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CAVITATION DAMAGE IN HYDRAULIC STRUCTURES

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Donald Colgate

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Donald Colgate
Hydraulic Engineer
United States Bureau of Reclamation
Denver, Colorado

INTRODUCTION

Cavitation is a hydrodynamic phenomenon including the inception, growth, and collapse of vapor cavities in a localized area where the dynamic pressure on a liquid has been reduced to the vapor pressure of the liquid. The type of cavitation considered in this writing is that which may be encountered in hydraulic structures and machines. The energy to sustain the vapor cavity is derived from flowing water, and the ambient pressure in the surrounding liquid controls the growth and collapse of the cavity. Cavitation in hydraulic structures is objectionable because the collapsing cavities produce intense noise and vibration, and flow boundaries in the cavity collapse zone are subjected to cavitation damage.[1]

LABORATORY TEST APPARATUS

Cavitation damage to hydraulic structures and machines is always objectionable, and often disastrous. However, a basic evaluation of the cavitation phenomenon cannot be readily made in field installations and must be almost exclusively a laboratory endeavor. The laboratory studies may be broadly divided into three classes:

1. A scale model in which flow boundary pressures are measured and converted to prototype pressures by direct scale ratio computations. When the computed prototype pressures indicate vapor pressure of water has been reached, cavitation is assumed to exist. The vapor cavities never actually form in such a model. These studies result in defining flow boundary shapes with the velocity-pressure limits to prevent the formation of cavitation.
2. A model, or test apparatus, in which a flow boundary shape is subjected to a flow velocity and ambient pressure of the proper magnitude to produce a cavitation cloud. The flow velocity may be quite low, and the ambient pressure very low; cavitation damage may or may not occur. In these tests, the results are generally studied visually. These studies result in defining the hydraulics of the cavitation cloud with respect to velocity and ambient pressure.
3. An apparatus capable of sufficient violence to produce damaging cavitation. The cavitation is forced to exist by any means available and the apparatus is generally operated at peak destructive conditions. These studies result in an evaluation of the comparative resistance to cavitation damage of various construction materials, or of various qualities of a material. Reliable cavitation damage resistance comparisons may be made when the various construction materials are tested in the same apparatus. Great care must be exercised in comparing cavitation damage resistance of construction materials if the various materials have been tested in different test apparatus.

INCIPIENT CAVITATION

At some location in a hydraulic system, a change in flow boundary geometry may cause an abrupt change in liquid flow direction. The reduced pressure in the flowing water resulting from the flow direction change, together with a sufficiently low ambient pressure field, will cause a cavitation "cloud" to form. The cloud will grow and travel with the flowing water to an area where the pressure field will collapse the cloud. Figure 1 shows the cavitation cloud formed during a laboratory study of an abrupt into-the-flow offset. The cloud could be controlled by judicious manipulation of the flow velocity and the ambient pressure. With the apparatus shown, an extensive study was made to determine the velocity-ambient pressure relationship at which incipient, or threshold cavitation existed for various shapes and sizes of into-the-flow offsets.

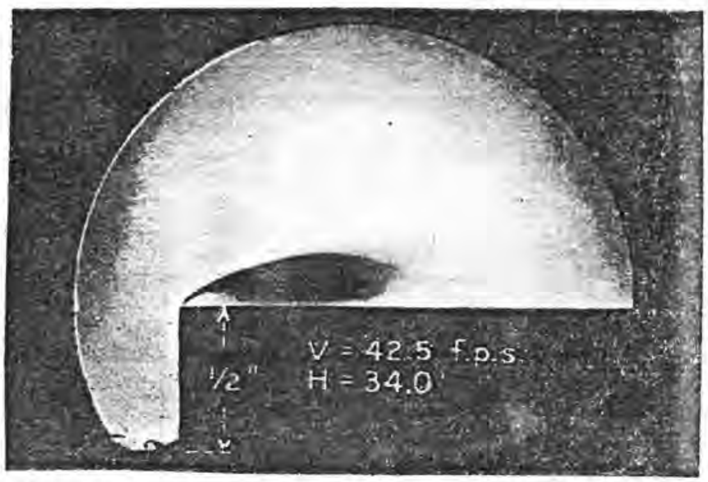

Figure 1 Cavitation Cloud in Test Apparatus. (Damage would occur only below the downstream half of the cloud in the cavity collapse zone.)

[1] The vapor cavities will be referred to as "cavitation" and the resultant flow boundary erosion as "cavitation damage."

A dimensionless parameter, the cavitation index, or sigma, is commonly used to plot or display the results of laboratory studies and describe the presence or state of cavitation. Sigma (σ) is the relationship $\sigma = \dfrac{H_{abs} - H_v}{V_o^2/2g}$ where H_{abs} is the absolute static pressure at some reference point, H_v is the vapor pressure of the liquid, and V_o is a reference velocity. The sigma for incipient cavitation is σ_i. For a specific flow passage or boundary size and shape, a sigma value smaller than the incipient sigma will indicate the existence of cavitation.[2]

Results obtained in the cavitation apparatus have been plotted for design considerations. For example, a simple field method for correcting an into-the-flow surface irregularity is to chamfer the leading edge of the irregularity. Figure 2 is a plot of the recommended chamfer dimensions related to the flow velocity and ambient pressure field. In the event the chamfer has only partially removed the irregularity, as shown in Figure 3, the problem has not been completely solved, merely transferred to a new location.

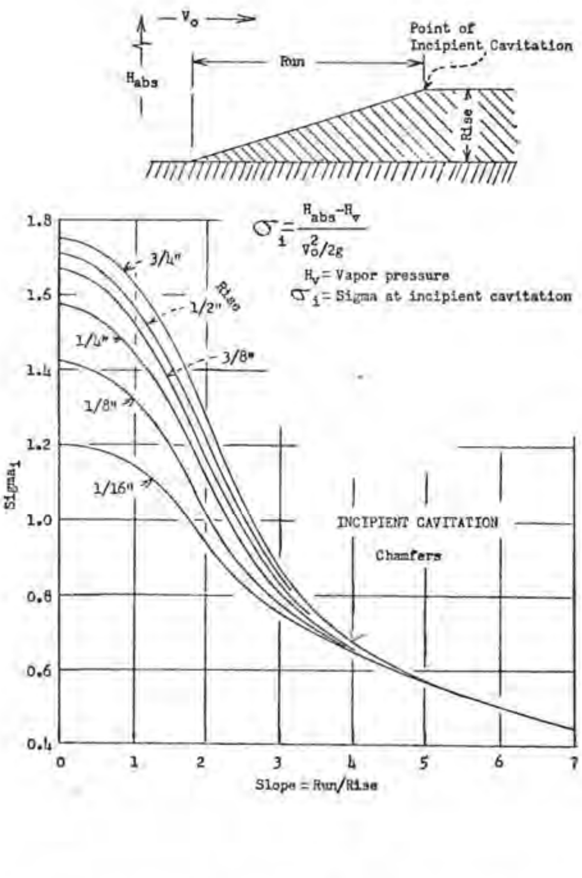

Figure 2 Incipient Cavitation for Chamfers.

[2] The vapor pressure of water in most operating structures is quite small, perhaps slightly more than one percent of the barometric pressure. In many of the charts prepared for field use, H_v in the numerator of the sigma computation has been omitted since it is of little significance.

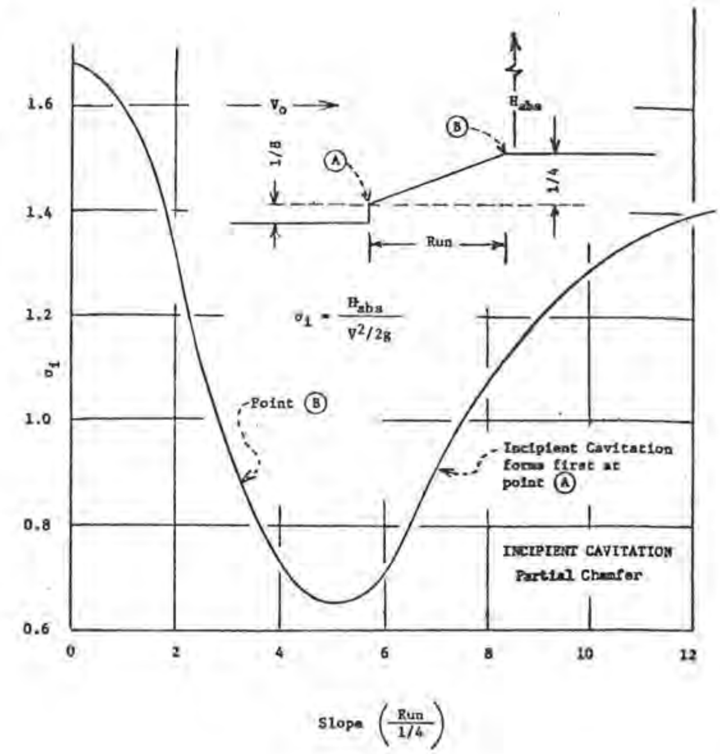

Figure 3 Incipient Cavitation - Incomplete Chamfers.

An into-the-flow offset could be modified by forming an elliptical chamfer on the leading edge as plotted in Figure 4. The elliptical chamfer should be used for rather large surface discontinuities. The elliptical shape shown in Figure 4 could be considered as one-half an elliptical pier nose. The sigma values shown would be applicable for both sides of the pier. (1)[3]

THE CAVITATION CLOUD AND DAMAGE

Before adequate recommendations may be made regarding repair or corrective modifications to hydraulic structures damaged by cavitation, it is necessary to understand the mechanism of the inception, growth and collapse of cavitation, and the mechanics of cavitation damage. Many experimental studies have been made regarding the relationship of flow velocity and cavitation damage. Although various experimenters have suggested a slightly different coefficient, either higher or lower, the average of the results indicates that cavitation damage varies as the sixth power of the velocity. (2) Figure 5 is a plot of the damage variation with the velocity variation. The damage relationship is valid only if the ambient pressure is adjusted to maintain a constant cavitation cloud size as the velocity is varied, and the damage is noted for the same time interval for each experimental test.

[3] Numbers in brackets designate references at the end of the paper.

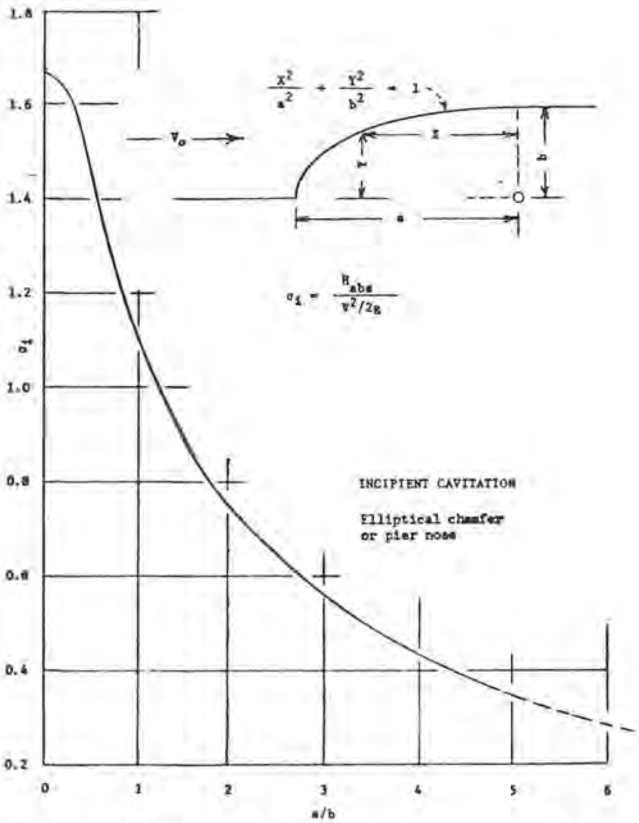

Figure 4 Incipient Cavitation - Elliptical Shapes

Figure 6 is an into-the-flow offset at the intersection between a steel gate frame and a concrete conduit wall downstream. The concrete has suffered cavitation damage. Compare the drawing in Figure 5 with the prototype photo in Figure 6. Note that the leading edge of the offset is undamaged by the impact of the flowing water. The original concrete surface is intact for a small distance downstream from the leading edge of the offset - this is the area under the cavitation cloud upstream from the cavity collapse zone. The depth of the cavitation damage in the cavity collapse area is greater than the height of the offset. If the damage had not been discovered, and the flow had continued, the damaged area would have progressed downstream, but the leading edge of the into-the-flow offset, and the small undamaged surface near the offset, would have remained intact.

Laboratory investigations have been made in which the flow velocity has been held constant and the ambient pressure field varied to produce various sizes of cavitation clouds and various intensities of cavitation damage. The compiled and averaged results determined from a literature survey are shown in Figure 7. An understanding of the concepts of the mechanics of cavitation damage displayed in Figures 5 and 7 will aid in identification and evaluation of the cause of damage found in prototype structures.

DAMAGE RESISTANCE OF CONSTRUCTION MATERIALS

All construction materials are susceptible to cavitation damage. The damaging action is undoubtedly one of high intensity mechanical blows in the area of cavity collapse. The resistance to cavitation damage of a few construction materials has been evaluated and is plotted in Figures 8 and 9.

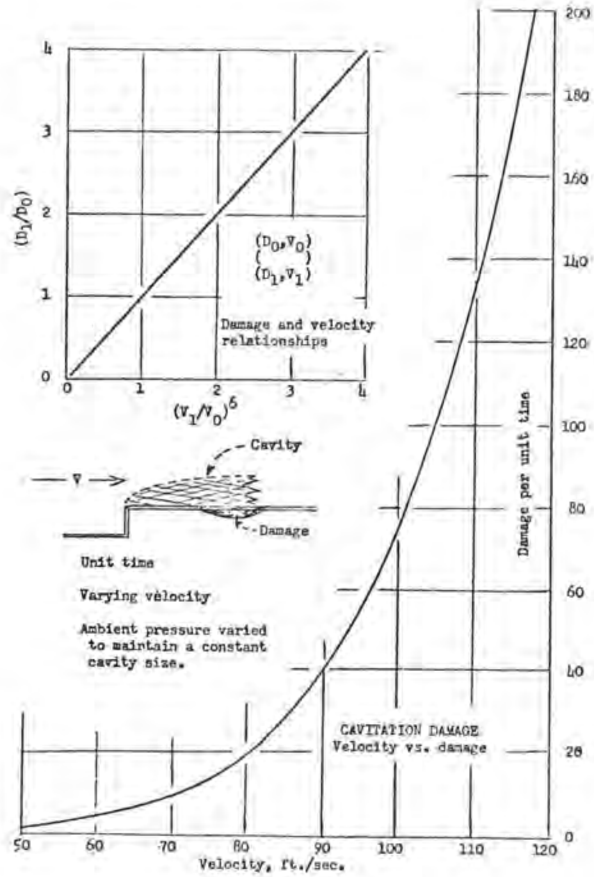

Figure 5 Cavitation Damage with Respect to Velocity.

The laboratory investigations leading to the three identified points in Figure 8 were observed by the author. The two charts were drawn by applying the knowledge of cavitation damage displayed in Figures 5 and 7 to the investigated test values.

The values for the three construction materials - carbon steel, aluminum, and copper - were deduced by comparing the cavitation damage rate of these materials to the stainless steel damage rate as tabulated in the myriad tests in reference (2). Each of the construction materials shown display a large variation in resistance to cavitation damage. "Concrete," for example, may be prepared in many different ways, resulting in a wide range of qualities. The values shown in Figures 8 and 9 must be considered average for an ordinary structural grade concrete without special additives or special placement. All "stainless steel" is relatively highly resistant to cavitation damage; however, "stainless steel" is a name applied to a family of steels with differing qualities. The stainless steel noted in Figures 8 and 9 was labeled "18-8 stainless."

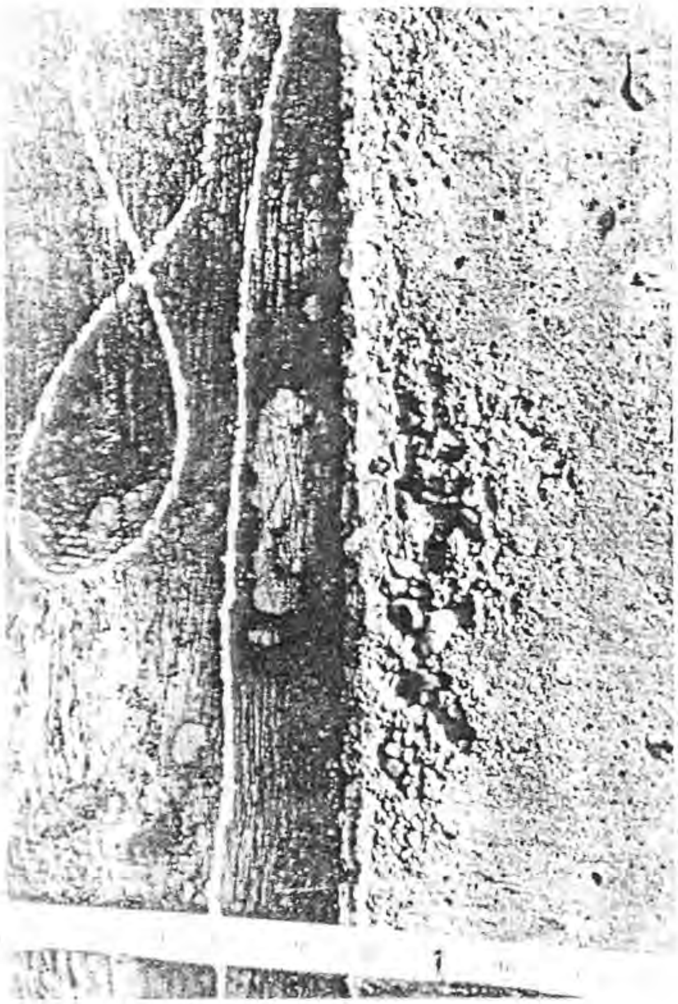

Figure 6 Cavitation Damage Caused by an Into-The-Flow Offset. (Intersection between a steel gate liner and the concrete conduit wall downstream. Flow is from left to right.)

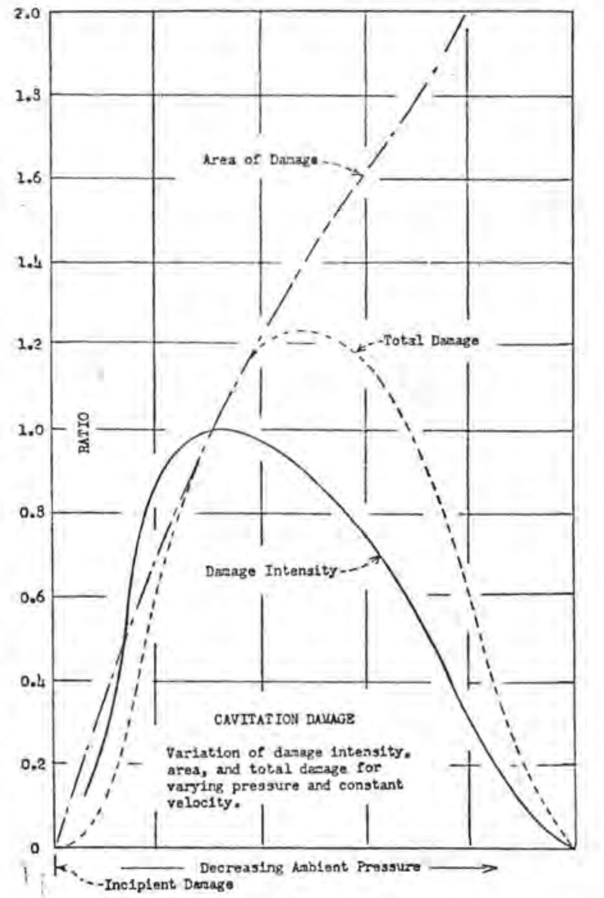

Figure 7 Cavitation Damage with Respect to Ambient Pressure.

IDENTIFICATION OF DAMAGE

A determination of the cause of damage to a prototype structure must be made before repair or corrective modifications are undertaken. Damage to hydraulic structures could be caused by a single force or a combination of forces such as abrasion by solids, freeze-thaw cycle damage, inferior construction material failure, fatigue or rupture from cyclic forces originating either internally or externally, cavitation, jet action, and others.

Some of the clues which should be considered to identify damage as cavitation damage include:

1. Flow velocity. Low flow velocities will not form damaging cavitation.
2. Upstream flow-surface, surface irregularities. For example, an offset as seen in Figure 6, could "trigger" cavitation.
3. Location. Cavitation damage and the assumed source of the cavitation must be in the proper relationship to each other. In Figure 6, the cavitation damage is directly downstream, but near the offset. The cavitation causing isolated damaged areas may

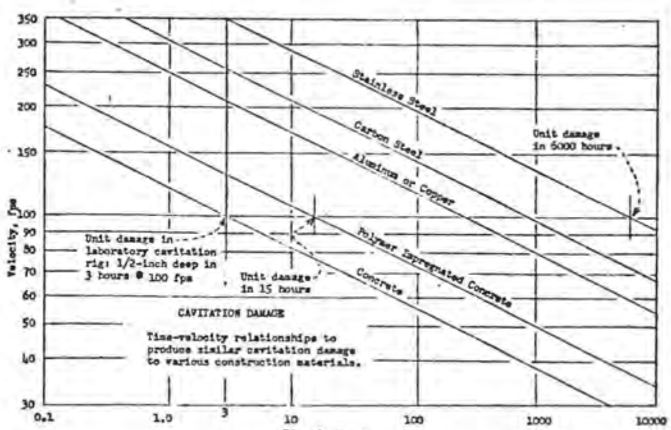

Figure 8 Unit Cavitation Damage of Construction Materials. (Ambient pressure adjusted to maintain a constant cavity size.)

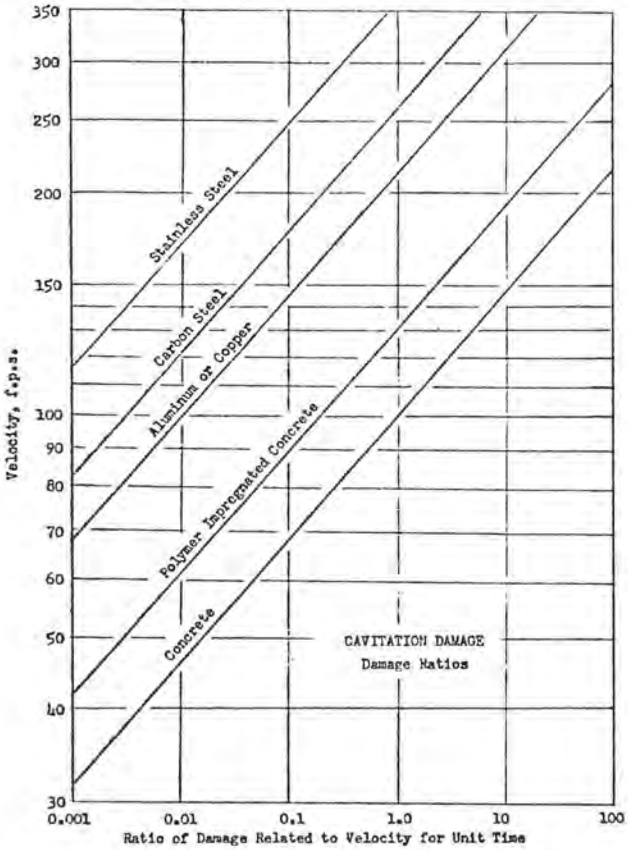

Figure 9 Rate of Cavitation Damage of Construction Materials Related to Flow Velocity. (Ambient pressure adjusted to maintain a constant cavity size.)

generally be traced to some inadvertent surface irregularity.

4. Flow passage shape. An abrupt change in flow direction, such as the right angled leading edge of the baffle pier in Figure 10, could produce cavitation pressures. The concrete removal on the side of the pier is obviously cavitation damage, and the damage location indicates that the leading corner of the pier caused the cavitation.
5. Similarity of damage in adjacent similar flow passages. Similar pier side damage, as shown in Figure 10, occurred on both sides of all piers in the basin. Adjacent uniform damaged areas as shown in Figure 11, may be assumed to be caused by flow passage design configuration.
6. Texture of damaged area. The damaging forces of cavitation occur in such a manner that fluid flow direction cannot be determined by a study of the texture of the damaged area. Figure 12 shows a damaged stainless steel butterfly valve which had been subjected to high velocity flow. Initial opinion was that the valve had been destroyed by cavitation. However, by gently

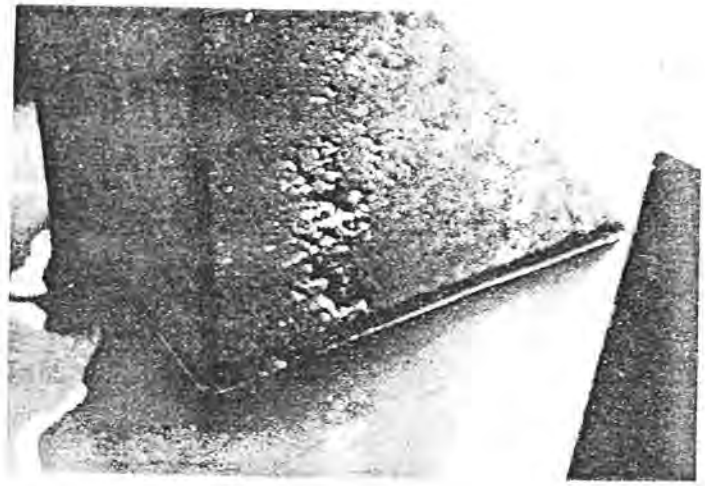

Figure 10 Cavitation Damage on the Side of a Concrete Baffle Block.

Figure 11 Cavitation Damage on a Chute Floor Downstream from Each of Two High Pressure Slide Gates. (Note: Each pocket of cavitation damage becomes a new source of cavitation which damages an area further downstream, causing the cascade appearance of the total damaged area.)

moving the palm of the hand across the damaged surface, the flow direction could be immediately determined. With hand movement in the direction of flow the surface felt relatively smooth, but points, burrs, and needles directed downstream prevented hand rubbing in the upstream direction. The damage was apparently caused by solid particle abrasion. The same type of test could be made on any damaged area for a determination of abrasion damage.

7. Catastrophic damage. In an area of damage of catastrophic proportions as shown in Figure 13, the total damage would be the result of many and varied forces. The major portion of the materials removed was

undoubtedly the result of jet action. However, the origin of the damage shown was caused by cavitation. A surface irregularity, still intact at the time of the photo, and the beginning cavitation damage, was visible at the upstream end of the damaged area. The examination for cavitation in this type of destruction would be only at the upstream extremity of the damaged area.

RECOMMENDATIONS FOR REPAIR

Repair or modification recommendations to prevent cavitation damage would depend on an evaluation of the cause and intensity of the cavitation. Future damage similar to that shown in Figures 6 and 13 could be prevented by removal of the inadvertant surface irregularities which caused the initial cavitation. Great care should be exercised in the repair to achieve a surface alignment within specified tolerances.

The recommended corrective action for the baffle block in Figure 10 would depend on the velocities involved. The block shown was subjected to a mild cavitation at relatively low velocities. The repair recommended was to retain the preliminary shape, but to repair the sides of the block with some construction material more resistant to cavitation erosion than the base concrete, which had been damaged. In a setting subjected to higher velocities, a change

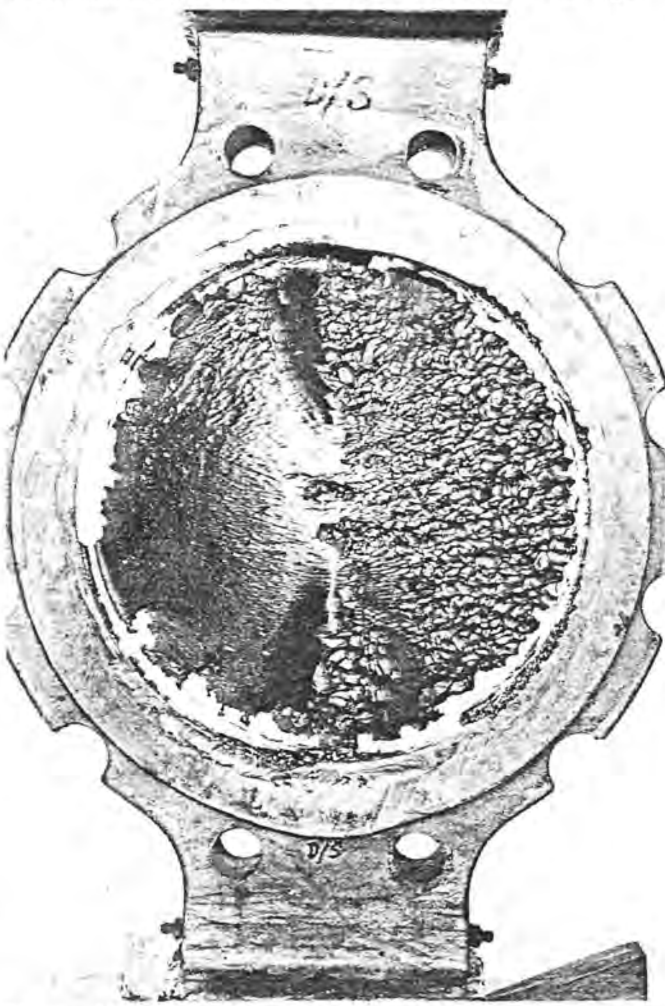

Figure 12 Stainless Steel Butterfly Valve Damaged by Abrasion.

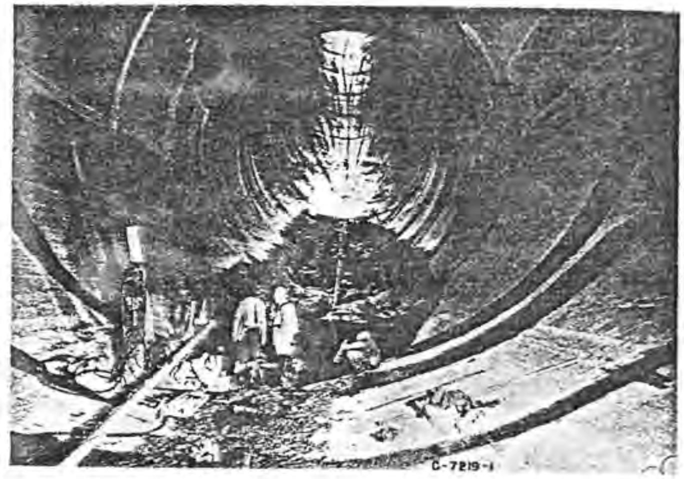

Figure 13 Catastrophic Damage in a Concrete-Lined Spillway Tunnel. Cavitation was the Initial Damaging Force.

of shape to streamline the block might be required. This later corrective measure must include a redesign of the baffle block since streamlining would reduce the efficiency of the intended purpose of the baffle block.

The cavitation which resulted in the damage shown in Figure 11 originated in the upstream conduit. Any shape modification would be difficult and very costly. The recommended corrective procedures were to repair the damaged areas to the original specified alignment, and to install a device upstream from the damaged area which would allow for the insufflation of air into the flowing water. Cavitation would still tend to form, but the presence of air in the collapsing cavity zone would cushion the damaging actions of the cavity collapse.

CONCLUSIONS

Infallible rules have not yet been defined for design and construction to eliminate the danger of cavitation in hydraulic structures and machines subjected to high velocity flow. This paper has presented general comments for use by laymen in the application of the results of laboratory investigations to the identification of cavitation damage. The application of the concepts presented here should aid the inspector of a damaged prototype structure to determine the cause of the damage and to recommend modifications or repairs which would allow the structure to operate in a trouble-free manner.

REFERENCES

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(2) Knapp, R. T., Daily, J. W., and Hammitt, F., "Cavitation", Engineering Societies Monographs, McGraw-Hill Book Company, 1970.