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: cavi-ration, 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.

CONTENTS

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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.

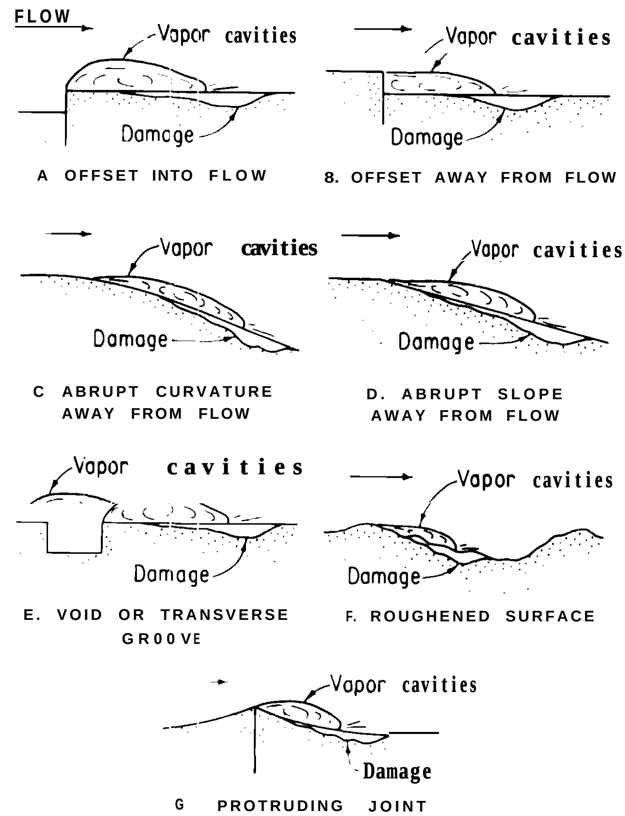


Fig. 2.1-Cavitation situations at surface irregularities

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 a cloud of cavities could start to form at Point c and then collapse at

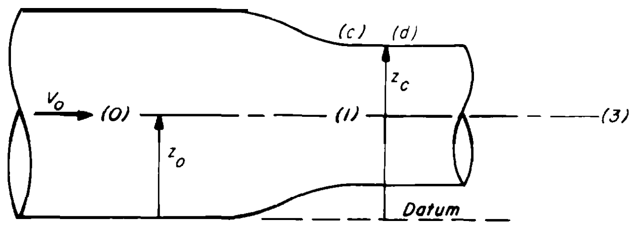


Fig. 2.2-Tunnel contraction

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; y 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 $\frac{1}{2} \rho v_0^2$

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

where p 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

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

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 σ_c, no matter which combination of pressure and velocity yields that σ_c.

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

Actual values of σ_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 σ_c may be below 0.2. For systems that produce strong vortices, σ_c may exceed 10. Values of σ_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 σ_c despite differences in scale, σ_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

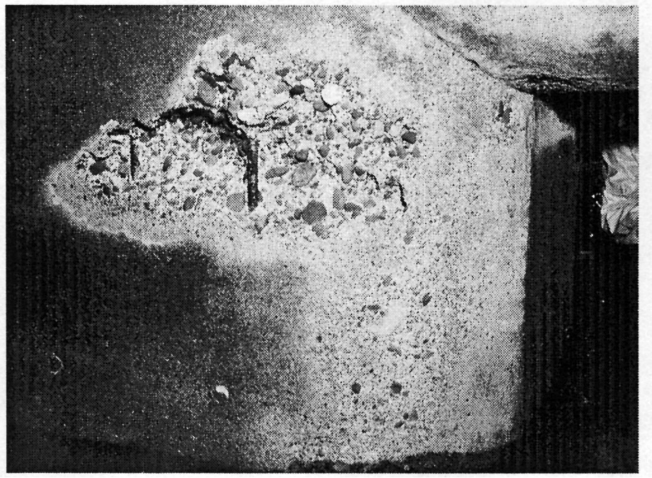


Fig. 2.3-Cavitation erosion of intake wall of a navigation lock at point of tunnel contraction

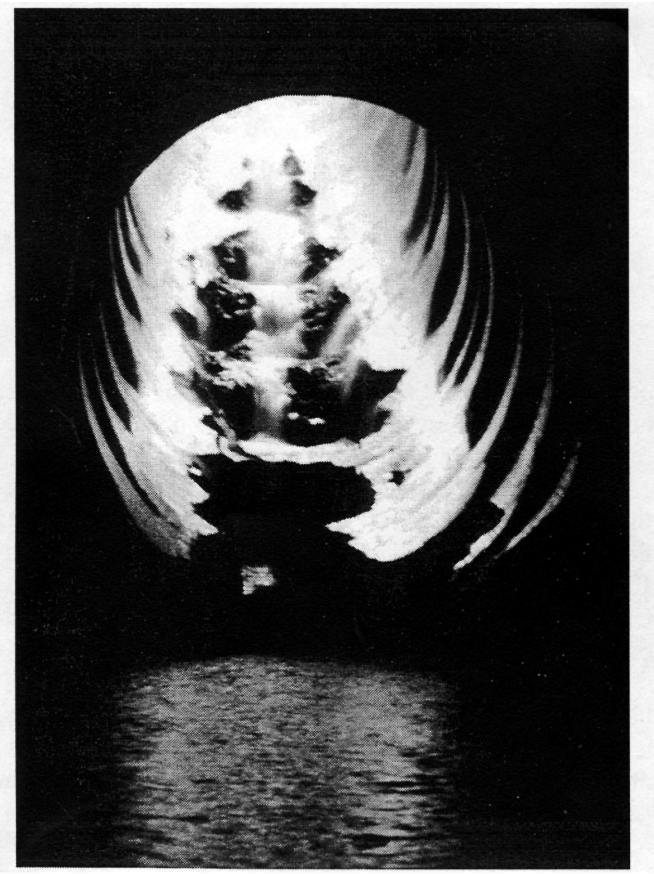


Fig. 2.4-``Christmas tree" configuration of cavitation damage on a high-head tunnel surface

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.

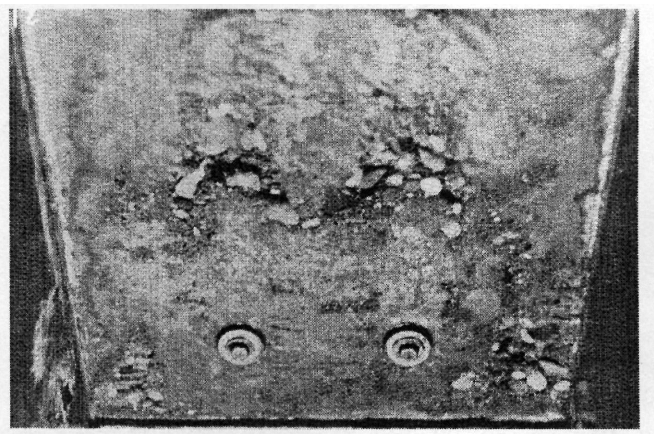


Fig. 2.5-Concrete test slab featuring cavitation producing devices

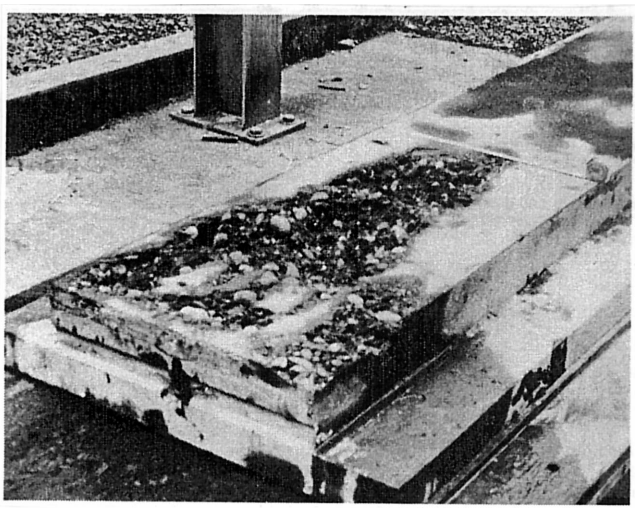


Fig. 2.6-Cavitation erosion pattern after 47 hours of testing at a 240 ft velocity head

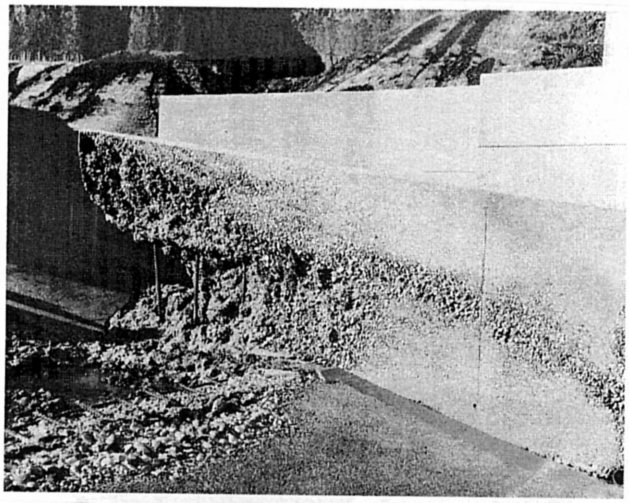


Fig. 2.7-Cavitation erosion of discharge outlet training wall and flip bucket

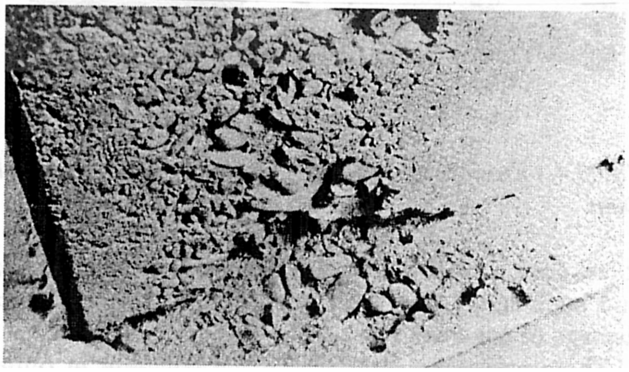


Fig. 2.8-Cavitation erosion of baffle block and floor in stilling basin

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

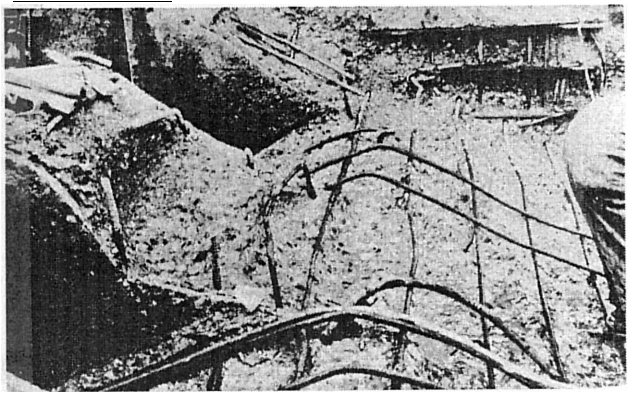


Fig. 3.1-Abrasion damage to concrete baffle blocks and floor area in Yellowtail Diversion Dam sluiceway, Montana

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.

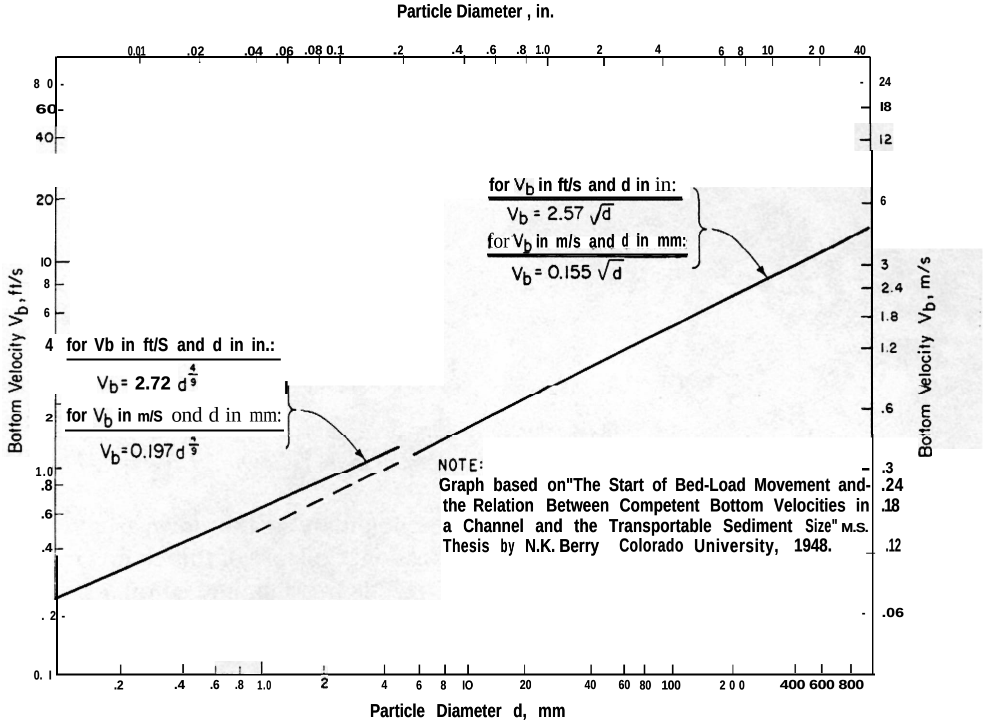


Fig. 3.2-Bottom velocity versus transported sediment size

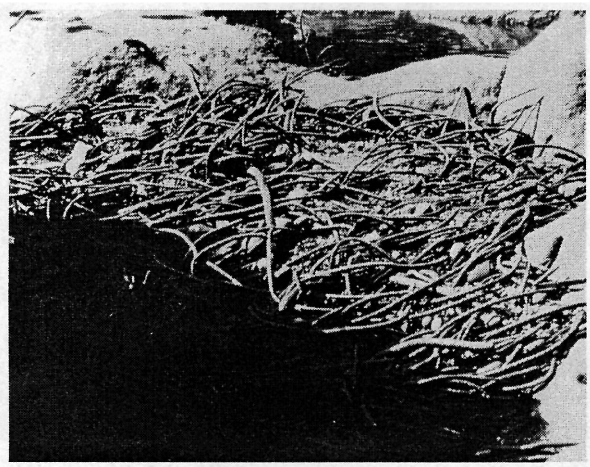


Fig. 3.3-Typical debris resulting from abrasion erosion of concrete

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^3 (1530 m^3) 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

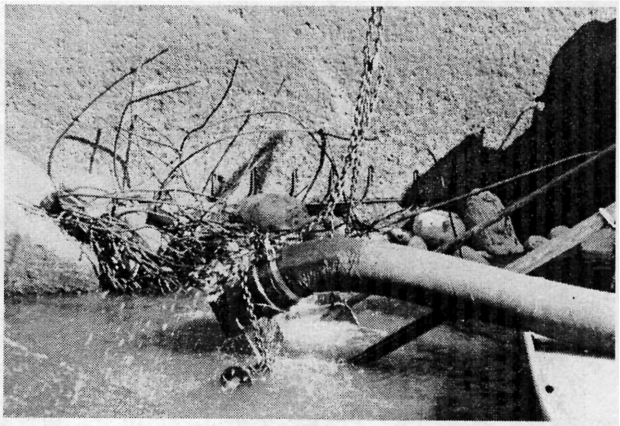


Fig. 3.5-Abrasion erosion damage to stilling basin, Nolin Dam

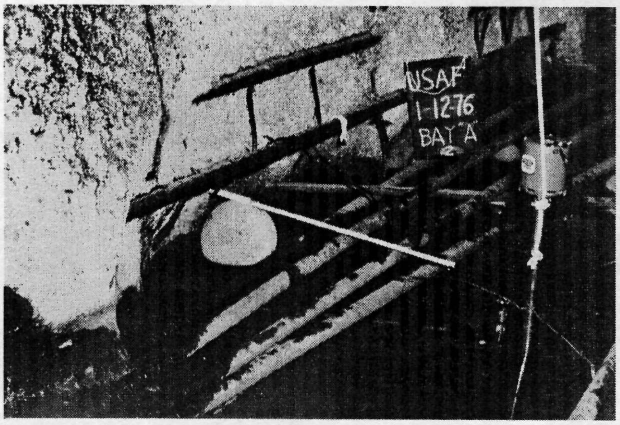


Fig. 3.6-Abrasion erosion damage to discharge lateral: Upper St. Anthony Falls Lock

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 (Holland 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 Wetzel (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 stroug 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 σ was defined by Eq. (2-l). When the value of σ 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 σ greater than the value at which damage begins.

A good way to avoid cavitation erosion is to make σ 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 σ is calculated for this case. From model studies, the mean prototype velo-

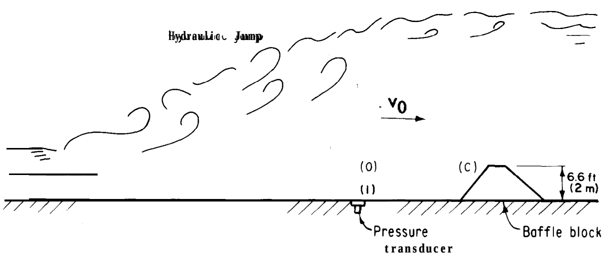
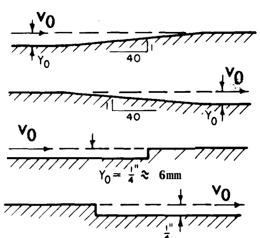


Fig. 5.1-Baffle block downstream from a low spillway

Structure or Irregularity	σ	References
Tunnel inlet	1.5	Tullis 1981
Sudden expansion in tunnel	1.0* 0.19	Russell and Ball 1967 Rouse and Jezdinsky 1966
Baffle blocks	1.4 & 2.3	Galperin et al. 1977
Gates and gate slots	0.2 to 3.0	Galperin et al. 1977 Ball 1959 Wagner 1967
Abraded concrete 3/4 in. max. depth of roughness	0.6	Ball 1976
	0.2	Ball 1976 Arndt 1977 Falvey 1982
	0.2	
	1.6	
	1.0	

*Unusual definition of σ

Fig. 5.2-Values of σ at beginning of cavitation damage

city at 0, immediately upstream from the baffle block, is found to be 30 ft/sec (9.1 m/sec), and the "minimum" prototype gage pressure, exceeded 90 percent of the time, is 7.1 psi (49 kPa). The barometric pressure for the prototype location is estimated to be 13.9 psi (95.8 kPa), so that the absolute pressure at 0, 6.6 ft (2.0 m) above Location 1, becomes

$$p_0 = 7.1 + 13.9 - \frac{(6.6 \times 62.4)}{144 \ in.^2/ft^2} = 18.1 \text{ psi}$$

Given that

$$p_v = 0.3 \text{ psi}$$

$$\rho = 1.94 \ \frac{lb \cdot sec^2}{ft^4}$$

and

$$z_c = z_0$$

it follows that

$$\sigma = \frac{p_0 - p_v}{\frac{1}{2} \rho v_0^2} \tag{5-1}$$

and

$$\sigma = \frac{(18.1 - 0.3)(144 \ in.^2/ft^2)(32.2 \ ft/sec^2)}{\frac{1}{2}(62.4)(30)^2} = 2.9$$

In SI units

$$p_0 = 49 + 95.8 - \left(2.0 \times 9.81 \frac{kgf/m^2}{Pa}\right) = 125 \text{ kPa}$$

Then, given that p_v = 2.1 kPa, ρ = 10^3 kg/m^3, and z_c = z_0

$$\sigma = \frac{(125 - 2.1)(1000)}{\frac{1}{2}(1000)(9.1)^2} = 2.9$$

This value of σ is well above the accepted damage value of 2.3 for this shape of sharp-edged pier (Galperin et al. 1977). Hence, cavitation damage is unlikely in the prototype.

A second, equally effective procedure to avoid cavitation is to use boundary shapes and tolerances characterized by low values of σ for incipient damage. For example, a carefully designed gate slot, with an offset and rounded downstream corner, may have a damage σ as low as 0.2. Unfortunately, the lowest value of a a designer can use may be fixed by unintentional surface imperfections in concrete, the need for small abrupt expansions in flow passages, or the likelihood that vortices will be generated by obstructions such as partially open sluice gates. To be realistic, one may have to expect boundary geometry that will cause cavitation damage, if σ drops below about 1.2.

A third choice, often inevitable, is to expect cavities to form at predetermined locations. In this case, the designer may: a) supply air to the flow, or b) use damage-resistant materials such as stainless steel, fiber-reinforced concrete, or polymer concrete systems.

Using damage-resistant materials will not eliminate damage, but may extend the useful life of a surface. This alternative is particularly attractive, for example, for constructing or repairing outlet works that will be used infrequently or abandoned after their purpose has been served.

In any case, values of σ at which cavitation erosion begins are needed for all sorts of boundary geometries. Sometimes critical values of σ may be estimated by theory, but they usually come from model or prototype tests.

5.2-Cavitation indexes for damage and construction tolerances

Fig. 5.2 lists a few values of σ at which cavitation begins and the references from which these values came. A designer should not use these numbers without studying the references. Some reasons for this are:

a. The exact geometry and test circumstances must be understood.

b. Authors use different locations for determining the reference parameters of Eq. (2-l). However, the general form of Eq. (2-l) is accepted by practitioners in the field.

c. Similitude in the model is difficult to achieve.

Many of the essential details involved in the original references are explained in Hamilton (1983 and 1984) which deals with the examples in Fig. 5.2.

The values of σ listed in Fig. 5.2 show the importance of good formwork and concrete finishing. For example, a 1/4-in. (6-mm) offset into the flow which could be caused by mismatched forms has a σ of 1.6, whereas a 1:40 chamfer has a σ only one-eighth this large. By the definition of σ, the allowable velocity past the chamfer would be $\sqrt{8}$ times the allowable velocity past the offset if $p_0 - p_v$ were the same in both cases. Thus, on a spillway or chute where $p_0 - p_v$ might be 17.4 psi (120 kPa), damage would begin behind the offset when the local velocity reached 40 ft/sec (12 m/sec), but the flow past the chamfer would cause no trouble until the velocity reached about 113 ft/sec (35 m/sec).

When forms are required, as on walls, ceilings, and steep slopes, skilled workmen may produce a nearly smooth and only slightly wavy surface for which σ may be as low as 0.4. Using the preceding $p_0 - p_v$ gives a damage velocity of 80 ft/sec (24 m/sec). A σ value of 0.2, on which the 113 ft/sec (35 m/sec) is based, may be achieved on plane, nearly horizontal surfaces by using a stiff screed controlled by steel wheels running on rails and hand floating and troweling.

Construction tolerances should be included in all contract documents. These establish permissible variation in dimension and location giving both the designer and the contractor parameters within which the work is to be performed. ACI 117 provides guidance in establishing practical tolerances. It is sometimes necessary that the specifications for concrete surfaces in high-velocity flow areas, or more specifically, areas characterized by low values of σ, be even more demanding. However, achieving more restrictive tolerances for hydraulic surfaces than those recommended by ACI 117 can become very costly or even impractical. The final specification requirements require judgment on the part of the designer (Schrader, 1983).

Joints can cause problems in meeting tolerances, even with the best workmanship. Some designers prefer to saw and break out areas where small offsets occur rather than to grind the offsets that are outside the specification. The trough or hole is then patched and hand finished in an effort to produce a surface more resistant to erosion than a ground surface would be. In some cases grinding to achieve alignment and smoothness is adequate. However, to help prevent the occurrence of aggregate popouts, a general rule of thumb is to limit the depth of grinding to one-half the maximum diameter of the coarse aggregate. Ground surfaces may also be protected by applying a low-viscosity, penetrating phenol epoxy-resin sealer (Borden et al. 1971). However, the smooth polished texture of the ground surface or the smoothness of a resin sealer creates a different boundary condition which may affect the flow characteristics. Cavitation damage has been observed downstream of such conditions in high velocity flow areas [in excess of 80 ft/sec (24 m/sec)] where there was no change in geometry or shape (Corps of Engineers, 1939).

The difficulty of achieving a near-perfect surface and the doubt that such a surface would remain smooth during years of use have led to designs that permit the introduction of air into the water to cushion the collapse of cavities when low pressures and high velocities prevail.

5.3-Using aeration to control damage

Laboratory and field tests have shown that surface irregularities will not cause cavitation damage if the air-water ratio in the layers of water near the solid boundary is about 8 percent by volume. The air in the water should be distributed rather uniformly in small bubbles.

When calculations show that flow without aeration is likely to cause damage, or when damage to a structure has occurred and aeration appears to be a remedy, the problem is dual: a) the air must be introduced into the flowing water and b) a portion of that air must remain near the flow/concrete boundary where it will be useful.

The migration of air bubbles involves two principles: a) bubbles in water move in a direction of decreasing water pressure, and b) turbulence disperses bubbles from regions of high air concentration toward regions of low concentration.

Careful attention must be given to the motion of bubbles due to pressure gradients. A flow of water surrounded by atmospheric pressure is called a free jet. In a free jet, there are no gradients except possibly weak local ones generated by residual turbulence, and the bubbles move with the water. There is no buoyant force. On a vertical curve that is convex, the bubble motion may have a component toward the bottom. In a flip bucket, which is concave, the bottom pressure is large and the bubbles move rapidly toward the free surface.

When aeration is required, air usually must be introduced at the bottom of the flow. These bubbles gradually move away from the floor in spite of the tendency for turbulent dispersion to hold them down. At the point where insufficient air is in the flow to protect the concrete from damage, a subsequent source of bottom air must be provided.

Aeration data measured on Bratsk Dam in the C.S.I.R. (formerly the U.S.S.R), which has a spillway about 295 ft (90 m) high and an aeration device, have been discussed by Semenkov and Lentyaev (1973) (See Table 5.1). Downstream from the aeration ramp, measurements showed that the air-water ratio in a 6-in. (150-mm) layer next to the concrete declined from 85 to

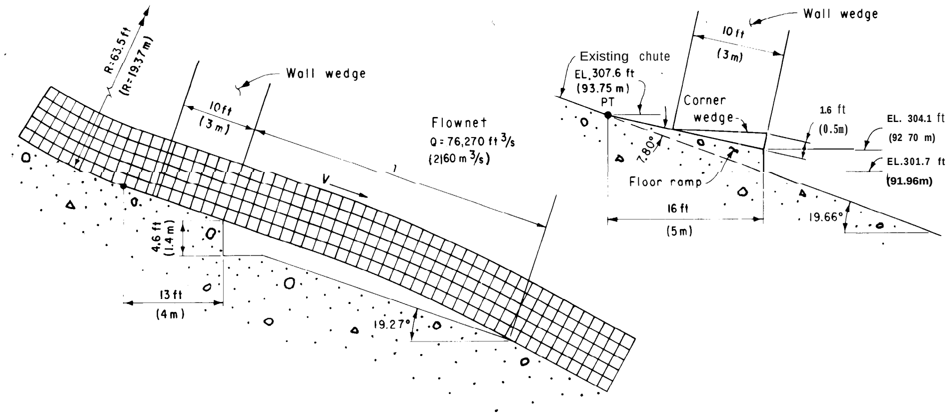


Fig. 5.3-Aeration ramps at King Talal Spillway

Table 5.1-Examples of use of air to prevent cavitation damage

Structure or description	References
Palisades Dam outlet sluices	Beichley and Ring, 1975
Yellowtail Dam spillway tunnel	Borden et al., 1971, Colgate 1971
Glen Canyon Dam spillway tunnel	Burgi, Moyes, and Gamble, 1984
Ust-Ilim Dam spillway	Qskolkov and Semenkov, 1973
Bratsk Dam spillway	Semenkov and Lentyaev, 1973
Foz do Areia spillway	Pinto et al., 1982
General	Galperin et al., 1977
Comprehensive	Hamilton, 1983 and 1984, Quintela, 1980

35 percent as the mixture flowed down the spillway a distance of 174 ft (53 m). If one assumes an exponential type of decay, the loss per foot was a little less than 2 percent of the local air-water ratio.

It is usually not feasible to supply air to flowing water by pumping or compressing the air because the volumes involved are too large. Instead, the flow is projected from a ramp or step as a free jet, and the water introduces air at the air-water interfaces. Then the turbulence within the jet disperses the air entrained at the interfaces into the main body of the jet. Fig. 5.3 shows typical aeration ramps for introducing air into the flow (Wei and DeFazio 1982).

To judge whether sufficient air will remain adjacent to the floor of a spillway, the amount of air that a turbulent jet will entrain must be estimated. The following equation for entrainment by the lower surface has been proposed (Hamilton 1983 and 1984)

$$q_a = \alpha v \ell \qquad (5\text{-}2)$$

in which q_a = volume rate of air entrainment per unit width of jet

α = coefficient

v = average jet velocity at midpoint of trajectory

ℓ = length of air space between the jet and the spillway floor.

Model and prototype measurements indicate that the value of the coefficient α lies between 0.01 and 0.04, depending upon velocity and upstream roughness.

The length of cavity ℓ (Fig. 5.3) is difficult to measure in prototypes and large models. Instead, the upper and lower profiles of the nappe can be estimated from two-dimensional irrotational flow theory. One method is to use a finite element technique for calculating nappe trajectories.

As indicated above, ramps and down-steps are used to induce the flow in a spillway or tunnel to spring free from the floor. A ramp is a wedge anchored to or integral with the floor and usually spans the tunnel or spillway bay. Ramps vary in length from 3 to 9 ft (1 to 3 m). Wall and corner wedges and wall offsets away from the flow also are used to cause the water to leave the sides of a conduit. The objective is to provide a sudden expansion of the solid boundaries. Such devices, often referred to as aerators, are visually depicted in Fig. 5.4 and 5.5. (See also Ball 1959, DeFazio and Wei 1983, and Russell and Ball 1967.)

Air is allowed to flow into a cavity beside or under a jet by providing passages as simple as the layout of the project will permit. Sometimes the required rates of airflow are enormous. For example, a cavity underneath a spillway nappe 49 ft (15 m) wide could entrain 5160 ft^3/sec (146 m^3/sec) of air. A single passageway at least 6.6 ft (2.0 m) in diameter would be needed to supply this amount.

Although offsets, slots, and ramps in conduits can introduce air into 'high-velocity flow to effectively control cavitation, if improperly designed they can accentuate the cavitation problem. For this reason, it is advisable to conduct physical hydraulic model studies to ensure the adequacy of a proposed aeration device.

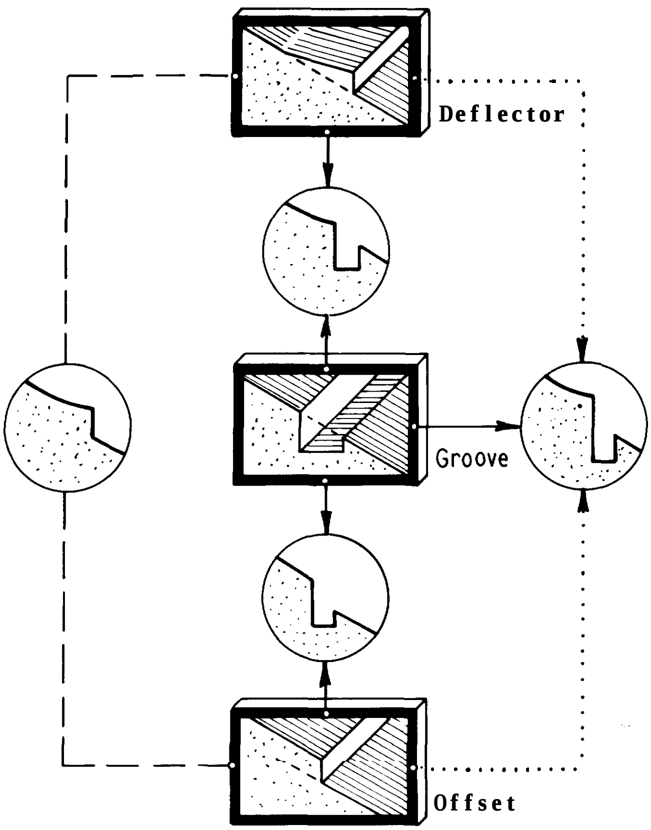


Fig. 5.4-Types of aerators (from Vischer, Volkart, and Siegen thaler, 1982)

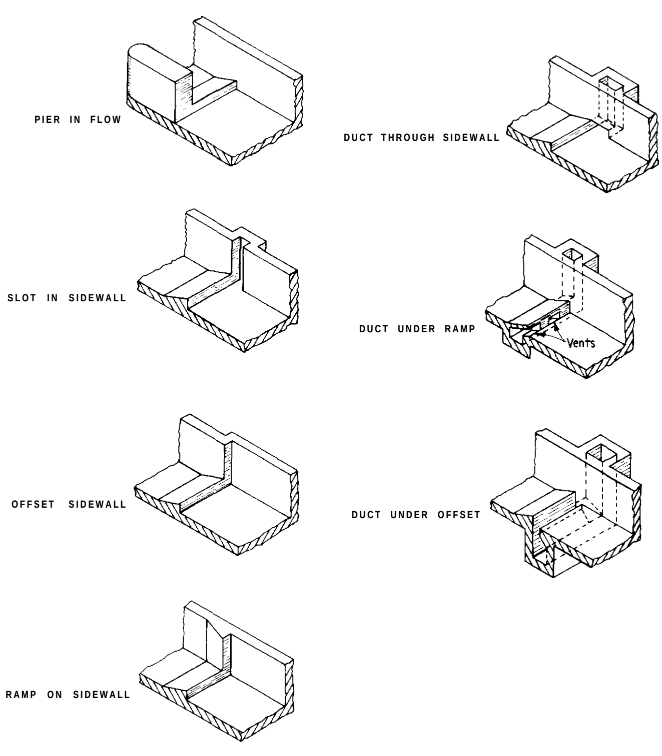


Fig. 5.5-Air supply to aerators (from Falvey, 1990)

5.4-Fatigue caused by vibration

In concrete, flexural fatigue is normally thought of in terms of beams bending under repeated relatively high amplitudes and low-frequency loads. A mass of concrete at the surface of an outlet or spillway ordinarily does not bend, but it does vibrate. In this case, the deformation is three-dimensional with low amplitude and high frequency. For instance, at McNary Dam the viiration was measured as 0.00002 in. (0.00051 mm) and 150 cycles per second (cps) for the transverse direction. Unfortunately, there are no reported studies of concrete fatigue caused by vibration.

A vibration test for concrete and epoxy/polymer materials is needed. Data from such a test would be useful for evaluating various construction and repair materials. A standard test has been developed for small samples of homogeneous materials which viirates the sample at 20,000 cps and 0.002 in. (0.051 mm) amplitude while it is submerged in the fluid. Stilling basin floors, walls, and outlets are essentially full-scale tests of the same type.

5.5-Materials

Although proper material selection can increase the cavitation resistance of concrete, the only totally effective solution is to reduce or eliminate the factors that trigger cavitation, because even the strongest materials cannot withstand the forces of cavitation indefinitely. The difficulty is that in the repair of damaged structures, the reduction or elimination of cavitation may be very difficult and costly. The next best solution is to replace the damaged concrete with more erosion-resistant materials.

In areas of new design where cavitation is expected to occur, designers may include the higher quality materials during the initial construction or include provisions for subsequent repairs in service. For example, in many installations, stainless steel liners are installed on the concrete perimeter downstream of slide gates to resist the damaging effects of cavitation. These liners, although quite durable, may pit and eventually have to be replaced.

The cavitation resistance of concrete where abrasion is not a factor can be increased by using a properly designed low water-cement ratio, high-strength concrete. The use of aggregate no larger than 1% in. (38 mm) nominal maximum size is recommended, and the use of water-reducing admixtures and chilled concrete has proven beneficial. Hard, dense aggregate and good bond between aggregate and mortar are essential to achieving increased cavitation resistance.

Cavitation-damaged areas have been successfully repaired using steel fiber reinforced concrete (ICOLD 1988). This material exhibits good impact resistance necessary to resist the many tiny point loads and appears to assist in arresting cracking and disintegration of the concrete matrix. The use of polymers as a matrix binder or a surface binder has also been found to improve substantially the cavitation resistance of both conventional

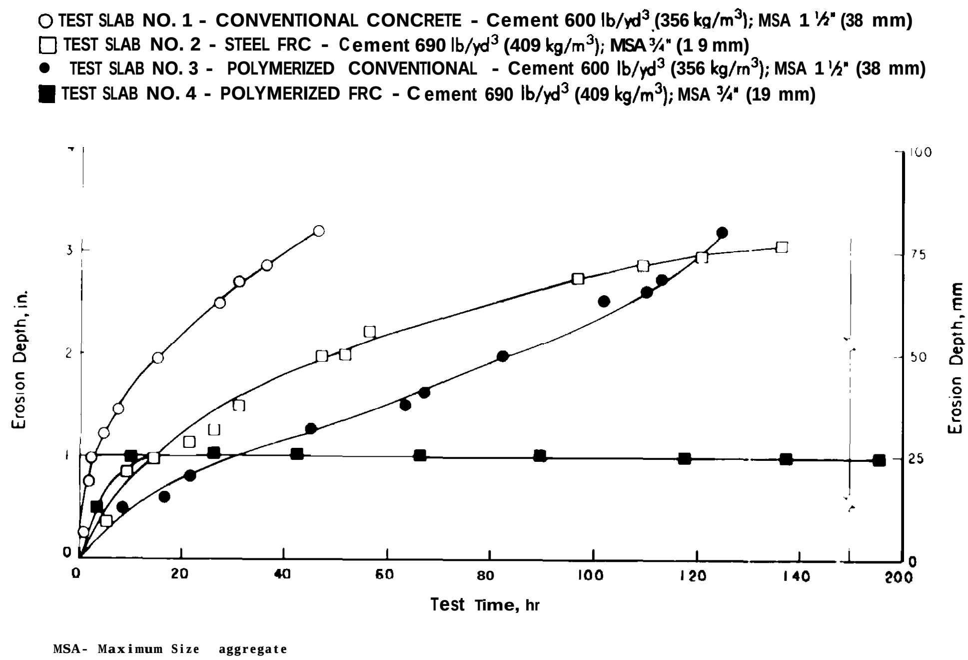


Fig. 5.6-Erosion depth versus time, Tarbela Dam concrete mixtures (from Houghton, Borge, and Paxton, 1978)

and fiber-reinforced concrete (Schrader 1978 and 1983b).

Some coatings, such as neoprene or polyurethane, have effectively reduced cavitation damage to concrete, but since near-perfect adhesion to the concrete is mandatory, the use of such coatings is not common. Once there is a tear or a chip in the coating, the entire coating is soon peeled off.

5.6-Materials testing

Because of the massive size of most hydraulic structures, full-scale prototype testing is usually not possible. Model testing can identify many potential problem areas, but determining the ultimate effect of hydraulic forces on the structure requires some judgment. In some cases, it is desirable to evaluate a material after it has been subjected for a reasonable period of time to flows of a magnitude approaching that expected during operation of the facility.

The U.S. Army Corps of Engineers has evaluated erosion resistance of materials at the Detroit Dam (Oregon) High Head Erosion test flume (Houghton, Borge, and Paxton 1978). Erosion testing at the facility consists of preparing test slabs 21 in. (530 mm) wide by 10 ft (3 m) long using the desired material, coating, or overlay. High-velocity water, in excess of 80 ft/sec (24 m/sec), is passed over the slabs for various durations, and the performance of the material is then evaluated. Cavitation erosion resistance is studied by embedding small obstacles in the test slabs which protrude into the flow (Fig. 2.5).

Materials and coating systems evaluated for Tarbela Dam repairs, were tested at the Detroit Dam facility. They included various concrete mixes, FRC, roller-compacted concrete, polymer-impregnated concrete, polymer-impregnated FRC, and several concrete coatings (Houghton, Borge, and Paxton 1978). Fig. 5.6 shows the performance of several of these materials subjected to flows with velocities of 120 ft/sec (37 m/sec).

5.7-Construction practices

Construction practices are of paramount importance when hydraulic surfaces may be exposed to high-velocity flow, particularly if aeration devices are not incorporated in design. Such surfaces must be as smooth as can be practically obtained (Schrader 1983b). Surface imperfections and deficiencies have been known to cause cavitation damage at flow velocities as low as 26 ft/sec (8 m/sec). Offsets no greater than ⅛ in. (3 mm) in height have been known to cause cavitation damage at flow velocities as low as 82 ft/sec (25 m/sec). Patching repairs improperly made at the time of construction have been known to fail under the stress of water flow or for other reasons, thereby providing the surface imperfections which triggered cavitation damage to the concrete farther downstream. This phenomenon occurred in the high head spillway tunnel at Yellowtail Dam, Montana, ultimately resulting in major cavitation and structural damage to the concrete lining (Borden et al. 1971; Colgate 1971). Accordingly, good construction practices as recommended in ACI 117, ACI 302.1R, ACI 304, ACI 308, ACI 309, and ACI 347 should be maintained both for new construction and repair. Formed and unformed surfaces should be carefully checked during each construction operation to confirm that they are within specific tolerances.

If the potential for cavitation damage exists, care should be taken in placing the reinforcement. The bars closest to the surface should be placed parallel to the direction of flow so as to offer the least resistance to flow in the event that erosion reaches the depth of the reinforcement. Extensive damage has been experienced where the reinforcement near the surface is normal to the direction of flow.

Where possible, transverse joints in concrete conduits or chutes should be minimized. These joints are generally in a location where the greatest problem exists in maintaining a continuously smooth hydraulic surface. One construction technique which has proven satisfactory in placement of reasonably smooth hydraulic surfaces is the traveling slipform screed. This technique can be applied to tunnel inverts and to spillway chute slabs. Information on the slipform screed can be found in Hurd (1979).

Proper curing of these surfaces is essential, since the development of surface hardness improves cavitation resistance.

CHAPTER 6-CONTROL OF ABRASION EROSION

6.1-Hydraulic considerations

Under appropriate flow conditions and transport of debris, all of the construction materials currently being used in hydraulic structures are to some degree susceptible to abrasion. While improvements in materials should reduce the rate of damage, these alone will not solve the problem. Until the adverse hydraulic conditions which can cause abrasion erosion damage are minimized or eliminated, it is extremely difficult for any of the construction materials currently being used to perform in the desired manner. Prior to construction or repair of major structures, hydraulic model studies of the structure should be conducted to identify potential causes of erosion damage and evaluate the effectiveness of various modifications in eliminating those undesirable hydraulic conditions. If the model test results indicate it is impractical to eliminate the undesirable hydraulic conditions, provisions should be made in design to minimize future damage. For example, good design practices should consider the following measures in the construction or repair of stilling basins:

a. Include provisions such as debris traps or low division walls to minimize circulation of debris.

b. Avoid use of baffles which are connected to stilling basin walls. Alternatively, considering their susceptibility to erosion, avoid use of appurtenances such as chute blocks and baffles altogether when the design makes this possible.

c. Use model tests for design and detailing of the terminus of the stilling basin and the exit channel, so as to maximize flushing of the stilling basin and to minimize chances of debris from the exit channel entering the basin.

Maintain balanced flows into the basins of existing structures, using all gates, to avoid discharge conditions where flow separation and eddy action are prevalent. Substantial discharges that can provide a good hydraulic jump without creating eddy action should be released periodically in an attempt to flush debris from the stilling basin. Guidance as to discharge and tailwater relations required for flushing should be developed through model or prototype tests, or both. Periodic inspections should be required to determine the presence of debris in the stilling basin and the extent of erosion. If the debris cannot be removed by flushing operations, water releases should be shut down and the basin cleaned by other means.

6.2-Materials evaluation

Materials, mixtures, and construction practices should be evaluated prior to use in hydraulic structures subjcctcd to abrasion-erosion damage. ASTM C1138 covers a procedure for determining the relative resistance of concrete to abrasion under water. This procedure simulates the abrasive action of waterborne particles (silt, sand, gravel, and other solid objects). This procedure is a slightly modified version of the test method (CRD-C 63) developed by the U.S. Army Corps of Engineers. The development of the test procedure and data from tests on a wide variety of materials and techniques have been described by Liu (1980).

6.3-Materials

A number of materials and techniques have been used in the construction and repair of structures subjected to abrasion erosion damage, with varying degrees of success. The degree of success is inversely proportional to the degree of exposure to those conditions conducive to erosion damage (McDonald 1980). No single material has shown consistently? superior performance when compared to others. Improvements in materials are expected to reduce the rate of concrete damage due to abrasion erosion. The following factors should be considered when selecting abrasion-resistant materials.

Abrasion-resistant concrete should include the largest maximum size aggregate particle, the maximum amount of the hardest available coarse aggregate and the lowest practical water-cementitious material ratio. The abrasion-erosion resistance of concrete containing chert aggregate has been shown to be approximately twice that of concrete containing limestone (Fig. 6.1). Given a good, hard aggregate, any practice that produces a stronger paste structure will increase abrasion-erosion resistance. In some cases where hard aggregate was not available, high-range water-reducing admixtures and silica fume have been used to develop very strong concrete-that is, concrete with a compressive strength of about 15,000 psi (100 MPa)-and to overcome problems with unsatisfactory aggregate (Holland 1983). Apparently, at these high compressive strengths, the hardened cement paste assumes a greater role in resisting abrasion-erosion damage and the aggregate quality becomes correspondingly less important.

Concrete, when producedwith shrinkage-compensating cement, and when properly proportioned and cured, has

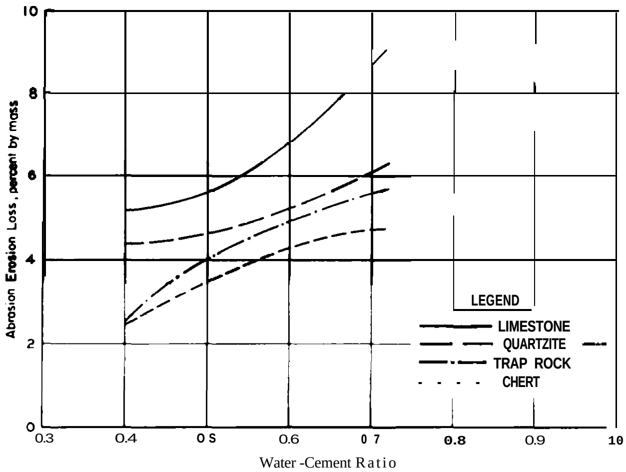


Fig. 6.1-Relationships between water-cement ratio and abrasion-erosion loss

an abrasion resistance from 30 to 40 percent higher than portland cement concrete of comparable mixture proportions, [ACI 223 (1970) and Klieger and Greening (1969)].

Steel fiber-reinforced concrete typically has more paste and mortar per unit volume of concrete, and therefore less coarse aggregate than comparable conventional concrete. Consequently, fiber-reinforced concrete would be expected to have a lower resistance to abrasion-erosion compared to conventional concrete. In laboratory tests, the abrasion loss of a range of fiber-reinforced concrete mixtures was consistently higher than that of conventional concrete mixtures with the same water-cement ratio and aggregate type (Liu and McDonald, 1981). However, the improved impact strength of fiber-reinforced concrete (Schrader, 1981) may be expected to reduce concrete spalling where large debris is being transported by high velocity flow (ACI 544.1R, 1982).

The abrasion-erosion resistance of vacuum-treated concrete, polymer concrete, polymer-impregnated concrete, and polymer-portland cement concrete is significantly superior to that of comparable conventional concrete. This is attributed to a stronger cement matrix. The increased costs associated with materials, production, and placing of these and any other special concretes in comparison with conventional concrete should be considered during the evaluation process.

Several types of surface coatings have exhibited good abrasion-erosion resistance in laboratory tests. These include polyurethanes, epoxy-resin mortar, furan-resin mortar, acrylic mortar, and iron-aggregate toppings. Problems in field application of surface coatings have been reported (McDonald 1980). These have been due primarily to improper surface preparation or thermal incompatibility between coatings and concrete. More recently, formulations have been developed which have coefficients of thermal expansion more similar to that of the concrete substrate.

CHAPTER 7-CONTROL OF EROSION BY CHEMICAL ATTACK

7.1-Control of erosion by mineral-free water

The mild acid attack possible with pure water rarely develops into deterioration that can cause severe structural damage. Generally, the mineral-free water will leach mortar on surfaces exposed to this water. This can be seen on exposed surfaces and at joints and cracks in concrete sections. As the surface mortar is leached from the concrete, more coarse aggregate is exposed, which naturally decreases the amount of mortar exposed. With less mortar exposed, less leaching occurs, and hence major structural problems do not usually result. The gradual erosion of the leached mortar can be minimized by use of special cements, addition of pozzolan to mixes, or use of a variety of protective coatings and sealants applied to concrete surfaces (Tuthill 1966).

7.2-Control of erosion from bacterial action

The process of sulfide generation in a sanitary sewer when insufficient dissolved oxygen is present in the wastewater has been discussed and illustrated by an ASCE-WPCF Joint Task Force (1982). This original work was performed by Pomeroy (1974). Continuing work by Pomeroy and Parkhurst, 1977, produced a quantitative method for sulfide prediction. Engineers involved with projects of this nature would be wise to also review the recommendations set forth in the ACPA *Concrete Pipe Handbook.*

Concrete conduits have served in sewer systems for many years without serious damage where the systems were properly designed and operated. The minimum adequate velocity of flow in the sewer for the strength and temperature of the sewage is usually 2 ft/sec (0.6 m/sec). Providing this velocity without excessive turbulence and providing proper ventilation of the sewer will generally prevent erosion by bacterial action. Turbulence is to be avoided because it is an H_2S releasing mechanism. Where conditions are such that generation of H_2S cannot be totally eliminated by the design of the system, then other means may be applied, such as:

1) using hydrogen peroxide or chlorine compounds to convert the H_2S (WPCF 1979).

a) $H_2O_2 + H_2S \rightarrow 2H_2O + S$

b)(1) $Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$

(2) $HOCl + H_2S \rightarrow S + HCl + H_2O$ (low pH)

(3) $S^{2-} + 4Cl_2 + 8OH^- \rightarrow SO_4^{2-} + 8Cl + 4H_2O$ (high pH)

2) introducing compressed air to keep sewage fresh and thereby prevent the development of the anaerobic environment;

3) using an acid-resistant pipe such as vitrified clay or polyvinyl chloride (PVC) pipe;

4) using acid-resisting liners on the crown of sewers; and/or

Table 7.1-Recommended cement types to use in concrete when mixing water contains sulfates

mg/l sulfate (as SO_4) in water	Cement type
0-150	Any type
150-1500	Type II, IP
1500-10,000	Type V, or Type I or II with a pozzolan which has been shown by test to provide comparable sulfate resistance when used in concrete, or Type K shrinkage-compensating
10,000 or more	Type V plus an approved pozzolan which has been determined by tests to improve sulfate resistance when used in concrete along with Type V

(from ACI 201.2R)

5) increasing the concrete section to allow a sacrificial thickness based on predicted erosion rates.

Graphical methods have been published for determining sulfide buildup in sanitary sewers, using the Pomeroy-Parkhurst equations (Kienow et al. 1982).

Parker (1951) lists the following remedial measures for the control of H_2S attack in concrete sewers:

I. Reduction-potential-generation
- inflow reduction
- partial purification
- chemical dosage to raise oxidation (but addition of nitrates is impracticable)
- aeration
- chlorination
- removal of slimes and silts
- velocity increase

II. Emissions
- turbulence reduction
- treatment with heavy metal salts (Cu, Fe, Zn)
- treatment with alkalies
- full flow in sewer

III. H_2S fixation on concrete
- ventilation
- periodic wetting
- use of resistant concrete
- ammoniation
- use of protective coatings

The designer faced with reducing bacterial action should be aware that a) chlorination may, under certain circumstances, be illegal because it can produce trihalomethane, a known carcinogen; and b) it may also be illegal to add lead salts (which usually are the only cost-effective choice) or other heavy metal salts to waste water.

Lining concrete pipe, walls, and conduit with polyvinyl chloride (PVC) sheets is an effective method of protecting the concrete and reducing surface roughness. This technique has been used commercially for many years. The designer should carefully determine whether the composition and thickness of PVC liners are appropriate for each application.

Further information on remedial measures for sanitary sewer systems is available in U.S. Environmental Protection Agency publication EPA/625/1-85/018 (1985).

7.3-Control of erosion by miscellaneous chemical causes

7.3.1 *Acid environments*-No portland cement concrete, regardless of its other ingredients, will withstand attack from water of high acid concentration. Where strong acid corrosion is indicated, other construction materials or an appropriate surface covering or treatment should be used. This may include applications of sulfur-concrete toppings, epoxy coatings, polymer impregnation, linseed-oil treatments, or other processes, each of which affects acid resistance differently. Replacement of a portion of the portland cement by a suitable amount of pozzolan selected for that property can improve the resistance of concrete to weak acid attack. Also, limestone or dolomite aggregates have been found to be beneficial in extending the life of structures exposed to acid attack (Biczók 1967).

Deterioration similar to that which occurs in the crown of sewers has also occurred above water level in tunnels which drain lakes, the waters of which contain sulfur and other materials that are susceptible to the formation of hydrogen sulfide by bacterial action.

PVC linings may also be used to control deterioration and erosion of concrete in acid environments.

7.3.2 *Alkali-aggregate reaction and chloride admixtures*-Deterioration of concrete caused by alkali-aggregate reaction and by chloride admixtures in the concrete mixture is not included in this discussion. Tuthill (1966) and ACI 201.2R provide information on these topics.

7.3.3 *Soils and ground waters*-Sulfates of sodium, magnesium, and calcium frequently encountered in the "alkali" soils and ground waters of the western United States attack concrete aggressively. ACI 201.2R discusses this in detail. Use of Type V sulfate-resisting cement, which is low in tricalcium aluminate (C_3A), is recommended whenever the sulfate in the water is within the ranges shown for its use in Table 7.1. The subject of designing a sulfate resistant concrete mixture is complex. It is generally agreed that limiting the C_3A content of the cement to the 3 to 5 percent range, as in a Type V cement, is beneficial. But the same could be said of Types I or II cements, where the C_3A content is so restricted. Other issues are also important. There include: restricting the tetracalcium aluminoferrite content (C_4AF) to 10 percent; providing air entrainment (an air entrained mix using Type II cement can be more sulfate resistant than a non-air entrained mix using Type V cement); replacing 20 to 30 percent of the cement content with a pozzolan or fly ash; and using a rich mix, with the water-cement ratio restricted to 0.50. The use of shrinkage-compensating cements, made with Type II or Type V portland cement clinker and adequately sulfated, produces concrete having sulfate resistance equal to or greater than portland cement made of the same type clinker (Mehta and Polivka 1975). Table 7.1 lists the recommended cement types for corresponding sulfate contents.

PART 3-MAINTENANCE AND REPAIR OF EROSION

CHAPTER 8-PERIODIC INSPECTIONS AND CORRECTIVE ACTION

8.1-General

The regular, periodic inspection of completed and operating hydraulic structures is extremely important. The observance of any erosion of concrete should be included in these inspections. The frequency of inspections is usually a function of use and evidence of distress. The inspections provide a means of routinely examining structural features as well as observing and discussing problems needing remedial action. ACI 201.1R, ACI 207.3R, and U.S. Department of the Army publication EM-1110-2-2002 (1979) provide detailed instructions for conducting extensive investigations.

8.2- Inspection program

The inspection program must be tailored to the specific type of structure. The designers should provide input to the program and identify items of primary and secondary importance. The actual inspection team should be composed of qualified technical personnel who know what to look for and can relate in common terminology. The size of the team is generally dependent on the number of technical disciplines required. The program should be established and monitored by an engineer who is experienced in design, construction, and operation of the project.

8.3-Inspection procedures

Prior to the on-site inspection, the team should thoroughly evaluate all available records, reports, and other documentation on the condition of the structure and maintenance and repair, and become familiar with previous recommendations. Some of the more important observations to make during an examination of hydraulic facilities are:

a. Identifying structural cracking, spalling, and displacements within the water passage

b. Identifying surface irregularities

1. Offset into or away from flow
2. Abrupt curvature away from flow
3. Abrupt slope away from flow
4. Local slope changes along flow surface
5. Void or transverse groove
6. Roughened or damaged surfaces which give evidence of cavitation or abrasion erosion
7. Structural imperfections and calcite deposits
8. Cracking, spalling, and rust stains from reinforcement

c. Inspecting gate slots, sills, and seals, including identification of offsets into the flow

d. Locating concrete erosion adjacent to embedded steel frames and steel liners and in downstream water passages

e. Finding vibration of gates and valves during operation

f. Observing defective welded connections and the pitting and/or cavitation of steel items

g. Observing equipment operation and maintenance

h. Making surveys and taking cross sections to determine the extent of damage

i. Investigating the condition of concrete by nondestructive methods or by core drilling and sampling, if distressed conditions warrant

j. Noting the nature and extent of debris in water passages

Observed conditions, the extent of the distress, and recommendations for action should be recorded by the inspection team for future reference. High-quality photographs of deficiencies are extremely beneficial and provide a permanent record which assists in identifying slow progressive failures. A report should be written for each inspection to record the condition of the project and to justify funding for repairs.

8.4-Reporting and evaluation

The inspection report may vary from a formal publication to a trip report or letter report. The report should include the standard items: who, why, what, where, and when. A pre-established outline is usually of value. An inspection checklist of deficiencies and subsequent corrective actions should be established from prior inspections. Any special items of interest may be shown in sketches or photos. The report should address existing and potential problems, and it should categorize the deficiencies relative to the urgency of corrective action and identify the extent of damage, probable cause of damage, and probable extent of damage if immediate repairs are not made. It is extremely important that the owner or agency distribute the report in accordance with applicable U.S. federal or state safety regulations.

When the inspection report indicates that remedial action is required, the next step may be either a supplemental investigation or the actual corrective action. Deficiencies noted in the inspection should be evaluated and categorized as to minor, major, or potentially catastrophic. The scope of work should be defined as early as possible in order to establish reliable budget estimates. Design for proper repair schemes sometimes requires model tests, redesign of portions of the structure, and materials investigations. Each of these items requires funding through the owner's program of operations. The more details identified in the scope of work, the more accurate the cost estimate. Wherever possible, it is important to correct the probable cause, so that the repairs will not have to be repeated in the near future.

CHAPTER 9-REPAIR METHODS AND MATERIALS

9.1-Design considerations

9.1.1 *General*-It is desirable to eliminate the cause of the erosion whenever possible; however, since this is not always possible, a variety of materials and material combinations is used for the repair of concrete. Some materials are better suited for certain repairs, and judgment should be exercised in the selection of the proper material. Consideration also should be given to the time available to make repairs, access points, logistics in material supply, ventilation, nature of the work, available equipment, and skill and experience of the local labor force.

Detailed descriptions of repair considerations and procedures may be found in the U.S. Bureau of Reclamation's *Concrete Manual* (1985).

9.1.2 *Consideration of materials*-A major factor which is critical to the success of a repair is the relative volume change between the repair material and the concrete substratum. Many materials change volume as they initially set or gel, almost all change volume with changes in moisture content, and all change volume with changes in temperature. If a repair material decreases sufficiently in volume relative to the concrete, it will develop cracks perpendicular to the interface, generally at a spacing related to the repair depth. Shear and tensile stresses also will develop at the interface with a maximum magnitude at the tip of each crack, and the stresses will cycle with each temperature and moisture cycle. ASTM C 884 evaluates a specific class of materials with respect to temperature change. Similar tests should be applied to all repair materials.

Since differential volume change imposes stresses at an interface between a repair material and the concrete, suitable preparation of that interface is essential to the success of the repair. Sound concrete may not be able to resist stresses imposed by a high volume change repair material, whereas it may resist those imposed by a low volume change material. ACI 503R has recommended that the interface between concrete and epoxy patches exhibit an absolute minimum tensile strength, by a specific test method, of 100 psi (0.69 MPa).

Normal portland cement concrete is generally the least expensive replacement material and will most nearly match the characteristics of the in-place concrete with regard to temperature change. Normal concrete will almost certainly be subject to an initial shrinkage relative to the original concrete and possibly thermal stresses from heat of hydration if the depth of replacement is sufficient to develop a significant temperature gradient within the repair.

The best way to minimize plastic and drying shrinkage is to minimize water content in the replacement concrete. Thus, stiff mixtures, with or without the incorporation of polymers or copolymers as a replacement for part of the mix water, may be considered. Stiff mixtures may require careful use of bonding agents and be more difficult to place and consolidate. It also may be difficult to consolidate stiff mixtures around reinforcing steel. The use of polymers can improve the useability of the concrete, but also substantially increases material costs, may present additional handling hazards, and may require special construction techniques.

9.2-Methods and materials

9.2.1 *Steel plating*-Installing stainless steel liner plates on concrete surfaces subject to cavitation erosion has been a generally successful method of protecting the concrete against cavitation erosion. Colgate's (1977) studies show stainless steel to be about four times more resistant to cavitation damage than ordinary concrete. The currently preferred stainless material is ASTM A 167, S30403 (formerly SS304L), from the standpoint of excellent corrosion and cavitation resistance, and weldability. The steel plates must be securely anchored in place and be sufficiently stiff to minimize the effects of vibration. Vibration of the liner plate can lead to fracturing and eventual failure of the underlying concrete or failure of the anchors. Grouting behind the plates to prevent vibration is recommended. Unfortunately, the steel plating may hide early signs of concrete distress.

This repair method, like many others, treats only the symptom of erosion and eventually, if the cavitation is not reduced or eliminated, the steel itself may become damaged by pitting.

9.2.2 *Dry-packed concrete*-Use of dry-packed concrete is generally limited to applications where the material can be tamped into cavities which have a depth at least as great as their width. These limited applications are necessary because the material is friable until compacted in place by tamping or ramming. The low water content of the dry-pack, combined with the density obtained by the compaction process, gives a patch that will experience very little drying shrinkage and will have expansion properties similar to the parent concrete.

Dry-pack should consist of one part cement to two parts masonry sand (passing No. 16 screen) (1.18 mm sieve). Latexes and other special admixtures can be used in the mixture when bonding or another special characteristic is desired. The consistency of the dry-pack mortar should be such that when balled in the hand, the hand is moist but not dirty. White cement can be blended with gray cement if appearance is important. The completed work should be moist-cured, just as any concrete.

Dry-packed concrete repairs, as is true of all repairs, require care on the part of both designer and constructor to insure that the final product meets the intended design. Properly made, dry-packed concrete repairs have proven to be very satisfactory.

"Damp-pack," a similar material discussed in U.S. Army Corps of Engineers Technical Report MRDL 2-74 (1974) and the ACI *Manual of Concrete Inspection (1981)*, can be sprayed onto existing concrete for repair of peeled areas and other shallow defects.

9.2.3 *Fiber-reinforced concrete (FRC)*-Conventional concrete typically performs poorly where the following material properties are important to the life of the structure or its performance: fatigue strength, cavitation and abrasion-erosion resistance, impact strength, flexural strength and strain capacity, post-cracking load-carrying capability, and high shear strength. FRC utilizes randomly oriented discrete fiber reinforcement in the mixture and offers a practical way of obtaining these properties for most applications. ICOLD Bulletin 40A (1988) describes its use in dams. FRC has been successfully used in some erosion situations. There are examples where FRC repairs have been resistant to the combined effects of cavitation and abrasion erosion by large rock and debris carried at high velocity. On the other hand, laboratory abrasion-erosion tests under conditions of low velocity carrying small-size particles have shown that the addition of fibers may not be beneficial, and in fact may be detrimental (Liu and McDonald 1981). ACI 544.1R and ACI publication SP-81 provide additional information regarding the use of FRC.

9.2.4 *Epoxy resins*-Resins are natural or synthetic, solid or semisolid organic materials of high molecular weight. Epoxies are one type of resin. These materials are typically used in preparation of special coatings or adhesives or as binders in epoxy-resin mortars and concretes. Several varieties of resin systems are routinely used for the repair of concrete structures. ACI 503R describes the properties, uses, preparations, mixtures, application, and handling requirements for epoxy resin systems.

The most common use of epoxy compounds is in bonding adhesives. Epoxies will bond to most building materials, with the possible exception of some plastics. Typical applications include the bonding of fresh concrete to existing concrete. Epoxies can be used also for bonding dry-pack material, fiber reinforced concrete, polymer concretes, and some latex-modified concretes to hardened concrete. Epoxy formulations have been developed recently which will bond to damp concrete and even bond to concrete under water. There are case histories of successful uses of these materials in hydraulic structures. To help assure proper selection and use of materials, consultation with product representatives is advised before an epoxy is specified or procured. ASTM C 881 is a specification for epoxy bonding systems useful in concrete repairs, and ACI 503.2 covers epoxy bonding in repair work.

Experience has shown that the application of epoxies can create serious problems in areas of high-velocity flow. If the finished surface has a very smooth or glassy texture, flow at the boundary can be disrupted and may have the effect of a geometric irregularity which could trigger cavitation. This texture problem can be minimized by using special finishing techniques and/or improving the surface texture of the patch with sand. Sometimes the patch can be too resistant to damage, with the result that the abutting original material erodes away, leaving an abrupt change in surface geometry and developing a condition worse than the original damage.

Epoxy mortars and epoxy concretes use epoxy resins for binder material instead of portland cement. These materials are ideal for repair of normally submerged concrete, where ambient temperatures are relatively constant. They are very expensive and can cause problems as a result of their internal heat generation. Mixed results have been observed in the epoxy-mortar repair of erosion of outlet surfaces, dentates, and baffle blocks (McDonald 1980). Depending on the epoxy formulation, the presence of moisture, either on the surface or absorbed in the concrete, can be an important factor and affect the success of the repair. ACI 503.4 is a specification for epoxy mortar in repair work.

The concept of improving concrete by incorporating the epoxy directly into the mix was encouraged by the successful latex modification of concrete (Murray and Schrader 1979). Several commercial products have been developed and research is continuing. The epoxies generally enhance the concrete's resistance to freeze-thaw spalling, chemical attack, and mechanical wear. Epoxy-modified concrete (Christie, McClain, and Melloan 1981) has a curing agent which is retarded by the water in the mixture. As the water is used up by cement hydration and drying, the epoxy resin begins to gel. Accordingly, the mixture will not become sticky until the portland cement begins to set, and this greatly extends the "pot life" of the wet concrete. To date, these materials have limited use in hydraulic structures.

9.2.5 *Acrylics and other polymer systems*-There are three main ways in which polymers have been incorporated into concrete to produce a material with improved properties as compared to conventional portland cement concrete. These are polymer-impregnated concrete (PIC), polymer-portland cement concrete (PPCC), and polymer concrete (PC).

Polymer-impregnated concrete (PIC) is a hydrated Portland-cement concrete that has been impregnated with a monomer which is subsequently polymerized in situ. By effectively case hardening the concrete surface, impregnation protects structures against the forces of cavitation (Schrader 1978) and abrasion erosion (Liu 1980). The depth of monomer penetration depends on the porosity of the concrete and the process and pressure under which the monomer is applied. In addition to noting that these materials are quite costly, the engineer is cautioned that some monomer systems can be hazardous and that monomer systems require care in handling and should be applied only by skilled workmen experienced in their use (DePuy 1975). Surface impregnation was used at Dworshak Dam in the repair of cavitation and abrasion erosion damage to the regulating outlet tunnels (Schrader and Kaden 1976a) and stilling basin (McDonald 1980, and Schrader and Kaden 1976b). High-head erosion testing of PIC at Detroit Dam test facility has shown excellent performance (U.S. Army Corps of Engineers 1977).

Polymer portland cement concrete (PPCC) is made by the addition of water-sipersible polymers directly into wet concrete mix. PPCC, compared to conventional concrete, has higher strength, increased flexibility, improved adhesion, superior abrasion and impact resistance, and usually better freeze-thaw performance and improved durability. These properties can vary considerably depending on the type of polymer being used. The most commonly used PPCC is latex-modified concrete (LMC). Latex is a dispersion of organic polymer particles in water. Typically, the fine aggregate and cement factors are higher for PPCC than for normal concrete.

Polymer concrete (PC) is a mixture of fine and coarse aggregate with a polymer used as the binder. This results in rapid-setting material with good chemical resistance and exceptional bonding characteristics. So far, polymer concrete has had limited use in large-scale repair of hydraulic structures because of the expense of large volumes of polymer for binder. Thermal compatibility with the parent concrete should be considered before using these materials.

Polymer concretes are finding application as concrete repair materials for patches and overlays, and as precast elements for repair of damaged surfaces (Fontana and Bartholomew 1981; Scanlon 1981; Kuhlmann 1981; Bhargava 1981). Field test installations with precast PC have been made on parapet walls at Deadwood Dam, Idaho, and as a repair of cavitation and abrasion damage in the stilling basin of American Falls Dam.

ACI 548R and ACI SP-58, "Polymers in Concrete (1978)," provide an overview of the properties and use of polymers in concrete. Smoak (1985) has described polymer impregnation and polymer concrete repairs at Grand Coulee Dam.

9.2.6 *Silica-fume concrete*-Laboratory tests have shown that the addition of an appropriate amount of silica fume and a high-range water-reducing admixture to a concrete mixture will greatly increase compressive strength. This, in turn, increases abrasion-erosion resistance (Holland 1983, 1986a, 1986b). As a result of these tests, concretes containing silica fume were used by the US Army Corps of Engineers to repair abrasion-erosion damage in the stilling basin at Kinzua Dam (Holland et al. 1986) and in the concrete lining of the low-flow channel. Los Angeles River (Holland and Gutschow 1987). Despite adverse exposure conditions, particularly at Kinzua Dam, the silica fume concrete continues to exhibit excellent resistance to abrasion erosion.

Silica fume offers potential for improving many properties of concrete. However, the very high compressive strength and resulting increase in abrasion-erosion resistance are particularly beneficial in repair of hydraulic structures. Silica fume concrete should be considered in repair of abrasion-erosion susceptible locations, particularly in those areas where available aggregate might not otherwise be acceptable. Guidance on the use of silica fume in concrete is given in ACI 226 (1987).

9.2.7 *Shotcretes*-Shotcrete has been used extensively in the repair of hydraulic structures. This method permits replacing concrete without the use of formwork, and the repair can be made in very restricted areas. Shotcrete, also known as pneumatically applied mortar, can be an economical alternative to other more conventional systems of repair. ACI 506R provides guidance in the manufacture and application of shotcrete. In addition to conventional shotcrete, modified concretes such as fiber-reinforced shotcrete, polymer shotcrete, and silica fume shotcrete have been applied by the air-blown or shotcrete method.

9.2.8 *Coatings*--High-head erosion tests have been conducted using both polyurethane and neoprene coatings (Houghton, Borge, and Paxton 1978). Both coatings exhibited good resistance to abrasion and cavitation. The problem with flexible coatings like these is their bond to the concrete surfaces. Once an edge or a portion of the coating is torn from the surface, the entire coating can be peeled off rather quickly by hydraulic force.

9.2.9 *Preplaced-aggregate concrete*-Preplaced-aggregate concrete, also referred to as "prepacked concrete," is used in the repair of large cavities and inaccessible areas. Clean, well-graded coarse aggregate, generally of 0.5 to 1.5 in. (12 to 38 mm) maximum size, is placed in the form. Neat cement grout or a sanded grout, with or without admixtures, is then pumped into the aggregate matrix through openings in the bottom of the forms or through grout pipes embedded in the aggregate. The grout is placed under pressure, and pressure is maintained until initial set. Concrete placed by this method has a low volume change because of the point-to-point contact of the aggregate; there is high bond strength to top bars for the same reason. The use of pozzolans, water-reducing admixtures, and low water contents is recommended to further reduce shrinkage and thermal volume changes, while maintaining the fluidity required for the grout to completely fill the voids in the aggregate. ACI 304.1R provides details and guidance for the use of preplaced-aggregate concrete.

9.2.10 *Pipe inserts*--For repair of small-diameter pipes, many of the methods discussed in the previous sections of this report are not applicable. A common construction practice today is to obtain a jointless, structurally sound pipe-inside-a-pipe without excavating the existing unsound pipe. One such method that has been used successfully is to insert a plastic pipe inside the deteriorated concrete pipe and then fill the annular space between the concrete and plastic liner with grout. With the proper selection of material for the plastic liner pipe insert, this repair method can provide a sound, chemically resistant lining (U.S. Dept. of Housing and Urban Development 1985, and U.S. Environmental Protection Agency 1983).

Another popular method is the installation of a resin saturated fiberglass "hose" into the pipeline. The hose is inserted into the pipeline using water pressure. After installation, the hose is filled with hot water to initiate the chemical reaction of the resin. The hardened resin forms a rigid pipe lining.

9.2.11 *Linings*-Tunnels, conduits, and pipes that have surface damage due to abrasion erosion, bacterial action, or chemical/acid attack can be protected from further damage with a non-bonded mechanically attached PVC lining. Depending on the extent of the damage, some patching of the concrete surface may be required before installation.

9.2.12 *Aeration slots*-The installation of an aeration slot is not only a consideration in the design of a new facility but often a very appropriate remedial addition to a structure experiencing cavitation erosion damage. Structural restoration and the addition of aeration slots has been used in the repair of several structures. See Section 5.3 for a more detailed discussion of this method. The addition of aeration slots will likely reduce the flow capacity of the structure significantly because of the added volume of entrained air.

CHAPTER l0--REFERENCES

l0.1-Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Concrete Institute

117 Standard Specifications for Tolerance for Concrete Construction and Materials
20l.lR Guide for Making a Condition Survey of Concrete in Service
201.2R Guide to Durable Concrete
207.3R Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions
223 Standard Practice for the Use of Shrinkage-Compensating Concrete
302.lR Guide for Concrete Floor and Slab Construction
304 Guide for Measuring, Mixing, Transporting, and Placing Concrete
308 Standard Practice for Curing Concrete
309R Guide for Consolidation of Concrete
347R Guide to Formwork for Concrete
503R Use of Epoxy Compounds with Concrete
503.2 Standard Specification for Bonding Plastic Concrete to Hardened Concrete with a Multi-Component Epoxy Adhesive
503.4 Standard Specification for Repairing Concrete with Epoxy Mortars
506R Guide to Shotcrete
506.2 Specification for Materials, Proportioning, and Application of Shotcrete
544.lR State-of-the-Art Report on Fiber Reinforced Concrete
544.2R Measurement of Properties of Fiber Reinforced Concrete
548.1R Guide for Use of Polymers in Concrete

American Society for Testing and Materials

A 167 Standard Specification for Stainless and Heat-Resisting Chromium-Nickel Steel Plate, Sheet, and Strip
C 150 Standard Specification for Portland Cement
C 131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C 418 Standard Test Method for Abrasion Resistance of Concrete by Sandblasting
C 535 Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
C 779 Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
C 881 Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete
C884 Standard Test Method for Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay
C 1138 Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)

U.S. Army Corps of Engineers

CRD-C 63-80 Test Method for Abrasion-Erosion Resistance of Concrete (Underwater Method)

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219

ASTM
1916 Race St.
Philadelphia, PA 19103

U.S. Army Corps of Engineers
U.S. Army Engineer Waterways Experiment Station
Vicksburg, MS 39180

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APPENDIX-NOTATION

α = coefficient
ℓ = length of air space between the jet and the spillway floor, ℓ*
p_0 = absolute pressure at a given Point 0, 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
v = average jet velocity at midpoint of trajectory, ℓ/T
v_0 = average velocity at section 0, ℓ/T
z_c = elevation of the vapor bubble, ℓ
z_0 = elevation at centerline of pipe, ℓ
γ = specific weight of water, F/ℓ^3
ρ = density of water, FT^2/ℓ^4
σ = cavitation index
σ_c = value of cavitation index at which cavitation initiates

* ℓ = length, F = force, T = time

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