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UNITED STATES
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HYDRAULIC LABORATORY REPORT NO. 100

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ON THE VIBRATION OF WEIRS

BY

PROFESSOR R. SEIFERT, VDI

Translation
by

H. G. Dewey, Jr.

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Denver, Colorado
October 13, 1941

UNITED STATES

DEPARTMENT OF THE INTERIOR

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ON THE VIBRATION OF WEIRS

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A Translation of

ÜBER SCHWINGUNGEN VON WEHREN

BY PROFESSOR R. SEIFERT, VDI

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
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Denver, Colorado
October 13, 1941

Laboratory Report No. 100
Hydraulic Laboratory
Compiled by: H. G. Dewey, Jr.
Reviewed by: J. E. Warnock

Subject: On the Vibration of Weirs.

INTRODUCTION

There are two types of weir[1] vibrations: one type occurs when raising an underflow gate, the vibration resulting from the compressed jet; and the second type occurs with an overflow gate, the vibration resulting from the jet flowing over the gate and spilling into the atmosphere. By means of model studies, it has been possible to clarify the forces acting in both of these cases. Thus measures for the elimination or prevention of vibrations were discovered in a model and were tried on the prototype.

As long as the regulating devices of movable weirs, sluices, and conduits were moderately large in width and water pressure, the flowing water caused no dangerous vibrations. They occurred at first, however, as the dimensions and water pressures were considerably increased. Vibrations then appeared so strong that, disregarding the disturbance to people living in the vicinity, the stability of the regulating gates, of the power plants, and of the foundation was endangered. In several cases, failure of structural members had already occurred due to fatigue

[1] Translator's note: The German word "wehr" may be translated as "weir" or "dam" as applied to hydraulic structures. The former probably applies to smaller structures and is used, therefore, in this translation.

or overstrain. The groping attempts to remove the vibrations by supplementary structural parts, without taking pains to understand the mechanical process of vibration excitation, were sometimes successful; however, these attempts had other drawbacks and, as a result, showed in any case, from the very first, no method for designing structures free from vibrations. Extensive research on the causes of weir vibration are not practical on a prototype structure because the essential conditions, such as the discharge, reservoir and tailwater elevations, total drop, and shape of weirs, cannot be changed arbitrarily and individually. Pure theoretical considerations also lead no further for there are vibrations even at rigid weirs, for example at the Hameler weir. Thus there remains only the model study to clarify the action of the forces and, in this way, to eliminate or to prevent the vibration of weirs.

In the following discussion, only existing structures are considered. The transference of the knowledge gained to sluice gates, conduit sluices, and valves is possible without further ado.

CAUSES OF WEIR VIBRATION

Weirs may start vibrating when either the regulating gates are raised a small amount permitting the jet to flow under the gate under the pressure of the headwater, or they may start vibrating when overflow gates are lowered, permitting the jet to spill over the lip of the gate into the atmosphere. On 1930, when the Waterway Administration at Hanover planned the new construction of the Dörverden sluiceway dam, demolished because of sand erosion, they turned, being warned by the failure of large dams of other administrations, to the Prussian Research Institute of Hydraulics, Soils Mechanics and Shipbuilding in Berlin, with the purpose of conducting fundamental research on the prevention of weir vibration.

The Research Institute undertook, first of all, observations and measurements on a large number of existing weirs, some of which vibrated

with underflow gates, in order to become familiar with the forms of vibration and the manifold conditions for which vibrations occur in a prototype. The measurements were made partly with existing apparatus (Geiger-Collins vibration instrument of the Cambridge Instrument Company, Pabst Indicator, Askania-Werke moving picture camera, very sensitive aneroid barometers, and others); partly with new apparatus (Waas recorder, Müller tuning fork) which had to be developed to measure, under the quite difficult local conditions, the frequency and amplitude of the structures; and partly with instruments which had to be developed to determine rapidly variations in air pressure (Müller-Jahnke pressure recorder in combination with a Siemen's oscillograph, and others). Similarly, it was necessary to make corresponding self-recording apparatus for the model experiments.

VIBRATIONS PRODUCED BY UNDERFLOW

The first experiments on the model dealt with the vibrations produced by the underflow of raised flood gates. Observations on prototypes had shown that vibrations occur especially for small gate openings, thus exactly in the region of gate positions most frequently used in regulating the discharge. The opinion proved to be incorrect that the vibrations originated from pulsations of the headwater or from the waves of the tailwater which struck against the structural members of the weir projecting into the tailwater. On the contrary, the flow around the sealing beam located at the lower edge of the gate was recognized as the cause of vibration whenever the beam had unfavorable shape.

For the clarification of the mechanics of vibration, a model capable of vibrating was constructed. A two-dimensional section of a sealing beam of a weir was constructed and suspended by springs to enable the beam to vibrate vertically (the possibility of torsional oscillation was foreseen, but was not exploited in the first series of tests). This model was placed in a glass channel 6.30 inches wide, with a tailwater depth of 5.91 feet, and with a discharge of 7 second-feet under a head of 45.93 feet. The shape of the sealing beam, the gate opening, and the

modulus of the spring could easily be varied; likewise, the head, the position of the weir underneath, and the discharge could easily be changed. The vibrations were recorded mechanically according to number and displacement. The sealing beam rested on a sill lying flush in the approach floor, corresponding to the usual prototype arrangement. The floor was connected by an apron on a 1 to 2 slope directly to a stilling basin deepened to 20 inches. The model then corresponded to the Dörverden weir to a scale ratio of 1 to 3.8. In general, there were two tailwater conditions investigated, which were maintained by a series of superimposed stops in the outlet of the channel; later on sills of various shapes projecting above the approach floor, various sloping aprons and stilling pools with modified slopes, and various starting points for the slopes were also investigated, changes which proved to be of considerable value.

At first the sealing beam in the vibration model was rigidly fixed and the average pressure heads were measured for changing heads, tailwater, and gate openings. The appropriate discharge was also measured in each case. In the case of rectangular or similar sealing beams, intense negative pressures occurred at certain points which caused, as a consequence, a separation of the jet (figure 1); nevertheless, it was possible to obtain by suitable curvature of the upstream edge of the sealing beam, a constant and gradual decrease of the headwater pressure to that of the tailwater pressure, with the jet throughout a wide range of gate openings continually adhering to the sealing beam (figure 2). Under this condition it is expected that no vibrations will occur.

The investigation on the vibrating suspended sealing beam of the model confirmed this hypothesis. The rectangular beam which has produced vibration on the prototype weir also vibrated in the model. It was observed directly how eddies in short, uniform time intervals formed in the region of the negative pressure, and how they drifted away after reaching a definite size, and, for a moment, yielded to the normal stream (figure 3). This pressure change at the sealing beam

produced elastic deformation in the weir which, in turn, contributed to the separating process of the flow and thus maintained the vibration. In this case the natural vibration of the steel structure also played a part (figure 4).

The vibrating seal beam showed a larger discharge than the non-vibrating beam, the former acting as a pump. The discharge coefficient of the square beam increased approximately 19 percent when vibrating; the coefficient depending on the spring tension, the deflection, and the average gate opening.

A broader series of tests were conducted on a 1 to 10 scale, 6-foot wide, complete model of a Havel weir which can be flowed under from two directions. The results of the partial model were confirmed.

After the action of the forces had been clarified, then existing vibrating dams could be made free from vibration by easy rebuilding, and new dams could be designed free from vibrations from the start for all important heights of lift. To do this, sufficiently large curvature is required at the inlet side of the sealing beam (figures 5 and 6) or, in the case of removing existing vibrations, individual additional members are required at the exit side in order to divide the jet into several parts (figure 7). The eddies in this case break away in different intervals of time, so that the parts of the eddies mutually disturb each other at the beginning of any vibration. In the case of weirs in which the flow sometimes occurs in one direction, sometime in the opposite direction, freedom from vibration may be obtained by alternate curvature of sealing beams on the upper or lower side. Such cases occur in inlet and outlet sluices in tidal regions.

VIBRATIONS PRODUCED BY OVERFLOW

Considerable difficulty occurred in the clarification of vibrations occurring with free fall jets at overflow sluice gates, drum gates, and the like. Measurements with the apparatus previously referred to were used, first of all, on a large number of vibrating prototype weirs. Small-scale model experiments were then conducted on

a portion of a gate, which gave many insights into the phenomena involved, but no complete knowledge.

The first supposition was that the vibration of the flap (Klappe) was produced by fluctuating regions of negative pressures in the jet, moving in uniform intervals of time on the back of the flap causing return flow and water rollers which disappeared and formed anew (figure 9). Vibrations would, therefore, so it was believed, be prevented if the flap had, as a result of its shape, no such regions of negative pressures above it.

This initial supposition proved to be false. At a prototype structure such flaps vibrated considerably without any regions of negative pressures being indicated. In any case varying pressure distribution on the flap did not produce vibration, but at the most promoted it. Model and prototype studies showed that the help of air under the jet was essential for the occurrence of flap vibration. A constant negative pressure with respect to the surrounding atmosphere was also detectable in addition to air-pressure vibration and pulsating air flow along the axis of the weir, similar to an organ-pipe vibration. The ventilation of the jet from pier recesses appeared to be of importance, while breaking-in of air in certain chronological sequence stopped the flap from vibrating. If this condition in the air pressure is considered as the cause of the flap vibrating, then it would be a matter of breaking up the jet in order to remove the negative pressure and also the air-pressure changes. The jet divider suggested for this purpose by the Research Institute for the 78-foot 9-inch weir openings of the Dörverden weir gave good results; in the case of the 138-foot weir openings the jet divider also gave good results, but not under all conditions, since for some flap positions, thicknesses of jet, tailwater elevations, and wind condition vibrations still occurred. The working together of all these variables, which can not be brought into action in the prototype as desired, remained unclear.

For that reason the Research Institute had to take up its problem

in new model studies when the Waterway Administration of Hanover requested that their dam for the storage regulation of the Weser River between Bremen and Minden be absolutely free from vibration. Supported by its existing knowledge of flap vibration, the Research Institute conducted systematic tests on a 20-foot wide model which represented the flap shape of the Dorverden weir to a scale ratio of 1 to 10. Thus the model corresponded to a width of weir of 200 feet; however, smaller segments of the model could be separated for investigation. The height of drop could be increased by lowering the tailwater as much as 32 feet and the flap could be rotated to any desired position. In general, an average, a low, and a high flap position was used. The flap was supported by rigid, but changeable, cylindrical springs which had different tensions. These investigations brought full clarification of the forces occurring for an overflowing jet, and thereby offered the possibility of obtaining, by means of certain constructional arrangements, the required dam flap absolutely free from vibration.

The results of these studies have been reviewed by many representatives of Government boards, research institutes, steel construction firms, etc. All were fully convinced. According to the knowledge obtained, the flap vibration was revealed as being an automatic coupled vibration in which three common parts are involved: the flap with its water load, the free jet, and an air cushion under the flap.

By means of the vibrating flap, the free jet becomes rippled with waves which are parallel to the rim of the flap (figures 8 and 9). These waves move and accelerate downward and become larger and more rapid with increasing drop h (figure 9). The range of projection of the jet changes continually.

Positive and negative air-pressure impulses occur alternately when the jet waves meet the tailwater, and by means of the air cushion the impulses are returned to the flap. In this way the vibrations are kept going, but only if they lie in the vicinity of the natural vibration of the flap with the water load and if they occur on the flap in correct

phase. If we interrupt this coupled vibration by a horizontal diaphragm in the air cushion, then no vibrations of the flap occur and no waves form in the free falling jet.

The vibrating flap transfers a certain energy to the jet by means of the lateral acceleration of the water. This energy produces the pressure change in the air cushion and thereby controls the process of vibration. Moreover, the energy loss due to the external resistance (friction, resonance, etc.) must be replaced, so the energy returned to the flap by the air cushion must be increased by this amount. This increase is drawn from the energy increase of the falling water. The air impacts also react on the free movable jet itself; the thinner the jet, the more it acts (figure 10). The size of the air cushion is also important, for the smaller it is the harder are the air impacts, and the more defined is the coupling of the vibration. The movements of the flap increase or decrease--according to the phase in which they coincide with the impacts of the rippled jet--directly with the variation of the air pressure under the flap. This pressure is only slight in a prototype structure because of the small deflection of the flap. In the model, however, the air-pressure variation is considerable, with its proportionately larger deflection. Thus the flap movements again affect the free jet because they produce compressions in the air cushion. Consequently, numerous processes are involved. Extensive tests on existing weirs are, therefore, but slightly suitable for an investigation of the nature of weir vibration, whereas the influence of each variable is more readily determined in the model.

The drop from the headwater to the tailwater has decisive importance in the occurrence of vibration (figure 11). For each flap position and, here again, for each jet thickness (that is, for each discharge) there are, in general, several drop ranges in which vibrations are possible corresponding to the number of waves of the rippled jet. If we pass through a range of vibration by means of a change in drop, then the deflection and rate of vibration of the flap change

approximately according to a resonance curve. The largest vibration deflections occur in the case of the attainment of the natural frequency of the gate with its water load.

The natural frequency decreases with increasing head of overflow, so that the vibrating zone moves toward the side of greatest drop. The relation between drop and frequency within each zone of vibration is fixed by the relation $f\sqrt{H}$ = a constant. In this relation, "f" denotes the frequency and "H" the drop; therefore, a definite frequency belongs to each drop. If the frequency of the flap for a change in drop varies too far from the natural frequency the vibration ceases. The manifold occurrence of regions of vibration for a given discharge is explained by the fact that the free jet possesses several waves on its course of fall from the headwater to the tailwater. If the lower jet waves are cut off completely by the raising of the tailwater (figures 8 and 9), even then coupling conditions are present, and a new vibration zone occurs in which the number of modulating waves is reduced by one. The zones of vibration may be classified into a general valid phase law. If "m" is the number of jet waves and if "k" is a constant, then $f\sqrt{H} = m \cdot k$ (figure 12).

The weir flap can produce two basic vibrations: those due to deflection and those due to torsion. The coupling process is the same for both forms of vibration, only the natural frequency and the vibration zone, are, in general, different from one another. In the case of torsional vibration the deflection at the ends of the flap is the greatest; in the middle of the flap the deflection is zero. By means of the torsion, inertia forces and the frequency are increased. If the natural frequencies of the deflection and torsional vibration lie close to one another, the superimposition of both types occurs.

Previously, the discussion treated existing vibrations. It may now be asked how vibrations arise from a state of rest. In this regard, it may be said that it is a question of an automatic formation. Any shaking

of the gate, a disturbance in the flow, a gust of wind on the jet, or the like, produces even a small natural vibration of the flap. This again changes the projection distance of the falling jet, ripples it, produces air impacts on the air cushion which in turn react upon the flap, and thereby ripples the jet more intensely. This coupling, which is started whenever the drop and natural vibration follows the relation $f \cdot \sqrt{H} = m \cdot k$, requires a certain time before the vibrations are in full progress. For that reason, in the case of rapid changes of jet thickness (lowering of a gate), or in the case of rapid changes of drop (filling a lock), vibrations cannot form.

EXPERIMENTAL RESULTS

The weaker the gate was suspended and the greater became its amplitude of vibration, then the smaller its frequency, the more intensely the falling jet became rippled, and thereby the exciting force of the air impacts on the flap increased. The thicker the jet and the greater are the oppressing water masses co-vibrating with the flap, the less the jet yields to the pressure variations in the air cushion, and the harder they strike the flap, but the flap exhibits greater inertia resistance against deflection because of its co-vibrating water mass. The moment of inertia of the flap itself likewise decreases the tendency for vibration. The greatest deflection occurs, therefore, for a certain drop and ceases for a certain thickness of jet. The amplitude and frequency are a measure of the danger of the structure to failure by fatigue of structural material or settlement of the foundation.

In the case of weir trembling or weir humming, a vibration which rarely occurs in rigid weirs, it is a question of a coupling between the air cushion acting as the spring of the vibrating structure and the freely falling rippled jet acting as the mass. There is developed, therefore, a coupling between the air cushion and the flap with its water load. The audible vibrations are rapid and are caused probably by the air-pressure changes at the point of separation. Since the jet intermittently carries down air from the air cushion, such changes of air pressure are probably conceivable. Even in the model for a rigidly set flap, high tailwater (that is, small air space), and a thick jet, a weir trembling

with violent, rapidly vibrating air-pressure variations could be produced. It is not essential that the flap at either end be in open contact with the outside atmosphere, or be entirely closed off; therefore, the assumed organ pipe vibrations do not appear to be operative. In the prototype they were probably caused by wind which struck obliquely against the pier recesses.

MEANS OF ELIMINATING VIBRATION

After the Research Institute had substantially clarified the mechanical processes of vibration, it was able to proceed with confidence to look for remedies for preventing flap vibration. A disturbance of the vibration process is possible in practice only by affecting the jet and it may be brought about reliably only by formations on the flap. Jet dividers suggested by the Research Institute proved to be a simple and sure method of eliminating vibration whenever they were put in sufficient numbers on the flap. The jet dividers may also prove to be effective against ice formations. The models studied for the Dortmunder Bridge Company and for the MAN (Company) likewise fulfilled the demand for freedom from vibration for all operating conditions.

The model for the Dortmunder Company consisted of a row of teeth with alternate upright and downward bent surfaces placed on the edge of the flap. At the points of impact separation plates projected upwards into the jet (figures 13 and 14). By means of this dentated border, the jet was divided into several strips with varying distances of projection, the separation plates aiding in dividing the jet. The model with separation plates was free from vibration for all operating conditions; in fact, the highest gate position was not free from vibration without them. The shape of the flap and of the deflecting surfaces must be correctly dimensioned so that the jet parts will separate from one another in all flap positions and for all thicknesses of jet.

In the study of the model for the MAN (Company), vibrations were removed by the construction of a so-called "sturgeon back," by means

of which the surface of the flap was placed higher in several sections (figure 15). The dentates of the "sturgeon back" rose the greatest amount at the discharge rim and continually decreased to zero toward the crest of the dam. The width of a dentate was equal to the distance between two dentates, so that half of the flap surface was covered by the construction (figures 15 and 16). The range of projection and thickness of jet was changed by these dentates, and for a sufficient rise of dentate, the model arrangement was completely free from vibration, but the discharge of the flap was reduced because of the dentates. The Research Institute then developed, with the use of small and large dentates an arrangement which obtained freedom from vibration with the least amount of dentates (figures 18 to 21). The surface covered in this case amounted to only one-seventh of the surface required for dentates with spaces between them equal to their width.

Prevention of vibration in this manner also caused an increase of water load on the flap because of the congested rim which, moreover, increased the lifting forces of the wind. Nevertheless, rigid construction of the flap was an advantage because it decreased the deflections and produced a larger moment of inertia.

Further investigations were made to clarify the processes of disturbing vibrations. Fundamental methods were found; the chief one, which concerns all methods of eliminating vibrations, was the dividing of the jet into several independent strips having different ranges of projection. The action of the dividers was not attributed to an equalization of pressure, but was due to the separation of the parts of the jet by changing its shape. The width of the undisturbed parts of the jet were decisive for the formation of vibration. The greater the discharge, the greater can be the spacing of the dividers or dentates, while the number of dentates may be decreased if the spacing toward the center of the flap is increased. The most certain method is a complete separation of the strips by splitting the jet which, without fail,

must be done for small heads of overflow.

The prevention of vibration was not obtained by means of trough-shaped depressions of the flap in the middle of the weir or at several points, even though continuous changes would occur in the jet thickness and distance of projection, because no separated strips could be obtained which would mutually disturb the various factors producing the vibration.

Other explanations of flap vibration have been investigated. Thus the surface tension of the jet was said to be a cause, and without which the mechanism of vibration in no way could be explained; however, this force was able, at the most, to affect appreciably only a thin, skin-like jet. This was borne out by the test of pouring ether, which has a much smaller surface tension compared with air than with water, on a thin jet in order to eliminate vibrations. Another explanation of the starting of jet vibration was sought in the waves which formed in the tailwater on both sides of the falling jet and which occurred under certain conditions in uniform fluctuations. In this case, however, cause was confused with effect. These oscillating waves were unable to impress waves on the falling jet, since the jet is, indeed, not rigid against bending and cannot be deflected by means of shearing forces opposite to the direction of flow. If small vibrations are removed occasionally by sieves placed at the points of impact at the tailwater, then it follows that the sieves supress rocking motions of the tailwater which would aid in the starting of the motion of the flap by means of air impacts.

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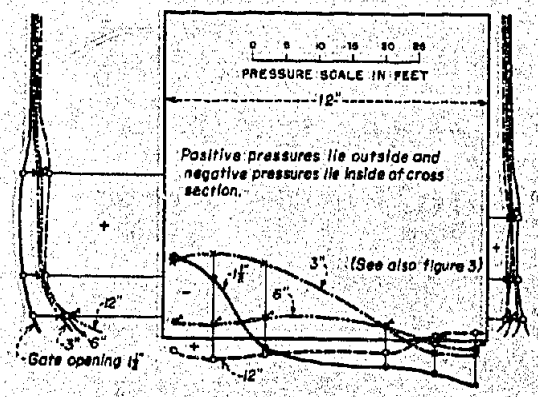


FIGURE 1 - PRESSURE ON SQUARE SEALING BEAM FOR VARIOUS GATE OPENINGS
HEAD = 16.73 FEET MODEL SCALE RATIO 1:3.8

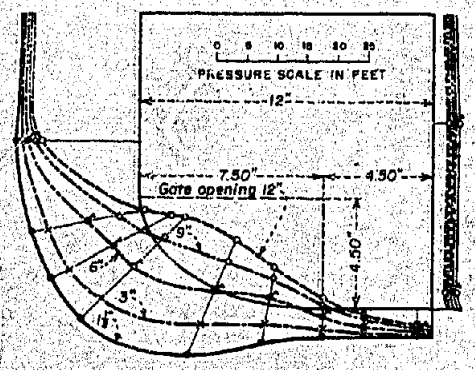


FIGURE 2 - PRESSURE ON ELLIPTICAL SEALING BEAM FOR VARIOUS GATE OPENINGS
HEAD = 16.73 FEET MODEL SCALE RATIO 1:3.8

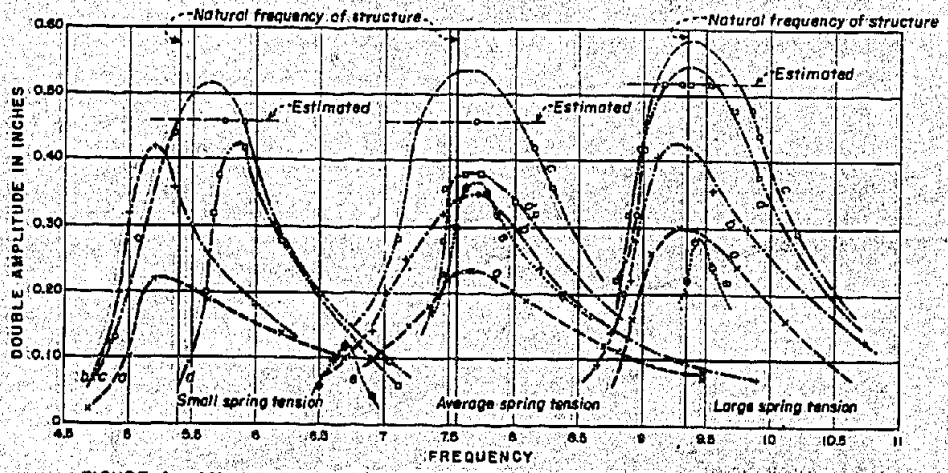


FIGURE 4 - AMPLITUDE VERSUS FREQUENCY FOR DIFFERENT SPRING TENSION WITH SQUARE SEALING BEAM IN MODEL
GATE OPENINGS: a = 3.15"; b = 3.94"; c = 4.72"; d = 5.51"; e = 6.30"

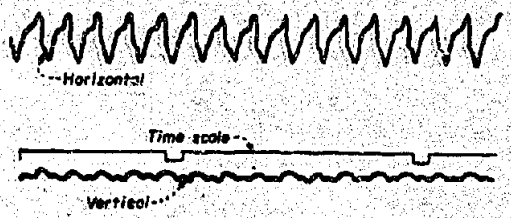


FIGURE 5 - VIBRATION OF AN UNDERFLOW GATE WITH SQUARE SEALING BEAM

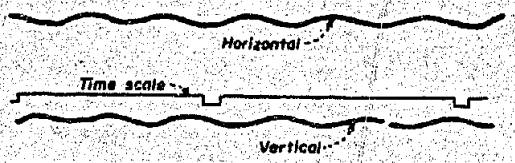


FIGURE 6 - VIBRATION OF AN UNDERFLOW GATE WITH ELLIPTICAL SEALING BEAM

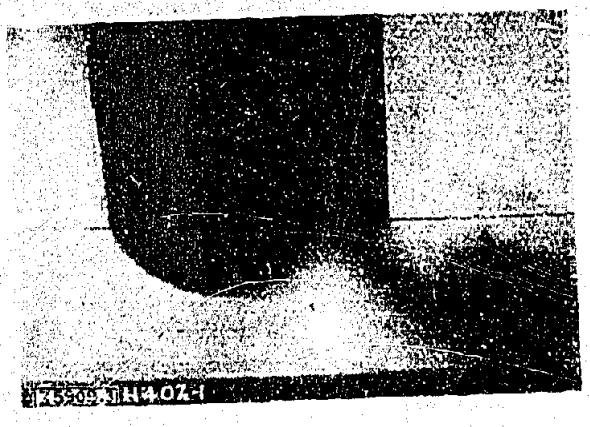


Figure 3 - Flow Pattern for Square
Sealing Beam in Model
(See also Figure 1)

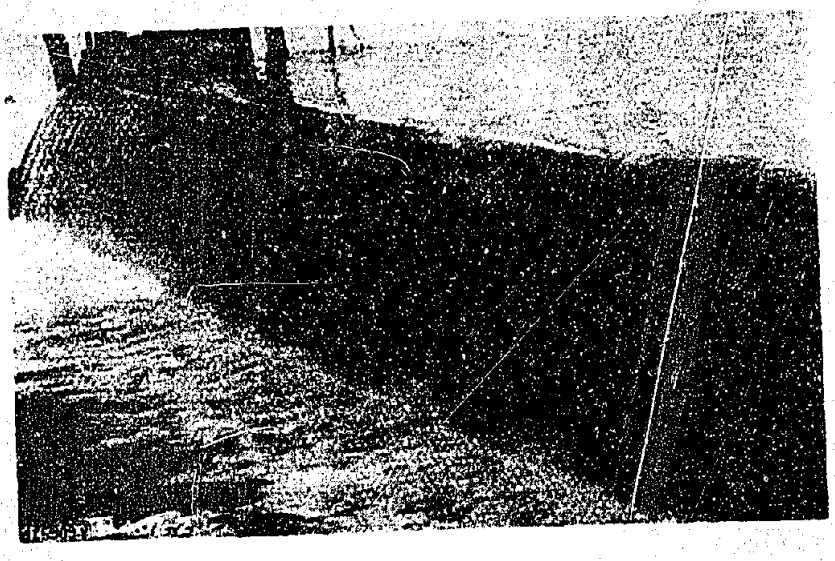


Figure 8 - Vibration for 7.87" Weir Head
(See also Figure 9)

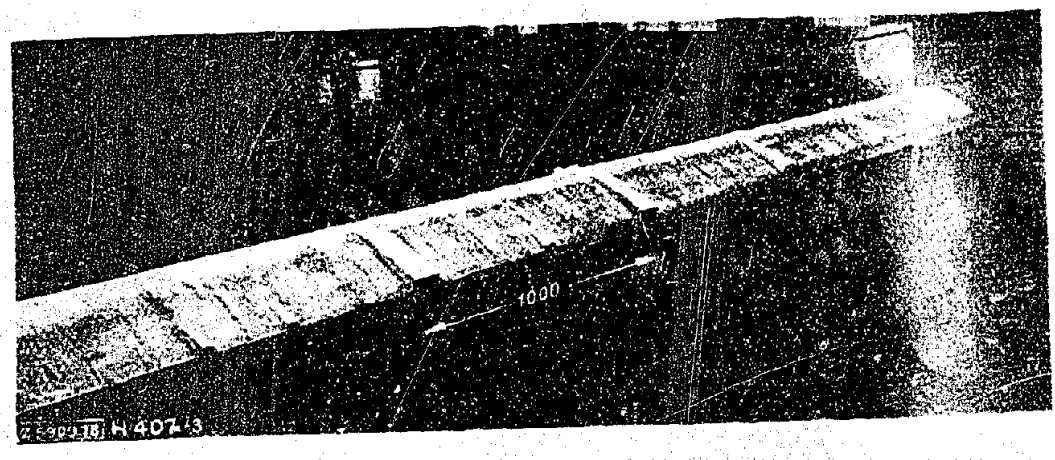


Figure 18 - Back of Flap with Reduced Dentates
(See also Figures 19 to 21)

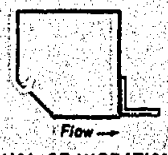


FIGURE 7 - REMOVAL OF VIBRATION WITH ANGLES ON THE DOWNSTREAM FACE OF SEALING BEAM

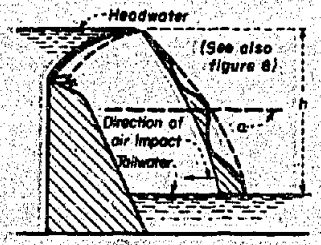


FIGURE 9 - BOUNDARIES OF UNDULATED JET
BY RAISING THE TAILWATER TO LINE "a" A COMPLETE WAVE IS CUT OFF

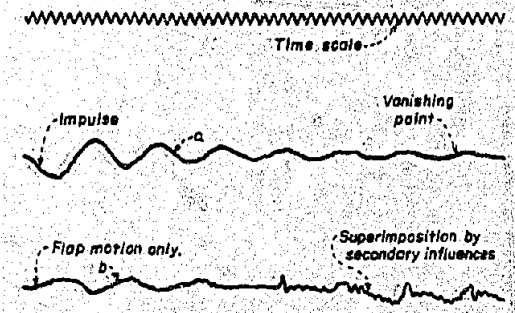


FIGURE 10 - REACTION OF FLAP MOVEMENT "a" ON VARIATION OF AIR PRESSURE "b" UNDER THE JET WITH PHASE DISPLACEMENT
HIGH FLAP POSITION - DISCHARGE 1.55 C.F.S.

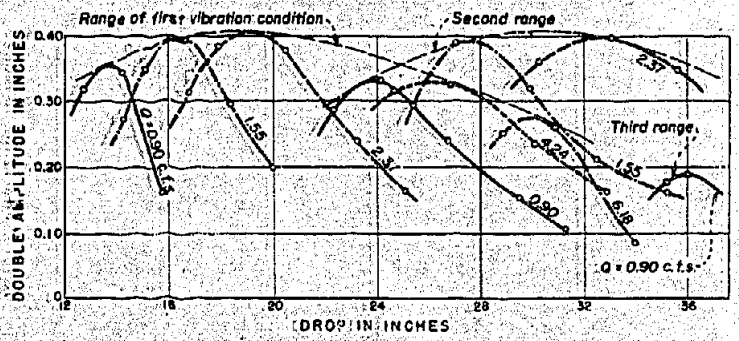


FIGURE 11 - AMPLITUDE VERSUS DROP FOR VARIOUS DISCHARGES
AVERAGE FLAP POSITION, AERATION CLOSED AT BOTH ENDS
MEASUREMENTS TAKEN AT CENTER OF DAM

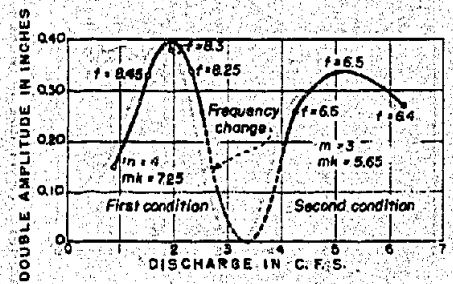


FIGURE 12 - AMPLITUDE VERSUS DISCHARGE
AVERAGE FLAP POSITION, AERATION CLOSED AT BOTH ENDS, DROP = 29.92"
f = FREQUENCY
k = A CONSTANT
m = NUMBER OF JET WAVES FORMED

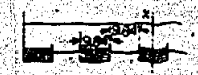


FIGURE 13 - DENTATED FLAP

FIGURE 14 - SECTION X-Y

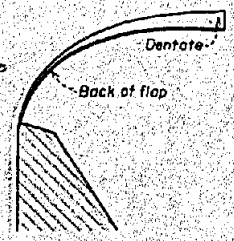
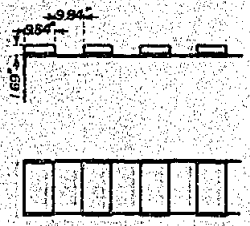
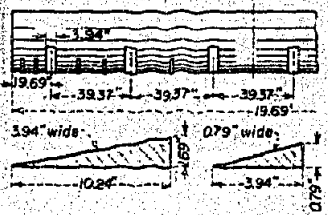


FIGURE 15 - DENTATE ON BACK OF FLAP



FIGURES 16 AND 17 - BACK OF FLAP WITH DENTATES AS IN FIGURE 15



FIGURES 19 TO 21 - DIMENSIONS OF BACK OF FLAP AND DENTATES AS IN FIGURE 18