

# 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, it can be designed to mitigate future erosion of the concrete. However, operational factors change or are not clearly known and hence erosion of concrete surfaces occurs and repairs must follow. This report briefly treats the subject of concrete erosion and repair and provides numerous references to detailed treatment of the subject.*

**Keywords:** abrasion; abrasion resistance; aeration; cavitation; chemical attack concrete dams; concrete pipes; corrosion; corrosion resistance; deterioration; erosion; grinding (material removal); high-strength concretes; **hydraulic structures**; maintenance; penstocks; pipe linings; pipes (tubes); pitting polymer concrete; renovating; repairs; **spillways**; tolerances (mechanics); wear.

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ACI 210R-93 supersedes ACI 210R-87 and became effective September 1, 1993. Minor revisions have been made to the report. Year designations have been removed from recommended references to make the current edition the referenced version.

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### PART I-CAUSES OF EROSION

#### CHAPTER 1-INTRODUCTION

Erosion is defined in this report as the progressive disintegration of a solid by cavitation, abrasion, or chemical action. This report is concerned with: 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, or debris; and 3) disintegration of the concrete in hydraulic structures by chemical attack. Other types of concrete deterioration are outside the scope of this report.

Ordinarily, concrete in properly designed, constructed, used, and maintained hydraulic structures will undergo years of erosion-free service. However, for a variety of reasons including inadequate design or construction, or operational and environmental changes, erosion does occur in hydraulic structures. This report deals with three major aspects of such concrete erosion:

Part 1 discusses the three major causes of concrete erosion in hydraulic structures: cavitation, abrasion, and chemical attack.

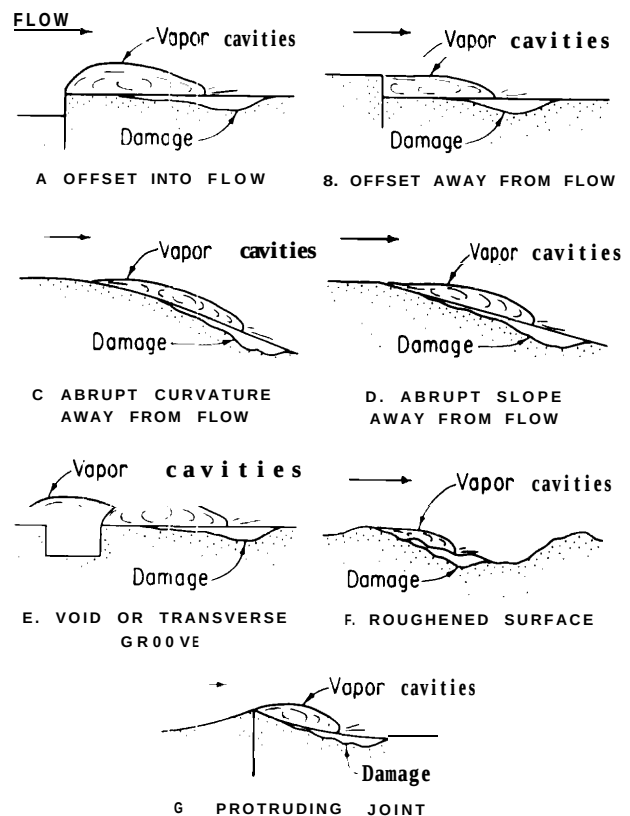


Fig. 2.1-Cavitation situations at surface irregularities

Part 2 discusses the options available to the designer and user to control concrete erosion in hydraulic structures.

Part 3 discusses the evaluation of erosion problems and provides information on repair techniques. Part 3 is not comprehensive, and is intended as a guide for the selection of a repair method and material.

### CHAPTER 2-EROSION BY CAVITATION

#### 2.1-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. Fig. 2.1 shows examples of concrete surface irregularities which 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 vortices.

When the geometry of flow boundaries causes streamlines to curve or converge, the pressure will drop in the direction toward the center of curvature or in the direction along the converging streamlines. For example, Fig. 2.2 shows a tunnel contraction in which cavities could start to form at Point c and then collapse at

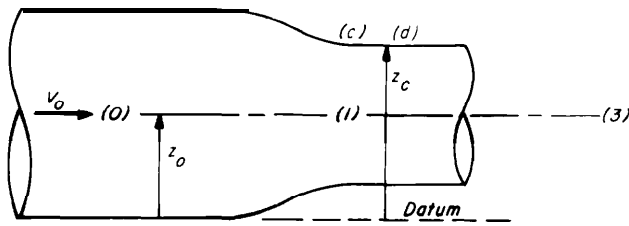


Fig. 2.2-Tunnel contraction

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 0, the local pressure near Point c will drop 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 very 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.

## 2.2-Cavitation index

The cavitation index is a dimensionless measure used to characterize the susceptibility of a system to cavitate. Fig. 2.2 illustrates the concept of the cavitation index. In such a system, the critical location for cavitation is at Point c.

The static fluid pressure at Location 1 will be

$$p_c + \gamma (z_c - z_0)$$

where  $p_c$  is the absolute static pressure at Point c;  $\gamma$  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 0.

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

$$p_0 - [p_c + \gamma (z_c - z_0)]$$

where  $p_0$  is the static pressure at 0.

The cavitation index normalizes this pressure drop to the dynamic pressure  $\frac{1}{2} \rho v_0^2$

$$\sigma = \frac{p_0 - [p_c + \gamma (z_c - z_0)]}{\frac{1}{2} \rho v_0^2} \quad \text{Eq. (2-1)}$$

where  $\rho$  is the density of the fluid (mass per unit volume) and  $v_0$  is the fluid velocity at 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 streamline from 0 to 1 required to produce cavitation at the crown is

$$p_0 - [p_v + \gamma (z_c - z_0)]$$

and the cavitation index at the condition of incipient cavitation is

$$\sigma_c = \frac{p_0 - p_v + \gamma (z_c - z_0)}{\frac{1}{2} \rho v_0^2} \quad (2-2)$$

It can be deduced from fluid mechanics considerations (Knapp, Daily, and Hammitt 1970) — and confirmed experimentally — that in a given system cavitation will begin at a specific  $\sigma_c$ , no matter which combination of pressure and velocity yields that  $\sigma_c$ .

If the system operates at a  $\sigma$  above  $\sigma_c$ , the system does not cavitate. If  $\sigma$  is below  $\sigma_c$ , the lower the value of  $\sigma$ , the more severe the cavitation action in a given system. Therefore, the designer should insure that the operating  $\sigma$  is safely above  $\sigma_c$  for the system's critical location.

Actual values of  $\sigma_c$  for different systems differ markedly, depending on the shape of flow passages, the shape of objects fixed in the flow, and the location where reference pressure and velocity are measured.

For a smooth surface with slight changes of slope in the direction of flow, the value of  $\sigma_c$  may be below 0.2. For systems that produce strong vortices,  $\sigma_c$  may exceed 10. Values of  $\sigma_c$  for various geometries are given in Chapter 5. Falvey (1982) provides additional information on predicting cavitation in spillways.

Since, in theory, a system having a given geometry will have a certain  $\sigma_c$  despite differences in scale,  $\sigma_c$  is a useful concept in model studies. Tullis (1981) describes modeling of cavitation in closed circuit flow. Cavitation considerations (such as surface tension) in scaling from model to prototype are discussed in Knapp, Daily, and Hammitt (1970) and Arndt (1981).

## 2.3-Cavitation damage

Cavitation bubbles will grow and travel with the flowing water to an area where the pressure field will cause collapse. Cavitation damage can begin at that point. When a cavitation bubble collapses or implodes close to or against a solid surface, an extremely high pressure is generated, which acts on an infinitesimal area of the surface for a very short time period. A succession of these high-energy impacts will damage almost any solid material. Tests on soft metal show initial cavitation damage in the form of tiny craters. Advanced stages of damage show

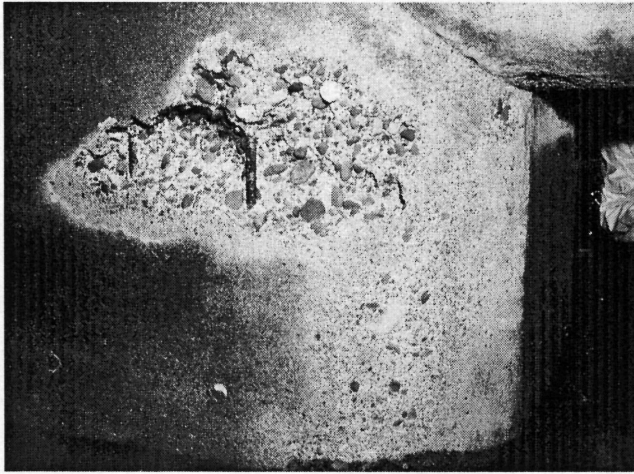


**Fig. 2.3-Cavitation erosion of intake wall of a navigation lock at point of tunnel contraction**

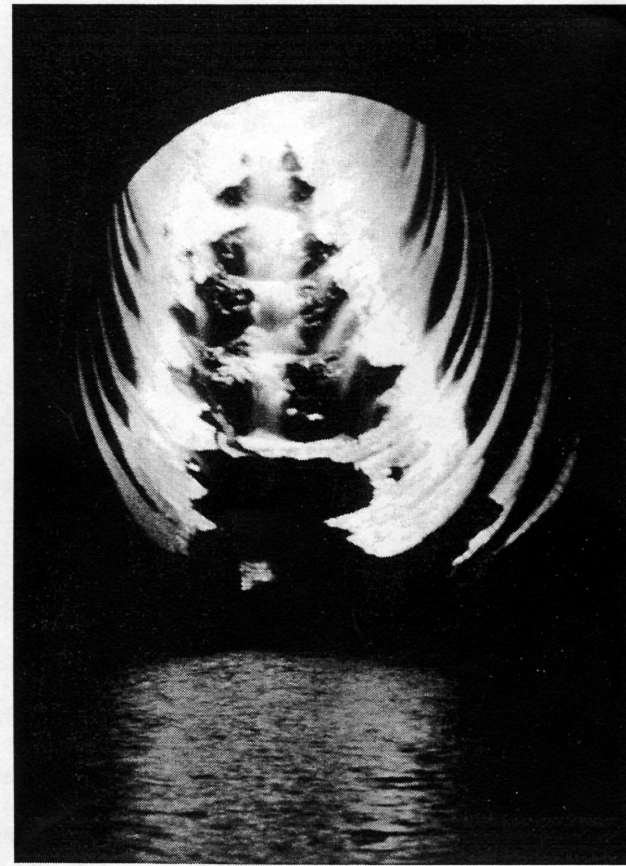


**Fig. 2.4-`Christmas tree` configuration of cavitation damage on a high-head tunnel surface**

an extremely rough honeycomb texture with some holes that penetrate the thickness of the metal. This type of pitting often occurs in pump impellers and marine propellers.

The progression of cavitation erosion in concrete is not as well documented as it is in metals. For both classes of material, however, the erosion progresses rapidly after an initial period of exposure slightly roughens the surface with tiny craters or pits. Possible

explanations are that: a) the material immediately beneath the surface is more vulnerable to attack; b) the cavitation impacts are focused by the geometry of the pits themselves; or c) the structure of the material has been weakened by repeated loading (fatigue). In any event, the photograph in Fig. 2.3 clearly shows a tendency for the erosion to follow the mortar matrix and undermine the aggregate. Severe cavitation damage will typically form a Christmas-tree configuration on spillway chute surfaces downstream from the point of origin as shown in Fig. 2.4.

Microfissures in the surface and between the mortar and coarse aggregate are believed to contribute to cavitation damage. Compression waves in the water that fills such interstices may produce tensile stresses which cause microcracks to propagate. Subsequent compression waves can then loosen pieces of the material. The simultaneous collapse of all of the cavities in a large cloud, or the supposedly slower collapse of a large vortex, quite probably is capable of suddenly exerting more than 100 atmospheres of pressure on an area of many square inches. Loud noise and structural vibration attest to the violence of impact. The elastic rebounds from a sequence of such blows may cause and propagate cracks and other damage, causing chunks of material to break loose.

Fig. 2.5 shows the progress of erosion of concrete downstream from two protruding bolts used to generate cavitation. The tests were made at a test facility located at Detroit Dam, Oregon. Fig. 2.6 shows cavitation damage on test panels after 47 hours of exposure to high-velocity flows in excess of 100 ft per second (ft/sec) [40 meters per second (m/sec)]. A large amount of cavitation erosion caused by a small offset at the upstream edge of the test slab is evident.

Fig. 2.7 shows severe cavitation damage that occurred to the flip bucket and training walls of an outlet structure at Lucky Peak Dam, Idaho. In this case, water velocities of 120 ft/sec (37 m/sec) passed through a gate structure into an open outlet manifold, part of which is shown here. Fig. 2.8 shows cavitation damage to the side of a baffle block and the floor in the stilling basin at Yellowtail Afterbay Dam, Montana.

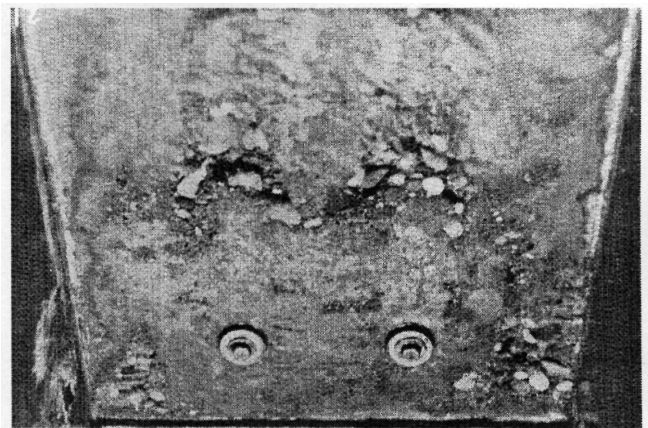


**Fig. 2.5-Concrete test slab featuring cavitation devices**

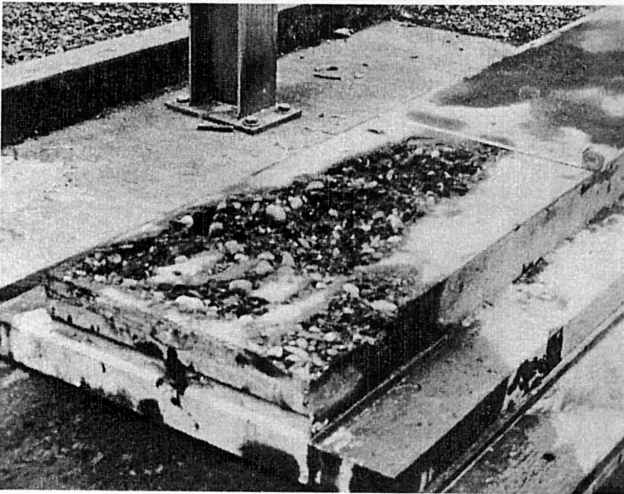


**Fig. 2.6-Cavitation erosion pattern after 47 hours of testing at a 240 ft velocity head**

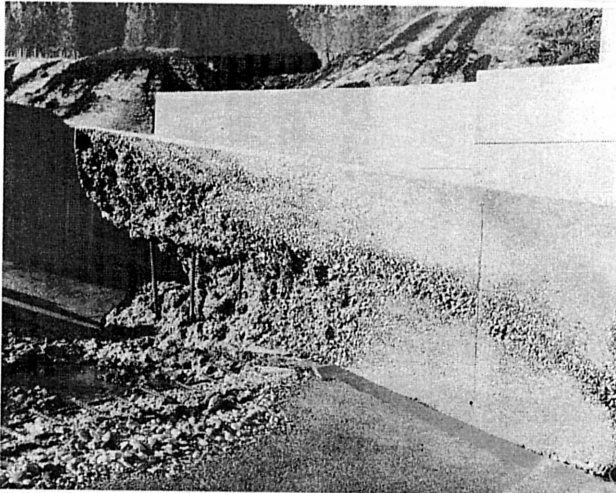


**Fig. 2.7-Cavitation erosion of discharge outlet training wall and flip bucket**

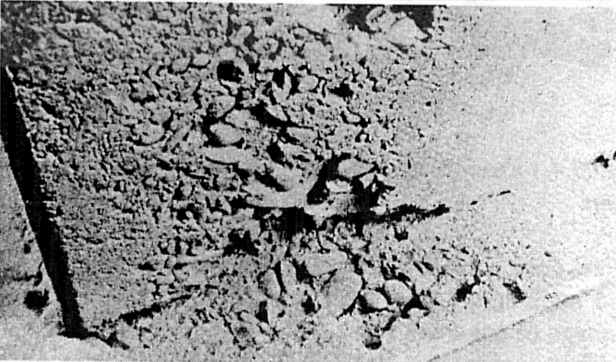


**Fig. 2.8-Cavitation erosion of baffle block and floor in stilling basin**

Once erosion has begun, the rate of erosion may be expected to increase because protruding pieces of aggregate become new generators of vapor cavities. In fact, a cavity cloud often is caused by the change in direction of

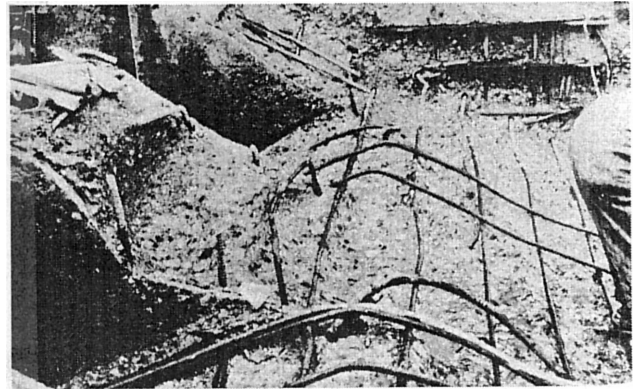


**Fig. 3.1-Abrasion damage to concrete baffle blocks and floor area in Yellowtail Diversion Dam sluiceway, Montana**

the boundary at the downstream rim of an eroded depression. Collapse of this cloud farther downstream starts a new depression, and so on, as indicated in Fig. 2.4.

Once cavitation damage has substantially altered the flow regime, other mechanisms then begin to act on the surface. These, fatigue due to vibrations of the mass, include high water velocities striking the irregular surface and mechanical failure due to vibrating reinforcing steel. Significant amounts of material may be removed by these added forces, thereby accelerating failure of the structure. This sequence of cavitation damage followed by high-impact damage from the moving water was clearly evident in the 1983 spillway tunnel failure at Glen Canyon Dam, Arizona.

## CHAPTER 3-EROSION BY ABRASION

### 3.1-General

Abrasion erosion damage results from the abrasive effects of waterborne silt, sand, gravel, rocks, ice, and other debris impinging on a concrete surface during operation of a hydraulic structure. Abrasion erosion is readily recognized by the smooth, worn-appearing concrete surface, which is distinguished from the small holes and pits formed by cavitation erosion, as can be compared in Fig. 2.8 and 3.1. Spillway aprons, stilling basins, sluiceways, drainage conduits or culverts, and tunnel linings are particularly susceptible to abrasion erosion.

The rate of erosion is dependent on a number of factors including the size, shape, quantity, and hardness of particles being transported, the velocity of the water, and the quality of the concrete. While high-quality concrete is capable of resisting high water velocities for many years with little or no damage, the concrete cannot withstand the abrasive action of debris grinding or repeatedly impacting on its surface. In such cases, abrasion erosion ranging in depth from a few inches (few centimeters) to several feet (a meter or more) can result depending on the flow conditions. Fig. 3.2 shows the relationship between fluid-bottom velocity and the size of particles which that velocity can transport.

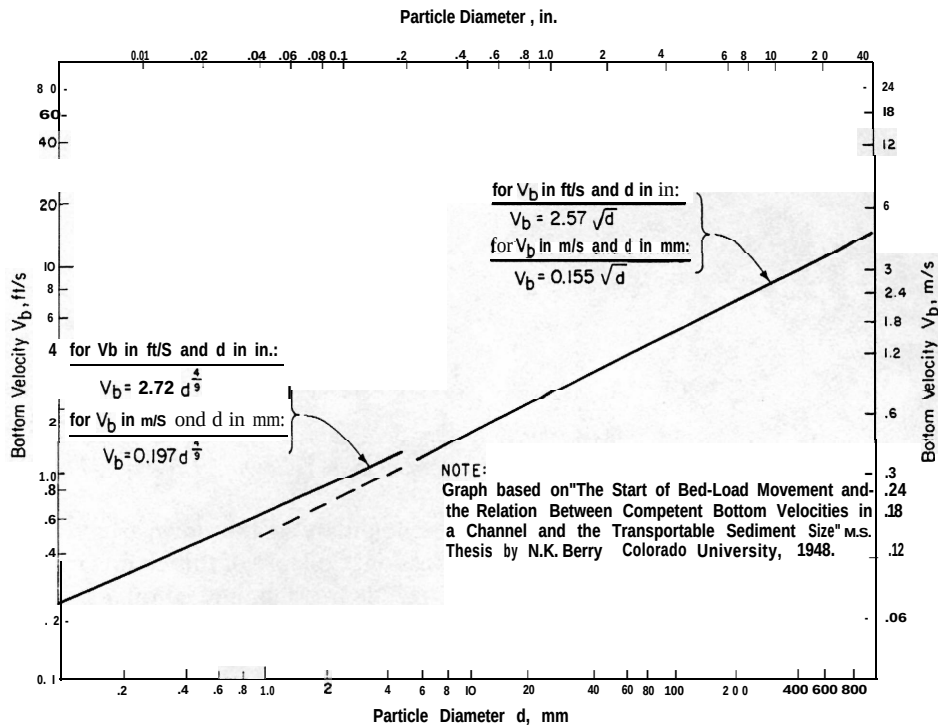


Fig. 3.2-Bottom velocity versus transported sediment size



Fig. 3.3-Typical debris resulting from abrasion erosion of concrete



Fig. 3.4-Erosion of stilling basin floor slab, Dworshak Dam

### 3.2-Stilling basin damage

A typical stilling basin design includes a downstream sill from 3 to 20 ft (1 to 6 m) high intended to create a permanent pool to aid in energy dissipation of high-velocity flows. Unfortunately, in many cases these pools also trap rocks and debris (Fig. 3.3). The stilling basins at Libby and Dworshak Dams, high-head hydroelectric structures, were eroded to maximum depths of approximately 6 and 10 ft (2 and 3 m), respectively. In the latter case, nearly 2000 yd<sup>3</sup> (1530 m<sup>3</sup>) of concrete and bedrock were eroded from the stilling basin (Fig. 3.4). Impact

forces associated with turbulent flows carrying large rocks and boulders at high velocity contribute to the surface damage of concrete.

There are many cases where the concrete in outlet works stilling basins of low-head structures has also exhibited abrasion erosion. Chute blocks and baffles within the basin are particularly susceptible to abrasion erosion by direct impact of waterborne materials. There also have been several cases where baffle blocks connected to the basin training walls have generated eddy currents behind these baffles, resulting in significant localized damage to

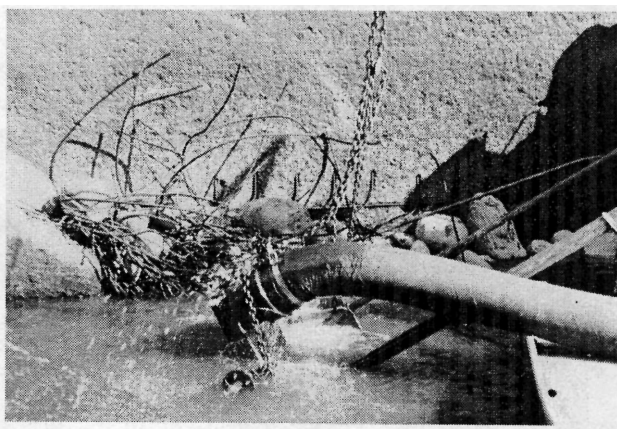


**Fig. 3.5-Abrasion erosion damage to stilling basin, Nolin Dam**



**Fig. 3.6-Abrasion erosion damage to discharge lateral: Upper St. Anthony Falls Lock**

the stilling basin walls and floor slab, as shown in Fig. 3.5.

In most cases, abrasion erosion damage in stilling basins has been the result of one or more of the following: a) construction diversion flows through constricted portions of the stilling basin, b) eddy currents created by diversion flows or powerhouse discharges adjacent to the basin, c) construction activities in the vicinity of the basin, particularly those involving cofferdams; d) nonsymmetrical discharges into the basin; e) separation of flow and eddy action within the basin sufficient to transport riprap from the exit channel into the basin; f) failure to clean basins after completion of construction work, and g) topography of the outflow channel (McDonald 1980).

### 3.3-Navigation lock damage

Hydraulic structures other than spillways are also subject to abrasion erosion damage. When Upper St. Anthony Falls navigation lock was dewatered to repair a damaged miter gate, an examination of the filling and emptying laterals and discharge laterals revealed considerable abrasion erosion (Fig. 3.6). This erosion of the

concrete to maximum depths of 23 in. (580 mm) was caused by rocks up to 18 in. (460 mm) in diameter, which had entered the laterals, apparently during discharge of the flood of record through the lock chamber. Subsequent filling and emptying of the lock during normal operation agitated those rocks, causing them to erode the concrete by grinding.

### 3.4-Tunnel lining damage

Concrete tunnel linings are susceptible to abrasion erosion damage, particularly when the water carries large quantities of sand, gravel, rocks, and other debris. There have been many instances where the concrete in both temporary and permanent diversion tunnels has experienced abrasion erosion damage. Generally, the tunnel floor or invert is the most heavily damaged. Wagner (1967) has described the performance of Glen Canyon Dam diversion tunnel outlets.

## CHAPTER 4-EROSION BY CHEMICAL ATTACK

### 4.1-Sources of chemical attack

The compounds present in hardened portland cement are attacked by water and by many salt and acid solutions; fortunately, in most hydraulic structures, the deleterious action on a mass of hardened portland cement concrete with a low permeability is so slow it is unimportant. However, there are situations where chemical attack can become serious and accelerate deterioration and erosion of the concrete.

Acidic environments can result in deterioration of exposed concrete surfaces. The acidic environment may range from low acid concentrations found in mineral-free water to high acid concentrations found in many processing plants. Alkali environments can also cause concrete deterioration. In the presence of moisture, alkali soils containing sulfates of magnesium, sodium, and calcium attack concrete, forming chemical compounds which imbibe water and swell, and can damage the concrete.

Hydrogen sulfide corrosion, a form of acid attack, is common in septic sanitary systems. Under certain conditions this corrosion can be very severe and cause early failure of a sanitary system.

### 4.2-Erosion by mineral-free water

Hydrated lime is one of the compounds formed when cement and water combine. It is readily dissolved by water and more aggressively dissolved by pure mineral-free water, found in some mountain streams. Dissolved carbon dioxide is contained in some fresh waters in sufficient quantity to make the water slightly acidic and add to its aggressiveness. Scandinavian countries have reported serious attacks by fresh water, both on exposed concrete surfaces and interior surfaces of conduits where porosity or cracks have provided access. In the United States, there are many instances where the surface of the concrete has been etched by fresh water flowing over it,

but serious damage from this cause is uncommon (Holand et al. 1980). This etching is particularly evident at hydraulic structures carrying runoff from high mountain streams in the Rocky Mountains and the Cascade Mountains of the central and western United States. A survey (ICOLD 1951) of the chemical composition of raw water in many reservoirs throughout the United States indicates a nearly neutral acid-alkaline balance (pH) for most of these waters.

#### 4.3-Erosion by miscellaneous causes

**4.3.1 Acidic environments**-Decaying vegetation is the most frequent source of acidity in natural waters. Decomposition of certain minerals may be a source of acidity in some localities. Running water that has a pH as low as 6.5 will leach lime from concrete, reducing its strength and making it more porous and less resistant to freezing and thawing and other chemical attack. The amount of lime leached from concrete is a function of the area exposed and the volume of concrete. Thin, small-diameter drains will deteriorate in a few years when exposed to mildly acidic waters, whereas thick pipe and massive structures will not be damaged significantly for many years under the same exposure, provided the cover over the reinforcing steel meets normal design standards.

Waters flowing from peat beds may have a pH as low as 5. Acid of this strength will aggressively attack concrete, and for this reason, when conveyances for ground water are being designed, the aggressiveness of the water should be tested to determine its compatibility with the concrete. This is particularly true in pressure conduits.

**4.3.2 Bacterial action**-Most of the literature addressing the problem of deterioration of concrete resulting from bacterial action has evolved because of the great impact of this corrosive mechanism on concrete sewer systems. This is a serious problem which, as Rigdon and Beardsley (1958) observed, occurs more readily in warm climates such as California, USA; Australia; and South Africa. This problem also occurs at the terminus of long pumped sewage force mains in the northern climates (Pomeroy 1974).

Sulfur-reducing bacteria belong to the genus of bacteria that derives the energy for its life processes from the reduction of some element other than carbon, such as nitrogen, sulfur, or iron (Rigdon and Beardsley 1958). Some of these bacteria are able to reduce the sulfates that are present in natural waters and produce hydrogen sulfide as a waste product. These bacteria, as stated by Wetzal (1975), are anaerobic.

Another group of bacteria takes the reduced sulfur and oxidizes it back so that sulfuric acid is formed. The genus *Thiobacillus* is the sulfur-oxidizing bacteria that is most destructive to concrete. It has a remarkable tolerance to acid. Concentrations of sulfuric acid as great as 5 percent do not completely inhibit its activity.

Sulfur-oxidizing bacteria are likely to be found wherever warmth, moisture, and reduced compounds of

sulfur are present. Generally, a free water surface is required, in combination with low dissolved oxygen in sewage and low velocities that permit the buildup of scum on the walls of a pipe in which the anaerobic sulfur-reducing bacteria can thrive. Certain conditions must prevail before the bacteria can produce hydrogen sulfide from sulfate-rich water. Sufficient moisture must be present to prevent the desiccation of the bacteria. There must be adequate supplies of hydrogen sulfide, carbon dioxide, nitrogen compounds, and oxygen. In addition, soluble compounds of phosphorus, iron, and other trace elements must be present in the moisture film.

Newly made concrete has a strongly alkaline surface with a pH of about 12. No species of sulfur bacteria can live in such a strongly alkaline environment. Therefore, the concrete is temporarily free from bacterially induced corrosion. Natural carbonation of the free lime by the carbon dioxide in the air slowly drops the pH of the concrete surface to 9 or less. At this level of alkalinity, the sulfur bacteria *Thiobacillus thioparus*, using hydrogen sulfide as the substrate, generate thiosulfuric and polythionic acid. The pH of the surface moisture steadily declines, and at a pH of about 5, *Thiobacillus concretivorus* begins to proliferate and produce high concentrations of sulfuric acid, dropping the pH to a level of 2 or less. The destructive mechanism in the corrosion of the concrete is the aggressive effect of the sulfate ions on the calcium aluminates in the cement paste.

The main concrete corrosion problem in a sewer, therefore, is chemical attack by this sulfuric acid which accumulates in the crown of the sewer. Information is available which may enable the designer to design, construct, and operate a sewer so that the development of sulfuric acid is reduced (Pomeroy 1974, ASCE-WPCF Joint Task Force 1982; ACPA 1981).

## PART 2-CONTROL OF EROSION

### CHAPTER 5--CONTROL OF CAVITATION EROSION

#### 5.1-Hydraulic design principles

In Chapter 2, Section 2.2, the cavitation index  $\sigma$  was defined by Eq. (2-1). When the value of  $\sigma$  at which cavitation damage begins is known, a designer can calculate velocity and pressure combinations that will avoid trouble. To produce a safe design, the object is to assure that the actual operating pressures and velocities will produce a value of  $\sigma$  greater than the value at which damage begins.

A good way to avoid cavitation erosion is to make  $\sigma$  large by keeping the pressure  $p_0$  high, and the velocity  $v_0$  low. For example, deeply submerged baffle piers in a stilling basin downstream from a low spillway are unlikely to be damaged by cavitation because both of these conditions are satisfied. This situation is illustrated in Fig. 5.1. The following example illustrates how to calculate  $\sigma$  for this case. From model studies, the mean prototype velo-