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Dynamic analysis of a Piano Key Weir situated on concrete dams

M. Kashiwayanagi
Electric Power Development Co., Ltd., Chigasaki, Japan

Z. Cao
JP Business Service Corporation, Tokyo, Japan

T. Oohashi
JP Design Co., Ltd., Tokyo, Japan

ABSTRACT: Piano Key Weirs (PKW) have been developed as spillways to provide better hydraulic characteristic than conventional free flow ogee-crest. Due to the structural characteristics of PKWs, the seismic safety evaluation is an essential issue in order to apply PKWs for dams located in an earthquake prone area. To clarify the earthquake-resistant capability of PKWs by numerical analyses, the virtual PKW situating on the concrete dam crest is designed so as to discharge 1200 m^3/s. The dynamic characteristics of PKW are investigated by numerical simulations using the PKW unit model, not combined in the dam. The behavior during a large earthquake is analyzed using the PKW model situated on a concrete dam crest of 100 m high. The conclusions are as follows. The predominant frequency of the PKW is almost 10 times of ones of the concrete dam, suggesting that the behavior of the PKW could be lightly affected by the interaction between the PKW and the dam. The investigation of hydrodynamic pressure acting inside of the PKW is challenging for the better seismic design of the PKW. The structural investigation such as reinforcement design and structural detail should be also the challenges to provide adequate earthquake-resistant capacity of the PKW.

RÉSUMÉ: Les déversoirs en escalier (Piano Key Weirs - PKW) ont été développés afin de fournir de meilleures caractéristiques hydrauliques que les déversoirs classiques en doucine (ogee). Compte tenu de leurs caractéristiques, l'évaluation de leur résistance aux séismes est essentielle pour les utiliser dans des zones sismiques. Des analyses numériques ont été réalisées afin de démontrer la capacité des PKW à résister aux séismes. Un PKW virtuel, d'une capacité d'évacuation de 1200m^3/s, est positionné sur la crête d'un barrage en béton. Les caractéristiques dynamiques du PKW sont étudiées par simulations numériques en utilisant un modèle du déversoir non couplé au barrage. Le comportement lors d'un fort séisme est analysé à l'aide d'un modèle situé en crête d'un barrage poids en béton de 100 m de hauteur. Les conclusions sont les suivantes. La fréquence dominante du PKW est près de 10 fois celle du barrage en béton, ce qui suggère que le comportement du déversoir pourrait être légèrement affecté par l'interaction entre celui-ci et le barrage. L'examen de la pression hydrodynamique agissant à l'intérieur du PKW pose des défis relatifs à la conception sismique du déversoir. L'analyse structurale, comme la conception des armatures et les détails de la structure, devrait également poser des défis afin d'assurer une résistance suffisante face aux séismes pour ce type de déversoirs.

1 INTRODUCTION

Heavy floods have occurred frequently of late and occasionally caused disasters. The climate change may affect the current characteristics of precipitation. A similar situation has been predicted worldwide in future. This is considered as the increase of flood risks in the management of dams and reservoirs. To cope with these risks, non-straight weirs such as labyrinth weirs and piano key weirs (referred to as PKW) have been nominated and studied as enhancement measures for the spillway capacity of existing dams in Europe since the 1960s (Schleiss 2011). PKW spillways have been improved to acquire several times the spill capacity under a low water head than that of labyrinth weirs. They additionally feature a small footprint due to the over-hang structure, enabling easier arrangement on the dam crest (Schleiss 2011, Erpicum et al. 2011). There are two Labyrinth weirs on the newly constructed dams of Tomata dam and Kin dam in Japan, but no PKW for neither new dams nor existing dams in Japan. Because PKW is a thin structure of reinforced concrete, and PKW 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 PKW for dams located in earthquake prone areas such as Japan. However few studies have been found on the seismic safety evaluation of PKW in literature (Erpicum et al. 2011, 2013 & 2017).

This paper focuses the seismic durability of PKW. The numerical simulations have been conducted to clarify the behavior of PKW arranged on the crest of a concrete dam during large earthquakes. The seismic durability of PKW is examined based on these results.

2 DESIGN OF VIRTUAL PKW

The virtual PKW is designed so as to secure certain additional flood discharge in the existing dam. The part of the virtual PKW is simplified and incorporated into the Finite Element Method (FEM) model to be arranged on the crest of a concrete gravity dam of 100 m high for the numerical simulations. This process enables flexible parametric studies in the numerical simulations. The existing dam for the design is high of 100 m class and equipped with five (5) gated spillways for 10,000 m^3/s flood. The PKW is designed to be situated on the dam crest to discharge an additional 1200 m^3/s which is routed at the reservoir water elevation less than the current flood water elevation (FWL, 264.5 m). The crest elevation of the PKW is set at EL 261 m, providing 1 m allowance for the wind surge of the reservoir to the current high water elevation (HWL, EL260 m). The design water depth of the PKW resulted in 3.5 m. The dimensions of the virtual PKW are linearly scaled using the dimensions of hydraulic models of PKWs which secure the required discharge in the hydraulic model tests (Machiels et al. 2011). The flowchart of the dimension determination and based hydraulic data are shown in Figures 1, 2, respectively. The virtual PKW arranged on the existing dam is illustrated in Figure 3.

As one of the design procedure of the PKW and the preliminary study prior to the dynamic analysis, the seismic design of the PKW is conducted using pseudo static method to confirm

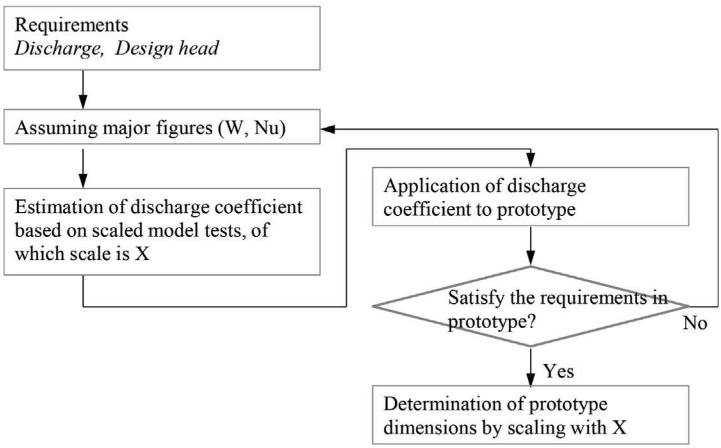


Figure 1. Design flowchart of PKW

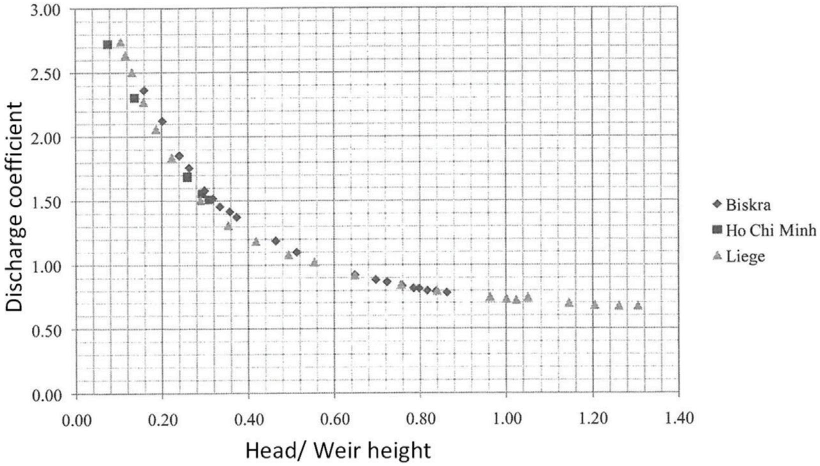
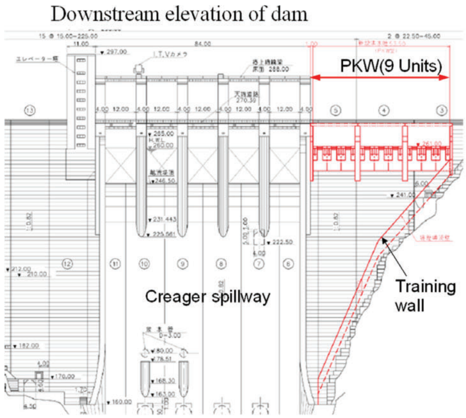
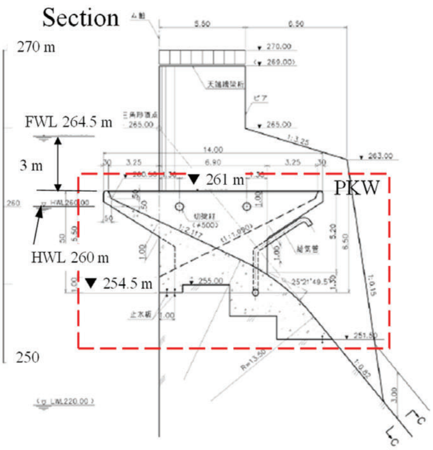


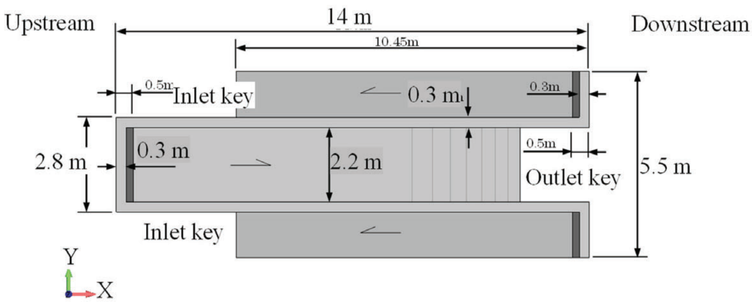
Figure 2. Results of hydraulic model test for the design of virtual PKW (Machiels et al. 2011)



(a) Downstream elevation



(b) Section



(c) Plan of PKW unit

Figure 3. Virtual PKW arranged on an existing dam

Table 1. Stability calculation of PKW using pseudo static method under 0.84 g horizontally

Water elevation (m)	Overturn (m)		Vertical stress on the foundation (t/m^2)			Sliding safety factor**	
	Estimated	Criteria	Estimated		Criteria	Estimated	Criteria
			Up-stream	Down-stream			
260 (HWL)*	-1.84	<1.85	20.57	0.03	>0	49	>4

* Refer to Figure 3b,

** Shear coefficient 0.75, Shear strength 300 t/m^2, incorporating typical design parameters. These criteria in the table are referred to the Japanese standard of the dam design.

stability during earthquakes. Hydrostatic pressure, hydrodynamic pressure, uplift and inertia force due to the earthquake are considered on the PKW independently. The seismic coefficient corresponding to one of the design loads of the dam is selected. By taking the conventional design manner of dams in Japan, the effect of the dam response is neglected here. The action of acceleration amplification at the dam crest will be examined in a later chapter. As a result, the criteria on overturn, stress on the foundation and sliding are secured in all combination of the water depth and directions of the inertia force under the seismic coefficient of 0.12. The critical coefficient is also studied and resulted in 0.84 g, which fails the overturn criterion. The results are summarized in Table 1.

3 DYNAMIC CHARACTERISTICS OF PKW

Authors have studied the dynamic characteristics of the PKW to understand the behavior during earthquakes (Kashiwayangai & Cao 2018). The numerical simulation using the independent PKW model, which is isolated from the dam, identify the fundamental vibration mode and the amplification characteristics of the PKW. These are shown in Figures 4, 5. Figure 5 shows nine (9) components of the matrix transfer function of the PKW, which consist of components of three directional responses corresponding to three directional inputs. Summarizing features, the bending response of the septal wall between keys dominates at the predominant frequency of 28.5 Hz, relatively higher than those of high concrete gravity dams (Figure 4). The amplification of the wall is significant in S_{xx} and S_{yy}, which are response characteristics in X and Y directions cited by the inputs of the same directions. It means that the responses in each direction are cited largely by the base vibrations in the same direction, which suggest less development of the directional interference (Figure 5). The latter is considered again with the dynamic responses of the dam and the PKW later.

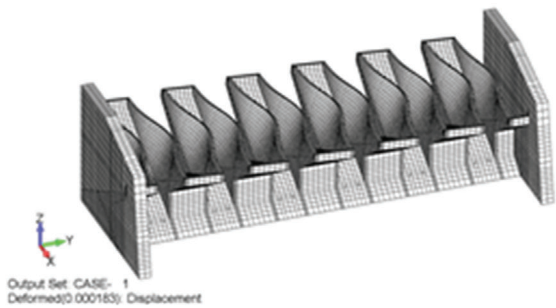


Figure 4. Predominant mode of PKW, 1st mode (28.57 Hz) (Kashiwayangai & Cao 2018)

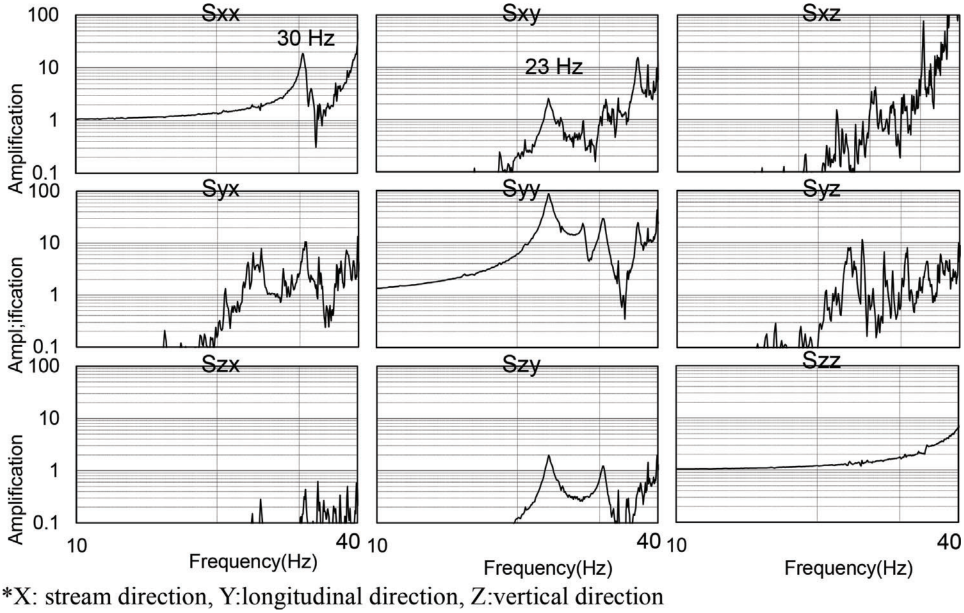


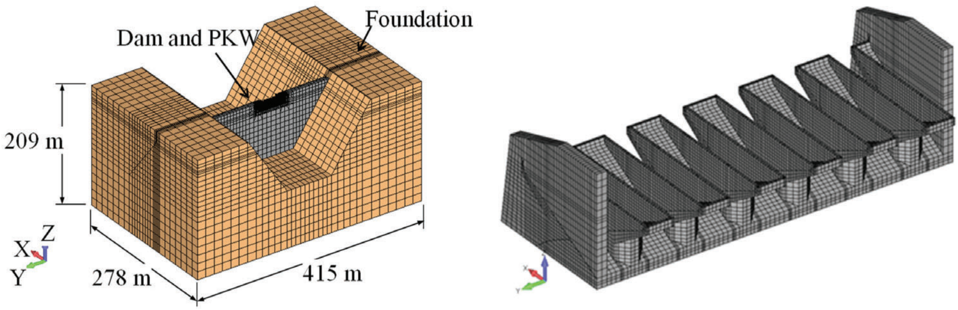
Figure 5. Transfer function matrix of septal wall of PKW from the base to the creat of PKW (Kashiwayangai & Cao 2018)

4 DYNAMIC ANALYSIS

4.1 *Condition of the analysis*

The behavior of the PKW during earthquakes is simulated by FEM analysis using the numerical model as shown in Figure 6, consisting of a 100 m high dam, foundation and a virtual PKW of 6 units. The numerical model is segmented as mesh into 10 m and 21 m for the dam and the foundation, respectively. The septal wall of the PKW of 0.3 m thick is divided in to three layers. The peripheral foundation is fixed with the damping condition (Miura et al. 1989). The artificial earthquake waves are set for the analysis as the strongest earthquakes, so called Level 2 and Level 1 earthquakes. The simulations are conducted in combination with the water depth and intensity of the earthquake. These are summarized in Table 2. The water loads act on the PKW in Case 2 only. The material properties of the model are assumed by referring the dynamic analysis of dams and are summarized in Table 3. The steel reinforced concrete of the PKW should be of less damping characteristic than the dam concrete due to less interaction among the sorrounding materials.

The earthquake waves on the model bottom are established by the following sequence. The artificial wave of Level 2 earthquake on the dam foundation is calculated so as to coincide with the expected response spectrum at the dam bottom (National Institute for Land and Infrastructure Management (ed.) 2005) as much as possible. The monitored earthquake wave at the foundation gallery (2004/10/23 17:56:08) of the existing concrete dam, Tagokura dam, which is 145 m high (Electric power development Co., Ltd.) is utilized as phase characteristics for making the artificial wave. The calculated Level 2 wave is transformed to the waves on the model bottom using the transfer function of the comprehensive model (Figure 6a) involving the impounded water effect. These complicated sequences are necessary for taking the interaction between the dam and the PKW into consideration, not simply applying the observed earthquake records on the dam crest. The Level 1 wave is scaled from the Level 2 wave so that the maximum acceleration will be 180 cm/s^2. Level 2 wave on the dam foundation, shown in Figure 7a, exhibits acceptable agreement with the expected response spectrum as shown in Figure 7b.



(a) Comprehensive view (b) Part view of PKW

Figure 6. Numerical model (Upstream view)

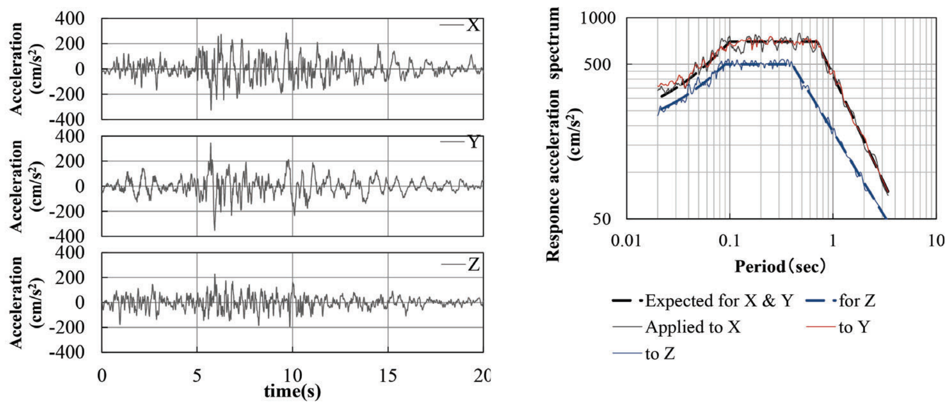
Table 2. Case of numerical simulation

Case	Condition	Water depth	Earthquake
Case-1	Unusual	Low water, corresponding to the base of PKW (EL 255 m)	Level 2
Case-2	Extreme	High water, corresponding to the crest of PKW (EL 261 m)	Level 1

Table 3. Material properties of the numerical model

Material	Shear modulus, G (N/mm^2)	Unit weight (g/cm^3)	Poisson's ratio	Damping
Concrete of PKW	13541.0*1	2.40	0.20	2%
Dam concrete	12000.0*2	2.40	0.20	5%
Foundation	6690.0	2.60	0.30	5%
Free field	6690.0	2.60	0.30	5%

*1 : Shear modulus for common concrete is multiplied by 1.3 as dynamic modulus.
*2 : Refer to the dynamic analysis of the existing concrete gravity dam



(a) Acceleration time history (b)Response spectrum

Figure 7. Artificial Level 2 earthquake on the dam foundation

The hydrodynamic pressure is considered in the dynamic analysis of the PKW. It is well known that hydrodynamic pressure caused by the interaction between structures and impounded water makes a certain alteration in the dynamic behavior of the structures. To estimate hydrodynamic pressure on the structures involving dams, the methods of FEM analysis using structure-reservoir coupled numerical model or added mass concept has been developed for the safety assessment under seismic loads. These methods are hardly applicable to PKW at this moment due to its complicated figure. In this paper, the following method is adopted to load the hydrodynamic pressure on the PKW. The added mass based on the Westergaard's formula is attached to the upstream surface of the PKW as well as the dam. It is assumed that the water stored in inlet keys of the PKW move together with the oscillation of the PKW without the interaction to the upstream water. This assumption results that the mass of the water can be distributed evenly on the surface of the inlet key as if the water is a part of the structure of the inlet key. The hydrodynamic pressure loaded on the PKW upstream area is illustrated in Figure 8. The assumption relating the hydrodynamic pressure on the PKW likely agrees with the high predominant frequency of the PKW (Figure 4), while the Westergaard's formula is based on the interaction between the rigid body and upstream water.

4.2 *Results of the analysis*

The dynamic response of the PKW is mainly presented as the results of the numerical simulations here. To overview the PKW response, the acceleration characteristics as the maximum distribution and time history are shown in Figures 9, 10 in Case 1 (ref. Table 2), which resulted larger responses than those in Case 2. The oscillation at the PKW bottom that is caused by the dynamic response of the dam crest propagates to the PKW crest according to its dynamic characteristics. Figure 9 indicates that the PKW behaves as it is a rigid body in the stream (X) direction and the significant local amplifications are found at the crest of the septal wall in the longitudinal (Y) direction and at the upstream crest in the vertical (Z) direction.

The dynamic characteristics of the PKW are represented by the transfer function between the bottom and the crest of the PKW. These are illustrated in Figure 11, corresponding to those at the upstream crest (Node 99368), the center of the septal wall (Node 99511) and the downstream crest (Node 99601). These all in X direction are identical, confirming the rigid behavior. The higher values in each direction suggest much amplification in these directions. Significant values in X and Y directions at certain frequencies indicate higher amplification occur at a selective frequency. High values in Z direction found above 30 Hz are negligible due to these high frequencies. These characteristics shown in Figures 9, 11 are consistent.

The outstanding peaks in frequency of 30 Hz and 23 Hz are designated as the predominant frequencies in X and Y directions, respectively in Figure 11 as marked by arrows. The response at 23 Hz in Y direction is compatible to the behavior of the fundamental mode, dominating at 28 Hz as shown in Figure 4. The disagreement in numbers is not conflictive. It is

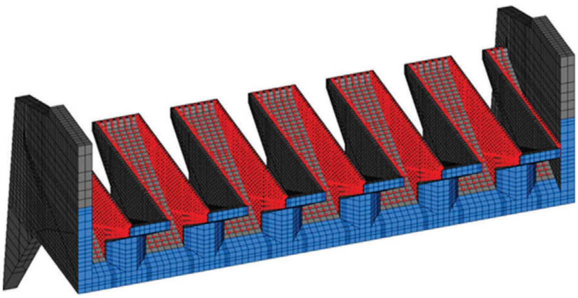
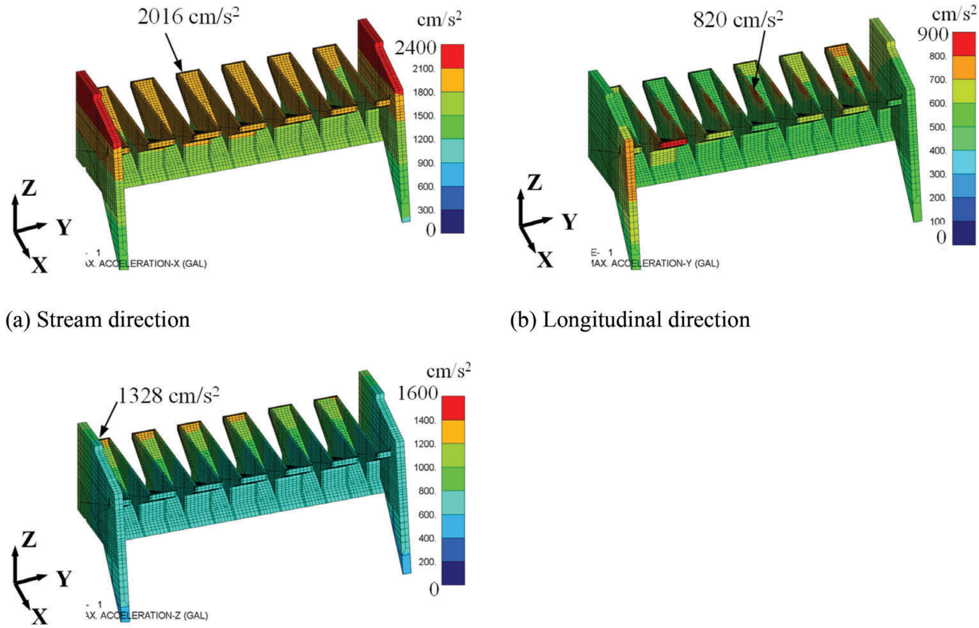


Figure 8. Definition of hydrodynamic pressure on PKW



(a) Stream direction

(b) Longitudinal direction

(c) Vertical direction

Note) All figures are downstream views.

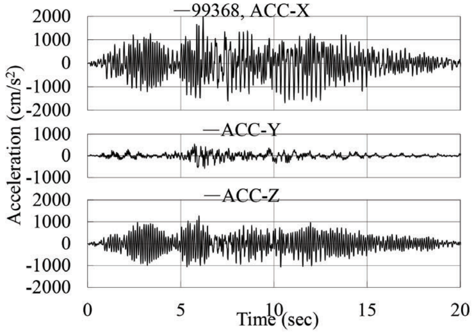
Figure 9. Max. response acceleration of Case 1

considered that the former features the whole behavior of the PKW while the latter features the local behavior of the septal wall.

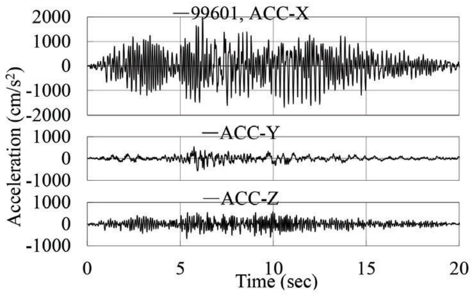
Taking the intricated configuration of PKW into account, the directional interference in the response of the structure may be prominent. Here the matrix transfer function (Cao & Kashiwayanagi 2018) that consists of 9 components of the transfer functions as shown in Figure 5 is compared to those in Figure 11. The predominant frequencies in X and Y directions are clearly designated in S_{xx} and S_{yy} components as similarly found in Figure 11. The non-diagonal components indicated by S_{ij} (i not equal to j, Response in j to input in i) represent the directional interference between i and j directions. The significant amplification is not found other than the predominant frequencies above-mentioned. It implies that the PKW responses independently to unidirectional excitation with less directional interference.

To examine the interaction between the dam and the PKW, both transfer functions are compared in Figure 12. These represent the amplification characteristics in frequency domain from the dam foundation to the dam crest, which is near the PKW foundation, and from the PKW foundation to the PKW crest. The dominant frequencies located above 20 Hz in the PKW, while ones of the dam locate below 15 Hz. Both involve no coincident frequencies. This fact implies less interaction between the dam and the PKW. The amplification of the dam is less than 1.0 above 20 Hz where the dominant frequencies of the PKW exist. This indicates that the dam response alleviates the excitation to the PKW comparing the excitation of the dam foundation. It can be concluded that these dynamic characteristics are advantages in the seismic safety of the PKW. In this study the common material properties are adopted to the dam and the PKW. If the extreme properties were adequate to both in a certain case, the conclusion would be invariant where the disagreement of both dominant frequencies is adequately open.

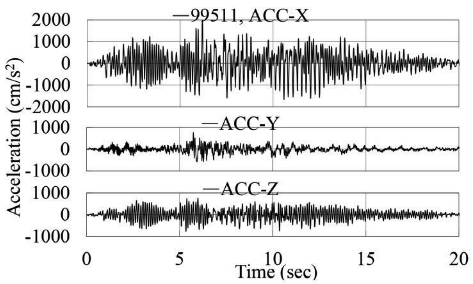
To examine the influence of the hydrodynamic effect on the PKW response, the transfer functions with and without the impounded water in the inlet keys of the PKW are compared



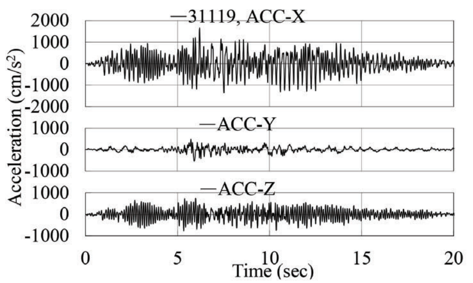
(a) Upstream nose (node 99368)



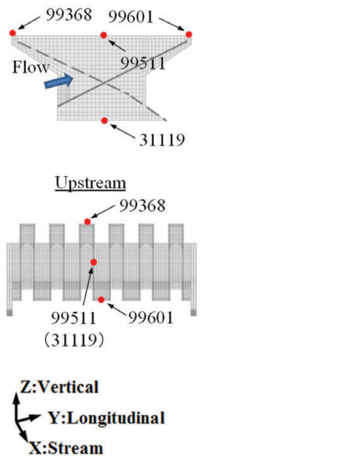
(b) Downstream stern (node 99601)



(c) Center of septal wall (node 99511)



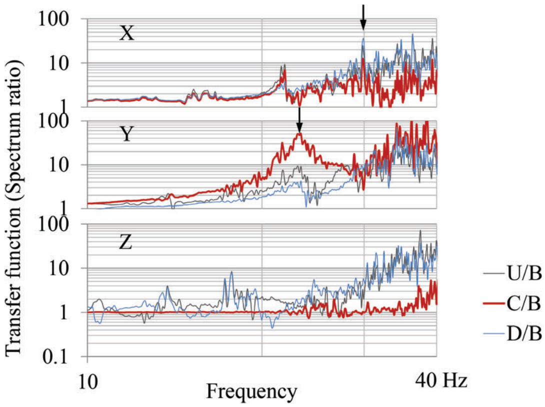
(d) Base of PKW (node 31119)



Key Map, Numbers indicate the node numbers of the numerical model

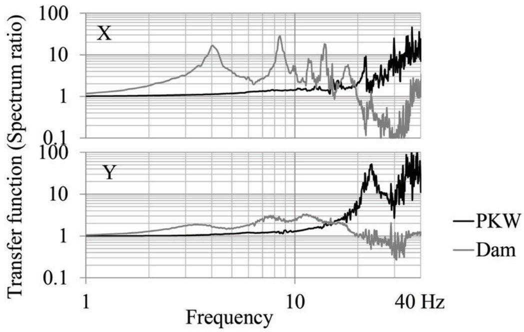
Figure 10. Time histories of response acceleration of PKW of Case 1

in Figure 13. It is obvious that the impounded water move the dominant frequencies lower. While the water weight confined in the inlet keys is incorporated in this study, the similar tendency is presumed by the adequate consideration of the hydrodynamic pressure in the inlet keys. While the dam of 100 m high is studied in this study, the lower dam will show higher dominant



Values corresponding to U, C and D for node 99368, 99511 and 99601 in Figure 10 are the responses to the wave at B point, node 31119 of the base of PKW. Arrows indicate the predominant frequencies in X and Y direction, respectively.

Figure 11. Response characteristics of the crest of PKW of Case 1



	X direction	Y direction
PKW	U/B	C/B
Dam	$B/B_{d\ X}$	$B/B_{d\ Y}$

U, C, B is referred to Figures 6, 11. $B_{d\ i}$ is a spectrum in *i* direction on the dam base.

Figure 12. Comparison of transfer characteristics between dam and PKW

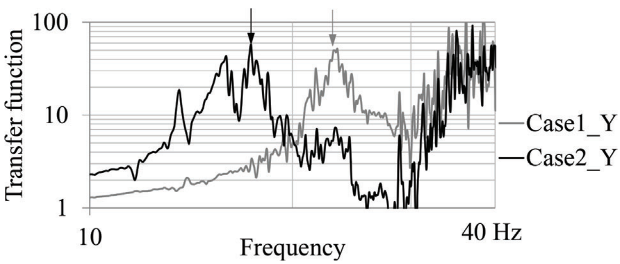
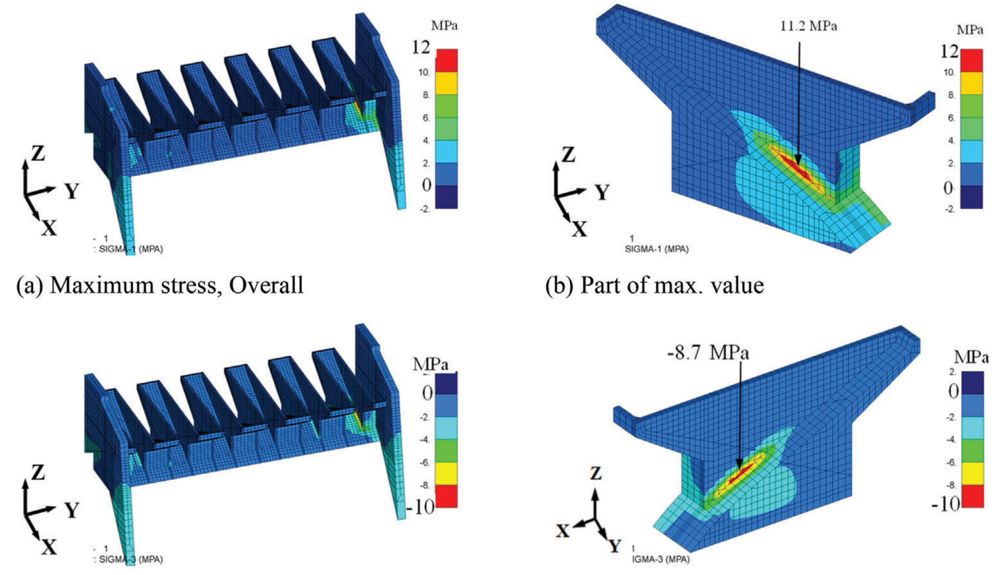


Figure 13. Effect of hydrodynamic pressure on the response of the septal wall of PKW



(a) Maximum stress, Overall

(b) Part of max. value

(c) Minimum stress, Overall

(d) Part of min. value

All are view from the downstream side.

Figure 14. Principal stress of Case 1

frequency, which could be nearer and overlap the dominant frequency of the PKW, taking the hydrodynamic influence into consideration. In such case, the interaction between the dam and the PKW would be significant. Therefore the adequate estimation of the hydrodynamic pressure on the PKW is the further challenge for the seismic safety evaluation of the PKW.

4.3 *Seismic durability of PKW*

The stress of the PKW under the seismic load is studied here. The distributions of the maximum and minimum principal stresses are illustrated in Figure 14 to the seismic load as shown in Figure 7. The highest maximum stress occurs as 11.2 MPa at the corner of the slope of the keys and the septal wall (Figure 14b) in the PKW unit next to the dam body (Figure 14a), while no critical values are found in other units. The value of 11.2 MPa exceeds the dynamic tension strength of the concrete, which could be presumed to be 1.5 times of the static tension strength, ranging from 4.5 ~ 7.5 MPa. The area of the critical values is localized. However the progressive tension damages could develop the collapse of the septal wall. On the other hand, the minimum stress is sufficiently lower than the compressive strength of the concrete.

Reinforcement design is necessary to secure the safety under earthquakes for the PKW. By rough calculation, the steel bars of 25 mm in diameter at 125 mm intervals provide enough durability to the PKW against the large earthquake designated in this study. The detailed design of the corner configuration such as haunch and/or the inventive connection to the dam could reduce the critical localized stress. These issues are challenges for the future.

5 CONCLUSIONS

The dynamic analysis using the numerical model consisting of the 100 m high dam and the 6 unit PKW is conducted to assess the dynamic characteristics and the durability of the PKW during earthquakes. The conclusions extracted from the studies are listed below.

1) The PKW behaves independently in each direction. The bending response of the septal wall between inlet and outlet keys dominates in the longitudinal direction of the dam. It is a major deformation mode. The response of the rigid body prevails in the stream direction.
2) For the PKW geometry chosen in this study, the predominant frequency of the PKW is much higher than those of 100m high concrete gravity dams. The excitation is reduced due to the low dynamic amplification of the dam in the higher frequency range close to the predominant frequency of the PKW. These dynamic characteristics of both are advantages in the seismic safety of the PKW.
3) The impounded water in the inlet keys moves the dominant frequencies of the PKW lower. Low dams will show higher dominant frequency, which could be nearer and overlap the dominant frequency of the PKW taking the hydrodynamic influence into consideration. In such case, the interaction between the dam and the PKW should be examined carefully.
4) The PKW is a promising countermeasure to the increasing flood risk even in earthquake prone areas by providing adequate reinforcement design in order to secure the safety during earthquakes. To enhance the durability of the PKW to earthquakes, the detailed configuration design of the corner between key slopes and septal walls and/or the inventive connection to the dam is recommended to reduce the critical localized stress.

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