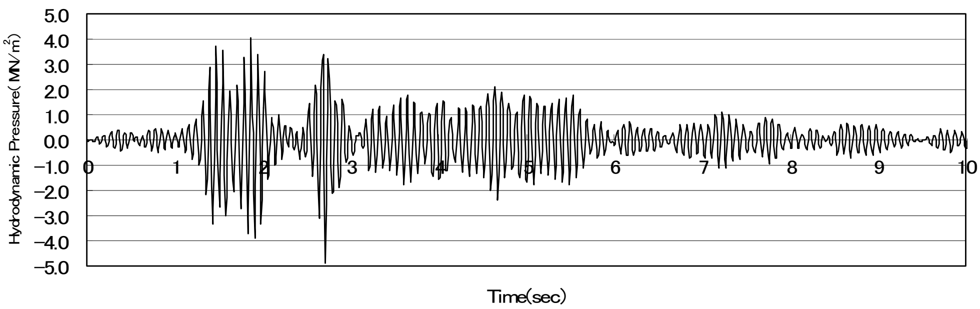


(b) Case considering the local dam body response

Fig. 15 Hydrodynamic Pressure Time History of the Gate under Overall Dam Body Vibration

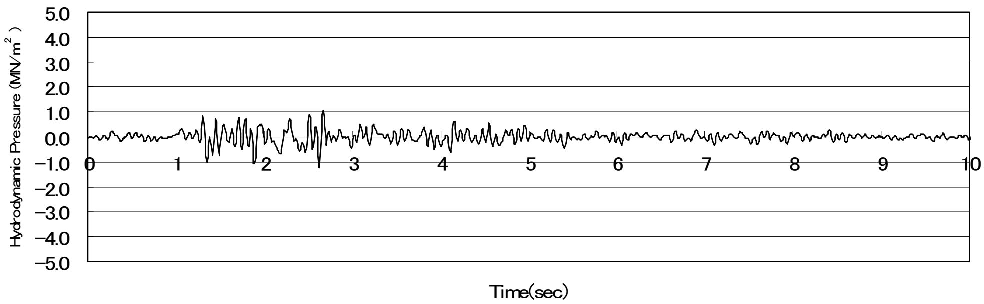


(a) Case considering the overall dam body response

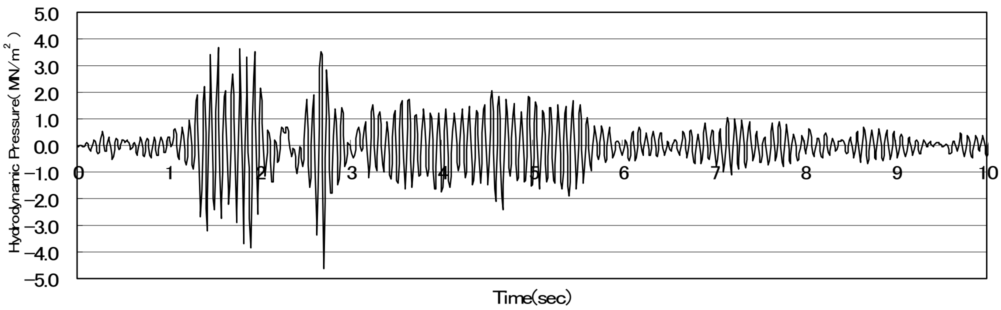


(b) Case considering the local dam body response

Fig. 16.Hydrodynamic Pressure Time History of the Gate under Relative Gate Vibration



(a) Case considering the overall dam body response



(b) Case considering the local dam body response

Fig. 17 Hydrodynamic Pressure Time History of the Gate under Combined Vibrations

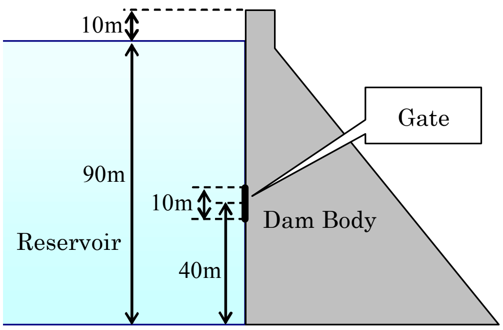


Fig. 18 Object of the Analysis

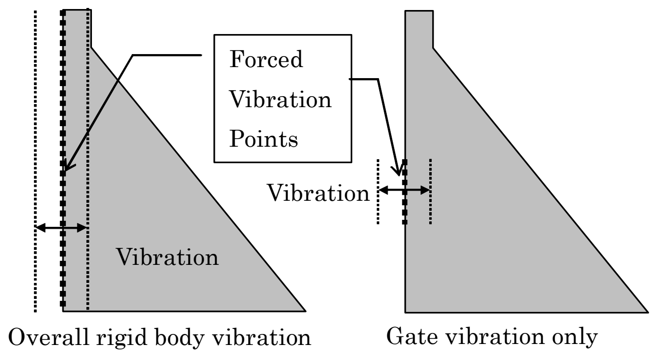


Fig. 19 Forced Vibration of Multiple Nodes

Table 3 Material Property Values

Item	Reservoir
Unit weight(kN/m^3)	9.80665
Underwater P wave velocity (m/s)	1.40E+03

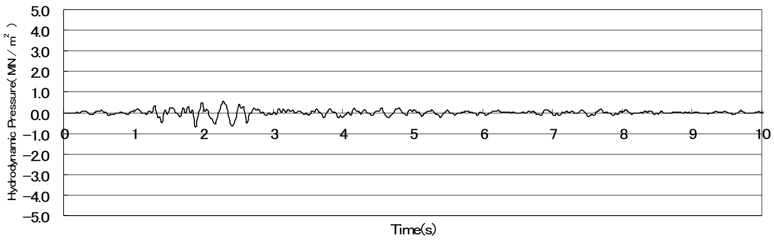


Fig. 20 Hydrodynamic Pressure Time History under Overall Dam Body Vibration

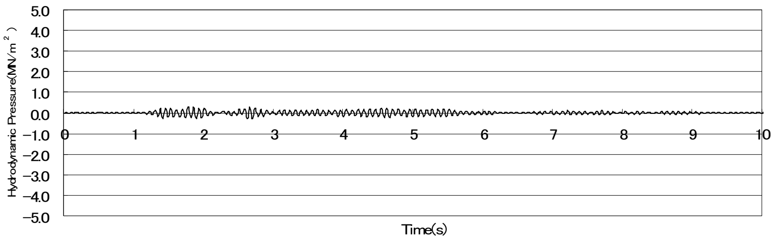


Fig. 21 Hydrodynamic Pressure Time History under Relative Gate Vibration

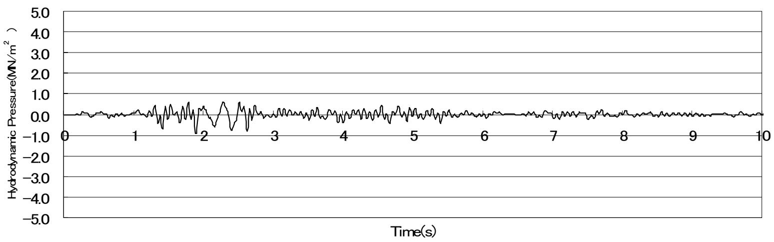
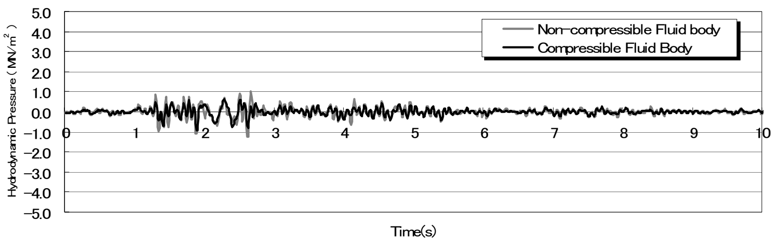
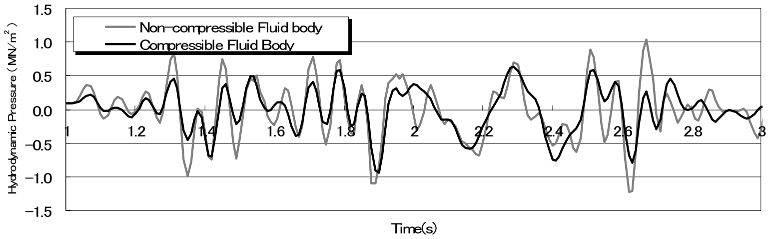


Fig. 22 Time History of Hydrodynamic Pressure under Combined Vibration



(a) All time range



(b) From 1.0 sec to 3.0 sec

Fig. 23 Time History of Hydrodynamic Pressure under Combined Vibration
– Comparison of Non-compressible Fluid and Compressible Fluid –