Report on the Erosion of Concrete in Hydraulic Structures

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This report outlines the causes, control, maintenance, and repair of erosion in hydraulic structures. Such erosion occurs from three major causes: cavitation, abrasion, and chemical attack. Design parameters, materials selection and quality, environmental factors, and other issues affecting the performance of concrete are discussed.

Evidence exists to suggest that, given the operating characteristics and conditions to which a hydraulic structure will be subjected, the concrete can be designed to mitigate future erosion. However, when operational factors change or are not clearly known and erosion of concrete surfaces occurs, repairs should follow. This report addresses the subject of concrete erosion, inspection techniques, and repair strategies, providing references to a more detailed treatment of the subject.

Keywords: abrasion; aeration; cavitation; chemical attack; concrete dams; corrosion; erosion; hydraulic structures; spillways.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Erosion is the progressive disintegration of a solid by: 1) cavitation; 2) abrasion; or 3) chemical action. Although concrete deteriorates for a variety of reasons, this report is concerned with specific factors that influence these three areas of erosion: 1) cavitation-erosion resulting from the collapse of vapor bubbles formed by pressure changes within a high-velocity water flow; 2) abrasion-erosion of concrete in hydraulic structures caused by water-transported silt, sand, gravel, ice, debris, or hydraulic jacking; and 3) chemical action-disintegration of the concrete in hydraulic structures by chemical attack.

Concrete in properly designed, constructed, used, and maintained hydraulic structures can provide 30 to 50 years of erosion-free service (Liu and Wang 2000). However, for reasons including inadequate design or construction, or operational and environmental changes, erosion does occur in hydraulic structures.

1.2—Scope

Concrete erosion in hydraulic structures caused by cavitation, abrasion, and chemical attack are included in this report. Options available to the designer and user to control concrete erosion in hydraulic structures are discussed, along with information on the inspection and evaluation of erosion problems. This report includes repair techniques, as well as a brief guide to methods and materials for repair. Other types of concrete deterioration are outside the scope of this report.

CHAPTER 2—NOTATION

2.1—Notation

F = force
l = length of air space between the jet and the spillway floor, ℓ (ℓ = length)
p = water pressure at a given point, F/ℓ^2
p_0 = absolute pressure at a given Point 0, F/ℓ^2
p_c = absolute pressure at a given Point c, F/ℓ^2
p_v = vapor pressure of water, F/ℓ^2
q_a = volume rate of air entrainment per unit width of jet, ℓ^3/T
q_d = amount of air a turbulent jet will entrain along its lower surface, ℓ^3/T
T = time
v = average jet velocity at midpoint of trajectory, ℓ/T
v_0 = average velocity at Section 0, ℓ/T
Y_0 = offset into the flow, ℓ
z_0 = elevation at centerline of pipe, ℓ
z_c = elevation of the vapor bubble, ℓ
α = width of jet coefficient based on turbulent intensity of the jet
Δp = change in pressure between two points, F/ℓ^2
γ = specific weight of water, F/ℓ^3 (62.4 lb/ft^3 [9.81 kN/m^3], temperature-dependent
ρ = mass density of water, FT^2/ℓ^4 (1.94 $\text{lb}\cdot\text{s}^2/\text{ft}^4$ [1000 kg/m^3], temperature-dependent)
σ = cavitation index
σ_c = value of cavitation index at which cavitation initiates

CHAPTER 3—EROSION BY CAVITATION

3.1—Mechanism of cavitation

Cavitation is the formation of bubbles or cavities in a liquid. In hydraulic structures, the liquid is water, and the cavities are filled with water vapor and air. The cavities form where the local pressure drops to a value that will cause the water to vaporize at the prevailing fluid temperature. Figure 3.1a shows examples of concrete surface irregularities that can trigger formation of these cavities. The pressure drop caused by these irregularities is generally abrupt and is caused by local high velocities and curved streamlines. Cavities often begin to form near curves or offsets in a flow boundary or at the centers of vortexes.

When the geometry of flow boundaries causes streamlines to curve or converge, the pressure may drop in the direction toward the center of curvature or in the direction along the converging streamlines. For example, Fig. 3.1b shows a tunnel contraction in which a cloud of cavities could start to form at Point (c) and then collapse at Point (d). The velocity near Point (c) is much higher than the average velocity in the tunnel upstream, and the streamlines near Point (c) are curved. Thus, for proper values of flow rate and tunnel pressure at Point (0), the local pressure near Point (c) drops to the vapor pressure of water and cavities will occur. Cavitation damage is produced when the vapor cavities collapse. The collapses that occur near Point (d) produce high instantaneous pressures that impact on the boundary surfaces and cause pitting, noise, and vibration. Pitting by cavitation is readily distinguished from the worn appearance caused by abrasion because cavitation pits cut around the harder coarse aggregate particles and have irregular and rough edges.

3.2—Cavitation index

The cavitation index is a dimensionless measure used to characterize the susceptibility of a system to cavitate. Figure 3.2 illustrates the design principle of the cavitation index in a tunnel contraction. In such a system, the critical location (or point) for cavitation is at Point (c) (Fig. 3.1b).

The static fluid pressure, where the velocity is essentially the same as the approach velocity, at Point (1) will be

$$p_1 = p_c + \gamma(z_c - z_0) \qquad (3.2a)$$

where p_c is the absolute static pressure at Point (c); γ is the specific weight of the fluid (weight per unit volume); z_c is the elevation at Point (c); and z_0 is the elevation at Point (0).

The pressure drop in the fluid as it moves along a streamline from the reference Point (0) to Point (1) will be

$$\Delta p = p_0 - [p_c + \gamma(z_c - z_0)] \qquad (3.2b)$$

where p_0 is the static pressure at Point (0).

The cavitation index normalizes this pressure drop to the dynamic pressure. Dynamic pressure is the difference between the total pressure (pressure at the point of stagnation) and the static pressure, $1/2\rho v_0^2$ (Eq. (3.2b)).

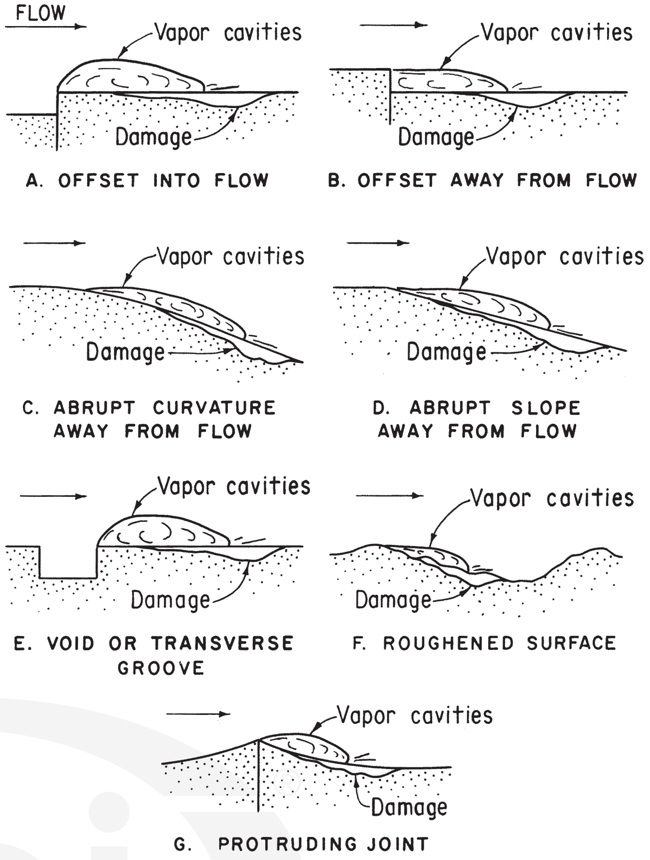

Fig. 3.1a—Cavitation situations at surface irregularities (Falvey 1990).

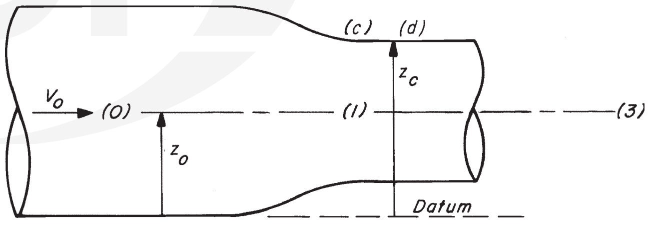

Fig. 3.1b—Tunnel contraction.

$$\sigma = \frac{p_0 - [p_c + \gamma(z_c - z_0)]}{1/2\rho v_0^2} \qquad (3.2c)$$

where ρ is the density of the fluid (mass per unit volume), and v_0 is the fluid velocity at Point (0).

Readers familiar with the field of fluid mechanics may recognize the cavitation index as a special form of the Euler number or pressure coefficient, a matter discussed in Rouse (1978).

If cavitation is just beginning and there is a bubble of vapor at Point (c), the pressure in the fluid adjacent to the bubble is approximately the pressure within the bubble, which is the vapor pressure p_v of the fluid at the fluid's temperature.

Therefore, the pressure drop along the flow from Point (0) to (1) required to produce cavitation at the crown is

$$\Delta p = p_v - [p_c + \gamma(z_c - z_0)]$$