Spillway gate design features which can cause vibration

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SYNOPSIS. Gate vibration is a serious problem which can result in structural damage or restrict operation at certain gate openings. Operators are mostly unaware that a risk of gate vibration exists. In some cases vibration of a gate will occur under specific hydraulic conditions which may become manifest only years after commissioning of the installation. Even when these conditions have been identified it may not be easy to reproduce them so that they can be investigated. Apparently steady state conditions may be subject to minor hydraulic disturbances which overcome the damping forces acting on the gate and initiate an unstable motion, giving rise to oscillations of increasing magnitude. A number of design features can cause gate vibration; the paper briefly describes these and the conditions under which their effect on the discharge flow at spillway gates is critical. Gate vibration may also arise due to maintenance and servicing problems, or to degradation over time.

INTRODUCTION

Few problems are more difficult to cope with than the vibration of hydraulic equipment (Cassidy 1996). It is not possible to provide an in depth understanding of generation of vibrations in one technical paper. Extensive work is available setting out the analytical factors of the vibrating system (Kolkman 1979, Naudascher et al 1994, ICOLD 1984); for an introduction to the subject, see Lewin (2001).

Surveys of existing installations suggest that the designers were not aware of critical hydraulic aspects which can affect the reliability of the plant. Even when the potential for vibration is present, gates may operate for a long time without incident. A change in hydraulic conditions or operating practice can result in unexpected gate vibration. When this occurs in extreme conditions or at unattended installations it is not certain that the problem will be recognised or detected in time.

The natural frequency of a gate depends on the rigidity per unit mass. When oscillation occurs the water at the gate face moves with it (the added mass).

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Any force due to the excitation frequency but in opposition is a damping force. At radial gates damping is due to the friction of the side seals and is relatively low. At vertical lift gates additional forces are caused by bearing friction at the guide rollers and, to a lesser extent, roller friction. Seal friction also depends on wear.

Because the natural period of vibration of a gate depends on its total mass (structural mass plus added mass), it will vary with the gate opening and the upstream water level. These two factors will also affect damping but not necessarily in the same ratio.

Because it is difficult and often impossible to predict the conditions when gate vibration is likely to occur, it is important that design features which can cause fluid excitation are not present.

CAUSES OF GATE VIBRATION

Side Seals

Figure 1 shows different side seal arrangements. Figure 1a, a gate side seal in the shape of a musical note is a conventional solution. 'L' shaped seals, Figures 1b and 1c, are used when the upstream water head is moderate (8 m or less) because the seals are more flexible and permit a larger clearance between the skin plate and the embedded seal contact plate. At higher heads the possibility of seal breakthrough increases.

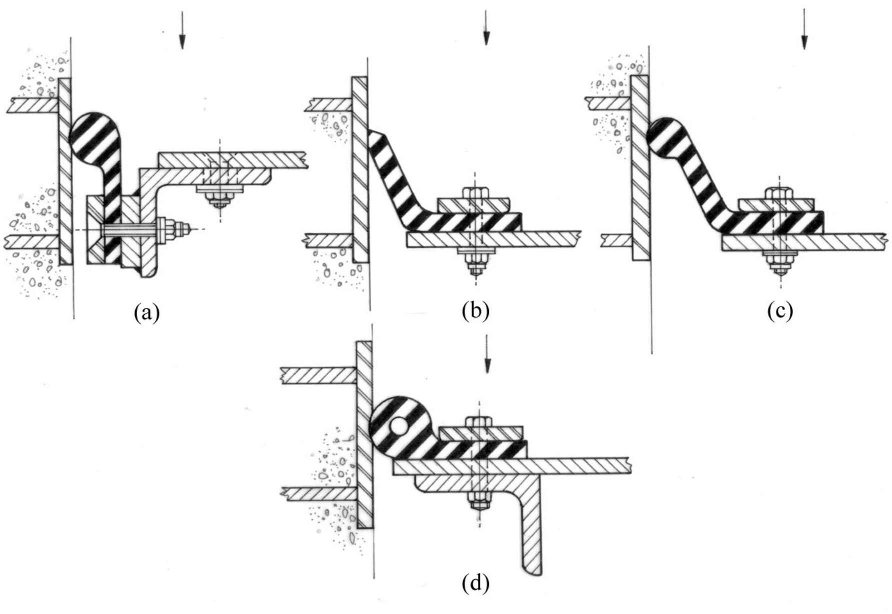


Figure 1. Side seals

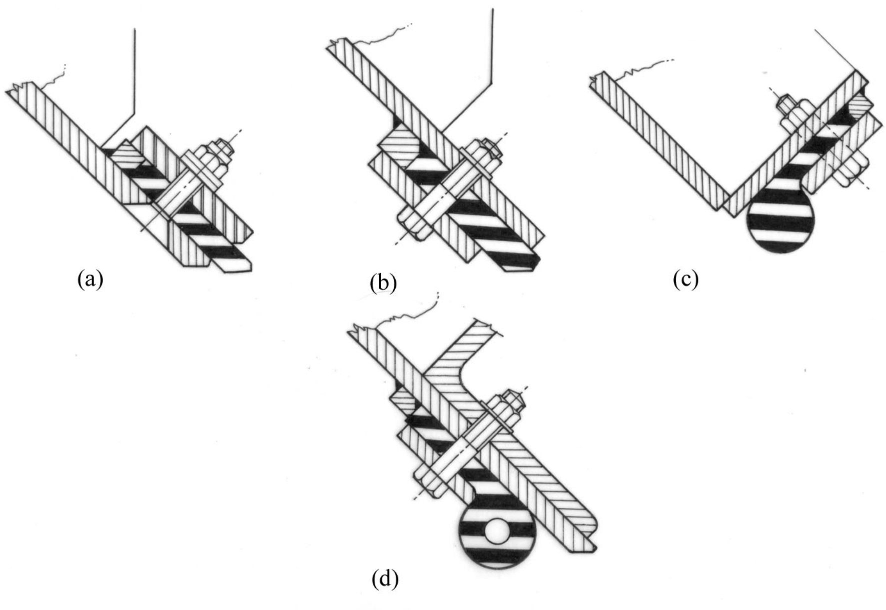
The seal arrangement in Figure 1d should not be used because it only permits deflection by compression of the seal, not by flexure. This severely limits the width of the gap which the seal can close.

Fluctuating discharge through a seal is a frequent cause of gate vibration. A breakthrough of upstream water results in a reduction in the water pressure which, in turn, causes the seal to close. This initiates another leakage flow. A regular repetition of fluctuating flow causes the gate to vibrate. Intermittent leakage flow through side seals requires rapid remedial action before the amplitude of gate vibration builds up.

Many old vertical lift gates use staunching bars as side seals. Because of the rigidity of the bars leakage is continuous, but at high gates leakage jets have caused cavitation erosion at low level. Kolkman (1984) mentions that noise, vibration, hammering, wear at the edges of leaking parts and damage to wheels have been caused by the shocks induced by the collapse stage of cavitation bubbles or voids.

Sill Seals

The seal should provide a sharp separation of flow under the gate. A seal in the shape of a musical note is therefore unsuitable, and only rectangular shaped rubber or elastomeric seals should be used (Figure 2). In both cases the flow can reattach, and when this is intermittent and regular, gate vibration can occur.



(a) (b) (c) (d)

Figure 2. Sill seals

The correct method of mounting the seal is shown in Figure 2a.

Figure 2b, which shows the seal upstream of the skin plate, causes flow attachment at the upper edge of the seal clamping plate due to the downward flow close to the gate lip – also a feature of Figure 2d.

In the case of Figure 2c, the upper end of the seal clamping plate tends to become more horizontal when the gate opening increases and cuts into the expanding flow under the gate. In Figure 2d, the skin plate projects into the flow as the gate rises, causing reattachment after discharge under the seal. Figures 2c and 2d are reproduced from 'as constructed' drawings of existing gates and are not isolated cases.

Leakage at the sill seal can cause gate vibration. Differential tightening of the screws holding the seal and the retaining plate can introduce slight waving of the seal which can cause leakage. A ferrule is usually fitted around the screw section through the seal. It is slightly less thick than the seal and permits even tightening of the nuts.

Unsteady Flow

High velocity flow through a narrow gap is unsteady. The natural frequency of a gate and its added mass of retained reservoir water tend to regularise the leakage discharge, causing gate vibration.

Gate sills can be distorted by closure when debris is lodged on the sill. In view of the risk of gate vibration, remedial work to eliminate discharge on this account should not be delayed.

If an initial opening of a gate is insufficient the flow is unsteady. To avoid vibration, gate manufacturers specify a minimum first gate opening of between 100 mm and 150 mm. Where gates are operated automatically this is incorporated into the control system. However, there are instances of gate installations which are manually operated where staff are not aware of this requirement, and it is not made explicit in the operating instructions.

Structural Considerations

Gate design guidelines to avoid vibration can be formulated (Lewin 2001).

(a) No structural member upstream or downstream of the control point should protrude into a line at 45 degrees from the point of flow control, as shown in Figure 3. Two references (Kolkman 1984; Hart et al 1979) suggest that members upstream of the control point should preferably be 60 degrees clear of the control point.

(b) It is better to arrange for the vortex trail to be shed from the extreme downstream edge of a gate in order to achieve flow conditions that are as steady as possible (Vrijer 1979).

(c) A sharp cut-off point should be provided at the lip (Schmidgall 1972).

Figure 3a illustrates vertical lift gates where a reinforcing girder is placed low. Discharge under the gate causes flow to attach to the web of the girder and the flange. The attachments are intermittent and severe gate vibration can occur.

Figures 3b and 3c show construction at the bottom of vertical lift gates which comply with the criteria to avoid vibration. The shape also reduces hydraulic downpull forces which can become a significant factor at high gates.

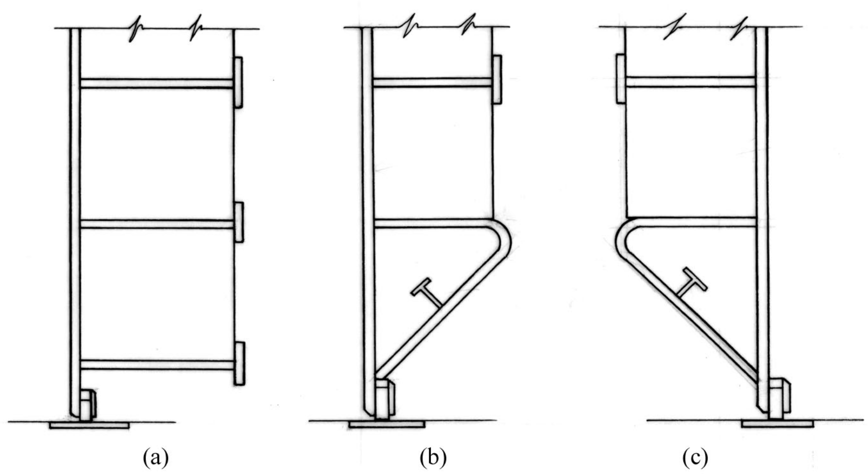


Figure 3. Structural reinforcement of gate bottoms

Other examples of a skin plate reinforcing member placed low are shown in Figure 4. An extreme case is Figure 4b, where the bottom of the gate was flat. It resulted in severe vibration. A number of gates of this design were installed at Pershore Mill (Bruce et al 1978).

The examples of gate construction illustrated in Figure 4 are not unique and a few gates of this type are still operational despite considerable age. They may have survived because they have been rarely used, and then only because they were mostly in the open position.

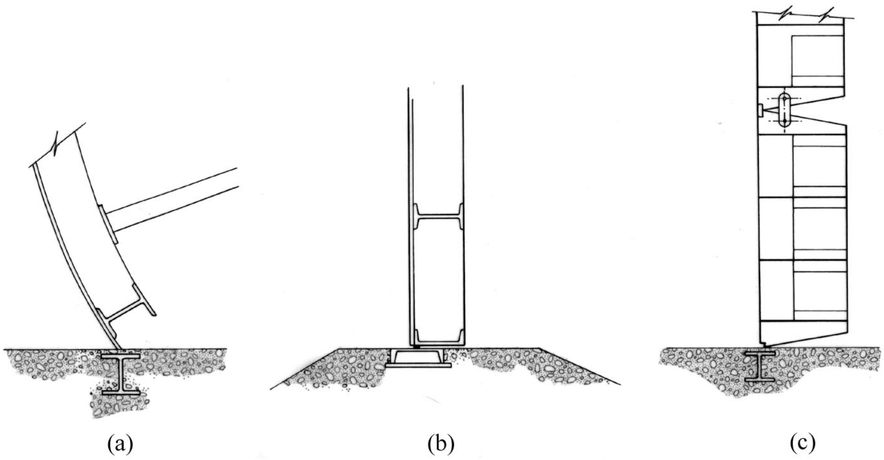


Figure 4. Unsuitable arrangement of structural stiffening members at the bottom section of gates

Figure 5 illustrates a radial gate where a low structural member stiffens the bottom of the skin plate. In the shut position it appears that the expanding flow under the gate will, on opening, satisfactorily clear the skin plate stiffening member. However, when the gate is raised the stiffening member rotates about the trunnion axis and the flow discharged under the gate attaches to the stiffening member. Detachment and reattachment occur and when this regularises it is likely to cause vibration.

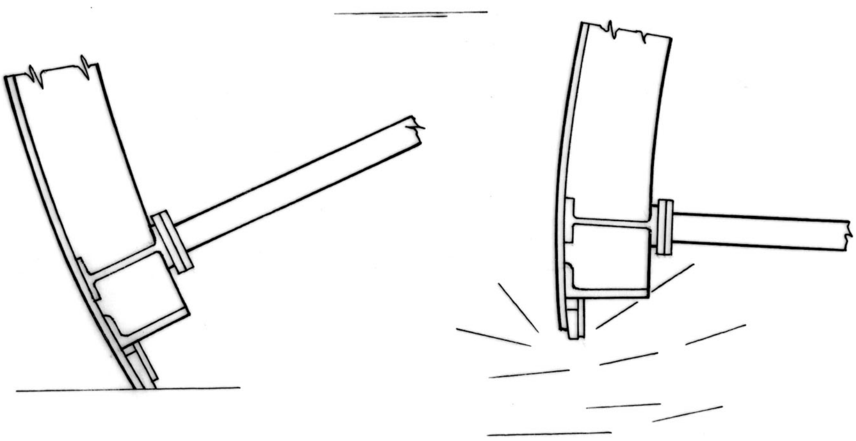


Figure 5. Structural reinforcement of the bottom of a radial gate which can cause flow reattachment when the gate is raised

Other Causes of Gate Vibration

Eddy Shedding

Regular eddy shedding can occur when there is an appreciable downstream water level, Figure 6. New radial gates in Australia suffered from persistent flow induced vibration (Hardwick et al 2000). The extended periods of large gate opening and low flow velocity were unusual. A model suggested that instability of a shear layer at the gate lip could be responsible for the excitation. The vibration was eliminated by mounting spoilers on the upstream of each prototype gate skin plate to break up the two dimensional character of the shear layer.

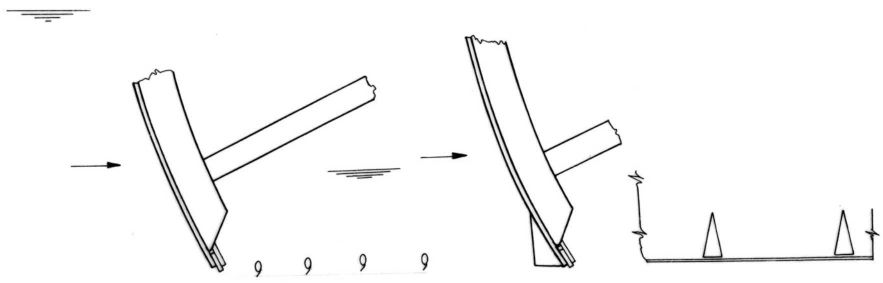


Figure 6. Regular eddy shedding at the bottom of radial gate

Off-Centre Trunnions

In 1967 a spillway gate 12 m high and 9 m wide on the Washii Dam in Japan collapsed (Ishii et al 1968). It was swept downstream, Figure 7. The cause was instability introduced by eccentricity of the trunnion bearings. The trunnions were located about 0.5 m above the true origin of the radius of the skin plate.

Eccentric trunnions were deliberately introduced on some large radial gates to reduce the hoisting forces. There is no record of violent vibration of these gates because the eccentricity was much lower than that of the Washii gate. The safe limit of eccentricity appears not to have been researched.

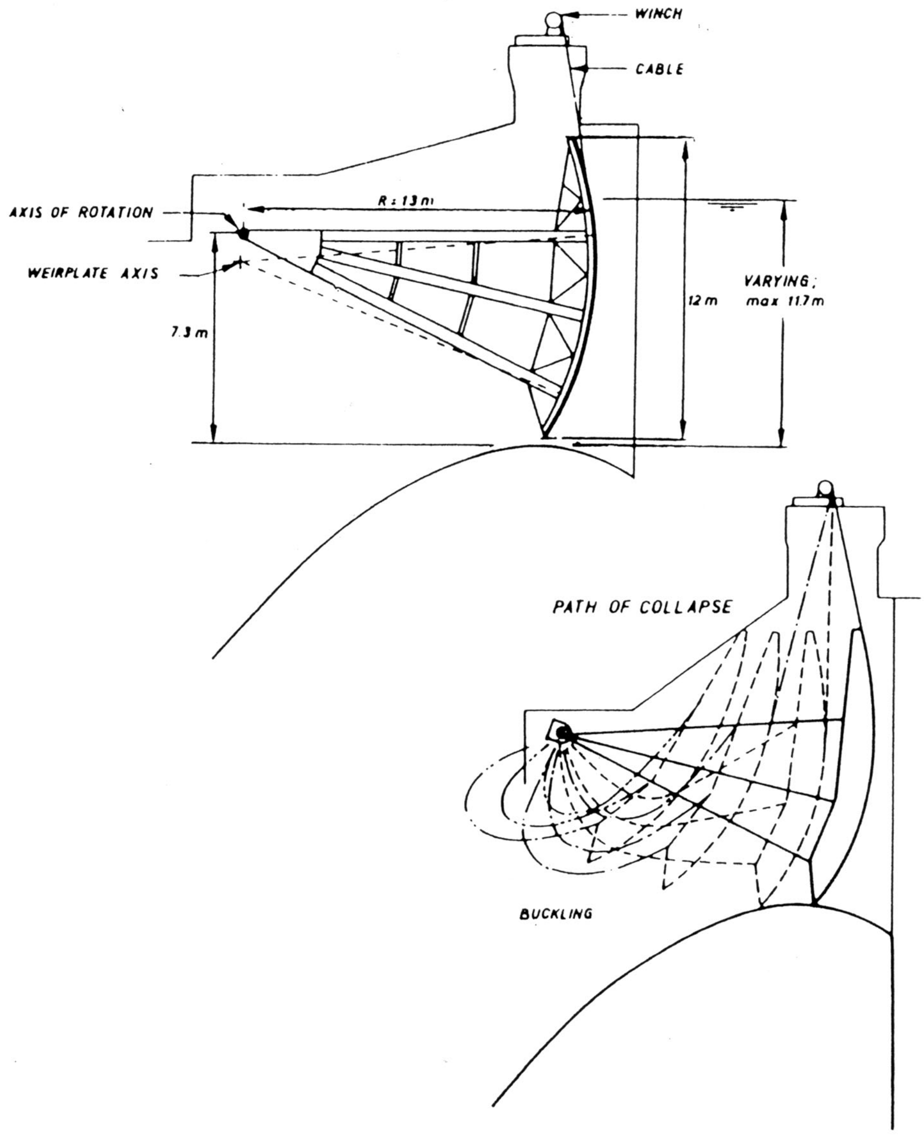


Figure 7. Spillway gate vibrations leading to the collapse of a gate (after Ishii et al)

Venting Overflow of Gates

Certain types of gates are designed to discharge by overflow, such as bottom-hinged gates, vertical lift gates and radial gates with hinged overflow sections. The objective may be to discharge floating debris or, at tidal barrages, to prevent salt water penetrating inland. At some river barrages, bottom-hinged gates are selected to improve appearance. A number of different designs are illustrated in Lewin (2001).

The volume of air enclosed beneath a nappe varies periodically and is excited by pressure fluctuations beneath the nappe. The pressure fluctuations excite the nappe which, in turn, fluctuates. The amplitude of nappe fluctuation is greatest at its lower end.

The falling nappe absorbs air, so unless air is admitted the nappe will eventually collapse, which can cause a serious shock to the system. Figure 8 shows two methods of effecting air supply. Flow dividers are one solution; a high overflow can drown them out and venting ducts in gate piers and abutments must be provided. Venting will also increase the pressure under the nappe, and the discharge and resulting velocities will decrease. This is important in controlling the occurrence of cavitation. Spacing of flow dividers and information to calculate air supply are given in Lewin (1983).

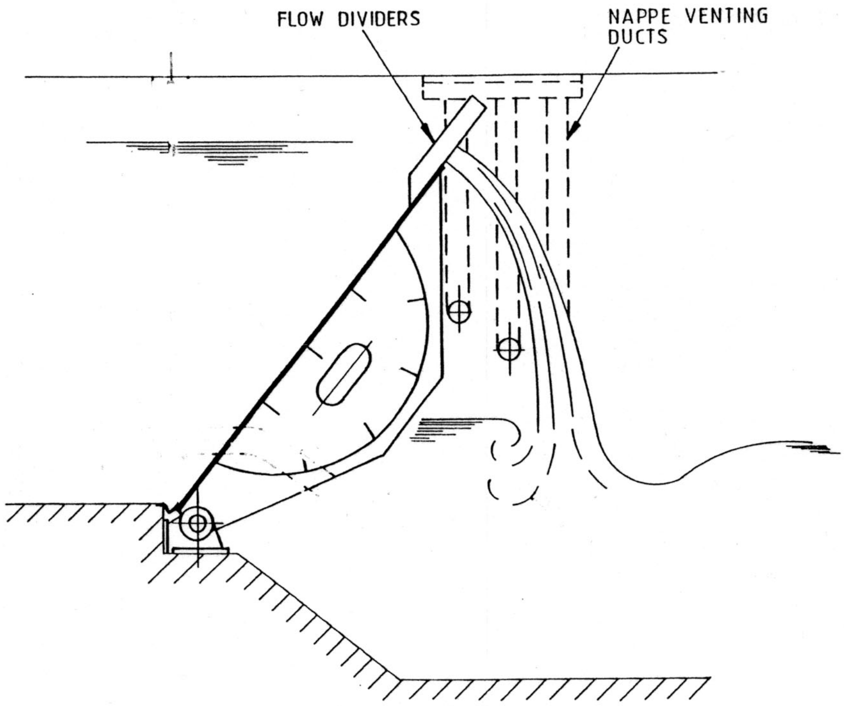


Figure 8. Venting the overflow of a gate

Structural Arrangement of Gate Arms and Stiffening Girders

Figure 9 illustrates preferred structural arrangements of the gate arms of a radial gate and the stiffening girders of wide span vertical lift gates.

There are no recorded examples where structural members close to the bottom of a gate of the type shown in Figure 9 have resulted in gate vibration, but in rivers which carry sand during flood discharge they have been seriously eroded. An example is the collapse of a gate on the Sukkur Barrage on the River Indus in Pakistan.

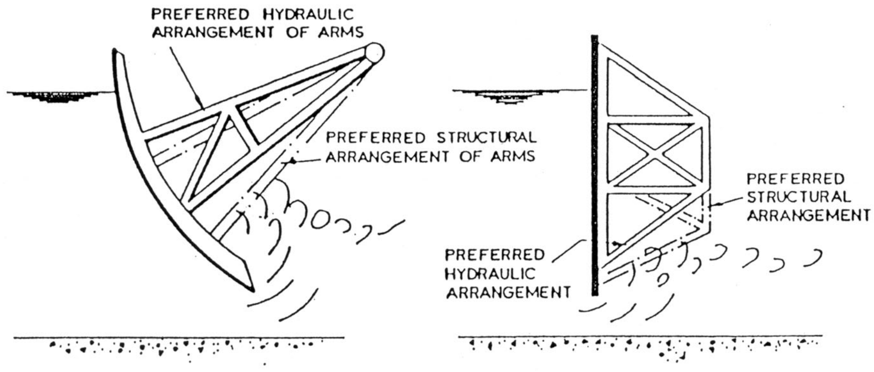


Figure 9. Preferred hydraulic structural arrangement of a gate subject to drowned discharge

<u>Slack of Vertical Lift Gates in Guide Channels</u>

Slack can be an important contributory cause of gate vibration at vertical lift gates. With Stoney Roller gates, slack is difficult to avoid because of their construction. The vibration of gates at the Toome Sluices in Northern Ireland was due to the interaction of a low webbed girder stiffening the Stoney Roller gates and slack of the roller assemblies in the guide channels.

<u>Hollow Cone Valves (Howell Bunger Valves)</u>

Causes of vibration of hollow cone valves are included here because many spillway gate installations use them to control compensating flows. Because of their simplicity and high discharge coefficient they are often the first choice of discharge valve.

The lower section of Figure 10 shows an open hollow cone valve. In this position the flow control may shift from the sleeve to the valve body (A to B) and intermittent attachment and reattachment may occur, resulting in severe vibration. Under these conditions the opening of the valve, that is, the sleeve travel, has to be limited.

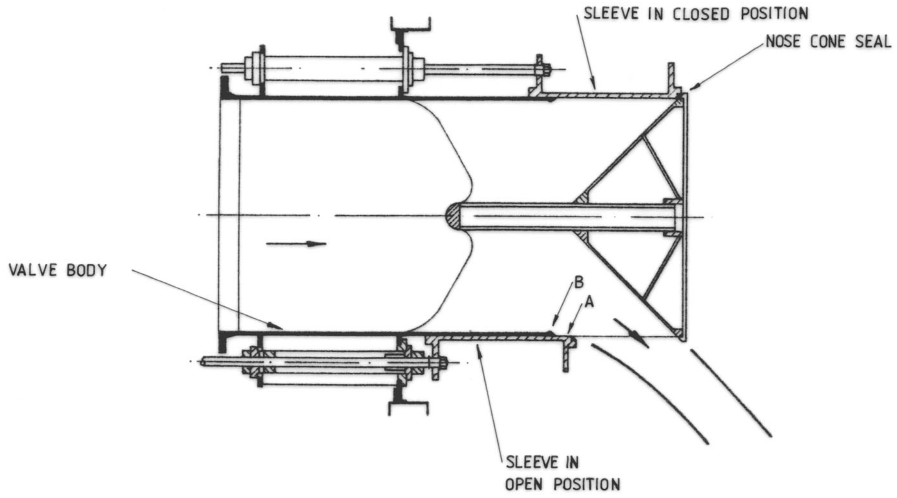


Figure 10. Hollow cone valve

Vane failures have occurred and have been attributed to a number of reasons, but the most likely one is hydroelastic instability causing vibration normal to the chords and twisting about the longitudinal axis. Destructive resonance occurs at a critical velocity at which the flow couples the two forms of vibration in such a way as to feed energy into the elastic system. Possible modes of vibration for a hollow cone valve are shown in Figure 11. Mercer (1970) has suggested equations for calculating parametric values which avoid failures.

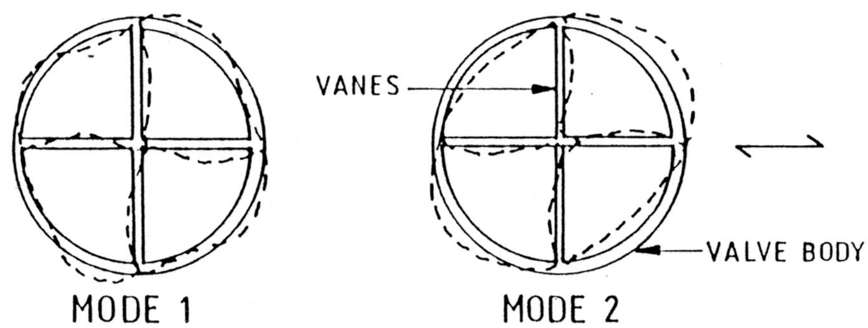


Figure 11. Possible vibration modes of hollow cone valves (after Mercer)

CONCLUSIONS

The design aspects discussed and illustrated in this paper which can cause or contribute to gate vibration are not comprehensive. For an understanding of gate vibration, references quoted in the introduction are recommended.

While it is possible to predict when gate vibration is likely to occur this is of limited practical application because causative factors, such as the vibrating mass, change throughout gate operation. However, model investigations can be valuable (Novak et al 1981; Kolkman 1976, Haszpra; 1979).

Vibration of low level gates at high head dams can be more severe as additional factors, such as demand for air supply, are present . A summary of design elements which are inimical to gate vibration would require a longer paper.

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