Dynamic Study of Simultaneous Underflow-Overflow Past Low Head Sluice Gates

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ABSTRACT. This paper presents a series of experimental investigations on low head sluice gate models considering the simultaneous underflow-overflow and underflow or overflow alone. The dynamic behaviour of the gates was studied in terms of pressure and gross force fluctuations on gate bottom or top for both vibrating and stationary gates. Spectrum analysis of force fluctuations was also made to identify the existence of resonance by comparing the natural frequency of the gate with the dominant frequency of force fluctuations. Analysis of the results revealed that pressure and force fluctuation coefficients are considerably higher for the simultaneous conditions of underflow-overflow, both on the gate bottom and top due to coupling effects and the coefficients are larger for vibrating gate than those of stationary one due to interaction of flow with gate movement. The effect of coupling or interaction seems to be further amplified due to quasi-resonance.

1. Introduction

Low head vertical lift sluice gates generally operate under conditions of underflow. While occasionally they may have to operate with overflow or simultaneous underflow-overflow leading to vibration in their own plane under certain circumstances. For examples: During flood when the head greatly exceeds the gate height, during lifting of lower leaves of a multi-leaf gate running in a single groove, and handling of stoplogs in running water. Although such conditions may exist only for a short duration of time, it is necessary that the gate system withstands them. Perhaps because of rare occurrence of such conditions, little attention has been given in the past to the problems of gates resulting from the conditions of simultaneous underflow-overflow. In the past, because of action of flow on the gate bottom or top, the in-plane gate vibration has attracted much attention by the investigators. While earlier researchers have suggested bevelling of the gate as one of the methods to reduce vibration, flat bottom gates are still in use. Flat bottom gates alone can provide insight into the causes and mechanism of in-plane vibrations. The characteristics of such vibration depend upon the nature of hydrodynamic
loading, which consists of mean and fluctuating pressures acting on gate bottom or top as the case may be. The dynamic response of such gates depends upon their own inertial, elastic and damping properties besides hydrodynamic loading\cite{1}. It is a well-known fact that flow past the gate interacts each other with gate bottom and the hydrodynamic loading in turn is influenced by the gate movement. In other words, there is an “interaction” phenomenon between the flow induced hydrodynamic loading and the vibration of the gate itself. Further, in the case of simultaneous underflow-overflow, the hydrodynamic loading on the gate bottom due to underflow is likely to influence the hydrodynamic loading on the gate top due to overflow and vice versa. The influence of such loading on gate bottom and top is termed as the “coupling” phenomenon. Thus in the individual cases of underflow or overflow, there is interaction alone while in the case of simultaneous underflow-overflow, there are both interaction and coupling which sometimes may lead to quasi-resonant conditions.

Among the studies available in literature on the vibration of gates, the case of underflow has received maximum attentions\cite{2,3,6,9,10,12-16}. The studies on overflow on the other hand, pertain mostly to the oscillation of nappe and its preventions. The studies have also been considered by few investigators\cite{4,12,13,17}. Simultaneous underflow-overflow case have received very little attention by the researchers like Petrikat\cite{16} in 1958, Naudascher\cite{11} in 1961 and Abelev et al.\cite{1} in 1977. While Petrikat’s study was based on drum or flat gates, Naudascher’s study was based on a particular design of prototype double leaf gate and on the other hand Abelev et al’s study was also a specific case of a vertical lift gate considering two basic categories of self excited vibration, one due to flow separation at gate lip and the consequent eddy shedding synchronizing with gate movement and the other due to overflow discharge fluctuations between the gate and the skinner wall on account of horizontal vibration. In spite of the fact that the vibration of the vertical lift gates during underflow-overflow could be far more severe and sometimes even disastrous, somehow it has not attracted much attention.

So far, the three cases of flow with respect to gate, \textit{i.e.}, underflow, overflow and simultaneous underflow-overflow have been studied independently without making an attempt to identify the effect of overflow on hydrodynamic loading of the gate bottom and the effect of underflow on the hydrodynamic loading of the gate top, when both flows are present. This effect termed as “Coupling” between underflow and overflow and which can be quantified through the following equivalences: Hydrodynamic loading on gate bottom due to simultaneous underflow-overflow \( \equiv \) hydrodynamic loading due to underflow alone + coupling effect of overflow on gate bottom, and hydrodynamic loading on gate top due to simultaneous underflow-overflow \( \equiv \) hydrodynamic loading due to overflow alone + coupling effect of underflow on gate top. This can be done by measuring the hydrodynamic loadings for all the three cases of flow and comparing them. The possibility of resonance or quasi-resonance to exist can be ascertained by comparing the dominant frequency of measured hydrodynamic fluctuations of forces with the natural frequency of the gate. The determination of the natural frequency of the gate requires the knowledge of added mass (the additional mass of water surrounding the gate takes part in the gate acceleration) due to in-plane vibration\cite{5}. 
Thus the present study has been planned with low head sluice gate models of flat bottom and top to identify the interaction, the coupling and quasi-resonance effect on simultaneous underflow-overflow in a more general matter.

2. Experimental Programs

The studies were carried out in a fixed bed rectangular flume 10 m long, 0.24 m wide and 0.6 m deep (Fig. 1) using gate models 0.3 m wide, 0.3 m high, and having 0.25, 0.05, and 0.1 m thickness in the direction of flow. The test section consists of a vertical groove and 1 mm clearance between the model and the wall to allow the gate to vibrate freely. A flexible horizontal beam of mild steel strap was suspended and held between two knife edges on each side. Downstream face of the gate was supported by freely rotating wheels mounted on grid frames which are anchored to flume walls. Pressure tapings were provided at close intervals at bottom and top of the gate and the pressures (mean and fluctuating components) were measured by using electronic inductive type differential pressure transducer (HBM, Germany). For gross force measurement, a strip of 85 mm × 15 mm was cut at center of 10 cm thick gate bottom, a thin phospher bronze sheet was fixed on the groove. Two semiconductor strain gauges were pasted on the inner surface of the sheet one at its end and the other at its centre to measure the strain developed in it due to turbulent flow below or above the gate resulting hydrodynamic force. The strain gauges are connected to the half-bridge circuit of the universal amplifier and strip chart recorder. Records of hydrodynamic force fluctuations on gate bottom and top were obtained independently and for simultaneous underflow-overflow, force on gate bottom or top were also measured separately (Fig. 2) and net force was not possible to measure due to laboratory limitations. The gate was tested for both vibrating and stationary conditions for comparison purposes. All the dynamic pressure and force recordings were precalibrated. The tube length for the pressure fluctuation measurements was also tested by checking the RMS value of known pressure fluctuations using variable tube lengths from 10 to 120 cm. The RMS values were found unchanged upto 95 cm above which the value starts to reduce due to damping effect for longer tube lengths. The height of gate was kept limited keeping in view the depth of flume, maximum gate opening and overflow head. Froude number of underflow ranged between 1 and 5 approximately and damping of gate suspension system was not varied using the same gate for force measurement during the investigations. The space behind the gate has been ventilated in order to exclude excitation due to nappe oscillation during overflow and simultaneous underflow-overflow cases. From the records it was seen that both pressure and force fluctuation data follow normal distribution and hence the mean and RMS values of the fluctuating components of the pressure and force were obtained and the coefficients $C_p$ and $C_F$ computed as follows:

a) For gate bottom (underflow)

$$C_{p'_b} = \frac{1}{\sqrt{\frac{\rho_v^2}{2}}} \frac{H_2}{H_1}$$  \hspace{1cm} (1)
where, \( \rho \) is the mass density of fluid, \( \gamma \) is the unit weight, \( v_1 \) is the velocity of flow under the gate and \( h_g \) is the overflow head above the gate top, \( H_1 \) and \( H_2 \) being the upstream and the downstream water depths respectively.

3. Discussion of the Results

3.1 Quantitative Evaluation of Interaction

Since the vibration in gates is primarily influenced by the fluctuations in the loading, the effect of interaction due to hydrodynamic loading on gate bottom or top during underflow and overflow or simultaneous conditions has been studied in terms of pressure and force fluctuations only using the following nondimensional functional relationships (Fig. 2):

i) On Gate Bottom

\[
Cp'_b = f_1 \left( \frac{x}{b}, \frac{F_g}{b}, \frac{a_0}{b}, \frac{B}{b}, \eta \right)
\]  

where, \( x/b \) is the length of the gate, \( F_g/b \) is the force per unit width of the gate, \( a_0/b \) is the amplitude of the forcing, \( B/b \) is the width of the gate, \( \eta \) is the damping ratio, and \( f_1 \) is the nondimensional force function.

b) For gate top (overflow)

\[
Cp'_f = \frac{\sqrt{\rho' \gamma}}{\gamma h_g}
\]  

\[
CF'_f = \frac{\sqrt{F'^2}}{F}
\]  

Fig. 1. Plan of experimental setup (not to scale).


\[ CF'_b = f_2 \left( F_g, \frac{a_0}{b}, \frac{B}{b}, \eta \right) \]  

(6)

**Fig. 2.** Definition sketch (a) Underflow, (b) Overflow, (c) Simultaneous underflow-overlow.
ii) On Gate Top

\[ Cp_i' = f_3 \left( \frac{x}{b}, \frac{h_g}{b}, \frac{B}{b}, \eta \right) \]  

(7)

\[ CF_i' = f_4 \left( \frac{h_g}{b}, \frac{B}{b}, \eta \right) \]  

(8)

In which \( \eta \) refers to dynamic parameter of gate (i.e., its natural frequency and damping), \( F_g \) is Froude number for low under the gate \((F_g = \frac{v_l}{\sqrt{a_0 g}})\), is the location point where the pressure is to be measured, \( B \) is the gate width, \( b \) is the gate thickness and \( a_0 \) is the gate opening.

The typical variation of \( Cp_b' \) on gate bottom during underflow for different ranges of Froude number is shown in Fig. 3 for both oscillating and stationary flat bottom gate \((B/b = 6.0)\). As it is clear from the figure that the \( Cp_b' \) value for vibrating gate is quite large compared to the same for stationary gate at comparable value of \( F_g \) which clearly demonstrates the interaction of flow with the gate oscillation. It is also seen that the value of \( Cp_b' \) attains an overall maximum at \( a_0/b = 0.6 \) to 0.7 due to flow reattachment and eddy shedding which also corroborates with earlier reporters on models and prototype gates \([3,11]\). The variation of force fluctuation coefficients, \( CF_b' \) with gate opening ratio, \( a_0/b \) for different ranges of Froude number is shown in Fig. 4 & 5 and it is noted that \( CF_b' \) value for vibrating gate is much larger than that for a stationary one due to interaction. To examine the interaction effect between the flow and the gate, a spectral analysis of force fluctuation was also carried out. The spectrum showed many peaks of varying magnitudes at different frequencies. It is understood that if a spectral peak occurs at a frequency close to the natural frequency of the gate, one can expect some kind of “quasi-resonance” resulting in increased amplitude of gate vibrations thereby increasing hydrodynamic force fluctuations. It is also seen that \( CF_b' \) was larger for vibrating gate even in cases with no dominant frequencies although having spectral energy peaks close to the natural frequency of the gate (Fig. 6), thereby showing the interaction effect. The variation of pressure fluctuation coefficient on \( Cp_t' \) gate top for different overflow head to top width ratio \( h_g/b \) is shown in Fig. 7, \((B/b = 3.0)\) and it is seen that \( Cp_t' \) increases with \( h_g/b \) and also \( Cp_t' \) increases with \( x/b \) showing a peak which occurred due to the coincidence of the point of flow reattachment on gate top surface. Also, \( Cp_t' \) is higher for vibrating gate than those for stationary one due to interaction. Similarly, Fig. 8 presents the variation of force fluctuation coefficient, \( CF_t' \) on gate top with \( h_g/b \) for different overflow heads and reveals that \( CF_t' \) is larger for vibrating gate than those for stationary one due to interaction. It is interesting to study the magnification of \( Cp_b' \) and \( CF_b' \) on gate bottom due to gate vibration with relevant parameters for underflow and simultaneous under-flow-overflow.

3.2 Quantification of Magnification and Coupling Effects for Underflow and Simultaneous Underflow-Overflow.

The magnification factor, \( M = CF_b' \) for vibrating gate/\( CF_b' \) for stationary gate of \( CF_b' \) has been studied for one gate only \((B/b = 3.0)\). Figure 9 shows the variation of \( M \) with \( F_g \) for all the data at different gate opening conditions with underflow gates. There ap-
pears an unmistakable trend in the figure, *i.e.*, the magnification factor \((M)\) decreases with increased value of \(F_g\) and here it is further interesting to note that Froude number has also significantly affected the ratio of \(CF'_b\) for vibrating and stationary gates[8].

**Fig. 3.** Variation of \(CF'_b\) with \(x/b\) for underflow.

**Fig. 4.** Variation of with \(CF'_b\) \(a_0/b\) for vibrating rate.
Fig. 5. Variation of $CF'_b$ with $a_0/b$ for stationary gate.

Fig. 6. Typical spectrum of force fluctuation on gate bottom.
Fig. 7. Variation of $Cp'$ with $x/b$ for overflow.

Fig. 8. Variation of $CF'$ with $h_g/b$ for overflow.
The variation of $C_p'_{b}$ on gate bottom for both simultaneous underflow-overflow shows a variation similar to that for underflow alone as in Fig. 10. While the magnitudes for simultaneous underflow-overflow gates are, however, greater than those for underflow alone, other conditions remain the same. Similar results were obtained for the variation of pressure fluctuation coefficient, $C_p'_{t}$, on gate top as shown in Fig. 10. As can be seen, the coefficients $C_p'_{t}$ are always higher for simultaneous underflow-overflow which indicates the effect of interaction and coupling. Figures 12 & 13 also show the variation of gross force fluctuation coefficients on gate bottom and top due to simultaneous underflow-overflow and revealed that both $C_F'_{b}$ and $C_F'_{t}$ are larger for simultaneous underflow-overflow than those of underflow or overflow alone indicating the effect of both interaction and coupling. It may also be mentioned here that the simultaneous flow cases have other variables such as $a_o/b$ and $F_g$, besides those for overflow alone and the separate influence of each of these parameters was not isolated in the above figures. The quantification of the effect of coupling during simultaneous conditions is thought to be essential for better understanding. In order to isolate the effect of interaction and coupling as well as quasi-resonance effects during simultaneous under-
flow-overflow. The magnitudes of force fluctuation coefficients $CF'_b$ or $CF'_t$ were compared with those of individual underflow or overflow alone on gate bottom or top respectively. For quasi-resonance, the natural frequency of the gate ($f_g$) was compared with the dominant frequencies of force fluctuations ($f_d$) as well as their peak values of spectral energies ($s_f$).

**Fig. 10.** Comparison of $Cp'_b$ variation with $x/b$ on gate bottom for simultaneous underflow-overflow with underflow alone for vibrating gate.

**Fig. 11.** Comparison of $Cp'_t$ with $x/b$ for simultaneous underflow-overflow with overflow alone on gate top.
Earlier while studying the variation of $C_{pb}'$, $C_{pt}'$ and $CF_t'$ for both simultaneous underflow-overflow and underflow or overflow alone for vibrating gates in previous section, it was brought out that these coefficients are magnified appreciably for simultaneous cases than those of underflow or overflow alone. In other words, there is coupling of underflow on overflow and vice versa during simultaneous cases of flow conditions. It may be interesting to study the magnification factors for the peak values of the coefficients, $C_{pb}'$, $C_{pt}'$, $CF_{bm}'$ and $CF_{tm}'$ with the relevant parameters such as $F_g$ on gate bottom and $h_g/b$ on gate top. The magnification factors,

$$M_{bp} = \frac{C_{pb}'_{bm}}{C_{pb}'_{bm}} \text{ for simultaneous case} / \frac{C_{pb}'_{bm}}{C_{pb}'_{bm}} \text{ for underflow alone} \text{ of } C_{pb}'_{bm} \text{ on gate bottom},$$

$$M_{bF} = \frac{CF_{bm}'}{CF_{bm}'} \text{ for simultaneous case} / \frac{CF_{bm}'}{CF_{bm}'} \text{ for underflow alone} \text{ of } CF_{bm}' \text{ on gate bottom},$$

$$M_{tp} = \frac{C_{pt}'_{tm}}{C_{pt}'_{tm}} \text{ for simultaneous case} / \frac{C_{pt}'_{tm}}{C_{pt}'_{tm}} \text{ for overflow alone} \text{ of } C_{pt}'_{tm} \text{ on gate top and}$$

$$M_{tf} = \frac{CF_{tm}'}{CF_{tm}'} \text{ for simultaneous case} / \frac{CF_{tm}'}{CF_{tm}'} \text{ for overflow alone} \text{ of } CF_{tm}' \text{ on gate top.}$$

These values were obtained from the experimental data for the cases of underflow, overflow and simultaneous underflow-overflow.

Fig. 12. Comparison of $CF_b'$ with $a_o/b$ for simultaneous underflow-overflow with underflow alone.

Fig. 13. Comparison of $CF_t'$ with $h_g/b$ for simultaneous underflow-overflow with overflow alone on gate.
Figure 14 shows the magnification of pressure fluctuation on gate bottom with Froude number indicating that almost all the data for simultaneous conditions have a $M_{bp}$ value higher than unity demonstrating coupling effect. While Fig. 15 presents the variation of magnification factor for force fluctuation on gate bottom during simultaneous conditions revealing that two cases lie on the same level which are slightly above the unity line indicating coupling effect only, also, one value for $M_{bF}$ lies above all showing large magnification which is due to quasi-resonance as well as coupling effects. The variation of magnification factors of pressure fluctuation, $M_{tp}$ with $h_g/b$ on gate top for simultaneous cases are shown in Fig. 16 and it is observed that all the values lie above the unity line demonstrating coupling effect. Figure 17 shows the variation of $M_{tF}$ with $h_g/b$ on gate top for simultaneous underflow-overflow. It reveals that four values of $M_{tF}$ are slightly above the unity line and almost lie on the same level indicating that the magnification is due to coupling only, while two values lie at significantly higher levels than those of other cases demonstrating the effect of quasi-resonance as well as coupling.

**Fig. 14.** Magnification of $Cp'_b$ for simultaneous underflow-overflow to underflow alone showing coupling effect.

**Fig. 15.** Magnification of $CF'_b$ for simultaneous underflow-overflow to underflow alone showing coupling effect.
Fig. 16. Magnification of \(Cp'_t\) for underflow-overflow to overflow alone showing coupling effect.

Fig. 17. Magnification of \(CF'_t\) for simultaneous underflow-overflow to overflow alone showing coupling effect.
Conclusion

1. The coefficient of pressure fluctuation $Cp_b'$ on gate bottom at gate opening ratio, $a_0/b$, equals to 0.6 to 0.7 due to flow separation and reattachment. The coefficients of pressure fluctuation, $Cp_b'$, and force fluctuation, $CF_b'$, on gate bottom for underflow have been found to be much larger for vibrating gate compared to the stationary one signifying the effect of interaction.

2. For simultaneous underflow-overflow, the coefficients of pressure and force fluctuations are considerably higher for both on gate bottom and top compared to corresponding values for underflow or overflow alone, which are due to coupling effect.

3. The effect of coupling or interaction seems to be further magnified, if and when, dominant frequency of force fluctuations is close to the natural frequency of the gate resulting in quasi-resonance.

References


Notations

\begin{align*}
a_0 & \quad \text{gate opening.} \\
b & \quad \text{gate thickness} \\
B & \quad \text{gate width.}
\end{align*}
\( CF' \) coefficient of force fluctuation.
\( CF_{gb} \) \( CF \) on gate bottom.
\( CF_{gt} \) \( CF \) on gate top.
\( Cp' \) pressure fluctuation coefficient.
\( Cp_{gb} \) \( Q \) on gate bottom.
\( Cp_{gt} \) \( C \) on gate top.
\( F \) force.
\( f_1\sim f_4 \) functions.
\( F \) mean force.
\[ \sqrt{F^2} \] RMS value of force fluctuation
\( F_g \) Froude number for underflow below the gate.
\( f_d \) dominant frequency of force fluctuations.
\( f_F \) frequency of force fluctuation data.
\( f_g \) gate natural frequency.
\( g \) acceleration due to gravity.
\( H_1, H_2 \) upstream and downstream heads.
\( h_g \) overflow head.
\( m \) peak value.
\( M \) magnification factor.
\( p \) the pressure.
\[ \sqrt{p'^2} \] RMS value of pressure fluctuation.
\( S_f \) spectral energy.
\( v_1 \) velocity under the gate.
\( x \) location point of pressure measurement.
\( \gamma \) unit weight of water.
\( \eta \) dynamic parameter.
\( \rho \) mass density of fluid.
دراسة ديناميكية الجريان الآني أفعال وأعلى بوابات الحجز ذوات الضاغط المنخفض

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المستخلص: تعرض هذه الدراسة نتائج بحوث عملية أجريت على فاصل بوابات حجر ذوات ضاغط منخفض، أخذوا في الاعتبار حالات الجريان الآني أفعال وأعلى البوابات، أو أفعالها أو أعلاها فقط. لقد تم دراسة السلوك الديناميككي للبوابات بدلالة التغييرات في الضغط والقوة على قاع أو قمة البوابة لكل من البوابات المتذبذبة والثابتة. أيضاً تم تحديد حالات حدوث الروتين مقارنة التردد الطبيعي للبوابة بالتردد الشائع للتغير في القوة، والذي تم تحديده باستخدام التحليل الطيفي. تبين من تحليل النتائج أن معاملات الضغط والقوة على البوابات عالية نسبياً في حالات الجريان الآني أفعال وأعلى البوابات. كما تبين أن هذه المعاملات أعلى نسبياً في حالات البوابات المتذبذبة مقارنة بالبوابات الثابتة. نتيجة "التأثير المتبادل" بين الجريان وذبذبة البوابات. أثبتت الدراسة أن وجود الروتين يؤدي إلى زيادة مفعول كلا من "المذدوج" و "التأثير المتبادل".