DYNAMIC BEHAVIOUR CHARACTERISTICS OF PIANO KEY WEIRS

Masayuki Kashiwayanagi[1], Zengyan Cao[2]
(1.Electric Power Development Co., Ltd., Chigasaki, 253-41, Japan；
2.JP Business Service Corporation, Tokyo, 135-8451, Japan)
Email: masayuki_kashiwayanagi@jpower.co.jp

ABSTRACT: A Piano Key Weir (PKW) has been developed as free flow ogee crest to provide better hydraulic characteristic than conventional weirs. A PKW additionally features a small footprint due to the over-hanged structure, enabling easer arrangement on the dam crest. Thirty (30) PKWs have been operated worldwide as of 2017. Due to the structural characteristics of a PKW, the seismic safety evaluation is an essential issue in order to apply PKWs for dams located in earthquake prone area. The dynamic behavior of PKW is investigated by numerical simulations using the simple PKW model and the composite model of the dam and the PKW. Directional interference of the oscillation of PKW is a key for the resonance between the dam and the PKW. The water interaction on PKW wall is examined.

Keywords: PKW, Predominant frequency, Transfer function matrix, Structure-water interaction, Directional interference

1 INTORODUCTION

Heavy floods have occurred frequently lately and occasionally caused disasters. The climate change may affect the current characteristics of precipitation. The similar situation has been prospected worldwide in future. It is also considered as the increase of flood risks in the management of dams and reservoirs.

A piano key weir (referred to as PKW) categorized in a Labyrinth weir is a free flow ogee crest with a non-straight planar geometry. PKW and Labyrinth weirs compose consecutively plural units of the rectangle or the zigzag geometry which enlarge the crest length so as to increase the spill capacity of the weirs larger than conventional straight weirs. The examples of a PKW are shown in Figure 1. These non-straight weirs have been nominated and studied as enhancement measures for the spillway capacity of existing dams in Europe since 1960s [1]. A PKW has been improved to acquire several times of the spill capacity under a low water head than one of a Labyrinth weir. It additionally features a small footprint due to the over-hanged structure, enabling easier arrangement on the dam crest [2]. Several PKWs have been constructed as the spillways for not a new dam, but existing dams in France since 2006. Thirty (30) PKWs have been listed in a PKW database [3] worldwide as of 2017.

There are two Labyrinth weirs of newly constructed dams of Tomata dam and Kin dam in Japan. However it is found that a PKW has been nominated neither for new dams nor existing dams in Japan. Because a PKW consists of thin reinforced concrete structures, and PKWs arranged on the dam crest are loaded additionally due to the dam response by an earthquake, the seismic safety evaluation is an essential issue in order to apply PKWs for dams located in earthquake prone area such as Japan. However few studies are found on the seismic safety examination of PKWs in the literatures [1],[2]. This paper focuses the dynamic behavior characteristics of PKWs. These are studied by numerical simulations for the purpose of the seismic safety evaluation of PKWs.

(a) Gloriettes dam (France)[1]　(b) Van Phong dam (Vietnam, Pictured by the Author[4])

Figure 1: Examples of a PKW

2 METHOD OF NUMERICAL SIMULATION

The studies are conducted on a representation of a numerical model, dynamic behavior of PKW itself and an interaction between a dam and a PKW arranged on the dam crest. The numerical model of PKW is composed several units involving inlet and outlet keys, and boundary parts in order to avoid the boundary influence. It is referred to as a simple PKW model. Another numerical model is a composite model with a dam, foundation and a PKW. The dynamic characteristics are explored by an eigenvalue analysis and a dynamic analysis using the simple PKW model. The interference among directional oscillations is examined based on the transfer function matrix [5] obtained by the dynamic analysis. The interaction between the dam and PKW is studied by the dynamic analysis using the composite model.

3 REPRESENTAION OF NUMERICAL MODEL

The objective PKW is designed to have the capacity of 1100 m^3/s additionally under the head of 3.5 m as shown in Figure 2. The detail of the design is skipped in this paper. It has 9 units and divided into three parts by the bridge piers. The simple PKW model consists of 6 units with the boundary walls. The behavior of the center units is focused to reduce the boundary influence.

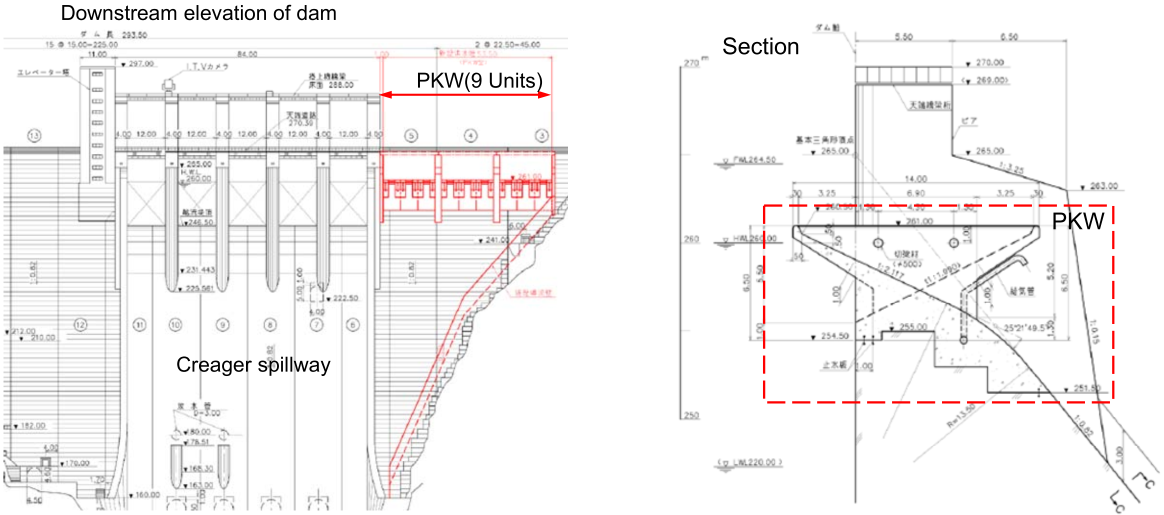
FEM elements are made up to satisfy following Equations (1) and (2) for the accurate analysis.

$$\frac{\Delta L}{V_s} \leq \frac{T_{\min}}{\pi} \tag{1}$$

$$\Delta t < \frac{T_{\min}}{\pi} \tag{2}$$

Where, ΔL :Maximum size of elements (m), V_s : Shear velocity of material (m/s), $T_{\min}$: Minimum period of oscillation (s), Δt : Time increment of dynamic analysis (s)

The dominant frequency and V_s of a PKW are presumed lower than 30 Hz and 2000 m/s, respectively. ΔL and Δt are estimated smaller than 21 m by Equation (1) and 0.01 s by Equation (2). Then ΔL of the dam and Δt is determined as 10 m and 0.01 s. Similarly ΔL of the foundation is determined as 21 m by assuming the shear velocity of foundation is 2000 m/s. ΔL of PKW is 1 m by arranging three layers in the wall between the inlet and the outlet keys. These FEM dimensions are summarized in Table 1. Elements of 50380 and 92397 are arranged for the simple PKW model and the composite model, respectively. The models are shown in Figure 3 with the detailed dimensions. Coordinates are defined as X, Y, and Z to stream, longitudinal to dam axis and vertical directions.

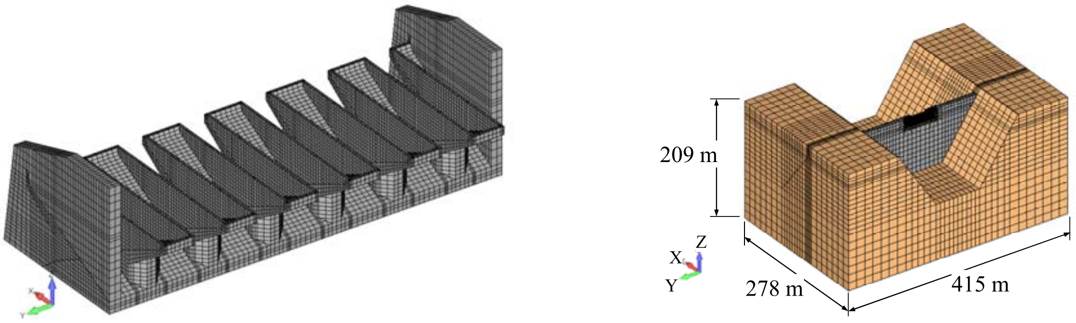


Note: PKW is drawn in red lines.

(a) Downstream elevation

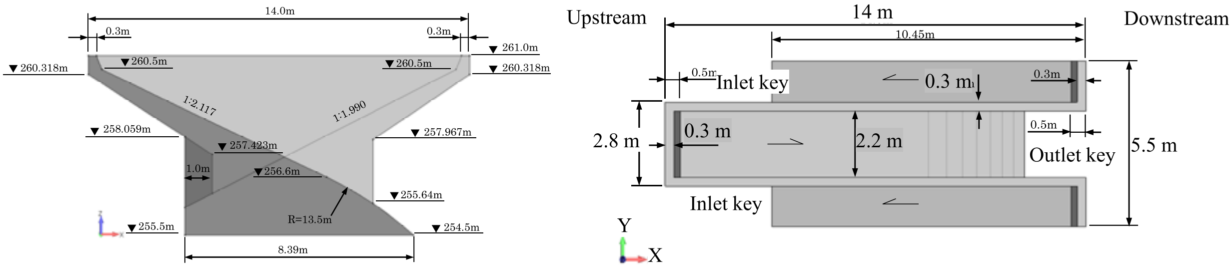
(b) Typical section

Figure 2: PKW design arranged on the dam crest



(a) Simple model, Upstream view

(b) Composite model, Upstream view



(c) Typical section of PKW

(d) Plan of PKW unit

Figure 3: Numerical model of PKW

Table 1: FEM dimensions of numerical models

Structure	Size of elements (m)		Time increment of calculation (s)	
	Maximum limit	Applied	Maximum limit	Applied
Dam	21	10	0.01	0.01
PKW	21	Less than 1		
Foundation	21	21		

4 DYNAMIC CHARACTERISTICS OF PKWs

4.1 Outline

The simple model as shown in Figure 2 (a) is fixed on the bottom and both sides for the calculation. No impound water is considered in the inlet keys. Material properties are determined as dynamic ones referring to ones of common concrete structures and reproduction analysis of dam behavior during an earthquake. These are summarized in Table 2.

Table 2: Material properties of numerical models of PKW

Material	G(N/mm^2)	Specific weight (g/cm^3)	Poisson's ratio	Damping
PKW	13541.0*	2.40	0.20	2 %
Dam concrete	12000.0	2.40	0.20	5 %
Foundation	6690.0	2.60	0.30	5 %
Free field	6690.0	2.60	0.30	5 %

Note *) 1.3 times of static shear modulus

4.2 Eigenvalue Analysis

The results of the eigenvalue analysis are summarized in Table 3 and Figure 4. The predominant oscillation is found in the separation wall between the inlet and the outlet keys. It is considered as bending deformation of the wall in the dam axis direction (Y-direction). The predominant frequency, 28.5 Hz is much higher than ones of concrete dams less than 150 m high.

Table 3: Eigenvalue analysis

mode	Frequency (Hz)	Period (s)	Effective mass(ton)		
			Stream direction (X)	Dam axis direction (Y)	Vertical direction (Z)
1	28.57	0.04	0.00	189.54	0.00
2	28.64	0.03	0.00	0.00	0.00
3	28.78	0.03	0.00	0.43	0.00
4	28.81	0.03	0.00	0.00	0.00
5	28.81	0.03	0.00	0.03	0.00
6	28.94	0.03	0.00	0.00	0.00
7	29.76	0.03	0.07	0.03	0.00
8	29.81	0.03	0.05	0.02	0.00
9	29.90	0.03	0.11	0.04	0.00
10	30.00	0.03	0.13	0.12	0.00

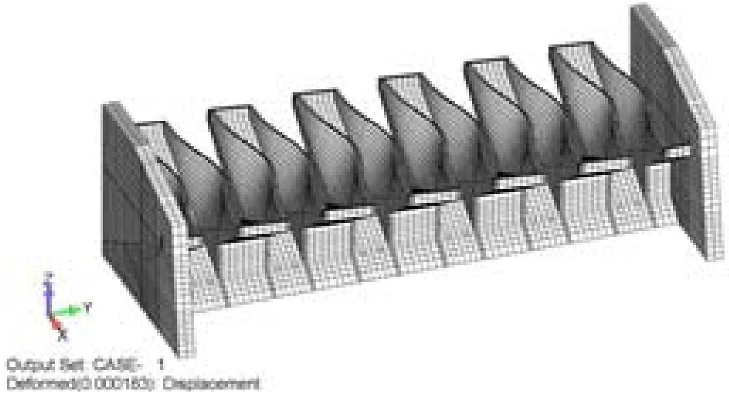


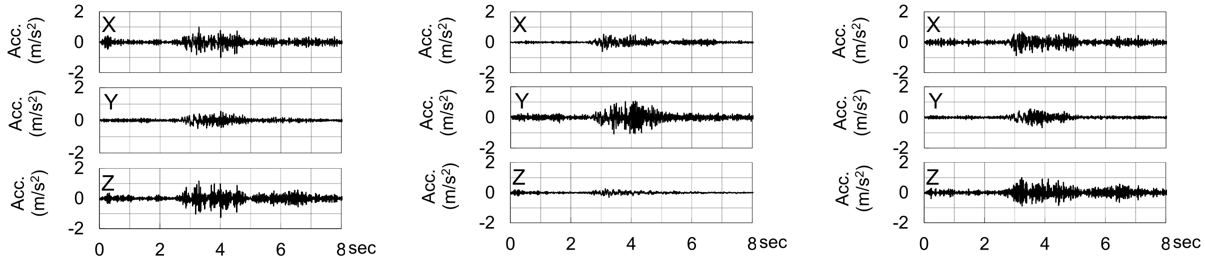
Figure 4: Predominant mode of PKW, 1st mode (28.57 Hz）

4.3 Dynamic Analysis

Dynamic behavior of PKW is more deeply examined based on the transfer function matrix [5]. The estimation of the transfer function matrix requires three sets of dynamic responses using the simple PKW model. Three sets of seismic records monitored in the existing arch dam (61 m high) foundation are applied. These maximum accelerations are ranging 11 to 65 (10^{-2} m/s^2).The calculation conditions are same as one of the eigenvalue analysis and slight damping is added to PKW concrete. The acceleration responses of the PKW are estimated at the representative points of PKW crest as shown in Figure 5 (c). One of these is shown in Figure 5(a) as an example.

The transfer function matrix is shown in Figure 6 for the center of the wall crest (node 56805), of which acceleration response is remarkable. The matrix indicates the directional transfer functions (S_{ij}) for the response of i-direction to the input of j-direction. The diagonal components (S_{xx}, S_{yy} and S_{zz}) of the matrix indicate the transfer functions of the response to the same directional input. The predominant frequencies are found and accompanied by larger response ratio in the stream direction (X-direction) and the dam axis direction (Y-direction). These are 30 Hz and 15 times, and 23 Hz and 90 times, respectively. The vertical one (Z-direction) is a response of a rigid body, which shows no predominant frequency and less ratio. Non-diagonal components (S_{ij}, where i is not equal to j. It is referred to as a contribution transfer function.) of the matrix show the response characteristics in the specific response to the different directional input. The similar peak frequencies of X- and Y-directions are found in contribution transfer functions. These values are less. It means that the contributions to the different directions are minor.

Summarizing above in Table 4, the response characteristics of the PKW are predominant horizontally in Y-direction and show less interference in the oscillation directions. The predominant oscillation in Y-direction results from the structural feature of the thin separate wall. The predominant frequency in Y-direction, 23 Hz shows some disagreement to ones of 1st mode, 28 Hz estimated in the eigenvalues analysis. The eigenvalues analysis identifies relatively local response of the separate wall. The transfer function matrix represents the whole structural response from the bottom to the crest of the PKW. The bending oscillation of the separate wall is predominant in either case and significant in the seismic safety evaluation for PKWs

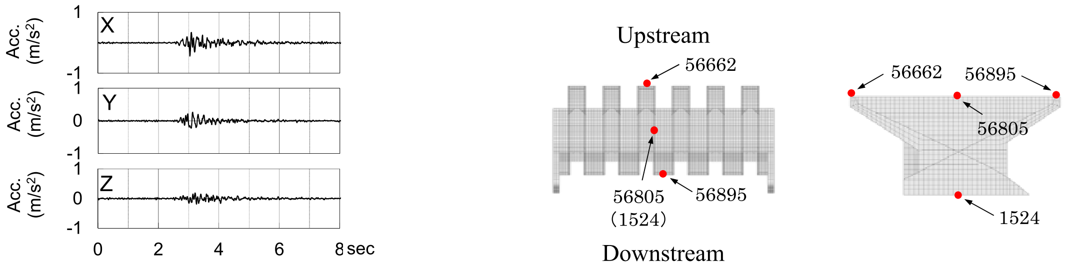


Upstream crest(Node 56662)

Crest of separation wall (Node 56805)

Downstream crest (Node 56895)

(a) Acceleration response of the crests of PKW



Bottom of PKW(Node 1524)

(b) Input wave at the bottom of PKW

(c) Representaive nodes

Figure 5: Example of acceleration response of PKW

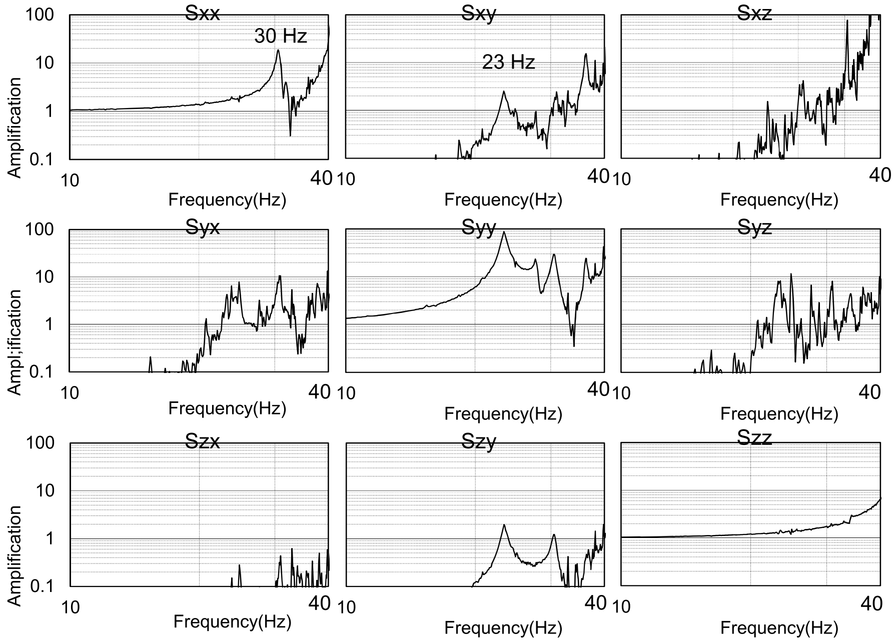


Figure 6: Transfer function matrix of PKW at the crest of the separate wall

Table 4: Summary of the examination of the dynamic behavior of PKWs

Oscillation direction	Eigenvalue analysis, Predominant mode	Dynamic analysis, Peak of transfer function
Stream direction (X-direction)	9th and 10th mode 29.9Hz and 30Hz Effective mass 0.11 and 0.13 ton	30 Hz Ratio 15
Dam axis direction (Y-direction)	1st mode 28.57Hz Effective mass 189 ton	23 Hz Ratio 90
Vertical direction (Z-direction)	Not seen under 10th mode	No predominant frequency

5 Interacition of dam and PKW

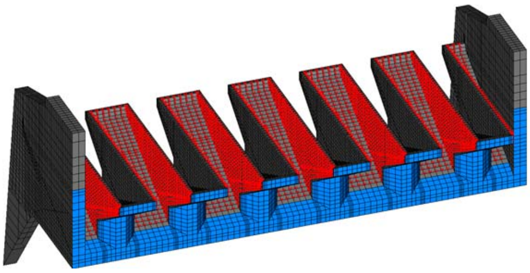
5.1 Condition of Analysis

A PKW arranged on the concrete gravity dam of 100 m high is studied to examine the interaction between the dam and the PKW by the dynamic simulation using the composite model (refer to Figure 3 (b)). The impound water in the inlet key is incorporated. The large earthquakes are applied at the bottom of the dam. These are converted to ones at the bottom of the numerical model using the three dimensional dam-foundation-reservoir model. The simulation cases are tabulated in Table 5. The composite model is arranged with viscous boundary [6] at the bottom and peripheral sides to simulate the virtual infinite free field. The material properties in Table 2 are applied.

The dynamic interaction between impound water and PKW should be incorporated in the Case-2. The dynamic effect of the impounded water in the inlet key will be influential to the behavior of the separation wall. Generally, direct simulation of the interaction of water and structures by FEM is common as well as the added mass method. Both methods are hard to apply to the PKW due to its complicated configuration so far. There are no proposed methods for the inlet key of PKW which is characterized by relatively steep slope and narrow area between the separate walls. It should be the technical issue to be examined in future for the seismic safety evaluation of PKWs. The water in the inlet keys is considered as confined water such as water in a tank in this study. The dynamic effect of the water in the inlet key on the wall is represented by adding the water mass in the inlet key onto the wall as shown in red area of Figure 7. The water in the inlet key behaves together with the wall as a rigid body. In addition, the added mass estimated by Westergaard's equation is loaded on the upstream surface of the PKW as shown in blue area of Figure 7. These additional loads for the interaction between the impounded water and the PKW are illustrated in Figure 7.

Table 5: Cases of dynamic simulation using a composite model

Case	Dam height	Water level	Earthquake	Water interaction
Case-1	100m	Low, corresponding to the bottom level of PKW	Huge	Not included
Case-2		High, corresponding to the crest level of PKW	Severe (1/2 of above)	Included



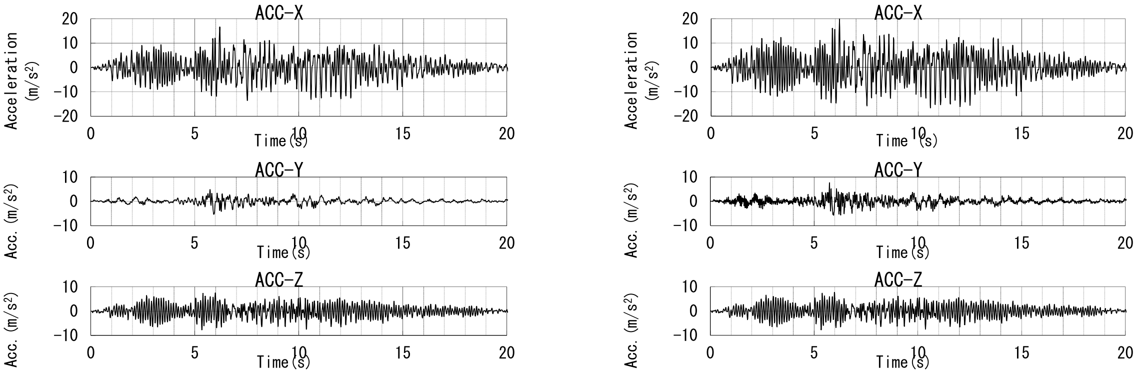
Blue area: added mass estimaed by Westergaard's equaltion, Red area: Mass of water in the inlet key

Figure 7: Water interaction on PKW

5.2 Acceleration Response

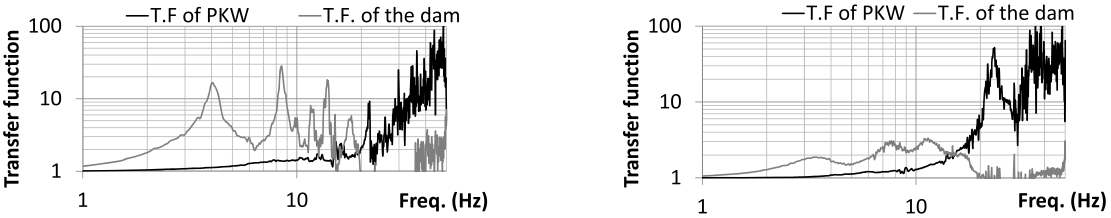
The response accelerations at the bottom and the crest of PKW are shown as time histories and transfer functions as an example in Figures 8 and 9, respectively. The transfer functions are estimated as response characteristics of the dam crest and the PKW crest in respect to the dam bottom. The interference of the water is demonstrated as the comparison of Cases 1 and 2 in Figure 10.

The amplification of the dam crest is dominant in X-direction at several specific frequencies. One of the PKW is dominant in Y-direction at 23 Hz which is far from the predominant frequencies of the dam. It implies that less interaction will be anticipated between the dam and the PKW. The lower the dam height is, the higher the frequency is anticipated in the higher predominant mode. It might incur a resonance of the dam's and the PKW's responses. However, it is considered that the response of PKW in Y-direction is not amplified excessively by the dam response, because the dam behaves with lower amplification in Y-direction and the directional interference is minor in PKW even the dam would provide much amplification in X-direction. The interaction of the water affects to restrain the oscillation and reduce the predominant frequency as shown in Figure 10. The decrease of the frequency is confirmed uniformly at the representative nodes except the downstream crest of node 56895, where the water depth is lowest.



(a) Bottom of PKW, Node 1524 in Figure 5(c)
(b) Separation wall, Node 56805 in Figure 5(c)

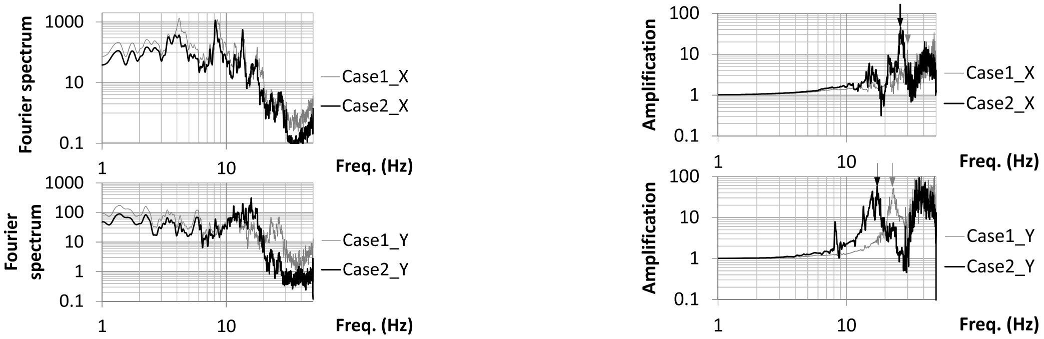
Figure 8: Acceleration response of PKW (Case 1)



Black: Upstream crest, Node 56662 in Figure 5(c), Gray: Dam crest at the same elevation
(a) X-direction

Black: Separation wall, Node 56805 in Figure 5(c), Gray: Dam crest at the same elevation
(b) Y-direction

Figure 9: Comparison of Transfer functions of PKW and dam responses in Case 1



Arrows show the predominant frequencies.
Case 1: without water interaction, Case 2: with water interaction
Upper: at the bottom of PKW, Lower: at the crest of PKW

Figure 10: Effect of water interaction at the crest of separation wall

6 CONCLUSION

The dynamic behavior characteristics of PKWs are examined by numerical simulations. The simple PKW model and the composite model of a dam and PKWs are developed for the simulation. The conclusions extracted from the studies are listed below.

(i) The oscillation of the PKW is predominant in the separate wall, which features the bending deformation in the dam axis direction and the predominant frequency of 23 Hz. The frequency of the PKW is much higher than the predominant frequency of the dam, on which the PKW is arranged.

(ii) The transfer function matrix of the PKW indicates that the directional interference is minor in the PKW oscillation. It means that the PKW is oscillated independently to the corresponding direction of the seismicity.

(iii) The dynamic response of the PKW situating on the dam crest is amplified by the dam response. It is considered, however that the response of the PKW in Y-direction is not amplified excessively by the dam response, because the dam behaves with lower amplification in Y-direction and the directional interference is minor in the PKW even the dam would provide much amplification in X-direction.

(iv) The interaction of the water affects to restrain the oscillation and reduce the predominant frequency of the PKW. However the estimation methods of the water interaction have not been established for the inlet key of the PKW which is characterized by relatively steep slope and narrow area between the separate walls. It should be the technical issue to be examined in future for the seismic safety evaluation of PKWs.

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