Testing and Inspection Techniques for Transportation and Offshore and Marine Structures

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Outline

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- Types of Transportation and Offshore and Marine Structures
- Construction QA/QC
- Concrete Deterioration Mechanisms
- Above-Water Testing and Inspection Techniques
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Background

- There are many transportation structures that are marine structures but not necessarily all marine structures are transportation structures.

- There are lots of commonalities in the testing and inspection techniques of the two types of structures, but some 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.
Testing and inspection techniques assure quality of new construction

Testing and inspection techniques help assess the condition of existing structures

Different environmental and exposure conditions (wetting/dry cycles, high chloride/sulfate, marine growth, wind loads, ice loads, vessel impacts)

Current ACI documents: 201.2R-16, ACI 201.1R-08, ACI 222R-01, ACI 228.2R-13

ACI 357-84, ACI 357.2R-10, ACI 357.3R-14

DNV-OS-C502 of Det Norske Veritas
Background (...continued)

- 90,500 dams
- 239 locks
- 11,900 levees (30,000 miles)
- Average age of water infrastructure 60 years
- Both qualitative and quantitative testing and inspection techniques needed
- Ownership of water infrastructure diverse
- Lack of uniform guidelines for testing and inspection
- “Technical experts and specialists may be required to evaluate individual features and conditions.” (NJ Dam Safety Inspection Prog.)
Offshore and Marine Structures

- Offshore structures are gigantic structures in the middle of sea, away from shores and in a marine environment.
- The world’s tallest structure is an offshore structure in the North Sea – Troll A Oil Platform.
- Height of 1,549 ft. including 994 ft. (303 m) below water.
- Most offshore structures are fixed.
- Constructed onshore and the floated to the site of installation.
Offshore and Marine Structures

Other Marine Structures

- Floating bridges
- Barges
- Concrete ships
- Docks
- Nearshore terminals
- Wharfs
- Dams, locks and levees
- Immersed concrete tunnels
- Breakwaters.
Offshore and Marine Structures
Offshore and Marine Structures
Offshore and Marine Structures

Photo: Washington State DOT
Construction QA/QC

- Construction QA/QC of offshore and marine structures is generally no different than any other structure.
- Offshore and marine structures are generally fabricated onshore and then transported to their location.
- Better QA/QC procedures can be employed in onshore fabrication yards than in cast-in-place construction on actual project sites.
- Construction defects and problems are relatively easy to be rectified in a fabrication yard than in cast-in-place construction.
- There is still a need for limited QA/QC on-site for offshore and marine structures, which can be performed on barges.
Construction QA/QC

Photo: U.S. Army Corps of Engineers
Construction QA/QC

Photo: U.S. Army Corps of Engineers
Qualification testing of constituent materials (cement, pozzolan, water, aggregates, admixtures, etc.)

ASR Damage at Mactaquac Generating Station in New Brunswick, Canada (Source: NB Power Corp.)
Construction QA/QC

- Proportioning of concrete mixtures
- 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 assure that concrete mixtures with required properties will be delivered on the project site as designed.
- Testing and inspection during pre-placement, placement, and post-placement phases of the construction
Construction QA/QC

- Pre-placement: base preparation formwork, joints, embedded items, reinforcing steel, cleanliness of placement equipment, weather conditions, and consolidation
- After placement: finishing, curing, repair of placement defects, and form removal
- Other testing may be added to the QA/QC program specific to the nature and sensitivity of the project
Concrete Deterioration Mechanisms

- Freezing and thawing
- Alkali-aggregate reactions
- Sulfate attack
- Corrosion of reinforcing steel
- Interactive effect of different deterioration mechanisms
Freezing and Thawing

- Freezing of internal moisture of concrete, and water entering from external sources.
- Freezing within the concrete is accompanied with an about 9% increase in volume.
- Low w/cm and good curing help control freezable internal moisture.
- Non-freezable aggregates and a cement paste with adequate air void system help protect freezing from external water.
- Surface scaling most visible damage, but can cause internal damage to concrete.
Alkali-Aggregate Reactions

- Reaction between aggregates of certain mineralogical compositions and alkalis in the cement, in the presence of moisture, creating expansive stresses in the concrete.
- 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).
- ASR is much more common and widespread than ACR.
- In ACR, certain dolomitic limestones react with the sodium or potassium hydroxide of concrete.
Alkali-Aggregate Reactions

- In ACR, some argillaceous dolomitic limestones, characterized by a matrix of fine calcite and clay minerals, react with the sodium or potassium hydroxide of concrete.
- ASR is an expansive chemical reaction involving alkalis contained in the cement paste and certain reactive forms of silica within the aggregates.
- A reaction between silica and alkalis produces an alkali-silica gel, which absorbs moisture and expands.
- Cements with Na$_2$O equivalent of more than 0.6% are susceptible to ASR when used with reactive aggregates.
Concrete Deterioration Mechanisms

Sulfate Attack

- Sulfate reactions in concrete could occur due to both internal and external sources of sulfates.
- Deleterious sulfate reactions generally occur from sulfates entering the concrete from external sources.
- Sulfates considered to be deleterious to concrete are generally the sulfates of sodium, potassium, calcium, and magnesium.
- Calcium sulfate in the cement reacts with $3\text{CaO}\cdot\text{Al}_2\text{O}_3$ (commonly known as C3A) to form $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{CaSO}_4\cdot32\text{H}_2\text{O}$ (ettringite).
Sulfate Attack

- Remaining available C3A reacts with the previously formed ettringite to create the compound $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O}$ (calcium monosulfoaluminate)
- Even this calcium monosulfoaluminate is not considered destructive if it forms at the time of placement of concrete
- When calcium monosulfoaluminate 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
**Concrete Deterioration Mechanisms**

**Corrosion of Reinforcing Steel**

- Normally, concrete is a highly alkaline material, with a pH of more than 12.5
- The high alkalinity provides protection against corrosion of embedded steel by forming a passive iron oxide film on the steel surface
- There are two mechanisms that destroy the passive film – carbonation, chloride ion attack
- Chloride ions attack and destroy the passive film even in the presence of high alkalinity
- Carbonation, a reaction between atmospheric $\text{CO}_2$ and $\text{Ca(OH)}_2$ of the paste leading to the formation of $\text{Ca(CO)}_3$. lowers the pH from more than 12.5 to less than 9 and destroys the passive film
Concrete 
Deterioration 
Mechanisms

Corrosion of 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 concrete pore solution acts as an electrolyte

\[
\begin{align*}
\text{Fe} & \rightarrow \text{Fe}^{++} + 2\text{e}^- \\
2\text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- & \rightarrow 4(\text{OH})^-
\end{align*}
\]
Interactive Effects

- High alkalinity is not desirable from the standpoint of alkali-aggregate reaction
- The alkalinity of concrete is primarily controlled by the alkalinity level of cement, but alkalis can also enter the concrete from seawater
- High alkalinity is desirable from the standpoint of reinforcing steel
- It is difficult to protect concrete from chlorides in a seawater environment
- An element of nature comes to the rescue of offshore and marine structures – lack of oxygen in submerged conditions
Sulfate attack and corrosion of reinforcing steel are two different concrete deterioration mechanisms. However, their deteriorating effects are not necessarily additive to each other. The reaction between C3A of cement and external sulfates entering the concrete is involved in the sulfate attack of concrete. C3A has the capability to bind chlorides in concrete. Less C3A for sulfate protection and more C3A for corrosion protection.
Concrete Deterioration Mechanisms

Interactive Effects

- 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
- The optimum C3A content may be 6% to 8%
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.

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.

Structures that need underwater testing and inspection include bridges, docks, nearshore terminals, wharfs, dams, locks, levees, and offshore oil platforms.
Above-Water Testing and Inspection Techniques

- **Visual Surveys** (discoloration and deposits, cracks, distresses)
- **Subsurface Delamination and Defect Surveys** (chain-Drag and hammer sounding, impact echo, infrared thermography, ground penetrating radar)
- **Reinforcing Steel Corrosion Condition Evaluation** (half-cell potential testing, corrosion rate measurements, cross-sectional loss measurement, concrete cover measurements, sampling and analysis for chloride ions, carbonation)
- **Concrete Property Tests** (compressive strength testing, rapid chloride permeability, petrographic analysis)
A good visual survey is the starting point of any testing and inspection program of an in-service structure.

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.

Visual Inspection soon after construction - baseline.
Discoloration and Deposits

- Discolorations and deposits on the concrete surface are generally good indicators of the reactions occurring within the concrete.
- For example, rust stains on the concrete surface are obvious signs of reinforcing steel corrosion.
- Cracking and spalling associated with 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.
- Leaching and efflorescence, which appear on the concrete surface as a white deposit.
Visual Surveys

Photo: U.S. Army Corps of Engineers
Cracks

- The type, severity (width, depth), and orientation (longitudinal, transverse, diagonal) of all the cracks should be documented
- Map cracking
- Pattern cracking
- Shrinkage cracking
- Random cracking
- Temperature cracking
- Good observation and documentation of cracks helps identify different deterioration mechanisms
- In some cases, crack patterns alone cannot identify the deterioration mechanism
Distresses

- There are many different types of distresses that can be visually observed and quantified with limited physical measurements
- These distresses could be both materials and load related
- Deflection, deformation, joint damage, subsidence (load related)
- Disintegration, leakage, mortar flaking, peeling, pitting, popout, scaling, and spalling (materials related)
- ACI 201.1R-08 provides a checklist of items that need to be included in a visual survey report
Delaminations are subsurface defects in concrete, which are not visible on the concrete surface.

A delamination is the separation of a concrete layer along a plane parallel to the concrete surface.

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.
Subsurface Delamination and Defect Surveys

Chain Drag/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
- ASTM D 4580 includes two more techniques, which have some level of automation
Impact Echo

- A small steel impactor introduces mechanical energy, in the form of stress waves in the concrete.
- These stress waves either travel through the entire thickness of the member or encounter a flaw and then reflect back to the surface.
- 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.
- Concrete without internal defects is characterized by a single primary frequency peak.
Infrared Thermography

- When heat flows through concrete, the presence of any defect in the concrete reduces the diffusion rate and causes localized temperature discontinuities.
- These contrasting discontinuities can be recorded by infrared cameras.
- 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.
- During the heat flow, a thermal gradient needs to occur for subsurface defects to appear as heat anomalies.
Subsurface Delamination and Defect Surveys

Ground Penetrating Radar

- GPR emits electromagnetic (EM) energy in the form of radio frequency pulses into the concrete
- When this EM 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
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 earlier.
Half-Cell Potential Testing

- Half-cell potential measurements provide an indication of the presence or absence of the corrosion of steel embedded in concrete.
- A high impedance voltmeter is used with the positive terminal of the voltmeter connected to the steel and the negative terminal to a Cu-CuSO₄ half-cell placed on the concrete surface.
- The half-cell potential values obtained are interpreted according to ASTM C-876.
  - More negative than -350 mV: active corrosion
  - More positive than -200 mV: no active corrosion
  - -200 mV to -350 mV: uncertain corrosion activity
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.

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.

The larger the amount of current required to shift the potential by a given amount, the higher is the corrosion rate.
Reinforcing Steel Corrosion Condition Evaluation

X-Sectional Loss Measurement

- In spalled concrete with exposed corroded reinforcing steel, the physical measurement of the cross-sectional loss of the reinforcing steel should be made.
- Cross-sectional loss measurement can be made 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.
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.
Chloride Sampling & Analysis

- Chloride ions are one of the destroyers of the passivity of reinforcing steel, leading to the corrosion process.
- 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 to initiate and propagate reinforcing steel corrosion.
- Chloride ion content threshold is a matter of ongoing debate within ACI Committee 222, Corrosion of Metals in Concrete, and new guidelines may be developed in the future.
- Concrete powder samples are retrieved from the structure and then analyzed in the laboratory according to AASHTO T-260 or AASHTO T332.
Carbonation Measurement

- 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
Reinforcing Steel Corrosion Condition Evaluation

Concrete Property Test

- There are several tests that can be performed to determine the properties of in-place concrete.
- Compressive strength testing and petrographic analysis on retrieved concrete cores are generally used.
- Compressive strength testing provides an indication of the degradation of the quality of concrete, which could result from harsh exposure conditions and associated deterioration mechanisms (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.
- ASTM C-856 in conjunction with ASTM C-457.
Underwater Testing and Inspection Techniques

- There are some federal agencies which have been involved in the underwater inspection of concrete structures
- U.S. 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
- Level I – Swim-by visual inspections by a diver
- Level II – Visual inspections requiring cleaning of the concrete surface
- Level III - Requires some form of semi-destructive or non-destructive testing technique (coring, drilling, and sampling, etc.)
Underwater Testing and Inspection Techniques

- **Visual inspections** (cameras, videos, remotely operated vehicles)
- **Non-Destructive Evaluation (NDE) Techniques** (Rebound Hammer, Sonic-Echo, Impulse Response, Ultrasonic Guided Waves, Acoustic Imaging)
- **Semi-Destructive Testing** (tools, types of testing, core hole repairs)
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.

- At a depth of 60 ft (18.3 m), the no-decompression time limit is 60 minutes (U.S. Navy Diving Manual).
- At a depth of 150 to 190 ft (45.7 to 57.9 m), the no-decompression time limit is 5 minutes.
Visual Inspections

Cameras

- Photographic documentation of the condition of the concrete structure in underwater inspections is particularly important.
- Cameras are currently available that can be used in underwater inspections.
- Cameras could be fitted with water housing or they could be waterproof without any attachments.
- The cameras are digital cameras equipped with a variety of lenses and digital flash units.
- 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.
Videos

- Currently video devices are available for underwater applications
- Video devices can be placed in a water housing or could be waterproof units on their own
- The video imaging and recording offers 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
- Video cameras are currently commercially available that can be connected to WiFi cables, as long as 300 ft (91.4 m)
ROVs

- Remotely Operated Vehicles (ROVs) are similar to the remote video imaging
- 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
- Designed for underwater operations that were either too inaccessible or too hazardous to divers
- 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.

- 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 the changes in the condition of the structure can be tracked.
Non-Destructive Evaluation (NDE) Techniques

**Rebound Hammer**

- Simplest NDE that can be performed on any structure, including above-water and underwater
- 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 device is enclosed in a waterproof housing for underwater applications, needs a diver.
- For evaluating relative uniformity of concrete in a test area.
Sonic-Echo

- Known by several names (sonic-echo, seismic-echo, and pulse echo)
- 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)
- A transducer, generally an accelerometer, is coupled to the top of the foundation shaft near the impact point
- 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
Sonic-Echo (...cont.)

- The time taken by the stress waves to travel down the foundation shaft and reflected back to the transducer, is measured by a data acquisition system in time domain.

- With 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.

- 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.
Non-Destructive Evaluation (NDE) Techniques

Impulse Response

- The 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.
- The main difference is that the impact response is analyzed in frequency domain compared to a time domain analysis in the sonic-echo technique.
- The hammer (rubber-tipped or metal-tipped) is instrumented with a force transducer.
- 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.
Non-Destructive Evaluation (NDE) Techniques

**Impulse Response**

- 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 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.

- The mobility plot provides additional information such as dynamic stiffness and change in the cross-section of the shaft.
Non-Destructive Evaluation (NDE) Techniques

UGW

- 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.

- The technique has traditionally been used in steel pipes.
Non-Destructive Evaluation (NDE) Techniques

UGW (...cont.)

- Efforts have been made to use reinforcing steel in reinforced concrete as a waveguide.
- The technique requires access to reinforcing steel or the prestressing strand at the location where the waves originate.
- Generally an ultrasonic transmitter and a receiver are placed at the exposed portion of reinforcing steel or prestressing strand.
- The analysis focuses on guided waves.
- 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.
**Acoustic Imaging**

- The technique is capable of creating images of channel bottom conditions, undermining, and submerged foundations.
- It can be used as part of a Level I inspection to help plan an underwater inspection more efficiently and safely.
- Acoustic imaging systems transmit sound waves which, after contacting an object, are reflected back to the equipment.
- Depending upon the equipment and software used, 2- and 3-dimensional images can be created.
- The technique is similar to sonar depth sounders, but operates at a much higher frequency (700 to 1400 kHz vs. 200 kHz), providing more clarity.
Non-Destructive Evaluation (NDE) Techniques

Acoustic Imaging (...cont.)

- Can be used in situations where underwater cameras cannot be used because of turbidity in the water
- The operating range of underwater cameras is limited to a few feet
- Acoustic imaging equipment can operate at distances of more than 200 feet
- Useful in hazardous conditions (high sea currents, low visibility, sunken vessels, accumulated debris, etc.)
- Extremely useful technique in ensuring the safety of divers and inspection personnel
- Complementary to other testing and inspection techniques
Semi-Destructive Testing

- 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, but it 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.
- 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.
Semi-Destructive Testing

Tools (...cont.)

- The generation of air bubbles in pneumatic power tools can be overcome with the use of hydraulic power tools.
- 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.
- In hydraulic power tools, a pump needs to be located remotely above water, which pumps water to the tool and the water is expelled underwater through the tool.
- Hydraulic power tools are much more labor intensive because they produce significant torque and vibrations for the diver to counteract.
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.

Core testing can also validate any NDE performed on the structure.

- 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)
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.
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.

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.

With all of the technological advancements currently available, the testing and inspection of submerged portions of offshore and marine structures is still a challenge.

Robotic testing and inspection of offshore and marine structures is probably the future.
Thank You!