Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 517

SEISMIC SAFETY OF GATED SPILLWAYS: MODELING HYDRODYNAMIC PRESSURE ON GATES

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ABSTRACT

Earthquake excitations of spillway induce gate and pier vibrations. These two structural components have different dynamic characteristics. The piers are stiff with short periods of vibration, while steel gates are more flexible with longer periods of vibration. Current analyses of gated spillways under seismic actions most often use Westergaard added mass theory to assess the hydrodynamic forces induced by the interaction of the reservoir with the structure. However, the use of the Westergaard theory, developed for a rigid concrete dam with an upstream vertical face, may lead to inadequate gated spillway safety assessment because it disregards the shape and flexibility of the gate-pier coupled system. A key question is to determine if in the case of flexible structures, hydrodynamic thrusts of gates and piers (a) will be acting in phase, thus being directly additive in time or (b) will be out of phase with some cancellation. To evaluate the dispersion of results using the Westergaard theory for gated spillways, this paper develops and compares different modeling strategies to assess the hydrodynamic forces arising during earthquakes that affect piers and gates. Finally, a flexible gate model using compressible fluid finite element in a coupled fluid structure interaction problem is studied. It is shown that for the gate analysed Westergaard added masses are producing an upper bound for seismically induced hydrodynamic forces.

Introduction

When a spillway goes through seismic excitations, gates and piers vibrate. These vibrations can cause large inertia forces and related distortions in piers and gates. Special attention should be devoted to the seismic assessment of gated spillways because gate operations could be compromised after a moderate earthquake, or gates could fail in a large seismic event. However, dam safety guidelines lack recommendation on how to model seismically induced hydrodynamic pressures on gate-pier systems (FERC 2002, USCOLD 1995).

It is known that the use of Westergaard's added mass theory, which is most often used to

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assess hydrodynamic forces, can lead to inadequate results because it does not take into account the shape and flexibility of the gate-pier interacting system (Adya 2008, Aslam et al. 2002).

This paper develops and compares different modeling strategies to assess hydrodynamic forces acting on typical piers and gates of an existing spillway built in 1933. The results obtained for a model which considers the structure as a rigid body using the seismic coefficient (pseudo-static) method are compared to (pseudo-dynamic) response spectra models which take into account the gate and pier flexibilities so as to evaluate the accuracy of Westergaard's theory (Bouaanani et al. 2003). For that, finite element analyses using 3D beam-columns and shell elements were performed to assess the maximum base shear. At first, an evaluation considering a single pier with two half gates was carried out. Then a model of three piers and two gates is analyzed so as to investigate the pier-gate-fluid interactions. A key question is to determine if in the case of flexible structures, hydrodynamic thrusts of gates and piers (a) will be acting in phase, thus being directly additive in time or (b) will be out of phase with some cancellation (Tinic et al. 1994). A special attention is devoted to identify the dynamic characteristics of each model (periods of vibration, and related mode shapes). Parametric analyses are then conducted for sinusoidal ground excitations with different frequency contents as well as ground motions typical of Eastern and Western North American conditions. It is shown that (a) mode shapes of gates and piers are decoupled if a hinge connection is used between the gate and the pier, (b) reductions in hydrodynamic thrusts are generally obtained when the gate and the pier are modeled separately using either added masses or fluid elements as compared to the added mass lumped pier-gate model. Finally, a finite element model of a flexible gate interacting with compressible fluid elements in a coupled fluid-structure analysis for the spillway analyzed indicates that Westergaard added masses provide an upper bound for seismically induced hydrodynamic forces.

Seismic Safety Assessment of Gated Spillways

Seismic analysis of concrete dams and spillways could be performed with a progressive methodology divided in four basic analysis levels of increasing complexity (Stefan et al. 2008). These are shown in Table1: (1) the pseudo-static (seismic coefficient method), (2) the pseudo-dynamic (response-spectra) method, (3) linear or nonlinear transient dynamic finite element methods, and (4) the transient rigid body dynamic method for cracked components. It is important to maintain consistency in modeling assumptions while comparing the results from one type of analysis to another. Obviously as the fundamental period of the structure tends to zero (rigid structure), the results of response spectrum or transient dynamic analysis should tend to the results obtained from the pseudo-static method (seismic coefficient).

Table 1: Progressive approach for seismic stability

Method	Excitation	Dynamic Characteristics	Response
1. Pseudo-static (seismic coefficient)	PGA (cracking) Sustained Acc. (stability)	Mass, Infinite stiffness (No dyn. amplification)	Non-oscillatory Equivalent static
2. Pseudo-dynamic (response-spectra)	Design spectra Peak (cracking) Sustained (stability)	Mass, Stiffness, Damping (Dyn. amplification)	Non-oscillatory Max. probable
3. Dynamic (FE) (Lin. / Non-Lin.)	Accelerogram	Mass, Stiffness, Damping (Dyn. amplification)	Oscillatory History (+ / -)

4. Dynamic (Rigid body)	Accelerogram	Mass, Restoring force (friction, inelastic impact)	Oscillatory

Modeling Seismic Hydrodynamic Pressures on Flexible Gates

The added-mass arising from dam-water interaction during earthquake ground acceleration was assessed using the formulation proposed by Westergaard. The formulation considers a dam with a vertical upstream face accelerated at its base as a rigid body with a continuous infinite length reservoir. Due to the infinite stiffness of the dam, the acceleration along the structure was considered constant and equal to the acceleration of the foundation. Westergaard showed that the hydrodynamic pressures exerted on the face of the dam due to the earthquake ground motion is equivalent to the inertia forces of a body of water attached to the dam and moving back and forth with the dam while the rest of the reservoir water remains inactive. The suggested variation for this body of water is parabolic with a base width equal to 7/8 of the height. The equation proposed by Westergaard for the hydrodynamic pressure assessment is shown in Eq. 1:

$$p = \frac{7}{8} \cdot \rho \cdot H \cdot \left(1 - \frac{z}{H}\right)^{0.5} \cdot a_g \tag{1}$$

where ρ is the water density, H is the reservoir height, z is the height from the base, and a_g is the ground acceleration. The total force F, caused by the hydrodynamic pressure, is obtained by multiplying the hydrodynamic pressure, p, by tributary area A_i, corresponding to each node in the upstream side of the finite element model of the dam. Noticing that $F = m \cdot a$, the added mass in each node of the upstream side is given by (all symbols are already detailed):

$$m_{Ai} = \frac{7}{8} \cdot \rho \cdot H \cdot \left(1 - \frac{z}{H}\right)^{0.5} \cdot A_i \tag{2}$$

The main parts of a typical gated spillway structure (piers and gates) have quite different dynamic properties due to important difference in their flexibility (the piers being much stiffer then the gates). The hydrodynamic model for a spillway should therefore differ to some extent from that of a rigid dam. Various hydrodynamic models for pier-gate systems based on the Westergaard theory are possible, as detailed on the next paragraph (e.g., the gate Westergaard masses can be added on pier or on gates). Moreover, the influence of the reservoir on the dynamic response of the spillway can be further investigated by using finite elements software that considers the fluid-structure interaction.

Hydrodynamic Model for Analyzed Gated Spillway

The gated spillway analyzed (Fig. 1) was built in 1933 and is located in Canada. It is ~ 300 m long and 10.82 m high. It comprises twenty 6.1 m x 12.4 m Stoney-roller gates each weighting 352 kN and resting on a raft foundation. The bridge and the railroad situated on the upper part of the structure weight 82 kN and 680 kN, respectively.

Two models were used to compute the dynamic response of the pier-gate-reservoir system (Fig. 2). Both models were built with the computer program SAP2000 (CSI 2009). The first structural model, *M1*, representing a single pier has 14 vertical and 13 horizontal beam-column elements (Fig. 2a). As the properties of the sections vary, vertical elements have different properties according to the section that they represent. The foundation flexibility is modeled using equivalent springs. The second structural model, *M2*, has 168 shell elements which were added to *M1* for modeling the gates (Fig. 2b). The connection between the piers and the gates is pinned. To simulate the presence of the neighboring piers and gates, which are not modeled, equivalent springs were added in both ends on *x* direction.

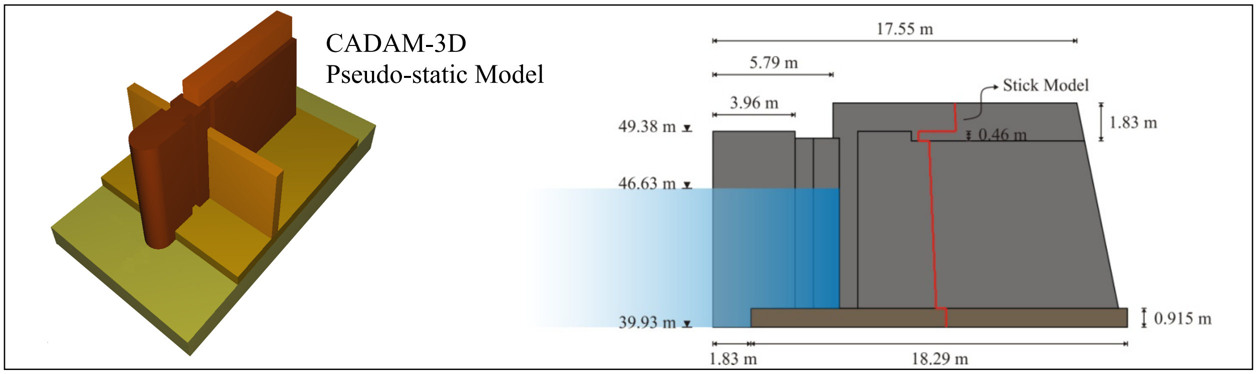

Figure 1. Analyzed gated spillway.

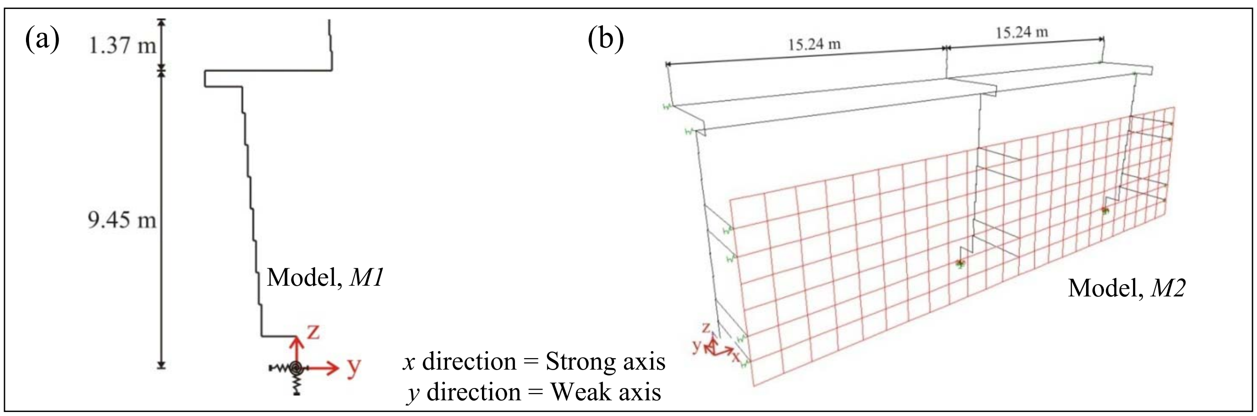

Figure 2. Models for analyzed spillway: (a) *M1*: one pier, and (b) *M2*: three piers with two gates.

For each model (*M1* and *M2*), four mass modeling methods for piers and gates were studied: (a) only pier self-mass is employed; (b) pier self-mass and pier Westergaard masses; (c) pier and gate self-mass (no Westergaard mass); (d) self-mass and Westergaard masses for both piers and gates. Thus, for example *M2b* is the model having 3 piers and 2 gates (Fig. 2b) with pier self-mass and Westergaard masses (no gate mass). Model *M1d* is frequently used in engineering practice. The masses on gates were treated the same way as those of the pier (Eq. 2).

Dynamic Characteristics of Spillway Model

Fig. 3 illustrates the first four vibration modes of the spillway pier alone (model *M1c*, Westergaard masses were disregarded on pier and gates). The modal participation mass ratios (MPMR) for the first and 2nd mode in *y* direction (weak axis) are 74% and 20%, respectively, for a total of 94%. The period for the 2nd mode in *y* (weak axis) is ~ 0.007 s. Figure 4 depicts the first vibration mode in *y* direction for gate and pier (model *M2d*). The period and modal participation ratios for two versions of the complete model *M2* (*M2c* and *M2d*) are shown in Table 2. The dynamic behavior of the spillway pier is practically the same (MPMR ≈ 90% for *y* mode 1 and 2) regardless of the number of modeled piers. For example, the first *y* mode of *M2c* (3 piers) is represented by two *y* modes (number 26 and 28 with the same period, Table 2), corresponding to the central and extreme piers, adding up to ~ 75% of mass participation (for the first mode of *M1c*, MPMR = 74%). The same situation is observed for the 2nd *y* mode (modes 75 and 76, Table 2).

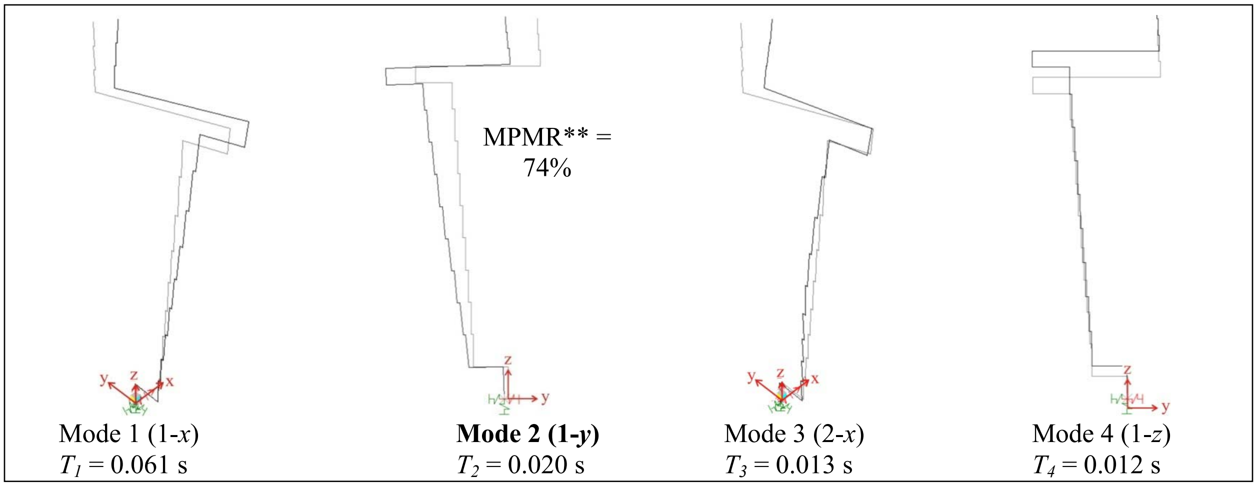

Figure 3. Mode shapes of the pier (model *M1c*).

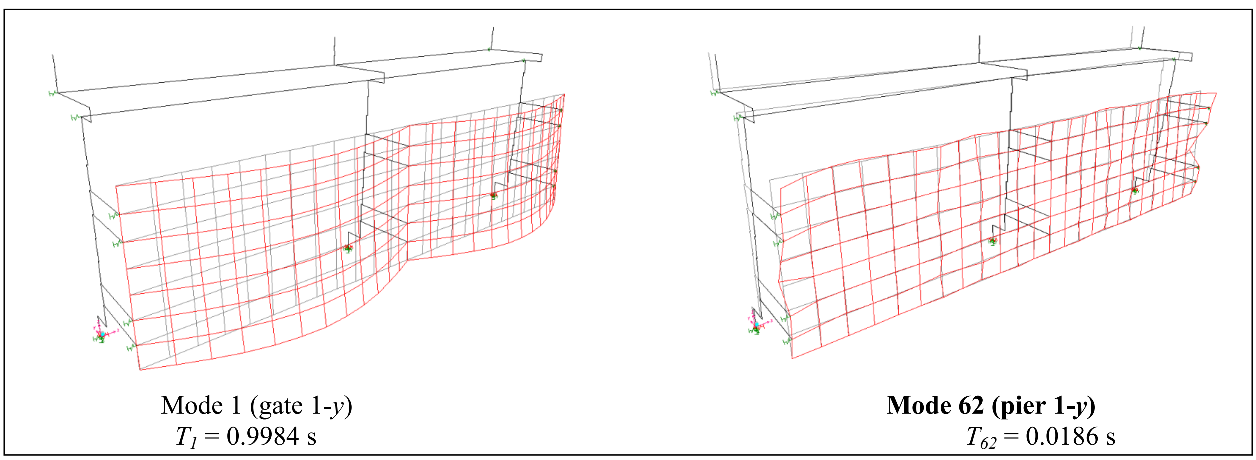

Figure 4. Mode shapes of the spillway (model *M2d*).

Table 2. Dynamic characteristic of models *M2c* and *M2d*.

Model *M2c* (Σ MPMR > 90%)			Model *M2d* (Σ MPMR > 90%)		
Mode No.*	Period (s)	MPMR**	Mode*	Period (s)	MPMR**
26 (pier)	0.0185	53%	62 (pier)	0.0186	44%
28 (pier)	0.0184	25%	60 (pier)	0.0187	25%
76 (pier)	0.0067	10%	1 (gate)	0.9984	9.7%
75 (pier)	0.0066	5.6%	110 (pier)	0.0069	8.9%

1 (gate)	0.3436	1.4%	109 (pier)	0.0068	4.8%

* Mode number; **MPMR = modal participation mass ratio in *y* (upstream/downstream) direction.

Table 2, indicates that added masses change only the periods and the MPMR for the gates, but not for the piers. The ratio of the added masses (266 ton) and the self-mass (36 ton) of the gate is 7.39. This large ratio explains why the gate is more sensitive to the added masses. The influence of added masses on the dynamic properties of the pier is small, as the ratio of the added masses (52 ton) and its self-mass (1320 ton) is only of 0.04. The dynamic characteristics of the pier-gate system are largely dominated by those of the pier. The reason for the higher MPMR ratio of the piers (> 85% no matter the model) can be (a) the uncoupled dynamic behavior of the pier-gate system due to the important difference in their flexibility, and (b) the quotient between the total mass of the gate and that of the pier: (36+266) / (1320+52) = 0.22. For some structures, it is possible to decompose the eigenmodes into two vectors belonging to degrees of freedom (DOF) of different parts of the structure; these two vectors have non null elements for one part of the structure and mutually zero elements for the other part. In the case of a spillway the decomposition can read: $\Phi^T = [\Phi_P;0]^T + [0;\Phi_G]^T$, where Φ^T is the complete eigenmode, Φ_P and Φ_G are the vector components for the pier's and for the gate's DOF. For computing the base shear (BS), one can prove that for this kind of eigenmodes the influence of the forces applied on one structural part will be null on the other. However, for real structures the decomposition is never perfect; there are small but non-null coupling elements. By carefully observing the mode shapes of the analyzed spillway it was concluded that they have a form that permits the decomposition. Thus, this particular form can explain the uncoupled dynamic behavior of the pier-gate system and the small influence of the gate's added masses on the BS computation of spillways exhibiting decoupled pier and gate mode shapes.

Earthquake Response Analysis

The earthquake response of the spillway was evaluated by performing four types of analysis with increasing level of complexity: pseudo-static (this analysis does not account for dynamic amplification), pseudo-dynamic, spectral and time history analyses. The seismic analyses are performed in upsteam/downstream (us/ds) direction with a peak ground acceleration PGA = 0.25g. To apply the pseudo-static method, a 3D solid model was developed with the computer program CADAM-3D (Leclerc et al. 2003). The seismic inertia forces are computed from the product of the masses and the ground acceleration (seismic coefficient). For pseudo-dynamic analysis (CADAM-3D), the spectral acceleration $S_a(T_1)$ at the fundamental period of vibration of the structure, T_1, is used instead of the seismic coefficient in the pseudo-static method (T_1 was obtained from the FE model). This procedure is usually conservative as the spectral acceleration $S_a(T_1)$ is multiplied by the total mass of the structure without computing modal participation factors as in the case of the classical response spectra analysis (USCOLD 1995). Five ground motions were considered for the linear elastic and spectral and time-history analyses (5% viscous damping): (a) two sinusoidal signals (5 Hz and 10 Hz); (b) an El Centro record (Imperial Valley, California - 1940); (c) a high frequency ground motions record spectrally matched to National Building Code of Canada (NBCC) design spectrum for Ottawa Valley; and (d) a record of the Saguenay earthquake (Québec, Canada - 1988). If necessary, the signals were scaled to obtain a PGA equal to 0.25g (Fig. 5). The spectral analysis was carried out using the complete quadratic combination (CQC) rule. The time history analysis was performed with an integration time step of $7.5 \cdot 10^{-4}$ s. The maximum base shear obtained in the pseudo-static, pseudo-dynamic, spectral and linear time-history analyses is shown in Table 3. By comparing the maximum BS for all eight hydrodynamic models (*M1a* to *M2d*), a difference of less than 5% was noticed between all models except *M1d*; the difference between *M1d* and all other models being ~ 20%. The explanation can be found in the important difference of dynamic characteristics of piers and gates producing many cancellations on BS computation or a different dynamic amplification (a dynamic separation of the response, Fig. 5). The simplified model *M1b* shows practically the same BS as *M2d* (~ 2% difference). However, *M2d* being the most complete model, it was selected for comparison in Table 3 with model *M1d* (frequently used in practice).

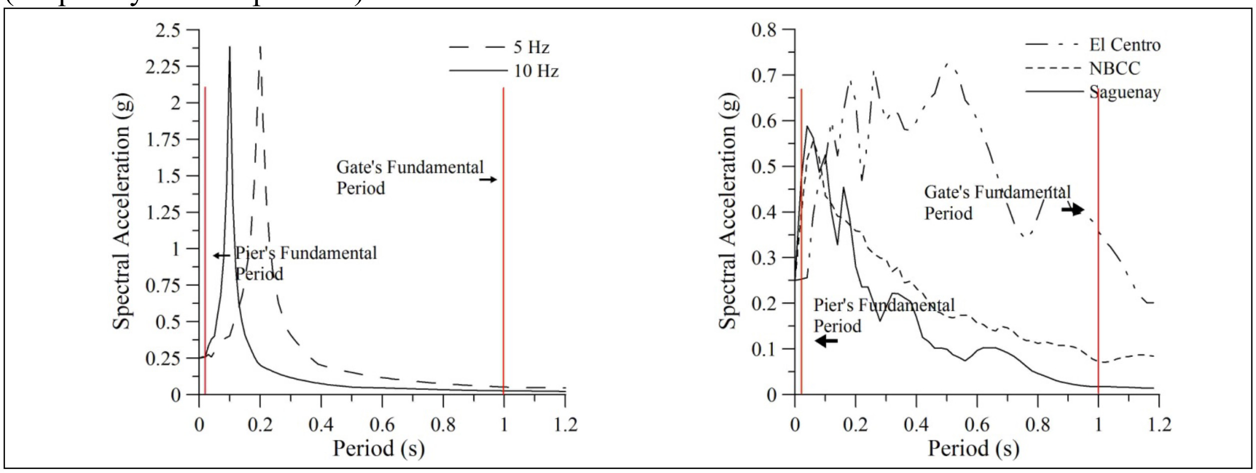

Figure 5. Acceleration response spectrum for 5% damping.

Table 3. Base shear forces, V_{max}, for the pseudo-static, pseudo-dynamic, spectral and linear time-history analyses (Westergaard masses on gates).

Excitation	Pseudo-static (CADAM-3D) [kN]	Pseudo-dynamic (CADAM-3D) [kN]	Spectral (kN) 1 pier (*M1d*)	Spectral (kN) 3 piers (*M2d*)	Linear Time History (kN) 1 pier (*M1d*)	Linear Time History (kN) 3 piers (*M2d*)
Sine 5Hz		3937	3401	2838	4089	3507
Sine 10Hz		4046	3556	2852	4422	3499
El Centro	3902	3904	3591	3007	4471	3713
Saguenay		4885	5012	4037	5642	4782
NBCC		6751	6562	4864	5892	5992

Table 4. Influence of Westergaard added mass on gates for pier response: linear time-history analysis (model *M2d vs M2c*).

Excitation	V_{max} [kN] *M2d* with added mass	V_{max} [kN] *M2c* no added mass	Difference (%)
Sine 5Hz	3507	3498	0.25
Sine 10Hz	3499	3524	-0.71
El Centro	3713	3687	0.70
Saguenay	4782	4778	0.08
NBCC	5992	5997	-0.08

To investigate the influence of Westergaard added masses on gates, the results obtained for a model where no Westergaard masses were added on gates (*M2c*) is compared with the results of the model containing masses on both piers and gates (*M2d*). Only a slight difference was found between the maximum BS (V_{max}) computed for these models (Table 4). However, as the maximum BS is an indicator of the global spillway performance, the local influence of added masses on gates can be more important. Moreover, the phase shift, influenced by the damping properties of the structure, can play a role in the time distribution of the response.

Fluid-Structure Interaction Analysis

A simplified Fluid-Structure Interaction (FSI) analysis of a wall-gate-reservoir system was also carried-out in this work to investigate the influence of water compressibility and gate flexibility. Figure 6 illustrates the finite element model built with the software ANSYS (2007) and used to conduct the FSI analysis. The gate's dimensions are the same as previously (L_S=12.18 m, and H_S=6.4 m). The wall is assumed rigid and is extended to $3L_S$ laterally on each side of the gate and the reservoir is truncated at a distance L_r=15H_S from the wall upstream face. The wall and the gate were modeled using 3D solid and shell finite elements, respectively, and the reservoir using potential-based fluid finite elements. Zero pressure boundary conditions are imposed at the surface and upstream end of the reservoir, while rigid boundary conditions implying null hydrodynamic pressure gradients are imposed on the lateral sides of the reservoir (Bouaanani and Lu 2009). The obtained first four vibration periods of the coupled wall-gate-reservoir system are given in Table 5 as well as the periods of the gate without reservoir.

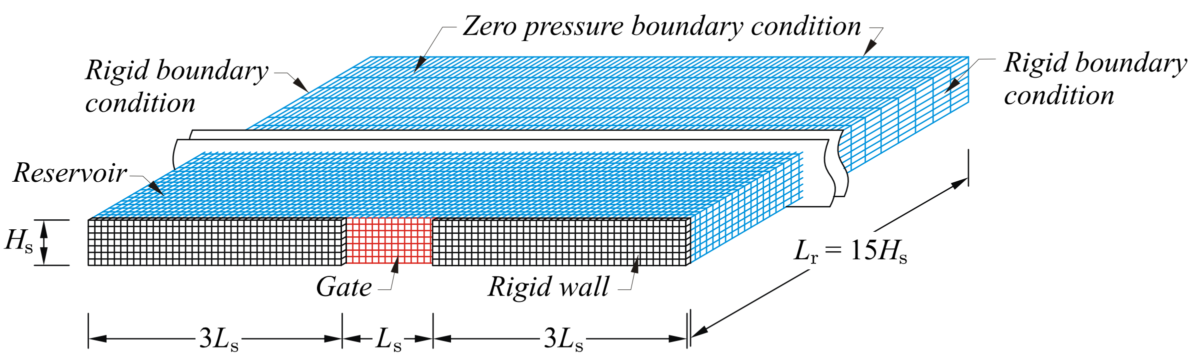

Figure 6. Finite element model of the wall-gate-reservoir system used for FSI analysis.

For purpose of comparison, a simplified analysis where the reservoir hydrodynamic loading is included using Westergaard added masses [Eq. (2)] lumped to the wall-gate finite element nodes was also conducted. Table 5 shows the vibration periods obtained and the corresponding Westergaard total added mass assuming a rigid gate. The total added masses M_i^* corresponding to each vibration mode of the gate were determined using the simplified equation proposed by Blevins (1979):

$$M_i^* = \left[\left(\frac{f_i^{uncoupled}}{f_i^{coupled}} \right)^2 - 1 \right] M_{gate} \quad (3)$$

where $f_i^{uncoupled}$ is the vibration frequency of the gate without reservoir (in vacuum), $f_i^{coupled}$ is the frequency of the coupled gate-reservoir system obtained using FSI analysis, and M_{gate} is the mass of the gate.

Table 5. Frequencies and added masses for the models studied.

Mode	Period (s)			Added mass (t)	
	Gate	Wall-gate-reservoir (FSI)	Wall-gate-reservoir (Westergaard)	Westergaard [Eq. (2)]	Blevins [Eq. (3)]
1	0.3424	0.9041	1.0368	290 (a single value)	214.25
2	0.1237	0.2261	0.3393		84.04
3	0.0845	0.1867	0.2616		139.43
4	0.0520	0.0897	0.1415		71.13
SRSS				290	278

Comparing the results obtained for the uncoupled (gate only) and coupled (wall-gate-reservoir) structures, confirms that Fluid-Structure interaction significantly increases the vibration periods of the system because of the added mass associated with vibrating water in contact with the gate. Table 5 also indicates that vibration periods obtained using Westergaard formulation are higher than those from FSI analysis because water compressibility and gate flexibility are included in the latter case. Similar trends were obtained in other studies (Barbosa 2008, Ribeiro et al. 2009). For each of the four vibration modes in Table 5, this effect is evidenced further by the Square Root of the Sum of the Squares (SRSS) where total added mass which is found higher when using Westergaard theory, i.e. 290 t, as compared to the formulation [Eq. (3)] (278t) including the effect of water compressibility coupled with the vibration mode of the flexible gate.

Conclusions

Dam safety guidelines lack specific recommendations of how to model hydrodynamic pressures on gates. It is shown herein that the gate flexibility plays a significant role in estimating the driving shear forces to be resisted by the piers. Lumping Westergaard added masses of the pier-gate system only on the pier can be an appropriate method for an upper bound evaluation of the maximum base shear for the pier. Several dynamic analyses were performed with two models, the first considering a single pier (with two half gates) and the second one being composed of three piers and two gates. It was determined that the dynamic response of the pier is more realistically modeled when the added masses on the gates are neglected. The limited participation of the gate's masses on the dynamic response of the pier is because the hydrodynamic loads on the gates and piers act out of phase with some cancellation, thus not being directly added in time. A simplified fluid-structure interaction analysis of a wall-gate-reservoir system was conducted to highlight the effects of water compressibility and gate flexibility on the dynamic response. The results confirmed that hydrodynamic effects increase the vibration periods of the system and that Westergaard formulation overestimates the added masses on the gate.

The seismic loads on spillways are greater when considering the Westergaard theory for added masses being lumped for the gate to the pier for the system analyzed. However, this kind of analysis may not be able to capture the effects of resonance, occurring in a certain frequency range, of typically coupled flexible spillway-reservoir system. In such cases finite element analysis accounting for fluid-structure interaction would be more appropriate.

Acknowledgements

The authors wish to thank the Canadian Bureau for International Education, Department of Foreign Affairs and International Trade Canada (DFAIT) for its Grant Students' Exchange Program (SEP) for the financial support provided to the first author while conducting research at École Polytechnique de Montréal, Québec, Canada, as well as the financial resources provided by the National Science and Engineering Research Council of Canada (NSERC).

References

Adya, A., 2008. FE modeling and numerical simulation for dynamic analysis of gravity dam spillway, *The 14th World Conference on Earthquake Engineering*, Beijing, China.

ANSYS, 2007. Documentation for ANSYS, ANSYS Academic Research, Release 11.0.

Aslam, M., E. L. Wilson, M. Button, and C. Ahlgren, 2002. Earthquake analysis of radial gates/dam including fluid-structure interaction, *22nd USSD Annual Meeting and Conference*, San Diego, California.

Barbosa, A. N., and L. J. Pedroso, 2008. A study of static and dynamic coupling of structures through an acoustic medium. In *Proceedings of the Sixth International Conference on Engineering Computational Technology*, ed. M. Papadrakakis, and B. H. V. Topping, paper 100. Stirlingshire: Civil-Comp Press.

Bouaanani, N., P. Paultre, and J. Proulx, 2003. A closed-form formulation for earthquake-induced hydrodynamic pressure on gravity dams. *Journal of Sound and Vibration* 33, 573-582.

Bouaanani, N., and F. Lu, 2009. Assessment of potential-based fluid finite elements for seismic analysis of dam-reservoir systems. Journal of Computers and Structures, Vol. 87, No. 3-4, 206-224.

CSI (Computers and Structures), 2009. *SAP2000 User's Manual*, CSI Inc., Berkeley, California.

FERC (Federal Energy Regulatory Commission), 2002. *Engineering guidelines for the evaluation of hydropower projects: Gravity Dams*, www.ferc.gov.

Leclerc, M., P. Léger, and R. Tinawi, 2003. Computer aided stability analysis of gravity dams – CADAM, *Advances in Engineering Software* 34 (7), 403-420.

Ribeiro, P. M. V., C. A. E. Melo, and L. J. Pedroso, 2009. Semi-analytical solution of dam-reservoir interaction in the fundamental mode shape, *Solid Mechanics in Brazil*, São Paulo, Brazil.

Stefan, M., A. Limoges, and P. Léger, 2008. Three-dimensional seismic stability evaluation of spillway structures considering concrete cracking, *CDA Annual Conference*, Canada.

Tinic, S., V. Langer, and P. Eyer, 1994. Seismic safety evaluation of an old weir in Switzerland, *10th European Conference on earthquake Engineering*, Vienna, Austria.

USCOLD (US Committee on Large Dams), 1995. *Guidelines for earthquake design and evaluation of structures appurtenant to dams*, Denver, Colorado.