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# Guide to Underwater Repair of Concrete

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## Guide to Underwater Repair of Concrete

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**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)

## Guide to Underwater Repair of Concrete

Reported by ACI Committee 546

Peter Barlow,\* Chair

Chris White, Secretary

Michael M. Chehab  
Kevin Conroy  
Marwan A. Daye  
Michael J. Garlich\*  
Paul E. Gaudette  
Timothy R. W. Gillespie

Matthew R. Hansen  
Susan Isble  
Lawrence F. Kahn  
Brian F. Keane  
Kenneth M. Lozen  
John S. Lund

James E. McDonald  
Terrence McDonald  
Jay H. Paul  
Johan L. Silfwerbrand  
Michael M. Sprinkel  
Aamer H. Syed

George I. Taylor  
Joseph E. Tomes  
David A. VanOcker  
Kurt Wagner  
David W. Whitmore\*

\*Subcommittee members who prepared this guide.

### Consulting Members

Peter Emmons  
Fred R. Goodwin  
Harald G. Greve

Noel P. Mailvaganam  
Kevin A. Michols  
Richard Montani

Don T. Pyle  
Nicholas R. Triandafilou  
Patrick M. Watson

*This document provides guidance on the selection and application of materials and methods for the repair and strengthening of concrete structures under water. An overview of materials and methods for underwater repair is presented as a guide for making a selection for a particular application.*

**Keywords:** anti-washout; cathodic protection; concrete removal; deterioration; diver; formwork; marine placement; pile-jackets; polymer(s); repair; surface preparation; tremie; underwater.

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## CHAPTER 1—GENERAL

### 1.1—Introduction

The repair of concrete structures under water presents many complex problems. Although the applicable basic repair procedures and materials are similar to those required in typical concrete repair, the harsh environmental conditions and specific problems associated with working under water or in the splash zone area (Fig. 1.1a) create many

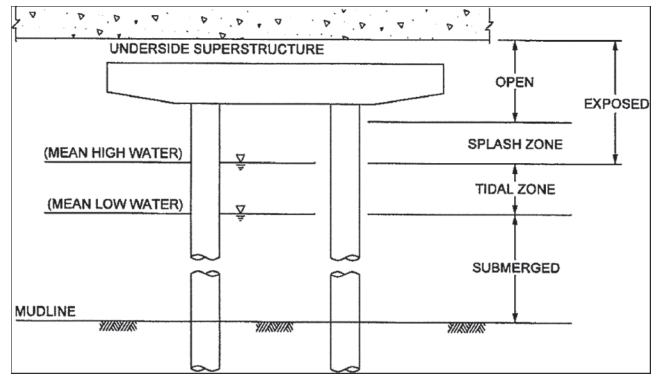


Fig. 1.1a—Repair zones: submerged, tidal, and exposed.

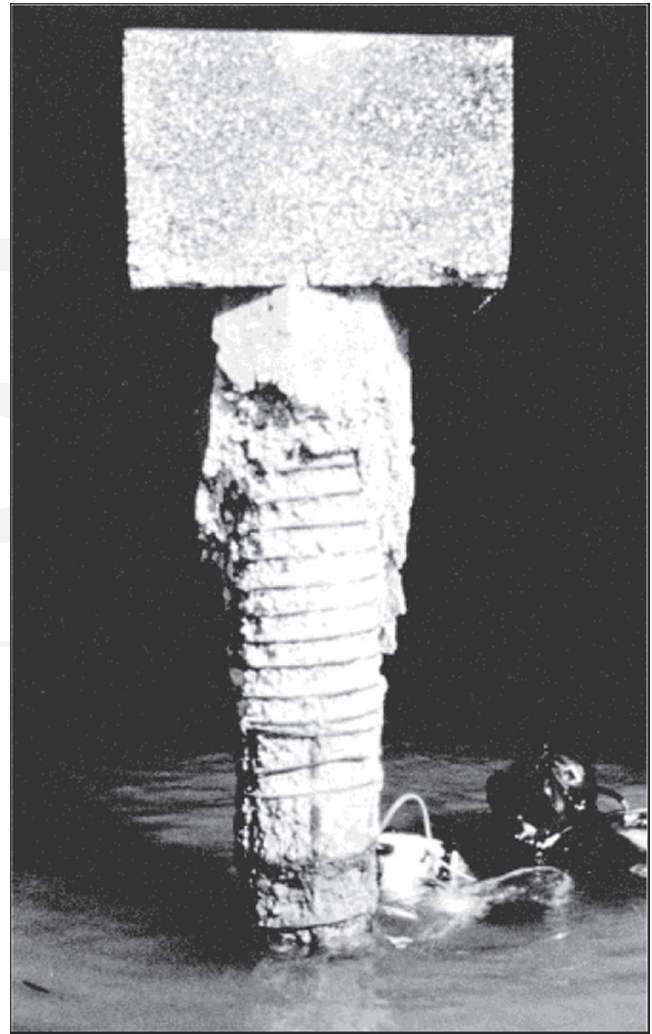


Fig. 1.1b—Deteriorated pile in tidal and exposed zones (image courtesy of M. J. Garlich).

differences. The repair of concrete under water is usually difficult, requiring specialized products and systems, and the services of highly qualified and experienced design professionals and contractors.

Proper evaluation of existing structural condition is the essential first step in designing long-term repairs. To be most effective, the evaluation procedure should begin with a review of historical information on the structure and its envi-

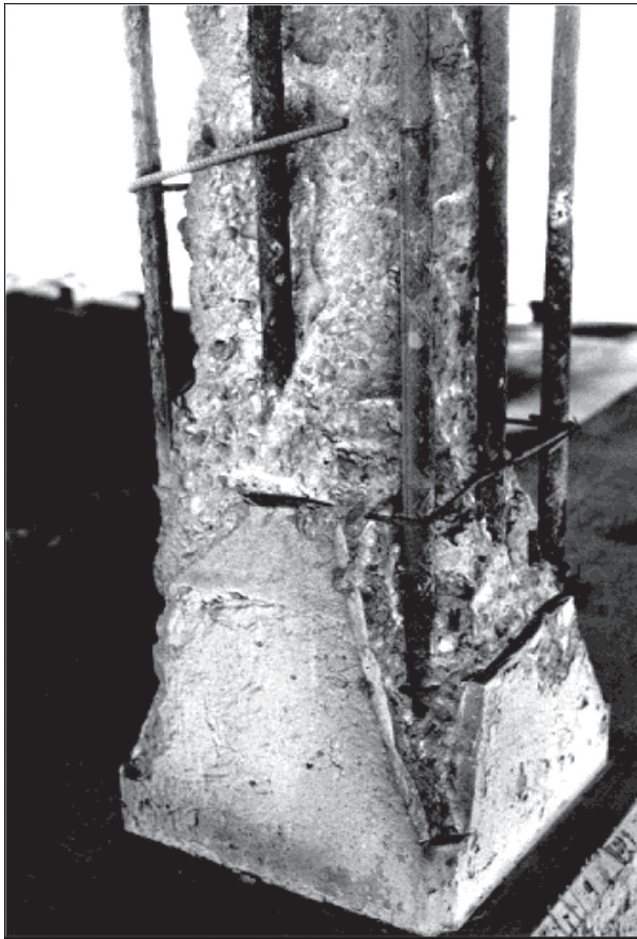


Fig. 1.1c—Advanced deterioration; pile has been cleaned (image courtesy of M. J. Garlich).

ronment, including any changes made to the structure over time and the records of prior on-site inspections or repairs. Accurate repairs can be designed only after the extent of deterioration is documented and the failure mechanism is determined. In addition, proper repair techniques and installation procedures should be followed to produce an optimum repair system.

Water containing oxygen and contaminants can aggressively attack concrete (Fig. 1.1b and 1.1c). Selecting appropriate repair materials and methods, and maintaining quality control not normally associated with repair above water are critical when working in a marine environment. As such, underwater repair of concrete is a specialized and highly technical part of concrete repair technology. Successful repairs can be achieved when these factors are carefully implemented. This guide provides an overview of underwater repair technology to assist the design professional, contractor, and owner in making repair decisions.

## 1.2—Scope

This guide covers the repair of concrete structures in the splash zone and underwater portions of structures located in lakes, rivers, seas, oceans, and groundwater. Concrete deterioration, investigation and testing procedures, preparation, materials and methodology, and inspection procedures are

described. Design considerations and references for underwater repair of concrete bridges, wharves, pipelines, piers, outfalls, bulkheads, and offshore structures are identified. Scour repair, however, is not included in this guide.

One option for repairing underwater structures is to construct a cofferdam around the structure and remove the water inside the cofferdam. Concrete repairs can then be installed in the dry, as discussed in [ACI 546R](#).

## CHAPTER 2—NOTATION AND DEFINITIONS

### 2.1—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology.” Definitions provided herein complement that resource.

**anti-washout admixture**—chemical admixture that reduces the loss of fine materials from cement-based materials when placed in water.

**tremie**—a pipe extending below water, generally with a funnel-shaped top, through which concrete can be deposited.

## CHAPTER 3—CAUSES OF DETERIORATION

### 3.1—Introduction

Concrete structures located in water are susceptible to various types of deterioration. The type and rate of deterioration depends on various factors including concrete properties, reinforcing type, construction practices, and environmental conditions. Generally, structures located in warm marine (salt water) environments experience more rapid deterioration. In many cases, observed deterioration is the result of several deterioration mechanisms acting concurrently ([Holland et al. 2014](#)).

### 3.2—Deficient construction practices

Underwater placement of concrete and other materials is often susceptible to deficient construction practices due to the difficult working conditions and the inability to provide adequate inspection during construction. Failure to follow specified procedures and good practice or outright carelessness may lead to construction errors. Typically, most of these errors do not lead directly to failure or deterioration of concrete. Instead, they enhance the adverse impacts of other mechanisms.

Deficient practices include:

- (a) Exceeding the target water-cementitious material ratio ( $w/cm$ )
- (b) Inadequate surface preparation
- (c) Improper alignment of formwork
- (d) Improper concrete placement and consolidation
- (e) Improper location of reinforcing steel
- (f) Movement of formwork during placement
- (g) Premature removal of forms or shores
- (h) Settlement of the concrete during hardening

Each of these construction errors is discussed in [USACE \(1995\)](#).

One deficiency observed in marine structures is the cracking of precast concrete piles resulting from improper

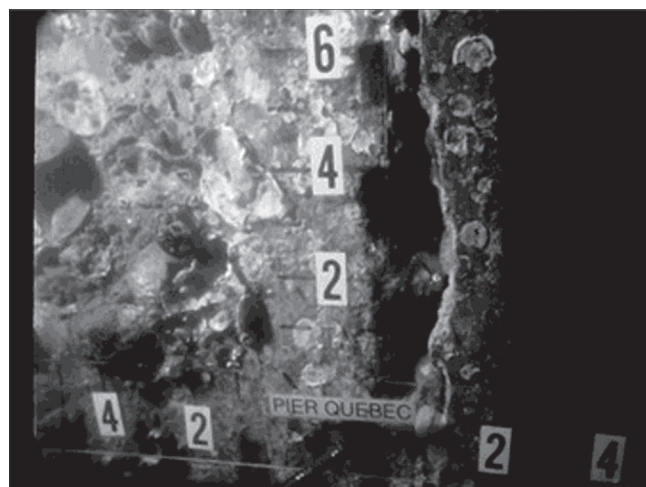


Fig. 3.2—Failure of precast pile attributed to delayed ettringite formation (image courtesy of T. Spencer).

driving practices. This problem is characterized by horizontal cracks generally occurring in the below-water portion of the pile. Both under water and in the splash zone, cracks in concrete increase concrete permeability near the crack. Thus, in seawater, chloride penetration is amplified both in depth and concentration in the immediate location of the crack, leading to the creation of an anode at the reinforcing bars in the vicinity of the crack. This usually does not lead to significant corrosion of steel reinforcement in underwater concrete because of the low oxygen availability and the sealing of the crack by lime, which leaches from the concrete and also comes from marine organisms. In the splash zone, however, the presence of such cracks can lead to the early onset of local reinforcing steel corrosion.

Failure of precast prestressed piles attributed to delayed ettringite formation (Fig. 3.2) has been reported (Spencer and Blaylock 1997; Stark et al. 1999). This deterioration is attributed to improper high temperature curing practices during manufacturing. Concrete distress due to delayed ettringite formation is characterized by cracking and softening of the concrete along with disintegration and loss of concrete. Observed deterioration has included near-total loss of concrete over substantial portions of affected piles.

### 3.3—Marine organisms

**3.3.1 Rock borers**—Marine organisms resembling ordinary clams are capable of boring into porous concrete, as well as rock. These organisms, known as pholads, make shallow oval-shaped burrows in the concrete. Rock-borers in warm-water areas are also able to dissolve and bore into concrete made with limestone aggregate, even if the aggregate and concrete is dense.

**3.3.2 Acid attack from acid-producing bacteria**—Anaerobic, sulfate-reducing bacteria can produce hydrogen sulfide. Sulfur-oxidizing bacteria, if also present, can oxidize the hydrogen sulfide to produce sulfuric acid, common in sewers. Also, oil-oxidizing bacteria can produce fatty acids in aerobic conditions, such as in the splash zone, which attacks the cement paste. In addition, the acids can reduce

the pH of the concrete to approximately 8 or lower, at which level the passive layer breaks down, and reinforcement corrosion may occur (Thornton 1978; Khoury et al. 1985). Deterioration is characterized by a loss of the cement matrix and a rough surface of exposed concrete aggregate. Aggregate loss may occur in severe cases. Microbial-induced deterioration resulting from the bacteria that release sulfuric acid, causing dissolution of concrete, has been reported as creating surface deterioration of concrete bridge piling in Texas (Hu et al. 2012).

### 3.4—Chemical attack

Concrete under water is susceptible to deterioration caused by a wide range of chemicals. This deterioration may be classified as that caused by chemicals outside the concrete, and that caused by chemicals present in the concrete constituents themselves. In cases of external attack, the water frequently provides a continuous fresh supply of these chemicals. The water also washes the reaction products away and removes loose aggregate particles, exposing new concrete surfaces to further attack.

Internal attack is accelerated by porous concrete, cracks, and voids. Alkali-silica reactions and corrosion of reinforcement are examples of internal attack. Internal deterioration also results when soluble constituents of concrete are leached out, resulting in lower concrete strengths and higher porosity.

Splash-zone concrete is particularly susceptible to chemical attack because of the abundant supply of oxygen and frequent wetting-and-drying cycles caused by daily wave or tidal action, and temperature fluctuations.

Chemicals present in water surrounding the concrete can cause deterioration that varies in rate from very rapid to very slow. The following are common forms of chemical attack.

**3.4.1 Acid attack**—Portland cement concrete is not resistant to attack by acids. In most cases, the chemical reaction between acid and portland cement hydration products, such as calcium hydroxide, results in the formation of water-soluble calcium compounds that are then leached away. ACI 201.2R and 515.2R describe acid attack in further detail. Symptoms of acid attack are loss of the cement paste and in severe cases, subsequent loss of coarse aggregate. If the acid has reached reinforcing steel, corrosion may be present.

**3.4.2 Sulfate attack**—Sulfates of sodium, potassium, calcium, or magnesium are often found in seawater, groundwater, rivers, and industrial water. The chemical reactions that take place between sulfate ions and portland cement hydration products result in reaction products that have a greater volume than the reactants. This volume change causes the development of stresses in the concrete that eventually lead to cracking and deterioration. ACI 201.2R describes additional details of the sulfate attack mechanism. Symptoms of sulfate attack include map-cracking and softening of the concrete. In prestressed piles, observed cracking is primarily vertical cracking, as the prestress force tends to prevent formation of the horizontal cracks.

**3.4.3 Magnesium ion attack**—Magnesium ion concentrations present in some groundwater and in seawater may react with the calcium-silicate hydrate, replacing calcium

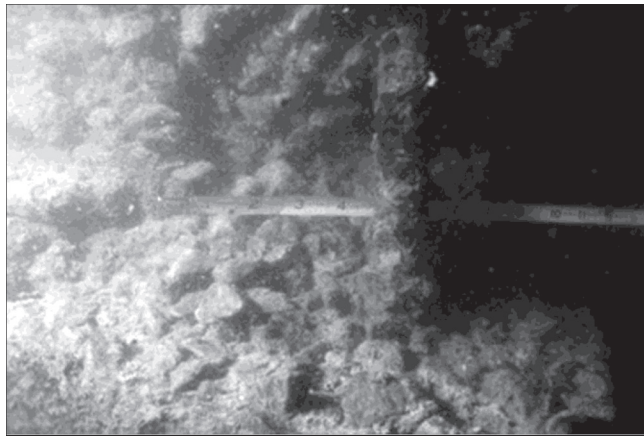


Fig. 3.4.5—Failure of concrete pile attributed to alkali-silica reaction (image courtesy of Collins Engineers, Inc.).

ions with magnesium. When this reaction occurs, there is a reduction in the amount of calcium-silicate hydrate present in the cement matrix that leads to a reduction in the strength of the cementitious material (Mehta and Monteiro 1993). Magnesium ion attack is characterized by a softening of the cement matrix of the outer concrete surface.

**3.4.4 Soft water attack**—Water with very low concentrations of dissolved minerals may leach calcium from the cement paste or aggregate (DePuy 1994). This is a particular problem with water that occurs with snow melt, but major deterioration from this mechanism is not a common event. Some process waterflows, such as demineralized water used for boilers, can also dissolve calcium from cement paste.

**3.4.5 Internal attack**—Several chemical reactions can take place between the constituents of the concrete. Typically, reaction products develop that occupy a volume greater than the original solid materials, resulting in increased stresses and cracking. The most common of these internal reactions is the alkali-silica reaction (Fig. 3.4.5). In this case, the alkalis present primarily in portland cement react with silica found in certain aggregates. The reaction gel expands when it is moistened, causing tensile stresses in the concrete. Alternating wetting and drying frequently associated with the aquatic splash-zone accelerates this reaction. Also, salt in marine environments can accelerate alkali-aggregate reactions by increasing the sodium ion concentration until it is above the minimum level necessary for alkali reactivity (Neville 1983; Spencer and Blaylock 1997; ACI 201.2R). Symptoms of alkali-aggregate attack are map- or pattern-cracking and swelling of the concrete. In prestressed piles, the horizontal cracks may not be present due to the precompression in the concrete.

### 3.5—Corrosion

**3.5.1 Introduction**—Corrosion of reinforcing steel is a serious threat to the durability and load-carrying capacity of concrete structures, particularly when considering the chlorides present in marine environments (ACI 222.3R). The serious nature of this problem is demonstrated by the many examples of cracked and spalled concrete at coastal locations caused by corrosion of the reinforcing steel (Fig. 3.5.1).



Fig. 3.5.1—Spalled and cracked concrete attributed to corrosion of the steel reinforcement (image courtesy of Collins Engineers, Inc.).

Corrosion occurs rapidly in permeable, porous concrete with inadequate cover over the reinforcing steel that is exposed alternately to saltwater splash and to air, as in tidal and splash zones. Chlorides of varying concentrations penetrate the concrete and, upon reaching the reinforcing steel, set up electrochemical reactions that corrode the reinforcing steel. Depassivation as a result of the reaction with atmospheric carbon dioxide ( $\text{CO}_2$ ) is greatly reduced in saturated concrete or concrete that is wet in service (Bentur et al. 1997). Corrosion products occupy several times the volume of the original metal and can develop internal pressures, creating a stress greater than the tensile strength of the concrete (Broomfield 1997). Cracks are developed along the reinforcing bars, and eventually the concrete cover spalls. This allows exposure to increased chlorides and causes corrosion of the steel reinforcement to accelerate. Symptoms of corrosion include concrete cracking oriented parallel to the reinforcement, spalling over reinforcement, and rust staining.

**3.5.2 The corrosion process**—Steel in concrete is normally protected chemically by the alkalinity of the concrete and is highly resistant to corrosion. The natural alkalinity of the concrete creates a thin, passivating layer on the surface of embedded reinforcement, which provides protection against corrosion. Greater depth of cover and less permeable concrete provide increased resistance to the ingress of chloride ions, which compromise the passivating film.

Corrosion of reinforcing steel is an electrochemical process that requires an electrolyte (such as moist, cation-laden concrete), two electrically connected metallic surfaces with different electrical potentials, and free oxygen (Burke and Bushman 1988).

The entry of the electrolytes and oxygen are facilitated in more permeable concrete. Water containing dissolved salt provides an electrolyte of low electrical resistivity, thus permitting corrosion currents to flow readily. Oxygen is an essential ingredient to the electrochemical reaction at the cathode of the corrosion cell. Consequently, steel in reinforced concrete completely and permanently immersed in water corrodes much slower than in splash zones because

oxygen is virtually excluded (ACI 222R). Wave action or other activities that mix the upper water surfaces with air may produce oxygen levels in the water sufficient to initiate corrosion below the normal water levels.

A severe exposure condition exists when part of the concrete structure is exposed to wetted cycles by saltwater, as by tides or sea spray. High concentrations of chlorides are produced by salt water being transported by capillary action upward through the concrete cover and evaporation of water from the surface, leaving behind salts (ACI 222R). The part that is alternately wetted has ample opportunity for contact with atmospheric oxygen. For this reason, reinforcing steel in concrete in aqueous environments corrodes faster in the tidal zone and spray areas than in other areas. Additional information on the mechanism of corrosion of steel in concrete is provided in ACI 222R.

### 3.6—Mechanical damage

Concrete structures in and around water are susceptible to various types of mechanical damage.

**3.6.1 Impact**—Impact damage to a concrete structure may range from the shallow spalling caused by a light impact from a barge striking a lock wall to total loss of a structure caused by a ship colliding with a bridge pier. Because the range of damage caused by impact can be so great, it is not possible to define a typical set of symptoms (AASHTO 2009).

In cases of less-than-catastrophic impact, the damage may be under water and, hence, undetected. In such an instance, the structure suffers not only from the direct result of the impact (typically cracking and spalling), but also from the indirect results of greater access to interior concrete and reinforcing steel by the water and water-borne contaminants.

**3.6.2 Abrasion**—Abrasion of underwater concrete is typically caused by water-borne particles (rocks, sand, and rubble) rubbing against and, to some degree, impacting against a concrete surface. Typical underwater abrasion could include damage to stilling basins of hydraulic structures, or damage to piers and piling caused by abrasive particles being carried by currents. Abrasion, such as in a stilling basin, typically produces a worn and polished concrete surface with heavily exposed or removed coarse aggregate. Abrasion damage to concrete is discussed in ACI 201.2R and ACI 207.6R. Abrasion damage may also be caused by the movement of ships moored to inadequately protected structures. Again, the damage allows greater access to the interior concrete, thus accelerating corrosion of reinforcement. In cold climates, ice movements can cause abrasion damage.

**3.6.3 Cavitation**—Cavitation is the formation of bubbles or cavities in a liquid. The bubbles are formed and, subsequently, destroyed by changing pressure conditions that result from discontinuities. Cavitation damage to concrete is caused by the implosion of the bubbles, which generates an extremely high pressure over a small area. Cavitation is a serious problem because the force exerted upon the concrete when the bubbles implode is large enough to remove concrete. Cavitation can result in damage ranging from minor surface deterioration to major concrete loss in tunnels and conduits. Cavitation damage initially appears as

very rough pitted areas on a concrete surface. The mechanism causing cavitation is self-supporting. Once initiated, damage worsens in the direction of flow. Details of cavitation damage are discussed in ACI 207.6R.

**3.6.4 Damage due to loads**—A concrete structure may be damaged by seismic forces or loads greater than those for which it was designed. The typical symptoms of such damage will be major structural cracking in tension or shear areas and spalling in compression areas.

### 3.7—Freezing and thawing damage

Deterioration of saturated concrete due to cycles of freezing and thawing has been observed in a large number of structures exposed to water and low temperatures (Fig. 3.7). Freezing of water in the pores of concrete can give rise to concrete stresses that can rupture the cement paste. The disruptive forces are due to water that, as it freezes, increases in volume by approximately 9 percent.

Concrete that is continuously submerged will usually perform well. In the tidal zone, however, it is subject to cycles of freezing and thawing in cold climates. Freezing occurs when the tide drops, exposing wet concrete. The water freezes in the concrete pores, expands, and tends to create large stresses. When the tide eventually rises, the ice melts and the cycle repeats. This cycling causes progressive deterioration of concrete unless it is adequately air entrained.

Extensive field and laboratory investigations have shown that the rate of deterioration due to freezing and thawing is considerably higher in salt water than in fresh water (Wiebenga 1980). This difference in resistance to freezing and thawing is normally ascribed to the generation of a higher hydraulic pressure in the pore system due to salt gradients and osmotic effects. Small air voids in the concrete will become water-filled after a long period of immersion. These voids may also be more easily filled when salt is present. In spite of the low frost resistance of concrete in saltwater, deterioration normally takes place slowly (Klieger 1994).

Concrete subjected to many freezing and thawing cycles in seawater can increase in volume due to the microcracks that result from inadequate freezing-and-thawing resistance.



Fig. 3.7—Concrete deterioration on a bridge pier attributed to cycles of freezing and thawing (image courtesy of Collins Engineers, Inc.).

This can cause increased deformations and stresses in structural members.

### 3.8—Salt scaling

Damage due to salt scaling in marine environments is usually limited to portions of the structure in the splash zone. When water with dissolved salts splashes onto a structure, some of it migrates into the concrete through cracks, surface voids, pores, and capillaries. As the concrete dries, the salt solution is concentrated, and, eventually, crystals form. When the salt then changes to a higher hydrate form, internal pressure results and the concrete disintegrates just beneath the surface (Mehta 1991). Other concrete deterioration mechanisms resulting from salt ingress are discussed in ACI 201.2R.

### 3.9—Scour

Scour occurs when water currents undermine the support of concrete structures. Correcting scour damage usually involves repairs to earth- or rock-supporting concrete foundations rather than repairs to concrete. Therefore, repair of scour damage is not included in this guide.

## CHAPTER 4—INVESTIGATION AND EVALUATION

### 4.1—Introduction

Structural investigations of underwater facilities are usually conducted as part of a routine preventive maintenance program, an initial construction inspection, a special examination prompted by an accident or catastrophic event, or a determination of the required repairs (Busby 1978; Popovics 1986; Sletten et al. 1977). The purpose of the investigation usually influences the inspection procedures and testing equipment used. The investigation and evaluation of underwater facilities should be directed by a licensed design professional. Information on underwater inspection procedures, classifications of inspection types, structure cleaning requirements, diver qualifications, and other guidance on underwater inspections are found in Childs (2001).

Underwater inspections are usually hampered by adverse conditions such as poor visibility, strong currents, cold water, marine growth, and debris buildup. Horizontal and vertical control for accurately locating the deteriorated or damaged area is difficult. A diving inspector wears cumbersome life-support systems and equipment, which also hampers the inspection mission. This section will focus primarily on inspection efforts conducted by a diving team. Most of the discussion, however, also applies to other inspections performed by ROVs and manned submersibles.

Underwater inspections usually take much longer to accomplish than inspections of similar structures located above the water surface. This necessitates more planning by the inspecting team to optimize their efforts. Inspection criteria and definitions are usually established before the actual inspection and the inspection team is briefed. The primary goal is to inspect the structural elements to detect any obvious damage. If a defect is observed, the inspector identifies and documents the type and extent of the defect.

The inspector also determines the location of the defect so repair crews can return later to make the repair, or another inspection team can reinvestigate, if necessary.

Divers who perform structural inspections should be trained to recognize and describe defects but may not have specific structural engineering training. In this case, another person with the appropriate engineering background is normally employed to interpret the results of the inspection, evaluate the severity of the defects, and make the appropriate condition assessment. Preferably, this person will be present during the inspection to direct the efforts of the divers or direct the use of video equipment.

**4.1.1 Planning the investigation**—Once the scope of the investigation has been defined, the client and the inspection team plan the mission. The purpose of the preinspection meeting is to help identify the equipment, the inspection techniques, and the type of documentation required.

Planning usually begins with a thorough review of the original design and construction drawings, and a review of the previous inspections and repairs, if any. The team should plan to conduct the investigation during optimum weather conditions to minimize hazardous conditions and the effects of reduced visibility.

**4.1.2 Recording inspection notes**—Inspection notes typically consist of a dive log with notations of specific features. These notes may be transcribed from a slate used by the diver, or from a work sheet filled out by topside personnel when voice communication is used in the operation. These notes may be supplemented with sketches, photographs, or video.

### 4.2—Underwater access technology

Underwater work is generally classified into one of two broad categories for accessing the work site: diving or a remotely operated vehicle (ROV).

Diving is the traditional method of performing tasks under water. In this category, the diver is equipped with life-support systems that provide breathable air and protection from the elements. Manned diving systems include SCUBA (self-contained underwater breathing apparatus) and surface-supplied air. When employing SCUBA, the diver is supplied with breathing air (or gas) from a tank carried by the diver. In surface supply diving, the breathing medium is supplied to the diver through a hose connected to the air (or gas) supply above water.

Performance of duties at higher than one atmosphere ambient pressure causes a multitude of physiological changes within the human body. For example, body tissues absorb and shed gases at different rates than those normally experienced on the surface. Because of this, the time available to perform work under water decreases rapidly with increased water depth. For example, industry standards allow a diver using compressed air to work at 30 ft (10 m) for an unlimited period of time. If work, however, is being performed at 60 ft (20 m), the diver can only work for approximately 60 minutes without special precautions to prevent decompression sickness. The sophistication (and hence, the cost) of the diving systems used on a project increases with increased depth.

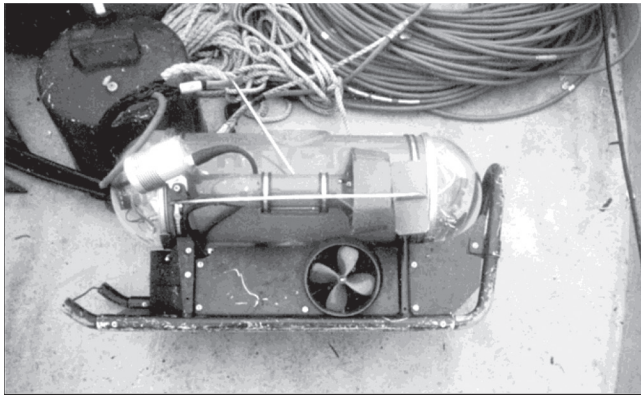


Fig. 4.2a—ROV (image courtesy of M. J. Garlich).

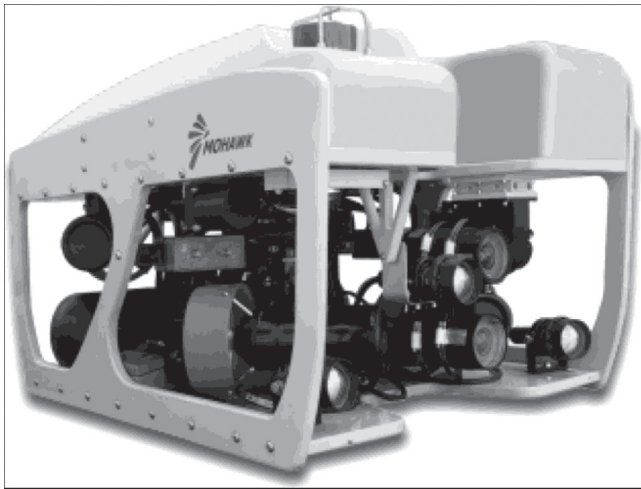


Fig. 4.2b—Flying eyeball ROV (image courtesy of Sub-Atlantic, Inc.).

When manned diving is used deeper than 180 ft (60 m) of water, most divers elect to use specially formulated mixtures of gases rather than compressed air. The technologies associated with mixed gas diving are changing rapidly as people work at greater depths. To increase efficiency, these diving operations are often enhanced with diving bells, which may be used to maintain the divers at working depths for extended periods of time. Using saturation diving techniques that may use underwater living chambers, divers may be supported at water depths where the work is performed for weeks at a time.

Some diving suits (Hard Suits, Inc. 1997) are capable of supporting divers at depths as great as 2100 ft (640 m) with an internal suit pressure of one atmosphere. The diver works in an ambient pressure equivalent to that on the surface; therefore, the time at depth is virtually unrestricted. The suit looks much like a hollow robot. The arms are equipped with claw-like operating devices, which reduce manual dexterity. The suits are cumbersome and difficult to position because mobility is provided by external propulsion devices, ballast tanks, or cables suspended from topside support vessels.

ROVs are underwater robots controlled by remote crews through an umbilical or tether (Fig. 4.2a) (Vadus and Busby 1979; Marine Technology Society 1984). The umbilical carries power to the ROV, along with command and control

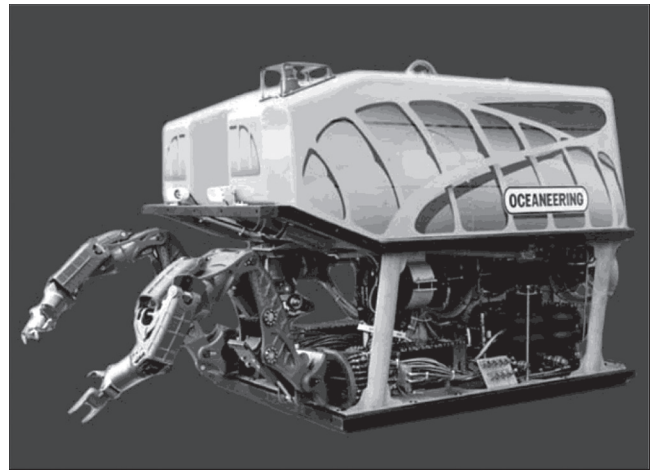


Fig. 4.2c—Work ROV (image courtesy of Oceaneering, Inc.).

signals from the crew. ROVs typically have free range of movement and range in size from small flying eyeball models (Fig. 4.2b) to larger work class models (Fig. 4.2c). Flying eyeball ROVs are typically equipped with only a camera and used for inspection or observation activities. Work class ROVs are also equipped with cameras, but can have manipulator arms, cutting tools, high-definition imaging sonar, and other equipment to assist in construction support (NRC 1996). More advanced tooling packages can be added for trenching, bolting pipeline flanges, and differential pressure work, such as hydroelectric facilities repairs. Advanced position systems are also being employed to increase the operation envelope on the ROVs, allowing real-time model-based positioning and enabling continued operations in zero visibility (Beck et al. 2008). Currently, many work class ROVs are rated to operate at depths up to 10,000 ft (3050 m).

### 4.3—Visual inspection

Visual inspections are the most common underwater investigations. These inspections are usually performed with a wide variety of simple hand tools. Physical measurement of a defect may be approximated using visual scaling, hand rulers, tape measures, finger sizes or hand spans, body lengths, and depth gauges. The selection of the tools depends on the accuracy of measurement required. Visual inspections provide the information for the written report, which is usually supplemented with photographic documentation, video documentation, or sketches.

Hand tools, such as scrapers and wire brushes, are often used for local cleaning to remove silt and marine growth during the inspection. Where large areas require cleaning to properly assess their conditions, or where extensive marine growth is present, more aggressive cleaning systems, as discussed in 5.4, may be used.

When SCUBA is used as the primary diving mode, communication with the surface is limited. The typical SCUBA mouthpiece does not allow the diver to speak. Use of a full-face mask in place of the traditional mouthpiece and mask, however, can accommodate either hardwired or wireless communication systems.

When surface-supplied air is used as the primary diving mode, the dive team has much more flexibility with the documentation of the inspection. The diver can relay descriptions of the observations directly to the topside team and also get direction from the team members on the surface.

Video cameras are either self-contained or umbilically served. The self-contained video camera is a hand-held instrument that contains both the video camera and the recorder and is operated by the diving inspector. The other type of video is served with a supplemental power and communication cord and is either attached to an underwater vehicle or held by the diver. The video image is sent along the umbilical cord to a monitor and recorder. The surface crew directs the diver or the ROV to position the camera. When there is voice communication, the diver can describe the details of the defect while directing the camera lens. The diver's voice may be recorded in real time with the image.

#### 4.4—Tactile inspection

Tactile inspections (inspections by touch) are, perhaps, the most difficult underwater inspections to perform, due to conditions of poor visibility. Tactile inspections are typically performed in heavily silted rivers, settling ponds, pipelines, or where the element to be inspected is totally or partially buried by silt. The diver merely runs his hands along the structural element to find a defect. The defect is usually quantified relative to the size of the inspector's hand and arm lengths. Once a defect is observed, the diver should clearly describe the position of the defect so that it may be located and repaired at a future date.

#### 4.5—Underwater nondestructive testing of concrete

The use of nondestructive testing (NDT) for the evaluation of concrete structures is described in [ACI 228.2R](#), which includes details on a variety of NDT methods. These methods can be used to obtain data on existing structures as well as to verify repair quality. Several of these methods have been modified to allow their use in underwater testing. Limitations on the various methods when used under water are consistent with those above water.

The following testing techniques and instruments are among those applicable to underwater work. Information regarding equipment is available from equipment manufacturers.

**4.5.1 Soundings**—Soundings are taken by striking the concrete surface to locate areas of internal voids or delamination of the concrete cover as might be caused by the effects of freezing and thawing or corrosion of reinforcement. Although the results are only qualitative in nature, the method is rapid, economical, and enables an expeditious determination of the overall condition. The inspector's ability to hear sound in water is reduced by waves, currents, and background noise. Soundings are the most elementary of NDT methods.

**4.5.2 Ultrasonic pulse velocity**—Ultrasonic pulse velocity ([ASTM C597](#)) is determined by measuring the time of transmission of a pulse of energy through a known distance of

concrete. Many factors affect the results, including aggregate content and reinforcing steel location. The results obtained are quantitative; however, they should be used only as an indication of the relative quality of concrete within a given structure.

Ultrasonics can be used successfully under water to help evaluate the condition of concrete structures. Commercially available instruments have been modified for underwater use. Laboratory and field tests of the instruments have demonstrated that the modifications had no effect on the output data ([Olson et al. 1994](#)). Both direct (transducers located directly across from one another on either side of the member) and indirect (both transducers located along the same face of the member) transmission methods can be used in the field to evaluate the uniformity of concrete and obtain a general condition rating. Detailed descriptions of these techniques are presented in [ACI 228.2R](#).

A special form of this technique is the pulse-echo method. The pulse-echo method has been used for the in-place determination of the length and condition of concrete piles. Low-frequency, impact echo-sounding devices have proven effective for locating deep delaminations in thick concrete members in the splash zone ([Olson 1996](#)).

**4.5.3 Magnetic reinforcing bar locator**—A commercially available magnetic reinforcing bar locator has been modified by the manufacturer for use under water ([Fig. 4.5.3](#)) ([Smith et al. 1991](#)). The magnetic reinforcing bar locator can be used to determine the location of reinforcing bars and prestressing cables in concrete and either measure the depth of concrete cover or determine the size of the reinforcing bar, if one or the other is known. Laboratory and field tests of the instrument demonstrated that the modification for underwater use had no effect on the output data ([Smith 1986](#)).

**4.5.4 Rebound hammer**—A standard rebound hammer ([ASTM C805/C805M](#)), modified for underwater use, can be used for rapid surveys of concrete surface hardness ([Fig. 4.5.4](#)). Water-saturated concrete produces rebound readings that are approximately five points lower than for the same

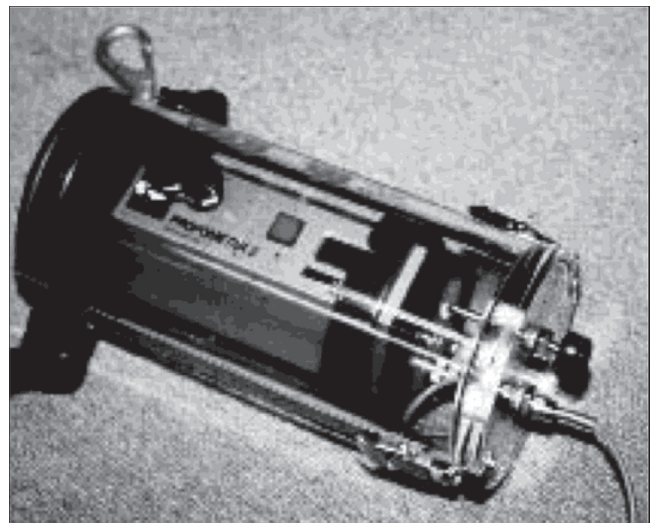


Fig. 4.5.3—Magnetic reinforcing bar locator (image courtesy of SDS Company).

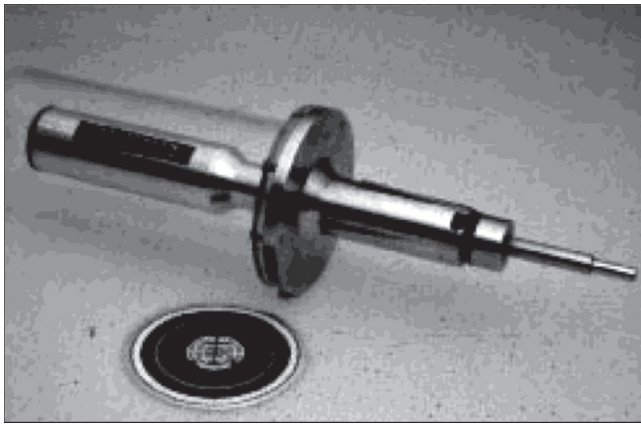


Fig. 4.5.4—Rebound hammer (image courtesy of the U.S. Navy).

concrete in a dry condition. This may make it difficult to test low-strength concrete (Smith 1986).

**4.5.5 Echosounders**—Echosounders (specialty fathometers), can be useful for underwater rehabilitation work using tremie concrete, both to delineate the void to be filled and to confirm the level of the tremie concrete placed (USACE 2002; FHWA 1989). They are also effective in checking scour depth in a stream bed. They consist of an ultrasonic transducer, which is suspended in the water, a sending/receiving device, and a recording chart or screen output that displays the water depth. High-frequency sound waves emitted from the transducer travel through the water until they strike the bottom and are reflected back to the transducer. The echosounder measures the transit time of these waves and converts it to water depth shown on the display. When an echosounder is used close to the structure, however, erroneous returns may occur from the underwater structural elements.

**4.5.6 Side-scan sonar**—A side-scan sonar system is similar to the standard bottom-looking echo sounder, except that the signal from the transducer is directed laterally, producing two side-looking beams (Clausner and Pope 1988). The system consists of a pair of transducers mounted in an underwater housing, or fish, and a dual-channel recorder connected to the fish by a conductive cable. The side-scan technique has been used to map surfaces other than the ocean bottom. Successful trials have been conducted on the slopes of ice islands and breakwaters, and on vertical pier structures. Although the side-scan sonar technique permits a broad-scale view of the underwater structure, the broad beam and lack of resolution make it unsuitable for obtaining the kind of data normally required from inspections of concrete structures (USACE 1994; Garlich and Chrozastowski 1989; Hard Suits, Inc. 1997).

**4.5.7 Scanning sonar**—Scanning sonar is similar to side-scan sonar in that the transducer emits acoustic pulses through the water perpendicular to the base; however, unlike side-scan sonar, which requires vessel movement to develop an image, the scanning sonar works best when it remains stationary. The acoustic images, which are representative of the echoed (backscattered) target intensity within the geometric coverage of the beam, are recorded in

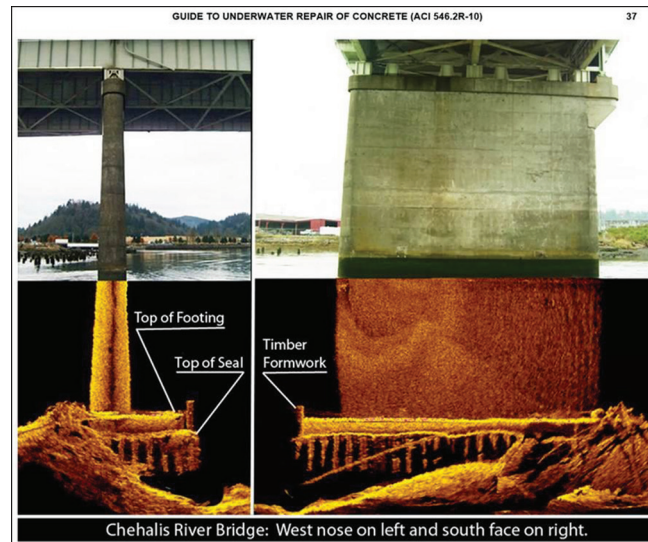


Fig. 4.5.7—Scanning image of concrete foundation (image courtesy of R. Forsyth).

a series of slices generated by the rotation of the transducer. Computer software is used to stitch these slices together to form a contiguous image. The primary benefit of scanning sonar is the ability to produce highly detailed images of the channel bottom and vertical components of submerged structures. Near-photo quality images can be generated for inclusion into inspection reports (Fig. 4.5.7). The primary limitation of scanning sonar is the inability to quickly and efficiently generate detailed images of large areas of the channel bottom. Also, depth of defects and shallow areas can be difficult to interpret. As a result, side-scan sonar or multi-beam sonar is a better solution for overall channel bottom-mapping or searching for a submerged object (Syler and Stromberg 2008).

**4.5.8 Multi-beam sonar**—Multi-beam sonar is essentially three-dimensional imaging underwater like LiDAR—laser scanning is above water. Scanning sonar consists of one beam that mechanically moves to build an image. Multi-beam sonar consists of numerous beams side-by-side. Computer software is used to stitch the beam returns together to form a real-time contiguous image. Similar to scanning sonar, the primary benefit of multi-beam sonar is the ability to produce highly detailed images of the channel bottom and submerged structures. The real-time images generated by multi-beam sonar can be used to produce high-resolution images, models, and videos. Multi-beam sonar can be deployed from a boat, from a water-side crane, or even set with a tripod on the channel bottom to collect data on voids in or under concrete foundations. Output data can determine the penetration depth of spalled, or undermined areas (Fig. 4.5.8). The primary limitation of multi-beam sonar is range, due to higher operating frequencies. As a result, side-scan sonar is a better solution for overall channel-bottom mapping or searching for submerged objects, and scanning sonar is a better solution for producing highly detailed still images of large submerged structures (Syler and Stromberg 2008).