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Guide to Underwater Repair of Concrete

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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. References are provided for obtaining additional information on selected materials and construction methods.

Keywords: cementitious; concrete; concrete removal; deterioration; evaluation; formwork; investigation; inspection; jackets; joints; materials; marine placement; polymer; protection; reinforcement; repair; strengthen; surface preparation; underwater; water.

CONTENTS

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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. 1.1) cause many differences. The repair of concrete under water is usually difficult, requiring specialized products and systems, and the services of highly qualified and experienced professionals. See ACI SP-8 and SP-65.

Proper evaluation of the present condition of the structure is the essential first step for designing long-term repairs. To be most effective, long-term evaluation requires historical information on the structure and its environment, including any changes, and the record of periodic on-site inspections or repairs. Comprehensive documentation of the cause and extent of deterioration, accurate design criteria, proper repair techniques, and quality assurance of the installation procedures and the repair will result in a better repair system. Longevity of the repair is the ultimate indicator of success.

Underwater concrete deterioration in tidal and splash zones is a serious economic problem (Fig. 1.2 and 1.3). Water that contains oxygen and contaminants can cause aggressive attack on concrete. Underwater repair of concrete is a specialized and highly technical part of concrete repair technology. It presents problems of selecting appropriate repair materials and methods, and of maintaining quality control not normally associated with repair above water. Sound engineering, quality workmanship and high-performance products and systems are extremely important. Successful repairs can be achieved when these factors are considered carefully and properly implemented. This guide provides an overview of the current status of underwater repair technology to aid the engineer, designer, contractor and owner in making decisions.

1.2—Scope

This guide is limited to concrete structures in the splash zone and underwater portions of typical lakes, rivers, oceans, and ground water. Concrete deterioration, environments, investigation and testing procedures, surface preparation, types of repair, repair methodology, and materials are described. Design considerations and references for underwater repair of concrete bridges, wharves, pipelines, piers, outfalls, bulkheads, and offshore structures are identified.

1.3—Diving technology

Underwater work can be generally classified into one of the three broad categories of diving: manned diving, a one-atmosphere armored suit or a manned submarine, or a remotely-operated vehicle (ROV).

Manned 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.

Performance of duties at higher than one atmosphere ambient pressure causes a multitude of physiological changes within the human body. For instance, 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 currently allow a diver using compressed air to work at 30 ft (10 m) for an unlimited period of time. However, if work is being performed at 60 ft (20 m), the diver can only work for approximately 60 min without special precautions to prevent

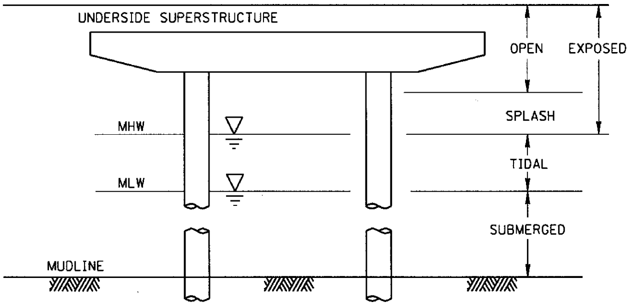

Fig. 1.1—Repair zones: submerged, tidal, exposed.

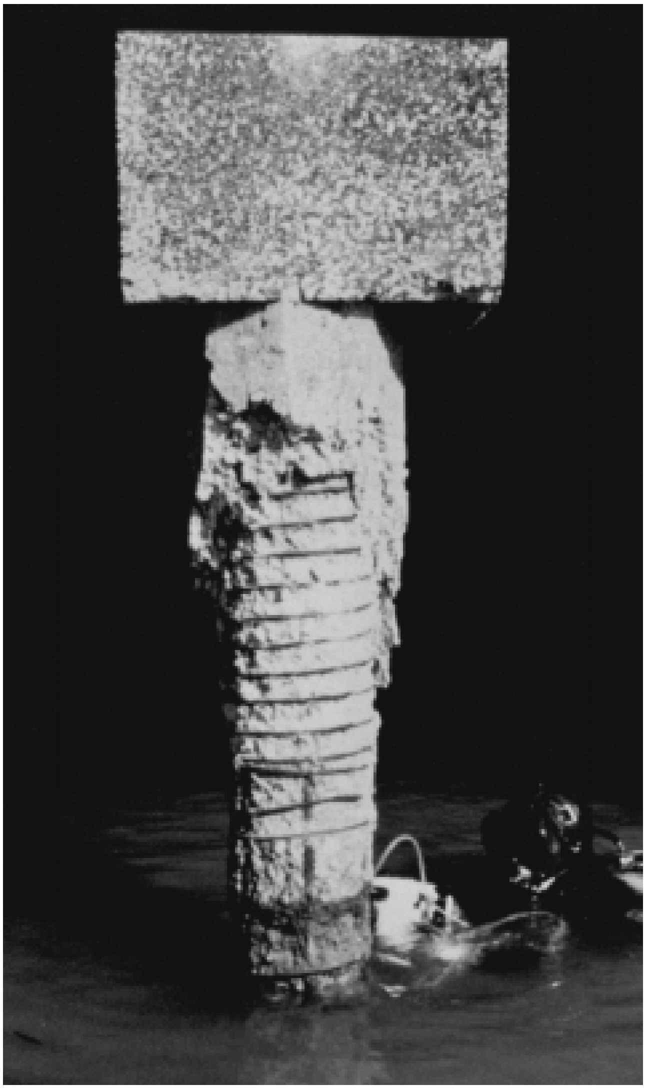

Fig. 1.2—Deteriorated piles in tidal and exposed zones. (Courtesy of I. Leon Glassgold.)

decompression sickness. The industry standard upper limit is 30 min work time at 90 ft (30 m) in seawater. If these limits are exceeded, precautions must be taken to decompress the diver. The sophistication (and hence the cost) of the diving systems used on a project increases with increased depth.

If 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. To increase efficiency, these diving operations are often enhanced with diving bells, which are used to maintain the divers at working depths for extended periods of time. Divers may be supported at equivalent water depths for weeks at a time. The technologies associated with mixed gas diving are changing rapidly as people work at deeper depths.

Fig. 1.3—Advanced deterioration, pile has been cleaned. (Courtesy of I. Leon Glassgold.)

Fig. 1.4—Remotely operated vehicle (ROV). (Courtesy of M. Garlich.)

A recent development is the One Atmosphere Diving Suit (Hard Suits, Inc., 1997). These suits are capable of supporting divers at depths as great as 2,100 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.

Mini-submarines are occasionally used to perform underwater work. These typically have crews of two or three. Most are equipped with video and photographic equipment. Some submarines are also equipped with robotic arms for performing tasks outside of the submarine. The lack of dexterity and limitations on the positioning capability of these vessels may hamper their effectiveness for inspection and repair work.

Remotely operated vehicles (ROVs) look much like an unmanned version of a submarine (Fig. 1.4) (Vadus and Busby, 1979). They are compact devices that are controlled by a remote crew. The operating crew and the vehicle communicate through an umbilical cord attached to the ROV. The crew operates the ROV with information provided by transponders attached to the frame of the ROV. ROV’s may be launched directly from the surface or from a submarine mother ship. Most ROV’s are equipped with video and still photography devices. The vehicle is positioned by ballast tanks and thrusters mounted on the frame. Some ROV’s also are equipped with robotic arms, used to perform tasks that do not need a high degree of dexterity. ROV’s have been used at depths of approximately 8,000 ft (2,400 m).

CHAPTER 2—CAUSES OF DETERIORATION

2.1—Marine organisms

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

2.1.2 *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. These acids attack portland cement paste in concrete, dissolving the surface. In addition, the acids can lower the pH of the concrete to a level where the reinforcement is no longer passivated. Once this occurs, corrosion in the reinforcing steel can begin, often at an accelerated rate (Thornton, 1978; Khoury et al., 1985).

2.2—Deficient construction practices and errors

Because of the difficult working conditions and the difficulty of providing adequate inspection during construction, underwater placement of concrete and other materials is often susceptible to errors and poor construction practices.

Deficient practices include the following: exceeding the specified water-cement (or water-cementitious materials) ratio, inadequate surface preparation, improper alignment of formwork, improper concrete placement and consolidation, improper location of reinforcing steel, movement of formwork during placement, premature removal of forms or shores, and settling of the concrete during hardening. Each of these practices is discussed in a manual prepared by the Corps of Engineers (Corps of Engineers, 1995).

One specialized deficiency common to marine structures is tension cracking of concrete piling, resulting from improper driving practices. 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 creation of an anode at the reinforcing bar. This usually does not lead to significant corrosion of underwater concrete because of the low oxygen content 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 localized corrosion.

Construction or design errors can result in formwork collapse, blowouts of pressurized caissons, and breaches in cofferdams. These situations usually require reconstruction and are beyond the scope of this guide.

2.3—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 situations 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 frequent wetting and drying, daily wave or tide action, and the abundant supply of oxygen.

Chemicals present in the water surrounding the concrete can cause deterioration that varies in rate from very rapid to very slow. Chemical attack is slowed considerably by low temperatures. The following discusses several of the more common types of chemical attacks on concrete.

2.3.1 *Acid attack*—Portland cement concrete is not resistant to attack by acids. In most cases the chemical reaction between acid and portland cement results in the formation of water-soluble calcium compounds that are then leached away. ACI 201.2R and ACI 515.1R describe acid attack in further detail.

2.3.2 *Sulfate attack*—Sulfates of sodium, potassium, calcium, or magnesium are often found in seawater, ground water rivers, or in industrial water. The chemical reactions that take place between sulfate ions and portland cement result in reaction products that have a greater volume than the original solid constituents. 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. It points out that, although seawater contains a high enough concentration of sulfate ions to cause concrete disruption, the reaction is usually less severe than would otherwise be expected. ACI 201.2R indicates that the chloride ions also present in seawater inhibit sulfate attack.

2.3.3 *Magnesium ion attack*—Magnesium ions present in ground water may react with the calcium silicate hydrate, replacing calcium ions with magnesium. When this reaction occurs, there is a reduction in cementitious properties, leading to deterioration.

2.3.4 *Soft water attack*—Soft water has very low concentrations of dissolved minerals and may leach calcium from the cement paste or aggregate. This is a particular problem if water flows continuously over the concrete so that chemical equilibrium is not achieved. This attack apparently takes place very slowly (DePuy, 1994).

2.3.5 *Internal attack*—Several 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. In this case the alkalis present primarily in portland cement react with silica found in certain aggregates. Alternating wetting and drying frequently associated with the aquatic splash zone does accelerate 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 (Nevielle, 1983). ACI 201.2R gives additional details.

2.4—Corrosion

2.4.1 *Introduction*—A significant number of cases indicate that corrosion of reinforcing steel has been and still is the most serious and critical threat to the durability and safety of concrete structures in marine environments (Gjorv, 1968). 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 (Halstead and Woodworth, 1955).

Corrosion occurs rapidly in permeable, porous concrete that is exposed alternately to salt-water splash and to air, as in tidal and splash zones. Chlorides of varying concentrations are deposited in the concrete, setting up electrochemical reactions and corroding the reinforcing steel. Corrosion products occupy several times the volume of the original metal and can develop internal pressures as high as 4700 psi (30 MPa), creating a stress many times greater than the tensile strength of the concrete (Rosa et al., 1913). Cracks form along the reinforcing bars and eventually the concrete cover spalls. This allows the corrosion of the steel reinforcement to accelerate.

2.4.2 *The corrosion process*—Steel in concrete is normally protected chemically by the alkalinity of the concrete, and is highly resistant to corrosion. This is due to a passivating film that forms on the surface of embedded reinforcement and provides protection against corrosion. Greater depth of cover and less permeable concrete also provide increased resistance to the ingress of chloride ions, which can 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).

When the concrete is permeable, the entry of the electrolyte and oxygen are facilitated. Water containing dissolved salt provides an electrolyte of low electrical resistivity, thus permitting corrosion currents to flow readily. Oxygen is essential to the electrochemical reaction at the cathode of the corrosion cell. Consequently, steel in reinforced concrete completely and permanently immersed in water does not corrode appreciably because oxygen is virtually excluded.

A severe exposure condition exists when part of the concrete structure is alternately wetted by salt water, as by tides or sea spray. 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 the spray areas than in other areas. Additional information on corrosion may be found in ACI 222R.

2.5—Mechanical damage

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

2.5.1 *Impact*—Impact damage to a concrete structure may range from the shallow spalling caused by a light impact from a barge brushing against 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, 1991).

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.

2.5.2 *Abrasion*—Abrasion is typically caused by water-borne particles (rocks, sand, or 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 by water-borne particles typically produces an appearance similar to that of sandblasted concrete. Abrasion damage to concrete is discussed in ACI 201.2R and ACI 210R. Abrasion damage is also caused by the movement of ships moored to inadequately protected structures. Again, the damage allows greater access to the interior concrete. In cold climates, ice is a major contributor of abrasion damage.

2.5.3 *Cavitation*—Cavitation damage to concrete is caused by the implosion of vapor bubbles carried in a stream of rapidly flowing water. The bubbles are formed and subsequently destroyed by changing pressure conditions that result from discontinuities in the flow path. Cavitation is a serious problem since the force exerted upon the concrete when the bubbles implode is large enough to remove concrete. Cavitation may result in damage ranging from minor surface deterioration to major concrete loss in tunnels and conduits. Cavitation damage initially appears as very rough areas on a concrete surface. Since the mechanism causing cavitation is self-supporting once initiated, damage then worsens in the direction of flow. Details of cavitation damage are discussed in ACI 210R.

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

2.6—Freezing and thawing damage

Deterioration of saturated concrete due to cycles of freezing and thawing action has been observed in a large number of structures exposed to water and low temperatures.

The freezing of water in the pores of concrete can give rise to stresses and cause rupture in the paste. The disruptive forces are due to the fact that as water freezes it increases in volume by about 9 percent.

Concrete that is continuously submerged will usually perform well. In the tidal zone, however, it is subject to active freeze-thaw cycling 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, 1985). 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 salt water, deterioration normally takes place very slowly. However, in tidal zones the concrete is also exposed to other types of deterioration processes (Klieger, 1994).

Concrete subjected to many freeze-thaw cycles in seawater can increase in volume due to the micro-cracks that result from inadequate freeze-thaw resistance. This can cause undesirable deformations in flexural members.

2.7—Salt scaling

Damage due to salt scaling is usually limited to portions of the structure in the splash zone in marine environments. 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.

2.8—Damage not included in this guide

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 3—EVALUATIONS AND INVESTIGATIONS

3.1—Introduction

Structural investigations of underwater facilities are usually conducted as part of a routine preventive maintenance program, as an initial construction inspection, as a special examination prompted by an accident or catastrophic event, or as a method for determining needed repairs (Busby, 1978; Popovics, 1986; Sletten, 1997). The purpose of the investigation usually influences the inspection procedures and testing equipment used.

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 observation is difficult. A diving inspector must wear 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. However, most of the discussion also applies to other inspections performed by ROV’s and submarines.

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 prior to 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 the type and extent of the defect to determine how serious the problem may be. 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.

Many divers who perform structural inspections do not have specific structural engineering training for this task. In this case, a second person is normally employed to interpret the results of the inspection and make the appropriate evaluations. Occasionally, this person will be present during the inspection to direct the efforts of the diver or direct the use of video equipment.

3.1.1 *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 pre-inspection 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 could plan to conduct the investigation during optimum weather conditions to minimize hazardous conditions and to reduce the effects of reduced visibility.

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 if voice communication is used in the operation. These notes may be supplemented with sketches, photographs, or video tape.

3.1.2 *Evaluating the findings*—As with any structural inspection, evaluation of the inspection results is perhaps the most difficult task. The evaluator studies the contents of the inspection report, then interprets the results based on his knowledge of the facility. The skill of the diver as an inspector is essential for the evaluation process to be meaningful. It is the diver's responsibility to qualify and quantify the condition and defect.

During this phase of the investigation, the evaluator must decide if the observed defects are minor or major. In addition, to help decide the actions required to ensure continued service of the facility, the evaluator also judges whether the defect will continue to degrade the structure or if the problem has stabilized.

3.1.3 *Deciding what actions to take*—Deciding on the appropriate action to take after a defect has been discovered depends on the potential hazard of the defect, the risk of continued structural deterioration, the technology available to repair the defect, the cost associated with the needed repair and the intended remaining life of the structure.

If the defect presents a hazard that threatens either the life safety of individuals working on or near the facility, or the continued operation of the facility, remedial action should be taken immediately. A critical structural condition is generally repaired promptly.

The logistics of a repair problem often dictate at least part of the solution. For example, repair of a pier may be relatively straightforward, but the repair of similar defects on an offshore arctic structure, or repair of an outfall for a hydroelectric structure, can be much more difficult.

If the defect does not threaten life safety or the immediate operation of a facility, the owner or operator of an underwater structure has more options. A minor defect is often merely monitored for continued deterioration. If none is noted, further action may not be required. However, if a defect is serious, repair is usually needed.

3.2—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 gages. 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 tape documentation, or sketches.

If 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. However, use of a full face mask in place of the traditional mouthpiece and mask can accommodate either hardwire or wireless communication systems. Wireless systems do not always work well. The hardwire system, which does work well, requires a partial umbilical to the surface, and therefore it may be more practical to provide surface-supplied air to give the diver extended time under water. Customarily the dive team records results of the inspection on slates and later transcribe the notes onto an inspection form.

If 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. If there is voice communication, the diver can describe the details of the defect as while directing the camera lens. The driver's voice may be recorded in real time with the image on the tape.

3.3—Tactile inspection

Tactile inspections (inspections by touch) are perhaps the most difficult underwater surveys. Usually conducted under conditions of extremely poor visibility, such as in a heavily-silted river, a settling pond, or a pipeline, they may also be required 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 found, the diver may have difficulty properly describing the position of the defect so that it may be located and repaired at a future date.

3.4—Underwater nondestructive testing of concrete

Studies of nondestructive testing (NDT) of concrete have shown that the following techniques and instruments are applicable to underwater work. Information regarding equipment is available from equipment manufacturers.

3.4.1 *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 and 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.

3.4.2 *Ultrasonic pulse velocity*—Ultrasonic pulse velocity (ASTM C 597) 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, but they are only relative in nature.

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 and indirect transmission methods can be used in the field to evaluate the uniformity of concrete and obtain a general condition rating. Direct ultrasonic transmission measurements generally can be made by an individual, while indirect measurements are facilitated by the use of two or more people.

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

3.4.3 *Magnetic reinforcing bar locator*—A commercially available magnetic reinforcing bar locator (or pachometer) has been successfully modified for underwater use. The pachometer can be used to determine the location of reinforcing bars 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. Techniques are available for approximating each variable if neither is known. Laboratory and field tests of the instrument demonstrated that the modification for underwater use had no effect on the output data.

3.4.4 *Impact hammer*—A standard impact hammer (ASTM C 805), modified for underwater use, can be used for rapid surveys of concrete surface hardness. However, the underwater readings are generally higher than comparable data obtained in dry conditions. These higher readings could be eliminated by further redesigning of the Schmidt hammer for underwater use. Data also can be normalized to eliminate the effect of higher underwater readings. However, measurement of low compressive strength concrete is limited because the modifications required for under water use lowered the detection threshold (Smith, 1986).

3.4.5 *Echosounders*—Another ultrasonic device, the 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 (Corps of Engineers, 1994; FHWA, 1989). They are also effective in checking scour depth in a stream bed. They consist of a transducer which is suspended in the water, a sending/receiving device, and a recording chart or screen output which 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. However, when an echosounder is used very close to the structure, erroneous returns may occur from the underwater structural elements.

3.4.6 *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. In the past several years, 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 required from inspections of concrete structures (Corps of Engineers, 1994; Garlich and Chrzastowski, 1989; Hard Suits, Inc., 1997; Lamberton, 1989).

3.4.7 *Radar*—Certain types of radar have been used to evaluate the condition of concrete up to 30 in. (800 mm) thick. Radar can detect delaminations, deteriorations, cracks, and voids. It can also detect and locate changes in material. Radar has been used successfully as an underwater inspection tool, and is being developed for possible future use. Radar with the antenna contained in a custom waterproof housing was used in 1994 in conjunction with pulse velocity testing to investigate the structural integrity in a concrete plug submerged 150 ft (46 m) in a water supply tunnel (Garlich, 1995).

3.4.8 *Underwater acoustic profilers*—Because of known prior developmental work on an experimental acoustic system, acoustic profiling has been considered for mapping underwater structures. Erosion and down faulting of submerged structures have always been difficult to accurately map using standard acoustic (sonic) surveys because of limitations of the various systems. Sonic surveys, side-scan sonar, and other underwater mapping tools are designed primarily to see targets rising above the plane of the sea floor.

In 1978, the U.S. Army Corps of Engineers in conjunction with a private contractor investigated a high resolution acoustic mapping system for use on a river lock evaluation (Thornton and Alexander, 1987). The first known attempt to develop an acoustic system suitable for mapping the surface contours of stilling basins, lock chamber floors, and other underwater structures, this system is similar to commercial depth sounders or echo sounders but has a greater degree of accuracy. The floor slabs of the main and auxiliary lock chambers were profiled, and defects previously located by divers were detected. Features of the stilling basin such as the concrete sill, the downstream diffusion baffles, and some abrasion-erosion holes were mapped and profiled. The accuracy of the system appeared to be adequate for defining bottom features in the field.

Work has continued on the system, which contains an acoustic subsystem, a positioning subsystem, and a compute-and-record subsystem. The system's capabilities allow it to "see" objects rising above the plane of the bottom, extract data from narrow depressions and areas close to vertical surfaces, provide continuous real-time data on the condition of the bottom surface, and record and store all data.

3.5—Sampling and destructive testing

In some cases, visual or nondestructive inspections do not adequately indicate the internal condition of a structure. Collecting concrete samples may be necessary.

3.5.1 *Cores*—Concrete cores are the most common type of samples. Conventional electric core drilling equipment is not readily adaptable for underwater use. However, conventional core drilling frames have been modified for underwater use by replacing electric power with hydraulic or pneumatic power drills. Drill base plates are usually bolted to the structure. Rather than have the operator apply thrust to the bit as is the usual case in above-water operation, pressure regulated rams or mechanical levers are used to apply this force.

A diver-operated coring apparatus can drill horizontal or vertical cores to a depth of 4 ft (1.2 m). The core diameters are up to 6 in. (150 mm). The equipment is light enough to be operated from an 18 ft. (5.5 m) boat. Larger cores also may be taken, brought to the surface, and sectioned in the laboratory to obtain test specimens of the proper dimensions.

Core holes should be patched after the core specimen is removed.

3.5.2 *Other sampling techniques*—Pneumatic or hydraulic powered saws and chipping hammers also can be used to take concrete samples from underwater structures. Samples of reinforcing bar are usually taken by cutting the bar with a torch, although a pneumatic or hydraulic powered saw with an abrasive or diamond blade can be used. Some high-pressure water jets can cut reinforcing steel.

3.5.3 *Sampling considerations for cores used in petrographic, spectrographic, and chemical analysis*—When samples are used to detect changes in the chemical composition or microstructure of the concrete, they are usually rinsed with distilled water after they reach the surface, then dried. If a case sample is of adequate size, the exterior portions of the sample, which may have been contaminated with seawater during the sampling operation, are removed and the interior sections are sent to the laboratory for petrographic investigation. If chloride content measures are needed, the exposed end surface of the sample is not removed, because it represents the degree of contamination in the original concrete. Cuttings and powder from concrete coring also can be analyzed, although recognition must be given to the fact that the material has been mixed and may have been contaminated by surface deposits (Dolar-Mantuani, 1983).

CHAPTER 4—PREPARATION FOR REPAIR

4.1—Concrete removal

General practice is to remove only the concrete that must be replaced while exposing sound concrete. This procedure minimizes the cost of the repair.

4.1.1 *High-pressure water jets*—High-pressure water jets provide an efficient procedure for removing deteriorated concrete, especially where the concrete's compressive strength is less than 3000 psi (20 MPa). Fresh water is supplied to the pump and transferred to a nozzle at 10,000 psi (70 MPa). To achieve success, the nozzles must be capable of developing an equivalent thrust in the opposite direction of the main nozzle to minimize the force exerted by the diver. This reduces diver fatigue, provides a safer work environment, and lowers concrete removal costs. Standard orifice nozzles are well suited to cutting concrete, but at high pressure, a standard orifice nozzle may cause cavitation bubbles at the surface of the concrete.

4.1.2 *Pneumatic or hydraulic powered chipping hammers*—Pneumatic or hydraulic powered chipping hammers designed for surface repairs are easily modified for underwater use. To absorb the reaction force of the chipping hammer, the diver must be tied off to the structure or another fixed element.

Pneumatic or hydraulic chipping hammers on the ends of surface-mounted booms with TV cameras provide an efficient concrete removal system without the need for a diver. The booms are commonly mounted to a stable structure to assure the necessary stability and operating safety. The TV camera lets the operator see below the surface and allows the operator to remove the deteriorated concrete.

4.1.3 *Pneumatic or hydraulic-powered saws*—Pneumatic or hydraulic saws designed for surface use can also be used under water. The necessary force to execute the work can be applied without the use of an external support. When this work is carried out in muddy or silty water a mechanical guide is employed, allowing the operator to continue even in low-visibility conditions.

4.2—Surface preparation

Typically, all marine growth, sediment, debris, and deteriorated concrete should be removed before repair concrete is placed into a structure. This cleaning is essential for good bond to occur between the newly placed concrete and the existing concrete. Numerous cleaning tools and techniques, such as high-pressure water jets, chippers, abrasive jetting equipment, and mechanical scrubbers have been designed specifically for cleaning and preparing the surface of the submerged portions of underwater structures.[11] The type of equipment required for an effective cleaning operation is determined by the type of fouling that is to be removed. Water jets operated by divers or fixed to self-propelled vehicles have been effective in most cleaning applications. Tools for removing underwater debris are also available. Air-lifts can be used to remove sediment and debris from water depths of up to about 75 ft (25 m).

The type of surface preparation and the required procedure varies with the site conditions as well as the specified objectives. In muddy or silty waters it is essential that the repair procedure be carried out the same day that the surface preparation has been completed to minimize the surface contamination that follows the cleaning operation.

4.2.1 *High pressure water jet*—High-pressure water jets can remove loose corrosion product from reinforcing steel during the concrete removal or cleaning process.

Fan jet nozzles on 10,000 psi (70 MPa) high-pressure water jets are an efficient method of removing marine growth and fouling on the surface. The optimum standoff distance for cleaning surfaces is $^1/_2$ to 3 in. (10 to 80 mm) with an impingement angle of 40 to 90 degrees. When operating with equipment that has a flow rate of 26 gal/min (100 l/min), cleaning rates of 4 to 7 ft^2/min (0.35 to 0.65 m^2/min) can be achieved on fouled concrete surfaces.

High-pressure water jets operating at 5000 psi (35 MPa) using a fan jet nozzle can clean previously prepared surfaces that have been contaminated by muddy or silty water.

4.2.2 *Abrasive blasting*—Abrasive blasting can be used as a final surface preparation for areas that have been prepared by pneumatic or hydraulic tools. The procedure will help to remove any fractured surfaces, and also cleans any sound surfaces that have been contaminated by muddy or silty waters.

Abrasive blasting offers the contractor an efficient method of cleaning marine growth and fouling from existing surfaces. However, crustaceans firmly attached to the concrete surface are not easily removed by abrasive blasting.

Abrasive blasting provides an effective and efficient method of removing corrosion product from the surfaces of the reinforcing steel. This procedure is beneficial to the long-term performance of the repair operation.

4.2.3 *Mechanical scrubbers*—Pneumatically or hydraulically-operated mechanical scrubbers can remove marine crustaceans efficiently and effectively, as well as clean small surface areas. Although these tools can clean surfaces effectively, they are not as efficient as high-pressure water jets or abrasive blasting for cleaning large areas.

4.3—Rehabilitation of reinforcement

Removing loose rust is the first step in rehabilitating reinforcement and can be done with high-pressure water jets or abrasive blasting. The back surfaces of the reinforcing steel are the most difficult places to clean, especially where the reinforcement is congested.

If the cross section of the reinforcing steel has been reduced, the situation should be evaluated by a structural engineer. The reduced section often can be strengthened with the addition of new reinforcing bars, but the original reinforcement has to be exposed beyond the corroded section a distance equal to the required design lap-splice length. Since the preparation costs are high, several small bars are frequently specified in lieu of one large bar to reduce the design lap-splice length.

Splicing new reinforcing bars onto the existing reinforcing steel is also possible. A variety of mechanical splices can be installed under water.

Welding new bar to existing bar is possible, but is rarely done. Since the carbon content or chemical composition of the existing and new reinforcing steel may not be known, welding is not recommended without further evaluation.

4.4—Chemical anchors

In many repairs, the forming or replacement material is anchored to the existing concrete substrate. Materials and procedures that perform well in dry applications are often inadequate for underwater applications. For example, the pullout strengths of anchors embedded in polyester resin under submerged conditions are as much as 50 percent less than the strength of similar anchors installed under dry conditions (Best and McDonald, 1990). This reduced tensile capacity is primarily attributed to the anchor installation procedure, although saponification can also be a factor. For details on an anchor installation procedure that eliminates the problem of resin and water mixing in the drill hole, see Corps of Engineers (1995). The cleanliness of the holes also effects anchor bond. When used in drilled holes that have not been thoroughly cleaned, chemical grouts can have significantly decreased bond strengths. Polyester resins and cement grouts have achieved acceptable bond in comparable conditions (Best and McDonald, 1990).

CHAPTER 5—FORMWORK

5.1—Rigid and semi-rigid forms

5.1.1 *Definition and description*—Rigid and semi-rigid forms inherently maintain a given shape, making them suitable for molding repairs into a final geometric shape. Semi-rigid forms differ from rigid forms in that they maintain some surface rigidity or stiffness when in place, but are capable of being bent into rounded shapes during placement. Both types of forms may be sacrificial, required to function only long enough to allow the repair material to cure. Such forms do not function as a structural element after the repair material has cured. Forms made of fiberglass or polymer materials are often used as part of the repair design to decrease the overall costs. When forms are designed to act as composite portions of the repair, such as epoxy concrete or precast concrete forms, they are mechanically attached to the final repair system and become an integral part of it.

5.1.2 *Physical properties*—As with traditional, above-water forming systems, the ability of the form to perform as needed during the repair is the primary concern, while the specific choice of material used to construct the form is secondary. Typical materials for rigid forms include, plywood, timber, steel, polymer based materials, and precast concrete.

Fig. 5.1—"Symonds" forms in place underwater for pumped repair. (Courtesy of M. Garlich.)

The forming system is generally selected based on performance, cost, ease of installation, ability to perform within the construction tolerances, and chemical compatibility with the repair medium. However, material selection for the forming systems that are designed to remain in place and act compositely with the final repair requires special consideration.

5.1.3 *Typical applications*—The specific geometry of the desired repair surface usually dictates the selection of a forming system. Rigid forms are most commonly used to form flat surfaces, and are suitable for flat wall surfaces such as caissons, seawalls, spillways, and foundations. They can also be fabricated in many geometric shapes. Rigid forms are typically characterized by a semi-rigid smooth forming surface backed by a series of stiffeners that restrict the deflection of the forming system. Plywood and steel frequently are used to form flat surfaces for wall repairs. In addition, they may be used to form columns.

Prefabricated steel, precast concrete, or composite steel-concrete panels can be used during underwater repair of stilling basins (Rail and Haynes, 1991). Each material has inherent advantages, and several factors, including abrasion resistance, uplift, anchors, joints, and weight should be considered when designing panels for a specific project.

A precast concrete, stay-in-place, forming system for lock-wall rehabilitation was developed by the U.S. Army Engineer Waterways Experiment Station (Fig. 5.1) (Abam, 1987a,b, 1989). A number of navigation locks were successfully rehabilitated using the system. In addition to resurfacing the lock chamber, precast concrete panels were used to overlay the back side of the river wall at Troy Lock in Troy, N.Y. The original plans for repairing this area required removing the extensively deteriorated concrete and replacing it with shotcrete. To accomplish a dry repair would have required construction of a cofferdam to dewater the area. Using the precast concrete form panels minimized concrete removal and eliminated the need for a cofferdam.

Fig. 5.2—Lower of three tiers of panels used to overlay the Troy Lock river wall wre placed and infilled under partially submerged conditions. (Courtesy of J. McDonald.)

Three rows of precast panels were used in the overlay. The bottom row of panels was installed and the infill concrete was placed under water (Miles, 1993). An anti-washout admixture allowed effective underwater placement of the infill concrete without a tremie seal having to be maintained. The application of precast concrete resulted in a significant savings compared with the originally proposed repair method.

Semi-rigid forms are typically used to form cylindrical shapes. They do not require stiffeners and may be designed as thin-shell, free-standing units. Thin-walled steel pipe, waterproofed cardboard, fiberglass, and polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) plastics are frequently used to form cylindrical shapes. Fiberglass, PVC and ABS plastics also can be preshaped in the factory to nearly any geometric design and to accommodate steel reinforcement, if necessary.

For pressure grouting, plastic jackets are the most commonly used forms. Wooden forms are also used for isolated or flat wall placements. The wood is lined with plastic to act as a bond breaker; after the grout has cured, the entire form is removed from the structure.

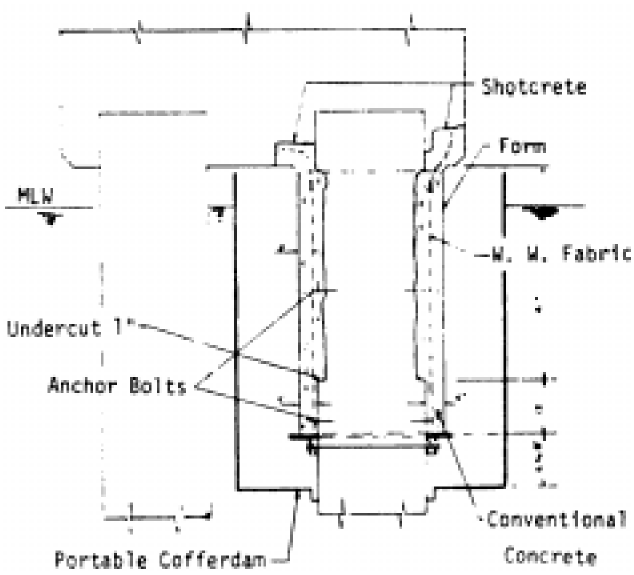

Fig. 5.3—Schematic showing "dry" pile repair. (Courtesy of I. Leon Glassgold.)

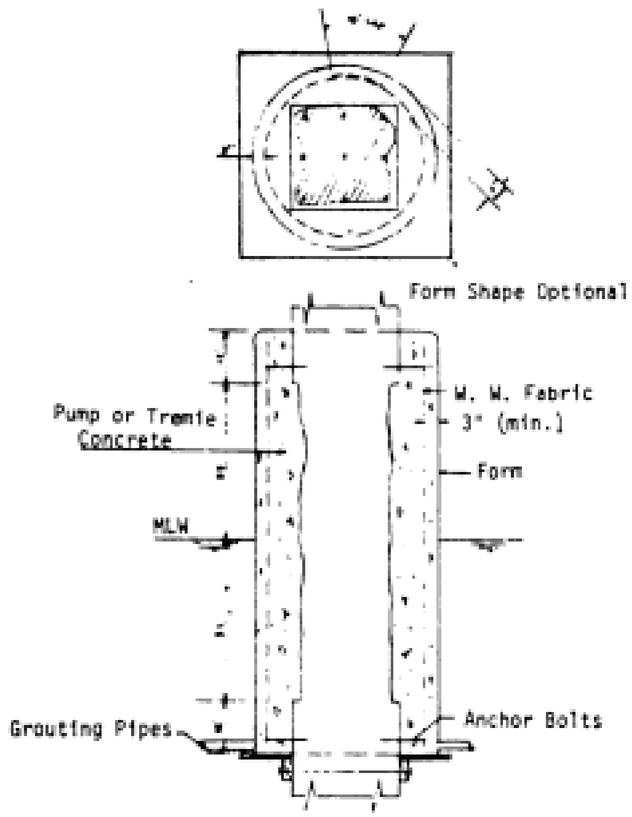

Fig. 5.4—Schematic showing "wet" pile repair. (Courtesy of I. Leon Glassgold.)

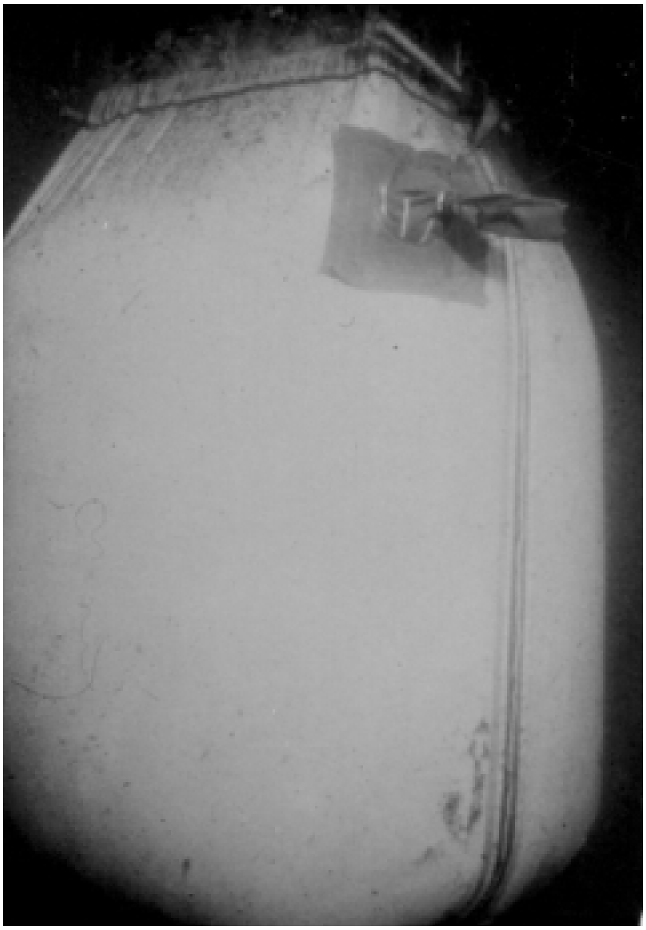

Fig. 5.5—Underwater view fabric form repair. (Courtesy of M. Garlich.)

5.1.4 *Selection considerations*—Rigid forms normally provide neat and clean outlines for the repairs. Properly designed, rigid forms will perform well within normal construction tolerances. Most rigid forms can be prefabricated and lowered into position with appropriate hoist equipment. Many rigid forms can be reused, which can be a significant cost savings for repetitive repair work. Most rigid forms for underwater repairs are much like the traditional forms used for above-water repair.

Semi-rigid forms are most commonly used in a cylindrical configuration, such as jackets around piles, columns, and other aquatic structures; however, they can also be used as bottom forms for flatwork and as general formwork for multi-shaped structures. Most repairs using semi-rigid forms do not require the incorporation of steel reinforcement within the form. However, if required, the jackets (including rigid, semi-rigid, and flexible forms) can be designed to accommodate a reinforcing cage. Semi-rigid forms are flexible enough to be wrapped around an existing structure (such as a pile), yet are rigid enough to retain their shape during placement of the repair materials. Some jackets are reusable; however, for most grouts and mortars the jackets cannot be removed and must be left in place as a sacrificial element. When left in place a sacrificial form may provide benefits by encapsulating the concrete structure, which slows diffusion of oxygen and chlorides to the concrete surface, helps to stop the growth of any marine life unintentionally left in the form, and may increase the abrasion resistance of the structure.

Cleaning existing concrete surfaces and reinforcing steel after the forms are installed is extremely difficult. Therefore, the integrity of the repair can be compromised if the repair

Fig. 5.6—Fabric form repair on timber pile. (Courtesy of M. Garlich.)

zone becomes contaminated with silts or marine growth after the forms are in place but prior to the placement of the repair material. With some rigid forming systems, proper consolidation of repair materials may be difficult. Most underwater formwork is rather small or segmented into small individual pieces. Large rigid forms can be cumbersome and difficult to place due to their mass, which must be manipulated by a diver.

The limitations of each of the forming systems are primarily related to the desired geometric tolerances of the final repair. Most forms are prefabricated to require only one or two divers to secure them in place. Coordinating more than two divers with a hoist operator on the surface is usually too difficult to be effective.

Rigid wooden forms are relatively lightweight and easy to work with under water. Precast concrete form panels are rather heavy, possibly restricting their deployment into final position. Placement of both types of panels under water requires good communication to reduce the hazards to the divers.

Underwater forms must be sealed by gaskets to prevent cement paste from leaking out through the joints. This can be especially serious in flowing water or waves.

5.1.5 *Installation procedures*—Rigid forms for flatwork or walls are typically prefabricated, lifted into position, and attached to the substrate using drilled-in expansion anchors (Fig. 5.2). After the repair concrete has cured, the form is generally removed, but can be left in place at the discretion of the designer.

Rigid, stay-in-place, precast-concrete, wall-panel forms are designed to perform monolithically with the cast-in-place concrete repair material. Wall panels are precast, lifted into position, and attached to the substrate. After the panel is secured, the space behind the wall panel is sealed as necessary to receive the fresh cast-in-place concrete (Abam, 1987b).

Rigid forms for pile repairs are generally prefabricated in two mated halves. A friction collar is set on the pile, and a base plate (usually plywood) is secured onto the collar. If reinforcement is included in the repair, it is normally set down on the base plate using the appropriate chairs to keep it off the bottom of the form. Spacers are installed on the reinforcing cage to set the clear cover to the form. The two halves of the pile form (steel pipe, PVC) are lowered into position individually, aligned, and fastened together. Normally, these forms are positioned and secured by one diver at a time, who either coordinates the lift of the form with a crane operator, or maneuvers the form by himself or with air bags to aid in the lifting. The concrete repair material (grout, concrete, epoxy mortar) is pumped into the form. After the repair is completed, the form and friction collar generally are removed (Fig. 5.3). Some applications allow these elements to be left in place. Fig. 5.4 shows an example of an underwater repair using rigid forms and a portable cofferdam, where shotcrete is used above the waterline.

Semi-rigid forms for pile repairs are generally prefabricated in one piece and are available in various sizes. The form is wrapped loosely around the pile above the water line where overhead clearance permits. Sections may be locked together to extend the overall length. The diver then pulls the form into position and completes the locking process to firmly attach the form to the structure. Many forms contain a compressible foam seal at the bottom (optional at the top), with spacers between the form and structure to correctly position the form. At this point some materials require dewatering, while others may not. The repair material (grout, concrete, epoxy mortar, or epoxy injection resin) is then pumped into the form. After the repair is completed the form may be left in place as a jacket.

5.2—Flexible forms

5.2.1 *Definition and description*—Flexible forming systems do not have the internal stiffness required to independently form the surface of concrete to a precise geometric shape. Examples of these types of systems include fabric pile jacketing forms, membrane plastics and fabric bags (Fig. 5.5 and 5.6). Flexible forms are fabricated from a multitude of materials, including burlap, membrane plastic, and synthetic fiber fabric.

5.2.2 *Typical applications*—For many years, piles commonly have been repaired using flexible forms. Applications for most flexible forms include the repair of piles, although these forming materials can be used for flat surfaces such as walls or mass-concrete elements such as groins. For pile repairs, the final product is typically an approximately cylindrical shape that surrounds the pile and extends for several feet above and below the damaged area. The fill may or may not be reinforced. For wall repairs, the finished shape is generally uneven or corrugated in appearance. For groin and breakwater repairs, the finished product is typically a mass with only generally definable shape.

5.2.3 *Selection consideration*—Flexible forms offer many advantages, including low initial cost, low weight, and ease and speed of installation. Most flexible forms are factory manufactured and field adjusted to meet the job requirements.

Formed fabric jackets with a zipper on one face are sometimes used in pile repairs. One diver usually deploys and erects a fabric form without the assistance of surface-based lifting equipment. Since the fabric form bonds to the surface of the repair concrete, the toughness of the fabric provides some supplemental abrasion resistance.

If a fabric form is allowed to rest on the free surface of the concrete placement, the concrete/water interface is partially protected from dilution. This helps reduce the laitance characteristic of typical tremie concrete. Impermeable plastic membranes for forming systems usually completely contain the cement particles, which may escape from similarly formed fabric systems.

The surfaces of flexible-formed concrete are generally irregular in appearance. Since fabrics or membranes offer no bending strength, formed surfaces are curved, although some flexible forms have been used for semi-flatwork applications. If a truly flat surface is desired, rigid forms must be used.

Fabric and membrane forms usually bond to the surface of the repair material during the concrete curing process. Prolonged exposure to ultra-violet light, abrasion, or impact may cause the form material to decompose or delaminate from the repair surface. Hence the surface will take on a ragged appearance with pieces of the form material dangling from the repair medium.

Since flexible forms have no inherent ability to maintain a given shape, they are not particularly well suited for situations where standoffs or chairs are needed to maintain minimum clear cover. Regardless of the configuration or orientation of the structure, fabric forms are difficult to hold in proper alignment, and once filled with concrete are very difficult to manipulate. This can result in insufficient cover due to form displacement.

Some commercially available forms have wide fabric mesh that allows cement paste particles to escape from the form. This can increase the water-cement ratio near the formed surface, and hence reduce the strength and increase the outside surface permeability of the repair. In addition, the release of the alkaline cement paste through the fabric weave into the free water may be an environmental concern in localities that support fish, mollusk, and crustacean populations. Conversely, some fabric form materials allow water to pass through the weave without allowing significant amounts of cement grains to pass.

Flexible forms are light and easily managed by one diver, but difficult to align true and plumb during the pumping operation. The overall weight of the concrete-filled system may pose problems and needs to be carefully considered.

Commercially available flexible forming systems come in a wide variety of materials. The physical properties of these materials may restrict their usage for certain applications. The tensile strength of typical fabrics are 200 to 400 psi (1.4 to 2.8 MPa). Some fabric forms (or zippers and seams on these forms) have ruptured during the filling process due to excessive pressure in the repair medium. This may restrict the rate of placement for repair materials.

It is not uncommon for the material to stretch as much as 10 percent under loads equal to 50 percent of the tensile breaking load. Therefore, allowance should either be made for the form to stretch during pumping operations (and the required volume of concrete increased), or this stretching should be restricted by installing external supports, such as hoops around piling repairs.

5.2.4 *Installation procedures*—Flexible-formed concrete can be classified into three generic geometric shapes. The repaired surface can be flatwork, such as wall repairs; vertical cylinders, such as a pile repair; or mass cast, such as might be used to encapsulate groins or breakwater features.

After vertical surfaces of concrete walls have been prepared to receive a repair, flexible forms may be positioned using a multitude of supplemental support methods. Some flexible forms have been supported with timber or steel wales, while others have been supported by reinforcing meshes forming ribs on the outer surface. The meshes may in turn be supported by wales or even supplemental piles driven near the repair zone. The repair material is then pumped into the form. Typically, the flexible-form membrane is left in place, but the external supports are removed.

When repairing piles, repair surfaces are normally cleaned to remove marine growth and other contaminants, and are occasionally roughened to enhance the bond between the pile and the repair material. Any reinforcement required for the repair is installed first and secured to the pile. Small-diameter PVC pipe is sometimes attached to the outer face of the reinforcement to maintain the required cover to the face of the form. The majority of flexible forms for pile repairs are shop prefabricated to the required length of the repair. The form jacket is then field modified as required and deployed by a diver to the repair zone. The diver completes the cylindrical shape by zipping up the bag. The top and bottom of the jacket is then secured to the respective sections of the pile repair zone. Wire or large hose clamps are often used. The repair material is then injected into the bag using one of several techniques, such as pumping concrete from the bottom, pumping from a hose located inside of the repair cavity while slowly withdrawing the hose, or using preplaced aggregates. The concrete is usually batched using $^3/_8$ in. (10 mm) maximum size coarse aggregate, which helps in the placement process. Using concrete or grout mixtures with small aggregate enables the diver to use smaller, more manageable hoses for placing the repair material. In most cases, a diver monitors the filling operation and may try to maintain the fabric form shape. After the repair zone is filled, it is common to continue pumping the concrete or grout until uncontaminated concrete or grout is observed extruding from the top of the form.

Individual fabric bags and flexible fabric mattresses are sometimes used in mass-placement applications to encapsulate an entire element in mass concrete. Mass placements are seldom reinforced. After the element has been cleaned and prepared for repair, a flexible form is placed around the feature and secured into position. Grout or concrete is then injected into the form until the desired shape has been achieved.

Pieces of reinforcing steel can be placed through adjacent fabric forms to tie together the mass concrete in adjoining zones. Some amount of mortar or concrete leakage is commonly observed when this technique is used.

CHAPTER 6—METHODS AND MATERIALS

6.1—General considerations

The design objective of the repair largely dictates the type of repair used on a project. For a minor spall or crack, a simple surface patch or crack injection system may be adequate to provide protection to the reinforcing steel. For major damage, where the load-carrying capacity of the element is compromised, the repair may either re-establish the strength of the original element, or perhaps even establish a new load path around the damaged area. The severity of the damage often determines the type of surface preparation, forming system, reinforcement arrangement, and repair medium used for the repairs.

6.2—Preplaced aggregate concrete

6.2.1 *Definition and description*—Preplaced aggregate concrete is defined in ACI 116R as concrete produced by placing coarse aggregate in a form and later injecting a portland cement-sand grout, usually with admixtures, to fill the voids between the coarse aggregate particles. Preplaced aggregate concrete is suitable for use in effecting repairs and making additions to concrete structures under water as described in this section. Detailed materials requirements and procedures on proportioning, mixing, handling and placing concrete, and references are given in ACI 304R and will not be repeated here.

6.2.2 *Materials*—The physical properties of preplaced aggregate concrete are essentially the same as conventionally mixed and placed concrete with respect to strength, modulus of elasticity, and thermal characteristics. The permeability of preplaced aggregate concrete can be significantly reduced when fly ash or silica fume are added to the grout. Of particular interest in connection with underwater repairs is the fact that the quality and properties of preplaced aggregate concrete are not affected by whether it is placed above or below water. The bond between preplaced aggregate concrete and a roughened existing concrete has been shown in unpublished reports to be better than 80 percent of the tensile strength (modulus of rupture) of the weaker concrete. Where drying shrinkage can occur, as in repairs that extend some distance above water, it is less than half that of conventional concrete. The durability of preplaced aggregate concrete appears to be excellent, based on informal reports. The procedure was developed in about 1950.

6.2.3 *Typical applications*—Preplaced aggregate concrete has been used extensively for repairing railway and highway bridge piers for many years, particularly for encasing and underpinning piers weakened by such factors as weathering, riverbed scour, exposed piling or cribbing, floating ice, and overloading. In many cases, piers have been enlarged to increase capacity to accommodate heavier deck loads, or to resist masses of floating ice or the impact of runaway river traffic. The method also has been widely applied to the repair of piers supporting control gates on spillways and hydroelectric outlet structures that have suffered damage from ice abrasion or freezing and thawing.

6.2.4 *Selection considerations*—The quality of preplaced aggregate concrete is not significantly reduced by placement under water because the grout is not significantly diluted by the water it displaces from the voids in the aggregate preplaced in the forms. Therefore, the cost of water-tight forms and dewatering may be eliminated and preparatory work can be done under water. If cofferdams are desired to permit visual inspection and the performance of preparatory work in the dry, the cofferdam need only be tight enough for pumps to hold the water down temporarily, then flooded prior to placing the preplaced aggregate concrete. This procedure eliminates the harmful effect of water moving upward through the preplaced aggregate concrete. The method may be used to fill relatively inaccessible voids under the structure or to consolidate the interiors of timber-crib or rock-filled piers.

When inspection and preparation are done under water, the cost of divers must be balanced against the expense of cofferdams that can be dewatered. Additionally, at least temporary dewatering may be required when inspection and preparatory work performed by divers is not adequate.

In water that is strongly polluted by organic materials, the prepared concrete surface and coarse aggregate resting in the forms may become unacceptably coated if grouting of underwater aggregate is delayed more than a few days. Where the surrounding water is turbid with clay or other settleable fines, such water may need to be excluded from the forms, either by using tight cofferdams or by flooding them with acceptably clean water to prevent inflow. In Japan, algae has been limited successfully by treating the water with inhibitors and placing a cover over the top to shut out sunlight.

6.2.5 *Installation procedures*—All damaged or weakened concrete is first removed to a predetermined depth or to sound material, whichever is greater. Where reinforcement is corroded, loose rust is removed or the bars replaced or supplemented as the situation requires. Applying bonding agents is neither necessary nor desirable. Forms are placed and carefully sealed at joints and at points of contact with concrete surfaces. Coarse aggregate is dropped into the formed areas, usually in 2 to 4 ft (0.6 to 1.2 m) lifts, taking care to avoid excessive segregation. Finally, the grout is pumped into the preplaced aggregate, starting at the lowest point(s), either through the forms or through preplaced vertical pipes, as described in ACI 304R. When the forms are full, it is good practice to spill a small portion of grout over the top of the form if it is open, or through vent holes or a venting section at the top of the form, to ensure that any trapped water, air or diluted grout are expelled. The forms are removed when the concrete has gained adequate strength; the above-water portions of the repairs are cured normally.

6.3—Tremie concrete

6.3.1 *Definition and description*—Tremie concrete is placed under water using a pipe, commonly referred to as a tremie or tremie pipe. The pipe is commonly referred to as a tremie. Tremie concrete differs from pumped concrete in that the concrete flow away from the tremie pipe is caused by gravity acting on the concrete mass in the tremie and not by pump pressure.

6.3.2 *Materials*—Tremie concretes typically have a high cementitious-materials content, which results in adequate compressive strengths for most underwater repair work. Concrete proportioned according to accepted guidelines for tremie placement generally gives excellent results (Holland, 1983). If underlying materials are properly cleaned, bond strength to concrete has been shown to be excellent.

Concretes ranging from fine grouts to those with $1^1/_2$-in.(40 mm) aggregates can be placed by tremie. Materials requirements and mixture proportioning are discussed in ACI 304R. Also see section 6.5.6.

6.3.3 *Typical uses*—Tremie concrete has been used in a wide variety of applications for underwater repair. At Tarbela Dam more than 90,000 yd^3 (68,800 m^3) of tremie concrete were placed to repair damage caused by cavitation (Holland, 1996). The Corps of Engineers has used tremie concrete to repair damage to stilling basins at several of its structures (McDonald, 1980). Tremie concrete is probably best suited for larger-volume repair placements where the tremie does not need to be relocated frequently, or for deeper placements where pumping is impractical. However, tremie methods have successfully been used for small grout placements such as filling cavities.

6.3.4 *Selection considerations*—The tremie method is relatively simple if well-established guidelines are followed. The equipment used in placing tremie concrete is rugged and simple, and therefore seldom malfunctions. Nevertheless, the tremie method still requires proper equipment and experienced personnel. These requirements may be more difficult to meet than if ordinary pumped concrete is used.

The major limitation for tremie placed concrete is caused by the mechanics of the technique. To seal the mouth of the tremie, a mound of concrete is built up at the beginning of the placement. The mouth of the tremie must remain embedded in this mound throughout the placement. The width of the placement is therefore dictated by the depth of this mound and the slope at which the concrete flows away from the tremie. Thin overlay placements under water usually cannot be accomplished using a tremie.

A second limitation is that water flow across the placement site must be stopped during the placement until the concrete has gained enough strength to resist being washed out of place. Flow control has been achieved by closing gates of structures, by building diversion boxes, or by placing the concrete under an upper form such as a heavy steel plate or weighted canvas, with a hole to accommodate the tremie.

Where the flow velocity of water across the placement is slow and laminar [approximately 3 ft/sec (1 m/sec)], anti-washout admixtures may prevent the concrete from being washed out of place. A small test placement made during the investigation or design phase of the repair can determine the suitability of anti-washout admixtures for a particular project.

6.3.5 *Installation procedures*—Successful tremie placement depends on keeping the concrete in the tremie separate from the water. Once the placement is started, the mouth of the tremie must remain embedded in the concrete to prevent concrete from dropping directly through water and becoming dispersed. Tremie placements for repair do not differ significantly from placements for new construction. ACI 304R contains recommendations for tremie placement.

6.4—Pumped concrete and grout

6.4.1 *Definition and description*—Pumped concrete is manufactured above water and pumped into place under water during a repair. This concrete depends upon the pressure of the pump, and sometimes upon gravity flow, to reach its final position in the repair.

Grouts are more fluid than concrete and generally do not contain coarse aggregate. Most grouts consist of portland cement and sand, and may contain fly ash and silica fume. Proprietary grouts may contain selected admixtures for pumping, adhesion, acceleration, dimensional stability, or other properties. Fluid grouts used to penetrate fissures, lenses, and small defects are made from very finely ground cement, known as “microfine cement.”

6.4.2 *Materials*—For concrete and grouts proportioned according to the generally accepted guidelines for pumped placement (ACI 304.2R), excellent results may be expected. Pumped concretes typically have high ratios of fine-to-coarse aggregate and cohesiveness will be improved. Grouts used under water sometimes have faster setting times to reduce loss due to erosion and wash-out. Materials should be selected that are relatively dimensionally stable in both the wet and dry environments to avoid the development of stress at the bond line. If the underlying materials have been properly cleaned, bond strength to hardened concrete has been shown to be excellent.

Concrete and grout pumps now available can pump a wide variety of mixtures comprised of cementitious materials with little difficulty. The cementitious mixtures should be developed with the specifics of the repair in mind and then reviewed for suitability for underwater pumping.

6.4.3 *Typical uses*—Pumped concrete is the most common method of placing concrete in underwater repairs, including those that are formed. It can be used in most applications where tremie concrete is applicable, but has the added advantage of having a smaller, more flexible hose that can reach difficult locations. The U. S. Army Corps of Engineers has pumped concrete under water to repair stilling basins (Neeley and Wickersham, 1989). On several such projects, the pumped concrete contained steel fibers and/or silica fume. Other uses include filling voids in or under structures.

Grouts are most commonly used to fill voids between concrete and forms or jackets such as in pile repair. They have also been used to repair smaller voids and larger cracks in and under concrete structures.

6.4.4 *Selection considerations*—The main advantage of pumped cementitious concrete and grout is that their physical properties are essentially the same as the concrete being repaired. Differences in modulus of elasticity and thermal expansion are negligible for most underwater work. Uncured cementitious materials are less hazardous than uncured epoxies. They are also easier to work with and less trouble-prone than polymers because they are less sensitive to temperature variations during mixing, placing and curing. They are also less likely to leak from small defects in forms and jackets than epoxy systems.

Pumping under water has the advantage of eliminating the equipment associated with a tremie placement, since the pump delivering the concrete or grout is also the placement device. The use of a pump with a boom may facilitate relocating the pump outlet site if the repair consists of a series of small placements.

As with tremie placements, successful underwater placement of concrete by pump requires the proper combination of appropriate concrete proportions and equipment, and personnel trained in underwater concrete placement. Typical pump contractors or pump operators may not have experience in underwater concrete placements.

In the past, some environmental agencies, such as the National Oceanographic and Atmospheric Agency (NOAA), have expressed concern about the effects of alkalis and washed-out cement particles on coral reefs and fish. On one project in the Florida Keys for the U.S. Army Corps of Engineers, these concerns were addressed, at least in part, by using anti-washout admixtures (*Concrete Products*, 1995; McKain and McKain, 1996).

The same limitations regarding underwater placements in thin sections and the requirement to eliminate water flow across a placement site that applied for tremie placements also apply for pumping under water. A special problem inherent in pumped concrete is that it is discharged in surges, which can result in more cement wash-out and laitance formation than tremie concrete.

6.4.5 *Installation procedures*—Successful pump placement under water, depends upon separating the initial concrete or grout that is placed at the start of the pumping from the water and upon maintaining that separation throughout the placement. The separation must be reestablished whenever the pump outlet is relocated. Underwater placements for repairs do not differ significantly from placements for new work. Additional guidance can be obtained ACI 304R.

6.5—Free dump through water

6.5.1 *Definition and description*—Free dump through water is the placement of freshly mixed concrete by allowing it to fall through water without the benefit of confinements such as a tremie pipe or pump line. Anti-washout admixtures may or may not be used.

6.5.2 *Materials*—Concrete that is to be allowed to free fall through water should contain anti-washout admixtures. Development of these admixtures was formerly concentrated in northern Europe, but has recently spread to Japan and the U.S. (Straube). The admixtures contain some or all of the following ingredients: high molecular weight polymers, superplasticizers, cellulose derivatives, and gums. When added to fresh concrete, the anti-washout admixtures improve the flow characteristics of the concrete.

Anti-washout admixtures are often used in concrete intended for underwater (Maage, 1984; Underwater Concrete, 1983b). The concrete also may contain abrasion resistant materials, silica fume (Makk and Tjugum, 1985), or other admixtures (Maage, 1984; Underwater Concrete, 1983b). An example of a mix design using an anti-washout admixture for the rehabilitation of an intake velocity cap is as follow (Hasan et al., 1993):

Cement, C, pcy	600	[354 kg/m^3]
Fly Ash, FA, pcy	90	[53.10 kg/m^3]
Silica Fume, SF, pcy	43	[27.10 kg/m^3]
Water/[C+FA+SF]*	0.40	
Fine Agg., pcy	1,467	[865.60 kg/m^3]
Coarse Agg., pcy	1,550	[678.50 kg/m^3]
Anti-washout admixture, gcy	0.60	[3.58 l/m^3]
High range water reducing admixture, gcy	1.90	[11.34 l/m^3]
Slump, in.	10	[254 mm]
24-hr Strength, psi	1,960	[13.50 MPa]

*Water to cementitious materials ratio.

Conflicting evidence exists on the quality of the in-place concrete when placed by the free dump method. Some laboratory work has indicated that once the free dump concrete is in place and set, its physical properties are equal to those of good quality concrete placed by conventional tremie or pump (Underwater Concrete, 1983a; Kajima Corp, 1985). In fact, there is some evidence that strength, bond and impermeability are actually improved, compared to normally placed underwater concrete (Maage, 1984; Makk and Tjugum, 1985). However, other large-scale field trials have been less successful, with the concrete being segregated and with wash-out of the cement. Another problem that can occur with this method is that water may be entrapped within the dumped concrete. The free-fall height should be limited to that required for opening the bucket so as to reduce the velocity of impact.

6.5.3 *Typical uses*—The free dump method is used for placing concrete containing anti-washout admixture under water in new construction and to repair old concrete.

6.5.4 *Selection considerations*—Free-fall concrete has been most successful in shallow water applications, where self-leveling concrete is not required.

Research results strongly suggest that fee-fall concrete is cohesive and is not harmful to the environment (Underwater Concrete, 1983a; Kajima Corp, 1985). Since the 1970s, the Sibo group in Osnabruck, Germany, has successfully placed thousands of cubic meters of concrete with an anti-washout

Fig. 6.1—Underwater view of hollow rock bolts grouted into existing construction. (Courtesy of M. Garlich.)

admixture by first spreading the concrete uniformly on pallets on the deck of a special barge, and then dropping the concrete through the water by tilting the pallets (Freese, Hofig, and Grotkopp, 1978). The primary advantage is, of course, the capability to place quality concrete under water without the use of cumbersome tremies and pumps.

Large doses of anti-washout admixture are usually needed to provide concrete of adequate cohesion to prevent washout and segregation during placement. Large amounts of anti-washout admixture increase the cost of the concrete. A concrete mixture that is cohesive enough to maintain its integrity while free-falling through water and yet is flowable enough to be self-leveling can be difficult to proportion. Concrete made with anti-washout admixtures is often tacky (Straube), sensitive to slight changes in the water-cementitious materials ratio and certain other admixtures (Gerwick, 1988), and sticky and difficult to remove from equipment (Maage, 1984). Information about its behavior under various field conditions and temperatures is limited.

Unless the concrete mixture is proportioned properly and the proper amount of anti-washout admixture is used in the mixture, significant washout and segregation can occur during placement. The shorter the fall through water, the greater the chance for success. If the free fall is limited to approximately 1 ft (0.3 m), the probability for successful application is excellent (Underwater Concrete, 1983a; Kajima Corp, 1985).

6.5.5 *Installation procedure*—Underwater concretes containing anti-washout admixtures can be batched and mixed in conventional concrete plants or ready-mix trucks (Underwater Concrete, 1983a; Kajima Corp, 1985). Placement may be by pump or inclined or vertical pipe without the need to maintain a tremie seal (Underwater Concrete, 1983a; Kajima Corp, 1985) or special equipment (Underwater Concrete, 1983b; Freese et al., 1978). The admixture is pre-batched in powder form into the concrete mixer by about 0.5 to 1.5 percent by mass of the cement (Makk and Tjugum, 1985). The admixture in liquid form is normally added to the concrete after all other ingredients have been blended together. The normal dosage is 0.05 to 0.15 gal/100 lb (0.4 to 1.1 l/100 kg) of cementitious material.

6.6—Epoxy grouting

6.6.1 *Definition and description*—Epoxy grouts are used for splash zone and underwater repairs. The materials typically consist of an epoxy resin that is curable under water; the resin is used either without aggregate for narrow void grouting, or mixed with specially graded silica sands and sometimes with larger aggregates to form an epoxy-polymer mortar or concrete.

The epoxy grouting process usually includes the epoxy grout and a jacket, creating a composite system. The jackets, concrete, and epoxy grouts have different physical properties. Adhesion of the epoxy grout to the concrete is important to the overall composite design. The jacket system protects the outer surface of the concrete structure against abrasion, reduces oxygen flow into the damaged area, and defends the structure from physical and chemical attack.

The guidelines used for void grouting are typically divided into two categories. A wide void is defined as a space between the jacket and concrete larger than $^3/_4$ in. (20 mm). A narrow void is defined as a $^1/_8$ to $^3/_4$ in. (3 to 20 mm).

6.6.2 *Materials*—Pourable epoxy grout materials usually contain silica sands. The amount of sand is dependent upon the epoxy material, void size and ambient temperatures. These materials may be either poured into place filling the void between the jacket and the existing concrete, or pumped into place. Pumpable epoxy mortars contain a larger quantity of silica sand than pourable mortars. They require a pumping system that allows larger particles (sand and possibly stone) to pass through the pump without causing segregation of the epoxy/aggregate mixture. Epoxy resins, blended with a select gradation of silica sands, silica or quartz flour, or other fillers to make a non-sag consistency, may be placed by hand. These are used for small quantity placements between the concrete structure and a permanent jacket system.

Epoxy grout is designed to bond to the concrete, eliminating a cold joint between the concrete and jacket system. The entire system provides additional reinforcement to the structure. The damaged area may be repaired with or without reinforcing steel. If reinforcement is used, epoxy mortars are intended to encapsulate and protect it.

When epoxy resins are used in repair it is intended that these materials become bonded with the concrete structure. Because the underwater environment creates unique challenges for these materials, documented performance history and testing per ASTM C 881 methods is advised.

The epoxy formulations are selected based upon the temperature at the time of application, and on the anticipated temperature range during the service life. Epoxy is mixed with aggregate or other fillers to form the epoxy grout. The filler extends the epoxy to reduce the overall costs of the polymer grouting repair and reduce heat buildup.

6.6.3 *Typical uses*—Plastic jackets and underwater-curable, epoxy-resin systems are used for the repair of eroded or structurally damaged splash zone concrete and underwater concrete structures. Epoxy systems are used for patching, grouting, and crack repair. They are also used to bond such items as anchor bolts (Fig. 6.1), reinforcing steel, and protective safety devices to concrete under water. Underwater-curable epoxy coatings are used to provide protection to concrete and other building materials from erosion and aggressive waters.

6.6.4 *Selection considerations*—Using epoxy grouts for the repair of splash zones and underwater areas of concrete has several advantages. The jacket system is light and does not add significant additional weight to the structure. A properly selected, designed, and installed system provides long-term protection from sand erosion, wave erosion, wet-dry cycles, floating debris, marine organisms, freeze-thaw damage, and salt and chemical intrusion.

The jacket repair method is fast and easy to install. Manufacturers of jacket systems offer standard sizes and shapes. Special shapes and sizes may be available upon request.

The epoxy portion of the system is the most critical in terms of application and cure. Good quality control standards for mixing and handling of the epoxy are essential for a successful application. The epoxy grout must be capable of being placed by pouring, pumping, or hand packing, and cured in the presence of fresh, brackish, or salt water at temperatures from 38 F (3 C) to 120 F (50 C) to satisfy placement in most North American water areas.

Epoxy grouts possess physical properties much different than those of the concrete being repaired. The compressive and tensile strengths of epoxies are typically much greater than those of the concrete substrate and are not usually a critical issue in repair design. The modulus of elasticity and the creep coefficient of the epoxies are more of a concern. No matter how high their strength, more flexible materials will not carry their portion of the load when acting monolithically with a stiffer material such as concrete.

The coefficient of thermal expansion is another important physical property of epoxies. Although underwater repairs are generally subjected to lower variations in temperature than above-water repairs, some underwater structures, such as those associated with power plants, may be subjected to large variations in temperature. Epoxy repair materials generally reach higher temperatures when they cure than cementitious mortars and concretes reach. These temperature rises can be significant when large voids are being filled. Because of this and cost considerations, epoxy repairs are generally limited to filling smaller voids or cracks.

When the narrow-void jacket system is used to fill cracks in piles, the cracks are usually not filled and the internal crack surfaces are not bonded together. In most cases, only the adjacent surface is encapsulated and protected. If the crack extends beyond the jacket coverage area, deterioration will develop or continue, possibly even under the jacket area.

Epoxy mortar installation requires workers with more specialized training and equipment than cementitious based repairs. Both the uncured resin and solvents that are commonly used are hazardous chemicals that require special handling and safety precautions. Epoxy is also more sensitive than portland cement-based materials to mixing, application and curing temperature. For example, epoxy mortars that are very workable when mixed in warm conditions on the surface could become very stiff when being applied in colder conditions under water. In addition, shelf life and temperature range during storage are more limited for epoxies. When filling forms with epoxy mortars, care should be taken to minimize or prevent the material from leaking out of small separations or defects in the forming system.

6.6.5 *Installation procedures*—For jacket-type repairs, the jacket is usually installed immediately after the surface preparations are completed, including the removal of loose or broken concrete and rust, and the epoxy is placed. Jacket placement is often accomplished from above the waterline on a barge or scaffolding. The jacket is wrapped around the structure and loosely locked so that it will not reopen in a strong current or waves. The jacket is then slipped down the structure into the water, where the diver pulls it into place. By pulling the locking device, the jacket is secured to the pile. A similar procedure is used for flat surface forming.

The epoxy should be carefully mixed according to the manufacturer's directions and with the specified amount of sand and coarse aggregate. Most manufacturers recommend immediate product placement after mixing, by pouring or pumping the material into the jacket cavity and displacing all water. Epoxy mortar or concrete should be rodded or vibrated during installation to remove air pockets.

Pumpable epoxy mortars are typically placed with a large diameter hose or pipe ($1^1/_2$ in. [25-35 mm]), which is inserted between the concrete structure and the permanent jacket system. The pipe is then slowly removed as the epoxy mortar fills the cavity and displaces the water.

Narrow voids are grouted with formulations of neat epoxy resin. The material is placed by a positive displacement pump, which mixes and sometimes heats the two-component resin system. The epoxy resin is pumped into the space between the concrete and jacket surfaces until all water is displaced. After the jacket is filled, it is capped with a trowelable epoxy mortar which is beveled at a 45 degree angle upward from the outer edge of the jacket to the surface of the structure. Experience has shown that in both freezing and warm environments, this technique improves the durability of the protective system.

6.7—Epoxy injection

6.7.1 *Description and definition*—Injection of epoxy resins into splash zone and underwater cracks and honeycombs in concrete structures has been successfully practiced since the 1960s in fresh and salt water environments. The injection process may be accomplished from the interior of pipes, tunnels, shafts, dams, floating-precast-box bridges, and piers. Piles and backfilled walls must be serviced from the waterside. The following text will concentrate on the water-side application methods of repair, even though dry-side applications are very similar.

The purpose of crack injection is to restore the integrity of the concrete or to seal cracks. Honeycombed areas within the concrete also can be repaired by the injection process. The injected epoxies fill the cracks and bond the crack surfaces together, restoring, at least in part, the concrete's original integrity and preventing any further water intrusion into the structure.

The physical properties of concrete repaired with epoxy injection are similar to the original concrete. The repair of concrete by crack injection will not increase the structure's load-carrying ability above the level of the original design.

6.7.2 *Materials*—Epoxies for resin injection are formulated in low viscosity and gel consistencies. The materials are 100 percent solid, 100 percent reactive, and have low shrinkage upon curing. The low-viscosity injection resin is used for voids narrower than $^1/_4$ in. (6 mm). An epoxy gel may be used for larger voids, from $^1/_4$ in. to $^3/_4$ in. The physical strength properties for both epoxy consistencies are typically equal. The resin is required to displace water within the void, adhere to a wet or moist surface, and then cure in that environment.

Not all epoxies are capable of bonding cracked concrete together, especially under water. An underwater concrete crack contains materials such as dissolved mineral salts, silt or clay, and debris from the corroding metal in addition to water. All of these materials interfere with good bond development unless they are removed. Ideally, the epoxy injection resin has two main duties to perform: first, it must displace all free water from within the crack or void; then it must cure and adhere to wet concrete and reinforcing steel surfaces. As a result, special epoxy formulations that are insensitive to water are required for underwater work.

The surface sealer must be capable of adhering to the concrete, set rapidly at the expected ambient temperatures and confine the epoxy injection resin while it is being injected and cured.

It is usually of either a hydraulic cement base or a paste consistency epoxy specially formulated to be placed and bond in the underwater environment. The selection of either a cement or epoxy formula is dependent upon water temperature, currents, setting time, and previous work experience of the divers or injection technicians.

6.7.3 *Typical uses*—Limitations of the underwater environment such as light, currents, temperature and contaminants on or in the crack limit the size of crack that can be injected from a practical standpoint. Considering these limitations, a low viscosity epoxy may penetrate cracks 0.015 in (0.38 mm) and larger; when the crack size is 0.10 or larger a gel consistency epoxy resin may be used. Both consistencies of materials are generally considered capable of bonding and repairing a cracked section when there is adequate adhesion to the surfaces of the crack and when at least 90% of the crack is filled.

Non-moving joints can be bonded together with epoxy resins, just like a crack. Anchor bolts and reinforcing steel can be grouted into concrete structures in the splash zone and under water with the injection process.

6.7.4 *Selection considerations*—Materials that meet the criteria for ASTM C 881, and can be verified to exhibit sufficient bond strength in a wet and saturated condition are excellent initial choices for material selection. Much of the underwater work done in North America is in water with temperature at or below 50 F (10 C). The epoxy material selected should be tested and verified to be capable to cure and bond at the anticipated ambient temperatures. In addition, the viscosity of the material needs to be compatible with the selected pumping equipment at the anticipated temperatures to ensure that the material will be able to penetrate the size of cracks to be repaired.

Selection of the correct epoxy formulation is important. Most epoxies will not bond or cure under water, especially below 50 F (10 C). At lower temperatures, it becomes more difficult to pump the epoxies into fine cracks because of the increased viscosity. Correct equipment selection, coupled with the proper epoxy, is essential.

Epoxy injected into cracks will act as an electrical insulator, possibly preventing the effective use of cathodic protection.

Epoxies may not provide full bond to contaminated crack surfaces, thereby limiting the epoxy's ability to fully seal a crack or to transfer forces across the crack. Epoxy injection will not stop corrosion once it has started. In aqueous environments, especially seawater, epoxy coatings in permeable concrete may delaminate from the reinforcing bars over time, allowing corrosion to proceed.

6.7.5 *Installation procedure*—Several types of epoxy pumping systems are used: (1) positive displacement pumps; (2) pressure pots; or (3) progressive cavity pumps. Type (1) pumps mix the epoxy just prior to entry into the crack, while types (2) and (3) require mixing the epoxy prior to pumping.

The exposed concrete surfaces on both sides of the crack are typically cleaned by high-pressure water blasting, abrasive blasting or other mechanical methods. Entry ports are used as inlets to carry the epoxy injection resin into the crack or void. The entry ports can be attached to the concrete surface and bonded into place with a hydraulic cement or epoxy paste. Ports may also be established by drilling into the crack and setting an entry port into the drilled hole. The size of the cavity to be injected, concrete thickness, and crack length all determine the proper spacing of the entry ports. Spacing of injection ports should be at least equal to the thickness of the cracked member being repaired or if the crack depth is previously determined then the spacing should be a minimum of the crack depth. The remainder of the exposed crack is sealed with fast setting hydraulic cement or epoxy paste.

The rapid setting cement formulations for surface sealing over cracks may have a working life of 3 to 5 min and a set time of an additional 3 to 15 min, depending on the water temperature. When a cement sealer is used, the crack is injected as soon as possible because the bond strength to old concrete surface may be affected by surface contaminants.

The surface seal can either be left in place or removed after the injection resin has cured.

The epoxy is injected at the lowest entry port and injection continues until all air, water and epoxy mixed with water is

Fig. 6.2—Hand placing underwater patch. (Courtesy of M. Garlich.)

forced out of the next adjacent port with clear epoxy resin. This process is continued until the entire crack length is inject.

The pressure used for epoxy injection need to be sufficient to displace materials at temperatures and depths anticipated and to completely fill the crack. Typical pumping pressures are from 20 to 150 psi (0.34 to 1.0 MPa). Care should be taken not to use pressures that could rupture the surface seal. Excessively high pressures have been known to damage concrete elements when the epoxy in the crack has no point of exit. Special care should be given during epoxy injection into laminar cracks where there is little or no reinforcement across the crack. The injection pressure must be kept very low to prevent hydraulic fracturing from widening or extending the crack. Stitch bolts across the crack are the only positive means of repairing such laminar cracks.

6.8—Hand placement

6.8.1 *Description and definition*—In an isolated location where the repair area is small, patching by hand placement may be preferable to other methods (Fig. 6.2). As with other repair methods, the surface should be cleaned before placing new material. Repairs made using this method may not be as durable as with other methods, but the cost may be less. Hand placed materials often fail because of poor workmanship.

6.8.2 *Cementitious products*—Accelerating admixtures can facilitate hand placement of cementitious mixtures. Concrete can be modified by hydrophobic, epoxy-resin mixes that can be for hand patching of thin sections. Concrete can also be modified with anti-washout admixtures and dropped through the water to divers waiting to apply it by hand. Conventional concrete has been placed in plastic bag with twist ties and dropped to waiting divers. See Section 6.5 for further information.

6.8.3 *Epoxy mortar products*—Epoxy mortars made with fine aggregate have also been applied by hand. These materials are typically mixed on the surface and lowered through the water to the work area below in a covered bucket. See Section 6.6 for further information.

6.9—Other underwater applications using concrete containing anti-washout admixtures

Concretes containing anti-washout admixtures also can be placed under water by tremie or pump, or slipform (Saucier and Neeley, 1987; Kepler, 1990). The highest quality underwater concrete placement can be achieved when the concrete contains a moderate dosage of anti-washout admixtures and is placed by either tremie or pump (Underwater Concrete, 1983a; Kajima Corp, 1985) directly to the point of placement. Concrete containing anti-washout admixtures has been successfully placed by tremie and by pump in numerous applications in the United States, Europe, and Japan. These applications have been in new construction and in repair of existing concrete structures. The Corps of Engineers has conducted extensive research into repair applications using concretes containing anti-washout admixtures and placed by tremie and pump (Neeley, 1988; Neeley et al., 1990; Khayat, 1991). The concrete can be proportioned to be self-leveling and to flow around reinforcing steel and other objects with ease. The increased cohesiveness imparted by the anti-washout admixtures makes the concrete pumpable. These concretes can also be placed in areas surrounded by slowly flowing water. Anti-washout admixtures in combination with certain water-reducing and air-entraining admixtures should be checked for compatibility. Any potentially troublesome problems with the fresh concrete can be detected in trial batches prior to the actual placement.

CHAPTER 7—INSPECTION OF REPAIRS

7.1—Introduction

Ideally, construction inspections are performed to verify that repairs have been made in accordance with the construction documents. Due to the expense associated with underwater inspections, they are not always performed. When an inspection is conducted, it may be performed either during the course of the construction phase or after all of the work is complete. There are advantages and disadvantages to each, since each procedure has unique problems.

7.2—Procedure

At the discretion of the owner, the contractor may be assigned the responsibility for performing the quality control of the project without further review by the engineer, the owner or an independent agency.

Alternatively, an engineer or independent agency can perform the inspections.

7.2.1 *Inspection techniques*—Most inspections are visual, with some use of small hand tools such as hammers or rulers. Occasionally, a core sample is taken to verify the adequacy of the repair. For further information regarding specific techniques used for the inspections, see Chapter 3.

Video is especially helpful to the owner if the inspection is being performed by the contractor, or by a diving agency that does not have specific expertise in construction inspection. An owner's representative may direct the diver and the video from the surface, if communication is available. However, video equipment requires reasonably clear water.

7.2.2 *Inspection during construction*—Inspections that are performed during construction are normally phased so the inspection team can observe certain critical tasks as they are performed. In the case of a large spall repair, the inspections may be phased so that the inspection team can observe the drilling and placement of dowels, the surface preparation, the reinforcing bar arrangement, the form, and the completed product. If the repair involves epoxy injection of small cracks, the inspections may check the cleaning, the placement of the injection ports, the placement of the surface crack sealer, the actual injection, and the completed repair. If inspections are performed during construction, they must be timed closely so the progress of the contractor is not unduly interrupted and so subsequent phases of work do not obscure the item to be inspected.

7.2.3 *Post-construction inspection*—Some owners are primarily concerned with the outward appearance of the repair and do not plan to own the structure for long. Other owners rely on cores or non-destructive tests after the work is complete to determine the quality of the repair. In these instances, only post-construction testing or inspections are performed. The actual timing of this type of inspection may not be especially critical; however, it should normally be performed soon after construction is complete. It may form the basis for payments to the contractor. Post-construction inspection does not hamper the contractor; however, it only verifies that work was done. It does not confirm that all phases of the work were performed in accordance with the contract documents.

7.3—Documentation

Documentation for the construction inspection should consist of a report accompanied by appropriate sketches and/or photographs, as appropriate. If video is used during the inspection, a copy of the video tape may also be included.

CHAPTER 8—DEVELOPING TECHNOLOGIES

8.1—Precast concrete elements and prefabricated steel elements

Precast concrete elements and pre-fabricated steel elements have been used on a very limited basis for repairing concrete structures under water. Difficulty of handling the elements under water, the need to secure effective attachment to the in-place concrete, the requirement for thoroughly cleaning the area to be repaired, and the design and sizing of the elements are obstacles to the application of these techniques.

In developing underwater repair concepts, both construction methods and prefabricated panel designs require attention. Divers are likely to be an integral part of repair projects, but for depths greater than 40 ft (12 m), severe bottom time limitations are placed on divers. Steel panels or composite steel-concrete panels would be preferred over concrete panels if abrasion resistance is important. However, if steel is selected, design details must assure that the steel panels remain serviceable under uplift forces from high-velocity water flow. Other approaches include abrasion-resistant, epoxy-coated steel or concrete panels. One design philosophy would be to use panels as large as possible to minimize joints between panels. The number of joints that are transverse to water flow should be minimized (Rail and Haynes, 1991; Abam, 1987a,b, 1989; McDonald, 1988; Miles, 1993).

Precast ferrocement elements are strong and light weight, which is an advantage in underwater repairs. Ferrocement is thin-shell concrete reinforced with closely-spaced, multiple-mesh layers of either wire fabric or expanded metal. Section thickness seldom exceeds 2 in. (50 mm), is usually less than half that, and may be as thin as 3/8 in. (10 mm). A 1/8-in. (3-mm) cover has been found to provide adequate protection for the mesh in marine environments when the mortar was made with a 1:2 cement/sand ratio and a water/cement ratio below 0.4. Ferrocement can undergo large strains without cracking. When cracks do appear they are closely spaced and limited in extent. See ACI 549.1R for more information on ferrocement. Ferrocement elements have been used in England to repair sewer inverts under water without taking the system out of service. Patents are pending on a similar system for use in the U.S.

CHAPTER 9—REFERENCES

9.1—Recommended references

The documents of the various standards producing organization referred to in this document are listed below with their serial designations:

American Concrete Institute (ACI)

116R	Cement and Concrete Terminology
201.2R	Guide to Durable Concrete
210R	Erosion of Concrete in Hydraulic Structures
222R	Corrosion of Metals in Concrete
304R	Guide for Measuring, Mixing, Transporting and Placing Concrete
304.2R	Placing Concrete by Pumping Methods
515.1R	Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete
549.1R	Guide for the Design, Construction, and Repair of Ferrocement

American Society for Testing and Materials (ASTM)

C 597	Standard Test Method for Pulse Velocity Through Concrete
C 805	Standard Test Method for Rebound Number of Hardened Concrete
C 881	Specification for Epoxy-Resin Base Bonding Systems for Concrete

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
100 Bar Harbor Drive
West Conshohocken, PA 19428

9.2—Cited references

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