National Cooperative Highway Research Program

NCHRP Synthesis 200

Underwater Bridge Maintenance and Repair

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

National Cooperative Highway Research Program

Synthesis of Highway Practice 200

Underwater Bridge Maintenance and Repair

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Topic Panel

TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis on underwater bridge maintenance and repair will be of special interest to bridge maintenance engineers and others involved with repair of bridge elements located below the waterline and in the splash zone. Procedures for correctly assessing the problem and engineering the repair within the constraints of individual situations, including bridge scour considerations, are described. Protection, maintenance, and repair of concrete, masonry, steel, and timber bridge foundation elements are also addressed. This synthesis updates the maintenance and repair portion of *NCHRP Synthesis 88: Underwater Inspection and Repair of Bridge Substructures.*

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board identifies and describes current practices and innovative repair techniques for problems associated with settlement, scour, and deterioration of underwater bridge elements. The synthesis considers various types of protection, maintenance, and repair work on bridge substructures, both underwater and in the splash zone, and includes techniques, and their effectiveness. Current research in the topic area and critical research needs are also identified. A limited bibliography is also provided.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of James E. Barnhart, Structure Maintenance and Inspection Engineer, Ohio Department of Transportation; Frank N. Lisle, Engineer of Maintenance, Transportation Research Board; William F. McCleese, REMR Program Manager, USAE Waterways Experiment Station; Wallace T. McKeel, Jr., Transportation Research Manager, Virginia Transportation Research Council; C. Dewey Oliver, District Structures and Facilities Engineer, Florida Department of Transportation; George P. Romack, Highway Engineer, Federal Highway Administration; Joseph T. Smith, Chief Design Engineer, Louisiana Department of Transportation and Development; and Y. Paul Virmani, Research Chemist, Federal Highway Administration Office of Engineering and Operations.

The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, Stephen F. Maher, Senior Program Officer, and Scott A. Sabol, Program Officer, National Cooperative Highway Research Program. This synthesis was edited by Linda S. Mason.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

UNDERWATER BRIDGE MAINTENANCE AND REPAIR

SUMMARY

This synthesis focuses on underwater repair procedures for bridge substructure elements. Many states are just beginning to document the extent of problems that need to be addressed by underwater repair. However, few states have the resources or expertise to perform underwater repairs. States have limited experience at selecting cost-effective underwater repair procedures.

An underwater repair should be made based on complete and thorough condition information. The repair should address the root cause of the damage rather than the symptoms. If the damage represents a potential structural problem, the repair should be engineered to address that problem and protect against recurrence. The practical limitations of working underwater should be considered in selecting the method of repair.

Repair of scour damage is the most common underwater repair identified in this research. Since scour damage is the most common cause of bridge failure and may occur quickly, it is important that potential scour problems be identified and protection devices installed. Protection devices include deflectors to direct or dissipate the force of the water and armoring material to reinforce the embankment. If significant scour has occurred, the repair should include support and protection of the damaged substructure element.

Because concrete is used in most bridge substructures, many of the underwater procedures identified in this synthesis involve repair of concrete substructure elements. Special construction techniques and admixtures have been developed for use of concrete underwater. Reinforcement corrosion is an important consideration, particularly in a saltwater environment. Once corrosion has started, it is difficult to stop and should not be hidden by a cosmetic repair. Salt-contaminated concrete must be removed from around the steel or a cathodic protection system should be considered.

Underwater repair procedures for concrete bridge elements include the use of special coatings, crack repair, and removal and replacement of the concrete. Admixtures used in underwater concrete include polymers, antiwashout admixtures, pozzolans, and corrosion inhibitors. Additional considerations in the design of marine concrete include the water-cement ratio, reinforcement cover, and permeability. Special underwater forming techniques include special jackets and fabric forms with zippers and injection spouts. Concrete is placed underwater using fabric bags, prepacked aggregate, tremies, and pumps; it can also be hand-placed and dropped from buckets directly into the water using special antiwashout admixtures.

Steel is not as commonly used as concrete as an underwater construction material because it is subject to corrosion. However, there are steel coatings that can be applied underwater. Cathodic protection can also be used to protect steel elements from corrosion. Underwater repair options for steel elements include splicing and jacketing.

Timber substructure elements are especially susceptible to damage from decay and marine organisms. Timber used for underwater bridge elements should be treated to protect against damage. Underwater repair options for timber elements include jacketing, splicing, stubbing, and posting.

Future research to advance the technology of bridge protection and repairs performed under water should address the need for techniques to work safely in fast-moving or turbulent water; and for improved construction equipment, repair materials, and monitoring devices.

CHAPTER ONE

INTRODUCTION

Repair of underwater bridge substructure elements is often time-consuming, complex, and costly. Numerous techniques have been proposed and practiced for underwater repair of structural elements and related scour damage; some have been effective and some have not.

This synthesis identifies and describes current practices and state-of-the-art innovative underwater repair techniques for problems associated with settlement, scour, and deterioration of underwater bridge elements. The synthesis considers various types of protection, maintenance, and repair work on bridge substructures, both underwater and in the splash zone, and includes techniques, materials, and their effectiveness. This synthesis updates the maintenance and repair portion of *Synthesis 88: Underwater Inspection and Repair of Bridge Substructures.*

RECENT FOCUS ON UNDERWATER PROBLEMS

In 1981, only 15 state transportation agencies routinely inspected bridge substructures below the waterline. Several collapses and near collapses related to failure of underwater bridge elements have since focused national attention on the inspection and maintenance of underwater bridge elements—the most publicized being the April 1987 Schoharie Creek failure.

In October 1988, revisions to the National Bridge Inspection Standards (NBIS) became effective *(1)*. The Federal Highway Administration (FHWA) issued a Technical Advisory, T 5140.20 *Scour at Bridges (2),* on September 16, 1993, for implementing the changes considered in the NBIS. These revisions stipulate that all public highway bridges requiring underwater inspection be identified, that an appropriate inspection procedure be defined, and that the frequency of inspection, not to exceed 5 years, be determined.

With the increased attention to underwater inspection and scour, bridge owners are faced with solving the problems and potential problems now documented. As part of this project a questionnaire was sent to all state departments of transportation and other selected large transportation agencies in North America. More than 50 responses to the questionnaire were received between July 1 and September 30, 1991. A copy of the questionnaire and a summary of the responses are included in Appendix A. Seventy-five percent of the agencies responding to the questionnaire have experience with underwater repairs, either with contract or in-house divers. Twenty percent of the agencies use in-house divers only and 60 percent use contract divers only. The most common type of underwater repair reported was related to channel scour affecting substructure components.

WORKING UNDER WATER VERSUS DEWATERING

In the past, bridge engineers have tended to think in terms of dewatering when underwater repairs were necessary. Sheet piling cofferdams were installed and the damaged area dewatered so that workers could perform the repair work using conventional, above-water methods. Dewatering permits the design engineer to use conventional solutions with confidence that they can be constructed and that the quality can be controlled.

Dewatering is not always feasible and may seem expensive compared to working in the dry. The expense of dewatering averages 40 percent of the repair cost on Army Corps of Engineers projects *(3)*. However, when it is feasible, dewatering may be less expensive than working underwater. The major problem is that bridge design engineers are not always sufficiently knowledgeable about repairing in the wet to make this decision, and advice of contractors or suppliers may be biased toward their products and methods. Increased emphasis on underwater inspection has increased the demand for information on effective and constructable repair techniques that can be performed by divers.

ASSESSING PROBLEMS

The first step in any successful repair is damage assessment. This involves a more comprehensive survey of the bridge element than is normally performed during routine inspection. If the damaged area is covered with marine growth, it must be cleaned. The boundaries and severity of the damage must be documented and accurately communicated to the contractor or crew that will be performing the repair. The amount of damage may increase substantially between the time of detection and the time the work is performed, if delays occur in repair implementation. Thus, the condition of the element should be monitored to assess the rate at which the damage is occurring.

Urgency is also an important consideration. The engineer must evaluate the problem to determine if it presents a potential hazard to public safety either now or before the repair can be completed. There may be justification for closing the bridge, providing temporary support, or expediting the repair.

The cause of the problem should also be addressed during the assessment and in the repair design. If the repair does not include a remedy for the problem that caused the damage, it is only temporary. Examples of causes of damage to bridge elements at or below the waterline include the following:

- Corrosion of the concrete reinforcement accelerated by saltwater,
- Damage caused by marine organisms such as rock borers and concrete-damaging bacteria,
- Chemical attack from contaminants in the water,
- Damage caused by freezing and thawing,
- Corrosion of structural steel elements,
- Wood marine-borer attack on timber elements,
- Impact of vessels or debris,
- Foundation scour/settlement,
- Loads on the bridge, and
- Movement of the bridge.

A surface assessment may be inadequate to determine the extent of damage. Sampling and testing are often required to determine the depth of contamination or the extent of deterioration. The quality of the subsurface concrete and timber is often the factor that justifies repair or replacement of the element. Examples of subsurface evaluation include

- Core extraction,
- Bore samples,
- Concrete petrographic, spectrographic, and chemical analysis,
- Ultrasonic testing,
- Exposure of concrete-reinforcing steel to assess corrosion, and
- Coupon sampling of steel elements.

ENGINEERING THE REPAIR

Solutions to underwater problems should be based on sound engineering. There is a tendency to make the problem fit a solution based on one of a few common underwater repair techniques that are marketed because they lend themselves to underwater application.

A major concern is that the repair may only hide a structural problem while it continues to worsen. In some circumstances, hiding a problem is worse than doing nothing. For example, when contaminated concrete and corroded reinforcing steel are left in place alongside new concrete, the corrosion process accelerates. Consequently, covering a reinforced concrete member with a stay-in-place form or jacket will not stop or prevent corrosion of the reinforcement. The member may look satisfactory while it is deteriorating to an unsafe condition.

The repair should address the deterioration process in the environment of the structure. If structural members are involved, the repair should be designed to provide the appropriate safety factor and redundancy. Unless special monitoring can be guaranteed, the repair should provide dependable service with the normal inspection and maintenance that can be realistically expected from the responsible agency.

Since most bridge engineers are not divers, it is important that they understand the problems and limitations in performing an underwater repair. It may be helpful for an experienced underwater repair contractor to provide constructability advice before the engineer proceeds with a repair design concept. Some repair schemes used above water are not cost-effective when performed by divers in underwater conditions. Time and cost of labor are more important considerations for underwater work. For example, it may be less expensive to accept that the deterioration will continue and modify the load path—such as by designing the repair to support the total load or by designing a supplemental supporting system—than to remove and replace the damaged portion of the element.

On contracted underwater repairs, construction quality control is the responsibility of the contractor. Quality assurance should be the responsibility of the bridge owner. There are often critical stages of the repair during which the quality of the work should be verified before it is covered. These stages should be identified and the quality assurance inspection performed by a competent person independent of the contractor. Underwater photographs or videos may be used to discuss problems and solicit advice.

CONTROLS ON WORK IN WATERWAYS

The restrictions and permits required by agencies such as the Environmental Protection Agency (EPA), the Corps of Engineers, and the Occupational Safety and Health Administration (OSHA) must also be considered when planning an underwater repair. A permit is required from the Corps of Engineers if the work will involve a navigable waterway, the EPA restricts pollution into the water or air, and OSHA regulates worker safety. These considerations may significantly influence the cost of repair alternatives. For example, leaving an old element in place and adding supplemental support may result in fewer environmental problems than the destructive removal of damaged material. Prefabricating the new element before it is placed in the water may also cause fewer environmental problems.

CHAPTER TWO

SCOUR

SCOUR EVALUATION

To prevent or repair a scour problem it is important to understand the type of scour and how it is caused. Aggradation and degradation are long-term changes in the elevation of the stream bed caused by the addition or removal of a major obstruction to the waterway, such as the construction of a dam. The stream cross-section can change due to a contraction of the flow or increased velocities. Changes to a part of the cross-section may be caused by local obstructions or turbulence. Lateral movements or shifting of the stream may also cause scour *(4)*. More detailed information on the evaluation of a bridge site for potential scour problems can be found in the FHWA Technical Advisory T 5140.23, *Evaluating Scour at Bridges,* dated October 28, 1991 *(5)*. Scour evaluation practices and procedures are documented in the FHWA publication, *Hydraulic Engineering Circular 18, Evaluation of Scour at Bridges (6)*.

To aid in the scour evaluation various instruments and monitors are available to measure the amount of scour that has occurred *(7)*.

- Ground-penetrating radar can be used in shallow, fresh water (less than 8 m [25 ft] deep) to obtain high-resolution, continuous, subsurface profiles.
- A tuned transducer can achieve 30 m (100 ft) of sub-bottom penetration with resolution of a few inches.
- A black-and-white fathometer can achieve resolution of a few inches with virtually no penetration of the river bottom. However, it does not show the extent of infilling of old scour holes.
- A color fathometer, properly calibrated, can be used to define sedimentary boundaries. Output is displayed on a color monitor.
- Side-scan sonar, using sound waves, can depict the bottom profile for a wide swath rather than that area directly below a specific traverse line *(8)*.

Direct monitoring devices, as opposed to the remote sensing devices described above, have been developed. These monitors are attached directly to each substructure element at the point of suspected or observed scour. Examples include the following:

- A non-metallic [polyvinyl chloride (PVC)] pipe is attached to the substructure unit as shown in Figure 1. The pipe has a metallic collar (horseshoe weight) attached to the outside of the pipe. This collar rests on the bottom of the scour hole. As scour occurs, the collar drops. When the flood subsides and infilling of the scour hole occurs, the collar stays at the bottom of the flood stage scour hole. A metal detector can then be inserted into the nonmetallic pipe to determine the depth of the metal collar.

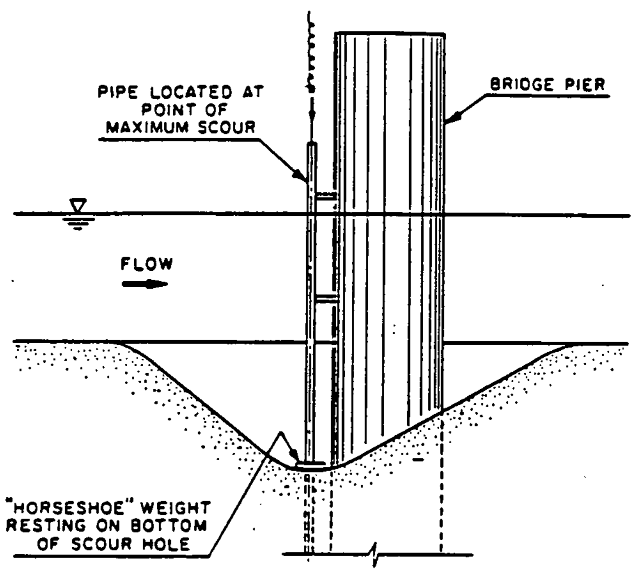


FIGURE 1 Scour-detection technique *(9)*.

- Cobalt 60 radioactive source (no more radioactive than a wristwatch) can be housed inside the collar. A gamma-ray probe is lowered inside the pipe to detect the level of the collar. The radioactive source allows the use of a metal, impact-resistant pipe.
- A steel rod inside a PVC pipe armored with a protective steel angle is attached to the substructure unit. The rod descends as scour occurs. This is a patented device that has been installed on five bridges in the state of New York.

NCHRP Project 21-3, *Instrumentation for Measuring Scour at Bridge Piers and Abutments,* is evaluating this technology and developing additional scour monitoring devices. Research is essentially complete and a monitoring phase has been initiated. *NCHRP Research Results Digest 189* reports on Phase 1 of this project.

PREVENTION OF PROBLEMS

Scour protection starts with the selection of the bridge site and layout. While moving the bridge is probably not a realistic option in solving scour problems, an understanding of the considerations in site selection can be helpful. Whenever possible, the site should be selected where there are minimal or no scouring currents. A scour-resistant foundation material is also desirable. The site may be a compromise between the ideal location to avoid scour and the location where the shortest, least costly bridge can be constructed. For example, high-bank approaches and narrow channels reduce bridge length, but they cause faster flood currents, subjecting the channel to scour around the bridge substructure. Repairs may also restrict the channel opening and increase the currents.

To minimize the effects of scour and stream migration, the new design, or repair, may include features such as additional approach spans, longer piles and deeper footings, sheet piling, training structures, and riprap (or other methods of ground covering and protection discussed later). Before repairs or modifications that restrict or redirect the stream flow are implemented, a hydraulic evaluation should be made to determine if they may cause damage elsewhere on the bridge or adjacent property.

Scour Countermeasures

Various scour countermeasures developed in the past have proven effective in controlling streambed erosion and scour around certain bridges. Spur dikes, jetties, and deflectors have been constructed to direct water away from bridge piers, abutments, or fill. Satisfactory results depend on knowledge of the hydrological and hydraulic characteristics of a site and an understanding of the function and limitations of the various devices. HEC-18 is a good reference on the subject *(6)*. If these devices are not designed and constructed correctly they can cause scour damage or erosion of adjacent property *(10)*.

Conventional spurs and dikes tend to cause scour and move a problem from one location to another. Newer devices are being tested that can be positioned to make the water and sediment move through a river curve as if it were straight. Iowa vanes *(11)* are an example of affordable, low-maintenance hydraulic training devices. The submerged vanes, shown in Figure 2, function as a secondary motion generator modifying the streambed flow pattern in the direction of the arrows, which can induce sand bar formation or reduce streambank erosion.

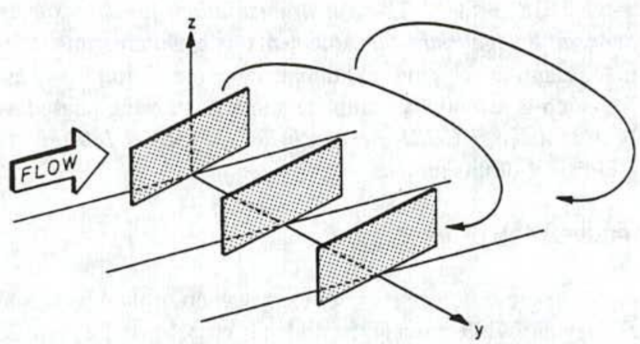


FIGURE 2 Iowa vanes *(11)*.

Sheet Piling

Foundations of piers and abutments can be protected against scour by placing sheet piling to keep material in place. Sheet piling should be driven to a depth where a stable soil condition exists (Figure 3). The water depth and velocity and the type of stream bed material are important considerations in the use of sheet piling to prevent or control scour. Louisiana, North Carolina, and Florida use sheet piles extensively to protect against scour. Because of the possibility of increased scour from the sheet piling installation, each application should be carefully analyzed.

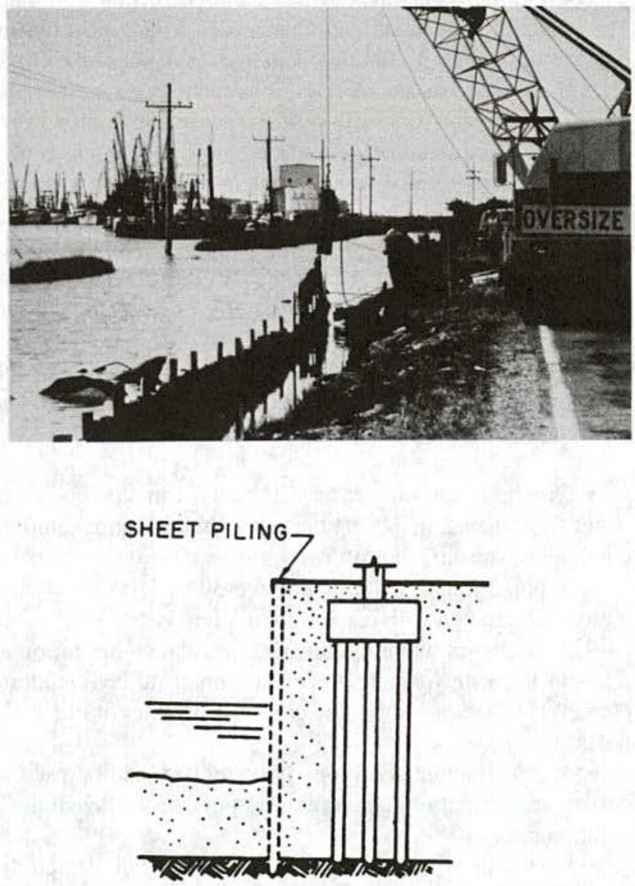


FIGURE 3 Foundation protection using steel sheet piling *(10)*. (Courtesy: Louisiana DOT)

Riprap

Riprap is a flexible ground covering for the abatement of scour. Riprap is placed as a protective layer and is composed of singular pieces of material that can adjust to deformations and subsidence of the subbase. Riprap is defined by Brown *(12)* as "a flexible channel or bank lining or facing consisting of a well graded mixture of rock, broken concrete, or other material usually dumped or hand-placed which provides protection from erosion." It is preferable not to allow the material to cascade down an embankment during placement. It should be end-dumped into place by truck with a minimal drop distance or placed with a crane or endloader to prevent segregation.

Riprap placed in front of an abutment can prevent streambed scour and undermining as shown in Figure 4. Riprap that extends from one streambank to the other is often referred to as streambed paving. Typical examples are shown in Figures 5 and 6.

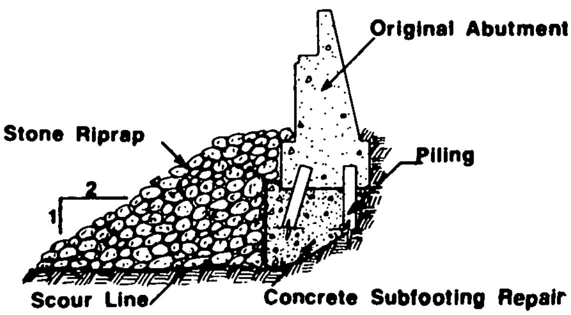


FIGURE 4 Abutment protection using riprap *(13)*.

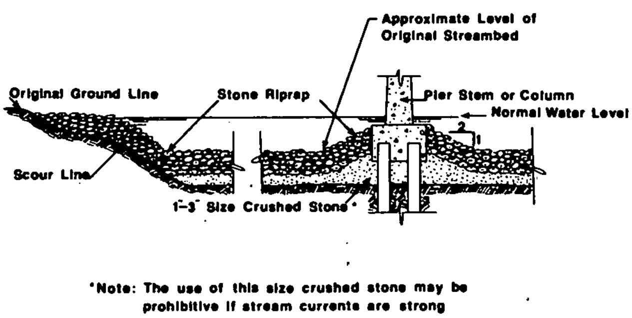


FIGURE 5 Pier protection using riprap *(13)*.

Riprap has the following advantages over a rigid protection system such as concrete slope protection:

- It is a flexible ground cover that can accommodate movement and subsidence of the subbase material.
- It is easier to place and repair than a rigid system.
- It has a comparatively low design and installation cost.
- Vegetative growth between the elements enhances the aesthetics and structural stability of the riprap.
- It is recoverable and can be stockpiled for later use.

Disadvantages include the following:

- Larger sizes may be difficult to obtain, transport, or position.
- A layer of riprap may restrict the channel opening or cause turbulence.
- Large riprap may restrict future options, such as pile driving.

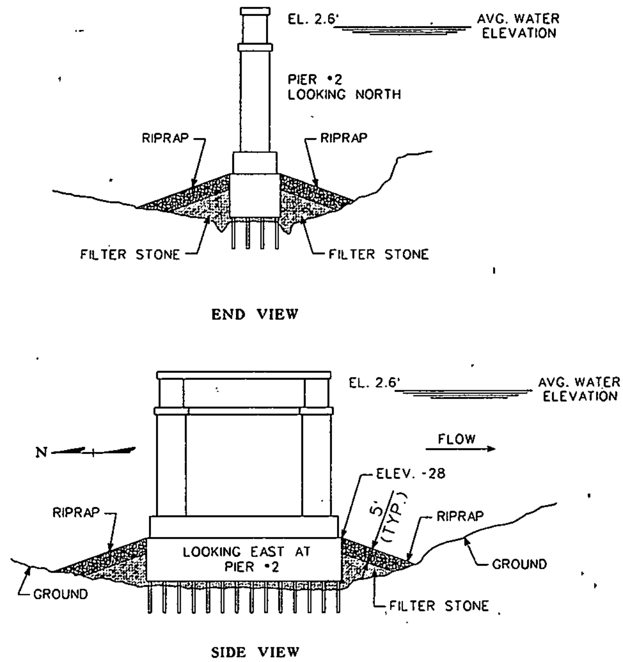


FIGURE 6 Scour rehabilitation. (From Louisiana DOT plan)

Details from a Louisiana Department of Transportation Scour Rehabilitation Plan are shown in Figure 6. The plans call for the removal of any debris. The base course may consist of sand, gravel, or shells. A plastic filter cloth is specified if sand or gravel (or both) is used in the base course. One-and-one-half m (5 ft) of riprap on a one-to-four maximum slope complete the installation. The contractor is required to place the aggregate filter cloth and riprap in a continuous operation and is not allowed to place more than 30 m (100 ft) of aggregate and filter cloth in front of the riprap during the operation.

The size and weight of the individual pieces of riprap should be selected to resist displacement by the water velocity and not create problems related to blockage or turbulence. HEC-18 *(6)* provides guidelines for sizing riprap. Potential environmental damage is also a consideration in the type of riprap and method of placement. Maine, Oregon, and Tennessee are among the many states that reported using riprap to protect against scour. Riprap can have various forms, as described below.

Rubble Riprap

Rubble riprap may consist of broken concrete, steel furnace slag, or rock spoils. In addition to the advantages listed previously for riprap, rubble riprap offers economy through the use of recycled materials. This may be important in areas without local rock quarries. Rubble riprap should contain no shale or other laminate material. Identification and removal of chemically weak material must also be considered. Since this material is normally ungraded and in awkward sizes and shapes, it must be carefully placed to be effective.

Hand-Placed Riprap

This type of riprap may consist of rock or rubble that is carefully placed in position. Hand-placed riprap has the advantage of presenting a neat and even surface. The surface will reduce streamflow turbulence and increase aesthetic value. The interlocking pieces allow for a steeper slope than dumped riprap. Because the material is hand placed, less material is required because a thinner layer of riprap will suffice. Hand-placed riprap has several disadvantages. It is labor intensive and therefore expensive to place. Hand-placed riprap is also more easily damaged by subbase subsidence than dumped riprap.

Wire-Enclosed Rock (Gabions)

Wire-enclosed rock riprap (gabions) consists of galvanized- or coated-wire-mesh baskets filled with rock of minimal size to be contained within the basket. The baskets are arranged and tied together as either a mattress for streambed paving, or in blocks to be stacked in a stepped fashion for streambank protection. States reporting the use of gabions include North Carolina, Pennsylvania, and Maine.

Wire-enclosed rock has the following advantages over loose riprap:

- It can accommodate minor settlement without exposing the subbase.
- It can be used where only rock of limited size or low quality is available.
- It can be used in thinner layers to reduce turbulence.
- The baskets are more resistant to movement and can be stacked at a steeper slope.

The disadvantages are as follows:

- It has limited flexibility, accommodating some base settlement.
- Plastic-coated wire cages are susceptible to corrosion. Abrasion and impact can cause cracks in the plastic coating, accelerating corrosion.
- The use of wire-enclosed rock is labor intensive.
- The rocks inside the enclosures can shift in the downstream direction, exposing filter material or causing loss of base material if no filter exists *(11)*.
- Undermining at edges may occur, requiring treatment.

Precast Concrete Blocks

Precast blocks are laid in a continuous blanket and joined together in some fashion. They have been used extensively in shoreline applications as wave dissipators.

Precast concrete blocks offer the following advantages:

- The blanket is flexible and can accommodate minor settlement of the base material.
- The modular elements allow relatively rapid installation with small equipment.
- Growth of vegetation is possible within the system, allowing for increased stability; this may also enhance the aesthetic value.
- The system does not hold water between the protection and the embankment.
- The system can be used for wave dissipation. (It is used extensively along shorelines in Louisiana.)

Precast concrete blocks have at least two disadvantages:

- Undermining at edges can occur. (This undermining can propagate until the entire system fails. The design of an appropriate edge treatment would alleviate this problem.)
- Precast concrete blocks are relatively expensive, due to labor costs involved with installing and joining individual blocks *(11)*.

Grouted Rock

Grouted rock consists of rock riprap with grout-filled voids. Concrete grout for underwater placement requires antiwashout admixtures. Antiwashout admixtures are used to minimize washout of fines and cement from the concrete that is in contact with flowing water, to prevent segregation of the concrete, and to inhibit water entrainment as the concrete is placed. States that use this method of scour protection include Connecticut and New Jersey. The surface is smoother than other types of riprap that reduce streamflow turbulence and increase the speed, which may or may not be an advantage. Clear advantages of grouted rock include the following:

- A monolithic armor of the subbase is provided.
- Use of smaller rocks allows use in areas where large rocks are not available.
- Filter material may not be necessary over the subgrade.

The following disadvantages are associated with grouted rock:

- Since this material is cast in place and unreinforced, this type of structure has relatively little strength *(12)*.
- The rigid structure resulting from the grouted rock does not accommodate subgrade subsidence.
- Undermining can be a problem at edges of the system.

Concrete Channel Protection

Cast-in-place concrete channel protection may be used to protect against scour. Typical installation includes the preparation of the subgrade by using a backhoe or excavator to cut the subgrade to the appropriate grade lines. A base course of gravel is placed. A 30-mil PVC liner is placed atop the gravel. The protection consists of a 7.6-cm (3-in.) concrete mat with wire mat reinforcement placed atop the PVC liner *(14)*.

To be effective, the edges of the concrete mat must extend below the scour line or into scour-resistant material. Since this is often difficult to accomplish, many states, such as Virginia, have used other methods of protection at scour-prone locations. Placing the concrete underwater requires the use of special procedures discussed in Chapter 3.

Concrete channel protection offers the following advantages:

- Strength, continuity, and impact resistance are afforded by the use of concrete placed on a properly prepared base material.
- The smooth surface reduces stream turbulence.
- Steeper banks can be constructed with the use of these stronger materials.

Concrete channel protection has the following disadvantages:

- Because the system is rigid, major deformations of the substrata will result in failure, rather than repositioning, of the system.
- The smooth channel surface increases the water velocity, which may cause problems downstream.
- Undermining at the edges of the system, especially at the toe, can occur.
- Outward displacement of the system due to hydrostatic pressure is possible.
- Failure due to sliding action is possible.
- This system is a relatively expensive form of scour abatement *(12)*.

Artificial Sea Grass

A new, proprietary underwater erosion- and scour-control plastic mat material was reported in the *Washington Post* in March 1992 *(15)*. The mats, anchored to the bottom of the channel for stability, resemble sea grass. The idea is to absorb the energy of underwater current and trap sediments deposited at the base. The mats are made of a polymer and have thousands of fronds that float when submerged. This new material should be considered unproven since no agency has reported its use.

Articulated Concrete Mattresses

The U.S. Army Corps of Engineers, Vicksburg, Mississippi, reports success in revetting the banks of the lower Mississippi River with articulated mats. The revetments are composed of wire fabric cast into concrete blocks to form a concrete mattress of designated length and width. The units are secured to the prepared river banks with steel cables. It is important that corrosion-resistant, high-strength wire be used to tie the concrete blocks together. At other installations, concrete or grout is also pumped into fabric mats and stayed with nylon cable and galvanized anchors to provide scour protection.

Riprap-Filled Cells

The U.S. Army Corps of Engineers (Vicksburg, Mississippi) also reported the use of plastic cells (grids) that are fabricated together into a blanket and filled with riprap to protect slopes against scour from wave action. Proprietary systems similar to this are available with different-shaped and -sized cells.

MAINTENANCE AND REPAIR

Bridge maintenance should include regular inspections of the channel around the structure to identify and report potential problems. The removal of debris that has accumulated in the channel can reduce turbulence or prevent a diversion or blockage of the water. Regular maintenance inspections should also identify changes in the channel profile before there is a threat to the structure, and then a protection system can be added. Inspection is especially important after major storms.

When scour damage to a substructure element is identified, efforts must be made to re-establish bearing and to protect the substructure unit from further scour damage. Typically, remedial schemes use a combination of repair/protection techniques.

Bagged Concrete

Concrete in bags may be used either to armor the foundation material from further scour or as a form for placing concrete if it is necessary to restore foundation bearing. Figure 7 shows a typical installation. (The tremie concrete used in this installation is discussed in Chapter 3.) Bagged concrete was first patented by Johann Steere in 1922 in Norway, and it was first used in the United States in 1968. Typically, the bags are filled with the dry concrete ingredients and placed in position. The bags are anchored together and to the substrata with dowels. The cement hydrates and hardens when exposed to water.

Bags may also be filled after being positioned underwater. Modern synthetic fibers such as nylon permit the bleedwater to be expelled, making this technology possible *(16)*. Because the synthetic fibers are woven into water-permeable fabric, the water-cement ratio can be quite low at the surface of the concrete. States using this method of scour protection include

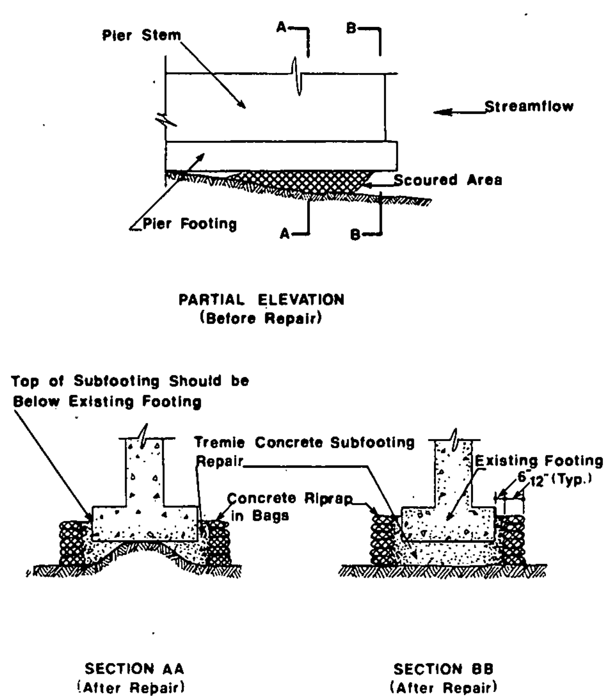


FIGURE 7 Bagged concrete rehabilitation *(13)*.

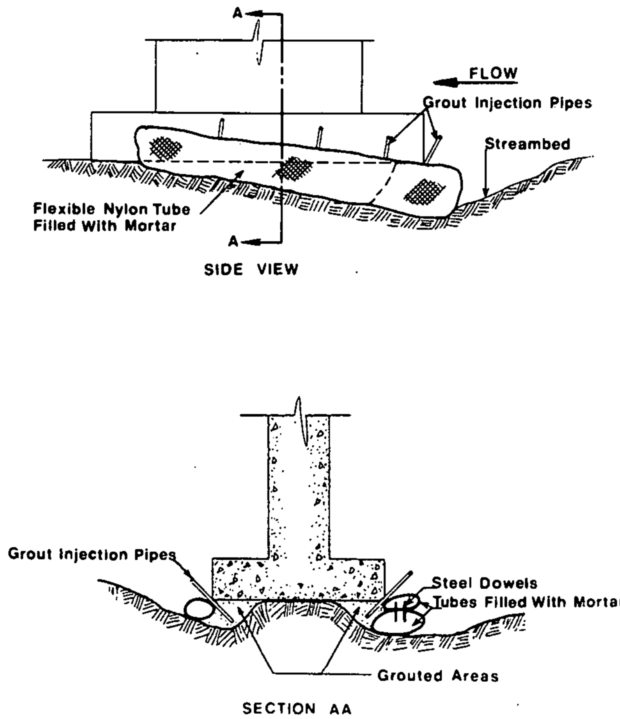


FIGURE 8 Concrete-filled tubes *(13)*.

Oregon, Pennsylvania, and New Hampshire. Bagged concrete offers the following advantages:

- It is versatile in size and application.
- It is well suited for a small crew with limited equipment since it can be handled and placed relatively easily underwater.
- It eliminates the need for forms.

Bagged concrete has some disadvantages, as shown below:

- Because the dry ingredients are often hand mixed and the water-cement ratio cannot be controlled, the strength and durability may not be as good as conventional cast-in-place concrete.
- The filled bags must be stored and kept dry before they are used.
- Bond and watertightness between bags is not as good as cast-in-place concrete.

Concrete-Filled Tubes

Flexible nylon tube forms can be filled with grout or concrete to fill scour pockets under substructure units. The nylon tube is placed in position and injected with cement grout or concrete as shown in Figure 8. The tubes may be fabricated to the required dimensions; when filled, the tube shown in the exhibit is 305 cm (10 ft) long, 115 cm (45 in.) wide by 64 cm (25 in.) thick. The tubes may be fabricated to the required dimensions. Before the grout or concrete hardens, the tubes are anchored together by steel dowels that are punched through the tube. Tubes are filled in place using a stay-in-place valve on the tube. Maine is one of the states reporting the use of this method of scour repair.

Concrete-filled tubes and concrete-filled bags made of synthetic fibers are basically the same, except for size and shape. Some agencies refer to both as bags. The advantages and disadvantages are basically the same. The tube could be considered a refinement of the bag with the following advantages:

- The tube is normally larger.
- The tube is sized to fit a void.
- The tube permits the concrete to shape itself to fill the void.

Prepacked Aggregate Concrete

Scour voids can also be filled with prepacked, open-graded concrete aggregate contained by forms and injected with cement grout through pipes *(17)*. When this repair is performed underwater the grout is injected from the bottom up. The injection pipe is lifted as grouting operations continue, ensuring that the bottom end of the pipe remains embedded within the freshly placed grout. The Corps of Engineers and Florida reported the use of this repair technique.

The forms should be watertight to control the loss of the grout, vented only at the top to indicate when the forms are full. The tops of the forms should consist of a highly permeable fabric held down with a wire mesh, which in turn is held down by plywood. This system allows venting while preventing the loss of fines and cement. The forms need to be held down by grouted doweling because of the pressure generated by the grout.

Prepacked concrete has the following advantages:

- Water-cement ratio and shrinkage can be low.
- Bonding characteristics are excellent.
- Concrete is not affected by dilution or washout.
- Forms need not be dewatered.
- The forms create flat, neat surfaces.
- This method fills voids that are difficult to access.

Prepacked aggregate concrete has the following disadvantages:

- Marine growth can accumulate on the preplaced aggregate in polluted waters if there is a delay in the construction operation, resulting in a poor grout/aggregate bond.
- Due to the pressure of pumping grout, special anchoring is recommended to hold the forms in place.
- The procedure may be relatively expensive. A cost analysis is recommended to compare alternatives such as a dewatering cofferdam for direct concrete placement *(18)*.

Sheet Piling

Sheet piling or corrugated metal can be used as formwork to retain either concrete or riprap for repair of scour damage.

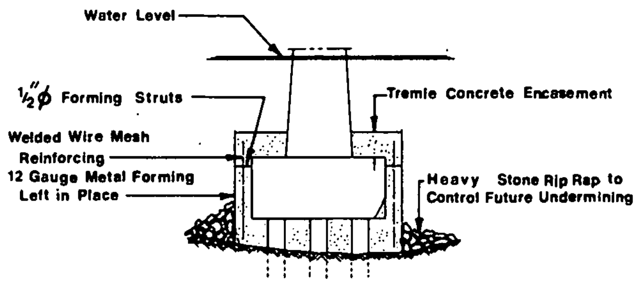


FIGURE 9 Example of sheet piling scour rehabilitiaton *(9)*.

If riprap is used within the form, a concrete cap may be used to retain the riprap. (Chapter 3 discusses placement of concrete underwater.) Additional riprap may be placed around the outside of the form to protect against further scour. This method is the oldest and most straightforward method of scour repair. A typical installation is shown in Figure 9. Sheet piling offers the following advantages:

- Normally, it does not obstruct the channel opening.
- It is economical and simple to design.
- It can be constructed and repaired in a short time.

The following considerations may be disadvantages at certain locations:

- The steel form is not corrosion-resistant.
- Special equipment is required to drive the sheet piling.

CHAPTER THREE

CONCRETE AND MASONRY ELEMENTS

Concrete is the predominant material used in the substructures of bridges that cross waterways and will be the focus of this chapter. Most of the information collected for this synthesis is related to reinforced concrete. However, some of the repairs for concrete can also be adapted to repairs of masonry elements. If a repair procedure can also be applied to masonry, it will be noted. Otherwise, it applies only to concrete.

Underwater and splash zone deterioration of concrete bridge elements can be a serious problem, both from structural and economic perspectives. Several factors contribute to the deterioration of concrete. The corrosion of reinforcing steel is usually the most critical and serious problem to affect the durability of concrete in a marine environment. Seawater contains salt, which accelerates the corrosion of the reinforcing steel and subsequent cracking of concrete. This problem occurs most frequently in the splash zone due to the increased availability of oxygen for the corrosion reaction in that area.

In saltwater, the initiation of the reinforcement corrosion is influenced by the permeability of the concrete. The space occupied by the reinforcing bar expands as the oxide (rust) material is formed, causing the concrete to crack internally and spall. Concrete cracks further expose the steel to the saltwater and accelerate the corrosion and damage. After corrosion begins in this environment, it is extremely difficult and expensive to remedy. Unless the steel is cleaned and the salt-contaminated concrete is removed, or cathodic protection is installed, the corrosion is not stopped by covering the area. As the corrosion continues to damage the bridge element, while being hidden by an ineffective repair, an unsafe situation may result without warning.

Concrete bridge elements located in water are also susceptible to deterioration caused by a wide range of chemicals, including acids and sulphates. After the surface is damaged by chemicals, the water washes away the loose aggregate particles, exposing fresh concrete surfaces for further attack. Concrete in a marine environment is also susceptible to collision and abrasion damage. Abrasion is the action caused by water-borne particles rubbing against a concrete surface. The symptoms of collision and abrasion are spalled concrete and worn concrete, respectively. Biological damage can also occur—rock borers are capable of boring into porous concrete.

PROTECTION

This section includes methods used to protect existing concrete bridge elements at or below the water level from damage other than scour, which has been covered in the previous section. Methods that combine protection and repair, such as concrete jackets, are included in the next section.

Coatings

Waterproof coatings applied in the dry can be effective in protecting the surface of concrete or reinforcing steel against damage from salt and other chemicals. Any protective coating must be applied to a clean surface that is not contaminated or beginning to deteriorate. If the coating traps contaminants that have penetrated the surface, it is unlikely to be successful.

Because of the problems related to dilution of the material, poor bond, and difficulty of application, the durability and service life of coatings applied underwater may not be as satisfactory as other repair methods. Cementitious and epoxy coatings have been applied underwater to protect concrete surfaces against abrasion, cover cracks, and make small repairs. These products are normally applied by hand as a thick mortar. The cementitious products often include antiwashout admixtures and accelerators. Cementitious materials are mixed above water and delivered to divers in a plastic bag. Epoxy resins applied under water must perform satisfactorily and cure under wet and low-surface-temperature conditions. Epoxy resins can be rolled into balls and dropped through the water to divers *(18)*.

Coatings and epoxy covers are relatively expensive and difficult or impossible to place underwater in large quantities for concrete abrasion resistance. However, one underwater epoxy coating, developed in France, has been used as a primer coat for epoxy mortar, as a binder for epoxy mortars, for sticking elements on concrete, for injection, and for paint. It has demonstrated good adhesion under water on various substrata, such as concrete stone, steel, and tile *(20)*.

The U.S. Army *(21)* tested 22 coating products from 13 producers. Testing included bond capacity in direct tension, bond capacity under structural stress, resistance to abrasion, resistance to freeze-thaw, resistance to impact, and thermal compatibility with concrete. The four top-performing products were two epoxy materials and two cement-based products. If thermal compatibility, bond to wet concrete, and cost are evaluation factors, the top performing cementitious product is likely the material of choice. It is a relatively inexpensive, hydraulic cement-based, non-metallic fiber-reinforced material. However, if resistance to abrasion and impact are factors, the top performing epoxy may be appropriate. It is a three-component, fast-cure epoxy mortar that costs approximately three times as much as the cementitious product.

The advantages and disadvantages vary depending on the type of coating. Generally, these products are less expensive and easier to install than other alternatives, but they should be applied to a clean, dry surface.

Cathodic Protection

Underwater cathodic protection (CP) has achieved favorable results in preventing and halting corrosion of reinforcing steel. CP can be provided by either a sacrificial anode or an impressed current flow from a rectifier power source. In a marine environment and underwater application, the sacrificial anode cathodic protection is often recommended because of the low resistivity environment. This system uses a metal (sacrificial) anode higher in the galvanic series than the reinforcing steel to be protected. Zinc is often used as a sacrificial anode; however, magnesium and aluminum may also be used *(10)*.

Zinc Sacrificial Anodes

Zinc anodes in the form of strips may be attached by a nonconductive material to the exposed concrete surface and by an electrical connection to the reinforcement to achieve cathodic protection. Recently, for pile protection, perforated sheets of scrap zinc have been fabricated into four-sided cages that are wrapped around the pile. The cage is held in place with wood or plastic recycled products and stainless steel bands as shown in Figure 10. Subsequent installations have used stainless steel bands with even better results. The cage is positioned so that its mid-elevation is at the high tide elevation. A reinforcing bar is exposed 2 feet above the cage to allow an electrical connection. This assembly has been used on a bridge on U.S. Route 90 in Jacksonville, Florida. Estimated life expectancy of this installation is a minimum of 5 years *(22)*.

For cathodic protection of reinforcing steel that is exposed after removing the deteriorated concrete, zinc anodes can be clamped directly to the reinforcing steel. An example is shown in Figures 11 and 12. Although local, small areas of exposed reinforcement may remain unpatched, larger concrete removal areas need patching and restoration to their original condition. Washington state also reported the use of sacrificial anode CP.

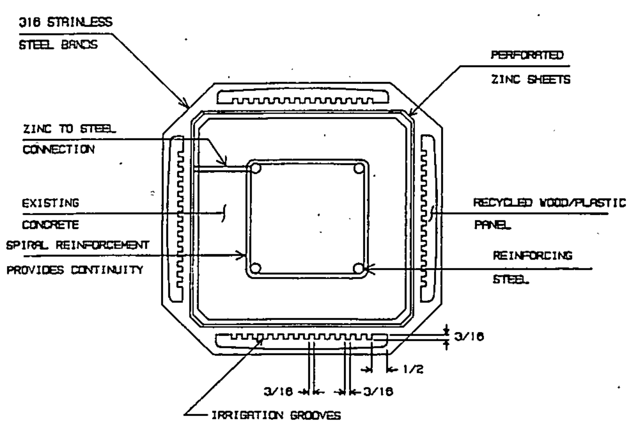


FIGURE 10 Passive cathodic protection for concrete piles using perforated zinc sheets *(22)*.

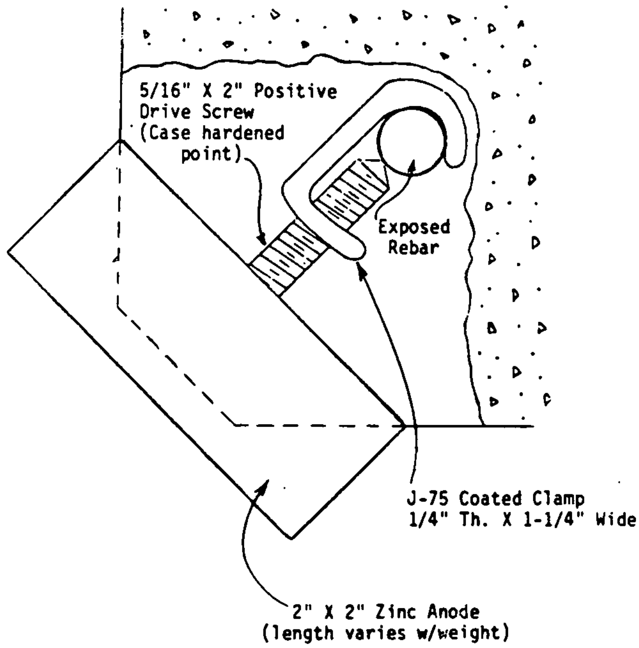


FIGURE 11 Passive cathodic protection for concrete piles using sacrificial anodes—cross-section *(10)*.

The advantages of these sacrificial zinc anode systems over conventional concrete repairs are that:

- They are more effective at reversing or reducing the corrosion rate.
- They are easier and less expensive to install in the wet.

Spray Zinc Sacrificial Anode

Passive cathodic protection (sacrificial anode system) may also be achieved by spraying a concrete surface with molten zinc. This procedure was first performed in the United States by the California Department of Transportation *(23)*. Florida has coated four of the 48 bridges in the Florida Keys with 380 sq m (4,100 sq ft) of metallized zinc spray coat.

When applied to salt-contaminated concrete, the procedure consists of locating and removing delaminated or deteriorated concrete, exposing the reinforcement, and sandblasting the exposed surface. The molten zinc is applied to the exposed reinforcing bar and the concrete surface to elevations 2 to 6 ft above the waterline and the limits of the spalling. The surface of the coating above the waterline may then be covered with a white cosmetic coating like parapets to minimize atmospheric consumption.

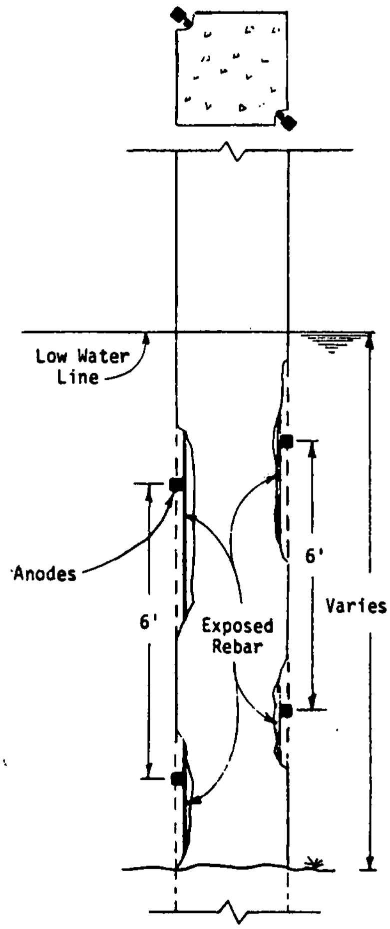


FIGURE 12 Passive cathodic protection for concrete piles using sacrificial anodes—side view *(10)*.

The advantages of this system are as follows:

- Anode service life of 5 to 10 years can be expected while reinforcement corrosion is stopped, whereas patching lasts only 3 to 5 years and corrosion damage continues during that period.
- The cost of this method is approximately half the cost of conventional repairs (patching).
- Patching of the damaged concrete surface is not required.
- The color of the spray zinc, in most cases, matches the existing concrete surface *(23)*.

Active CP Systems

Active CP using an externally supplied impressed current is possible; however, this system is mainly used to protect reinforced concrete units in the dry. CP with an impressed current system is difficult to accomplish underwater since water is an electrically conductive medium. Florida DOT is using an impressed current system with three anodes, (1) conductive rubber, (2) titanium mesh anchored and covered with cast-in-place concrete, and (3) spray zinc.

MAINTENANCE AND REPAIR

Pressure Injection of Cracks

When cracks expose the reinforcing steel to moisture, the stage is set for the corrosion process to begin. In saltwater environments corrosion can occur very fast. With the proper selection of a water-compatible adhesive, normally an epoxy resin, dormant (non-moving) cracks saturated with water can be repaired. The procedure can also repair other small voids such as delaminations or honeycombed areas near the surface of the concrete. Pressure injection can be used, within limits, against a hydraulic head provided the injection pressure is adjusted upward to counteract the pressure of the hydraulic head. The material must displace the water as it is injected into the crack to ensure that the crack is properly sealed, resulting in a watertight monolithic structural bond.

Epoxies must have certain characteristics to cure and to bond the cracked concrete together. The concrete crack contains damaging materials such as water, contaminants carried by water, dissolved mineral salts, and debris from the rusting reinforcing steel. The typical low surface temperature of concrete under water eliminates many epoxy products due to their inability to cure properly under such conditions. The epoxy injection resins suitable for filling cracks are formulated for low viscosity, and they do not shrink appreciably. The surface wetability of epoxy resin is of major importance, because the resin should displace all water in the crack, adhere to a wet surface, and then cure in that environment.

The crack-filling procedure involves cleaning the crack using a high-pressure water jet system and shaping the surface of the concrete directly above the crack so that it can be sealed with a grout. Injection ports are installed in holes drilled by a hydraulic or pneumatic drill to intersect the crack. Then, the surface of the crack is sealed with a grout material suitable for underwater use, such as the cementitious or epoxy mortar described earlier. The purpose of the grout is to retain the adhesive as it is pumped into the crack. The adhesive is pressure-injected into the crack through the ports that are embedded in the grout at regular intervals. The injection sequence begins at the bottom and advances upward. The injection moves up when the adhesive reaches and begins to flow from the next port above the nozzle. Epoxy resin is mixed either before or after pumping. Cracks varying in width from 0.005 cm (0.002 in.) to 0.6 cm (0.25 in.) *(17)* may be injected successfully.

Epoxy pressure injection has gained widespread acceptance as a cost-effective method to bond together and seal cracked structural concrete members. States reporting its use for underwater repairs include North Carolina, Virginia, and Louisiana. The following precautions should be noted:

- Organisms growing inside the crack, especially those found underwater, can reduce the successful welding of cracks.

• Corrosion debris can also reduce the effectiveness of pressure injection.

• Injection is labor-intensive. Time and patience are required for the successful injection project.

• As the temperature drops below 50°F, it becomes more difficult to pump the epoxies into fine cracks.

• Experience on the part of the diver in injection and the formulation of the epoxy are very important.

The cause of the crack is an important consideration in selecting a repair. For example, if the crack was caused by settlement that has since stabilized, the crack is dormant and epoxy injection is a viable method of repair. If the movement, or stress, that caused the crack is still present, the epoxy bond is not likely to be successful or the concrete will crack elsewhere to relieve the stress. If the crack is active, not dormant, it may be better to fill the crack with a flexible sealant and allow it to act as a joint. (To determine if a crack is dormant, it can be measured at different times, a crack monitoring gauge can be attached to the surface, or the surface of the crack can be filled with a grout and checked later.)

It is best to schedule crack-filling operations in the early spring when the crack is largest due to colder temperatures. This allows cracks to be in compression when the concrete expands; cracks filled during summer or early fall, when they are narrow, would cause the adhesive to be in tension during cooler periods.

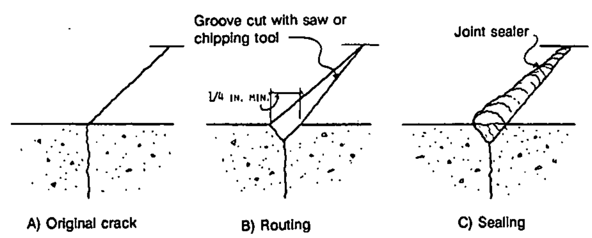


FIGURE 13 Repair of crack by routing and sealing *(17)*.

Routing and Sealing Cracks

In this method the crack is enlarged at the concrete surface and filled with either epoxy or a urethane as shown in Figure 13. Cracks up to 1.9 cm (0.75 in.) may be repaired in this manner. The advantage of this system is its simplicity. However, if the crack is not dormant, a flexible sealer must be used and bonding of the flexible sealer may be a problem when attempted in the wet. If a flexible sealer is used, the size and shape of the slot that it occupies is very important to permit the material to stretch rather than tear. Versions of this type of repair have been performed in many states, including Virginia and Hawaii. This method of repair could also be applied to masonry substructure elements.

Stitching

Stitching is an alternative for repairing large cracks underwater, however, it was not reported as being used by states contacted. In this procedure, holes are drilled on both sides of the crack and a U-shaped bar is grouted in place. The U-shaped bar is sometimes called a stitching dog. This procedure is shown in Figure 14. This method can be used to re-establish the tensile strength of a member in bending.

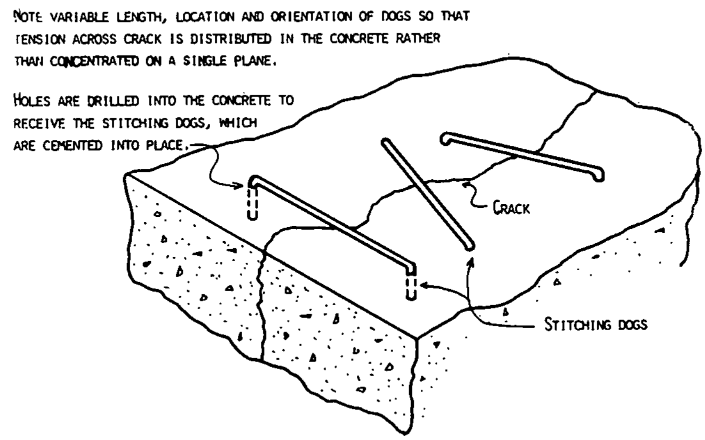


FIGURE 14 Repair of crack by stitching *(17)*.

The repair method should be used with caution because of the following disadvantages:

• Unless the cause of the crack is corrected, this method may encourage cracks to develop elsewhere in the structure.

• Unless both sides of a crack are stitched, the unstitched side may continue to open, causing alignment problems.

• If unprotected, the exposed bar is susceptible to corrosion, particularly in a marine environment.

• The finished repair is not attractive.

Concrete Removal and Surface Preparation

Unless cathodic protection is used, salt-contaminated concrete and rust must be removed from contact with reinforcing steel to ensure that corrosion damage will not continue. However, concrete removal, especially under water, is labor intensive, difficult, and costly. Consequently, alternatives to concrete removal such as structural jackets or auxiliary members should be considered.

Concrete removal may also be a problem on certain substructure elements if auxiliary support is required because of the reduced section of the supporting member. In this situation, it may be more practical to encapsulate the damage with a structural jacket than to replace it. The repair would be designed to be structurally adequate to carry all, or a significant portion, of the load supported by the damaged element.

Concrete removal can be accomplished with high-pressure water jets or chipping hammers. Construction joints between old and new concrete should be saw-cut prior to concrete removal to prevent feather edges. Care should be taken during the concrete removal to avoid damage to the existing steel and to the bond between sound concrete and embedded steel. Rust is removed with high-pressure water jets or with abrasive blasting. If the steel section is reduced substantially by corrosion damage, additional reinforcement may be necessary. Mechanical splices are preferable to welding. It is recommended that smaller lap bars be used to minimize the required lap length if mechanical or weld splices are not used.

Surface preparation is required after concrete removal and prior to repair. All loose and fractured concrete, marine organisms, and silt are removed by high-pressure water jets, abrasive blasting, or mechanical scrubbers. In order to reduce the accumulation of new surface deposits where the water is heavily laden with contaminants, repairs should be made the day of final surface preparation.

Concrete Removal Equipment

Hydraulic- or pneumatic-powered concrete saws may be adapted for underwater use. The debris created by the saw may obstruct divers' vision, but this problem can be overcome with the use of a guide to direct the cutting blade.

Hydraulic- or pneumatic-powered chipping hammers may be adapted for underwater removal of concrete and marine growth. Hand-operated chipping hammers require a secure attachment to enable the diver to control the force and take care not to damage sound concrete. If damage to the reinforcement is not a concern, a surface-mounted chipper might be operated from above the water, guided by the use of a video camera.

Water jets may be used under water for concrete removal and for surface preparation by the removal of marine growth. Retrojets that counteract the removal force and smaller flexible delivery lines are needed for safer hand operation by divers. An abrasive blasting technique, similar to sandblasting, is available that uses a water jet and an abrasive to clean the concrete surface. Mechanical grinders are also available for cleaning concrete surfaces.

The U.S. Army Corps of Engineers evaluated the effectiveness of procedures and devices for underwater cleaning of their concrete structures. Figure 15 lists the types of cleaning tools recommended based on the extent of fouling and surface area *(24)*.

Fouling	Size	Material		
		Concrete	Steel	Timber
Light	Massive	Self-propelled vehicles		Waterjets
	Large	Waterjets and hand held power tools[1]		
	Limited Access	High pressure waterjets		
Moderate	Massive	Self-propelled vehicles		Waterjets/ power tools
	Large	Power tools/ waterjets	2	Power tools/ waterjets
	Limited Access	High pressure waterjets		
Heavy	Massive	Self-propelled vehicles		N/A
	Large	Power tools	Power tools/ waterjets	Power tools
	Limited Access	High pressure waterjets		

Notes:
(1) Hand tools for limited spot cleaning of light and loose fouling.
(2) Abrasive waterjets for paint removal or bare metal finish on steel structures.

FIGURE 15 Underwater cleaning tools *(24)*.

Grouting Dowels

Dowels are usually used to bond the old and new concrete together mechanically when another adequate bond cannot be obtained. They may also be used to bond a concrete repair to a masonry substructure. Steel dowels are generally used to anchor the repair material. The dowels are usually installed by (1) drilling a hole, slightly larger in diameter than the dowel, into the old concrete, (2) cleaning the hole, (3) inserting a capsule containing either polyester resin or vinylester resin, and (4) spinning the anchor into the hole. Although this system is reported to produce a satisfactory bond under dry conditions, failures of anchors embedded in polyester resin under wet conditions have occurred. The reason for the failures was that the adhesive capsule or cartridge inserted into the drill hole did not displace all of the water in the hole. The trapped water remained between the adhesive container and the drill hole and became mixed with the adhesive, reducing the tensile capacity *(25)*.

A two-step anchor installation procedure was developed that eliminated the bond problem (Figure 16). In this procedure a small amount of adhesive was injected into the bottom of the drill hole first. Once the injection was completed, insertion of a prepackaged resin capsule displaced the remainder of the water in the hole prior to anchor insertion.

Grouting dowels can be labor-intensive, particularly under water. The Naval Civil Engineering Laboratory has developed power-actuated doweling equipment for underwater use *(20)*. No information is available on states using this equipment. Also, a proprietary system has been developed that uses a cartridge system for doweling. The cartridge contains chemicals and additives for doweling. This system is corrosion-proof and requires no welding or grout.

Concrete as a Repair Material

Most seawater is composed of approximately 3.5 percent soluble salts (e.g., chlorides, sulfates) that can cause corrosion of the reinforcing steel and deterioration of concrete. Marine concrete can be grouped into three exposure zones: submerged, splash, and atmospheric. The submerged zone is continuously covered by seawater; the splash zone is subject to continuous wetting/drying and oxygen supply; and the atmospheric zone is above the splash zone and subject to occasional seawater spray.

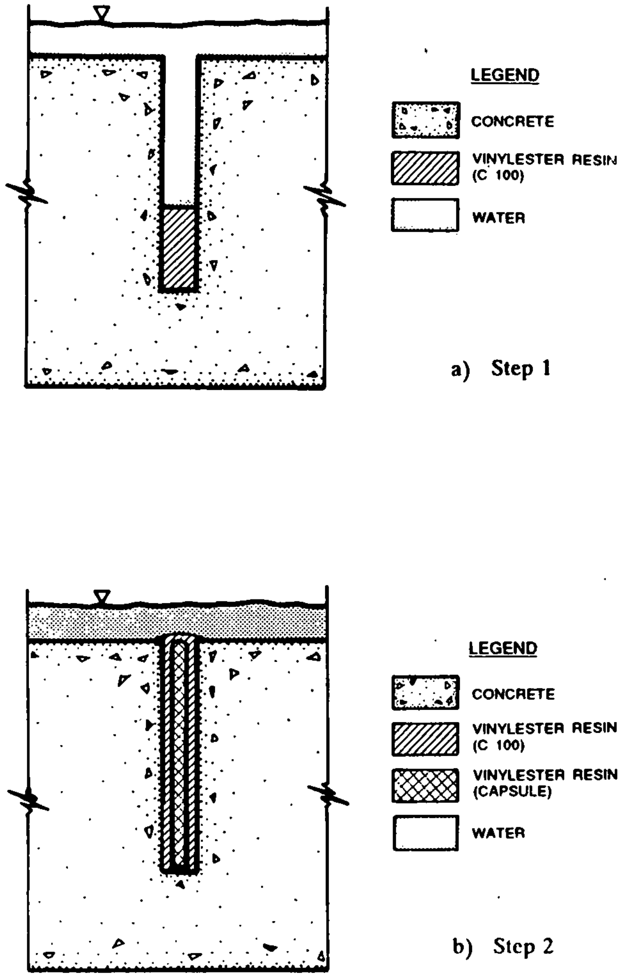


FIGURE 16 Installation procedure for anchor embedment *(25).*

Concrete in the submerged zone is not as vulnerable to reinforcing steel corrosion as concrete in the other two zones, mainly because the oxygen supply is lower. Nevertheless, concrete in all three zones is vulnerable to deterioration. The permeability of concrete, and its potential cracking, are of prime concern in marine applications. Concrete should be crack-free and have very low permeability and sufficient thickness over the reinforcing steel so that the corrosive substances cannot reach the reinforcement and cause problems. Another concern is the washout of fines and cement from the fresh concrete in contact with flowing water. Thus, washout and water entrainment of fresh concrete should be prevented.

The following subsections discuss some important considerations for concrete placed under water.

Water-Cement Ratio

American Concrete Institute (ACI) Standard 318 restricts the water-cement ratio (W/C) to a maximum of 0.40 for corrosion protection of concrete exposed to seawater. Water-reducing admixtures are commonly used to provide workable mixes and enhance cement distribution for low W/C concrete.

Concrete Cover

In the splash zone (i.e., the worst condition), ACI recommends a minimum 6.4 cm (2.5 in.) concrete cover to protect reinforcing steel and 8.9 cm (3.5 in.) cover over post-tensioning ducts. If the concrete cover is increased by 1.3 cm (1/2 in.), ACI allows a 0.45 water-cement ratio.

Cement Content

Increased cement increases strength and reduces permeability of concrete; however, this may be offset by increased shrinkage cracking from additional water requirements and increased thermal stresses. ACI standard 357 recommends a compressive strength of 352 k/cm sq (5,000 psi).

Pozzolans

The addition of a high-quality pozzolan such as silica fume, fly ash, or blast furnace slag to the concrete mix has been demonstrated to decrease permeability and increase resistance to corrosion. Many states, including Florida, are requiring pozzolans for enhanced corrosion protection in harsh environments. Typically, proportions used (by weight of cement) are: 15 percent to 20 percent fly ash, 50 percent to 70 percent slag, or 5 percent to 10 percent condensed silica fume *(22).* When protection from chloride intrusion is required, such as a pile jacket in saltwater, states are beginning to use pozzolan-blended cement.

Antiwashout Admixtures

Antiwashout admixtures are used to minimize washout of fines and cement from concrete in contact with flowing water, prevent segregation of the concrete, reduce bleeding, decrease migration of moisture within the concrete mix, and inhibit water entrainment as the concrete is placed. Antiwashout admixtures are cellulose derivatives that increase water retentivity by binding up the free water in the mix. Antiwashout admixtures are supplied either as a powder or as a liquid. They work by slowing movement of cement and paste within the mix, but maintaining fluidity. These admixtures tend to make the concrete sticky. A water reducer or high-range water reducer may be necessary with antiwashout admixtures to maintain slump. Slumps up to 8 inches are possible. High-range water reducers can entrain excessive air in the range of 9 percent to 14 percent. The use of a non-air-entraining admixture such as tributyl phosphate or octyl alcohol is recommended. Trial batching is recommended for final adjustment of mix properties. It is reported that concrete mixes containing antiwashout admixtures with either silica fume or fly ash can create higher-quality repairs at equal or lower cost than similar concretes made with high-silica fume or high cement contents and no antiwashout admixtures *(26).*

Air-Entraining Admixtures

In areas where cycles of freezing and thawing can be expected, portions of concrete exposed to freezing and thawing should have air-entraining admixtures incorporated into the concrete mix design *(27)*. The air-entraining admixture should be adjusted (increased) when pozzolans, such as fly ash, are used.

Aggregate

The shape of the aggregate used in the underwater mix may be a compromise between workability and strength. The use of round aggregate increases concrete flow in tremie construction where concrete must flow horizontally great distances to fill a large volume *(25)*; however, angular-shaped aggregates produce more strength.

Corrosion Protection

Corrosion protection may be applied directly to the reinforcing steel. Epoxy-coated reinforcement is commonly used in new construction and occasionally in repairs. The experience with epoxy-coated steel has generally been very good; however, recently there have been some problems with corrosion of epoxy-coated steel in harsh marine environments. The problems, first reported by the Florida Department of Transportation (DOT), are associated with damage to the coating and they may be solved by improved quality control of the coating application or of the handling during construction. More recently, corrosion-inhibitor concrete admixtures have been used to protect the reinforcement. Corrosion-inhibitor admixtures may be more practical than epoxy coating for field repair application.

Polymer Repair Materials

The most common polymer material used in bridge repair is epoxy. On nonstructural protective pile jackets polymer grouts or mortars, mixed with sand, are pumped into the annular void inside the fiberglass jackets. When mixed with a selected grading of silica sand or quartz flour, polymers such as epoxy can be placed by hand packing because of their high viscosity. Epoxy grout is abrasion-resistant and chemically inert. Epoxy can flow up to 6.1 m (20 ft) without problems in placement *(20)*. Polymers are sometimes selected instead of cementitious materials for concrete repair because they are tough and abrasion-resistant when placed in thin layers. While failures have been reported due to brittleness and loss of bond, improvements have also been reported. States that have used this repair include Virginia and Washington.

Polymers have the following disadvantages:

- Mixing, handling, and curing are critical to the success of the material.
- Polymer material is more expensive than cement.
- Generally, epoxies will not cure at temperatures below 10°C (50°F) and are difficult to pump, as noted previously.
- Past performance problems include failure due to brittleness, loss of bond, and general lack of compatibility with concrete.

Portland cement concrete combined with a monomer, prepolymer, or a dispersed polymer to form a polymer network can be designed as a concrete repair material for underwater use *(20)*. This material is reported to provide good bond, but has a short set time. It is most advantageous for small repairs by divers.

Forms

Forming materials and techniques have been developed specifically for underwater application. Forms are used to encase damaged concrete or masonry substructure units. Some pile jacketing forms are proprietary and marketed as a repair package. The shape, size, and location of the damaged element will often dictate the forming system used for the repairs. For underwater application, the cost of the forms is less a controlling factor than suitability and ease of erection.

Forming materials such as timber and steel are made rigid with stiffeners and used as flat surfaces. Thin sheets of timber and steel may be shaped to cylindrical surfaces; however, preshaped flexible forms made of cardboard, fiberglass, and plastic are available. Forms are often designed to remain in place and function as part of the final repair. Examples are shown in Figures 17 and 18. Forms may provide abrasion resistance and/or support for the damaged member. Commonly available polyethylene drainage pipe is also used as a form. In some repairs it may be more economical and quicker to encase all piling with a jacketing wall (one concrete placement), rather than jacketing individual piles.

Fabric forms are relatively inexpensive and can be handled easily by a diver. While the appearance of the final repair is

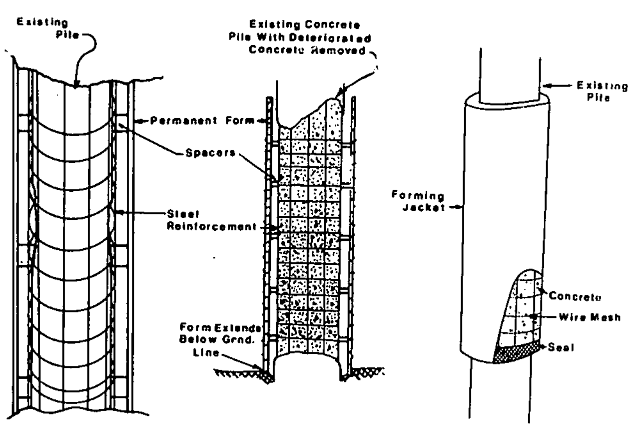
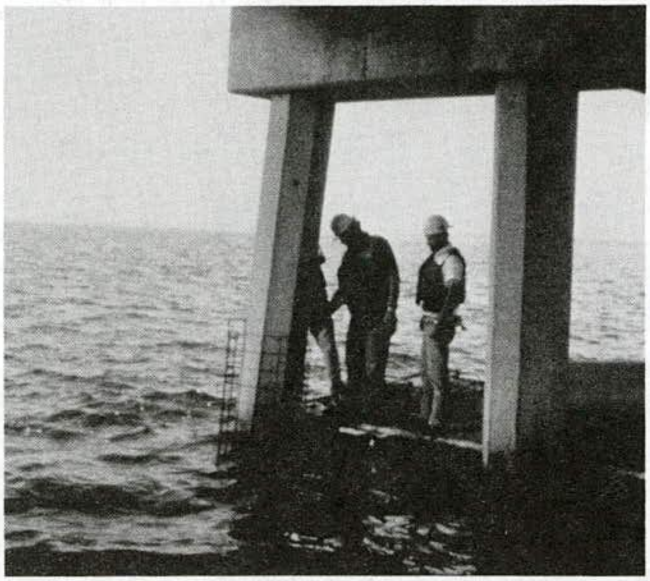


FIGURE 17 Permanent pile jacket forms for concrete piles (after *19*).



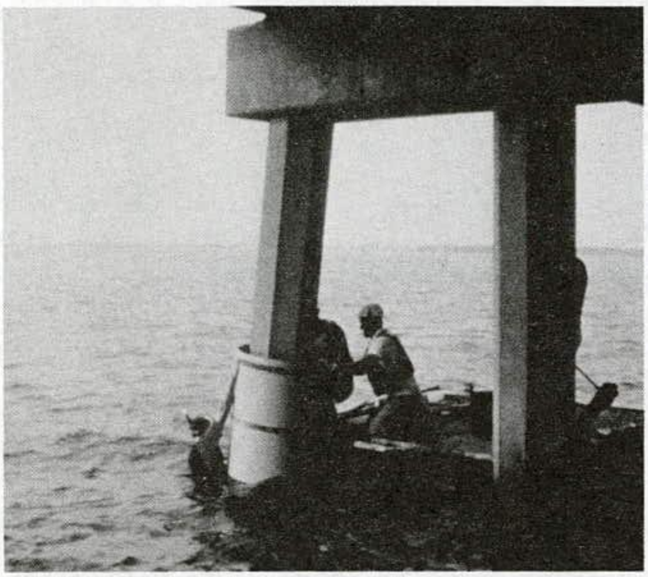


FIGURE 18 Permanent pile jacket forms. (Courtesy: North Carolina DOT).

often irregular in thickness, shape, and texture, this is not a problem when used under water. Fabric forms are available with zippers for ease of installation, with spouts for pumping the repair material into the form, and with pressure seals to hold the material inside the form. This is Louisiana's preferred method of pile repair (Figure 19). While fabric forms are most often used for pile repairs, they are also being used for other repairs, such as to hold pumped concrete under scour-damaged footings (Figure 8).

Some pile jacket repairs consist of a filler/coating material, such as cementitious grout or epoxy, that is pumped into the space between the existing concrete and the form. Bags of dry concrete mix, discussed previously and in the next section, serve as a form for a subfooting repair that is filled with concrete.

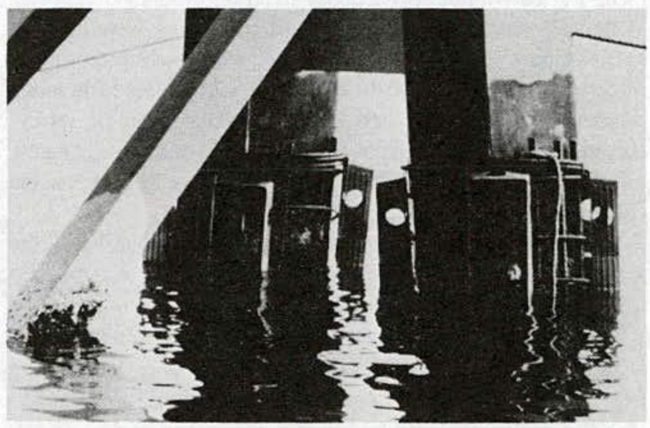
Stay-in-place concrete repair forms such as fabric bags or constrict the stream flow and increase vulnerability to scour or water backup.

Placing Concrete Underwater

While a limited amount of water is needed for hydration of the cement and workability of the concrete, additional water will damage the mix. As the ratio of water to cement is increased, permeability increases and strength decreases. As it falls through the water, conventional concrete dumped with no confinement will lose fine particles, become segregated, or be completely dispursed, depending on the distance and current. Saltwater mixed with the concrete will cause corrosion of the reinforcing steel. Special techniques to protect concrete as it is placed under water will be discussed later in this section. Concrete cures under water with no special treatment because it requires moisture to cure. The following methods of underwater concrete placement are also used to encase or face substructure units originally constructed of other materials, such as masonry.

Bagged Concrete

Concrete placed in bags can be used to repair deteriorated or damaged portions of concrete or masonry substructure ele-



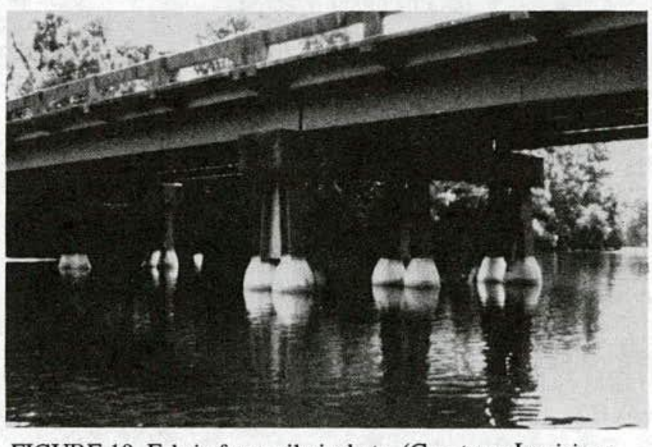


FIGURE 19 Fabric form pile jackets. (Courtesy: Louisiana DOT)

ments under water. Conventional bagged concrete repairs are made with small fabric bags prefilled with dry concrete mix (often only sand and cement are used) and anchored together to form the exterior of the repair. The bags are small enough to be placed in position by hand. The interior portion of the repair is then filled with a tremie concrete or dewatered and filled with concrete. This method of repair is quick and can be performed by small crews with minimal skill and equipment. It is often used when the water is shallow enough not to require diving equipment.

Bagged concrete use increased to take advantage of the durability and high strength of synthetic fibers to produce forms for casting concrete under water. These bags are durable enough to contain pumped concrete for use in marine environments exposed to cyclic changes and to provide sufficient abrasion resistance. The properties of fabric-formed concrete are essentially the same as those of concrete cast in conventional rigid forms with one exception: the water-cement ratio of the concrete can be quite low at the surface since the permeable fabric allows bleedwater to be expelled through these bags. Use of this method was reported in many states, including Georgia, Connecticut, and Virginia.

Figure 20 provides an example of an underwater repair performed at a bridge pier in the state of New York using bagged concrete *(16)*. The underwater deterioration was in the footing where large voids extended under the pier along its face. The deterioration reached a maximum depth of 150 cm (5 ft) and extended about 180 cm (6 ft). Bags were 335 cm (11 ft) long by 150 cm (60 in.) wide, with the volume of the filled bag of about 1.8 cu m (65 cu ft). Construction included removal of the deteriorated concrete, installation of epoxy-coated dowels, placement of fabric bags, pumping of concrete into bags, and pumping of grout to fill the gap between the existing concrete and fabric-formed concrete.

Bagged concrete was selected as the best alternative for the following reasons:

- The bag dimensions are not limited to a certain size.
- It is well suited to a small crew and does not require heavy equipment or handling of forms.
- Its cost is relatively low.
- It produces durable repair material.

Prepacked Aggregate Concrete

In this method, after the area to be repaired is properly prepared and forms are in place, graded course aggregate is placed in the form. A cement-sand grout is then injected into the area containing the aggregate, displacing the water and filling the voids between the aggregate. This technique is particularly effective for underwater repairs where it would be difficult to place premixed concrete because of forming restrictions. Agencies reporting its use include Florida DOT and the U.S. Army Corps of Engineers.

The same strength, thermal characteristics, and modulus of elasticity can be achieved with prepackaged aggregate concrete as with concrete mixed conventionally. (A discussion of

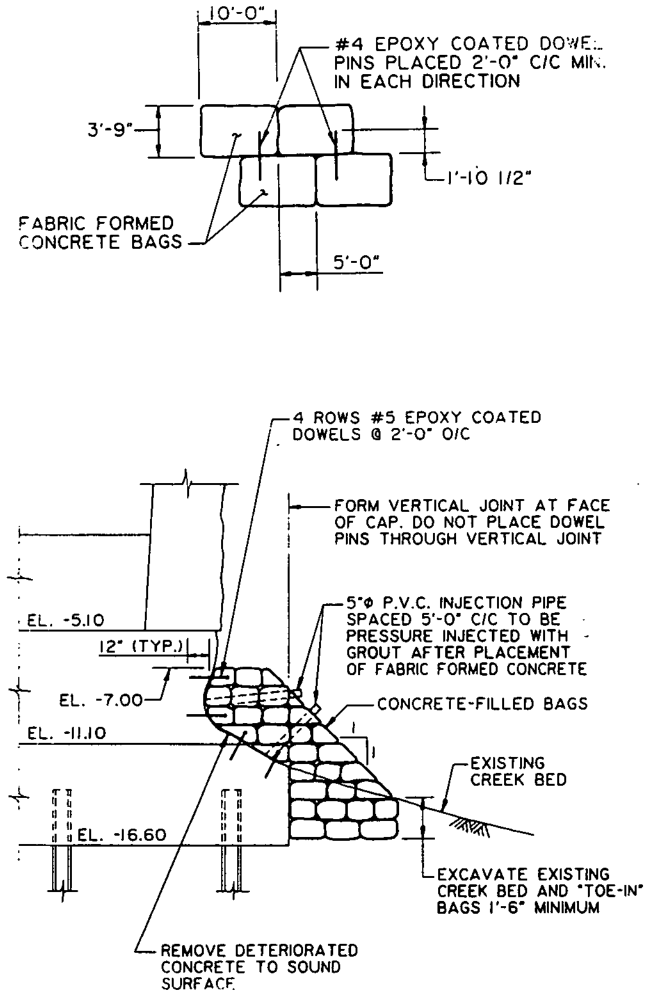


FIGURE 20 Fabric-formed concrete bags *(16)*.

prepacked aggregate concrete is provided in Chapter Two.) Complete filling of voids is sometimes difficult. Generally, an expansive grout with a fairly high water-cement ratio is used to provide fluidity. When antiwashout admixtures are added to the grout, forms do not have to be as watertight *(20)*.

Mix characteristics of prepacked aggregate concrete are slightly different from conventional concrete. The proportion of aggregate is higher than that in conventional concrete. All aggregate particles are in point-to-point contact to reduce drying shrinkage. Drying shrinkage of prepacked aggregate concrete can be at least 50 percent that of conventional concrete. Coarse aggregate should not be smaller than 0.5 in., and it should not be larger than one-third the minimum thickness of the repair concrete. The grout contains cement, usually a pozzolan such as fly ash, fine aggregate, and a grout fluidifier. Enough water is added to produce a slurry with the consistency of thick pea soup. Fine aggregate (sand) is generally graded to a fineness modulus of 1.3 to 2.1. This reduces the bleeding of the grout and prevents bleedwater from collecting under the coarse aggregate. Fly ash improves the impermeability of the mix and retards setting time. The grout fluidifier keeps the water-cement ratio low (usually 0.42 to 0.50). In addition, the fluidifier produces a small amount of expansion to prevent settlement and any water from collecting under the coarse aggregate *(29)*.

Tremie

Tremie concrete is placed under water through a gravity-filled pipe, which is called a tremie. The underwater portion of the pipe is kept full of plastic concrete at all times during the placement. Concrete placement starts at the lowest point and displaces the water as it fills the area. A mound of concrete is built up at the beginning of the placement. The bottom of the tremie must stay embedded in this mound throughout the placement to seal the tremie. The concrete is forced into the occupied area by gravity from the weight of the material in the tremie. The thickness of placement is limited to the depth of the mound of concrete. While most tremie concrete is placed without a diver, a diver is helpful in keeping the pipe submerged.

Tremie concrete is best suited for larger-volume repairs where there is no need to relocate the tremie frequently or for deep placements where it would not be practical to pump the concrete. Tremie concrete placement is simple with little equipment to malfunction. It is the most common method of placing concrete under water. States that reported its use for concrete repair include Virginia and North Carolina.

While no information was available on states using anything other than the conventional straight pipe, advances in tremie pipe design include the hydro-valve, a Dutch-patented device that uses a flexible hose that collapses under hydrostatic pressure to pass the concrete to underwater deposition in small amounts. Segregation is minimized by the slow movement of concrete down the hose. This equipment is shown in Figure 21. Figure 22 shows a similar double-tube tremie method. The steel tube that encloses the collapsible tube has slits in the side that allow water to enter and flatten the collapsible tube to squeeze the concrete through the tube.

Pumped Concrete

Pumped concrete is placed under water using the same equipment as above water. It is placed in a similar manner as tremie concrete except that the problem of getting the concrete into the tremie is eliminated. A direct transfer of concrete is provided, and the pump provides the force in moving the concrete. Unlike tremie, relocation is not a problem. Like tremie, the placement must start at the bottom and the hose or pipe must be submerged in the fresh concrete during placement but there is less need to lift the pipe. A handle on the end of the pipe will help the diver position it. Devices such as the A-Betong-Sabema system shown in Figure 23 attach to the end of the pump line and provide a pneumatic valve that terminates the flow of concrete and prevents water entering the hose when it is not submerged in concrete. Another type of valve,

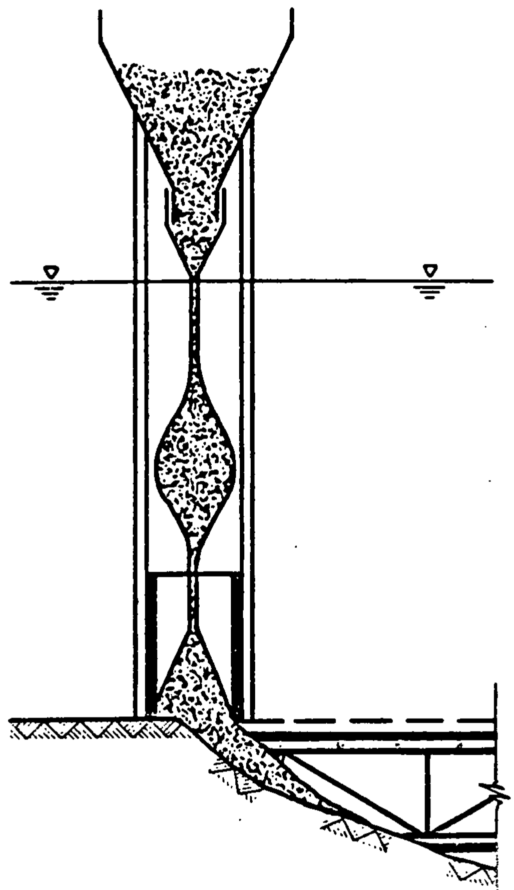


FIGURE 21 Dutch patented hydro-valve method *(20)*

which looks like a duck's bill, has only one moving part. The valve is 46 cm (18 in.) long and fits over the end of the pump line. The valve does not require control from the surface and the placing operation does not require the end of the hose to be immersed in the placed concrete. Information on the use of these devices by U.S. agencies was not available.

Free Dump

In recent years, antiwashout concrete admixtures have been developed to minimize the loss of fines and reduce segregation from concrete placed under water. This admixture makes the concrete mix more cohesive, yet sufficiently flowable for placement. However, it loses some self-leveling properties and tends to stick to equipment. Evidence of this method's success to date is somewhat limited, consisting of small quantities mixed near the site. Therefore, it should be specified with caution when high-quality concrete is not a primary consideration, and used only when there is minimal water current and drop distance; say 1 m (3 ft)±.

Hand-Placed Concrete

Hand-placed concrete is mortar or concrete placed by hand by a diver and packed or rammed for consolidation. This

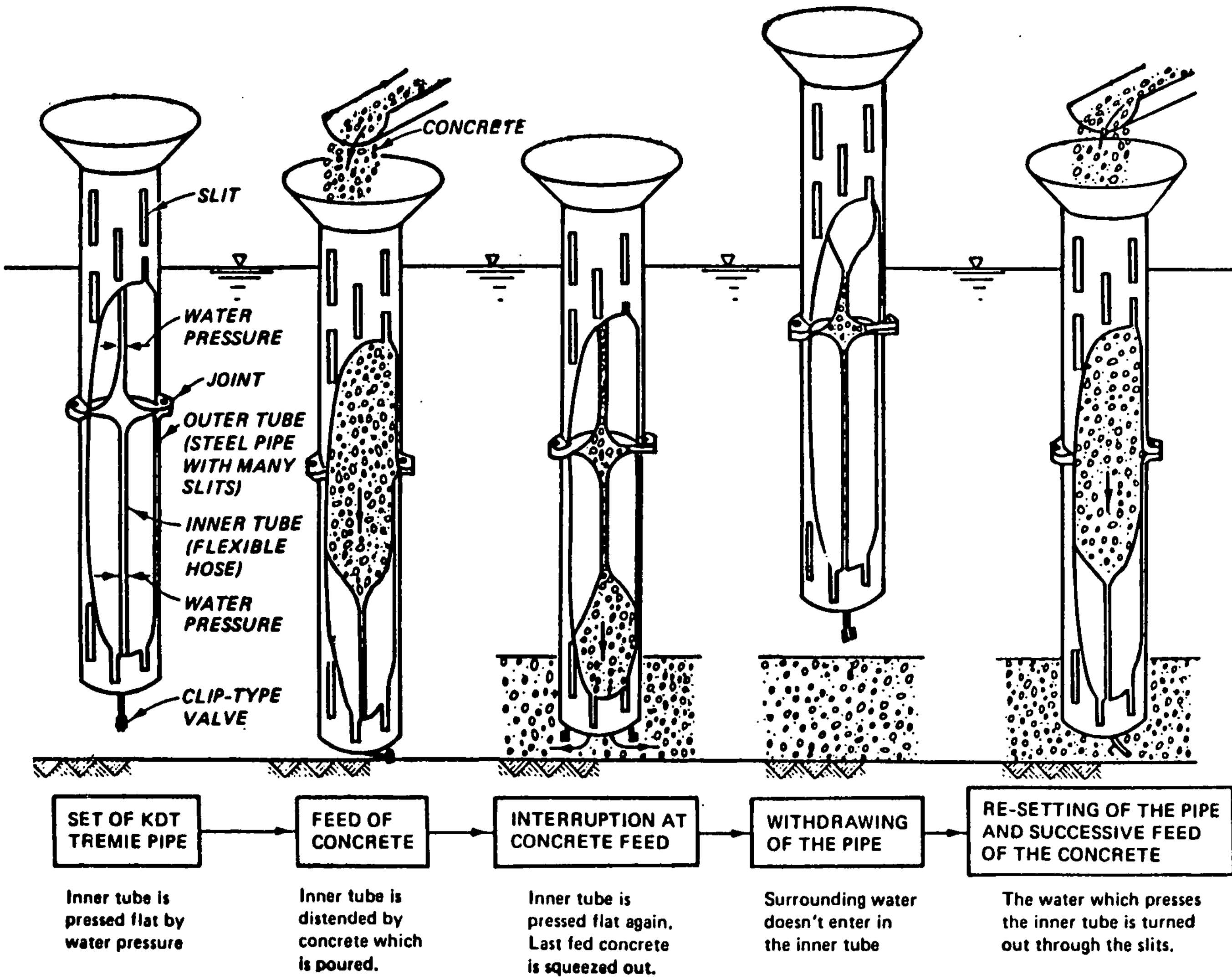


FIGURE 22 Kajima double-tube tremie method *(20)*.

method is best suited for isolated repair sites. Use of accelerators, antiwashout admixtures, and a low water-cement ratio is recommended *(17, 18)*. The method is best suited for deep and narrow cavities. The concrete can be delivered to the diver by a bucket on a rope conveyor assembly or can be dropped to the diver in baseball-sized quantities through a pipe with holes cut in the sides to allow displaced water to escape, easing the descent of the concrete. Small quantities needed for patching can also be delivered to the diver in plastic bags.

Hand-placed concrete offers the following advantages:

- It is a low-cost repair method requiring little equipment.
- It can be used on vertical surfaces.
- It can be formulated to have little shrinkage because it can have a low water-cement ratio.

Concrete Pile Repairs

The survey conducted for this synthesis indicated that piles are the most common bridge elements repaired underwater. Iowa, Maryland, Massachusetts, and Ohio are a few of the states reporting pile repairs. Deteriorated reinforced-concrete and prestressed-concrete piles can be encased in a concrete jacket. Deteriorated concrete is removed before the jacket is placed. One method of accomplishing this under water is by using high-pressure water jets. Welded wire fabric or a reinforcement cage is wrapped around the repair area. Encasement will compensate for the cross-sectional loss and strengthen the pile. A reinforcing steel cage or reinforcing wire is placed around the pile before forms are placed. The reinforcement is usually epoxy-coated for protection against corrosion. Standoffs are placed on the reinforcement before it is drawn tight to the pile.

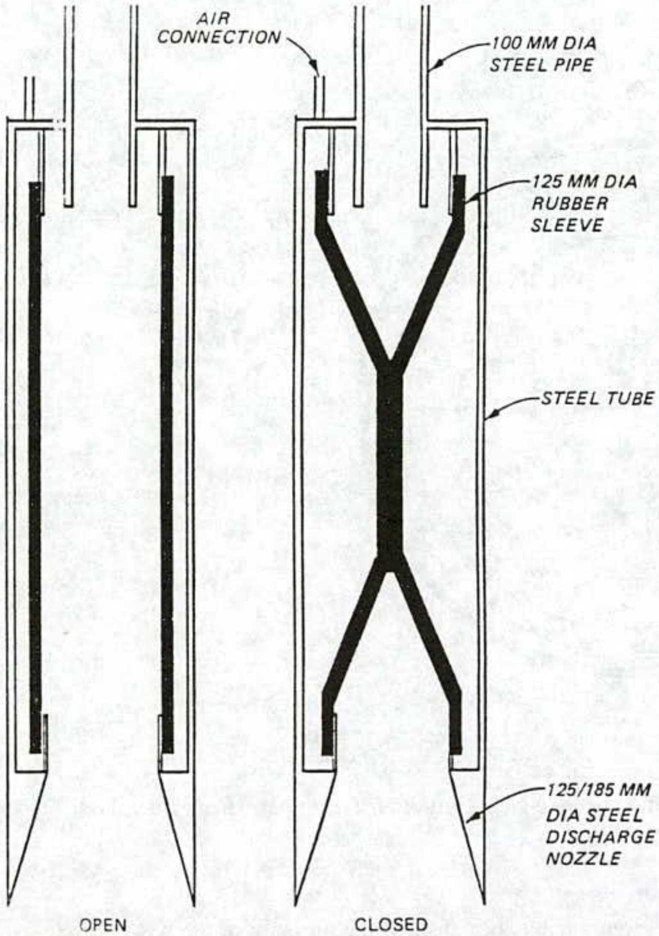


FIGURE 23 A-Betong-Sabema valve *(20)*.

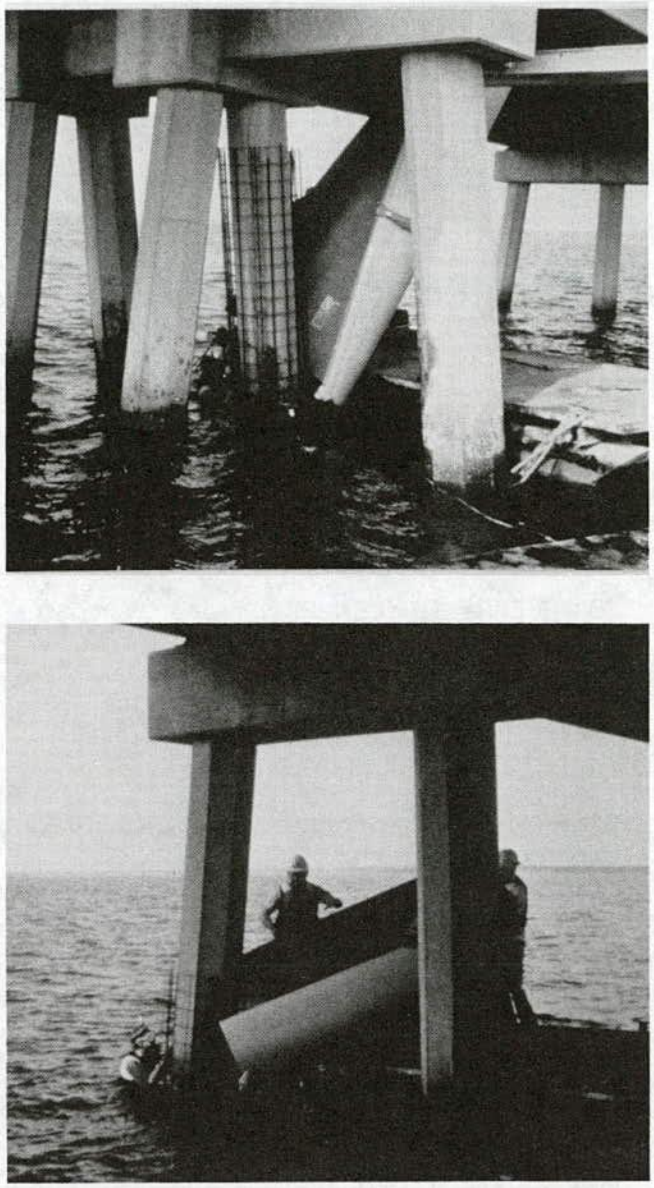


FIGURE 24 Pile jackets being installed. (Courtesy: North Carolina DOT)

Rigid or flexible forms are then installed and sealed. Concrete is placed in the forms either by tremie or pumping under water. After the concrete is placed, the forms are either left in place permanently for further protection of the pile, or removed when the concrete is cured.

When a pile jacket repair is intended to perform only as a protective coating, a cementitious grout or epoxy resin is pumped into the annular opening between the existing concrete and the form, and the use of reinforcement is eliminated.

A fiberglass form is often used to construct pile jackets. The form has a vertical seam, so that it can be fitted around the pile. Then, top and bottom centering devices and a bottom seal are placed. The jacket should extend approximately 2 feet beyond the damaged area at each end of the pile to account for any concrete segregation near the bottom or loose materials at the top of the new concrete. The form is secured in place with bolted bands, tightened to ensure full enclosure. If the length of the repair exceeds the length of the form, the pile may be repaired in two lifts. If the damage extends below the mudline, trenches are dug at the bottom to extend the repair into the mud zone. Figure 24 shows the use of fiberglass forms for pile jackets by the North Carolina DOT.

On a similar repair in California, a 2-in.-diameter pumpline was used to deliver concrete from a ready-mix truck. The bottom end of the pumpline was connected to a 2-in.-diameter tremie pipe. Unlike large conventional tremie placement, sealing of the 2-in.-diameter tremie pipe prior to discharging concrete under water was difficult. It was concluded that greater concrete quality may be obtained by using an effective start-up valve at the bottom of the small-diameter tremie pipe so that water inside the submerged pipe can be removed prior to concrete placement. It was also concluded that highly flowable concrete with an initial slump of approximately 22 cm (9 in.) should be used to ensure proper filling of small and congested repair areas underwater. Throughout concrete placement, tightness of the bottom seal and longitudinal joint along the jacket was monitored by divers *(30)*.

Figure 25 shows a proposed City of New York repair of prestressed concrete piles of the Rikers Island Bridge. The piles for the piers are 138-mm- (54-in.-) diameter prestressed

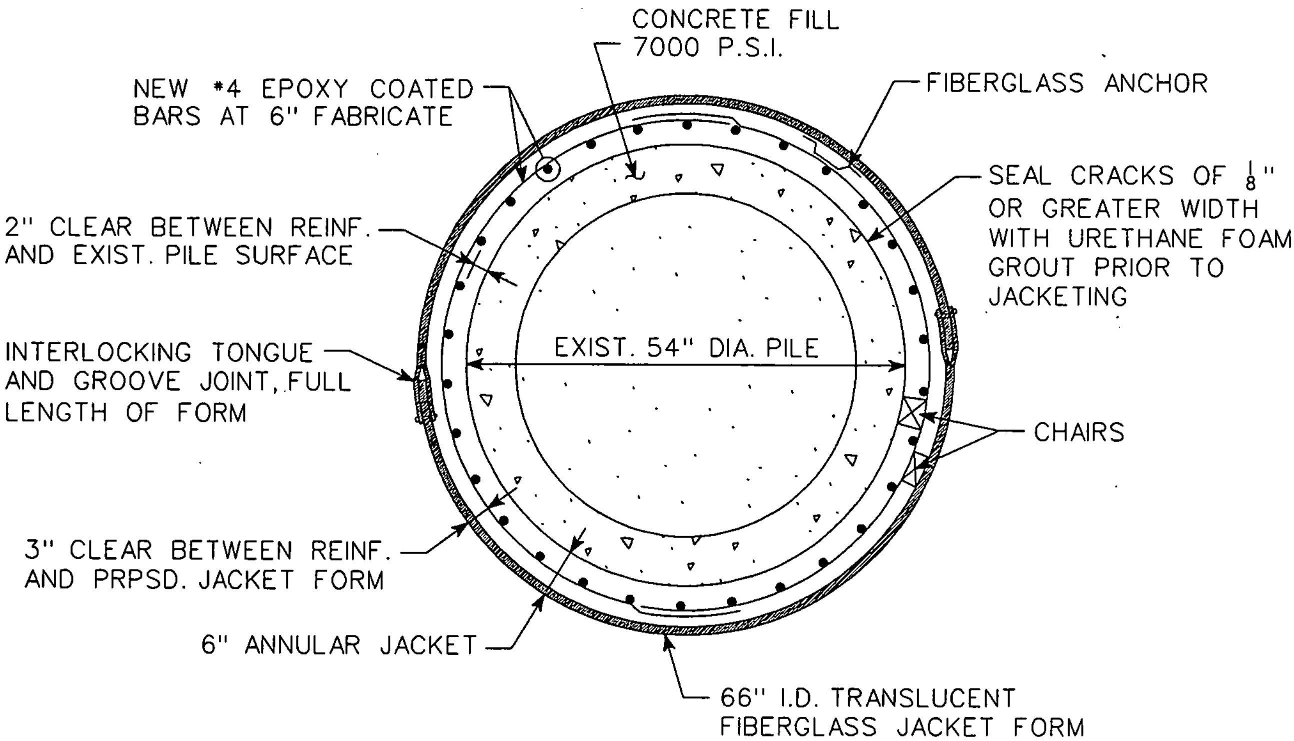


FIGURE 25 Hollow prestressed concrete pile repaired with tubular concrete jacket with translucent permanent fiberglass form *(after 25)*.

hollow concrete piles with a 5-in. wall thickness. The piles vary in length from 16 m (54 ft) to 38 m (118 ft). Many piles have vertical cracks over the prestressing strands. Rusting of the prestressing strands could be easily observed at large cracks. The loss of prestress force is not a concern in the piles, since they are already driven. However, the loss of section and discontinuity of the ring compression area of the concrete section to carry vertical loads is a major concern.

The planned method of repair is to clean the piles, seal all the cracks, and cast a structural concrete jacket around each pile. The jacket will provide structural confinement to the pile and prevent further separation of the concrete segments created by the cracks. Extension of the jacket beyond the terminus of the cracks would serve as a load transfer device in case the original pile fails. In addition, the jacket provides protection against further deterioration. To achieve the desired repair, a method of providing a permanent fiberglass form that would protect the pile surface and contain the reinforced concrete structural jacket was designed. The type of fiberglass form was selected because it could be installed easily by divers. Experience from earlier designs of fiberglass forms indicated several potential erection problems with larger forms—misalignment of lap-type joints, and inadequate fasteners that were unable to withstand the pressure of the wet concrete, resulting in loss of the permanent form. The design of the newer forms was aimed at correcting those potential problems.

The final design incorporates a 15-cm- (6-in.-) thick reinforced concrete jacket with a strength of 480 kg/cm sq (7,000 psi). Reinforcement includes both vertical and horizontal epoxy-coated bars. The permanent form for the jacket is a 163-cm- (66-in.-) diameter translucent fiberglass form coated to provide ultraviolet protection and to match the color of the existing concrete. The form is to be constructed in two halves, each with a matchmarked tongue-and-groove joint. In addition, the form is to be banded with stainless steel bands at 1.2 meter (4 ft) spacing vertically. This will brace the form to endure the pressure of the wet concrete and prevent loss of the form due to possible fastener failure in tongue-and-groove joints.

The planned method of concrete placement requires the use of special bands with five pumping ports spaced around the perimeter of the jacket. The bands are to be spaced 1.5 m (5 ft) vertically. Concrete placement is to begin at the bottom, with concrete pumped in 1.5 m (5 ft) lifts. Concrete will be delivered by a manifold supplying five pump hoses to each of the five ports in the band *(31)*.

CHAPTER FOUR

STEEL ELEMENTS

Steel substructure elements are subject to corrosion. An inspection of 142 underwater steel bridge pile bents in Mississippi revealed that approximately 20 percent were deteriorated *(32)*. In all cases the main culprit was corrosion of steel. Steel members located above the waterline, but within the splash zone, can corrode because of the available oxygen. Their corrosion is accelerated by saltwater and the effects of wetting and drying cycles. Submerged steel members can corrode because of the concentration of dissolved oxygen, electrical conductivity under water, and because of contact with chemical compounds. Corrosion of steel members located below the mudline can result from electrical conductivity and chemical compounds. While heavy marine growth tends to mitigate corrosion, the presence of limited growth may increase the amount of pitting.

PROTECTION

Coatings

Coatings protect the steel from corrosion by isolating the steel surface from the corrosive environment. The steel surface is usually prepared by abrasive blasting, water blasting, or wire brushing. Coatings can be applied with a putty knife, brush, roller, or by hand/glove. The survey results did not indicate whether states apply protective coatings to steel members at or below the waterline. The conclusions of a study of 11 coatings for underwater application by the U.S. Army Corps of Engineers in 1988 are listed below:

- Commercially sold products for coating immersed steel surfaces are either the putty-like, splash-zone compounds developed in the 1960s, or the thinner, brushable products developed in recent years.
- Commercially available splash-zone compounds are generally applied satisfactorily to give thick (e.g., 188 mil) protective coatings, but are slow and expensive to apply. Also, they cannot be applied in water below 15°C (60°F).
- Commercially available products for application by brush under water are usually much more difficult to apply than indicated in the suppliers' advertising. Only two products were easily applied by brush both in the laboratory and by a diver.
- Abrasive blasting is the recommended method of surface preparation for steel to be coated underwater to achieve required bonding strength.
- It may be possible to select a satisfactory product by specifying a minimum pull (bonding) strength rather than naming a proprietary product. Based on the tests, adhesion values (to sand-blasted steel in saltwater) of 40 kg/cm^2 for a brushable product and 20 kg/cm^2 for a splash-zone compound are recommended *(33)*.

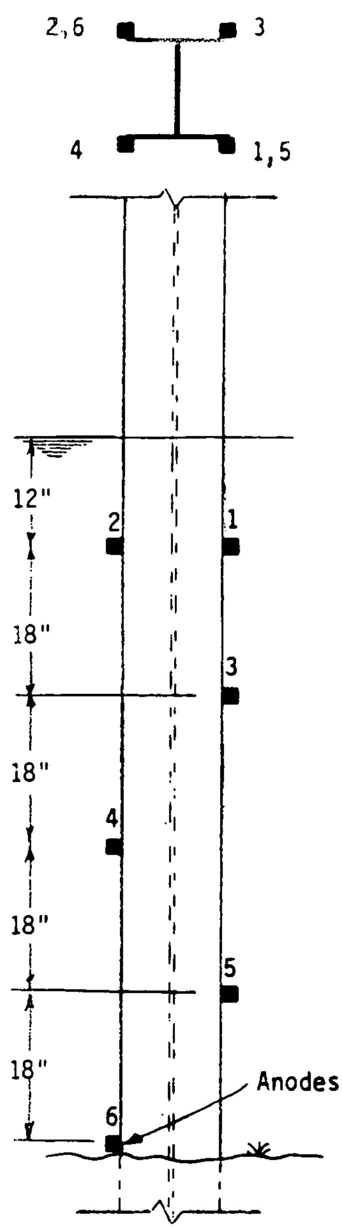


FIGURE 26 Passive cathodic protection for steel piles using small sacrificial zinc anodes *(10)*.

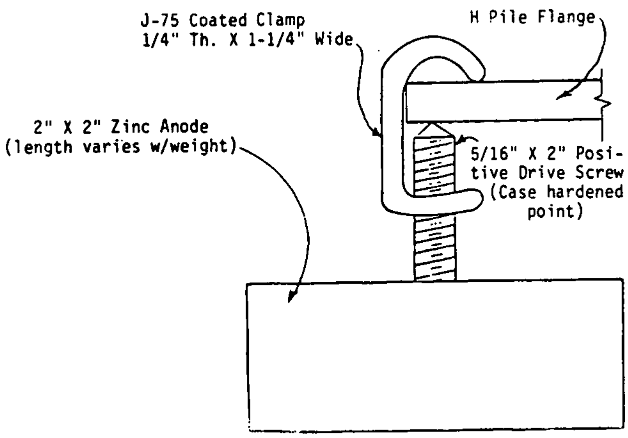


FIGURE 27 Passive cathodic protection for steel piles using zinc anodes—attachment details *(10)*.

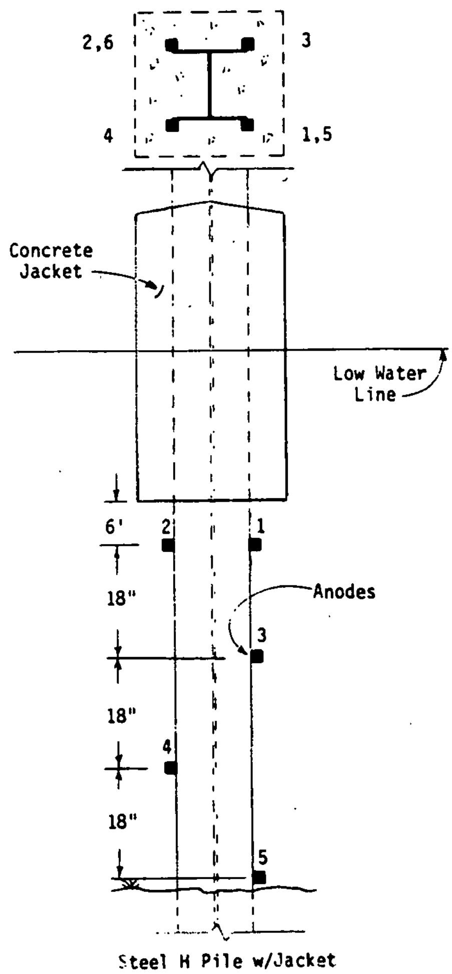


FIGURE 28 Passive cathodic protection for steel piles using small sacrificial zinc anode—pile partially jacketed *(10)*.

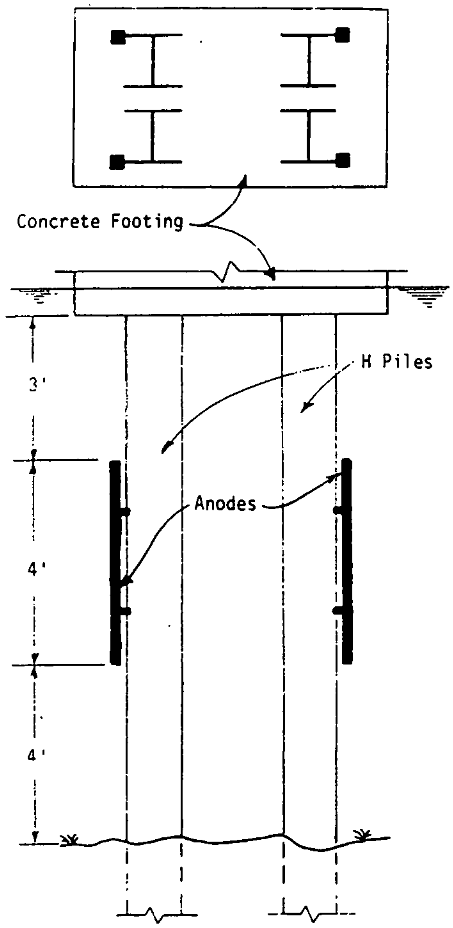


FIGURE 29 Passive cathodic protection using large sacrificial zinc anodes *(10)*.

Cathodic Protection

Cathodic protection is used by oil companies and ship owners to protect steel from corrosion in seawater. In new structures corrosion can be prevented, and in existing structures corrosion of the steel can be halted. Both sacrificial anode and impressed current cathodic protection can be used. However, impressed current systems are difficult to use underwater because water is an electrically conductive medium and the components of an impressed current system require considerable inspection and maintenance in this environment. A relatively inexpensive method used by Florida for the attachment of small sacrificial zinc anodes to steel H piles below water is shown in Figures 26 and 27. In this method, two anodes are placed on opposite flanges 30 cm (12 in.) below the waterline, and alternate anodes are placed on each flange every 45 cm (18 in.) to the mudline. Figure 28 shows the same cathodic protection method applied to a steel pile with a partial concrete jacket in the splash zone. When the steel pile is not totally jacketed, the potential for accelerated corrosion exists in the uncovered zone of the pile. Cathodic protection of the uncovered zone of the pile will prevent that problem. In Figures 28 and 29, sacrificial anode cathodic protection is accomplished through use of large zinc or aluminum anodes. Figure 29 shows the same method as Figure 30, except that the cathodic protection is applied to partially jacketed steel H piles. Large anodes are attached to the flanges of steel piles *(10)*.

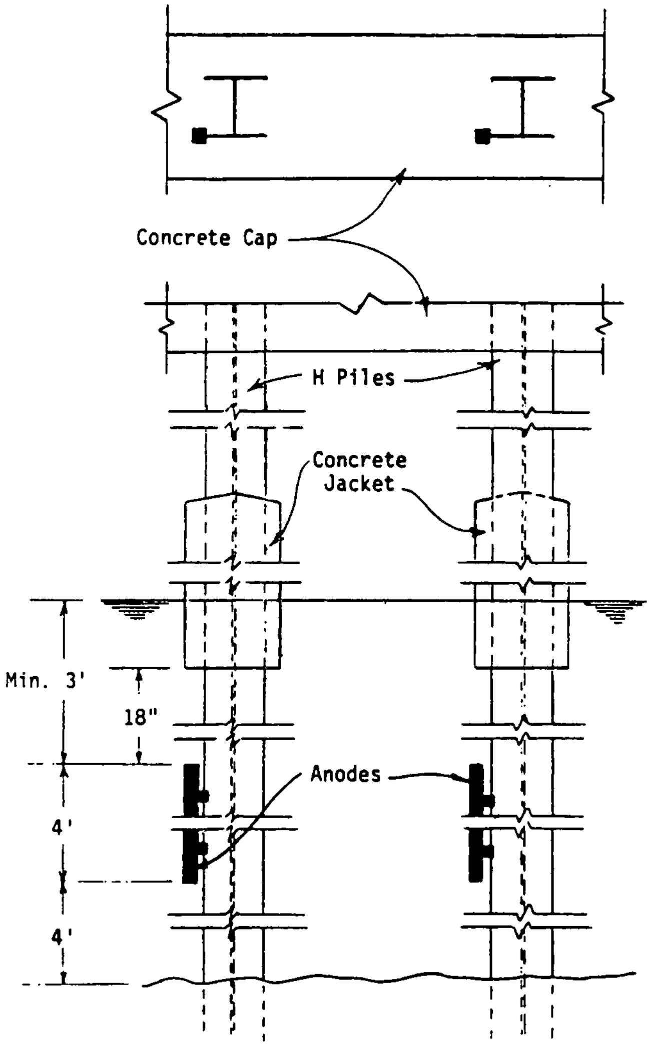


FIGURE 30 Passive cathodic protection for steel piles using large sacrificial zinc anodes—pile partially jacketed *(10)*.

MAINTENANCE AND REPAIR

When corrosion of a steel pile is not extensive and the section loss does not impair the structural function of the pile, the steel surface can be cleaned and protected against further corrosion through application of a coating or cathodic protection. Steel piles are cleaned by removing marine growth and corrosion by hand scraping, grinding with hydraulic tools, or by a high-pressure water jet system. When the loss of section impairs the structural function of the pile, repairs should be undertaken to strengthen it.

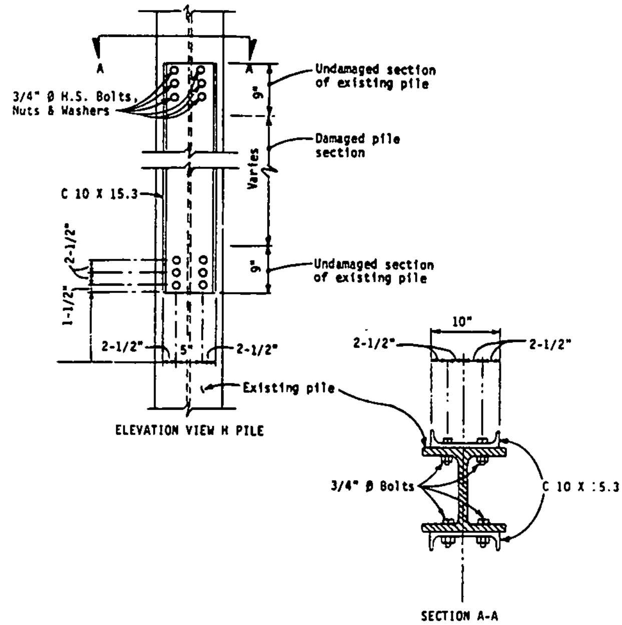


FIGURE 31 Steel pile reinforcement *(10)*.

Splicing New Steel

For severely corroded steel piles, new steel sections may be spliced onto the pile to restore strength. Figure 31 shows a method of splicing a channel to a steel H-pile. Note that the channel runs past the deteriorated steel area and is fastened to the sound steel area. Figure 31 shows bolt fasteners; however, welding can also be used. It is important to determine the type of steel in the original member. Fasteners can be subject to galvanic corrosion in the marine environment when the composition of the fastener metal is different from that of the steel pile. Thus, the fastener should be selected so that it will be galvanically protected by the steel pile or the splice plate. *Guidelines for Successful Use of Marine Fasteners (34)* provides details on corrosion of fasteners and their base metal compatibility. Arc welding has been performed successfully in underwater construction; however, lower strength and ductility should be expected of underwater welds than similar welds made in air. Reductions of 80 percent in strength and 50 percent in ductility have been reported *(10)* due to the quenching action of the water.

Pile Jacketing

Jacketing of steel piles is basically the same as described previously for concrete piles. Pennsylvania, New Hampshire, and Maryland reported steel pile jacketing. Both flexible and rigid forms can be used. Often fiberglass and plastic forms are used to ease erection in underwater applications. First, all steel is cleaned to remove marine growth and corrosion. Next, stands-offs are placed on the pile flanges before the forms are installed and concrete is placed. Figure 32 shows stand-offs.

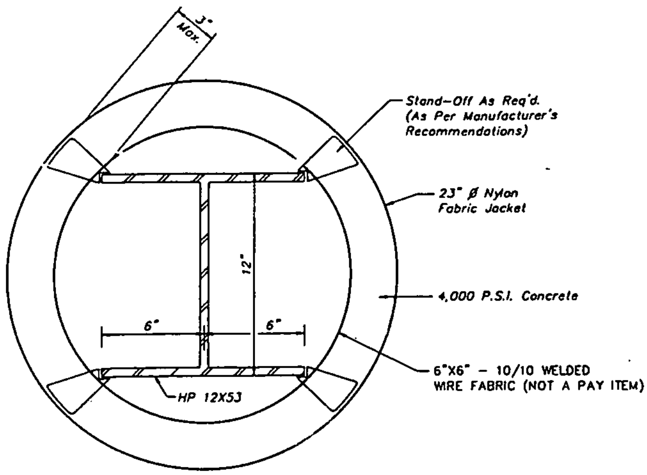


FIGURE 32 Steel pile concrete jackets. (From Mississippi DOT plan).

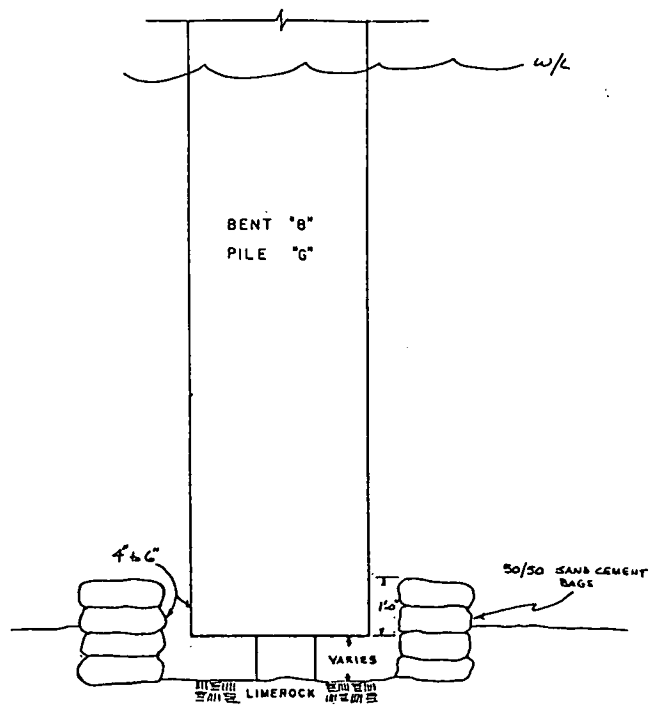


FIGURE 34 Scour repair of jacketed piles using sand-cement bags. (From Mississippi DOT plan).

inside a flexible form welded wire fabric is typically used to reinforce the concrete against cracking.

Concrete jackets can accelerate corrosion on a steel pile when both concrete and water are in contact with the steel. A corrosion cell will develop either below the bottom of jacket or above the top of jacket. The Mississippi study (32) reported that concrete encasement around the steel piles usually did not extend to the mudline and, due to the fluctuation of waterlines, the waterline usually extended above the top of the concrete encasement. Most of the corrosion problems occurred near the top or bottom of the concrete encasement. For these reasons, concrete jackets should be extended at least 60 cm (2 ft) into the mudline and 60 cm (2 ft) above the high waterline. In Figure 33, partially encased steel piles are corrected by removing the existing concrete encasement above the waterline, excavating around the piles to below the mudline, and encasing the waterline. The new encasement overlaps the existing encasement a minimum of 15 cm (6 in.).

When concrete jackets extend into the mudline, some type of protection against scour, as shown in Figures 33 and 34, may be required. In Figure 33, the area around the pile is back-filled with the existing material and riprap. In Figure 34, the excavated area around the pile is encircled with sand-cement bags and filled with concrete.

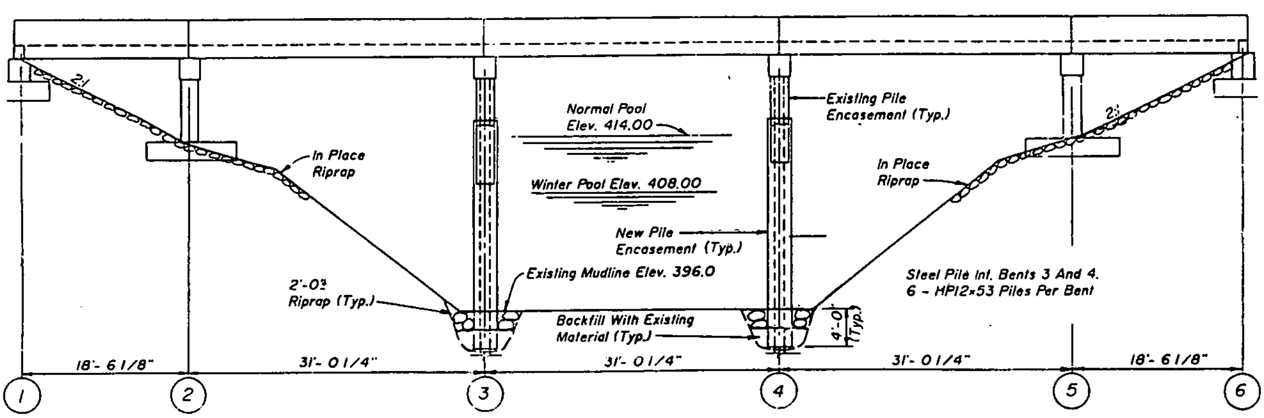


FIGURE 33 Scour repair of jacketed piles using riprap. (From Mississippi DOT plan).

CHAPTER FIVE

TIMBER ELEMENTS

Wood members can rot through fungal processes and can be consumed by marine organisms. Submerged timbers can deteriorate because of marine borer attack. Marine borers encountered in U.S. waters are either surface borers or internal borers that tunnel into the member. No untreated wood is immune to marine-borer attack.

PROTECTION

Timber used in bridge construction is normally treated with an oil type preservative such as creosote, pentachlorophenol (penta), or copper naphthenate. This treatment is effective in preventing decay associated with moisture and insect intrusion. Since the treatment does not penetrate the member, additional protection is needed at locations where the member is cut or holes are drilled. A protective covering should be added in the field when untreated portions of the timber are exposed.

Existing timber piles may be protected against abrasion, impact, and marine-borer attack by a protective jacket. The jacket must fit tightly to be effective against marine borers. Both plastic and metallic jackets have been used. Plastic jackets, such as PVC, are recommended due to their lower cost and ease of installation. However, installation of a plastic jacket is not recommended where timber piling is subject to impact and abrasion. A fiberglass or steel jacket would provide more protection against impact or abrasion; however, they may not be cost-effective. Another consideration is how the condition of the timber will be monitored beneath the jacket.

MAINTENANCE AND REPAIR

Once wood decay has begun, it tends to grow exponentially *(32)*. Certain natural processes, such as a decrease in oxygen, can mitigate the decay; however, this is very difficult to accomplish when the pile is constantly exposed to water. Procedures such as jacket installation can repair damage due to abrasion or marine borers. Borer-damaged piles can also be repaired by placing a fill around the damaged area. A suitable retainer to hold the fill in place should be constructed. Riprap may also reduce the oxygen content of the water and arrest the decay. The literature also identified epoxy injection to fill relatively small decay voids in the pile. Maintenance is usually too late when a reduction of 10 to 15 percent in the cross-sectional area has occurred *(10)*. In that case, repair or replacement of the pile should be considered.

Replacement

The most common method of addressing a damaged timber member is removal and replacement of the entire member. This could involve replacement of a timber beam, cap, column, or pile. Agencies report that properly treated, good quality timber replacement members are becoming increasingly expensive and difficult to obtain.

Piles are the most common type of timber bridge member used under water. States such as North Carolina, Louisiana, Mississippi, and Washington routinely have their bridge crews replace deteriorated timber piles with new ones. Replacement of a pile rarely requires that the work be performed under water. Piles are driven from above the water adjacent to the damaged pile, which is normally left in place. Portions of the deck may be removed to drive the pile at the required location. Bents are also added or supplemented using this procedure.

Repair

Often the pile damage is restricted to the wet-dry area near the waterline. Less expensive, more temporary repairs may involve strength restoration of the section, or cutting out the damaged area and replacing it with a sound section. Strength restoration is usually accomplished by concrete jacketing. Jackets are cast in place around the damaged area using various forming materials including old 190-L (50-gal) steel drums. Bolted-steel jackets may also be used for timber pile repairs. Removal and replacement of the damaged area has been accomplished by pile stubbing and pile posting.

Jacketing

Reinforced concrete jackets are typically used to strengthen deteriorated timber piling sections. A jacket-type form is wrapped around the length of the damaged area. The form is usually made of fiber-reinforced plastic or fabric. Reinforcing steel is placed around the pile in the form and concrete is pumped into the form from the bottom (Figure 35). North Carolina reported that, in cases where it does not result in an unacceptable opening, encasing all piling with a cast-in-place concrete wall may be less expensive than encasing a few individual pilings.

Prefabricated concrete has also been used to jacket deteriorated timber piles. First, prefabricated half-cylinders are

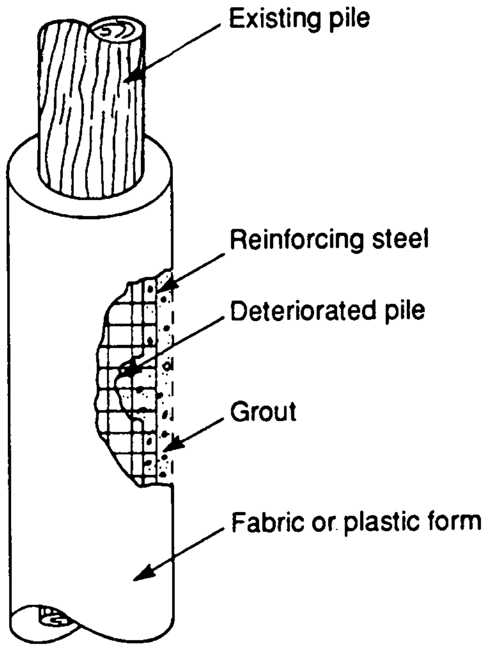


FIGURE 35 Concrete jacketing of timber piles *(35)*.

placed around the pile above the waterline. Next, side joints are shotcreted and the unit lowered into the water. A second section is placed on the first section and the process is continued until a completed encasement is jetted several feet below the mudline. The annular space is then filled with concrete grout *(10)*. This procedure can be adapted to jacket deteriorated timber piles with custom-fitted steel cylinders, which may be galvanized. In that case the joints can be welded and the annular space filled with injected epoxy.

Stubbing

This procedure consists of cutting out the deteriorated section of the pile and replacing it with reinforced concrete. If deterioration extends to the pile cap, then the entire upper section is removed and a temporary shoring may be necessary. Chainsaws are available that can be used under water. After the deteriorated section is removed, a pin is driven into the exposed sound stump and a flexible form housing reinforcing bars is attached to the stump. The pin provides integrity between the wood and concrete sections. Concrete is pumped into the form and allowed to harden before the loads are transmitted.

Posting/Splicing

Similar to stubbing, posting involves cutting out the deteriorated section and replacing it with a new section, except that the new section is treated wood instead of reinforced concrete. Agencies have performed many different versions of this repair, some more refined than others. Since the wood treatment does not penetrate into the center of a timber member, it is important that cut ends be protected. A temporary shoring may be required if the cap cannot transmit the loads to adjacent piles. If several piles are damaged, the entire row may be cut off at the same height and a horizontal sill added. New columns are placed on the sill above the piles and the cap is installed in its original position. Buckling is always a concern when piles or columns are spliced. Various methods have been used to reinforce the splice including internal pins, timber scabs, metal straps, and casting the joint in concrete.

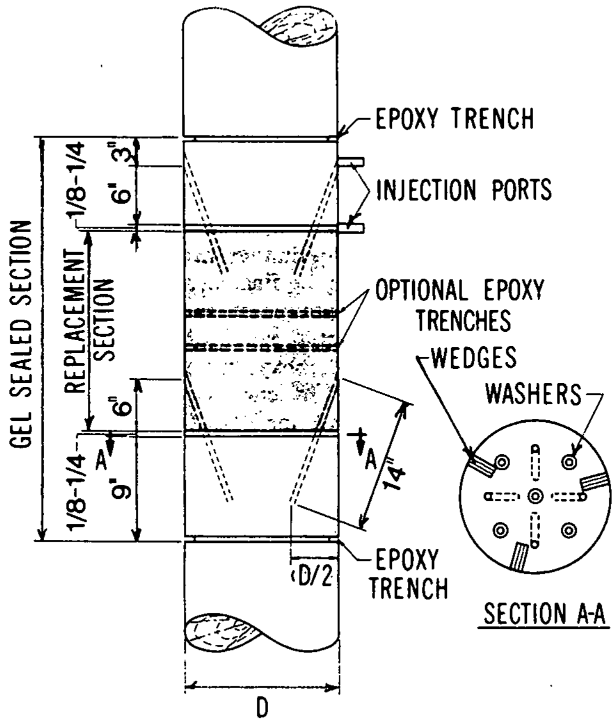


FIGURE 36 Posting a deteriorated timber pile *(35)*.

An example of posting is shown in Figure 36. This procedure was primarily developed for repair of timber piles above water *(35)*. However, the concept can be used to repair timber piles underwater as well. After the damaged section is removed, the new section is positioned with narrow gaps at the top and bottom and is wedged tightly against the existing pile cutoffs. Next, holes are bored at a steep downward angle above each joint and steel pins are driven through the holes to join the two sections. Finally, the sides of the joints are sealed and epoxy is injected into the holes, bonding the new and old sections.

CHAPTER SIX

CONCLUSIONS AND RESEARCH NEEDS

Conclusions

Current underwater bridge inspection programs are documenting the condition of submerged substructure elements. Agencies are faced with the need to respond to the inspection findings with protection and repair procedures, and they are finding that the economics may be very different between the procedures performed in dry conditions and the best procedure for underwater application. Special equipment is required for underwater application. Special construction materials may also be required. Construction procedures that can be performed under water are often more difficult and always more time-consuming than when they are performed in the dry.

Good design at the beginning of the project can minimize later maintenance and repairs. The limitations of underwater work must be considered in planning protection and repair procedures. Alternatives such as replacement or prefabrication of components, which would not be considered if the repair were performed in the dry, may be the most cost-effective solutions for underwater application.

The limitations of underwater inspection and maintenance should also be considered in developing the repair methodology. Since the underwater elements are rarely inspected more frequently than a 5-year inspection cycle and deterioration may be more difficult to control under water, the quality, inspectability, and service life of the repairs are very important, particularly when the safety factor or structural redundancy of the element is limited. Predesigned underwater repair systems should not be used unless they are engineered specifically for the type of damage and bridge to be repaired.

Research Needs

The following topics are suggested for future research to advance the technology of bridge protection and repair performed underwater:

1. Strong water currents present difficult obstacles when performing underwater repairs. Operations are often restricted to certain times of the day, such as "slack tides," and ideal weather conditions. The cost of underwater work could be reduced if improved technology were developed to permit the diver to work safely and to provide surface support safely in fast-moving or turbulent water.

2. There is a need to develop or modify construction equipment for use under water. For example:

   a. A device to attach to the side of the substructure element that would dry the surface and apply a coating or sealer could be developed.
   b. Video cameras and remote controls could be developed to minimize the diving time.
   c. The application of robotics to perform underwater repairs also has the potential to increase the options for the bridge engineer.

3. Research should also focus on repair materials for underwater application. For example:

   a. Non-corrosive fiber-reinforced tendons for use in structural repairs should be developed.
   b. Bonding materials, sealers, and protective coatings that can be applied to a wet surface should be tried.
   c. Low-permeability concrete for underwater placement should be tested.

4. More research is needed to develop or identify devices for monitoring the condition of underwater bridge elements. For example:

   a. Affordable, effective detection devices are needed to continuously monitor scour of critical bridges. Ideally, the device would also include a means of warning the traveling public in the event of a problem related to flash flooding.
   b. A device for use underwater to inspect the condition of concrete members covered by stay-in-place forms or protective coverings is needed.

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GLOSSARY

A-Betong-Sabema System: A device used to place concrete underwater.
Aggradation: Increase in streambed elevation due to deposition of transported material.
Annular Space: Volume between the outside surface of a solid and the inside surface of a second solid.
Antiwashout Admixture: Concrete mix ingredient which allows concrete to be placed in moving water.
Armoring: Protection of scourable material with non-erodible material.

Cathodic Protection: Equipment and materials used to arrest the corrosion process of reinforcing steel embedded in concrete through an electrochemical process.
Cobalt 60 Radioactive Source: A transportable source for X rays used in the field to test for flaws in welds, etc.
Coupon Sampling: Method in which a small piece of a structural steel member is removed to determine its engineering properties.

Deflectors: Hydraulic structures used to redirect stream flow away from scour-critical bridge features.
Dewatering Cofferdam: A construction method in which (1) sheet piles are driven in a river bottom so as to encircle a substructure unit, (2) the bottom is sealed with tremie concrete, and (3) water is removed to allow repair work in the dry.

Fathometer: Electronic device used to measure water depths.

Galvanic Corrosion: Corrosion which occurs when two dissimilar metals, or similar metals of different quality, come into contact.
Gamma-Ray Probe: Gamma-ray detector which is lowered inside a pipe to detect the location of a gamma-ray source which rests at the bottom of a scour hole outside the pipe.

Hydro-Valve: A device used to place concrete underwater.

Impressed Current Cathodic Protection: Equipment and materials which use an external power source to arrest the corrosion of reinforcing steel in concrete.
Injection Spout (Port): A hole drilled in concrete through a crack; polymers are injected into the port to seal the crack.
Iowa Vanes: Hydraulic structure consisting of vertical paddle boards set on the river bottom and slightly skewed to the direction of flow; used to redirect stream flow away from scour-critical bridge features.

Jetty: Hydraulic structure consisting of a projection into a water course used to redirect stream flow away from scour-critical bridge features.

Monomer: Molecules which consist of single units—see POLYMER.

Passive Cathodic Protection: Equipment and materials which use a sacrificial anode system to arrest the corrosion of reinforcing steel in concrete.
Polymer: Hard, glassy solids commonly called plastics, produced through a chemical process by which a monomer is converted into a polymer.
Posting: Timber pile repair process in which (1) the damaged section is removed, (2) a new section is inserted, and (3) the joints are injected with epoxy.
Pozzolan: A material which itself possesses little or no cementitious value, but in finely divided form and in the presence of moisture will react to form compounds possessing cementitious properties.
Prepacked Aggregate Concrete: A construction method in which uniformly graded aggregate is placed within forms and injected with cement grout through pipes to form concrete material.

Quality Assurance: An external process in which quality is maintained as production proceeds by those involved in the project.

Remote Sensing Devices: Devices which do not need to be in contact with the object under investigation.

Sacrificial Anode Cathodic Protection: See PASSIVE CATHODIC PROTECTION.
Sediment: Material deposited by moving water.
Sonar-Side Scan: Sound waves used to detect bottom irregularities.
Spectrographic Analysis: Test method in which a material to be investigated is heated to a vapor, then exposed to a light source. The spectrum of the reflected light is studied to view the critical components of the material.
Spur Dikes: Hydraulic structures used to redirect stream flow away from scour-critical bridge features.
Stitching/Stitching Dog: Crack-repair method in which stitching dogs (U-shaped rods) are grouted in place with one leg of the U on either side of the crack.
Stubbing: Timber pile repair method in which the deteriorated section is removed and replaced with cast-in-place concrete.

Tendons: High-strength steel bars or cables used to prestress concrete.

Timber Scabs: Timber pieces used as splice plates to joint a replacement section to the existing member. Similar to POSTING.

Tremie: A device used to place concrete underwater consisting of a funnel and a flexible pipe. During placement the pipe must extend into the fresh concrete and maintain a continuous discharge.

Tremie Concrete: Concrete placed underwater using a tremie.

Turbulence: The irregular flow of water caused by stream-channel irregularities.

Ultrasonic Testing: Electronic process which uses very high-frequency sound waves to detect flaws within materials

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Topic Code	Description
1	General Interest
2	Scour
2A	Scour Evaluation
2B	Scour Prevention
2C	Scour Maintenance
2D	Scour Repair
3	Concrete
3A	Concrete Protection
3B	Concrete Maintenance
3C	Concrete Assessment
3D	Concrete Repair
4	Steel
4A	Steel Protection
4B	Steel Maintenance
4C	Steel Assessment
4D	Steel Repair
5	Timber
5A	Timber Protection
5B	Timber Maintenance
5C	Timber Assessment
5D	Timber Repair

1. 2D D.M. Corda, R.B. Peel, and A.M. Vaysburd. Underwater Pier Repair. In *Transportation Research Record No. 1290,* Vol. 1, TRB, Washington, D.C., 1991, pp. 93–100.

During an underwater inspection of the Bayville Bridge, located on Long Island, divers detected several areas of concrete deterioration. Mortar joints between granite stones on the piers were seriously eroded, allowing stones to dislodge and to displace from the pier face. Concrete behind stones appeared to be soft and severely disintegrated with exposed course aggregate. Subsequent cores revealed persistent problems in the quality of the concrete, including segregation, voids, zones of trapped laitance, and zones of honeycombed concrete. The pier was also scoured 4 to 6 ft underneath the footing and 1 to 2 ft deep. Repair options included tremie concrete, preplaced aggregate concrete, bottom-opening bucket, pumped concrete, and bagged concrete. Tremie concrete was not used because this method is most suited for new construction involving large quantities of concrete because concrete mixes suitable for tremie placement are highly susceptible to washout. According to current research, antiwashout admixtures and silica fume admixtures can eliminate the washout problem (Gerwick review of technology for underwater repair of concrete subjected to abrasion erosion, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi). Slightly excessive amounts of antiwashout admixture renders concrete so adhesive as to be unworkable. The key is to use antiwashout admixtures in conjunction with a water reducer to increase slump. Fabric-formed concrete was proposed in a patent in Norway in 1922 to build underwater concrete structures by filling large bags with concrete and placing them with a crane. Since the fabric is highly water-permeable, excess water used for pumping can be expelled through the fabric, causing a pronounced reduction in the water-cement ratio at and near the concrete surface. Concrete-filled bags are more versatile—that is, not tied to a certain form size, better suited for a small crew, and do not involve the use of cranes to handle forms—and relatively low-cost. They can provide durable, high-quality repair material. Bag dimensions were 10 ft long, 45 in. wide, and 25 in. thick. Removal of deteriorated concrete had to be comprehensive for a successful repair. The void face was repaired by removal of deteriorated concrete using 30-lb chipping hammers. Loose material was cleaned using water-jetting techniques. No. 5 grade 60-epoxy-coated hooked dowels grouted in 1-in. drilled holes were installed next. The holes were air-percussion drilled

to allow installation. The existing streambed was excavated using an airlift to a depth of 1 to 6 ft to provide lateral stability for the initial course of 3,500-psi concrete-filled bags. Adjacent bags were joined by inserting reinforcing dowels into the freshly filled bags of concrete. The ends of dowels were ground smooth to facilitate penetration through this fabric without tearing.

2. 3D K.H. Khayat and W.T. Hester. Evaluation of Concrete Admixtures for Underwater Pile Repairs. *Cement, Concrete and Aggregates,* CCAGDP, Vol. 13, No. 1, ASTM, Summer 1991, pp. 32–41.

Concrete mixes for use in filling the annular spaces between jackets and piles were studied. Four concrete mixes were selected to repair 8-ft-high mock-up piles located above water. Annular space was first filled with water and then concrete. Concrete was discharged below the surface of the freshly placed concrete. The testing program indicates that concrete mixtures containing antiwashout admixtures and either silica fume or fly ash can secure higher quality repairs at equal or lower costs than similar concretes made with high-silica-fume or high-cement concrete and no antiwashout admixtures.

3. 3D R.P. Brown and J.S. Tinnea. Cathodic Protection Design Problems for Reinforced Concrete. *Materials Performance,* Vol. 30, No. 8, National Association of Corrosion Engineers, August 1991, pp. 28–31.

In marine environments, daily tidal changes and seasonal tidal levels/greatly affect cathodic protection current distribution. Splash zone areas and areas immediately above (approximately 3 ft) require additional cathodic protection current and should be powered through a separate current to allow proper control.

4. 3A H.C. Lamberton, Jr., and A.J. Santz, *et al. NCHRP Synthesis of Highway Practice No. 88: Underwater Inspection and Repair of Bridge Substructures.* TRB, National Research Council, Washington, D.C., December 1981, 77 pp.

Often concrete problems are associated with chemical reaction. Deterioration is most severe in tropical marine environments. Physical erosion below the waterline can be caused by abrasion. The water-cement ratio must be low, materials must be non-reactive, adequate concrete cover should be maintained, and surface treatments may be specified. Zinc anodes can be attached to reinforcing steel and concrete piles. The procedure for clamping anodes to the exposed reinforcing bar is provided. Basic steps in underwater concrete repair include removal of all marine growth and deteriorated concrete. Restore reinforcing steel to original condition. Seal by injection any cracks in the remaining concrete, replace the concrete, and apply protective treatment. Methods used by divers to perform underwater epoxy injection down to 60 ft are similar to methods described elsewhere, except that the epoxy surface sealer takes 3 days to harden sufficiently to withstand injection pressure. Quickset cement can be placed by hand on concrete structures requiring small quantities of patching. Some contractors have devised various methods of conveying the mixture to the divers, including a rope pulley system using two buckets or a PVC pipe with small holes drilled into it allowing softball sized portions of the mix to be dropped down to the diver.

5. 3 F. Dimmick, Sr. *Underwater Concrete Repair State-of-the-Art Report.* Draft No. 7, Subcommittee 546-1, American Concrete Institute (Unpublished), 39 pp.

Report covers the history of diving technology; causes of deterioration, corrosion, and mechanical damage; inspection techniques; underwater nondestructive testing; and repair techniques. Repair techniques include general concrete removal, rigid forms, flexible forms, preplaced aggregate, tremie concrete, pumped concrete, free-dumped concrete, chemical grouting, and cementitious grouting.

6. 3D M.D. Luther. High Performance Silica Fume (Micro silica)—Modified Cementitious Repair Material. In *Cement Admixtures and Concrete 1990: Transportation Research Record No. 1284,* TRB, National Research Council, Washington, D.C., 1990, pp. 88–94.

The cohesiveness of mixes containing silica fume make them suitable for underwater applications. Several successful underwater repairs of dams have been completed. One project in England used silica fume grout in a tremie placement in which the coarse aggregate was replaced.

7. 3D W.R. Malisch. Advances in Underwater Treatment Repair Methods. *Concrete Construction,* September 1991, pp. 665–668.

With antiwashout admixtures, it is no longer necessary to maintain a continuous tremie seal. Antiwashout admixtures are water soluble polymers that physically bind the mixed water in concrete. This slows the movement of mixed water, but concrete fluidity is maintained.

8. 3D J.E. McDonald. *Maintenance and Preservation of Concrete Structures; Repair of Erosion-Damaged Concrete Structures.* Technical report C78-4, Report No. 2, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi, 1980.

Dewatering hydraulic structures before repairs can average 40 percent of total repair costs.

9. 3D W.T. Hester, K.H. Khayat, and B.C. Gerwick, Jr. Properties of Concretes for Thin Underwater Placements and Repairs. *Proc.*, SP 114-34, Vol. 1, American Concrete Institute, 1989.
Most antiwashout admixtures consist of microbial polysaccharides such as welan dumm or polysaccharide derives such as hydroxypropyl methyl cellulose and hydroethyl cellulose.

10. 3D D.R. Morgan. Development in Shotcrete for Repairs and Rehabilitation. *Concrete Construction*, September 1991, pp. 659–664.
Scandinavian countries pioneered the use of silica fume in wet-mix shotcrete in the late 1970s. Researchers in British Columbia, Canada, conducted lab investigations using dry-mix shotcrete and found that the benefits include improved resistance to washout where freshly applied shotcrete was subject to running water or tidal cycling. In New Brunswick, Canada, the tidal range is 28 ft with temperatures as low as -22° F. A concrete berth was rehabilitated during low tide.

11. 3A L. Flynn. Metalizing Protects Rebar From Corrosion. *Roads and Bridges*, August 1991, pp. 58–59.
Seven Mile Bridge carrying U.S. Rte. 1 over the Florida Keys began to deteriorate after 9 years of service. Sacrificial molten zinc is being sprayed on the exposed rebar and surrounding concrete to stop accelerated deterioration. The zinc is applied to elevations 2 to 6 ft above the waterline and the limits of the spalling.

12. 3D Abrasion/Erosion Resistant Concrete Used to Repair French Dam. *Concrete Repair Bulletin*, International Association of Concrete Repairs Specialists, March–April 1991, p. 9.
Fondag Concrete is well known for its rapid hardening. Less well known is its resistance to abrasion, erosion, and cavitation. A French dam was repaired using the Fondag concrete with synthetic aluminous aggregate which develops a strong chemical bond with the angular faces of the very hard and non-porous aggregate. A strength of 13,000 psi was developed.

13. 3A R.J. Kessler, R.G. Powers, and I.R. Lasa. Cathodic Protection Using Scrap and Recycled Materials. *Methods Performance*, June 1991, pp. 29–31.
A cathodic system for marine piling in the splash zone consists of scrap zinc sheets mechanically connected to reinforcing steel and clamped against the concrete surface with wood-plastic byproducts.

14. 4A R.R. Avent and M. Whitmer. Imminent Collapse Halted at Mississippi Bridge. *Roads and Bridges*, April 1990, p. 65.
A channel span pier supported on 12 steel piles had suffered 17 ft of scour, exposing 12 ft of the piles. Scour, corrosion, local buckling, and collision of barges had combined to place this bent in jeopardy. Piles were encased in jackets extending from the underside of the seal to 3 ft below the existing mudline.

15. 1 J.T. Johnson. Computerized Underwater Inspection Maintenance and Repair. *Oil and Gas Australia*, November 1985.
Computer-aided inspection package imposes a standard format on inspection reports through word processing and CADD use.

16. 1 C.A. Keeney. *Procedures and Devices for Underwater Cleaning of Civil Works Structures*. Technical Report REMR-CS-8. Repair, Evaluation Maintenance and Rehabilitation Research Program, Department of the Navy, Naval Civil Engineering Laboratory, U.S. Army Corps of Engineers, Washington, D.C., 1987, 46 pp.
Report covers hand tools; powered hand tools, including brushes and water jets; self-propelled vehicles; and excavation and debris removal including excavation techniques and debris removal.

17. 3D J.F. Best and J.E. McDonald. *Spall Repair of Wet Concrete Surfaces*. Technical Report REMR-CS-25. Department of the Army, U.S. Army Corps of Engineers, Washington, D.C., January 1990, 23 pp.
A total of 22 products from 13 different producers were submitted for testing. Testing included bond capacity in direct tension, bond capacity under structural stress, resistance to abrasion, resistance to cycles of freezing and thawing, impact resistance, and thermal compatibility with concrete. The overall performance rating indicates products P-5 (three-component, fast-curing epoxy mortar) and P-3 (hydraulic cement-based, fiber-reinforced material) to be nearly equal in outperforming the other products tested. These two materials were followed closely in performance rating by products P-1 (three-component, modified epoxy resin-based grout) and P-2 (fast-setting and very rapidly hardening cement mortar) with two each of the top performing products epoxy materials (P-5 and P-1) and cement-based products (P-3 and P-2). The choice of which material should

be specified will likely depend on the job requirements. If thermal compatibility, bonding to wet concrete, and costs are of highest priority, product P-3 is likely the material of choice; however, if resistance to abrasion and impact are primary considerations, product P-5 may be the appropriate repair material. Manufacturer provides proprietary dry products and non-metallic fibers for product P-3. User supplies sand and cement. Initial set takes approximately 15 to 30 minutes. Product cost is $55/ft^3$. Product P-5 working time is about 30 minutes at 70°F. Full cure varies with ambient temperatures and the cost is $169/ft^3$.

18. 2B S.A. Brown and E.S. Clyde. *Design of Riprap Revetment.* Report FHWA-IP-89-06 HEC-11. FHWA, U.S. Department of Transportation, March 1989, 169 pp.

Revetment types discussed include rock riprap, hand-placed riprap, rubble riprap, wire-enclosed rock, precast concrete block, grouted rock, and paved lining.

19. 2A E.V. Richardson and J.R. Richardson. *Bridge Scour.* Presented at Bridge Scour Symposium, sponsored by FHWA, October 1989, 35 pp.

Total scour is composed of long-term aggradation and degradation, contraction scour, local scour, and lateral shifting of the stream. Clear-water scour and live-bed scour are also discussed.

20. 2A F.P. Haeni and S.R. Gorin. *Post Flood Measurement of Re-filled Scour Hole at the Bulkeley Bridge in Hartford, Connecticut.* Presented at Bridge Scour Symposium, sponsored by FHWA, October 1989, 30 pp.

Various devices to measure depth of floodstage scour holes that have been backfilled were evaluated. Methods include ground-penetrating radar, sound waves, tuned transducer, black-and-white fathometer, and color fathometer.

21. 2A B.W. Melville, R. Ettema, and S.C. Jain. *Measurement of Bridge Scour.* Presented at Bridge Scour Symposium, sponsored by FHWA, October 1989, 11 pp.

Prototype instruments for scour-depth measurement of flood-condition scour holes were assessed. One instrument consists of a metal ring around a non-metallic pipe that is attached to a pier and drops as scour occurs. A metal detector probe inside the pipe measures depth of the ring. A radioactive source can be used in the metal ring so that a metallic, impact-resistant tube can be substituted for non-metallic pipe.

22. 2A L. Bedingfield and N. Hourani. *Scour Surveying and Countermeasures in Massachusetts.* Presented at Bridge Scour Symposium, sponsored by FHWA, October 1989, 24 pp.

Countermeasures at three bridges were discussed. Countermeasures consisted of sheet piling filled with riprap and capped with concrete, plus streambed paving.

23. 2C A. J. Odgaard and Y. Wang. *Sediment Control in Bridge Waterways.* Presented at Bridge Scour Symposium, co-sponsored by FHWA, October 1990, 10 pp.

Iowa vanes are used to redirect streamflow to prevent erosion.

24. 3D R.P. Webster and L.E. Kukacka. *In-Situ Repair of Deteriorated Concrete and Hydraulic Structures: Feasibility Study.* Technical Report REMR-CS-6. U.S. Army Engineers Waterways Experiment Station, U.S. Army Corps of Engineers, May 1987, 80 pp.

Report covers methods and materials for repair of concrete. Methods include pressure injection, routing and sealing, stitching, adding reinforcement, drilling and grouting, flexible-sealing grouting, dry-pack mortar, surface treatments, polymer impregnation, coatings, jacketing, shotcreting, and other methods.

25. 3D B.C. Gerwick, Inc. *Review of the State-of-the-Art for Underwater Repair Using Abrasion Resistant Concrete.* Technical Report REMR-C-CS-19. Department of the Army, U.S. Army Corps of Engineers, Washington, D.C., September 1988, 42 pp.

Report covers concrete placement methods and admixtures. Included are vacuum processing, polymer concrete, hydro-valve method, pumped concrete, and doweling.

26. 3A R.W. Drisko and J.R. Yanez. *Underwater Applied Coatings: A State-of-the-Art Investigation.* Technical Report REMR-EM-3. Department of the Army, U.S. Army Corps of Engineers, Washington, D.C., October 1988, 30 pp.

Eleven coatings for application to steel were tested. Variables included dry steel surface, wetted steel, and steel immersed in freshwater and saltwater. Also tested were various surface preparation and application procedures. Only one product (a basic epoxy formulation) was easily applied by a diver with a brush and cured to give a good film. Another, thicker, two-component epoxy splash zone compound was applied with more difficulty by hand and cured to give a film inferior to laboratory specimens.

27. 3D B.D. Neeley. *Evaluation of Concrete Mixtures for Use in Underwater Repairs.* Technical Report REMR-CS-18. Department of the Army, U.S. Army Corps of Engineers, Washington, D.C., April 1988, 130 pp.

A series of concrete mixes were proportioned for underwater use. It was found that traditional mixes were not suitable for underwater use, especially those with high W/C. Low W/C is more resistant to abrasion and washout. Some antiwashout admixtures and high-range water reducers can be incompatible. Fly ash can improve washout and abrasion resistance. Silica fume can improve washout resistance.

28. B.A. Suprenant. Designing Concrete for Exposure to Seawater. *Concrete Construction Magazine,* Vol. 36, No. 12, December 1991, pp. 837–877.

Topics include marine environment and mix design.

29. S.R. Gorin and F.P. Haeni. *Use of Surface-Geophysical Methods to Assess Riverbed Scour at Bridge Piers.* Report 88-4212. U.S. Geological Survey, Water Resources Investigation, 33 pp.

30. Florida Department of Transportation. *Bridge Repair Manual.* FDOT Item 844, p. 2.

31. T.L. Klemens. Who Says You Can't Pave Underwater? *Highway & Heavy Construction.* Vol. 134, No. 10, August 1991, p. 64.

An aquifer ditch is paved underwater.

APPENDIX A

QUESTIONNAIRE—SURVEY OF CURRENT UNDERWATER BRIDGE MAINTENANCE AND REPAIR

A questionnaire to survey the current underwater bridge maintenance and repair methods was developed to identify sources of information for this synthesis. The questionnaire was sent to transportation agencies in the United States and Canada by the National Academy of Sciences, Transportation Research Board. The contents of the questionnaire follow:

Organization Responding to Questionnaire

Name: ____________________

Address: ____________________

Person Responding to this Questionnaire

Name: ____________________

Telephone Number: ____________________

Please list the 3 most common types of underwater (scour line) problems (in order of occurrence) identified on your bridges.

(1) ____________________

(2) ____________________

(3) ____________________

What type of underwater maintenance/repair work does your organization perform with in-house personnel?

____

____

What type of underwater maintenance/repair work does your organization contract?

____

____

Has your organization performed underwater repair work using divers?

In-house divers: ☐ Yes ☐ No Contract divers: ☐ Yes ☐ No

Please provide other potential sources of this type information (other than state DOTs) such as cities, diving contractors, construction contractors, engineering consultants and suppliers.

Organization	Name	Telephone Number

Please list the different types of underwater (and splash zone) maintenance and repair work performed by your organization within the past ten years. Include the number of bridges per type of work and a name and telephone number of a contact to provide details of each type.

Type Maintenance/Repair	No. Bridges	Name and Phone No. to Call

Please add additional sheets as necessary and include copies of available plans, sketches and photographs, cost data, and comments related to construction problems and effectiveness of work if possible. Return questionnaire and other materials to:

Ron L. Purvis, P.E.
Wilbur Smith Associates
2921 Telestar Court
Falls Church, VA 22042

APPENDIX B

SUMMARY OF THE QUESTIONNAIRE RESPONSES

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Alabama Highway Dept.	(1) Scour around footings & piling. (2) Loss of section due to corrosion & deterioration. (3) Damaged members.	(1) U/W inspections. (2) Scour profiles. (3) U/W burning & welding. (4) Pile encasements. (5) Footing repairs. (6) Scour repairs. (7) Crack repairs. (8) Drift removal.	Same as in-house.	Yes	Yes	Pile encasement Footing repair Inspection Scour protection	60± 10± 250/yr± 250 ±
Alberta Transportation & Utilities	(1) Abutment scour/erosion. (2) Bank/abutment stability.	(1) Restoration. (2) Reinforcement. (3) Construction of erosion and scour protection works including abutments, piers, guidebanks, groynes, & approach streambanks. • Majority of work is related to placement of riprap. • Bridge size culverts are generally repaired by dewatering the site.	Very little work is contracted except for major scour/erosion works.	No	Yes	Erosion/scour repair of major bridges Erosion/scour repair of standard bridges & culverts	50 150
California State Dept. of Transportation	(1) Channel degradation. (2) Local scour. (3) Debris buildup with local scour.	None.	All.	No	Yes	Pile encasement Training wall Riprap	3 3 5
Colorado Dept. of Transportation	None.	(1) Stream degradation is a problem. We have added 6 to 8 ft. of concrete under footing on 6 bridges to encase exposed piling.					
Connecticut Dept. of Transportation	(1) Undermining of substructure and placing riprap. (2) Repairs and repointing of stone abutments & piers. (3) Repairs to concrete elements; i.e., scaling & spalling.	None.	All the work listed in the first question.	No	Yes	Repoint masonry Bagged repair of underlining Replace riprap	1 6± 100±

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Florida Dept. of Transportation	(1) Local scour. (2) Debris build-up. (3) Unpredictability of tidal scour.	(1) Projects which can be accomplished in short time frame. (2) Projects which must be done immediately.	(1) Major work that would tie up state crews that they could not respond to emergencies.	Yes	Yes	Replace scoured material with rock, sandbags and/or grout Debris removal Crutch/helper bents	
Georgia Dept. of Transportation	(1) Local scour from debris. (2) Local scour from the structure. (3) Stream migration.	(1) Pile encasement. (2) Underwater placement of riprap. (3) Grout bag placement. (4) Underwater grouting of foundation voids.	(1) Pile encasement. (2) Bent retrofits.	Yes	Yes	Pile encasement Underwater placement of riprap Grout bag placement & underwater grouting Bent retrofits	200 7 5 2
Hawaii Dept. of Transportation	(1) Scour under abutments. (2) Scour around piles, exposing a longer unsupported length. (3) Scour at piers.	(1) Fill in scour areas. (2) Repair cracking & spalling of concrete.	(1) Identical to in-house.	No	Yes	Scour repairs Spalls & cracks in concrete Repairing of piles.	Not availabl e
Idaho Transportation Dept.	(1) Local scour around piers, pilings. (2) Spalling of concrete piers. (3) Deterioration of underwater steel components.	Very limited. (1) Some spall repair & pouring concrete collars around pilings. (2) Scour repairs.	(1) All major repair work.	Yes	No	Pour concrete collars around piling Minor spall repair Scour repair	1 2 10

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Illinois Dept. of Transportation	(1) Scour (2) Concrete spalling.	(1) Riprap placement. (2) Tree & brush removal. (3) Minor concrete repair. (4) Slopewall repair.	(1) Riprap placement. (2) Gabions. (3) Revetment map. (4) Spur dikes. (5) Channel improvements. (6) Relief structures. (7) Lengthening bridges.	No	Yes	Riprap placement Spur dike construction	
Indiana Dept. of Transportation	(1) Pile deterioration near waterline. (2) Degradation of stream flowline exposing pier & abutment foundations.	None.	(1) Line channel bottom with riprap adjacent to exposed footings.	No	No	None.	
Iowa Dept. of Transportation	(1) Flood debris accumulation & consequent scour. (2) Streambed degradation. (3) Channel meander.	(1) Rebuild berms and/or protect berms with riprap. (2) Minor channel realignment.	(1) Major channel alignment and/or berm protection. (2) Construction of weirs, check dams and jetties.	No	No	Repair pier damage.	1
Kansas Dept. of Transportation	(1) Channel degradation. (2) Channel migration. (3) Local scour.	(1) Berm erosion & minor channel scour repair using dumped rock. • No underwater work performed.	(1) Sheet pile driven to encase scoured pier, encasement filled with concrete.	No	No	Local pier scour	10
Louisiana Dept. of Transportation & Development	(1) Scour at pilings, piers & footings. (2) Collisions due to marine traffic. (3) Scour at abutments. (4) Drift build-up.	None.	(1) Underwater pile repair. (2) Scour build-up with rock mattresses.	No	Yes	Pile repair Scour repair	10 10
Maine Dept. of Transportation	(1) Loss of stone protection or local scour. (2) Undermining of footings. (3) Channel degradation.	(1) Repair of riprap & shallow underpinning.	(1) Grout bags for underpinning in deep water. (2) Heavy riprap placement. (3) Jacket piles w/ concrete.	No	Yes	Grout bag underpinning Riprap placement - concrete Riprap repair - in-house	10 7 50±
Manitoba Dept. of Highways & Transportation	(1) Concrete deterioration. (2) Channel scour. (3) Riverbank scour.	None.	(1) All work including inspection.	No	Yes		

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Maryland State Highway Administration	(1) Scour/undermining. (2) Timber pile deterioration. (3) Concrete pile deterioration.	None.	Any that is required. Examples: (1) Grout bag repair for scour & undermining problems. (2) Pile repair above & below splash zones (incl. protective jackets).	No	Yes	Pile repair Scour protection Underpinning	Not availabl e
Massachusettes Dept. of Public Works	(1) Scour of riverbed at piers & abutments. (2) Undermining of footings at piers & abutments. (3) Timber pile deterioration.	(1) Installation of temporary scour countermeasures in locations where scour/undermining has occurred. (2) Repair undermined bridges: (a) construct forms underwater; (b) pump concrete beneath footings to fill undermined area. (3) Refasten timber bracing on pile bents. (4) Emergency pile repair. (5) Removal of debris that is obstructing channels beneath bridges. (6) Search & recovery of parts & equipment that fall from bridges. (7) Emergency submarine cable installation.	(1) Placement of riprap to correct riverbed scour. (2) Placement of tremie concrete to repair undermining. (3) Pile rehabilitation.	Yes	Yes	Repair of riverbed scour Repair of undermined footings Pile rehabilitation Route 495/ Merrimack River	6 ea. 8 ea. 4 ea.
Military Traffic Management Command	While we are most interested in bridge maintenance on public highways, we do not perform underwater inspections.						
Minnesota Dept. of Transportation	(1) Deterioration of pier at waterline. (2) Scour in vicinity of pier. (3) Deterioration of pier below waterline.	(1) All types.	(1) All types.	No	Yes	Records do not provide distinction between work above or below waterline.	

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Mississippi State Highway Dept.	(1) Loss of bearing capacity from erosion. (2) Corrosion of exposed steel piles in brakish water.	(1) Filling scour holes w/ riprap. (2) Timber piles are replaced by in-house personnel; however, they perform work above water.	Generally, all work performed underwater is contracted. Examples: (1) Pile encasements. (2) Epoxy injection of cracked concrete piles.	No	Yes	Pile replacement Pile encasement	Numer-ous 2
Missouri Highway & Transportation Dept.	(1) Deteriorated piling. (2) Undermined footings. (3) Deteriorated concrete.	(1) Only small repair work. We try to dewater with cofferdams whenever possible.	(1) Any other than minor repair work.	No	No	Always dewater for maint & repair work. No underwater repair experience.	
Nebraska Dept. of Roads	None.	None.	None.	No	No		
Nevada Dept. of Transportation	(1) Channel degradation. (2) Localized scour. (3) Timber pile deterioration.	(1) Riprap placement in localized scour/erosion areas.	(1) Almost everything other than minor riprap work.	No	No	Bridge replacement Scour repair	5 5
New Hampshire Dept. of Transportation	(1) Concrete deterioration. (2) Undermining. (3) Rusting (piles & metal culverts).	(1) Shallow water toewalls & facing of concrete. (2) Some shallow water pile encasements.	(1) Deep water work.	No	Yes	Underwater grout bags Shallow water pile encasements Shallow water toewalls & facings Deep water pile encasements	3 1 Lots 2

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
New Jersey Turnpike Authority	(1) Pile casing loss. (2) Deterioration of concrete encasement. (3) Changes in streambed.	None.	(1) Substructure concrete repairs. (2) Casing replacement & repairs. (3) Cap stone joint repairs. (4) Grouting of cracks & openings. (5) Coating of casings.	No	Yes	Cap stone joint repairs Substructure concrete repairs Casing repl./repairs Grouting of cracks/ openings Coating of casings	2 3 5 2 1
New Jersey Dept. of Transportation	(1) Cracks in concrete substructure units. (2) Spalls in concrete substructure units. (3) Undermining (local & contraction scour) of substructure units).	(1) Placement of grout filled bags & pumping of concrete under footings in shallow streams. (2) Fabri-Form is used when contract maintenance of scour is called for in repair scheme.	(1) Scour repair and pile repair.	No	Yes	Local scour Pile splice	50± 10±
Newfoundland Dept. of Works, Services & Transportation	(1) Scour beneath footing. (2) Erosion of concrete of footings. (3) Corrosion of steel pilings.	Very little.	(1) Repair of undermining by underpinning footings.	No	Yes	Underpinning footings Piling repair	10 5
North Dakota Dept. of Transportation	(1) Scour holes in streambed.	(1) Fill holes with riprap.	None.	No	No	Fill scour holes with riprap	50±

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
North Carolina Dept. of Transportation	(1) Reduction of pile penetration. (2) Exposure of footings. (3) Undermining spread footings. (4) Channel change.	(1) Scour repair. (2) Concrete pile rehab. (3) Concrete pile jacket. (4) Concrete pier column repair. (5) Epoxy injection of cracked concrete. (6) Drift removal. (7) Submarine cable placement/movable spans. (8) Substructure removal.	None.	Yes	No	Scour repair Concrete pile jackets Concrete pier column repair Concrete pile rehabilitation	57 11 3 1
Nova Scotia Dept. of Transportation & Communications	(1) Scour of streambed. (2) Stream alignment shift. (3) Concrete deterioration.	(1) Replacement of timber cribs & piling.	(1) Concrete repair. (2) Steel work. (3) Pressure grouting.	No	Yes	Steel & concrete pier restoration Concrete repair, pressure grouting, concrete stabilization " " Shotcrete, concrete repair, streambed stabilization	1 6 6 6
Ohio Dept. of Transportation	(1) Footer undermining due to streambed degradation. (2) Meandering streams which undercut abutments. (3) Steel piling deterioration at flow line (on capped pile piers).	(1) Footer underpinning. (2) Pile encasement. (3) Rock channel protection. (4) Sheet pile cut-off walls/dams.	(1) Pile encasement. (2) Footer underpinning. (3) Grout injection. (4) Rock channel protection. (5) Sheet pile cut-off walls/dams.	No	Yes	Fender repair Scour repair Pile restoration Pier protection	1 1 2 1
Oklahoma Dept. of Transportation	(1) Flowline degradation. (2) Scour. (3) Pier movement/settlement.	None.	(1) Scour repair and/or protection. (2) Epoxy injection of cracks in piers.	No	Yes		

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS?		DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
				IN-HOUSE	CONT.		
Oregon Dept. of Transportation - Highway Division	(1) Streambed erosion (footing underscour). (2) Drift accumulation/collision damage. (3) Marine borers.	(1) Riprap placement (2) Drift removal (3) Concrete patching (4) Piling repl/repair.	(1) Major structural repairs. (2) Major riprap work. (3) Piling replacement (4) Repair of catastrophic fender damage.	Yes	Yes	Riprap replacement Bag concrete repair Protective pile wrap install. Pile repair/repl.	5 6 3 1

ORGANIZATION RESPONDING	THREE MOST COMMON PROBLEMS	TYPE OF UNDERWATER MAINT/REPAIR WORK PERFORMED IN-HOUSE	TYPE OF UNDERWATER MAINT/REPAIR WORK CONTRACTED	PERFORMED UNDERWATER REPAIR USING DIVERS? IN-HOUSE	CONT.	DIFFERENT TYPES OF MAINT/REPAIR WORK PERFORMED IN LAST 10 YRS	NO. BRIDGES
Pennsylvania Dept. of Transportation - Bureau of Design	(1) Undermining/loss of foundation materials underneath and in front of the abutments/piers, causing settlement/tilting. (2) Poor channel alignments. (3) Sediment deposits/obstructions changing direction/velocity of steam flow.	(1) Placement/dumping of rock stones in scoured holes around abutments/piers. (2) Placement of grout filled concrete bags. (3) Cast-in-place cut-off walls. (4) Spur dikes. (5) Channel cleaning.	(1) Rock/stone placement. (2) Grout bagging. (3) Concrete placement for major undermined, scoured conditions, which may require special tools, eqmt., techniques & personnel for proper and permanent rehab in time.	Yes	Yes	Sheet piling around pier & underpinning undermined area w/ Class C concrete.	Unknown
						Footing underpinning - general procedure.	
						State manual for maint.	
						Tilted abt. rehab by conc. underpin, dumped rock & tieback to dead man-concrete block.	1
						Underscour area to be filled w/ intrusion grout after placement of fabric from bags around scoured portion of pier.	1
						Filling undermined-scoured hole w/ AASHTO #3 coarse aggregate & toping w/ gabion mats for protection.	
						Filling w/ fine aggregates &	

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				IN-HOUSE	CONT.		
Saskatchewan Highways & Transportation	(1) Channel bank erosion. (2) Erosion under abutments. (3) Channelbed degradation.	(1) Riprapping. (2) Groynes. (3) Restoration at abutments.	(1) Work involving dewatering.			Erosion protection Restoration	?
South Carolina Dept. of Highways and Public Transportation	(1) Embankment erosion due to inadequate bridge opening at above normal flow rates (mainly on maint. bridges). (2) Embankment & local loss of material due to debris collection restricting the opening. (3) Embankment and/or local loss due to improper substructure skew angle.	(1) Placement of fill material & riprap. (2) Placement of concrete pile encasements in low water conditions.	(1) Concrete pile encasements. (2) Bracing struts. (3) Pile seal encasements.	No	No	Low water pile encasements Deep water pile encasements Pile seal encasement	100± 10± 1
South Dakota Dept. of Transportation	(1) Concrete damage from freeze/thaw action near the waterline (wet/dry zone). (2) Abutment scour. (3) Bent scour.	(1) Repair concrete damage from freeze/thaw action near waterline. (2) Repair abutment scour. (3) Repair bent scour.	(1) Same as in-house depending on workload.	Yes	Yes	Encasing columns with corrugated metal pipe & filled with concrete for freeze/thaw damage Restoration of berms or channel to original shape & providing erosion protection Underpinning bent & abutment locations	Numerous Numerous Numerous
Tennessee Dept. of Transportation	(1) Degradation & lateral streambed movement. (2) Unknown pile lengths or footing elevations - lack of record. (3) Poor bridge alignment to channel & debris collection on piers.	(1) Riprap blankets around piers & pile bents in water less than 6' deep.	(1) Placement of riprap & gabion mattress. (2) Driving sheet piling for cofferdams. (3) Pouring concrete subfootings. (4) Deep water (>6' deep) repairs. (4) Built check dams.	No	No		

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				IN-HOUSE	CONT.		
Tennessee Dept. of Transportation (2nd response)	(1) Local scour & streambed degradation at bridge substructures. (2) Timber substructure deterioration. (3) Substructure settlement.	(1) Placement of riprap protection & pouring of concrete at substructure foundations.	(1) Underwater inspection, hydraulic & scour analysis, and preparation of repair plans for scour countermeasures. (2) Placement of cement grout under bridge footings to encase piling exposed to scour. (3) Placement of riprap to protect against local and contraction scour.	No	No	Placement of riprap protection & cement grout encasement of pile footings Placement of riprap protection Concrete encasement of timber substructures Emergency repairs for undermined footings on timber piling Emergency repairs for settlement of pier	44 Unknown 1 1 1
Texas State Dept. of Highways & Public Transportation	(1) Piling exposure. (2) Corrosion of steel piling. (3) Spalling of concrete piling/columns.	Virtually none - most all is contracted out.	Most all underwater work is contracted out.	No	Yes	Concrete column repair	4 1 3
USDA Forest Service	(1) Undermining. (2) Timber rotting. (3) Concrete cavitation.	(1) Undermining repair. (2) Timber posting.	(1) Undermining. (2) Posting of piles.	Yes	Yes	Undermining of substructures Posting of timber substructures Cavitation repair	50 20 5
Vermont Agency of Transportation	(1) Undermining (loss of supporting material). (2) Concrete deterioration.	(1) Minor concrete repairs. (2) Scour repair/prevention.	(1) Major repairs relating to undermining ($40,000+ projects)	No	No	Not available.	

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				IN-HOUSE	CONT.		
Virginia Dept. of Transportation	(1) Deterioration of tremie seal concrete below footing. (2) Undermine of footings on firm material due to tree & wood debris build-up. (3) Concrete deterioration in columns & footings due to age and swift currents.	(1) Limited concrete formwork (pile jackets, footing repair, etc.) in shallow water <10'. (2) Removal of tree buildup on piers. (3) Placement of riprap around pier footings exposed or undermined.	(1) Extensive concrete formwork. (2) Work in hazardous conditions. (3) Concrete and undermine repair >10'.	Yes	Yes	Concrete tremie & undermine repair Concrete tremie repair Undermine repair of footings	3 1 6
Washington State Dept. of Transportation	(1) Drift removal. (2) Timber pile deterioration. (3) Concrete footing & pier deterioration.	None.	(1) All work requiring diving including anode attachment for cathodic protection of steel piling.	No	Yes	Drift removal Pile repair Anode attachment	2 to 3 1 Ferry terminals
West Virginia Dept. of Transportation	(1) Scour of foundation material. (2) Erosion of concrete.	None.	None.	No	No	None.	
Wyoming Transportation Dept.	(1) Undermining of substructure footings. (2) Loss of section; i.e., timber, concrete, steel. (3) Degrading of stream channel (head cutting).	(1) Filling localized scour holes w/ dumped riprap (2) Channel cleanout of debris.	(1) Bridge replacements. (2) Supplementary bents/piers.	No	No		

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