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

DELWAR HUSAIN

Civil Eng. Dept., College of Engineering,
King Saud University, Riyadh, Saudi Arabia

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[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[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[4,12,13,17]. Simultaneous underflow-overflow case have received very little attention by the researchers like Petrikat[16] in 1958, Naudascher[11] in 1961 and Abelev *et al.*[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, *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 ≡ hydrodynamic loading due to underflow alone + coupling effect of overflow on gate bottom, and hydrodynamic loading on gate top due to simultaneous underflow-overflow ≡ 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[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 tappings 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 Cp and CF computed as follows:

a) For gate bottom (underflow)

$$Cp'_b = \frac{\sqrt{\overline{p'^2}}}{\frac{1}{2}\rho v_1^2} \frac{H_2}{H_1} \tag{1}$$

Delwar Husain

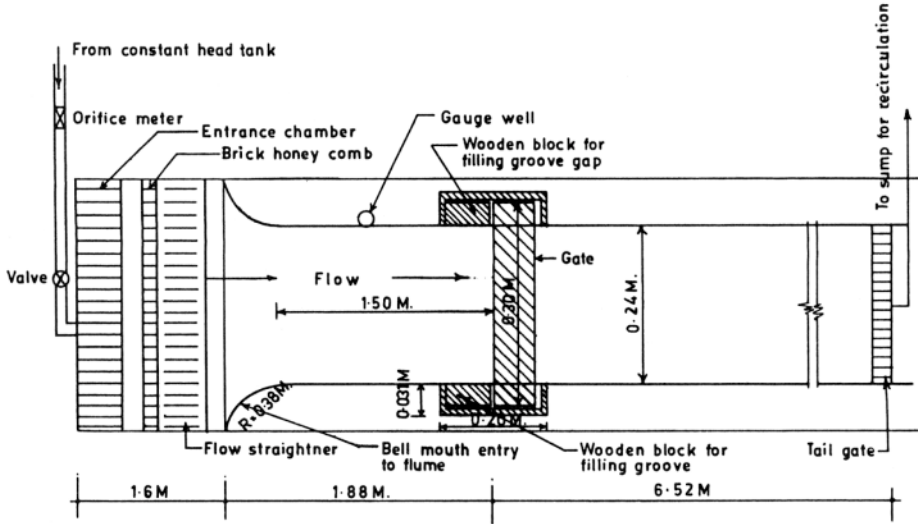$$CF_b' = \frac{\sqrt{F'^2}}{\overline{F}} \frac{H_2}{H_1} \tag{2}$$

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

b) For gate top (overflow)

$$Cp_t' = \frac{\sqrt{\overline{p}'^2}}{\gamma h_g} \tag{3}$$

$$CF_t' = \frac{\sqrt{F'^2}}{F} \tag{4}$$

where, ρ is the mass density of fluid, γ 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):
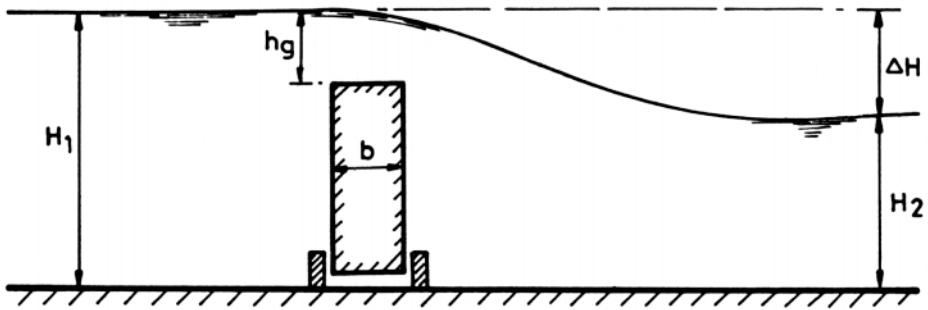
i) *On Gate Bottom*

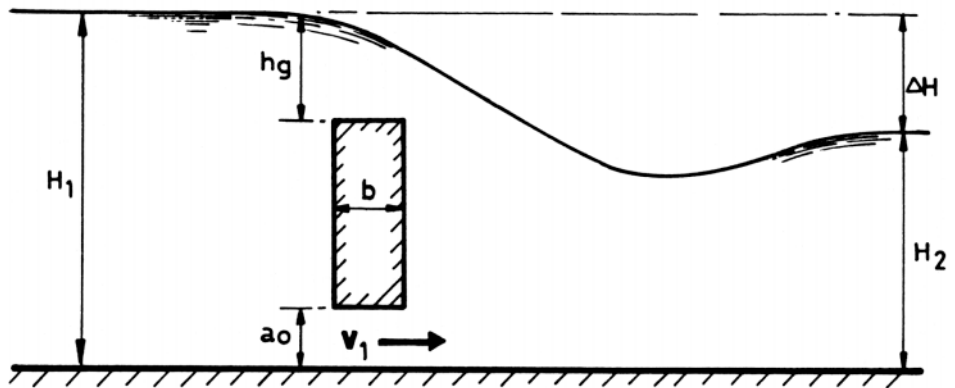$$Cp_b' = f_1\left(\frac{x}{b}, F_g, \frac{a_0}{b} \frac{B}{b}, \eta\right) \tag{5}$$

$$CF'_b = f_2\left(F_g, \frac{a_0}{b}, \frac{B}{b}, \eta\right) \tag{6}$$
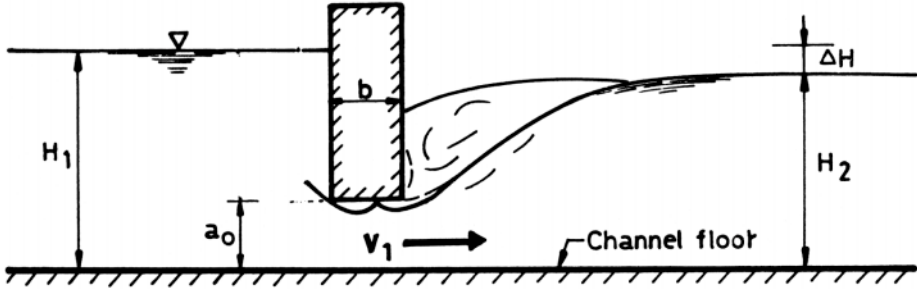
FIG. 2. Definition sketch (a) Underflow, (b) Overflow, (c) Simultaneous underflow-overlow.

ii) On Gate Top

$$Cp_t' = f_3\left(\frac{x}{b}, \frac{h_g}{b}, \frac{B}{n}, \eta\right) \tag{7}$$

$$CF_t' = f_4\left(\frac{h_g}{b}, \frac{B}{b}, \eta\right) \tag{8}$$

In which η refers to dynamic parameter of gate (*i.e.* its natural frequency and damping), F_g is Froude number for low under the gate ($F_g = v_1 / \sqrt{a_0 g}$), 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].
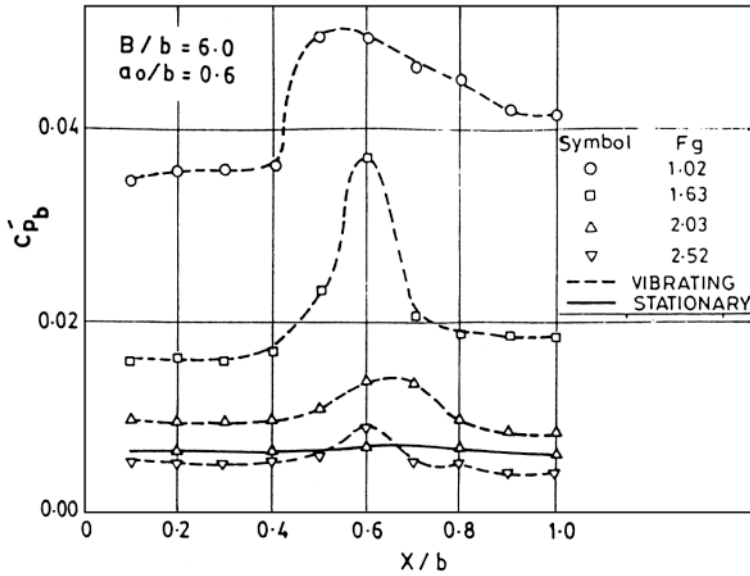

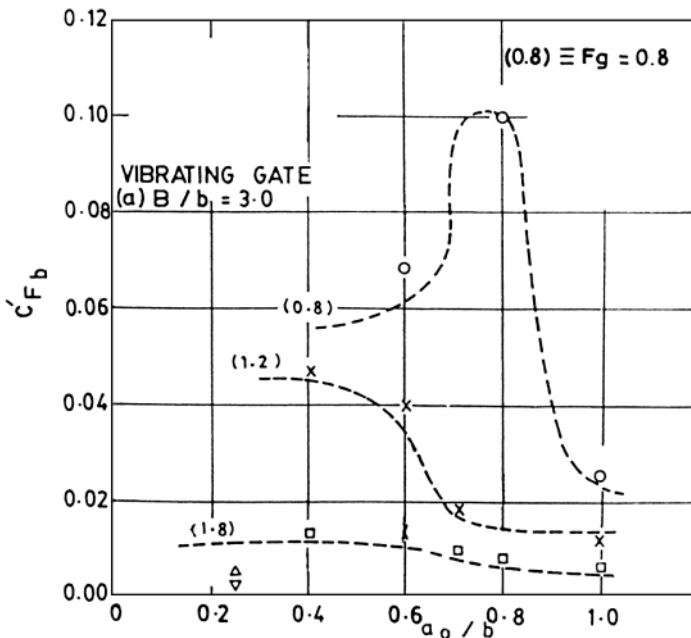
FIG. 3. Variation of CF'_b with *x/b* for underflow.

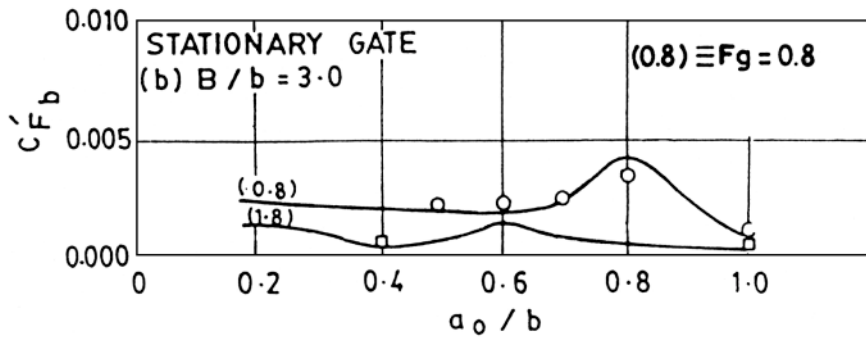FIG. 4. Variation of with CF'_b a_0/b for vibrating rate.

Delwar Husain

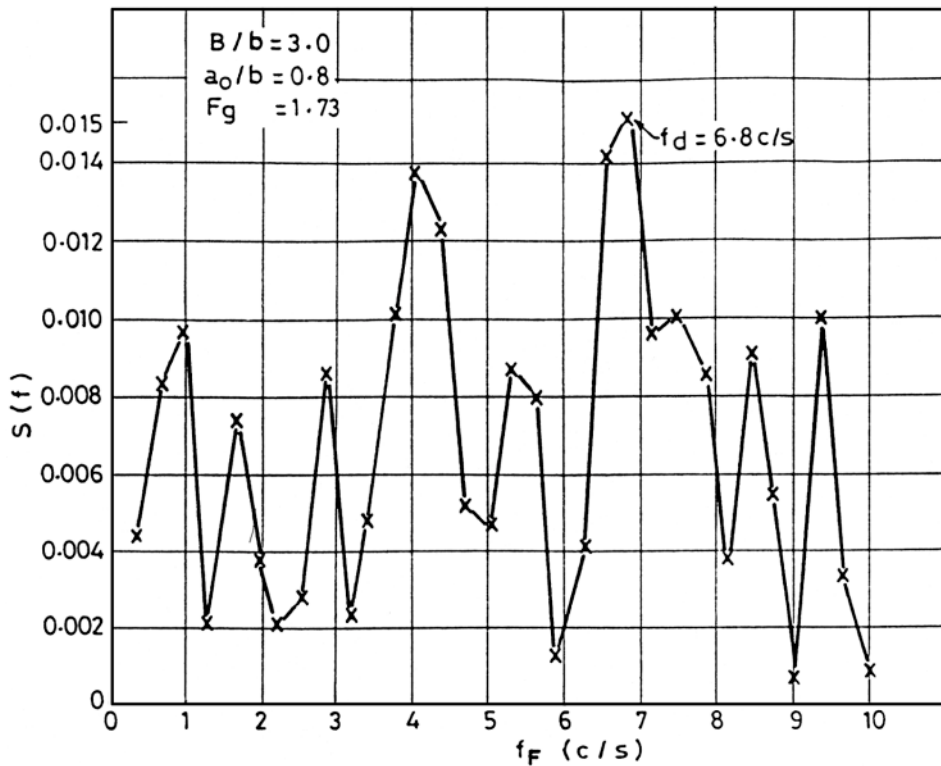FIG. 5. Variation of CF'_b with a_0/b for stationary gate.

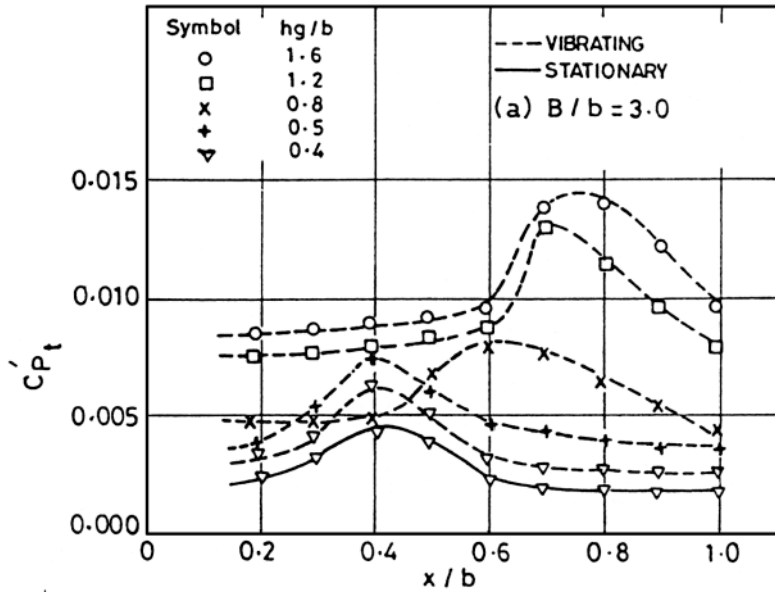FIG. 6. Typical spectrum of force fluctuation on gate bottom.

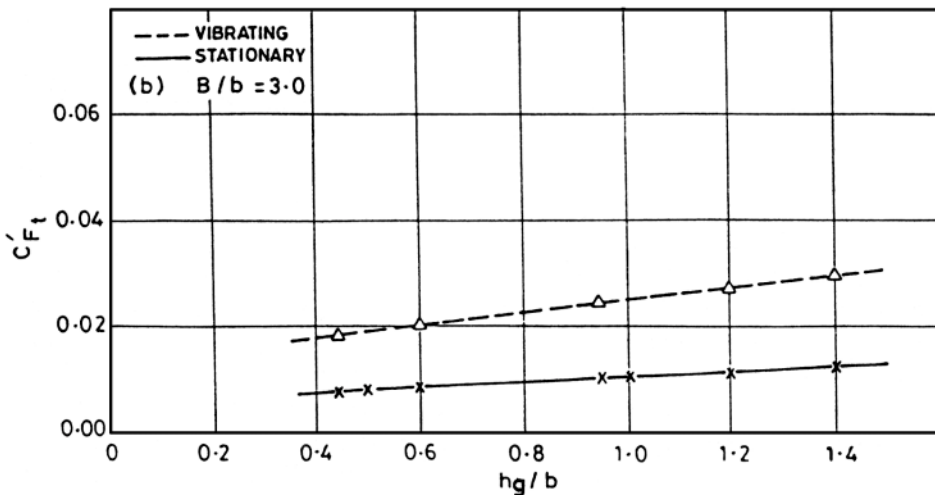FIG. 7. Variation of Cp'_t with *x/b* for overflow.

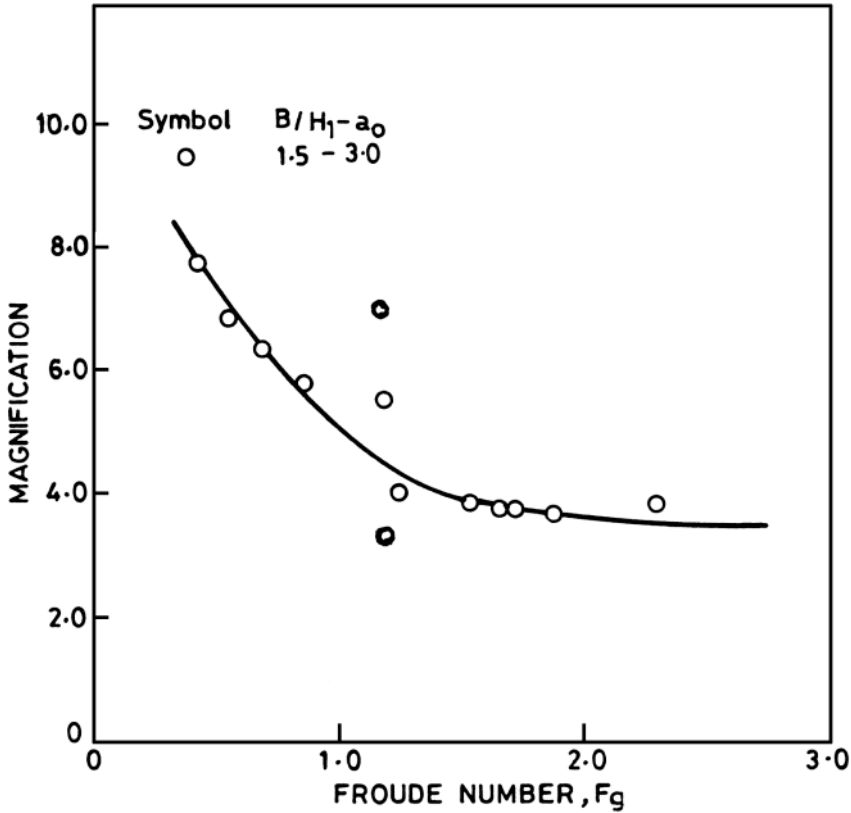FIG. 8. Variation of CF'_t with h_g/b for overflow.

FIG. 9. Variation of magnification due to interaction, M with F_g.

The variation of Cp'_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, Cp'_t, on gate top as shown in Fig. 10. As can be seen, the coefficients Cp'_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 CF'_b and CF'_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_0/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).
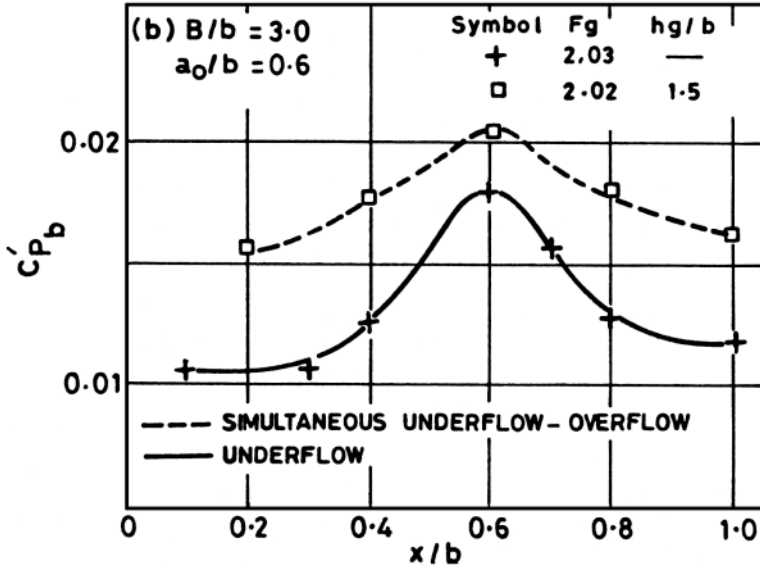

F ɪ ɢ. 10. Comparison of Cp'_b variation with x/b on gate bottom for simultaneous underflow-overflow with underflow alone for vibrating gate.
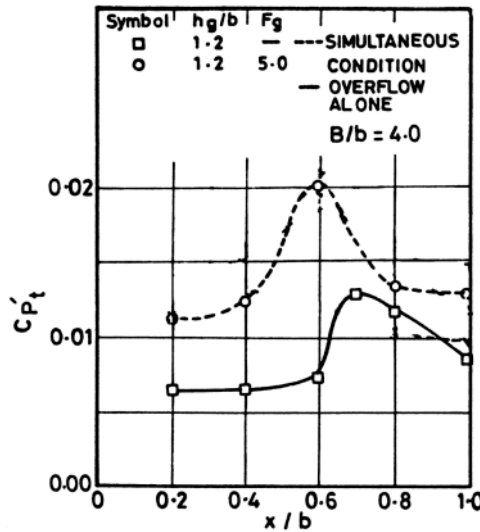

F ɪ ɢ. 11. Comparison of Cp'_t with x/b for simultaneous underflow-overflow with overflow alone on gate top.
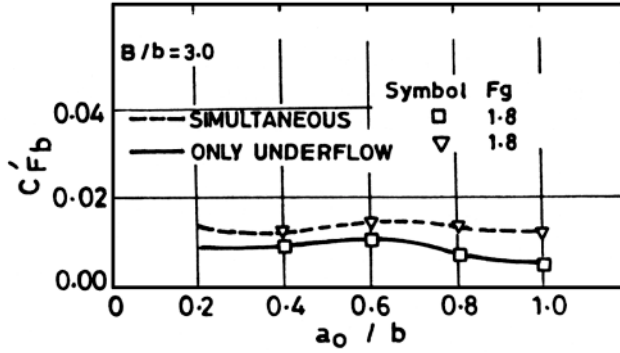
Delwar Husain

F<small>IG</small>. 12. Comparison of CF'_b with a_0/b for simultaneous underflow-overflow with underflow alone.
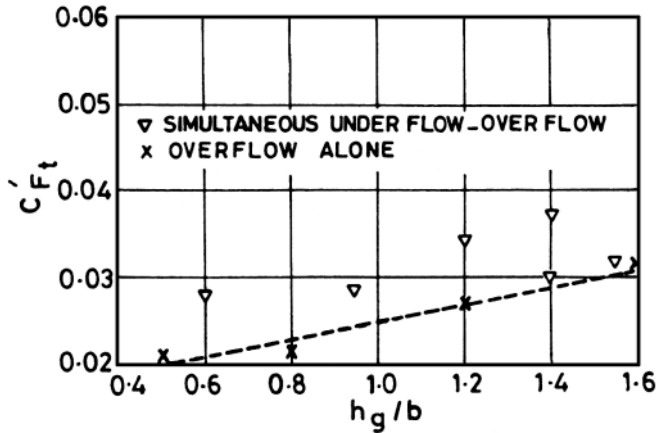

F<small>IG</small>. 13. Comparison of CF'_t with h_g/b for simultaneous underflow-overflow with overflow alone on gate

Earlier while studying the variation of Cp'_b , Cp'_t 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, $Cp'_{pm}, Cp'_{tm}, CF'_{bm}$ 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} [$= Cp'_{bm}$ for simultaneous case / Cp'_{bm} for underflow alone] of Cp'_{bm} on gate bottom,

M_{bF} [$= CF'_{bm}$ for simultaneous case / CF'_{bm} for underflow alone] of CF'_{bm} on gate bottom,

M_{tp} [$= Cp'_{tm}$ for simultaneous case / Cp'_{tm} for overflow alone] of Cp'_{tm} on gate top and

M_{tf} [$= CF'_{tm}$ for simultaneous case / CF'_{tm} for overflow alone] of CF'_{tm} on gate top. These values were obtained from the experimental data for the cases of underflow, overflow and simultaneous underflow-overflow.

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.

Delwar Husain

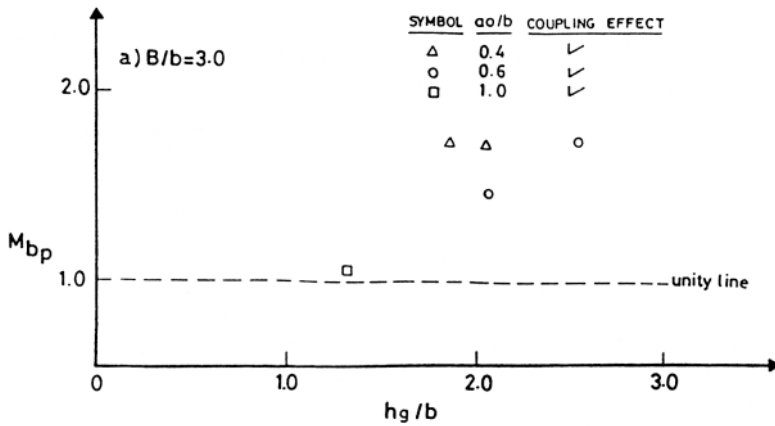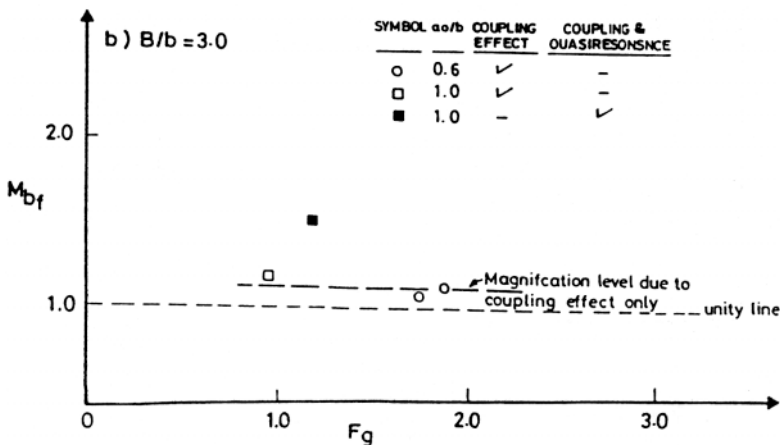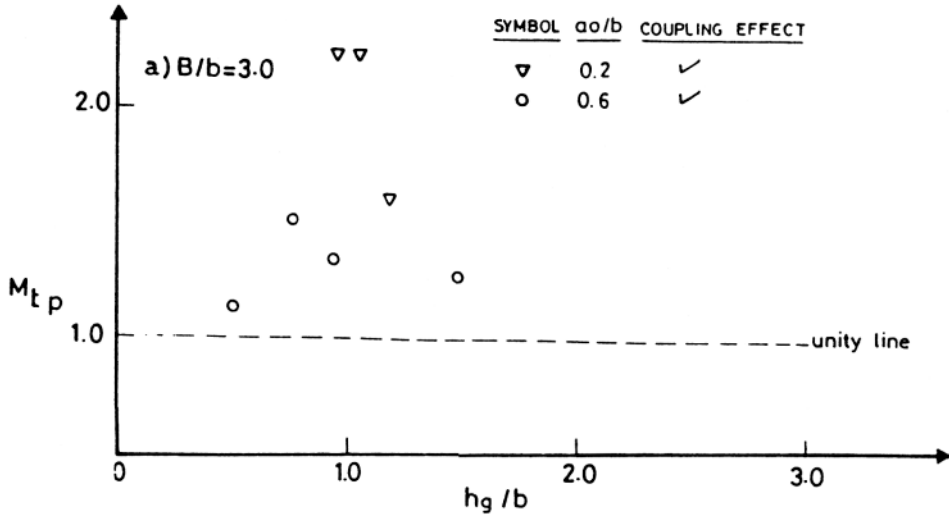FIG. 16. Magnification of Cp'_t for underflow-overflow to overflow alone showing coupling effect.
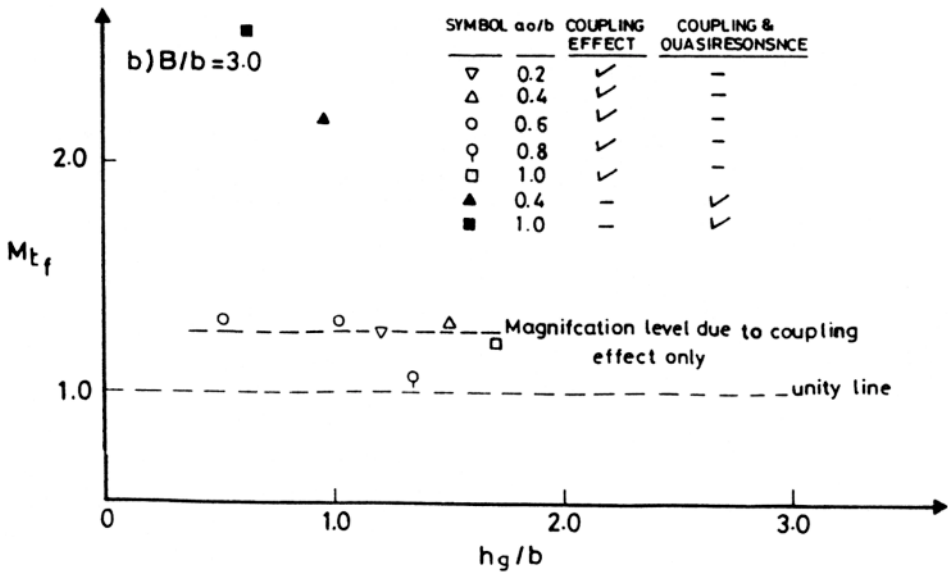

FIG. 17. Magnification of CF'_t for simultaneous underflow-overflow to overflow alone showing coupling effect.

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

[1] **Abelev, A.S., Dolnikov, L.L.** and **Viling, V.,** *On Dynamic Criterion for Vertical Leaf Sluice Gate Considering Hydrodynamic Damping, XVII Congress IAHR, Baden-Baden, Germany* (1977).

[2] **Bhargava, V.P.** and **Narasimhan, S.,** Characteristics of hydrodynamic loading on fixed and vibrating gates, 2*nd Int. Symposium on Stochastic Hydraulics, Lund, Sweden* (1976).

[3] **Hardwick, J.D.,** Flow Induced Vibration of Vertical Lift Gates, *Proc. ASCE, JHD,* **100**(HY3): (1974).

[4] **Homma, M.** and **Ogihara, K.,** *Theoretical Analysis of Flap Gate Oscillations,* XVII Congress IAHR, Baden-Baden, Germany (1977).

[5] **Husain, D., Pande, P.K., Vittal, N.** and **Chandra, B.,** Added mass of vibrating vertical lift gates, *VII National Symposium on Earthquake Engineering, University of Roorkee, Nov. 10-12* (1982).

[6] **Husain, D., Pande, P.K., Vital, N.** and **Chandra, B.,** *Hydrodynamic Loading on Vibrating Vertical Lift Gates,* IAHR XX Congress, Moscow (1983).

[7] **Husain, D.** and **Vittal, N.,** Dynamic Response Analysis of Vibrating Gate due to Hydrodynamical Loading, *First Int. Conference on Aero-Hydroelasticity, ICAHE-93,* Beijing,China, Oct. (1993).

[8] **Kolkman, P.A.,** *Analysis of Vibration Measurements to Underflow type of Gate,* X Congress, IAHR, London, UK (1963).

[9] **Kolkman, P.A.,** *Flow Induced Gate Vibration,* Report No. 164, Delft Hydraulics Laboratory, Delft, The Netherlands (1976).

[10] **Kolkman, P.A.,** *Self Excited Gate Vibrations,* VII Congress IAHR, Baden-Baden, Germany (1977).

[11] **Naudascher, E.,** Vibration of Gates due to Underflow-Overflow, *Proc. ASCE, JHD,* **87**(HY5): (1961).

[12] **Naudascher, E.,** *Hydrodynamic Forces,* IAHR Hydrodynamic Structures Design Manual, No. 3, AA Balkema, Rotterdam (1991).

[13] **Naudascher, E.** and **Rockwell, D.,** *Flow-Induced Vibration, an Engineering Guide,* Hydraulics Structures Design Manual Series, IAHR, A.A. Balkema Publishers (1994).

[14] **Ogihara, K.,** Hydrodynamic forces on moving gates, *Trans. Japanese Society of Civil Engineers,* **3:** (1971).

[15] **Perkins, J.A.,** *Model Investigation of the Vibration of a Vertical Lift Gate,* X Congress IAHR, London, UK (1963).

[16] **Petrikat, K.,** Vibration tests on weirs and bottom gates, *Journal of Water Power,* **10:** (1958).

[17] **Treiber, B.,** Theoretical Study of Nappe Oscillations, *IUTAM-IAHR, Symposium, Karlsruhe, Germany* (1972).

Notations

a_0 gate opening.

b   gate thickness

B   gate width.

CF' coefficient of force fluctuation.
CF'_b CF on gate bottom.
CF'_t CF on gate top.
Cp'' pressure fluctuation coefficient.
Cp'_b Cp on gate bottom.
CF'_t Cp on gate top.
F force.
f_1-f_4 functions.
$\overline{F}$ mean force.

$\sqrt{\overline{F}^2}$ 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.
hg overflow head.
m peak value.
M magnification factor.
p the pressure.

$\sqrt{\overline{p}'^2}$ RMS value of pressure fluctuation.

S_f spectral energy.
v_1 velocity under the gate.
x location point of pressure measurement.
γ unit weight of water.
η dynamic parameter.
ρ mass density of fluid.

دراسـة ديناميكيـة الجـريان الآني أسفـل وأعـلى بوابات الحجز ذوات الضاغـط المنخفض

دلوار حسين

قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود
الريـــــــاض – المملكة العربية السعودية

المستخلص .   تعرض هذه الدراسة نتائج بحوث معـملية أجريت على نماذج بوابات حجز ذوات ضاغط منخفض ، أخذًا في الاعتبار حالات الجريان الآني أسـفل وأعـلى البـوابات ، أو أسـفلهـا أو أعـلاهـا فـقط . لقـد تم دراسـة السلوك الديناميكي للبوابات بدلالة التغيرات في الضغط والقوة على قاع أو قمة البوابة لكل من البـوابات المتذبذبة والثابتة . أيضًا تم تحديد حـالات حـدوث الرنين بمقارنـة التردد الطبيعي للبوابة بالتردد الشائع للتغير في القوة ، والذي تم تحديده باستخدام التحليل الطيفي . تبين من تحليل النتائج أن معاملات الضغط والقوة على البوابات عاليـة نسبيًا في حالات الجريان الآني أسفل وأعـلى البوابات . كما تبين أن هذه المعاملات أعلى نسبيًا في حالات البوابات المتذبذبة مقارنة بالبوابات الثابتة ، نتيجة « التأثير المتبادل » بين الجريان وذبذبة البوابات . أثبتت الدراسة أن وجود الرنين يؤدي إلى زيادة مفعول كلا من « المزدوج » و « التأثير المتبادل » .