

ACI 207.6R-17

# Report on the Erosion of Concrete in Hydraulic Structures

Reported by ACI Committee 207



American Concrete Institute  
*Always advancing*



## **Report on the Erosion of Concrete in Hydraulic Structures**

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

**American Concrete Institute**  
**38800 Country Club Drive**  
**Farmington Hills, MI 48331**  
**Phone: +1.248.848.3700**  
**Fax: +1.248.848.3701**

[www.concrete.org](http://www.concrete.org)

# Report on the Erosion of Concrete in Hydraulic Structures

Reported by ACI Committee 207

John W. Gajda, Chair

Christopher C. Ferraro, Secretary

Fares Y. Abdo  
Oscar R. Antommattei  
Terrence E. Arnold  
Katie J. Bartojay\*  
Teck L. Chua  
Timothy P. Dolen

Darrell Elliot†  
Barry D. Fehl  
Mario Garza  
Melissa O. Harrison  
Michael G. Hernandez  
James K. Hicks

Rodney E. Holderbaum  
Ronald L. Kozikowski  
Tibor J. Pataky  
Jonathan L. Poole  
Henry B. Prenger  
Ernest A. Rogalla

Ernest K. Schrader  
Kuntay K. Talay  
Nathaniel F. Tarbox  
Stephen B. Tatro  
Michael A. Whisonant  
Fouad H. Yazbeck

## Consulting Members

Jeffrey C. Allen  
Randall P. Bass  
Anthony A. Bombich

Robert W. Cannon  
Eric J. Ditchey  
Brian A. Forbes

Allen J. Hulshizer  
Richard A. Kaden  
William F. Kepler

David E. Kiefer

\*Primary author of this report.

†Deceased.

Committee 207 would like to thank the following individuals for their contribution to this report: J. Ballentine, J. F. Best, G. Mass, W. McEwen, M. Petrovsky, and M. Stegallo.

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

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

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

## CONTENTS

### CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

1.1—Introduction, p. 2

1.2—Scope, p. 2

### CHAPTER 2—NOTATION, p. 2

2.1—Notation, p. 2

### CHAPTER 3—EROSION BY CAVITATION, p. 3

3.1—Mechanism of cavitation, p. 3

3.2—Cavitation index, p. 3

3.3—Cavitation damage, p. 4

### CHAPTER 4—EROSION BY ABRASION, p. 6

4.1—General, p. 6

4.2—Stilling basin damage, p. 6

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

ACI 207.6R-17 supersedes ACI 210R-93(08) and was adopted and published September 2017.

Copyright © 2017, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

- 4.3—Power plant tailrace damage, p. 7
- 4.4—Navigation lock damage, p. 8
- 4.5—Tunnel lining damage, p. 8
- 4.6—Hydraulic jacking, p. 8

## CHAPTER 5—EROSION BY CHEMICAL ATTACK, p. 9

- 5.1—Sources of external chemical attack, p. 9
- 5.2—Erosion by mineral-free water, p. 9
- 5.3—Erosion by miscellaneous causes, p. 9

## CHAPTER 6—CONTROL OF CAVITATION EROSION, p. 10

- 6.1—Hydraulic design principles, p. 10
  - Example 1, p. 10
- 6.2—Cavitation indexes for damage and construction tolerances, p. 11
  - Example 2, p. 11
- 6.3—Using aeration to control damage, p. 12
- 6.4—Materials, p. 13
- 6.5—Materials testing, p. 14
- 6.6—Construction practices, p. 14

## CHAPTER 7—CONTROL OF ABRASION EROSION, p. 15

- 7.1—Hydraulic considerations, p. 15
- 7.2—Materials evaluation, p. 16
- 7.3—Materials, p. 16

## CHAPTER 8—CONTROL OF EROSION BY CHEMICAL ATTACK, p. 17

- 8.1—Control of erosion by mineral-free water, p. 17
- 8.2—Control of erosion from acid attack due to bacterial action, p. 18
- 8.3—Control of erosion by miscellaneous chemical causes, p. 18

## CHAPTER 9—PERIODIC INSPECTIONS AND CORRECTIVE ACTION, p. 19

- 9.1—General, p. 19
- 9.2—Inspection program, p. 19
- 9.3—Inspection procedures, p. 19
- 9.4—Reporting and evaluation, p. 19

## CHAPTER 10—REPAIR METHODS AND MATERIALS, p. 20

- 10.1—Design considerations, p. 20
- 10.2—Methods and materials, p. 20

## CHAPTER 11—REFERENCES, p. 22

- Authored documents, p. 23

## CHAPTER 1—INTRODUCTION AND SCOPE

### 1.1—Introduction

Erosion is the progressive disintegration of a solid by: 1) cavitation; 2) abrasion; or 3) chemical action. Although

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

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

### 1.2—Scope

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

## CHAPTER 2—NOTATION

### 2.1—Notation

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

**CHAPTER 3—EROSION BY CAVITATION**

**3.1—Mechanism of cavitation**

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

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

**3.2—Cavitation index**

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

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

$$p_1 = p_c + \gamma(z_c - z_0) \tag{3.2a}$$

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 Point (0).

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

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

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

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

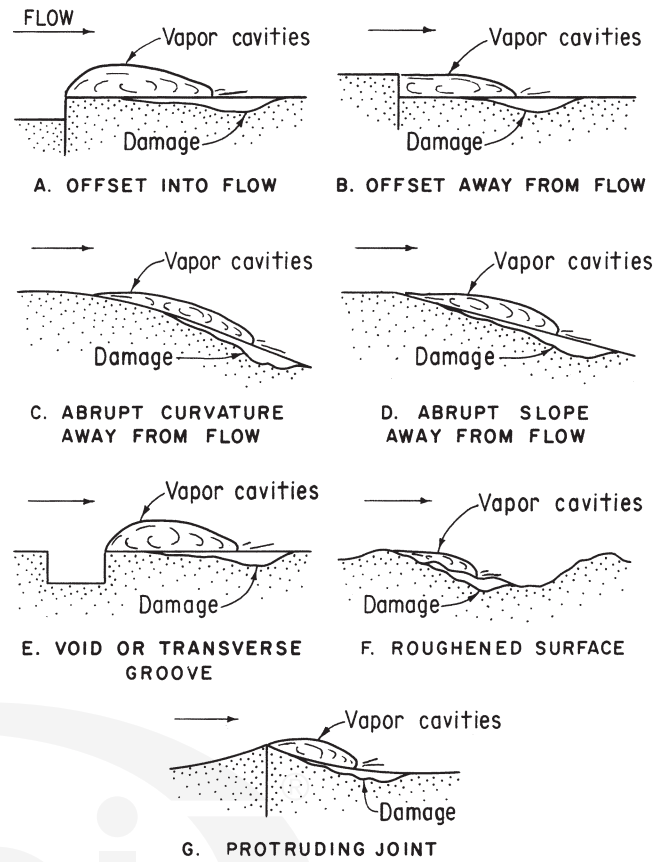


Fig. 3.1a—Cavitation situations at surface irregularities (Falvey 1990).

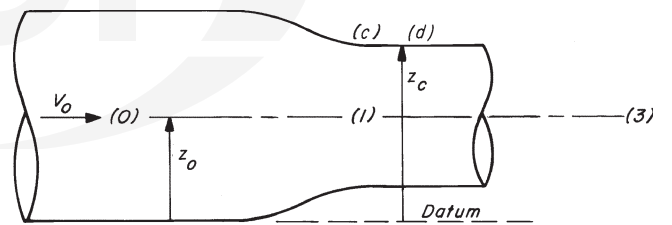


Fig. 3.1b—Tunnel contraction.

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

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

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

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

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

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