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Numerical Prediction of Flow Induced Vibrations in Underflow Sluice Gates

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Abstract

Vertical rising underflow weirs commonly manage the water levels of small rivers and supply currents. The flow underneath the sluice gate provokes unsteady flow structure generation, which causes structural loads on the weir. The suspension of the vertical rising weirs responds. The resulting vibrations and oscillations of the gate at its eigenfrequency can cause additional or amplification of the flow structures, closing the feedback loop. Resonance can lead to significant damage and even fatigue of the weir. We simulate the multiphase flow numerically using the large eddy simulation approach to investigate such critical conditions and impose the unsteady loads as boundary conditions for structural calculations. The coherent flow structures induced at the leading edge of the sluice gate interact by a leap-frogging phenomenon, causing upstream running surface waves to clash against the sluice gate. The structural computations reveal that the low-frequency loads induced by these water waves due to vortex leap-frogging are dominating.

Keyword: *Multiphase flow simulation, Fluid/structure interaction, Finite element analysis*

1. Introduction

Sluice gates are movable weirs regulating the water flow. The open gap height determines the water flow rate and, thus, the water level upstream and downstream of the gate. Sluice gates are efficient constructions to preserve the river environment, protect hydroelectric power plants and, above all, prevent flooding. The unsteady underflow causes oscillating displacement of the sluice gate, which leads to vibrations. Typically, the flow separation occurs at the sluice gate's leading edge, as shown in Fig. 1, which generates large-scale flow structures and unsteady forces on the sluice gate. The sluice gate actively reacts with a dynamic movement and thereby causes additional vortical flow instabilities. If the natural frequency of the sluice gate suspension (which characterises the dynamic behaviour) coincides sufficiently with the flow-induced excitation frequency, resonance can occur. The high vibration amplitudes caused by resonance can lead to fatigue and collapse of the sluice gate. Roth and Hager [10] showed that the dynamic load on a sluice gate can significantly exceed the hydrostatic pressure load.

The eigenfrequency of oscillating vertical rising underflow weirs, f_n, in water can be described by the equation [5],

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \left(\frac{c}{2m}\right)^2}\ , \tag{1}$$

where k is the spring stiffness, m is the oscillating lumped mass, and c is the equivalent damping of the system. To avoid strong vibrations, the suspension of the sluice gate must be designed such that its eigenfrequency does not fall within the range of unsteady flow excitation frequencies, f. Thus, the ratio of the frequencies, f/f_n, is used as a dimensionless parameter to represent resonance between the vibration excitation and the sluice gates eigenfrequency. The excitation frequency of the unsteady flow phenomena can be characterised by the Strouhal number,

$$St = \frac{f \cdot \ell}{u}\ ,$$

where ℓ and u represent a characteristic length and a characteristic velocity. The sluice gate thickness, d_s, and the average velocity in the gap are commonly used as the characteristic scales. A simple relation between the

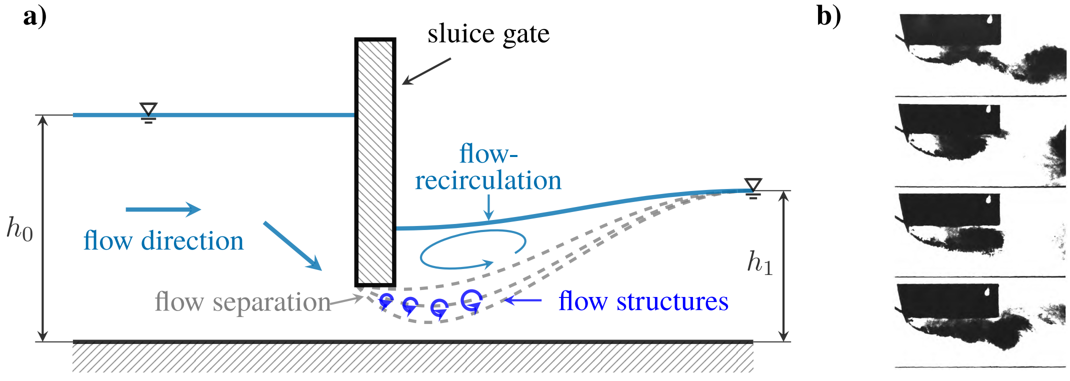

Fig. 1: A sketch of the flow phenomena underneath a sluice gate is shown in figure (a). Ink visualisations of the unsteady vortex formation at the lower edge of sluice gate [6] are portrayed in figure (b).

dimensionless parameters and observed sluice gate vibrations could not be established. Billeter and Staubli [1] have charted the vibration modes for a plane sluice gate, which shows that the oscillation behaviour depends on the reduced velocity $1/St = \tilde{u}$ and the excitation frequency. The difficulty in classifying the sluice gate vibrations, even for simple model tests, illustrates the complexity of the problem. Some weir systems vibrate in the direction of flow [at about $1-2\ Hz$, 2], other weir systems vibrate in the vertical direction [at about $10\ Hz$, 4] and some sluice gates oscillate in many directions [at about $0.2-40\ Hz$, 8]. Special coupled vibration modes were measured at sluice gates for flood protection [9].

The challenge of numerically predicting such sluice gate oscillations is the correct modelling of the structural-mechanical constraints while resolving the fluid dynamic excitation forces. The nature of the problem requires considerable computational resources. Therefore, crude simplifications have often been made. For example, Erdbrink et al. [3] simulated only the two-dimensional problem, and Jafari et al. [7] limited the degrees of freedom of the swinging sluice gate. The three-dimensionality of the flow excitation has not yet been considered in flow simulations. In order to shade light into the three-dimensional excitation phenomena, large-eddy simulations of the discharge flow underneath a vertical rising weir are performed. The resulting pressures on the sluice gate are then fed into structural simulations to compute the occurring stresses.

2. Numerical Methodology

The geometrical simulation setup is illustrated in Fig. 2 (a) and consists of an upstream reservoir, the sluice gate, and a downstream run-out basin. The sluice gate is $0.5\ m$ wide, $0.01\ m$ thick, and risen to a gap height of $0.04\ m$. The water levels in the upstream reservoir and downstream run-out basin are set to 0.35

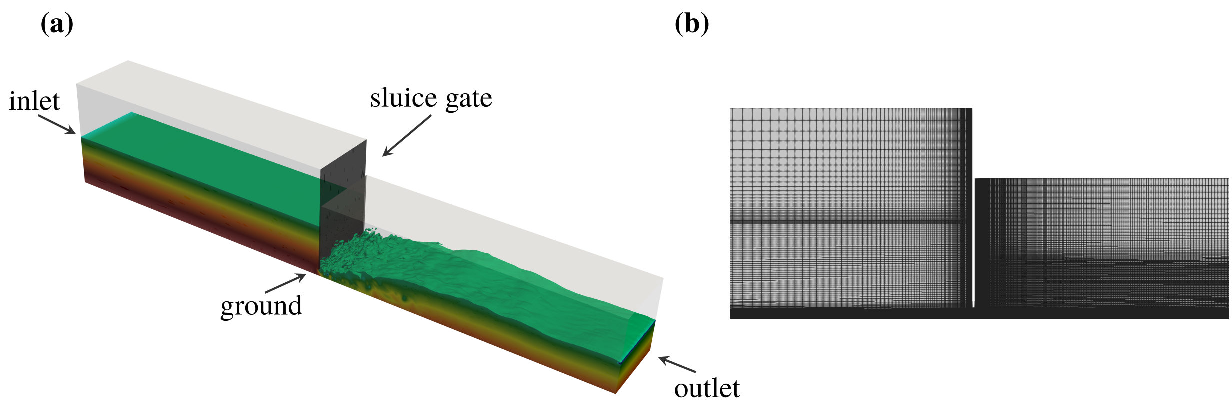

Fig. 2: The geometrical setup is shown in subfigure (a). A detail of the computational mesh in a mid-plane view is shown in subfigure (b).

m and $0.15\ m$, respectively. The ground and the sluice gate are no-slip walls, whereas the lateral sides are modelled as slip walls. Stagnant ambient conditions are specified at the top boundaries. The geometry is discretised by a block-structured grid consisting of 30 million hexahedral cells. The mesh is refined towards solid surfaces (i.e. $y^+ < 1$), unsteady flow regions, and near free water surfaces, as shown in Fig. 2 (b).

The incompressible Navier-Stokes equations are solved numerically with the volume-of-fluid approach to simulate the multiphase flow. The volume fraction advection equation is solved using the Flux-Corrected Transport (FCT) method. The Multidimensional Universal Limiter for Explicit Solutions (MULES) approach is employed to maintain a sharply bounded phase interface. The pimple algorithm, a combination of the simple and piso algorithms, is used to solve the pressure-velocity coupling, where the pressure correction equation and the non-orthogonal correction are updated three times for each outer iteration. A Crank-Nicolson scheme is used for time advancement, where the time step was set to $5 \cdot 10^{-5}\ s$. A cubic scheme is used for the convective terms, and a second-order central scheme is used for the diffusive terms. The advection of the volume fraction field has been calculated using a van Leer limited scheme. A dynamic large-eddy simulation approach is employed to handle the unresolved turbulent flow scales. The suitability of the employed numerical approach with the selected schemes and mesh resolution is demonstrated in Fig. 5 (b), showing the turbulence cascade has been resolved for about an order of magnitude.

The commercial finite-element solver of ANSYS Mechanical has been used to calculate the transient structural stress. The static pressure distribution of the flow simulation has been sampled for $2.1\ s$ at 200 Hz and imposed as the load on the sluice gate. The gate is assumed to be fixed laterally.

3. Results

Fig. 3 (a) shows the time-averaged water distribution resulting at the underflow sluice gate. The higher water level on the reservoir side provides the hydrostatic pressure energy driving the flow with high velocity underneath the sluice gate. The flow resistance applied at the outlet causes the water to dam up far downstream of the sluice gate. The high-velocity flow decelerates by mixing with the dammed-up water. Eventually, the dammed-up water reverses on top of the high-velocity flow towards the sluice gate. This interaction causes flow structures and water surface motion, as shown in Fig. 3 (b). Fig. 3 (c) reveals the origin of the strongest hydrodynamic flow structures by showing the time-averaged pressure fluctuations. Clearly, the

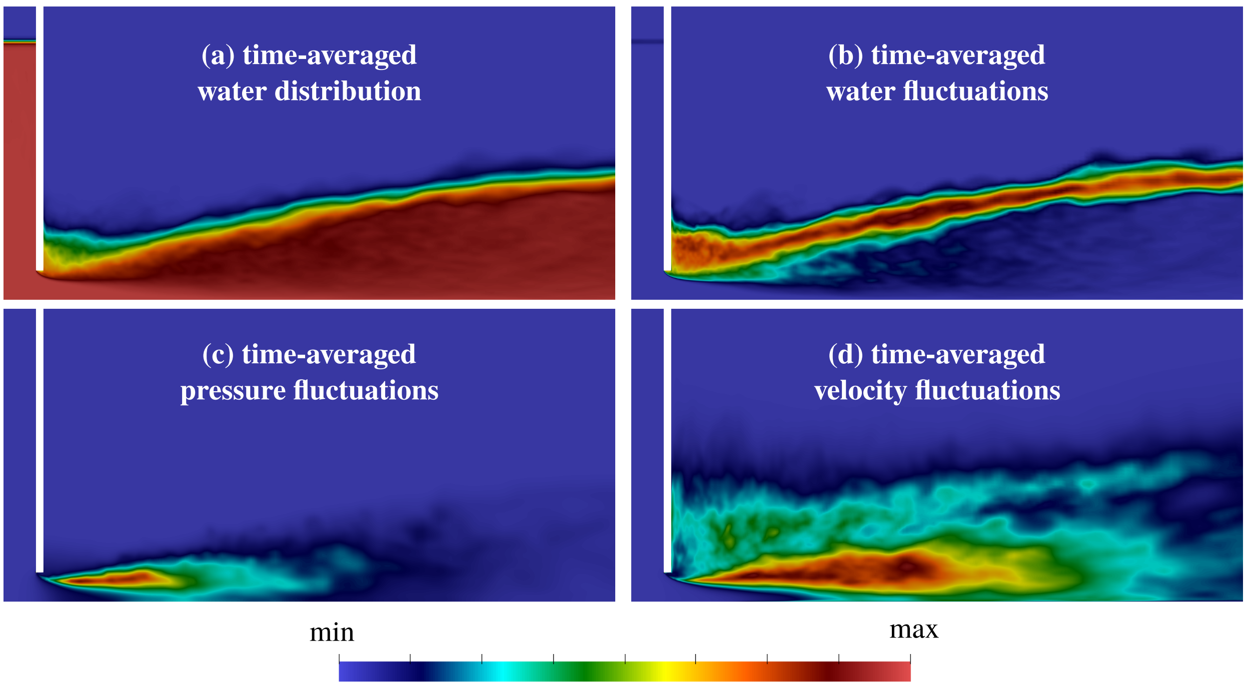

Fig. 3: The flow characteristics underneath and downstream of the sluice gate are illustrated in terms of statistical time-averaged quantities, i.e. water distribution, (a), water fluctuations, (b), pressure fluctuations, (c), and velocity fluctuations, (d), in the mid-plane view.

lower leading edge of the sluice gate causes vortex rollup in the established shear layer. The time-averaged velocity fluctuations shown in Fig. 3 (d) exhibit better the extent of flow unsteadiness downstream of the sluice gate, including the air fluctuations on top of the water surface.

The general unsteady phenomena arising with the flow underneath the plane sluice gate are shown as a series of pressure contours in Fig. 4. The sluice gate's leading edge plays a central role in the instability-related excitation. Vortices, notable as local minima of static pressure, are shed in the shear layer forming due to flow separation at this leading edge with relatively high frequency. After a short propagation distance, some vortices interact and eventually migrate close to the water surface, where they remain nearly static. The following vortex convects underneath, where the two vortical flow structures affect each other and interact. With this interaction, vortical flow structures unite into a single vortical structure, gaining strength. This phenomenon where larger eddies interact and one eddy overtakes another is called *leap-frogging*.

The water level in Fig. 4 indicates that the water surface waves are large compared to the shedding vortices. Hence, the vortices shedding from the edge of the sluice gate have little impact on water wave formation. The perturbations possess only the size and power to generate surface waves of significant magnitude when vortices interact.

Fig. 5 (a) gives an impression of the vortical flow structures generated at the lower leading edge of

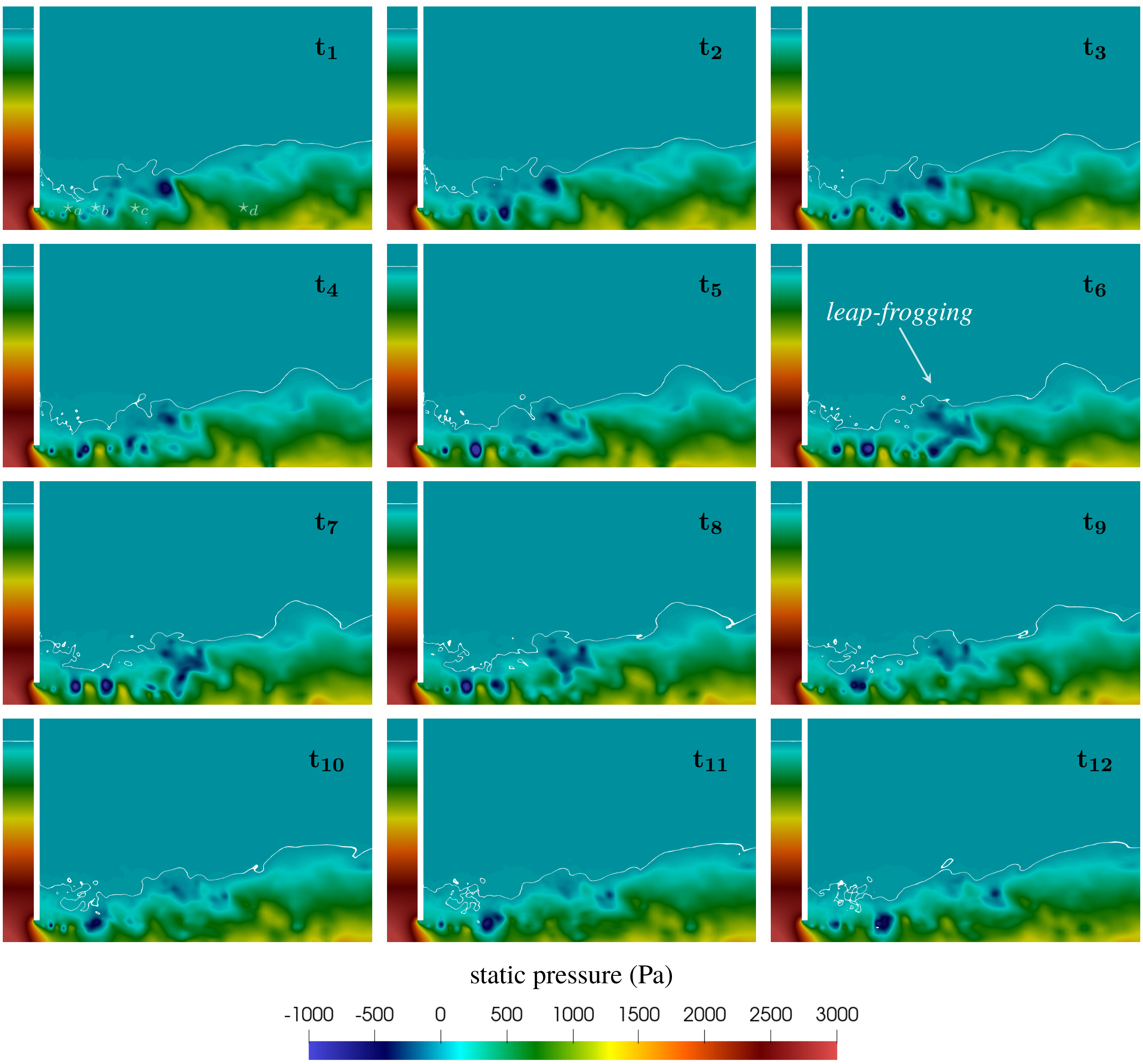

Fig. 4: The contour plots of static pressure show the temporal evolution in the mid-plane view. A white line represents the air-water interface.

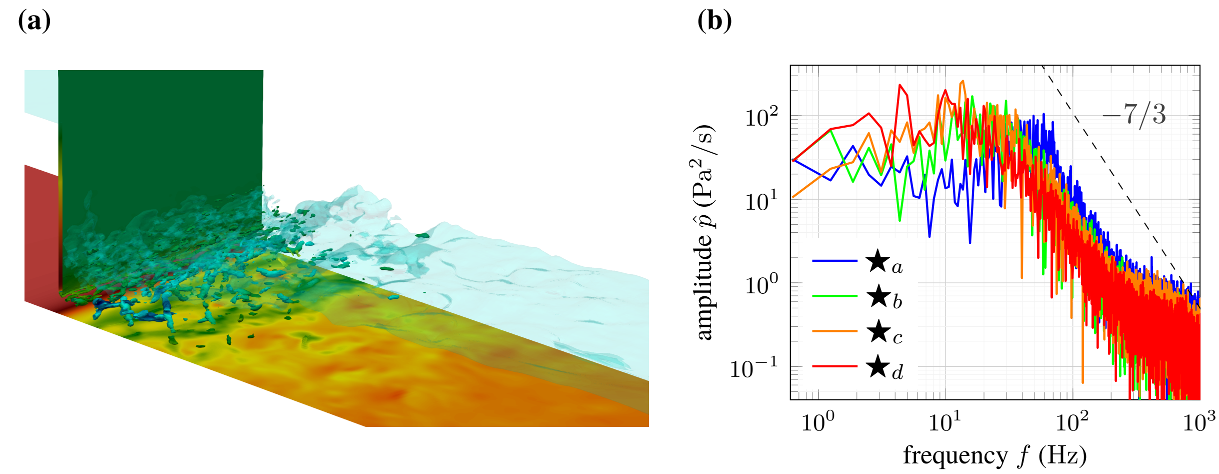

Fig. 5: The vortical flow structures are visualised by the Q-criterium in subfigure (a), where the colour represents the static pressure and the water surface is in transparent turquoise. The spectral densities of the pressures recorded in different locations, specified in Fig. 4 t_1, are plotted in subfigure (b).

the sluice gate. The vortical flow structures do not separate off the sluice gate at the same time over the entire width and evolve quickly into turbulence. However, the static pressure signature on the ground surface indicates an alternating pattern of low and high pressures over the whole width of the sluice gate. These pressure patterns are larger than the initial vortical flow structures shed from the sluice gate's lower leading edge and are caused by recombined vortices.

Fig. 5 (b) reveals the initial shedding frequency range, i.e. 30 to 60 Hz, of the vortical flow structures induced at the lower leading edge of the sluice gate. The high-pressure fluctuation amplitudes shift to lower frequencies when the probe monitoring location is moved downstream. This represents the inherent change of the flow fluctuations due to vortex recombination.

Fig. 6 (a) shows that the cumulative forces acting on the sluice gate exhibit temporal fluctuations. A fast Fourier decomposition of the forces reveals that the dominant frequency is 1.26 Hz. The fluctuation amplitudes are of the order of a few percent of the static load. The strength of the vortical flow structures scales with the head difference over the sluice gate (governing the underflow velocity), which is low, as illustrated in Fig. 3 (a). The stresses acting on the sluice gate are plotted in Fig. 6 (b), which shows smooth symmetric contours. These indicate that the static and low-frequent loads are dominant, whereas the unsteady hydrodynamic loads are low for the selected sluice gate operating conditions.

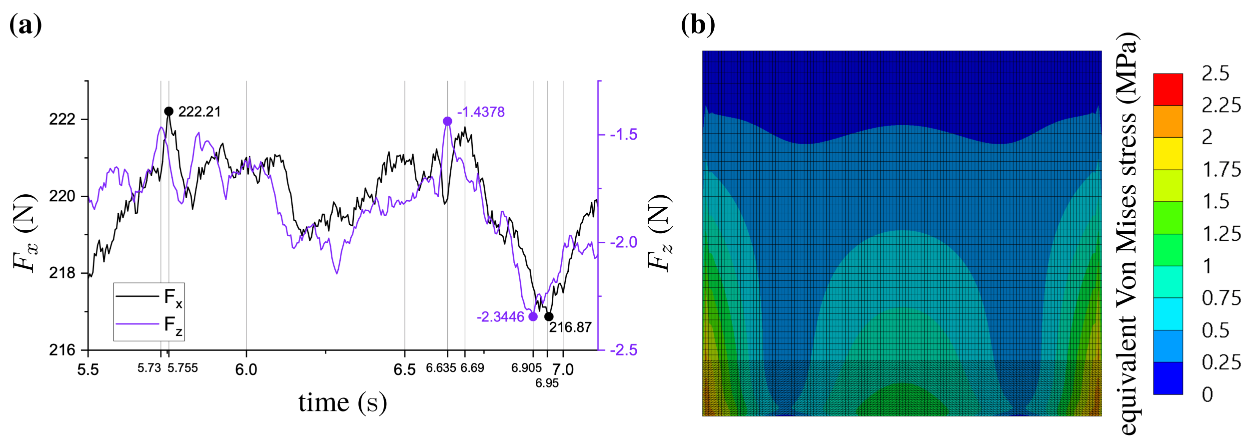

Fig. 6: The cumulative forces acting on the sluice gate are presented in subfigure (a), where the x-coordinate points into the streamwise direction and the z-coordinate points into the vertical direction. The equivalent Von Mises stress on the sluice gate is plotted at the time 6.635 s in subfigure (b).

4. Conclusion

The unsteady flow underneath a vertical rising sluice gate has been simulated numerically by employing the volume-of-fluid approach. A vortical flow structure interaction mechanism, i.e. vortex leap-frogging, was identified to generate large water waves impacting the sluice gate. The unsteady pressure loads have been applied as boundary conditions to calculate the structural loads on the weir with the finite element method. Employing fixed constraints to the lateral sides revealed that the static and low-frequent loads dominate, which correspond to the upstream running surface waves caused by the vortex leap-leap-froggingfrogging phenomenon.

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