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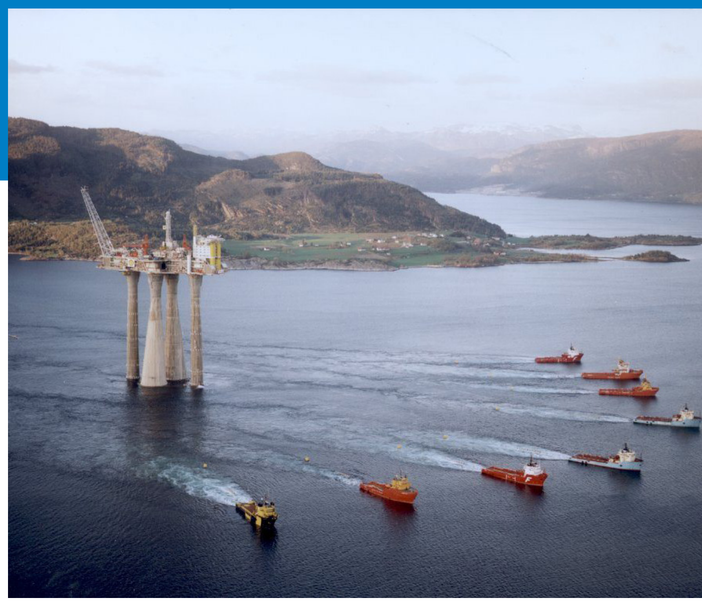

Offshore and Marine Concrete Structures: Past, Present, and Future

SP-337

Editor:
Mohammad S. Khan

American Concrete Institute
Always advancing

Offshore and Marine Concrete Structures: Past, Present, and Future

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PREFACE

Offshore and marine concrete structures have not received enough attention in the recent past, at least in the United States. The complexity and safety concerns associated with these structures are such that they probably need more attention compared to many other types of concrete structures. Also, offshore and marine concrete structures are so global in nature that there is a higher need for better coordination and synchronization of design, construction, inspection, and maintenance practices in different parts of the world.

A two-part session, titled “Offshore and Marine Concrete Structures: Past, Present, and Future,” was held at the Spring 2019 ACI Concrete Convention and Exposition on March 24-28 in Quebec City, Quebec, Canada. The session, sponsored by ACI Committee 357, Offshore and Marine Concrete Structures, highlighted accomplishments of the past, current state-of-the-practice, and a path for the future. This ACI Special Publication (SP) is a compilation of select papers presented at the session. The efforts of all the reviewers in assuring the quality of this publication is greatly acknowledged.

Mohammad S. Khan, Ph.D. P.E.
Editor

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Testing and Inspection Techniques for Offshore and Marine Structures

Mohammad S. Khan

Synopsis: Offshore and marine structures present special testing and inspection challenges due to their difficult accessibility and lack of visibility below water. Some of the testing and inspection personnel need to be divers, and some of the testing and inspection techniques become impractical in submerged conditions even with a diver. Thus, non-destructive evaluation (NDE) techniques that can be applied from above water, coupled with limited underwater inspections, offer the most practical solution for the testing and inspection of offshore and marine structures. This paper reviews and analyzes various above-water and underwater techniques that can be used for offshore and marine structures. Above-water techniques include visual inspections, chloride ion analysis, carbonation depth measurement, half-cell potential measurement, corrosion rate measurement, strength testing, and petrographic analysis. Whereas, the underwater techniques include diver-assisted visual inspections, real-time video imaging, modified versions of some of the above-water techniques, sonic-echo, impulse response, ultrasonic guided waves (UGW), and limited semi-destructive testing. Advantages and limitations of various techniques have been discussed. Finally, areas of future research have been identified, which can improve the efficiency, effectiveness, cost, and safety of testing and inspection techniques used in offshore and marine structures.

Keywords: condition assessment, evaluation, inspection, marine, NDE, offshore, structural evaluation, underwater, testing

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INTRODUCTION

Testing and inspection play an important role during the life cycle of a structure since almost all structures experience some form and extent of deterioration, and testing and inspection help identify and quantify them. Also, the information generated from testing and inspection forms the basis of an effective repair and rehabilitation strategy to assure the continued and safe use of the structure. Testing and inspection of offshore and marine structures is of particular significance since the environmental and exposure conditions to which these structures are exposed to are generally more aggressive than other structures. These include continuous cycles of wetting and drying in the splash zone, high concentrations of chlorides and sulfates in the seawater, marine growth around the structure, high wind loads from hurricanes, ice loads in the arctic, and occasional accidental impacts from vessels and other objects.

In the current available literature, it is often difficult to find a document where practitioners can easily identify the options available to them for testing and inspection of offshore and marine structures. American Concrete Institute (ACI) Committee 357, Offshore and Marine Concrete Structures, has three active documents, including ACI 357-84 (Reapproved 1997)—Guide for the Design and Construction of Fixed Offshore Concrete Structures [1], ACI 357.2R-10—Report on Floating and Float-In Concrete Structures [2], and ACI 357.3R-14—Guide for Design and Construction of Waterfront and Coastal Marine Concrete Structures [3]. All three documents are in different stages of revision, and they all have a section on testing and inspection. However, the details on testing and inspection in all three documents are limited and references have been made to standard testing and inspection procedures, without addressing the exceptions and variations offshore and marine structures pose. The information presented in this paper fills this gap and also contributes to revisions of these documents in the future.

The Offshore Standard DNV-OS-C502 of Det Norske Veritas [4] is a good consolidated document for the design, materials, construction, and in-service inspection, maintenance and condition monitoring of offshore concrete structures with reasonable level of details and guidance on design and analysis aspects. However, the document does not provide enough details and guidance on quantitative testing and inspection techniques.

The information presented in this paper is not only useful for the testing and inspection of offshore and marine structures, but it is also useful for the testing and inspection of the nation's water infrastructure assets, which include more than 90,500 dams, 239 locks, and 11,900 levees that traverse 30,000 miles of land-water interface. This water infrastructure was constructed between the 1930's and 1970's, and has an average age of about 60 years. Both quantitative and qualitative testing and inspection data are needed for the maintenance and preservation of these water infrastructure assets. The ownership of these water infrastructure assets is extremely diverse and includes federal, state, and local governments, and private companies. For example, almost two-thirds of the dams are privately owned and the remaining are distributed among various federal, state, and local agencies. Due to this diversity in ownership, there is a lack of uniform guidelines for the testing and inspection of these water infrastructure assets.

The permitting and inspection of hydropower facilities is regulated by the Federal Energy Regulatory Commission (FERC). FERC Regulations Part 12 Subpart D lists the inspection and reporting requirements of these facilities, which include settlement, movement, erosion, seepage, leakage, cracking, deterioration, seismicity, and internal stresses and hydrostatic pressures in structures or their foundations or abutments. This is just a list, without any details on how measurements should be made and what techniques should be used. Furthermore, for facilities not regulated by FERC, the states generally regulate the inspections and they have their own set of requirements. For example, The New Jersey Dam Safety Inspection Program is primarily based on visual inspections and analytical studies, including hydrologic and hydraulics analysis, dam breach analysis, geotechnical and seepage analysis, and structural stability analysis. Regarding quantitative testing and inspection techniques, the state's guidelines only make a statement "technical experts and specialists may be required to evaluate individual features and conditions."

TYPES OF OFFSHORE AND MARINE STRUCTURES

Offshore structures are gigantic structures in the middle of the sea, away from shores and in a marine environment. Contrary to popular belief, the world's tallest structure is not a building, rather it is an offshore concrete structure (Figure 1), with a height of 1,549 ft (472 m) including 994 ft (303 m) below water. There are other structures which are in a marine environment, but not necessarily in the middle of the sea. These marine structures may be connected or adjacent to the shores. Oil platforms, which are used for the extraction and storage of petroleum and natural gas from below the seabed, account for most of the offshore structures. The construction of these offshore structures started in the early 1970's and still continues. The majority of these offshore structures are in the North Sea. Ekofisk field, constructed in 1973 in the Norwegian region of the North Sea, is the first among offshore concrete structures and the Hebron facility in Canada, completed in 2017, is the most recent. Major offshore concrete structures are fixed, meaning that they are anchored to the seabed and their massive weight provides their stability, and often referred to as gravity-based structures. However, offshore structures can be floating as well, for example, offshore terminals. Even fixed-type offshore structures are initially floating and then made fixed. They are generally constructed onshore and then floated to the location of their installation.

Figure 1—Troll A Oil Platform in the North Sea, completed in 1995 (*Source: Kjell Tore Fosså, Kvaerner*)

There are many types of marine structures, which may be fixed, initially floating or permanently floating, but not classified as offshore structures. These include floating bridges, barges, concrete ships, docks, nearshore terminals, wharfs, dams, locks, levees, immersed concrete tunnels, and breakwaters. One of the advantages of floating structures is that they can be deployed from site-to-site on an as-needed basis. They can be floated to one site, fixed during the project duration by anchoring, mooring or ballasting, and then, upon completion of the project, refloated and moved to another project site. Reinforced and prestressed concrete ships have been in use for 100 years and their use intensified during World War II, when more than 100 vessels were constructed under a U.S. Maritime Commission project [5]. Reinforced and prestressed concrete barges have been used for more than 50 years for transportation of goods and as a platform for operations, processing, and storage for a variety of industries, including oil and gas, agriculture, and construction. Similarly, floating bridges, several in the state of Washington, have been in use for more than 50 years (Figure 2). The 13,290 ft (4,050 m) long tunnel connecting Sweden and Denmark, which opened to traffic in 2000, is a good example of an immersed concrete tunnel.

Figure 2—State Route 520 Floating Bridge, Opened to Traffic in 2016 (*Source: Washington State DOT*)

Precast concrete structures, in combination with cast-in-place concrete, have been used in the construction of dams, utilizing a construction process known as “In-the-Wet.” The most recent example is the construction of $3 billion Olmstead Dam, which was in the making for 30 years when it opened in August 2018. On this project, the shell of the dam was constructed offsite in parts and then transported to the project site on barges. The dam shells also serve as left-in-place formwork where the in-place tremie concrete is placed (Figures 3 and 4).

CONSTRUCTION QUALITY ASSURANCE-QUALITY CONTROL

The construction quality assurance-quality control (QA/QC) of offshore and marine concrete structures is generally no different than any other concrete structure considering the majority of these structures are fabricated onshore and then transported to their location. Even better QA/QC procedures can be employed on fabrication sites than cast-in-place construction on actual project sites where all the uncertainties cannot be predicted accurately, weather conditions being one of them. Also, fabrication sites offer the advantage of standardized procedures and practices that have been in place for similar work. Construction defects and problems are relatively easy to rectify on a fabrication site than in cast-in-place construction. There is still a need for limited QA/QC on-site for offshore and marine structures, such as Olmstead Dam, but it can easily be performed on barges that serve as work platforms for these structures (Figures 3 and 4).

Figure 3—Tremie Concrete Placement at Olmstead Dam in August 2016 (*Source: U.S. Army Corps of Engineers*)

Figure 4—Olmstead Locks and Dam, Completed in August 2018 (*Source: U.S. Army Corps of Engineers*)

A typical QA/QC program includes qualification testing of constituent materials (e.g., cement, pozzolan, water, aggregates, admixtures, etc.), proportioning of a concrete mixture, and testing and inspection during pre-placement, placement, and post-placement phases of the construction. The qualification testing and selection of constituent materials is extremely important because selection of unsuitable constituent materials could have lasting consequences due to the harsh environmental and exposure conditions of offshore and marine structures and the difficulty they present in accessibility during their service life. For example, selection of reactive aggregates and cements with high alkali content could lead to alkali-silica reactions (ASR) that is difficult to mitigate once the structure is placed in service (Figure 5).

Figure 5— ASR Damage in a Dam Pier at David Terry Lock and Dam in Pine Bluff, Arkansas (*Source: U.S. Army Corps of Engineers*)

ACI Committee 211, Proportioning Concrete Mixtures, has a number of documents that provide guidance on proportioning concrete mixtures that meet project specifications. Trial batches in real field conditions help ensure that concrete mixtures with required properties will be delivered on the project site as designed. Before the concrete placement, there are a number of factors that need to be observed and verified. These include base preparation (soil/rock foundation), formwork, joints, embedded items, reinforcing steel, cleanliness of placement equipment, weather conditions, and consolidation. After-placement observations include finishing, curing, repair of placement defects, and form removal. The tests performed during the placement of concrete include slump (ASTM C143/143M), entrained air content (ASTM C231/231M and ASTM C173/C173M), concrete temperature, unit weight and yield (ASTM C138/138M), and compressive strength (ASTM C39/39M) [3]. Other testing may be added to the QA/QC program specific to the nature and sensitivity of the project, for example, rapid chloride permeability testing (ASTM C1202/AASHTO T-277).

Temperature monitoring and control in offshore and marine structures during placement is very important as they are generally classified as mass concrete due to their large volumes. Large thermal gradients can develop in these structures during placement and initial stages after placement if appropriate measures are not taken to control the temperature. The temperature control measures include the use of low heat generating cements, supplementary cementitious materials, aggregates with low coefficient of thermal expansion, cooling of constituent materials before placement, chilled mixing water, and surface insulation [6]. Wireless sensors are available that can be attached to the reinforcing steel or formwork and the temperatures can be monitored remotely as the concrete is placed, hardens, and cures.

CONCRETE DETERIORATION MECHANISMS

There are a number of ACI documents and numerous publications that describe various concrete deterioration mechanisms, which constructed facilities experience in different environmental and exposure conditions. ACI 201.2R-16—Guide to Durable Concrete [7] and ACI 222R-01—Protection of Metals in Concrete Against Corrosion [8] are good sources of such information. Some of the concrete deterioration mechanisms commonly encountered in offshore and marine structures are briefly described below:

Freezing and Thawing

Freezing and thawing damage is caused by freezing of the internal moisture in concrete, which may be available as part of the microstructure of concrete or may enter concrete from external sources. Freezing within the concrete is accompanied with an about 9% increase in volume, which exerts tensile stresses in the concrete pore structure and if these tensile stresses exceed the tensile strength of concrete, the concrete cracks. Offshore and marine structures, by nature, are exposed to a large body of water and there is no shortage of water entering the concrete externally, even if there is not sufficient freezable moisture in the concrete microstructure initially. A low water-to-cementitious materials ratio (*w/cm*), along with good curing, helps control the amount of freezable water in the concrete microstructure. A low *w/cm* is a starting point for any good quality strong and durable concrete. In order to protect concrete from freezing and thawing damage due to moisture entering from external sources, concrete must be produced with aggregates that are not susceptible to freezing and thawing and a paste that has uniformly dispersed air voids serving as stress relieving sites during freezing of moisture in the concrete. Concrete in its early age, before it has developed sufficient strength, must be protected from the cycles of freezing and thawing by controlling excessive drying and maintaining adequate temperature (curing). The development of a compressive strength of at least 3,500 psi (25 MPa) and 4,500 psi (32 MPa), if exposed to deicing salts, is generally recommended if concrete is expected to experience repeated cycles of freezing and thawing [7]. Surface scaling, which is the loss of mortar from the concrete surface, is the most visible manifestation of freezing and thawing damage. However, freezing and thawing can also cause internal deterioration of concrete compromising its structural integrity.

Alkali-Aggregate Reaction

Alkali-aggregate reaction (AAR) is a reaction between aggregates of certain mineralogical compositions and alkalis in the cement, in the presence of moisture, creating expansive stresses in the concrete which concrete cannot withstand. Depending upon the type and mineralogical composition of the aggregate, this reaction can be classified as an alkali-carbonate reaction (ACR) or alkali-silica reaction (ASR). Of these two reactions, ASR is much more common and widespread than ACR. In ACR, some argillaceous dolomitic limestones, characterized by a matrix of fine calcite and clay minerals with scattered dolomite rhombohedra, react with the sodium or potassium hydroxide of concrete in a manner that dolomite crystals of composition $Ca{\bullet}Mg(CO_3)_2$ are converted to magnesium hydroxide (brucite), calcium carbonate, and alkali carbonate, as represented by the following equation (R represents Na^+ or K^+):

$$Ca{\bullet}Mg(CO_3)_2 + 2ROH \rightarrow CaCO_3 + Mg(OH)_2 + R_2CO_3$$

This reaction, often referred to as dedolomitization, causes the affected aggregates to expand and crack, with the cracks extending to the cement paste. The alkali carbonate produced in the dedolomitization process may react with calcium hydroxide in the cement paste to regenerate alkalis for further continued reaction.

ASR is an expansive chemical reaction involving alkalis contained in the cement paste and certain reactive forms of silica within the aggregates. Hydroxyl ions in the concrete pore solution attack siliceous constituents of certain aggregates and liberate silica in the concrete pore solution, ready for reaction with alkali ions Na^+ and K^+. A reaction between silica and these alkali ions produces an alkali-silica gel, which absorbs moisture and expands, leading to the cracking of the aggregates, cement paste, and ultimately the concrete matrix. Cements with Na_2O equivalent of more than 0.6% are susceptible to ASR when used with reactive aggregates. Na_2O equivalent is defined as $Na_2O + 0.658\ K_2O$, and is a term used to express the total amount of sodium and potassium alkalis in the cement. Portland cement is generally the source of alkalis in concrete, however, alkalis can also enter the concrete from external sources, such as seawater. The types of aggregates that are susceptible to ASR include shale, sandstone, siliceous carbonate rock, chert, flint, quartzite, quartz-arenite, gneiss, argillite, granite, greywacke, siltstone, arenite, arkose, and hornfels. Reactive minerals susceptible to ASR include opal, tridymite, cristobalite, volcanic glass, cryptocrystalline quartz, and strained quartz [7].

Sulfate Attack

Sulfate reactions in concrete could occur due to both internal and external sources of sulfates. However, it is believed that deleterious sulfate reactions generally occur from sulfates entering the concrete from external sources. Seawater, to which most offshore and marine structures are exposed to, is a rich source of such external sulfates. Ancient seabed deposits are known to be one of the original sources of these sulfates. Sulfates considered to be deleterious to concrete are generally the sulfates of sodium, potassium, calcium, and magnesium. Calcium sulfate, also known as gypsum, is part of the cement and intentionally added during the cement manufacturing process to control rapid or flash setting of concrete. It is also believed to improve strength development and control drying shrinkage during the initial placement of concrete. When cement is mixed with water, the calcium sulfate ($CaSO_4 \bullet 2H_2O$) reacts with tricalcium aluminate ($3CaO \bullet Al_2O_3$, also denoted in as "C3A") to form a product ettringite ($3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$), as represented by the equation below.

$$3CaO \bullet Al_2O_3 + 3(CaSO_4 \bullet 2H_2O) + 26H_2O \rightarrow 3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$$

Most of the gypsum present in cement is generally consumed in the formation of the initial ettringite. The ettringite formed in the initial stages of mixing and placement of concrete is normal and not considered to be deleterious. However, all the C3A may not be consumed in this reaction and the remaining available C3A reacts with the previously formed ettringite to create the following compound, known as calcium monosulfoaluminate:

$$3CaO \bullet Al_2O_3 \bullet CaSO_4 \bullet 12H_2O$$

Even this calcium monosulfoaluminate is not considered destructive if it forms at the time of placement of concrete, when it can move and position itself in the concrete matrix. However, during the service life of concrete, the calcium monosulfoaluminate can react with sulfates entering the concrete from external sources, and when it reacts with external sulfates, it regenerates ettringite. The formation of ettringite in hardened concrete is detrimental because ettringite crystals at this stage do not have an available space to reside, resulting in expansive forces.

In addition to deleterious chemical sulfate reactions, sulfate attack could cause physical attack. When concrete is exposed to a sulfate rich aqueous environment and water evaporates from the concrete surface, such as in splash zones, an accumulation of sulfate salts can occur, resulting in physical salt attack or salt weathering [7].

Corrosion of Reinforcing Steel

Normally, concrete is a highly alkaline material, with a pH of more than 12.5, and this high alkalinity provides protection against corrosion of embedded steel by forming a passive iron oxide film on the steel surface. The formation of this passive film is in itself a corrosion reaction, which occurs at the time of construction when the bare reinforcing steel comes in contact with wet concrete [8]. However, once this passive film is formed on the steel surface and as long as the high alkalinity of the concrete ($pH > 12.5$) is maintained, further corrosion reactions practically stop. Thus, beneficial corrosion reactions at the steel-concrete interface, at the time of concrete placement, are needed to prevent deleterious corrosion reactions later during the service life of concrete.

There are two commonly recognized mechanisms that destroy the passive film and make the steel susceptible to corrosion; one is chloride ion attack and the other is carbonation. Chloride ions attack and destroy the passive film even in the presence of high alkalinity. These chloride ion attacks on the passive film regardless of whether they are localized or widespread, facilitate the onset of corrosion. Carbonation is a reaction between atmospheric CO_2 and the cement paste in concrete, which converts the $Ca(OH)_2$ of the paste to $Ca(CO)_3$. This reaction lowers the alkalinity of concrete from more than 12.5 to less than 9, and thus destroys the passive film on the reinforcing steel. Once the passivity of the reinforcing steel is destroyed, an electrochemical corrosion cell sets up with the formation of anodic and cathodic sites and corrosion initiates and propagates in the presence of moisture and oxygen. The locations where the passivity of the reinforcing steel is destroyed act as anodic sites and the locations where the passivity is still intact act as cathodic sites. The following equations represent the corrosion reactions at the anodic and cathodic sites, respectively:

$$Fe \rightarrow Fe^{++} + 2e^{-}$$

$$2H_2O + O_2 + 4e^{-} \rightarrow 4(OH)^{-}$$

The pore solution of concrete serves as an electrolyte in this electrochemical corrosion process. A porous concrete pore structure, with low electrical resistivity, is conducive to corrosion reactions as opposed to a dense concrete matrix with high electrical resistivity. The ferrous ions combine with oxygen or hydroxyl ions and produce various forms of corrosion products. These corrosion products are larger in volume than the original volume of ferrous from which they are formed, causing an expansion at the steel-concrete interface, which leads to cracking and spalling of the concrete cover [7-9].

Interactive Effect of Different Concrete Deterioration Mechanisms

From the foregoing discussion of various concrete deterioration mechanisms, it is apparent that alkalinity of the concrete plays an important role in the onset and progress of several of these deterioration mechanisms. For example, a high alkaline environment, represented by a Na_2O equivalent of more than 0.6%, is not desirable from the standpoint of alkali-aggregate reactions. The alkalinity of concrete is primarily controlled by the alkalinity level of cement. However, alkalis can enter the concrete from the surrounding seawater. Thus, it is important that the aggregates used in offshore and marine structures are not susceptible to either ACR or ASR. On the other hand, high alkalinity of concrete is desirable from the standpoint of reinforcing steel corrosion. High alkalinity is required for the formation and maintenance of a passive film on the steel surface. However, it is almost impossible to protect offshore and marine structures from chloride ion attack, which break the passive film, as most of these structures are exposed to an aqueous environment rich in chloride ions. The quality and thickness of the concrete cover over reinforcing steel, a dense and impermeable concrete, is the primary protection against chloride ion attack in offshore and marine structures. However, there is an element of nature that comes to the rescue of offshore and marine structures in protecting them from reinforcing steel corrosion. Oxygen, along with moisture, is needed for the onset and propagation of any corrosion reactions. The availability of oxygen in completely submerged conditions is severely diminished. Thus, corrosion of reinforcing steel in submerged portions of offshore and marine structures is not much of a concern. However, it is still a serious concern for portions of the structures in the splash zone and those completely above water.

Sulfate attack and corrosion of reinforcing steel are two different concrete deterioration mechanisms, but when chlorides and sulfates are present in large amounts together, such as in seawater, their deteriorating effects are not necessarily mutually exclusive. The reaction of tricalcium aluminate (C3A) in cement and external sulfates entering the concrete is involved in the sulfate attack of concrete. Thus, generally, a low C3A cement is recommended for controlling sulfate attack. For example, for ASTM V sulfate-resistant cement, a maximum C3A content of 5% is permitted. However, C3A is beneficial in controlling the corrosion of reinforcing steel in concrete as it has the capability to bind the chlorides present in different constituents of the concrete and also the chlorides entering the concrete from external sources. C3A contents as high as 10% are recommended for concrete completely submerged in seawater if *w/cm* is maintained below 0.45. The chloride binding attributes of C3A are also helpful in controlling sulfate attack. C3A bound with chlorides is not available for participating in reactions associated with sulfate attack. Thus, in deeply submerged portions of offshore and marine structures, the deterioration induced by both reinforcing steel corrosion and sulfate attack are reduced to a great extent with an optimum level of C3A [7,8].

With these interactive effects of different concrete deterioration mechanisms, the following practices can help protect offshore and marine structures from different deterioration mechanisms:

- Use of a low *w/cm* concrete mixture.
- Use of adequate concrete cover over reinforcing steel.
- Use of aggregates that are not susceptible to freezing and thawing damage, alkali-carbonate reaction (ACR), and alkali-silica reaction (ASR).
- Use of a cement with a C3A content that is optimum for protection against both sulfate attack and reinforcing steel corrosion. This optimum C3A content may be 6% to 8%.

TESTING AND INSPECTION OF OFFSHORE AND MARINE STRUCTURES

The diversity of offshore and marine structures and the difficulty in accessing their components, particularly those in submerged conditions, presents special testing and inspection challenges compared to above-ground structures. The testing and inspection of the portions of the offshore and marine structures above water, including in the splash zone, can be treated like any other structure, and, thus, the testing and inspection techniques used in general structures will be briefly described here. However, underwater testing and inspection techniques are specific to offshore and marine structures, including bridges, docks, nearshore terminals, wharfs, dams, locks, levees, and offshore oil platforms. The application and limitations of such techniques are highlighted in this section.

Above-Water Testing and Inspection Techniques

Visual Surveys

A good visual survey is the starting point of any testing and inspection program of an in-service structure. In many cases, a visual survey is needed to define the scope of a testing and inspection program. A visual survey is a detailed observation and documentation of the deterioration visible on the concrete surface, along with photographic documentation. A good understanding of various concrete deterioration mechanisms and their interactive effects is needed to perform a visual survey, which may be sufficient on its own or help formulate an economical qualitative and quantitative testing and inspection program. A visual survey soon after construction and then at periodic intervals during the service life of the structure can provide the most meaningful information on changes in the condition of the structure and the need for timely and appropriate remedial actions. The collection of records and specifications related to materials, construction, and maintenance are part of the visual survey. ACI 201.1R-08—Guide for Conducting a Visual Inspection of Concrete in Service [10], as the name implies, provides good guidelines for the visual survey of in-service concrete structures. It describes different types of cracks and distresses that concrete may experience during its service life. Some of the observations that need to be made during a visual survey are briefly discussed below.

Discoloration and Deposits: Discolorations and deposits on the concrete surface are generally good indicators of the reactions occurring within the concrete (Figure 6). For example, rust stains on the concrete surface are obvious signs of reinforcing steel corrosion, and the cracking and spalling associated with these rust stains should be carefully documented. If there is any exposed corroded reinforcing steel, the cross-sectional loss of the reinforcing steel should be physically measured. Another example is leaching and efflorescence, which appear on the concrete surface as a white deposit. These deposits are generally sulfate and carbonate compounds of sodium, potassium, and calcium, which are created by dissolution of some parts of the hydrated concrete by water, their movement to the concrete surface, and then their eventual evaporation and precipitation. Excessive leaching and efflorescence may weaken the pore structure of concrete. More importantly, they are indicators of a porous concrete where water can easily flow in and flow out, facilitating other concrete deterioration mechanisms.

Figure 6—Rust Stains and Efflorescence Visible (Right Side) During the Chickamauga Lock Replacement Project in Tennessee (*Source: U.S. Army Corps of Engineers*)

Cracks: The type, severity (width, depth), and orientation (longitudinal, transverse, diagonal) of all the cracks should be noted. These include map cracking, pattern cracking, shrinkage cracking, random cracking, and temperature cracking. This information helps identify the deterioration mechanisms responsible for these cracks. In some cases, crack patterns alone cannot identify the deterioration mechanism and further testing and inspection may be needed. For example, map cracking could be due to shrinkage or as a result of alkali-aggregate reactions.

Distresses: There are many different types of distresses that can be visually observed and quantified with limited physical measurements. These distresses, which could be both materials and load related, include deflection, deformation, disintegration, exudation, joint damage, leakage, mortar flaking, peeling, pitting, popout, scaling, and spalling. ACI 201.1R-08 provides a checklist of items that need to be included in a visual survey report [10].

Subsurface Delamination and Defect Surveys

Delaminations are subsurface defects in concrete, which are not visible on the concrete surface, and, thus, may not be captured in visual surveys. A delamination is the separation of a concrete layer along a plane parallel to the concrete surface, which may be separation from another concrete layer or from the reinforcing steel. Separation of overlay from base concrete is an example of delamination of different concrete layers. In the case of corrosion-induced delaminations, the expansion of corrosion products exerts tensile stress within the surrounding concrete and causes a loss of bond between reinforcing steel and the concrete. This loss of bond, which creates a gap between reinforcement and concrete, is initially classified as delaminations, but eventually may lead to the spalling of concrete cover over the steel [11]. Some of the commonly used techniques in delamination surveys are described below.

Chain-Drag and Hammer Sounding: Chain-drag is the most common and traditional technique for detecting delaminations in concrete. It involves dragging a chain on the concrete surface under investigation and listening to its acoustic response. An intact concrete element produces a clear ringing sound, whereas delaminated concrete produces a dull or hollow sound. The technique has been standardized in ASTM D 4580 for bridge deck applications, but the principles apply to any concrete structure. On vertical concrete surfaces, a hammer is typically used for sounding, and likewise the type of sound generated from the hammer's impact can identify delaminations. These manual acoustic-based techniques are simple and relatively inexpensive when small test areas are involved. However, for large test areas, other techniques may be more economical. ASTM D 4580 includes two more techniques, which are still acoustic-based, but have some level of automation. One of the techniques is an electro-mechanical sounding device and the other technique is a rotary percussion device [11].

Impact Echo: In the impact-echo technique, a small steel impactor introduces mechanical energy, in the form of stress waves, into a concrete member. These stress waves either travel through the entire thickness of the member or encounter a flaw within the concrete member and then reflect back to its surface. These discovered flaws may be gaps created by a failed surface layer or a failed overlay, inadequately consolidated concrete, settlement of concrete when in its plastic stage, or delamination caused by corrosion of reinforcing steel. A transducer mounted on the surface of the concrete, and close to the impact point, receives the reflected stress waves. Resonant echoes from the member thickness or flaws can be analyzed relatively easily by their acoustic frequencies. Fast Fourier Transform (FFT) analysis is involved in the analytical process, and the resulting amplitude spectra help identify the dominant frequencies present in the echoed waveform. Concrete members without any internal defects are characterized by a single primary frequency peak, which represents the thickness of the member [11]. Zhang et al. [12] used impact echo, along with chain-drag and hammer sounding, to assess the condition and estimate remaining service life of the Ruskin Dam Spillway in British Columbia, Canada.

Infrared Thermography: Thermography takes advantage of the phenomenon that occurs when heat flows through concrete; the presence of any defect in the concrete reduces the diffusion rate and causes localized temperature discontinuities to become detectable on the surface of the concrete. These contrasting discontinuities can be recorded by infrared cameras. In this technique, subsurface defects are located by measuring surface temperature under conditions of heat flow. The solar radiation during daytime causes a heat flow into the concrete and cooling during nighttime causes a heat flow out of the concrete. Sunshine conditions during the daytime and clear skies during the nighttime create ideal conditions for the required heat flow. Also, during the heat flow, a thermal gradient needs to occur for subsurface defects to appear as heat anomalies. The recommended time for infrared thermography surveys is soon after sunrise or one-half to one hour after the sunset as these are the times when a maximum thermal gradient occurs. Also, the concrete should be free from debris and surface moisture. Considering the weather constraints associated with this technique, an artificial source of heating can be used to create the required heat flow and gradient within the concrete, as discussed by ACI 228.2R-13 [13] and Dumoulin et al. [14].

Ground Penetrating Radar: Ground penetrating radar (GPR) technology has been developed over the last three decades, however, its application is still limited. GPR emits electromagnetic energy that is projected in the form of radio frequency pulses into the concrete. When this electromagnetic energy comes in contact with an interface between two materials of different electromagnetic properties, some of the energy is reflected from the interface and the remaining energy propagates through the interface. The amplitude of the signals reflecting from the interface or propagating through the interface depends upon the difference in the dielectric properties of the materials at the interface. The radio frequency reflections are received by the radar antenna, which are processed for detecting delaminations. Accurate data interpretation in GPR is critical to its successful use. Because the images in GPR represent the amplitude of radar-reflected signals from interfaces within a structural element having different electromagnetic properties, the interpretation of subsurface radar feedback requires significant expertise on the part of the interpreter. Thus, research still continues toward a better understanding of reflected GPR signals, for example, recent studies by Raju et al. [15] and Rhee et al. [16].

Reinforcing Steel Corrosion Condition Evaluation

Corrosion of reinforcing steel in concrete is one of the major causes of deterioration in offshore and marine structures. The deterioration starts with the delamination of the concrete at the concrete-steel interface, which can progress to spalling of the entire concrete cover over the reinforcing steel. Rust stains and cracks appear on the concrete surface between the stages of delamination and spalling. Various techniques for detecting corrosion-induced delaminations are described in the preceding section. This section describes several testing and inspection techniques that can be used in detailed corrosion condition evaluation of offshore and marine structures.

Half-Cell Potential Testing: Half-cell potential measurements provide an indication of the presence or absence of the corrosion of steel embedded in concrete. In this test procedure, a high impedance voltmeter is used with the positive terminal of the voltmeter connected to the steel and the negative terminal to a Cu-$CuSO_4$ half-cell placed on the concrete surface. The half-cell potential values obtained are interpreted according to the guidelines of ASTM C-876. Half-cell potential values more negative than -350 mV indicate more than 90% probability that corrosion is occurring at the surface of the steel. On the other hand, half-cell potential values more positive than -200 mV indicate more than 90% probability that corrosion is not occurring at the surface of the steel. Corrosion activity is uncertain for half-cell potential values between -200 mV and -350 mV. If steel is continuous in a structural element, such as a pier cap or pier column, the voltmeter is connected to steel at one location, and half-cell potential values recorded for the entire structural element by placing the half-cell on the concrete surface at different locations, generally on a grid.

Corrosion Rate Measurements: Half-cell potential measurement is a good screening tool for determining the likelihood of corrosion. However, the areas identified as exhibiting active corrosion should be tested for corrosion rate to quantify the corrosion activity. Corrosion rate measurements based on polarization resistance technique are generally used in the evaluation of reinforced concrete. In this technique, the application of a small amount of current on a corroding metal in a conductive solution causes corresponding change in the potential and yields a linear relationship. A three-electrode system is used in these measurements. The reinforcing steel or prestressing strand being tested is referred to as "working electrode." The electrode through which current is induced in the steel is referred to as "counter electrode." Finally the electrode used to measure the potential change as a result of the application of current is referred to as "reference electrode." This reference electrode is generally a Cu-$CuSO_4$ electrode commonly used in half-cell potential measurements. The system is equipped with high precision voltmeter, ammeter, and timer for the application and measurement of current and potential. In general terms, the larger the amount of current required to shift the potential by a given amount, the higher is the corrosion rate [8,17].

Cross-Sectional Loss Measurement of Reinforcing Steel: In situations where corrosion has progressed to an extent that the concrete cover is spalled and the reinforcing steel is exposed, the physical measurement of the cross-sectional loss of the reinforcing steel should be made. This can be done by removing the corrosion products, cleaning the reinforcing steel, measuring the remaining cross-section using a caliper, and then comparing it with the original cross-section. Cross-sectional loss measurements are useful in determining the structural integrity of the reinforced concrete members and the entire structure [8].

Concrete Cover Measurements: A magnetic cover meter is generally used to non-destructively locate reinforcing steel and provide an estimate of the concrete cover over reinforcing steel. Concrete cover measurements, along with other information, are useful in assessing the performance of a structure. If favorable conditions exist for the initiation and propagation of corrosion, inadequate cover usually contributes to the early cracking and spalling of concrete.

Sampling and Analysis for Chloride Ions: As discussed earlier, chloride ions are one of the destroyers of the passivity of reinforcing steel, leading to the corrosion process. Research in the past has established the threshold chloride ion content in concrete that is required for the initiation and propagation of reinforcing steel corrosion. Acid soluble chloride ion content 1.0 to 1.5 lb/yd^3 (0.6 to 0.9 kg/m^3) of concrete is generally considered as threshold in the United States [8]. Chloride ion content threshold is a matter of on-going debate within ACI Committee 222, Corrosion of Metals in Concrete, and new guidelines may be developed in the future. Concrete powder samples can be retrieved from the structure and then analyzed in the laboratory according to AASHTO T-260, which is a titration based method and includes both water soluble and acid soluble test procedures. AASHTO T-332 offers a rapid acid soluble test procedure, based on specific ion probe, which can also be used for chloride ion analysis of the concrete powder samples. AASHTO T-332 was originally developed as part of the Strategic Highway Research Program and later revised based on the findings of Khan [18].

Carbonation: As discussed earlier, carbonation is a reaction which lowers the alkalinity of concrete to a level at which the passive iron oxide film is no longer stable (pH < 9.5). Carbonation is a slow process, it starts from the surface and progresses through the depth of concrete. Carbonation becomes a concern when it reaches to the level of steel. Depth of carbonation can be measured simply using a phenolphthalein test. A solution of phenolphthalein in ethanol is applied on a freshly cut or drilled concrete surface. A non-carbonated concrete surface turns pink and a carbonated concrete surface remains colorless.

Concrete Property Tests

There are several tests that can be performed to determine the properties of in-place concrete. Two commonly used tests, compressive strength testing and petrographic analysis are discussed here. Compressive strength measurements of cores retrieved from the structure provide an indication of the degradation of the quality of concrete, which could result from harsh exposure conditions and associated deterioration mechanisms. Concrete compressive strength tests are performed in conformance with ASTM C-39. A petrographic analysis is performed to assess the general overall quality of concrete and determine cause(s) of concrete deterioration other than reinforcing steel corrosion, such as freeze-thaw damage, ASR, and sulfate attack. In this analysis, polished concrete and thin sections are studied under microscope and information such as *w/cm*, aggregate content, pozzolans, amount and distribution of entrained air, and presence or absence of different deterioration mechanisms is obtained. Concrete mixture proportions determined from petrographic analysis can be compared with original mixture designs. The petrographic analysis is performed in accordance with ASTM C-856. An air void analysis, generally as supplement and part of petrographic analysis, is performed according to ASTM C-457.

Underwater Testing and Inspection Techniques

The testing and inspection techniques described in this section are the techniques that can be used for the submerged portions of offshore and marine structures. Testing and inspection of the submerged portions of the structures presents special challenges, which include weather, sea current, marine growth, visibility, and accessibility. The depths to which these structures extend below the surface of water, which could be several hundred feet, is probably the biggest challenge. Considering these challenges, a testing and inspection program for offshore and marine structures should be carefully planned, utilizing remote and nondestructive evaluation (NDE) techniques to the extent possible.

Levels of Underwater Inspections

There are some federal agencies which have been involved in the underwater inspection of concrete structures, including the Navy, U.S. Army Corps of Engineers, and the Federal Highway Administration (FHWA). The underwater inspection of bridges is a major issue and the FHWA has developed an underwater bridge inspection manual [19]. Much of the information in this manual is applicable to almost any concrete structure with its foundations in shallow to moderate depths of water. The underwater inspection is generally classified into three levels of inspection, depending upon the complexity of the testing and inspection involved. These include Level I, Level II, and Level III, as described below.

Level I Inspections: These inspections are close visual inspection of the entire submerged portion of concrete structures, which could be aided with handheld lights. The inspections, generally referred to as "swim-by" inspections, are performed by professional divers who could be equipped with waterproof cameras, video equipment, and other lightweight probing and testing devices. The intent of these inspections is to have an understanding of the general overall condition of the structures and identify any suspect deteriorated areas which may need cleaning of the surface and/or detailed testing and evaluation, as described in Level II and Level III inspections below.

Level II Inspections: A Level II inspection is still a visual inspection, but it requires cleaning of the concrete surface, which might be covered with aquatic or marine growth. In fresh water, any aquatic growth can be easily removed by wiping with glove-covered hands. However, the surface cleaning in salt and brackish water is more challenging, time-consuming, and may require the use of a hard bush. The areas selected for cleaning are representative of the suspect deteriorated areas of the structure. After cleaning, a close visual examination may provide important information to assess the condition of the structure or lead to a Level III inspection.

Level III Inspections: The intent of Level III inspections is to identify and quantify deterioration that is not visible on the surface, but is suspected to be occurring internally, as manifested by signs such as cracks and rust stains. A Level III inspection requires the use of some form of semi-destructive or non-destructive testing technique, and, thus, requires extensive cleaning to make the concrete surface accessible and suitable for such testing. Coring, drilling, and sampling may be needed as part of Level III inspections.

Visual Inspections

Underwater visual inspections require technical skills to observe, document, and discern the condition of submerged concrete along with diving skills to move and remain under water for significant amount of time. The divers are exposed to a variety of physiological hazards, including pressure, temperature extremes, oxygen deficiency, and nitrogen narcosis. As the depth of diving increases, the ability of a diver to remain in water with no-decompression decreases. For example, according to U.S. Navy Diving Manual, at a depth of 60 ft (18.3 m), the no-decompression time limit is 60 minutes. Whereas, at a depth of 150 to 190 ft (45.7 to 57.9 m), the no-decompression time limit is 5 minutes. Thus, it appears that at a depth of 150 ft (45.7 m) and beyond, a meaningful underwater visual inspection is not practical. The U.S. Occupational Safety and Health Administration (OSHA) regulations, 29 Code of Federal Regulations, Part 1910 (29 CFR 1910), Subpart T-Commercial Diving Operations, regulate all diving operations [19]. Some of the tools that can be used in underwater visual inspections are briefly described below.

Camera: Photographic documentation of the condition of the concrete structure in underwater inspections is particularly important because if there is a need to go back to the test site to confirm any observation, it might not be possible or it might be too expensive. Thus, it is important to do the things right the first time and in as much detail as possible. Fortunately, cameras are currently available that can be used in underwater inspections. These could be cameras fitted with water housing or waterproof cameras without any attachments. The cameras are digital cameras equipped with a variety of lenses and digital flash units (Figure 7). Also, these cameras are generally calibrated in apparent distances, because in submerged conditions the apparent distances are about three-fourths of the actual distances and objects appear larger than their actual size. In case of extremely turbid waters when the visibility is very low, sometimes clearwater boxes are used to photograph the structural element. These clearwater boxes are rectangular clear acrylic plastic boxes filled with clean water. When pressed against the concrete surface, they displace the dirty water and a camera placed on the opposite face of the box can capture an image of the concrete surface through the clear water [19].

Video: Similar to underwater cameras, currently video devices are available for underwater applications. These video devices can be placed in a water housing or could be waterproof units on their own. The video imaging and recording in visual inspections offer the advantage of voice recording of the inspector which can later be transcribed to a text format. The video devices can be used with an umbilical cable to the surface for real-time viewing and monitoring. With advances in wireless technology, video cameras are currently commercially available that can be connected to WiFi cables, as long as 300 ft (91.4 m). The wet end of these WiFi cables is connected to the video camera and the dry end is connected to a cellular phone above water. These video cameras do not need to be carried underwater by a diver, rather they can be lowered in water from above water. Once the WiFi connection is established, the position of the camera can be controlled from above water and underwater video imaging can be viewed in real-time. These video cameras are fitted with light sources.

Figure 7—A Diver Taking a Photograph of a Bridge Substructure with a Digital Camera in Waterproof Housing (*Source: Federal Highway Administration [19]*)

Remotely Operated Vehicles: Remotely Operated Vehicles (ROVs) are similar to the remote video imaging, described above. An ROV is a tethered underwater video camera platform, which may also be fitted with some testing equipment which incorporate an electric or electro-hydraulic propulsion system. The ROV is monitored and controlled from above water using a video system and "joystick" type of controls. These ROVs have been in use for several decades and were designed for underwater operations that were either too inaccessible or too hazardous to divers. These include deep polluted, contaminated, or extremely cold waters. The ROVs are not effective in murky waters and high sea currents.

Non-Destructive Evaluation (NDE) Techniques

If visual inspection of the entire submerged portion of the structure can be successfully performed and it convincingly indicates that the general overall condition of the structure is good, no further testing is required. However, if due to accessibility and other constraints, the visual inspection of the entire submerged portion of the structure cannot be performed, available NDE techniques should be employed to assess the condition of the structure. Even if visual inspections indicate that the overall condition of the structure is good, the use of NDE techniques is recommended to collect baseline data. When the same NDE techniques are repeated at specified intervals of testing and inspection, the changes in the condition of the structure can be tracked, the rate of deterioration of the structure can be modeled, and the remaining service life of the structure can be estimated.

Some of the NDE techniques described as above-water testing and inspection techniques can also be used for underwater inspections with or without modifications. For example, hammer sounding used for above-water inspections can also be used for underwater inspections. Some of the subsurface delamination/defect identification techniques such as impact echo and ground penetrating radar can be used for underwater inspections by fitting them with waterproof casings. Magnetic cover meters, used for locating rebars, have been successfully used for underwater inspections when encased in waterproof casings. Other NDE techniques that can be used in the testing and inspection of submerged portions of structures are described below.

Rebound Hammer: Rebound hammer, also known as Schmidt hammer, is the simplest NDE that can be performed on any structure and any portion of the structure, including submerged portions of offshore and marine structures. However, for testing a submerged portion of the structure, the technique cannot be used from above water, rather it needs to be performed by a diver, which could be done in conjunction with visual inspections. The device is enclosed in a waterproof housing for underwater applications [19]. This is a technique for evaluating relative uniformity of concrete quality in a test area, and it can also be used to estimate the strength of concrete if a correlation can be established between rebound numbers and the strength of concrete measured by testing core samples from representative locations. In this technique, the device is placed on the concrete surface and pressed against a spring loaded plunger until a mass within the hammer is released causing an impact on the concrete surface. The rebound of the mass within the hammer depends on the hardness of the concrete surface layer and is assigned a rebound number. The major limitation of the technique is that the measurements reflect only the surface hardness of concrete and provide a relative measure of concrete quality in a test area. The technique has been standardized by ASTM C-805. The need to take concrete cores to establish a correlation between rebound number and compressive strength defeats the NDE benefits of the technique.

Sonic-Echo: This NDE technique is known by various names, including sonic-echo, seismic-echo, and pulse echo. In this technique, a small impact is made at the top of the foundation shaft, using a small sledge hammer with a head of approximately 2.2 lb (1 kg). The impact generates low-strain stress waves which travel down the foundation shaft and reflect back when either they encounter a defect within the foundation shaft or at the end of the shaft where they meet another medium. The time taken by the stress waves to travel down the foundation shaft and reflected back to a transducer, generally an accelerometer coupled to the top of the foundation shaft near the impact point, is measured by a data acquisition system in time domain. The round trip travel time of the stress waves is referred to as transit time. With the known length of the foundation shaft and measured transit time of the stress wave to return to the transducer, the velocity of the stress wave can be calculated. On the other hand, if the velocity of the stress wave is known, the length of the foundation shaft can be calculated. When the length of the foundation shaft is known, an earlier-than-expected arrival of the wave at the transducer indicates that the stress wave has encountered a defect within the concrete. There is a limiting length-to-diameter ratio (L/d) beyond which all stress waves dissipate. For concrete foundations in medium stiff clays, this L/d is typically 30. However, for offshore and marine structures where the shaft is in water, a typical L/d is not known. If no reflected stress waves are recorded, it means that the concrete in the upper portion of the shaft has no defects or irregularities [13].

Impulse Response: This NDE technique is similar to sonic-echo technique in that it is also based on the reflection of a low-strain stress wave in response to a mechanical impact at the top of the foundation shaft. However, the main difference is that the impact response is analyzed in frequency domain compared to a time domain analysis in the sonic-echo technique. A small sledge hammer, similar to sonic-echo, is used to impact the top of the shaft, but, in this case, the hammer is instrumented with a force transducer. The hammer head is generally 3 lb (1.5 kg) with a rubber tip. However, metal-tipped hammer heads can also be used. Rubber-tipped hammer heads generate frequencies in the range of 0 to 1,000 Hz, whereas, metal-tipped hammer heads generate frequencies in the range of

0 to 3,000 Hz or higher. The load cell installed in the hammer head measures the force input and a geophone placed at the top of the foundation shaft measures the vertical response of the shaft. The force and velocity time-domain signals are analyzed using an FFT algorithm, which convert the data to the frequency domain. The velocity is divided by force at each frequency value, which provides the normalized response, transfer function, or frequency response function (FRF). This information is used to generate a graph of shaft mobility versus frequency, generally referred to as a mobility plot. As in sonic-echo testing, with known shaft length, an earlier-than-expected return of the stress wave indicates the presence of an anomaly in the concrete. However, in this technique, the mobility plot provides additional information such as dynamic stiffness and change in the cross-section of the shaft. For example, if there is a growth in the cross-section of the shaft due to expansive deterioration mechanisms such as alkali-aggregate reactions, this technique can determine the growth. Similarly, if there is a loss in the cross-section of the shaft due to impact of a ship, abrasion, or spalling due to corrosion of reinforcing steel, this technique can help. Similar to sonic-echo, the stress waves may dissipate along the length of the shaft. However, even if no reflected stress waves are detected from the base of the shaft, dynamic stiffness, compared over time, is still useful information [13].

Ultrasonic Guided Waves: Ultrasonic guided waves (UGW) are combinations of longitudinal and shear waves that travel along a thin plate, serving as a waveguide, which interfaces with another material of significantly different impedance. At this interface of different materials, some waves refract or leak into the other material, but the majority of the waves reflect back to the waveguide and combine with the wave traveling along the waveguide to produce a composite wave. The presence of a boundary or interface is essential in this technique [20,21]. The technique has traditionally been used in steel pipes. When the pipe is not embedded, the pipe serves as the waveguide and the surrounding air serves as the other interfacing material. Since there is a large difference in the impedance of steel and air, the majority of the waves reflect back to the steel-air interface and combine with the wave traveling along the pipe. Efforts have been made to use reinforcing steel in reinforced concrete and prestressing strand in prestressed concrete as waveguides, where the surrounding concrete or grout serves as the other interfacing material. However, since the impedance differential between steel and concrete is not as much as the impedance differential between steel and air, more waves leak into the concrete, and, thus, the propagation length of the guided wave may be limited. Another limitation of the technique is that it requires access to reinforcing steel or the prestressing strand at the location where the waves originate. In this technique, generally an ultrasonic transmitter and a receiver are placed at the exposed portion of reinforcing steel or prestressing strand, and the analysis focusses on the guided wave. In some studies, leaked waves have also been analyzed. Most UGW studies have utilized frequencies of the order of 150 kHz or lower. An analysis of the amplitude, velocity, and time of flight of the signals can provide information on debonding between the steel and concrete, corrosion, and also on material properties of the concrete. For example, as the debonding length between concrete and steel increases, the amplitude and velocity of the transmitted signals increase [22].

Semi-Destructive Testing

As described above, visual inspection and NDE techniques have their limitations to the extent and reliability of information that can be obtained on the condition of submerged portions of offshore and marine concrete structures. Thus, some level of testing of in-place concrete, which could be achieved by retrieving concrete cores and testing them in the laboratory, is desirable. This is particularly true for structures that have been in service for a number of years and are showing visible signs of deterioration. Visual inspection and NDE techniques do not necessarily overestimate the condition of the concrete, but they can also underestimate the condition of the concrete. It is possible that some signs of deterioration are limited to the surface. However, this can only be confirmed by testing core samples retrieved from the structure.

Tools: Underwater concrete coring by professional divers has been successfully performed in the past. Both pneumatic and hydraulic coring machines are commercially available and can be used for underwater applications. The pneumatic tools require great care and maintenance when used in underwater applications. They need to be properly lubricated prior to use, and, after use, they need to be immediately disassembled, dried, and lubricated again. The use of pneumatic power tools is limited to depths of 100 to 150 ft (30.5 to 45.7 m). Another limitation of pneumatic tools is that they generate streams of air bubble which can obscure the vision of the diver. The generation of air bubbles in pneumatic power tools can be overcome with the use of hydraulic power tools. Also, hydraulic power tools are much more rugged and strong compared to pneumatic power tools. For a similar size cylinder-piston design, hydraulic power tools can deliver as much as 25 times more force than pneumatic power tools. However, hydraulic power tools have their own limitations. A pump needs to be located remotely above water, which pumps water to the tool and the water is expelled underwater through the tool. Furthermore, hydraulic power tools are much more labor intensive because they produce significant torque and vibrations for the diver to counteract [19].

Types of Testing: Despite difficulty involved in underwater coring, cores retrieved from submerged portions of offshore and marine structures can provide valuable information on the actual condition of the concrete. They can also validate any NDE performed on the structure. Various tests that can be performed on the retrieved cores include compressive strength testing (ASTM C-39), chloride ion analysis (AASHTO T-260, AASHTO T-332), chloride permeability (AASHTO T-277), sulfate ion analysis (AASHTO T-290), pH analysis (AASHTO T-289), air void analysis (ASTM C-457), and petrographic analysis (ASTM C-856). As noted earlier, petrographic analysis can help identify the presence of any deterioration mechanisms, such as freeze-thaw damage, ASR, and sulfate attack. It can also provide important information on mixture proportions and constituents of the in-place concrete.

Core Hole Repairs: The use of semi-destructive testing techniques should be to an extent and in a way that the structure is not weakened and the structural integrity is not compromised as a result of the testing. The Concrete core locations should be properly repaired and sealed to ensure that they do not become future access points for water and other deleterious substances in the concrete. ACI 546.2R-10—Guide to Underwater Repair of Concrete provides guidelines for underwater repair of concrete [23].

SUMMARY

Testing and inspection of concrete structures is needed at the time of construction to ensure that they are constructed as designed and specified and also during their service life to ensure that they are performing safely as planned and anticipated. The testing and inspection of offshore and marine structures is of particular importance due to their aggressive exposure conditions and the difficulties they present in accessibility. Some of the in-service offshore structures, used in oil drilling and processing operations, are as much as about 1,000 ft (305 m) below water. There are many offshore structures across the world. In addition to these offshore structures, which are in the middle of the sea, there are numerous onshore and nearshore concrete structures which are classified as marine structures. These include floating bridges, barges, concrete ships, docks, nearshore terminals, wharfs, dams, locks, levees, immersed concrete tunnels, and breakwaters. In general, there is a lack of standards, specifications, and guidelines for the testing and inspection of offshore and marine structures, and the available information is too scattered. There is even a lack of uniformity in the procedures and protocols of the regulatory agencies that regulate many of these offshore and marine structures. This paper provides a basic framework for the procedures used during testing and inspection of offshore and marine structures, which could be developed into comprehensive and detailed guidelines.

The fact that most offshore and marine structures are constructed onshore on fabrication sites and then floated to the actual project site in the water is a major advantage from the standpoint of assuring the quality of new construction. This makes the QA/QC of offshore and marine structures no different than any other structure. Even better and stricter QA/QC procedures can be employed on fabrication sites than in cast-in-place construction. This is probably one of the reasons many offshore structures in the North Sea and other parts of the world are still performing well after 40 years of their service. They are designed and constructed with the intent of being trouble and maintenance free, knowing from the beginning that the testing and inspection of these gigantic structures is not easy once they are in place. In any QA/QC program, the selection of constituent materials of the concrete is of utmost importance, particularly the use of non-reactive and non-freezable aggregates. It is impractical to stop some of the deleterious reactions involving reactive aggregates in a marine environment.

A thorough understanding of various concrete deterioration mechanism, particularly their interactive effects, is needed to perform the testing and evaluation of offshore and marine structures. For example, seawater is full of chlorides and sulfates and these levels of chlorides and sulfates can deteriorate any concrete quickly in a wet-dry environment. However, submerged portions of offshore and marine structures have shown good performance despite this aggressive exposure. There is an element of the nature which comes to the rescue of offshore and marine structures in protecting them from reinforcing steel corrosion. Oxygen, along with moisture, is needed for the onset and propagation of any corrosion reactions. The availability of oxygen in completely submerged conditions is severely diminished. Thus, corrosion of reinforcing steel in submerged portions of offshore and marine structures is not much of a concern. Furthermore, some of the measures taken to control reinforcing steel corrosion, such as a relatively high C3A content, can also mitigate sulfate attack. Low *w/cm*, adequate concrete cover, non-reactive and non-freezable aggregates, and an adequate air void system in the cement paste are some of the other factors that contribute to a good concrete performance.

The testing and inspection of above water and splash zone portions of offshore and marine structures is no different than that of any other structure, with the exception that a boat or barge may be needed to access the test locations. Almost all the techniques used in general structures can be used at such locations. These include visual inspections, chain-drag/hammer sounding, impact echo, infrared thermography, ground penetrating radar, chloride ion analysis, carbonation depth measurement, half-cell potential measurement, corrosion rate measurement, strength testing, and petrographic analysis. The shafts of some of the offshore structures have a wall thickness of more than 3 ft (0.9 m) and are fitted with an elevator, which can take people from above water to the sea floor. Almost any NDE technique can be applied on the interior walls of these shaft walls.

With all of the technological advancements currently available, the testing and inspection of submerged portions of offshore and marine structures is still a challenge. Underwater visual inspections need a professional diver with knowledge and experience in concrete condition evaluation surveys. Combining these two attributes becomes highly specialized. The visual inspections can be aided by cameras and video equipment designed or modified for underwater applications. Real-time video imaging can be performed through ROVs or by lowering equipment in water with cords, which also serve as WiFi cables, and are used to control the position of the video equipment from above water.

Some of the NDE techniques used for above water testing can be used underwater with appropriate modifications. These include impact echo and ground penetrating radar. Other NDE techniques that are better suited for underwater applications include sonic-echo, impulse response, and UGW. Sonic-wave and impulse response have been used in the evaluation of foundations embedded in soil for many years. However, there is not much documentation on the use of these techniques in offshore and marine structures where concrete interfaces with water and not soil. Length-to-diameter ratio is one of the limitations of both of these techniques where the stress waves dissipate beyond a shaft L/d of 30. Ultrasonic guided wave is an emerging technology for any concrete application and it has the potential of non-destructively evaluating corrosion-induced debonding at the concrete-steel interface and other concrete properties.

With proper understanding of concrete deterioration mechanisms, particularly their interactive effects, and careful and detailed visual inspections, a cost-effective and safe testing and inspection program can be designed and implemented that can provide a realistic assessment of the condition of concrete structures and help extend their service life.

FUTURE RESEARCH

The on-going technological advancements in automation and robotics present an opportunity for robotic testing and inspection of offshore and marine structures. Robotic fish have been created for marine studies, which can swim along with natural fish. Along similar lines, marine robots of the future may be able to perform visual inspection and even certain level of non-destructive and semi-destructive testing. The effectiveness of various underwater NDE techniques (sonic-echo, impulse response, UGW), discussed in this paper, is not proven and need to be further researched. It appears that diver-assisted visual inspections, remote video imaging, NDE, and semi-destructive testing are all generally limited to a water depth of 100 to 150 ft (30.5 to 45.7 m). The effectiveness of these techniques at larger depths should be researched.

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