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PREVENTION OF CAVITATION ON CHUTES AND SPILLWAYS

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Abstract

Cavitation damage in hydraulic structures is a function of the cavitation potential, the duration of the operation, the boundary roughness and alignment, and the strength of the materials from which the boundary is constructed. a method of locating sites of cavitation damage in spillways is presented. Curves delineating damage as a function of the cavitation potential and the duration of operation are given. The curves allow a determination of areas in which attention to surface tolerances can protect the boundary. In addition, they can be used to define when aeration grooves must be used. Some methods of preventing cavitation damage, other than aeration grooves, are discussed. The flow conditions which dictate the various cavitation preventation methods are delineated.

Introduction

The problem of damage by cavitation is not a new experience in the Bureau. As early as 1915, cavitation was producing maintenance problems in outlet works. The first major damage in spillways occurred in 1941. After four months of operation through the Arizona spillway tunnel of Hoover Dam, a large hole developed in the concrete lining. The hole was 34-m long, 19-m wide, and it had a maximum depth of 11-m. At the time, cavitation was only one of six possible causes conjectured as the reason for the damage (1). We now know that cavitation was the significant contributor to the damage.

In 1945 hydraulic model studies were performed on the Hoover Dam spillway to determine if an aeration groove could be used to protect the flow surface (2). It was concluded that the aereation devices would not be effective because the grooves either filled with water or the air apparently did not remain near the flow surface. In retrospect, the model scale was too small (1:60) to give accurate estimates

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of air flow properties. In 1953, research studies in a cavitation erosion facility showed that extremely small amounts of air in the flow would significantly reduce the cavitation caused damage (3). The first application of this idea came in 1960 when damage to the low level outlet works of Grand Coulee Dam was eliminated through the use of aeration grooves. Following severe damage to the tunnel spillway at Yellowtail Dam in 1967, an aeration groove successfully eliminated all further damage to the structure (4). Since 1975 aeration grooves have been installed on other outlet works and spillways. Designs based upon past experience may not always be successful because of differing flow conditions. Therefore, a method of investigating the placement of aeration grooves was needed.

The purpose of this paper is to describe the results of a method of investigating the cavitation damage potential in spillways and high velocity chutes. The method is based upon a dimensionless number which describes the formation of cavitation. The damage potential was evaluated using observations from field structures. The study has permitted the development of criteria which indicates when adherance to surface tolerances will protect the spillway, when changes to the design are necessary, when aeration grooves are necessary, and when the design must be abandonded.

Location of Cavitation Inception

In the past the potential for cavitation damage was evaluated by considering only the flow velocity. For instance, a common rule of thumb states that cavitation will occur for velocities exceeding 10 m/s. This rule neglects the effect of the pressure at the boundary and cannot explain the apparent anomolous appearance of severe damage downstream of vertical bends. A much better indicator of the potential for cavitation inception is the cavitation index

$$K = (p_0 - p_v)/(\rho V^2/2) \tag{1}$$

In this equation, the reference pressure is the piezometric pressure at the boundary. On steep slopes the value of the piezometric pressure relative to the flow depth is given by

$$p_0/\gamma = d \cos\theta \tag{2}$$

In vertical bends, the piezometric pressure can be approximated by the addition of centrifugal force term (in addition to the slope correction). Assuming rotational flow the expression is

$$p_0/\gamma = d \cos\theta + (d/g)(V^2/r) \tag{3}$$

The cavitation index for the flow surface can be calculated for any chute or tunnel spillway using a standard backwater computation with the appropriate piezometric pressures being substituted for the flow depth.

After the flow cavitation indices are calculated for the entire chute and a wide range of flow rates, the values are compared with the cavitation potential of typical isolated roughness elements. For example the cavitation potential of a 90-degree into-the-flow offset is about 1.8 considering a blunt velocity profile. If the flow index is less than 1.8 cavitation will occur. The cavitation index of a triangular element with a vertical upstream face considering the boundary layer thickness is given by (5)

$$\sigma = 0.152 (h/\delta)^{0.361} (V/\nu)^{0.196} \qquad (4)$$

For uniformly rough surfaces the boundary cavitation index is given by

$$\sigma = 16\ C = 16 \tau / (\rho V^2/2) \qquad (5)$$

Other roughness elements have similar expressions for the cavitation potential.

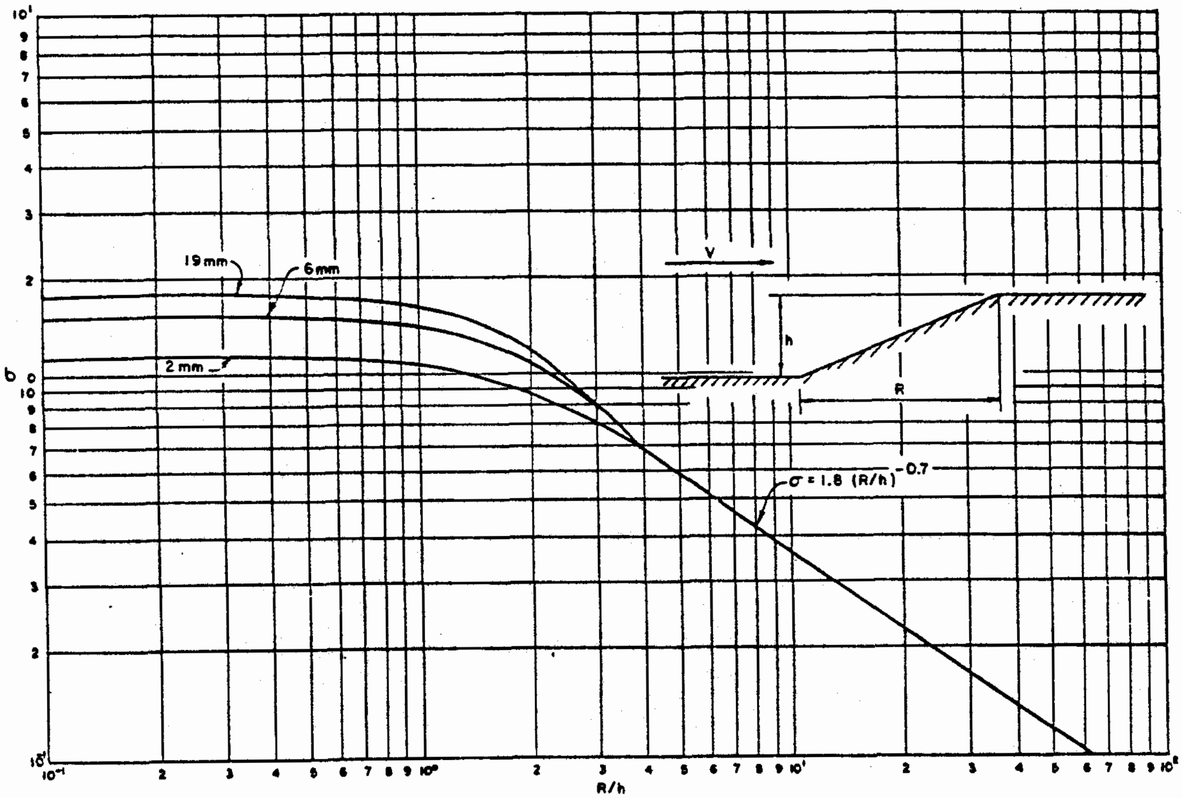

Figure 1. Incipient Cavitation Index of Into-the-flow Chamfers

The boundary cavitation index has the same form as equation (1). Cavitation will occur when the flow cavitation index is less than or equal to the boundary cavitation index.

Often it is desirable to know how to grind off sudden offsets on a flow surface to eliminate the potential for cavitation inception. Studies of the cavitation potential of chamfers give this type of information (6), (7), figure 1. To use the figure, the flow cavitation index K is set equal to the boundary index and the corresponding chamfer is read. An example of the results for the Glen Canyon Dam spillway tunnels is given in figure 2. The characteristics of two field tests and the projected characteristics of three other flow rates are shown. It should be noted that the two most critical flow rates are 340 m /s and 990 m /s. The maximum design flow represents a less critical case. In figure 2, the required chamfer should be interpreted as the chamfer which is needed to eliminate cavitation. It can be seen that chamfers up to 1:50 are required. In practice a 1:20 chamfer is the maximum that can be constructed.

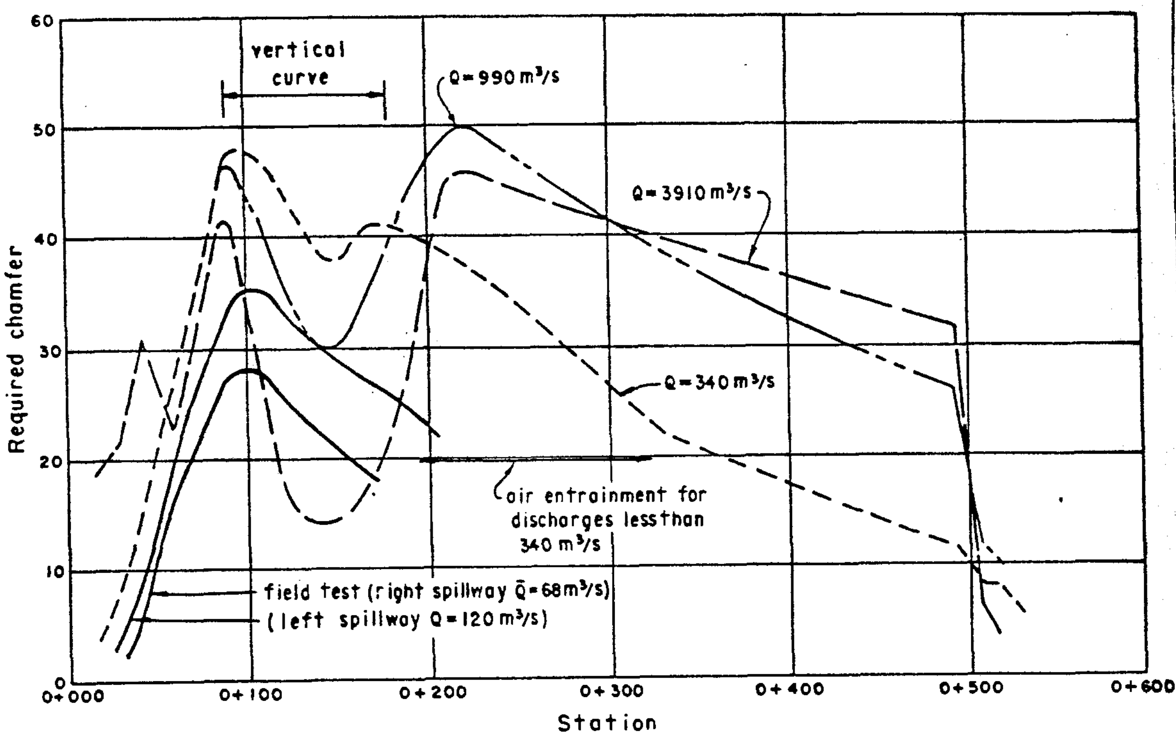

Figure 2. Incipient Cavitation Index of the Glen Canyon Dam Spillway Tunnels

Cavitation Damage Potential

The location of cavitation inception is of interest, but the more important factor is the location at which damage will begin. The location of the damage is a function of the cavitation potential, the material from which the surface is constructed and the duration of operation. The location at which damage starts can only be determined by prototype observations. Unfortunately for the cavitation studies, spillways do not operate very often. The available data from five Bureau tunnel spillways and two foreign chute spillways indicate a relative good correlation between the flow cavitation index and the time of operation, figure 3.

Since all of the spillways are made of about the same strength of concrete, the curves can be applied to other spillways and chutes. In the curves, major damage is defined as damage which produced cavities in the flow surface deeper than 1 m. Incipient damage is refers to cavities that require special care to detect. Minor damage lies between these extremes.

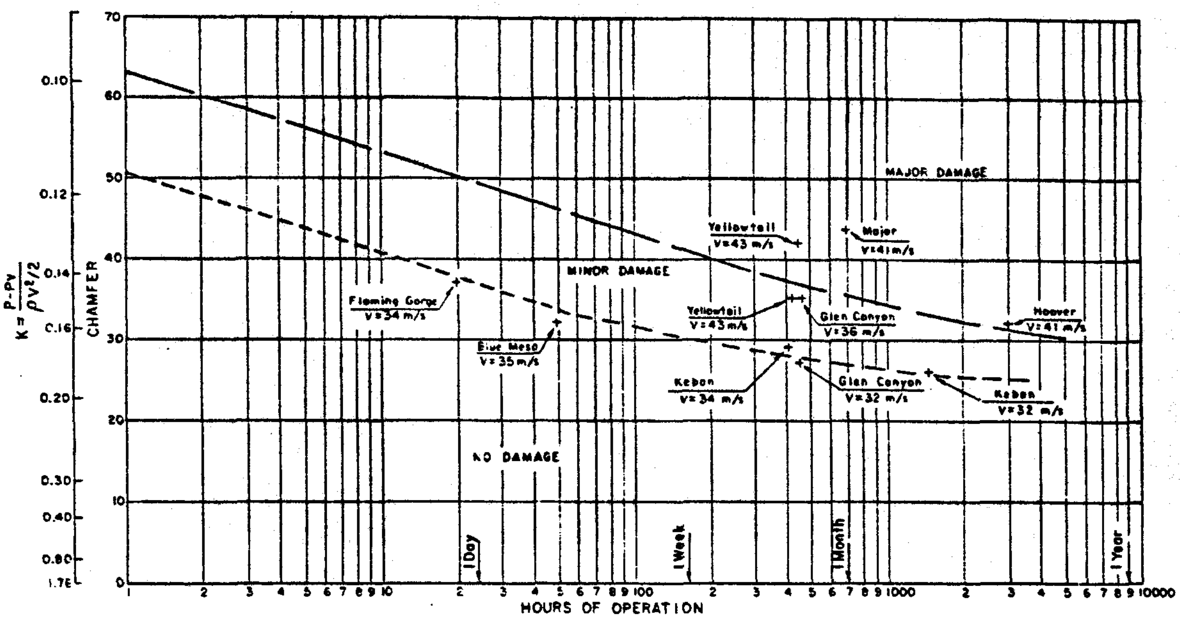

Figure 3. Cavitation Damage in Spillways and Chutes

Cavitation Damage Prevention Criteria

The observations of damage in the field and practical construction constraints indicate criteria which can be used to prevent damage on chutes and spillways. These criteria are based on the flow cavitation index.

For flow cavitation indices greater than 1.80, no flow surface protection is required.

For flow cavitation indices greater than 0.25, the flow surface can be protected by flow surface treatment. In this range, all surface roughnesses should be ground to the chamfers indicated by figure 1.

For flow cavitation indices between 0.17 and 0.25, the flow surface can be protected by modifying the design. One method of changing the design is to increase the curvature of the boundary.

For flow cavitation indices between 0.12 and 0.17, the flow surface can be protected through the addition of aeration grooves or steps. If the design cannot be modified then this limit should be from 0.12 to 0.25.

For flow cavitation indices less than 0.12, the surface probably cannot be protected and a different configuration is indicated. For instance, a tunnel spillway should be changed to a plunge pool, etc.

Notation

d = water depth measured normal to flow surface
g = gravitational acceleration
h = height of offset
p = reference pressure
p = vapor pressure of water
r = radius of curvature of boundary
C = skin friction coefficient
K = flow cavitation index
V = mean velocity
δ = boundary layer thickness
ν = kinematic viscosity
σ = incipient cavitation index for isolated roughness
τ = wall shear
ρ = water density
θ = angle of invert with horizontal
γ = specific force of water

References

1. Warnock, J.E., Experiences of the Bureau of Reclamation, Cavitation in Hydraulic Structures - A Symposium, Proceedings American Society of Civil Engineers, vol 71, No. 7, Sep 1945

2. Bradley, J.N., A Study of Air Injection Into the Flow in the Boulder Dam Spillway Tunnels - Boulder Canyon Project, Bureau of Reclamation, Division of Research, Report No. 186, Oct 1945

3. Peterka, A.J., The Effect of Entrained Air in Cavitation Pitting, International Association for Hydraulic Research Minneapolis, Minn, Aug 1953

4. Borden, R.C., Colgate, D., Legas, J., Selander, C.E., Documentation of Operation, Damage, Repair, and Testing of Yellowtail Dam Spillway, Bureau of Reclamtion, Report No. REC-ERC-71-23, May 1971

5. Arndt, R.E.A., Hall, J.W.,Bohn, J.C., Bechtel, W.T., Influence of Surface Irregularities on Cavitation Performance, Journal of Ship Research, Vol 23, Sep, 1979

6. Colgate, D., Cavitation Damage in Hydraulic Structures, International Conference on Wear of Materials, St. Louis, Mo., Apr 1977

7. Jin, T., Lin, C, Liu, X., Cavitation Inception of Gate Slots, Department of Hydraulic Water Conservancy and Hydro-electric Power, Scientific Research Institute, Beijing, China, 1980

Key Words:

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