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Underwater Bridge Repair, Rehabilitation, and Countermeasures Reference Manual

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16. Abstract Repairs to underwater bridge elements have been successfully completed for many years. However, the increased age of the Nation's bridges and related structures, as well as the increased emphasis in regular underwater inspection since the revisions to the National Bridge Inspection Standards in 1988, indicates an increased need to perform repairs to elements located below or in water. This manual is intended to serve as a reference for design engineers, construction inspectors, resident engineers, inspection divers, and other administrative and technical staff whose work tasks include the repair or rehabilitation of elements of bridges or similar structures located below water. The manual addresses a variety of design and construction issues in determining the feasibility of, and selecting the repair or rehabilitation methodology for, underwater projects. This information can aid in developing cost-effective and durable repair and rehabilitation designs. The catalog for NHI Courses can be found on the National Highway Institute web site: www.nhi.fhwa.dot.gov		
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)A Section 508 conformant version of the SI (Modern Metric) Conversion Factors table may be found at: http://www.fhwa.dot.gov/publications/convtabl.cfm.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACQ	Alkaline Copper Quaternary
ACZA	Ammoniacal Copper Zinc Arsenate
ADE	Agency Defined Elements
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
AGE	Arterial Gas Embolism
amp	Ampere
ASTM	American Society for Testing and Materials
ata	Atmosphere Absolute
atm	Atmosphere
AWPA	American Wood Protection Association
AWS	American Welding Society
BFRP	Basalt Fiber Reinforced Polymer
BIRM	Bridge Inspector's Reference Manual
BME	Bridge Management Elements
CAD	Computer-Aided Design
CCA	Chromated Copper Arsenate
CFR	Code of Federal Regulations
CFRP	Carbon Fiber Reinforced Polymer
CP	Cathodic Protection
CS	Condition State
DCS	Decompression Sickness
DOT	Department of Transportation
FHWA	Federal Highway Administration
FRP	Fiber Reinforced Polymer
fsw	Feet of Seawater
ft	Foot or Feet
GFRP	Glass Fiber Reinforced Polymer
GPM	Gallons per Minute

GPR	Ground Penetrating Radar
GPS	Global Positioning System
HDPE	High density polyethylene
HP	High Pressure
Hwy	Highway
I	Interstate
IAW	International Association Welding
ID	Identification
JHA	Job Hazard Analysis
LP	Low Pressure
MBE	Manual for Bridge Evaluation (AASHTO)
MBEI	Manual for Bridge Element Inspection (AASHTO)
MEL	Maritime Employers Liability
MHW	Mean High Water
MIC	Microbial Induced Corrosion
MLLW	Mean Lower Low Water
MPT	Magnetic Particle Testing
NBE	National Bridge Elements
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards (23 CFR 650 Subpart C)
NDT	Nondestructive Testing
NHI	National Highway Institute
NHS	National Highway System
NOAA	National Oceanic and Atmospheric Administration
NSTM	Nonredundant steel tension member
Ohm (Ω)	Electrical Resistance
OSHA	Occupational Safety and Health Administration
PM	Preventive Maintenance
POA	Plan of Action
PPA	Preplaced-Aggregate Concrete
ppm	Parts per Million
PSC	Prestressed concrete
QA	Quality Assurance

QC	Quality Control
QTY	Quantity
RC	Reinforced concrete
ROV	Remotely operated vehicle
SCBA	Self-contained breathing apparatus
SCUBA	Self-contained underwater breathing apparatus
SI	International Symbol of Units
SNBI	Specifications for the National Bridge Inventory
SSA	Surface-supplied air
US	United States
UIP	Underwater Inspection Plan
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
USGS	United States Geological Survey

GLOSSARY

A

AASHTO Manual. The term *AASHTO Manual* means the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Bridge Evaluation, 3rd Edition, 2018 with the 2019 and 2020 Interim Revisions* (MBE) with sections 1.4, 2.2, 4.2, 6, and 8, excluding the 3rd paragraph in Article 6B.7.1. (23 CFR 650.317(a)(1))

AASHTO MBEI. *AASHTO Manual for Bridge Element Inspection* is a reference for standardized element definitions, element quantity calculations, condition state definitions, element feasible actions, and inspection conventions. This manual is used for element descriptions, quantity calculations, and condition state definitions. (23 CFR 650.317(a)(4)) (2nd edition, 2019)

Abutment. Part of the bridge substructure at either end of bridge that transfers loads from superstructure to foundation and provides lateral support for the approach roadway embankment.

Aggradation. Progressive raising of a streambed by deposition of sediment.

Aggregate. Hard inert material such as sand, gravel, or crushed rock that may be combined with a cementing material to form mortar or concrete.

Anchor Pier. A pier functioning to resist an uplifting force, for example: The end reaction of an anchor arm of a cantilever bridge. This pier functions as a normal pier structure when subjected to certain conditions of superstructure loading.

Anode. The positively charged pole of a corrosion cell at which oxidation occurs.

Apron. A form of scour (erosion) protection consisting of timber, concrete, riprap, paving, or other construction material placed adjacent to abutments and piers to prevent undermining.

Aramid Fibers (*aromatic polyamide***).** A class of heat-resistant and strong synthetic fibers.

Arc Blow. The magnetic flux set up by the ground current combines with the flux around the electrode, causing a high flux concentration that blows the arc away from the ground connection.

As-built Plans. Plans made after the construction of a project, showing all field changes to the final design plans (i.e., showing how the bridge was actually built).

Ascent Time. The time interval between leaving the deepest point of the dive and returning to the surface.

B

Backfill. Material, usually soil or coarse aggregate, used to fill the unoccupied portion of a substructure excavation, such as behind an abutment stem and backwall.

Backwall. The topmost portion of an abutment above the elevation of the bridge seat functioning primarily as a retaining wall with a live load surcharge; it may also serve as a support for the extreme end of the bridge deck and the approach slab.

Backwater. The water of a stream retained at an elevation above its normal level through the controlling effect of a condition existing at a downstream location, such as a flood, an ice jam, or other obstruction.

Bank. Sloped sides of a waterway channel or approach roadway, short for embankment.

Base Metal. The surface metal of a steel element to be incorporated in a welded joint; also known as structure metal, parent metal.

Batter. The inclination of a surface in relation to a horizontal or a vertical plane, commonly designated on bridge detail plans as a ratio (e.g., 1:3, H:V); see **rake.**

Batter Pile. A pile driven in an inclined position to resist forces that act in other than a vertical direction. It may be computed to withstand these forces or, instead, may be used as a subsidiary part or portion of a structure to improve its general rigidity.

Bearing Seat. A prepared horizontal surface at or near the top of a substructure unit upon which the bearings are placed.

Bedform. Recognizable relief feature on the bed of a channel, such as a ripple, dune, plane bed, antidune, or bar. Bedforms are a consequence of the interaction between hydraulic forces (boundary shear stress) and the bed sediment.

Bed Load. Sediment that moves by rolling, sliding, or skipping along the bed and is essentially in contact with the streambed.

Bedrock. The undisturbed rock layer below the surface soil.

Bent. a substructure unit made up of two or more column or column-like members connected at their top-most ends by a cap, strut, or other member holding them in their correct positions.

Berm. (Berme.) The line, whether straight or curved, that defines the location where the top surface of an approach embankment or causeway is intersected by the surface of the side slope. This term is synonymous with ―Roadway Berm.

Blanket. A protection against stream scour placed adjacent to abutments and piers, covering the streambed for a distance from these structures considered adequate.

Bottom Time. The total elapsed time measured in minutes from the time when the diver leaves the surface in descent to the time that the diver begins ascent.

Box Culvert. A culvert of rectangular or square cross-section.

Bracing. A system of secondary members maintaining the geometric configuration of primary members.

Breathing Mixture. Air or a mixture of gases breathed by a diver which contains a physiologically appropriate proportion of oxygen.

Breastwall. The portion of an abutment between the wings and beneath the bridge seat; the breast wall supports the superstructure loads and retains the approach fill; see **stem.**

Bridge. "A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it includes multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening." (23 CFR 650.305)

Bridge Elements. Individual parts of a bridge that are subsets of bridge components, inventoried separately as functional groups. Elements inventoried on the bridge include: the total quantity for each element and the element quantity that exists in each of four condition states reported to the NBI in accordance with 23 U.S.C. 144(d)(2).

Bridge Inspector's Reference Manual (BIRM). A comprehensive FHWA manual on procedures and techniques for inspecting and evaluating a variety of in-service highway bridges. This manual is available at: https://www.fhwa.dot.gov/bridge/nbis/pubs/nhi23024.pdf. (23 CFR 650.305)

Bridge Pad. The raised, leveled area upon which the pedestal, shoe, sole, plate or other corresponding element of the superstructure takes bearing by contact. Also called Bridge Seat Bearing Area.

Bridge Seat. The top surface of an abutment or pier upon which the superstructure span is placed and supported; for an abutment it is the surface forming the support for the superstructure and from which the backwall rises; for a pier, it is the entire top surface.

Bulkhead. A retaining wall-like structure commonly composed of driven sheet piles or a barrier of wooden timbers or reinforced concrete members.

Butt Weld. A weld joining two plates or shapes end to end; also splice weld.

C

Caisson. A rectangular or cylindrical chamber for keeping water or soft ground from flowing into an excavation.

Cap. The topmost portion of a pier or a pile bent that serves to distribute the loads upon the columns or piles and to hold them in their proper relative positions; see **pier cap**, **pile cap.**

Capillary Action. The process by which water is drawn from a wet area to a dry area through the pores of a material.

Capstone. 1. The topmost stone of a masonry pillar, column, or other structure requiring the use of a single capping element. 2. One of the stones used in the construction of a stone parapet to make up its topmost or weather course. Commonly this course projects on both the inside and outside beyond the general surface of the courses below it.

Cathode. A surface that accepts electrons and does not corrode.

Cement Paste. The plastic combination of cement and water that supplies the cementing action in concrete.

Cement Matrix. The binding medium in a mortar or concrete produced by the hardening of the cement content of the mortar, concrete mixture of inert aggregates, or hydraulic cement and water.

Channel Profile. A longitudinal section of a channel along its centerline.

Classification Societies. A society for the promulgation of rules for the construction of vessels, the supervision of such construction, the classification of vessels according to merit, and the publication of a register listing them and classifying their essential features.

Cofferdam. A temporary dam-like structure constructed around an excavation to exclude water; see **sheet pile cofferdam**.

Column Bent. A bent-shaped pier that uses columns incorporated with a cap beam.

Composite. Composite materials are engineered materials made from two or more constituent materials with significantly different physical or chemical properties. Composites use a polymer matrix material, often called a resin solution. There are many different polymers available, including polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, and polypropylene. The reinforcement materials are fibers or ground minerals.

Concrete. A stone-like mass made from a mixture of aggregates and cementing material, which is moldable prior to hardening.

Consolidation. The time-dependent change in volume of a soil mass under compressive load caused by water slowly escaping from the pores or voids of the soil.

Continuous Spans. Spans designed to extend without joints over one or more intermediate supports.

Creep. An inelastic deformation that occurs under a constant load, below the yield point, and increases with time.

Culvert. A drainage structure beneath an embankment (e.g., corrugated metal pipe, concrete box culvert).

Cutwater. A wedge-shaped projection on a bridge pier, which divides the flow of water and prevents debris buildup against the pier.

Cyclical Maintenance. Activities performed on pre-determined intervals that aim to preserve and delay the deterioration of bridge elements or components conditions.

Cylinder. A pressure vessel for the storage of gases.

Cylinder Pier. A type of pier produced by sinking a cylindrical steel shell to a desired depth and filling it with concrete. The foundation excavation may be made by open dredging within the shell, and the sinking of the shell may proceed simultaneously with the dredging.

D

Debris. Material including floating wood, trash, suspended sediment, or bed load moved by a flowing stream.

Decompression. The reduction of environmental or ambient pressure to atmospheric pressure.

Decompression Chamber. A pressure vessel for human occupancy, such as a surface decompression chamber, closed bell, or deep diving system used to decompress divers and to treat decompression sickness.

Decompression Schedule. A time-depth profile with a specified bottom time and depth, whose application is calculated to reduce the pressure on a diver safely.

Decompression Sickness. A condition with a variety of symptoms that may result from the formation of gas or gas bubbles in the blood or other tissues of divers during or subsequent to ascent or other pressure reduction. Residual audio-vestibular or neurological symptoms involve permanent damage to the hearing or balance system or to the peripheral or central nervous system, respectively. Serious symptoms involve the sensory or neurological systems significantly and include numbness, paralysis, visual and hearing disturbances, choking, shock, and unconsciousness. Pain-only symptoms are limited to localized joint and muscle pain, minor muscle weakness and skin itching, tingling, or redness. Pain-only symptoms that recur during or after recompression therapy are classified as serious symptoms.

Degradation. General progressive lowering of a stream channel by scour.

Diaphragm. A transverse member placed within a member or superstructure system to distribute stresses and improves strength and rigidity; see **bracing.**

Dimension Stone. A stone of relatively large dimensions, the face surface of which is either chisel or margin drafted but otherwise rough and irregular; commonly called either —rock face or —quarry face.

Diver. A specially trained individual who inspects the underwater portion of a bridge substructure and the surrounding channel.

Dolphin. A group of piles driven close together or a caisson placed to protect portions of a bridge exposed to possible damage by collision with river or marine traffic.

Downline. A piece of substantial cordage running from a point at the surface to the underwater workplace and kept under some tension. It can be used as a guideline for divers descending or ascending, for depth control, and as a guide for transfer of tools and equipment between the surface and the diver.

Drilled Shaft. A deep foundation system constructed by the excavation of a cylindrical shaft that is filled with concrete. The term “caisson” is a common misnomer often used interchangeably with drilled shaft in modern language.

Dry Suit (variable volume). A diving suit capable of being inflated for buoyancy or insulation, which keeps the diver’s body essentially dry.

Dumbbell Pier. A pier consisting of two cylindrical or rectangular-shaped piers joined by an integral web.

E

Ebb Tide. The flow of water from the bay or estuary to the ocean.

Efflorescence. A deposit on concrete, brick, stone, or mortar caused by the crystallization of carbonates brought to the surface by moisture in the masonry or concrete. Efflorescence is a combination of calcium carbonate leached out of the cement paste and other recrystallized carbonate and chloride compounds.

Electrolyte. A medium of air, soil, or liquid carrying ionic current between two metal surfaces, the anode, and the cathode.

Element Level Bridge Inspection Data. Quantitative condition assessment data, collected during bridge inspections that indicates the severity and extent of defects in bridge elements. (23 CFR 650.305)

Epoxy. A synthetic resin that cures or hardens by a chemical reaction between components that are mixed together shortly before use.

Erosion. Wearing away of soil by flowing water not associated with a channel; see **scour.**

Ettringite. An internal deficiency that occurs in concrete from the reaction of sulfates, calcium aluminates, and water (BIRM).

Exudation. A white deposit found on the underside of concrete structures due to the leaching of cement materials from the concrete matrix.

F

Factor of Safety. A factor or allowance predicated by common engineering practice upon the failure stress or stresses assumed to exist in a structure or a member or part thereof. Its purpose is to provide a margin in the strength, rigidity, deformation, and endurance of a structure or its component parts compensating for irregularities existing in structural materials and workmanship, uncertainties involved in mathematical analysis and stress distribution, service deterioration and other unevaluated conditions.

Falsework. A temporary wooden or metal framework built to support the weight of a structure during the period of its construction and until it becomes self-supporting.

Fascia. An outside, covering member designed on the basis of architectural effect rather than strength and rigidity, although its function may involve both.

Fascia Girder. An exposed outermost girder of a span sometimes treated architecturally or otherwise to provide an attractive appearance.

Fender. A structure that acts as a buffer to protect the portions of a bridge exposed to floating debris and water-borne traffic from collision damage; sometimes called an ice guard in regions with ice floes.

Fender Pier. A pier-like structure that performs the same service as a fender but is generally more substantially built. These structures may be constructed entirely or in part of stone or concrete masonry.

Fiber Reinforced Polymer Composite. Fiber reinforced polymer composite (FRP) is also known as fiberglass reinforced plastic and is a composite made from glass fiber or carbon fiber reinforcement in a plastic (polymer) matrix. With reinforcement of the plastic matrix, a wide variety of physical strengths and properties can be designed into the material. Additionally, the type and configuration of the reinforcement can be selected, along with the type of polymer and additives within the matrix.

Fiberglass. A material made from extremely fine fibers of glass. It is used as a reinforcing agent for many polymer products; the resulting composite material is properly known as fiber reinforced polymer (FRP) or glass reinforced plastic (GRP).

Fill. Material, usually earth, used to change the surface contour of an area, or to construct an embankment.

Filler Metal. Metal prepared in wire, rod, electrode, or other adaptable form to be fused with the structure metal in the formation of a weld.

Flange. The (usually) horizontal parts of a rolled I-shaped beam or of a built-up girder extending transversely across the top and bottom of the web.

Floating Bridge. A bridge supported by floating on pontoons moored to the lakebed or riverbed; a portion may be removable to facilitate navigation.

Flood Frequency. The average time interval in years in which a flow of a given magnitude, taken from an infinite series, will recur.

Flood Tide. Flow of water from the ocean to the bay or estuary.

Footing. The enlarged, lower portion of a substructure that distributes the structure load either to the earth or to supporting piles; the most common footing is the concrete slab; footer is a colloquial term for footing.

Forms. The molds that hold concrete in place while it is hardening; also known as form work, shuttering; see **lagging**, **stay-in-place forms**.

Foundation. The supporting material upon which the substructure portion of a bridge is placed.

Foundation Grillage. A construction consisting of steel, timber, or concrete members placed in layers. Each layer is normal to those above and below it, and the members within a layer are generally parallel, producing a crib or grid-like effect. Grillages are usually placed under very heavy concentrated loads.

Foundation Load. The load resulting from traffic, superstructure, substructure, approach embankment, approach causeway, or other incidental load increment imposed upon a given foundation area.

Foundation Pile. A pile, whether of wood, reinforced concrete, or metal used to reinforce a foundation and render it satisfactory for the supporting of superimposed loads.

Foundation Seal. A mass of concrete placed underwater within a cofferdam for the base portion of the structure to close or seal the cofferdam against incoming water; see **tremie.**

Foundation Stone. The stone or one of the stones of a course having contact with the foundation of a structure.

Feet of Seawater (fsw). A unit of pressure generally defined as 1/33 of a standard atmosphere, which represents the pressure exerted by a foot of seawater having a specific gravity of 1.027, equal to approximately 0.445 pounds per square inch (psi).

Full-face Diving Mask. A type of diving mask that seals the whole of the diver's face from the water and contains a mouthpiece, demand valve, or constant flow gas supply that provides the diver with breathing gas.

G

Grillage. A platform-like construction or assemblage used to ensure the distribution of loads upon unconsolidated soil material.

Grout. Mortar having a sufficient water content to render it free-flowing, used for filling (grouting) the joints in masonry, for fixing anchor bolts, and for filling cored spaces; usually a thin mix of cement, water, and sometimes sand or admixtures.

Guard Pier. (Fender Pier.) A pier-like structure built at right angles with the alignment of a bridge or at an angle therewith conforming to the flow of the stream current and having adequate length, width, and other provisions to protect the swing span in its open position from a collision with passing vessels or other water-borne equipment and materials. It also serves to protect the supporting center pier of the swing-span from injury and may or may not be equipped with a rest pier upon which the swing span in its open position may be latched. The type of construction varies with navigation and stream conditions, from a simple pile and timber structure or a wooden crib-stone ballasted structure to a solid masonry one or to a combination construction. In locations where ice floes or other water-borne materials may accumulate upon the upstream pier end, a cutwater or a starling is an essential detail.

H

Hammerhead Pier. A pier with a single cylindrical or rectangular shaft and a relatively long, transverse cap; also known as a tee pier or cantilever pier.

Hands-on Inspection. Inspection within arms-length of the member. Inspection uses visual techniques that may be supplemented by nondestructive evaluation techniques. (23 CFR 650.305)

H-Beam. (H-Pile.) a rolled steel bearing pile having an H-shaped cross-section.

Head. A measure of water pressure expressed in terms of an equivalent weight or pressure exerted by a column of water; the height of the equivalent column of water is the head.

Headwater. The source or the upstream waters of a stream.

Heavy Gear Diving. Diving that uses standard deep-sea dress, including helmet and brass breastplate, suit of rubberized canvas, and heavy weighted shoes.

Helmet. (Open-circuit or surface-supplied). Breathing and protective equipment that encloses the diver's head.

Hyperbaric Conditions. Pressure conditions in excess of surface pressure (1 ata).

I

Ice Floe. A large flat free mass of floating ice.

In-Depth Inspection. A close-up, detailed inspection of one or more bridge members located above or below water, using visual or nondestructive evaluation techniques as required to identify any deficiencies not readily detectable using routine inspection procedures. Hands-on inspection may be necessary at some locations. In-depth inspections may occur more or less frequently than routine inspections, as outlined in bridge-specific inspection procedures. (23 CFR 650.305)

Initial Inspection. The first inspection of a new, replaced, or rehabilitated bridge. This inspection serves to record required bridge inventory data, establish baseline conditions, and establish the intervals for other inspection types. (23 CFR 650.305)

Inspection Report. The document summarizes the bridge inspection findings and recommendations, and identifies the team leader responsible for the inspection and report. (23 CFR 650.305)

In-the-Dry. A phrase used to describe construction work completed below the water surface within a cofferdam, dikes, or portable dams creating a dry work environment.

In-the-Wet. A phrase used to describe construction work completed below the water surface without the use of a cofferdam, dikes, or portable dams.

Inventory Data. All data reported to the National Bridge Inventory in accordance with the Specifications for the National Bridge Inventory. (23 CFR 650.317(b)(1)).

Isotropic. Having the same material properties in all directions, e.g., steel.

L

Lateral Restraint. Bracing that restricts lateral movement of a bridge element or component.

Limnoria. *Limnoria Tripunctata*, a free-swimming crustacean (wood gribble) found in salt water and brackish water that attacks timber piles by burrowing into the outside surface, eventually producing an hourglass shape.

Load Posting. Regulatory signs installed in accordance with the *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD)and State or local law that represent the maximum vehicular live load that the bridge may safely carry. (23 CFR 650.305)

Load Rating. The analysis to determine the safe vehicular live load carrying capacity of a bridge using bridge plans supplemented by measurements and other information gathered from an inspection. (23 CFR 650.305)

Lockout. The placement of a lockout device on an energy-isolating device, in accordance with an established procedure, ensuring that the energy-isolating device and the equipment being controlled cannot be operated until the lockout device is removed. (29 CFR 1910.147)

M

Magnetic Arc Blow (Arc Wander). Arc deflection caused by the distortion of a magnetic field produced by an electric arc current.

Mask. (Open-circuit or surface-supplied). Breathing and protective equipment that covers a diver's face.

Masonry. The portion of a structure composed of stone, brick, or concrete block placed in courses and usually cemented with mortar.

Meander. A twisting, winding action from side to side; characterizes the serpentine curvature of a narrow, slow-flowing stream in a wide flood plain.

Modulus of Elasticity. The tendency of an object to deform along an axis when opposing forces are applied along that axis; it is defined as the ratio of tensile stress to tensile strain.

Mortar. Paste of portland cement, sand, and water laid between bricks, stones, or blocks.

N

National Bridge Inspection Standards (NBIS). Federal regulations establishing national policy regarding bridge inspection organization, bridge inspection frequency, inspector qualifications, inventory requirements, report formats, and inspection and rating procedures, as described in 23 CFR 650 Subpart C.

National Bridge Inventory (NBI). An aggregation of State transportation department, Federal agency, and Tribal government bridge and associated highway data maintained by the Federal Highway Administration (FHWA). The NBIS requires each State transportation department, Federal agency, and Tribal government to prepare and maintain a bridge inventory, which must be submitted to FHWA in accordance with these specifications on an annual basis or whenever requested. (23 CFR 650.315)

Navigable Waterway. Navigable waterways are determined by the Commandant of the United States Coast Guard. 33 CRF 2.36(a), defines navigable waterways as consisting of:

> "Territorial seas of the United States.
> Internal waters of the United States that are subject to tidal influence; and
> Internal waters of the United States not subject to tidal influence that:
> a. Are or have been used, or are or have been susceptible for use, by themselves or in connection with other waters, as highways for substantial interstate or foreign commerce, notwithstanding natural or man-made obstructions that require portage, or
> b. A governmental or non-governmental body having expertise in waterway improvement, determines to be capable of improvement at a reasonable cost (a favorable balance between cost and need) to provide, by themselves or in connection with other waters, highways for substantial interstate or foreign commerce."

No-decompression Diving. Diving that involves depths and times shallow and short enough so that controlled ascent can be made without stops or stages, e.g., dives within the time-depth limits of the no-decompression table in the *U.S. Navy Diving Manual*.

Non-isotropic. Having different physical properties along different axis, e.g., unreinforced concrete is strong in compression, but relatively weak in tension.

P

Pedestal. Concrete or built-up metal member constructed on top of a bridge seat for the purpose of providing a specific bearing seat elevation.

Penetration. When applied to creosoted lumber, the depth to which the surface wood is permeated by the creosote oil; when applied to pile driving; the depth a pile tip is driven into the ground.

Pier. A substructure unit that supports the spans of a multi-span superstructure at an intermediate location between its abutments.

Pivot Pier. Center Pier. A term applied to the center bearing pier supporting a swing span while operating throughout an opening-closing cycle. This pier is commonly circular in shape but may be hexagonal, octagonal, or even square in plan.

Pier Cap. The topmost horizontal portion of a pier that distributes loads from the superstructure to the vertical pier elements.

Pile. A shaft-like linear member which carries loads to underlying rock or soil strata.

Pile Bent. A row of driven or placed piles extending above the ground surface supporting a pile cap; see **bent**.

Pile Cap. A slab or beam that acts to secure the piles in position laterally and provides a bridge seat to receive and distribute superstructure loads.

Pile Foundation. A foundation supported by piles in sufficient number and to a depth adequate to develop the bearing resistance required to support the substructure load.

Pile Splice. One of the means of joining one pile upon the end of another to provide greater penetration length.

Piling. Collective term applied to a group of piles in a construction; see **pile**, **sheet piles.**

Plinth Course. The course of courses of stone forming the base portion of an abutment, pier, parapet, or retaining wall and having a projection or extension beyond the general surface of the main body of the structure.

Pneumofathometer. A depth measuring device indicating depth in fsw, consisting of an open-ended hose fixed to the diver, with the other end connected to an air supply and pressure gauge at the surface.

Pointing. The operations incident to the compacting of the mortar in the outermost portion of a joint and the troweling or other treatment of its exposed surface to secure water tightness or desired architectural effect or both.

Polymer. See **Composite.**

Pressure. Force per unit of area. In diving, pressure denotes an exposure greater than surface pressure (1 atm).

Protective System. A system used to protect bridges from environmental forces that cause steel and concrete to deteriorate and timber to decay, typically a coating system.

Pultrusion. A continuous process for manufacturing composites that have a uniform cross-sectional shape. The process consists of pulling a fiber-reinforcing material through a resin impregnation chamber or bath and through a shaping die, where the resin is subsequently cured. There are several types of pultrusion equipment, such as open bath, resin injection, and direct die injection equipment. (40 CFR 63.5935)

Q

Quality Assurance (QA). The use of sampling and other measures to assure the adequacy of quality control procedures to verify or measure the quality level of the entire bridge inspection and load rating program. (23 CFR 650.305)

Quality Control (QC). Procedures that are intended to maintain the quality of a bridge inspection and load rating at or above a specified level. (23 CFR 650.305)

Quenching. Rapidly cooling a piece of metal to achieve or modify specific properties like hardness, strength, or toughness.

R

Rake. An angle of inclination of a surface in relation to a vertical plane, also known as batter.

Reach. Section of a stream or river along which similar hydrologic conditions exist, such as discharge, depth, area, and slope.

Rebar. See **Reinforcing Bar.**

Recompression. An increase in pressure that is calculated to eliminate the symptoms of decompression sickness when applied to a diver in a pressure vessel for human occupancy as therapy.

Reinforcement. Rods or mesh embedded in concrete to strengthen it.

Reinforcing Bar. A steel bar, plain or with a deformed surface that bonds to the concrete and supplies tensile strength to the concrete.

Resin. See **Composite.**

Rest Pier. A pier supporting the end of a movable bridge span when in its closed position.

Rigid Frame Pier. A pier with two or more columns and a horizontal beam on top constructed monolithically to act like a frame.

Riprap. Stones, blocks of concrete, or other objects placed upon river and stream beds and banks, lake, tidal or other shores to prevent scour by water flow or wave action.

Risk. The exposure to the possibility of structural safety or serviceability loss during the interval between inspections. It is the combination of the probability of an event and its consequence. (23 CFR 650.305)

Runoff. The quantity of precipitation that flows from a catchment area past a given point over a certain period.

S

Sacrificial Protection. See **Cathodic Protection.**

Scour. Erosion of streambed or bank material due to flowing water; often considered as being localized around piers and abutments of bridges. (23 CFR 650.305)

Scour Appraisal. A risk-based and data-driven determination of a bridge's vulnerability to scour, resulting from the least stable result of scour that is either observed or estimated through a scour evaluation or a scour assessment. (23 CFR 650.305)

Scour Assessment. The determination of an existing bridge's vulnerability to scour that considers stream stability and scour potential as described in HEC 20 and other scour-related data sources. (23 CFR 650.305)

Scour Critical Bridge. A bridge with a foundation member that is unstable or may become unstable, as determined by the scour appraisal. (23 CFR 650.305)

Scour Evaluation. The application of hydraulic analysis as described in "Evaluating Scour at Bridges," 5th Ed., Hydraulic Engineering Circular (HEC) No. 18, FHWA-HIF-12-003, April 2012 (HEC 18) and "Stream Stability at Highway Structures," 4th Ed., HEC No. 20, FHWA-HIF-12-004, April 2012 (HEC 20) to estimate scour depths and determine bridge and substructure stability considering potential scour. (23 CFR 650.305)

Scour Plan of Action (POA). Procedures for bridge inspectors and engineers in managing each bridge determined to be scour critical or that has unknown foundations. (23 CFR 650.305)

Scuba Diving. A diving mode independent of surface supply in which the diver uses open circuit self-contained underwater breathing apparatus.

Sheet Pile Cofferdam. A wall-like barrier composed of driven piling constructed to surround the area to be occupied by a structure and permit dewatering of the enclosure so that the excavation may be performed in the open air.

Sheet Piles. Flattened Z-shaped interlocking piles driven into the ground to keep earth or water out of an excavation or to protect an embankment.

Sheet Piling. A general or collective term used to describe a number of sheet piles installed to form a crib, cofferdam, bulkhead, etc.; also known as sheeting.

Silt. Very finely divided siliceous or other hard rock material removed from its mother rock through erosive action rather than chemical decomposition.

Slope. The inclination of a surface expressed as a ratio of one unit of rise or fall for so many horizontal units.

Slope Protection. A thin surfacing of stone, concrete or other material deposited upon a sloped surface to prevent its disintegration by rain, wind, or other erosive action; also known as slope pavement.

Specifications for the National Bridge Inventory (SNBI). Developed in coordination with the NBIS regulation (23 CFR 650, Subpart C), the AASHTO MBE*,* the AASHTO MBEI, and the FHWA BIRM. The SNBI is incorporated by reference (23 CFR 650.317) in the NBIS regulation and provides the specifications for reporting data for highway bridges, open to the public, to the FHWA for inclusion in the NBI.

Splash Zone. The section of a structure in a marine environment that is recurrently exposed to air and water due to changing tides or wave action.

Spur Dike. A projecting jetty-like construction placed adjacent to an abutment or embankment to prevent scour.

Standby Diver. A diver available to go to the aid of another diver in the water.

Starling. An extension at the upstream end only, or at both the upstream and downstream ends of a pier built with surfaces battered, thus forming a cutwater to divide and deflect the stream waters and floating debris and, correspondingly, when on the downstream end, functioning to reduce crosscurrents, swirl and eddy action which are productive of depositions of sand, silt, and detritus downstream from the pier.

Stem. The vertical wall portion of an abutment retaining wall or solid pier; see **Breastwall.**

Stone Masonry. The portion of a structure composed of stone generally placed in courses with mortar.

T

Tagout. The placement of a tagout device on an energy isolating device, in accordance with an established procedure, to indicate that the energy isolating device and the equipment being controlled may not be operated until the tagout device is removed. (29 CFR 1910.147)

Tail Water. Water ponded below the outlet of a waterway, thereby reducing the amount of flow through the waterway; see **Headwater.**

Team Leader. The on-site, nationally certified bridge inspector in charge of an inspection team and responsible for planning, preparing, performing, and reporting on bridge field inspections. (23 CFR 650.305)

Teredo. *Teredo Navalis* a marine borer, mollusk (shipworm) that enters timber piles and burrows parallel to the wood grain, forming interior tunnels.

Thermoplastic. A polymer that turns into a liquid when heated and freezes to a very glassy state when cooled.

Tidal Zone. The portion of a structural element in a marine environment between the Mean Lower Low Water (MLLW) and the Mean High Water (MHW), based on the MLLW datum.

Toe Wall. A relatively low retaining wall placed near the “toe-of-slope” location of an embankment to protect against scour or to prevent the accumulation of stream debris, also known as footwall.

Tremie. A steel tube, usually with a hopper on the top that is fed concrete from a pump by discharging from a bucket or directly from a ready-mix truck.

Trestle. A bridge structure consisting of spans supported on braced towers or frame bents.

U

Umbilical. The composite hose bundle between a dive location and a diver or bell, or between a diver and a bell that supplies the diver or bell with breathing gas, communications, power, or heat as appropriate to the diving mode or conditions and includes a safety line between the diver and the dive location.

Underwater Bridge Inspection Diver. Diver who performs inspection of the underwater portion of the bridge and has completed FHWA-approved underwater bridge inspection training scoring 70 percent or greater on an end-of-course assessment. (23 CFR 650.309(e))

Underwater Inspection. Inspection of the underwater portion of a bridge substructure and the surrounding channel, which cannot be inspected visually at low water or by wading or probing, and generally requiring diving or other appropriate techniques. (23 CFR 650.305)

Unknown Foundations. Foundations of bridges over waterways where complete details are unknown because either the foundation type and depth are unknown, or the foundation type is known, but its depth is unknown, and therefore cannot be appraised for scour vulnerability. (23 CFR 650.305)

V

Volume Tank. A pressure vessel connected to the outlet of a compressor and used as an air reservoir.

W

Wale. (Wale-Piece, Waler.) A wooden, metal, or composite piece or an assemblage of pieces placed either inside or outside, or both inside and outside, the wall portion of a crib, cofferdam, or similar structure, usually in a horizontal position, to maintain its shape and increase its rigidity, stability, and strength.

Waterway Area. The entire area beneath the bridge that is available to pass flood flows.

Waterway Opening. The available width for the passage of water beneath a bridge.

Wingwall. The retaining wall extension of an abutment intended to restrain and hold in place the side slope material of an approach roadway embankment.

Work Site. A vessel or surface structure from which dives are supported or the underwater location where work is being performed.

IMAGE SOURCES

The following organizations provided figures in this reference manual:

- ***Global Diving and Salvage.***
  Figure 22. Photo. Marine construction site.
  Figure 29. Photo. Dive team and support equipment on a construction site.
  Figure 30. Photo. Commonly used pneumatic underwater tools.
  Figure 34. Photo. Diver operating a water blasting system.
- ***PCL Construction.***
  Figure 25. Photo. Conventional cofferdam around a bridge pier.
  Figure 28. Photo. Example of proprietary barrier systems.
- ***JF Brennan Company.***
  Figure 39. Photo. Grout pump.
  Figure 50. Photo. Reinforcing steel prepared for repair.
- ***SubSalve USA.***
  Figure 43. Photo. Diver using a lift bag.

FHWA is the source of all other figures in this manual.

CHAPTER 1. UNDERWATER REPAIR AND REHABILITATION OF BRIDGES AND STRUCTURES

1.1 INTRODUCTION

1.1.1 Purpose

This manual is intended to serve as a reference for engineers, inspectors, and other technical personnel involved in the design, construction, inspection, or administration of underwater bridge repair and rehabilitation projects. It addresses design and construction issues that should be considered when evaluating various construction options to ensure a successful project.

1.1.2 Background

As the Nation's network of structures and bridges ages beyond their initially designed service life, efforts should be made to preserve these vital resources. Costs associated with replacement can be prohibitively high, necessitating the need to focus on repair and rehabilitation strategies. The location of bridge components underwater presents unique challenges to repair and rehabilitation activities. This manual will highlight and evaluate these challenges and solutions to aid the reader in developing cost-effective and durable repair and rehabilitation designs and procedures.

1.1.3 Scope

This manual is intended for bridge engineers, bridge owners, and bridge preservation practitioners who prepare plans or oversee bridge repair and rehabilitation programs and activities.

1.1.4 Bridge Preservation and Preventive Maintenance

Bridge preservation is actions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good or fair condition; and extend their service life. Preservation actions may be cyclic or condition-driven activities, as illustrated in Figure 1. Cyclical maintenance activities typically do not involve underwater bridge components.

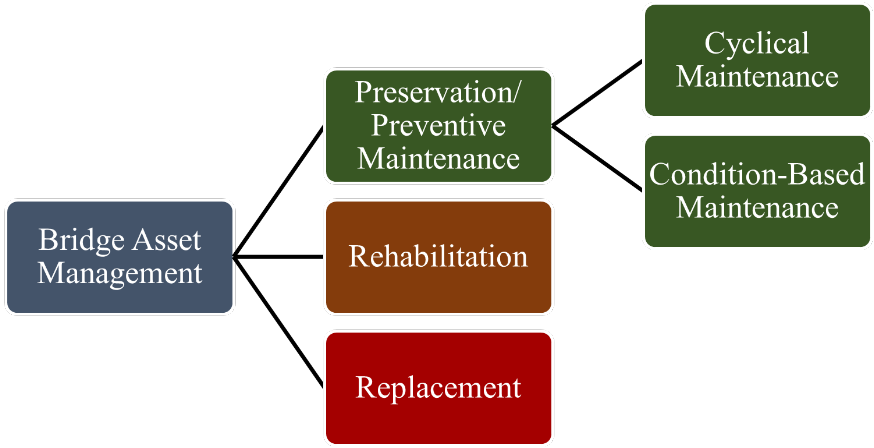

Figure 1. Graphic. Bridge action categories from the FHWA Bridge Preservation Guide, 2018.

Effective bridge preservation actions are intended to delay the need for costly rehabilitation or replacement before the onset of advanced deterioration. Bridge preservation should target bridges and bridge components that are in good or fair condition and still meet traffic demands. Figure 2 illustrates applicable work programs based on a bridge's condition over time. Bridge conditions are assessed through the National Bridge Inspection Standards, (NBIS) (23 CFR 650.305) required safety inspections and reported to the National Bridge Inventory (NBI). Bridge inspection reports help agencies identify which bridges may be good candidates for preservation.

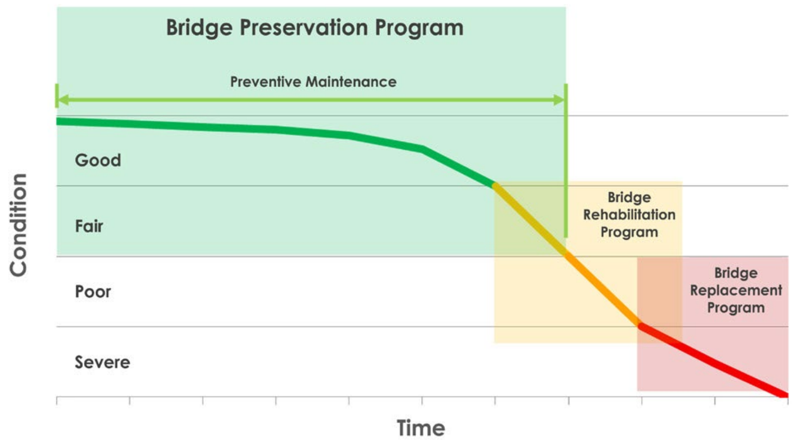

Figure 2. Graph. Bridge condition over time.

Preventive maintenance (PM) can be a cost-effective means of extending the service life of highway bridges. PM activities retard future deterioration and avoid large expenses in bridge rehabilitation or replacements. PM includes cyclical and condition-based activities, although cyclical PM activities do not typically involve underwater bridge components.

Condition-based maintenance activities are performed on bridge components or elements in response to deterioration identified through an inspection process. Condition-based maintenance improves the condition of that element but does not always result in an increase in the overall component condition rating (Table 2). Examples of common underwater maintenance activities are listed in Table 1.

Table 1. Examples of underwater condition-based maintenance activities.

Maintenance Activity	Components
Patch/Repair Substructure Concrete	Substructure/Culvert
Protective Coat/Concrete/Steel Substructure	Substructure/Culvert
Electrochemical Chloride Extraction (ECE) Treatment/ Cathodic Protection (CP) System	Substructure/Culvert
Spot/Zone/Full Painting Steel Substructure	Substructure
Pile Preservations (jackets/wraps/CP)	Substructure
Channel Cleaning/Debris Removal	Channel
Scour Countermeasure (installation/repair)	Channel

1.1.5 Rehabilitation

Rehabilitation can involve major work necessary to restore the structural integrity of a bridge. Bridge rehabilitation projects provide complete or nearly complete restoration of bridge elements or components. Each inspected bridge element is assigned a condition state (CS) ranging from one to four. Refer to the *Specifications for the National Bridge Inventory (SNBI)* for more information on bridge component condition ratings and bridge element condition states. Rehabilitation may be more cost-effective than preservation when elements are in poor (CS3) or severe (CS4) condition. Refer to Table 2 for information on how element condition states may be used to determine the most cost-effective action.

Table 2. Common actions based on bridge element condition states.

Condition State	Description of Element Condition	Common Actions [1]
1	Varies depending on element—Good	Preservation/Cyclic Maintenance
2	Varies depending on element—Fair	Cyclic Maintenance or Condition-Based Maintenance when cost-effective
3	Varies depending on element—Poor	Condition-Based Maintenance, or Rehabilitation—when quantity of poor exceeds a limit that condition-based maintenance is not cost-effective, or Replacement—when rehabilitation is not cost-effective.
4	Varies depending on element—Severe	Rehabilitation or Replacement

[1] The appropriate action for an element will also be dependent on the element quantity in each condition state.

Rehabilitation work can be done on one or multiple structural elements or components and can include repair and preservation activities as part of a rehabilitation project. These projects may involve significant engineering resources for design, a lengthy completion schedule, and considerable costs.

1.1.6 Underwater Inspection Report

The underwater bridge inspection report is an important resource when preparing rehabilitation plans or planning maintenance activities for elements below water. The routine underwater inspection report can allow the designer to narrow the project scope based on observed and reported conditions not typically accessible during a routine inspection. However, the design team should verify the report data through a special inspection to confirm quantities and conditions to be addressed in the design and preparation of the repair, rehabilitation and maintenance plans and specifications.

1.1.7 Performance Monitoring

Work performed during a repair, rehabilitation, or maintenance project should be monitored to ensure the desired performance. Performance monitoring is especially important when work is conducted underwater. The underwater environment makes construction activities challenging and can cause more rapid deterioration than above-water work.

Qualified topside inspectors or divers should inspect underwater work during construction. A baseline condition should be established immediately after work is complete, which can be used to evaluate performance over time.

Routine above-water inspections are normally performed every 24 months, while underwater inspections are typically performed every 60 months. Special attention should be given to underwater work during each inspection and compared to the post-repair baseline conditions reported by construction inspectors. Monitoring performance should continue for the remaining life of the structure. In rare situations, a special inspection may be warranted more frequently to monitor an underwater repair, especially if unique construction techniques are used or the repair is critical to bridge performance.

CHAPTER 2. UNDERWATER CONDITION ASSESSMENT AND STRUCTURAL ANALYSIS

2.1 INTRODUCTION

A thorough understanding of the existing conditions is important to a quality repair, rehabilitation, or maintenance project. It is not uncommon for a multidiscipline engineering team to be involved in complex repair projects, while some simple projects are performed by maintenance personnel using standard procedures. When applicable, underwater bridge elements are typically repaired in conjunction with above-water bridge components to improve efficiency and reduce cost.

2.2 CONDITION ASSESSMENT

2.2.1 General

A special underwater inspection for design purposes can be performed to confirm and accurately quantify the deterioration of underwater elements to be repaired. Routine underwater inspection reports can help the design team focus their scope. However, they may not be adequate to prepare comprehensive repair plans.

Deterioration of underwater bridge elements may be caused by vessel impact, environmental conditions, low-quality original construction materials and methods, bridge scour, or natural disasters such as earthquakes or floods.

Concrete is the most common material used to construct bridge substructures; however, various bridge types and substructure components can include members of steel, timber, and masonry. Deterioration mechanisms will only be briefly summarized in this manual.

2.2.2 Concrete

Concrete is the most common construction material for bridge substructures. The typical area where concrete deterioration first occurs is near the splash zone on submerged substructures. The cyclic wetting, drying, and high oxygenation of near-surface water in this region create conditions that can accelerate deterioration. This is also where freeze-thaw cycles are most active in cold climates.

Concrete deteriorates at a faster rate in salt water than it does in fresh water due to dissolved salts. Chlorides in the water from dissolved salts can penetrate the concrete and, over time, reach the reinforcing steel, causing corrosion. Reinforcing steel creates internal stress in the concrete because iron oxide, or rust, expands as it corrodes. This internal stress will ultimately cause cracks and spalls in the concrete, exposing the corroding reinforcement. Increased concrete cover and admixtures to reduce concrete permeability can delay chloride migration from the surface to the reinforcing steel.

In rare cases, the materials used in making the concrete can react with each other, causing the components' expansion and creating internal stress. An example of these reactions is an alkali-silica reaction (ASR), where alkalis present in the portland cement react with silica in the aggregate. Symptoms of ASR are map or pattern cracking and concrete swelling. Additional testing is needed to positively identify the presence of ASR.

In rare situations, various naturally occurring minerals in the water can react with components used in concrete and reduce durability and strength. Sampling and extensive testing may be needed to determine with certainty the deterioration mechanism when the cause is not readily apparent.

Concrete deterioration may be accelerated by poor initial construction or repair methods. These include:

- Exceeding specified water-cement ratios.
- Poor placement and consolidation.
- Inadequate reinforcing cover.
- Poor surface preparation.
- Construction damage due to coated reinforcing.
- Improper pile driving practices.

Visual and tactile inspections (Level I and Level II inspections) of concrete structures can typically identify the location of spalls, cracks, and delamination. In addition, these inspections may also identify cracking patterns, soft surfaces, and disintegration. Additional testing (Level III inspection) may include removing cores to perform laboratory testing and petrographic analyses. In most cases, Level III testing is performed on areas where internal deterioration is suspected. Coring concrete members when the observed cracking patterns do not appear related to corrosion or impact damage may be done as part of a Level III inspection. Core testing may include a petrographic analysis to examine the possible effect of chemical attacks such as alkali-aggregate reaction or delayed ettringite formation.

2.2.3 Steel

Steel corrosion can reduce the cross-sectional area of steel members when the steel protective system has failed or been damaged (Figure 3). Corrosion generally progresses faster in salt or brackish water or where various contaminants or natural corrosive substances, such as tannic acid, are present in fresh water.

Steel members can sustain damage during seismic events or impact caused by vessels or timber debris during flooding. Deformation of steel primary members can alter the load-carrying capacity of a bridge or create stress concentrations, which can later lead to cracks. Deformation should be accurately measured in detail and provided to a qualified engineering team to evaluate the damage.

Figure 3. Photo. Extreme section loss in a steel pile. (Source FHWA).

Visual and tactile inspections (Level I and Level II inspections) can typically identify areas of severe damage. Tools such as calipers or ultrasonic testing equipment (Level III inspection) can provide accurate data on remaining steel thickness, which is needed to perform a structural analysis of the steel member. The original steel thickness is also needed to assess the impact section loss has on member capacity. Original steel thickness can generally be obtained from plans or at a member location unaffected by deterioration.

2.2.4 Timber

Timber members are susceptible to natural decay and insect damage. Marine borers can damage timber in salt water. In addition, timber has natural abnormalities and discontinuities that can impact durability and performance. Common damage in timber members includes crushing, checking, and splitting, as well as abrasion resulting from ice, debris, or abrasive sediments carried in the flow.

Visual and tactile inspections (Level I and Level II inspections) can identify external areas of decay and physical damage; however, they will not identify internal deterioration. The physical sounding of timber members with a hammer is a common method to identify internal deterioration; however, this method can only detect near-surface defects. Typically, more extensive testing (Level III inspection) should be conducted to determine marine organisms' presence and identify internal deterioration. Refer to the FHWA *Underwater Bridge Inspection Reference Manual, September 2023* for methods to inspect timber for internal damage.

When internal damage is detected, it is important to measure the extent of the damage. It is not uncommon for timber members with internal decay to have an outer shell in good condition. This outer shell can provide good residual capacity to a timber pile, and accurate documentation of the extent of the decay can help determine the repair approach.

2.2.5 Masonry

Masonry elements are uncommon in modern bridge construction; however, they were used to construct bridge substructures before 1930. Deterioration of masonry structures includes weathering of stone or brick and erosion of mortar from joints (Figure 4). Physical damage can include spalling, cracking, and even loss of stones or brick. Most masonry substructures are repaired using concrete.

Figure 4. Photo. Masonry pier with weathered stone and mortar loss. (Source FHWA).

2.2.6 Scour

Foundations located in moving water are subject to the effects of scour, which can undermine spread footings and pile caps and increase exposed pile or drilled shaft lengths. Section 6.7 further addresses issues resulting from the effects of scour, along with countermeasures.

2.3 STRUCTURAL ANALYSIS

2.3.1 Introduction

Evaluating the effects of deterioration or damage on a substructure can be difficult. The engineer should decide whether the deterioration or damage affects the load-carrying capacity of the component. A nonstructural defect may affect the appearance or reduce durability but not member capacity. Assessing the effects of physical member defects, often the result of a known event, is generally less difficult than assessing the effects of material deterioration.

2.3.2 Spread Footings

Spread footings are designed to transfer bridge loads directly to bearing strata. Most spread footings are placed on non-erodible rock. However, limited geotechnical information during the bridge design process can result in spread footings placed on erodible strata (Figure 5). When a spread footing becomes undermined, load transfer begins to be impacted. Any undermining of a spread footing should be considered a critical finding and thoroughly investigated by a team of engineering experts to evaluate the impact. Undermining is discussed in more detail in Section 2.3.7.

Figure 5. Photo. Undermined spread footing. (Source FHWA).

2.3.3 Pile Foundations

Foundation piles are designed as either end bearing, skin friction, or with a combination of load transfer mechanisms. Pile capacity can be reduced by physical damage or scour. Concrete, steel, and timber are commonly used materials for foundation piles. Figure 6 shows an example of a pier footing founded on prestressed concrete piles.

Figure 6. Photo. Pile-supported footings. (Source FHWA).

Localized buckling can occur when corrosion or abrasion significantly reduces a steel pile's cross-section. Therefore, the exact location and precise measurement of the remaining cross-section are required for an accurate structural analysis.

Concrete pile capacity can be reduced by large spalls and corrosion of reinforcing steel. Accurate measurements are needed, and concrete testing may be necessary to assess pile condition.

Timber piles can have their cross-section reduced from the inside by decay and marine borers. In addition, exterior damage of timber piles can be caused by abrasion, mechanical damage, or insect or marine borer infestation. The *Underwater Bridge Inspection Reference Manual* presents specific tools to quantify internal section loss in timber piles.

When scour lowers the channel bottom around a pile, the unbraced length is increased, which can reduce the pile's load-carrying capacity. Additionally, if the pile relies on skin friction to develop the load capacity, further reduction in the pile capacity can occur. A thorough structural analysis should include a review of original design criteria, including soil information, pile driving records, and original design calculations. If design data is unavailable, the structural engineer should make appropriate conservative assumptions to determine the impact on pile capacity. Soil borings may be needed to evaluate geotechnical conditions, and extensive testing, such as pile integrity testing, may be needed to determine pile as-built lengths. In-situ pile length determination is generally relatively easy for steel and concrete piles; however, natural anomalies found in timber piles can make it challenging to determine a timber pile's length after installation.

2.3.4 Drilled Shafts

Drilled shafts, sometimes also referred to as caissons, are deep concrete foundations that transfer loads to bearing strata. They can vary in size significantly, with diameters as small as a few feet to more than 15 feet. Like piles, drilled shafts can be damaged by vessel impact and are susceptible to concrete deterioration, as discussed previously in this manual. Drilled shafts are also susceptible to deficiencies caused by construction practices which can result in poor-quality concrete and voids. Refer to Figure 7 for an example of a drilled shaft bent.

Figure 7. Photo. Drilled shaft bent. (Source FHWA).

If there is a poor seal, voids can develop along the seams of removable-type steel casings used to construct a drilled shaft. Water can enter removable type steel casing and wash the concrete out, creating voids or low-quality concrete along the seams. In extreme cases, the reinforcing steel can be exposed, and the capacity of the drilled shaft can be impacted.

Scour can also impact drilled shafts by increasing the unbraced length. In some cases, the shaft below the end of the steel casing is exposed, as evident by a highly irregular surface where the shaft was formed by natural soil. While the irregular surface is not considered a defect, it is a good indication that scour has occurred.

Significant increases in unbraced length and large voids should be evaluated by a structural engineer to determine the impact on load-carrying capacity.

2.3.5 Pier Walls

Pier walls are normally large substructures that transfer significant loads to the bridge foundation elements (Figure 8). Pier walls are susceptible to concrete deterioration mechanisms as previously discussed, especially in the splash zone and the near-surface water region.

Figure 8. Photo. Reinforced concrete pier wall. (Source FHWA).

Pier walls can normally withstand the impact of small vessels and some timber debris without a reduction in load-carrying capacity. Likewise, spalls and surface deficiencies typically do not impact load transfer appreciably; however, extreme cases of spalling and surface deficiencies should be evaluated in detail. Large vessels and barges, normally operating in navigable waterways, can cause significant impact damage to pier walls. If a significant vessel impact occurs, the pier may need to be evaluated by structural and geotechnical engineers. Normally an in-depth underwater inspection is needed to quantify all damage below water.

Scour can undermine pier wall foundations and should be thoroughly documented. Undermining is discussed in Section 2.3.7 below in more detail.

2.3.6 Caissons

Drilled shafts in modern bridge construction have largely replaced caissons, and the terms “drilled shaft” and “caissons” are used interchangeably in present-day vocabulary. Traditional caissons, as described here and shown in Figure 9, have been used on large bridges since the late 1800s. These caissons are large watertight chambers open on the bottom with a cutting edge along the perimeter. Water is forced out of the caisson with compressed air, and soil is removed from the bottom allowing the caisson to sink into the channel bottom.

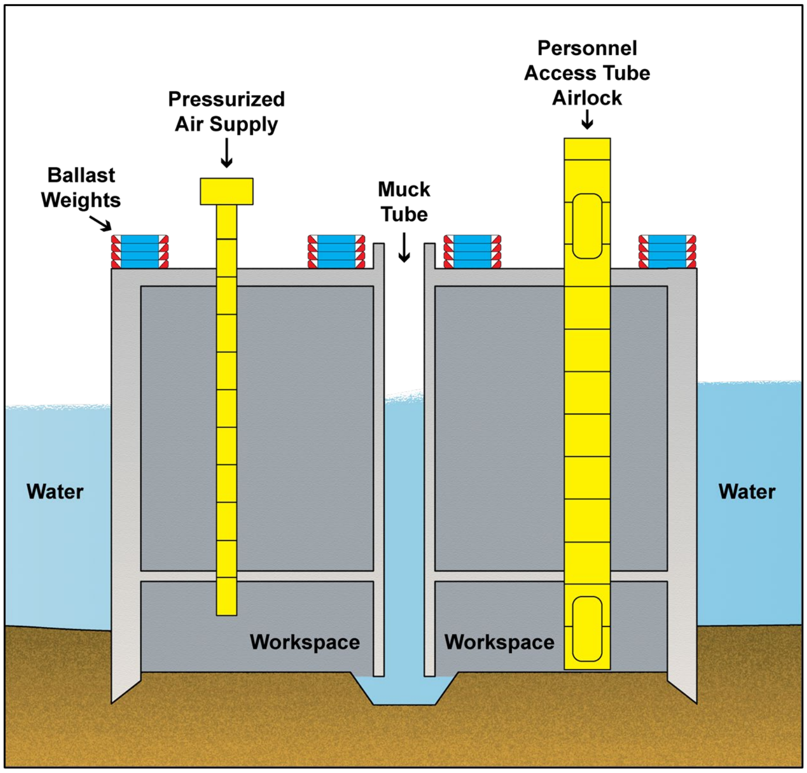

Figure 9. Illustration. Traditional caisson.

Today, the term caisson applies to footings sunk into position by excavation through or beneath the caisson structure. Refer to Section 2.3.4 for information on drilled shafts.

2.3.7 Undermining

Undermining can impact a bridge substructure's ability to transfer loads to bearing material. Undermining is more significant on spread footings than on pile-supported footings (Figure 10). Any undermining found on a spread footing is a critical finding and typically needs further investigation.

Since the maximum scour typically occurs during a high-water event, when undermining is discovered, infilling after the event could obscure the full extent of undermining. Undermining not only reduces the bearing area of a spread footing, but it can also reduce footing lateral restraint. Depending on the extent and location of the undermining, it may need evaluation.

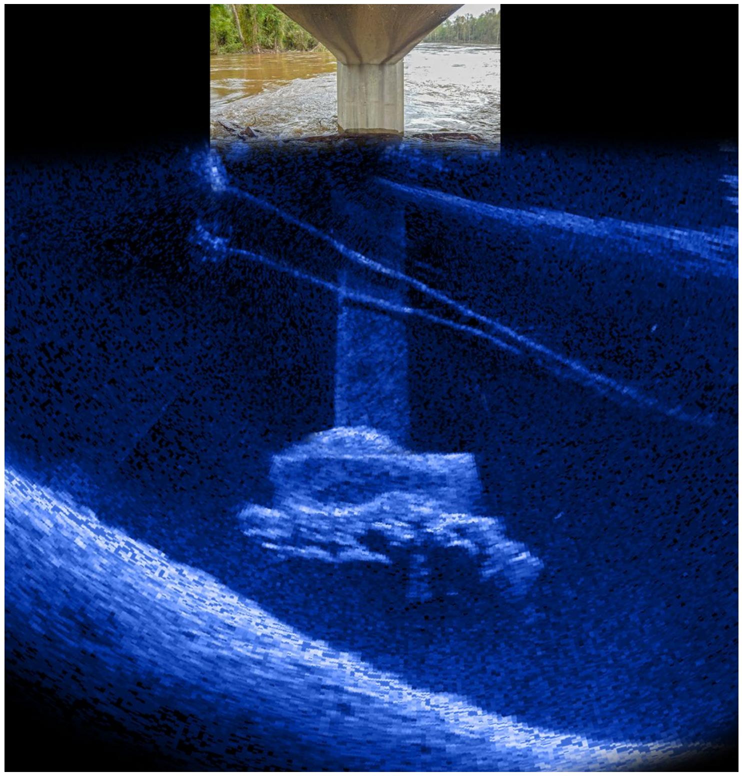

Figure 10. Graphic. Combined 2D acoustic image revealing an undermined footing. (Source FHWA).

CHAPTER 3. CONSTRUCTION MATERIALS

3.1 INTRODUCTION

Construction materials used for bridge repair are typically selected based on the original construction material type and the site's environmental characteristics. Agency or owner regulations, design and construction specifications, material availability, and the repair objective can also influence the material selection. For example, a temporary emergency repair of a steel pile may not require a protective coating over the steel.

This chapter introduces materials available for use in repair projects, and how these materials can be utilized in bridge repair applications is discussed in Chapters 6 and 7.

3.2 CONCRETE

3.2.1 General

Concrete is a common material used in bridge construction. Special equipment and skill are typically needed to place concrete in the splash zone or underwater. Examples of applications for underwater concrete include nonstructural applications such as foundation seals and structural repairs on pier walls, piles, columns, and footings.

3.2.2 Environmental Considerations for Concrete

Environmental factors at the bridge site can significantly impact the durability and performance of concrete members. These factors may include freeze thaw cycles, flow rates, pollution, and water chemistry. Many waterways carry sand or other abrasive particles downstream, resulting in increased abrasion rates of the upstream-facing portion of concrete members. In colder climates, ice floes are another factor that can have a deleterious effect on concrete, where an ice guard or other armament may be warranted as part of the repair.

Water chemistry is a major factor when determining the proper approach for preserving or repairing a concrete substructure. Water chemistry can be negatively impacted by farming operations, textile plants upstream of the bridge site, or pollution from stormwater runoff. Low pH, salt or chemical deicing agents, and elevated sulfate or chloride levels can rapidly deteriorate concrete and should be considered before implementing repairs.

Table 3 and Table 4 illustrate how environmental conditions can be used to classify the aggressiveness of the environment on concrete. If any of the environmental conditions outlined in Table 3 exist, the Florida Department of Transportation (FDOT) environmental classification is "extremely aggressive." Similarly, if any of the environmental conditions outlined in Table 4 exist, the FDOT environmental classification is "slightly aggressive."

Table 3. Extremely aggressive substructure FDOT environmental classification for concrete based on environmental conditions. (Source: FDOT Structures Manual)

Environment	Environmental Conditions			
	pH (ppm)	Cl (ppm)	SO_4 (ppm)	Resistivity, Ω (Ohm-cm)
Water	< 5.0	> 2,000	> 1,500	< 500
Soil	< 5.0	> 2,000	> 2,000	< 500

Table 4. Slightly aggressive substructure FDOT environmental classification for concrete based on environmental conditions. (Source: FDOT Structures Manual)

Environment	Environmental Conditions			
	pH (ppm)	Cl (ppm)	SO_4 (ppm)	Resistivity, Ω (Ohm-cm)
Water	> 6.0	< 500	< 150	> 3,000
Soil	> 6.0	< 500	< 1,000	> 3,000

For all other sites not falling into the two categories above, the classification of "moderately aggressive" would be appropriate.

3.2.3 Mix Design

Mix design is critical when concrete is placed underwater or in the splash zone. The aggregate size is an important consideration in mix design for underwater concrete. If a pump is going to be used to place the concrete, the maximum aggregate size is usually ¾-inch or less. Larger aggregates can be used if tremie installation methods are used and reinforcing spacing allows it. If the installation is nonreinforced, the maximum aggregate size is normally 1½-inches.

Admixtures are used to improve the characteristics of underwater concrete. Improved workability can be achieved by using air-entraining admixtures, and retarding admixtures can be beneficial in larger pours to maintain as high a slump as possible during installation. Normally a slump between 6 to 9 inches is desirable for placing underwater concrete.

Relatively rich mixtures with water cement ratios of 45 to 55 percent by volume of total aggregate, and air contents of up to approximately 5 percent, are typically used for underwater concrete mix designs. The mix design should be tested at the project site before final approval using an underwater placement box to evaluate surface flatness, laitance, and concrete quality at the farthest distance from the tremie or pump discharge. The placement box is a wooden form simulating the size and characteristics of the repair and is typically constructed as close to the intended construction site as possible to simulate actual conditions expected during the installation. While production concrete is being placed, it is advisable to perform regular slump and air content tests to ensure flowability during installation.

3.2.4 Placement

The two primary methods used to place concrete underwater are by a tremie or a concrete pump. A tremie uses a pipe to allow concrete to flow by gravity to the placement location below water (Figure 11). A concrete pump uses pressure to force the concrete through a hose or pipe to the destination. Both these techniques require special care to ensure the integrity of the concrete mass during installation by keeping the concrete isolated from the surrounding water. After a large enough mass of concrete is deposited, the discharge of the tremie or pump is maintained inside the mass concrete for 3 to 5 feet, protecting most of the concrete from direct contact with the water. Careful monitoring of the underwater pour is needed to ensure quality concrete placement. Loss of seal is the most common cause of low-quality concrete placement underwater.

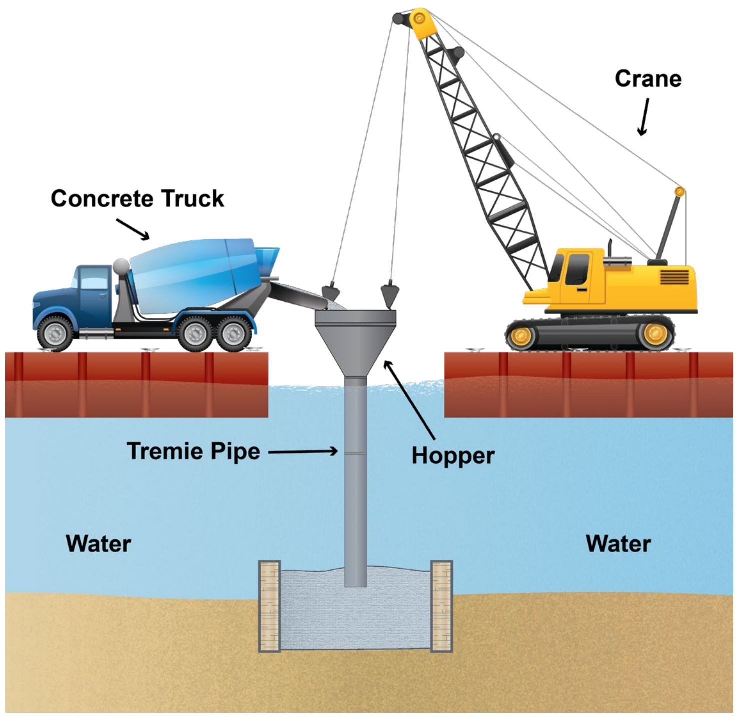

Figure 11. Illustration. Concrete being placed underwater with a tremie.

3.2.5 Reinforcing

Concrete placed underwater moves to its final position by gravity or pressure without vibration. It is typically impossible to visually monitor progress, so it is important that reinforcing be spaced and sized to allow maximum possible openings between bars with consideration to aggregate size so concrete can flow unimpeded. In addition, the formwork design should be watertight and allow the displaced water a pathway to vent as the concrete fills the volume.

3.3 STEEL

3.3.1 General

Steel is a commonly used bridge construction material. Pile bents are often constructed using steel H-piles (Figure 12) and steel pipe piles. Concrete piers can have foundation elements constructed with concrete footings supported by steel piles, as shown in Figure 13. Additionally, steel sheet piles are often used for retaining walls at bridge sites and, in certain instances, can be designed to carry bridge loads as a part of the foundation.

Figure 12. Photo. Steel H-pile bent. (Source FHWA).

Figure 13. Graphic. Pier with concrete footing on steel H-piles. (Source FHWA).

3.3.2 Environmental Considerations for Steel

Bridge site environmental conditions have a significant impact on steel durability and performance. For example, bare steel in fresh water will corrode slower than bare steel in salt water. Additionally, when water flows around a substructure, the turbulence can increase dissolved oxygen in the water from the air, providing ideal conditions to accelerate corrosion in the steel. Similarly, an area of steel subjected to repeated wetting and drying cycles, such as in tidal or splash zones, will have increased corrosion rates (Figure 14). Some waterways situated predominately in warmer climates may promote microbial-induced corrosion (MIC) on submerged steel substructure members. The presence of certain contaminants or chemicals, typically found near highly developed or industrialized areas, could increase the steel corrosion rate.

Figure 14. Photo. Steel pile corrosion at the waterline. (Source FHWA).

Another significant environmental condition that can impact steel bridge components is the waterway's characteristics and how they interact with the bridge. For instance, a fast-flowing river can move bed material, such as sand or cobble, which acts as an abrasive agent on the steel. Abrasive bed material can effectively remove the protective coating and reduce the cross-section of the steel member near the channel bottom.

Table 5 illustrates an example of the range of environmental conditions and how water characteristics can be used to classify the aggressiveness of the environment on steel structures.

Table 5. Substructure FDOT environmental classification for steel based on various environmental conditions. (Source: FDOT Structures Manual)

Classification	**Environment**	**Environmental Conditions**			
		pH (ppm)	Cl (ppm)	SO_4 (ppm)	Resistivity, Ω (Ohm-cm)
Extremely Aggressive	Water and Soil	< 6.0	> 2,000	N.A.	< 1,000
Slightly Aggressive	Water and Soil	> 7.0	< 500	N.A.	> 5,000

For all other sites not falling into the two categories above, the classification of “moderately aggressive” would be appropriate.

3.3.3 Steel Coatings

Coatings are the first line of defense to prevent steel corrosion. Coatings are typically applied to all exposed surfaces of a steel member. Steel piles are also coated several feet below the channel bottom at a minimum for foundation piles, but it is not uncommon for them to be entirely coated at the fabricator before shipment.

Materials used in repair and rehabilitation projects may be uncoated when they arrive at the construction site because field modification is anticipated. When the steel used for repair has no protective coating, a coating system is applied in the field after fitment is confirmed and adjustments are made. Refer to Figure 15 of steel plates installed to strengthen a steel pile, which were field modified and coated onsite.

Figure 15. Photo. Field-coated steel plate installed as part of a pile repair. (Source FHWA).

All coating systems should be inspected for damage when received on the construction site, and touch-ups should be made based on the manufacturers' recommendations prior to and after installation.

Some common coating systems used for bridge substructures are galvanizing, epoxy, and paint. Concrete pile wraps or jackets can also be used to provide a protective barrier against water and marine organisms. It is important to consult local design codes and environmental regulations when selecting a coating system for a repair or rehabilitation project based on site-specific conditions and project needs. Additionally, proprietary coating systems specifically designed for underwater applications are available where steel coating repairs are needed.

3.3.4 Sacrificial Steel Thickness

Future corrosion should be considered in the design of steel bridge components and may include the use of sacrificial steel thickness. Table 6 shows an example of the expected annual section loss of steel foundations in various environments. Designers should consult state and agency-specific design standards to determine the sacrificial thickness required in their locale and for their specific application.

Table 6. Example of Steel section loss (inch per year) in various environmental conditions. (Source: Washington State Department of Transportation Bridge Design Manual)

Location	Marine or Non-Marine: Corrosive	Non-Marine: Non-Corrosive
Soil embedded zone (undisturbed soil)	0.001	0.0005
Soil embedded zone (fill or disturbed soils)	0.0015	0.00075
Immersed zone	0.003	0.0015
Tidal zone	0.004	-
Splash zone	0.006	-
Atmospheric	0.002	0.001

3.4 MASONRY

3.4.1 General

Bridge substructures prior to 1930 were commonly built with masonry (Figure 16). This practice became far less prevalent around the mid-twentieth century, and the technique is typically not used in modern bridge construction. Concrete is typically used to repair masonry elements unless a bridge is of historical importance and warrants a masonry repair.

Figure 16. Photo. Stone masonry pier wall. (Source FHWA).

3.4.2 Stone

Masonry substructures are typically made of granite, limestone, or sandstone (Figure 17). The type of stone used was normally dependent on geographic location. Replacement stone is generally available from nearby local quarries and can be cut to required specifications based on need. Stone specifications should include requirements for compressive strength, modulus of rupture, and durability based on project requirements. The stone should be aged before use to allow the moisture content to stabilize and any stone stress to relax.

Figure 17. Photo. Stone materials commonly used for bridge substructures. (Source FHWA).

3.4.3 Mortar

Masonry mortars consist of fine sand, portland cement, and hydrated lime or lime putty (Figure 18). Mortars with higher cement contents have greater strength and durability, while higher proportions of lime yield a more plastic mortar. Mortar strength is selected based on structural requirements. Mortars in older structures typically contain higher proportions of lime making them softer than modern high-cement-content mortars. The use of modern mortar to repair older structures can damage the existing stone due to overstressing when the mortar expands.

Therefore, when specifying mortars for repair, the properties of the existing mortar should match to the extent practical.

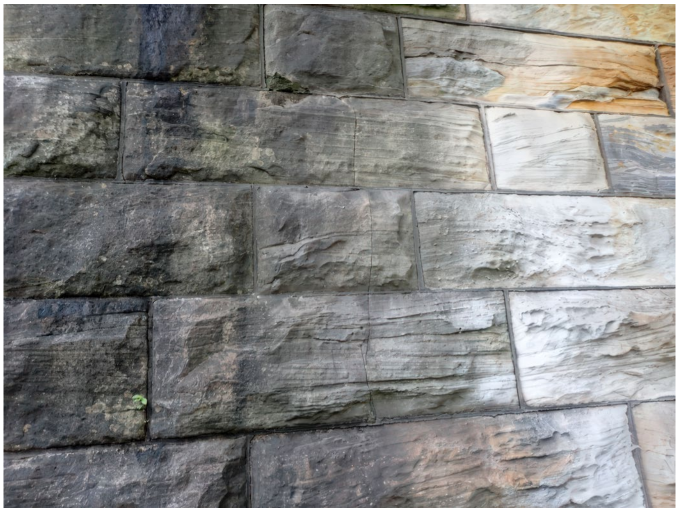

Figure 18. Photo. Mortar securing stones of a masonry substructure. (Source FHWA).

3.5 TIMBER

3.5.1 General

Timber is the oldest known construction material. It is a renewable resource and can be easily shaped with common tools to accommodate a variety of applications. Timber is also susceptible to damage by weathering, decay, and attack by insects and marine organisms. See Figure 19 for an example of a timber pile bent.

Figure 19. Photo. Timber pile bent. (Source FHWA).

3.5.2 Preservatives

Preservative treatments are applied to timber piles and sawn members to prevent biological deterioration. Preservatives should be applied to timber members by vacuum-pressure treatment. The following preservatives are commonly used in timber bridge construction and repair:

- Chromated Copper Arsenate (CCA)
- Acid Copper Chromate (ACC)
- Ammoniacal Copper Zinc Arsenate (ACZA)
- Coal-Tar Creosote
- Pentachlorophenol
- Copper Naphthenate
- Copper Azole
- Oxine-Copper
- Alkaline Copper Quaternary (ACQ)

The various treatments of the timber member typically used in bridge construction or repairs are summarized in Table 7.

Table 7. AWPA use categories that apply to timber bridge members.
(Source: American Wood Protection Association (AWPA))

Use Category	Brief Description
UC4B	Ground Contact, Heavy Duty
UC4C	Ground Contact, Extreme Duty
UC5A	Marine Use, Northern Waters (Salt or Brackish)
UC5B	Marine Use, Central Waters (Salt or Brackish)
UC5C	Marine Use, Southern Waters (Salt or Brackish)

3.5.3 Decay Resistant Species

The natural resistance to decay and attack of timber varies with the species. Some tropical woods have been marketed as virtually decay-resistant, typically resulting from a high resin content and density. Selection of timber should be based on specific performance history in similar environments, noting that such natural resistance can vary within species and even within the same tree.

3.5.4 Installation Considerations

Timber members should be fully fabricated before preservative treatment. However, almost every repair using timber will need field cuts or drilled holes for installation. Since the preservative treatment applied at fabrication will not fully penetrate the member, all field cuts and holes typically are treated in the field with similar preservative.

Another consideration during installation should be abandoned bolt holes which remain when old members are removed. For example, when bracing is replaced on a timber pile bent, the new bracing seldom matches exactly the location of the old bracing, exposing the old bolt holes. When possible, these abandoned bolt holes should be plugged with treated timber dowels or filler material.

Untreated or exposed abandoned bolt holes provide a pathway for moisture and organisms to access the untreated interior wood promoting decay and accelerated deterioration.

3.6 COMPOSITES

3.6.1 General

Composite materials are seldom used as a primary material on bridge repair and rehabilitation projects; however, they are frequently used on fender systems to protect bridge substructures. Composites normally consist of a polymer resin with reinforcement fibers. Typically referred to as fiber reinforced polymer (FRP), the polymer resin protects and binds the fibers together, forming a structural member and allowing for load distribution. For structural applications, basalt fibers (BFRP) and glass fibers (GFRP) are the most common due to their cost advantages. However, carbon fibers (CFRP) and other types, such as aramid fibers, are sometimes used. Resins are most commonly polyester or epoxy formulations.

Depending on the FRP components and systems, the composite (matrix) is often vulnerable to the effects of moisture, temperature, ultraviolet light, chemical attack, and other environmental impacts, which is why they are seldom used as primary material elements on bridge substructures.

3.6.2 Mechanical Properties

The mechanical properties of composite polymer materials differ in several ways from the properties of steel and concrete. Several of the major differences are summarized below:

- FRP members generally have different mechanical properties in each direction (they are non-isotropic) due to the fiber orientation and possibly the manufacturing process. This also means that physical properties, such as improved bending or shear, can be specifically engineered by the manufacturer for a given application.
- Composite systems have high strength-to-weight ratios due to the high tensile strength of the lightweight fibers used for reinforcing.
- The modulus of elasticity of composites is low, which increases deflections. The modulus of the fibers may be high, but the resin modulus is very low.
- Failure strength and other properties are time dependent. The allowable sustained load is smaller than the allowable short-term load.
- FRP materials are subject to larger creep deformation than steel or concrete. Many designs are controlled by creep-limited stresses.
- Properties are temperature dependent and may be significantly impacted at temperatures above approximately 180 degrees Fahrenheit. Conversely, some materials become brittle at very cold temperatures.

3.6.3 Typical Applications

Many bridge owners are now using composites for both new bridges and repairs. Below are some common applications for FRP composites related to bridge substructure elements:

- Combat corrosion in highly corrosive marine environments by replacing carbon steel rebars in reinforced concrete structures with FRP rebars in pile bent caps (Figure 20), pier columns and caps, retaining walls, and drainage structures.
- As a protective fender system or dolphin versus the traditional fender systems with timber or steel H-piles and timber wales (Figure 21).
- As a durable and reduced maintenance structural component alternative to steel sheet pile walls in marine environments.
- As a protective wrap for pile jackets in marine environments using proprietary fiberglass outer shells.

Figure 20. Photo. GRFP rebars in a pile bent cap. (Source FHWA).

Figure 21. Photo. Composite fender system. (Source FHWA).

The following are resources for more information on composites. It should be noted that use of these is not a Federal requirement.

- *AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*, 1st Edition, 2012.
- *AASHTO LRFD Bridge Design Guide Specifications for GFRP Reinforced Concrete*, 2nd Edition, 2018.
- *Florida Department of Transportation, Structures Manual*, Vol. 4, Fiber Reinforced Polymer Guidelines, 2022.

CHAPTER 4.
FACTORS THAT IMPACT UNDERWATER REPAIR APPROACH

4.1 INTRODUCTION

Many construction activities that are performed above water can be performed below water. Site conditions, State and agency regulations, and construction equipment availability are factors to consider when determining if an activity can be completed underwater.

4.2 GENERAL CONSTRUCTION OPTIONS

Underwater construction is typically more complicated, more expensive, and of a longer duration when compared to construction in a dry environment.

4.2.1 Repairs Performed In-the-Dry

In-the-wet refers to construction work performed underwater. Performing repairs below water often involves the use of commercial divers. The support system and equipment divers use are typically smaller and less costly than that required to produce a dry work site.

Working in the water has unique challenges. The site, water quality, channel velocity, working depth below the water surface, and regulatory conditions can impact a repair team's ability to construct and inspect underwater repair work. Each of these factors can substantially reduce work productivity and increase repair costs.

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4.3 CONSIDERATIONS

4.3.1 Site Access

Marine construction activities are usually more costly than similar activities on land. Costs can increase even further if divers are used. Site access can require barges, cranes, temporary structures, boats, and larger staffing levels. Mobilization costs can be significant, especially if the landside staging area and boat ramp are miles from the work site.

Marine vessel traffic may impact the work site and warrant constant monitoring during repairs. Refer to Figure 22 for an example of a marine construction site. Work times on some waterways may be restricted to accommodate marine traffic and require removing construction equipment from the waterway when not in use at the end of each work shift. These issues are typically addressed during the design phase through the permitting process and coordination with local marine authorities and the United States Coast Guard.

Figure 22. Photo. Marine construction site. (Source Global Diving and Salvage).

4.3.2 Water Conditions

Water conditions should be considered when planning underwater repair work. These include currents, tides, water depth, temperature, possible contamination, and visibility.

River flow and tidal currents are present in most waterways. There can also be discharges from outfall pipes, dams, and intersecting streams and rivers that may impact site conditions. Currents and tides can fluctuate daily, affecting divers' ability to work. A diver's ability to work decreases as stream flow increases. High flow rates can also adversely impact pile-driving operations and concrete placement system performance.

Alternative construction methods can be used to support work in high flow, including the use of dive shields deployed from an anchored barge or platform, as shown in Figure 23. The shield will block the water flow locally, creating an area where the diver can work effectively. Costs are typically high, and workspace is restricted when special equipment like a shield is used.

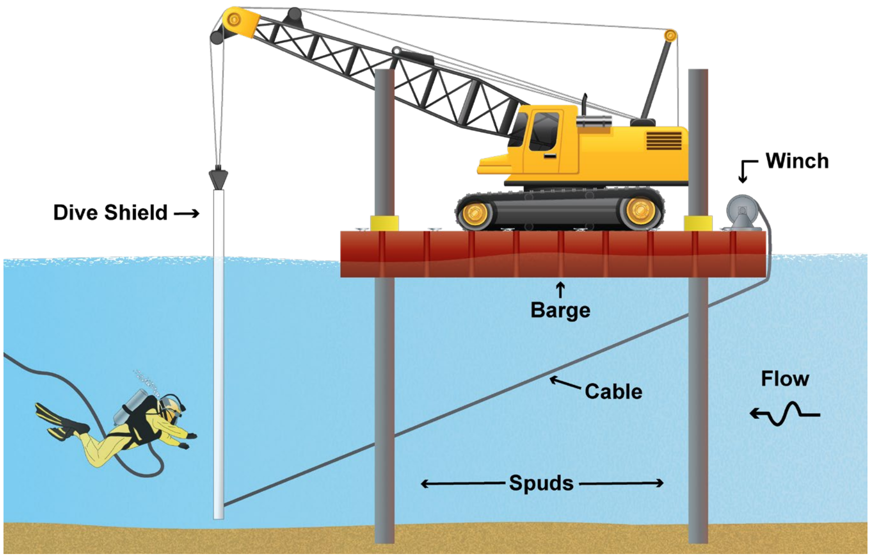


Figure 23. Illustration. Dive shield deployed from a barge.

Depth has a significant effect on work productivity and construction costs. The amount of time a diver can safely work underwater is reduced as depth increases. The graph in Figure 24 illustrates the relationship between available bottom time and water depth. Productivity is also impacted by visibility, temperature, and the strenuousness of the work tasks to be performed.

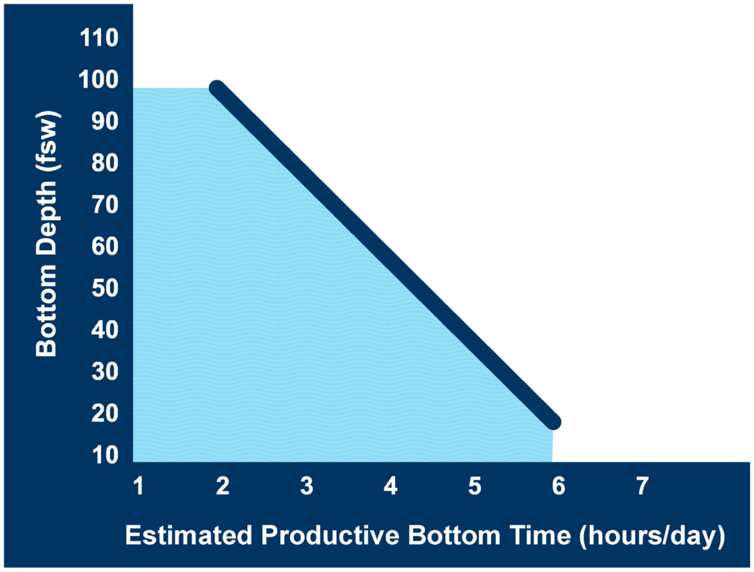


Figure 24. Graph. Bottom time vs. Depth.

Diving operations can be conducted in a wide range of water temperatures utilizing special dive suits to regulate the diver's body temperature. However, the various suits have different support requirements to consider when planning a repair project.

Extreme temperatures may also affect material properties. Cold temperatures can increase cure times or impede the curing process of polymers. Similarly, elevated temperatures may increase the set time of some cementitious repair materials. Material properties and compatibility of repair systems should be verified during the design phase and closely monitored during construction.

Underwater visibility can also impact a diver's productivity. Typically, diver productivity significantly decreases when visibility is less than 3 feet. However, if permitted under local environmental regulations, it may be possible to pump clear water to the worksite to mitigate low-visibility impacts, improving visibility and productivity.

4.3.3 Regulatory

Government and owner regulations can substantially affect how repair work is performed. For instance, construction time and operations may be governed by the presence of aquatic vegetation such as seagrass, endangered species, fish runs, spawning seasons, and the presence of birds and land animals in the project area. Coordinating with regulatory agencies, such as the State fish and wildlife services and the water management district, typically takes place during the design and planning phase. It may also be necessary to demonstrate to these agencies that no construction materials or processes will degrade the water quality. For example, some government agencies require chemical data submissions for concrete and admixtures. Similarly, mortar tests or other cementitious material leakage through forms may be required to show that the cement particles and alkalinity will not affect marine life. Regulatory agencies may also specify fish survival tests during construction to evaluate the effects of repair work on marine life.

In addition to preventing harmful materials from entering the waterways, it is also important to ensure that existing contamination is not reintroduced to the ecosystem. Of particular importance is the presence of contaminated channel bottom sediments. In areas where bottom sediments are polluted, it may not be possible to excavate or perform operations, such as pile driving, that may disturb the soil. When excavation and pile driving is permitted, the turbidity can be controlled, but not eliminated, through turbidity or silt curtains. Soil removed from the channel may be classified as hazardous and require the use of approved disposal sites and methods.

When working in or near the water, pollution effects on the diver and the construction workers should be considered. Water tests should be performed regularly in the repair area to determine the water's chemical composition and additional precautions that may be required during construction. Divers typically take special precautions, such as the use of sealed dry suits and helmets, to adequately protect them from any hazardous chemicals or pollutants that may be in the water. These chemicals may also adversely affect surface preparation and material placement during construction.

Construction practices can also have an adverse effect on the marine environment. Water column pressure waves created during the pile driving process are becoming an environmental concern, as they can kill fish near the driving operation. One method to reduce this effect is to place air bubble curtains around the pile being driven to inhibit wave transmission. Underwater explosives also produce pressure waves, and control measures such as air curtains are usually required.

4.4 METHODS TO OBTAIN DRY WORK ENVIRONMENTS

4.4.1 Cofferdams

Conventional cofferdams are typically constructed by driving steel sheet piling around an existing foundation to resist soil and water pressures (Figure 25). The area between the cofferdam and the work area is dewatered, allowing for work in a dry condition.

The cofferdam is typically designed to resist hydrostatic pressure, soil load, river flow, and high-water events. Existing construction debris and the configuration of the existing structure can impact construction, especially if unknown conditions exist.

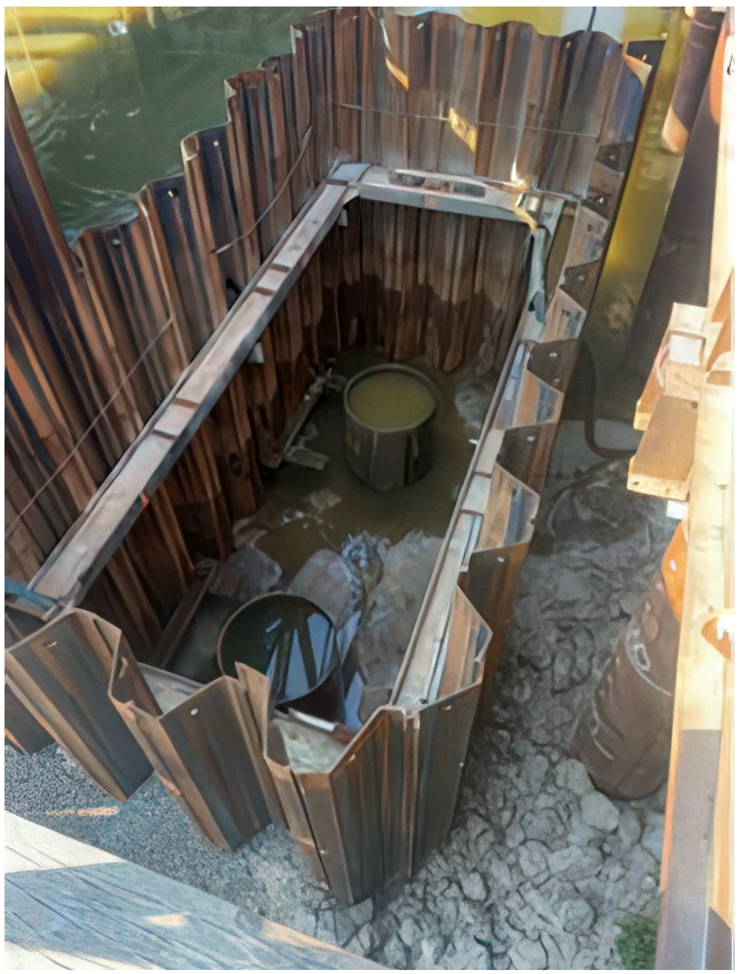


Figure 25. Photo. Conventional cofferdam around a bridge pier.
(Source PCL Construction).

Limpet, or open-bottom, cofferdams are three-sided cofferdams that provide access to pier faces and similar areas (Figure 26). Compressible edge seals are typically used along the cofferdam sides to limit water inflow, with mechanical anchors providing additional support. Water pressure on the face of the cofferdam increases as the inside is pumped out, holding the cofferdam in place. Open-bottom cofferdams can be custom fabricated to match unusual geometric surfaces. The seal edge is a critical feature of the open-bottom cofferdam, and surface preparation may be needed on the structure to allow a good seal.

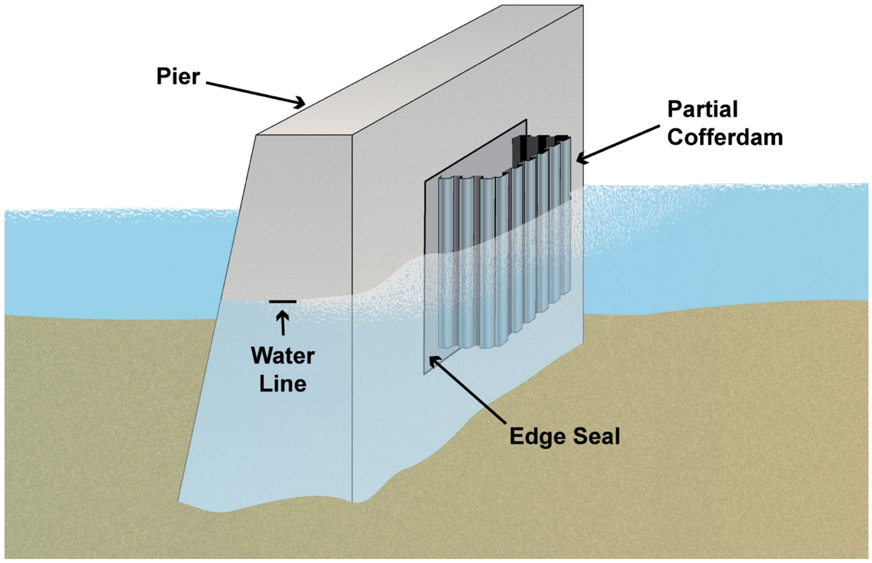


Figure 26. Illustration. Open-bottom cofferdam.

Most cofferdams will experience leakage, and provisions should be made for continued pumping, which may require personnel to be on-site even when construction activity is not underway.

4.4.2 Dikes

Dikes can be constructed around work areas to provide a dry work condition, as shown in Figure 27. A variety of materials can be used to construct a dike, including roadside barriers and plastic sheeting, sandbags, and compacted clay. Dikes are commonly used in shallow water areas that have limited flow. In addition, compacted clay and other materials used in dike construction may have to be disposed of as contaminated material after use.

Figure 27. Photo. Dike around construction site. (Source FHWA).

4.4.3 Proprietary Barrier Systems

Several types of proprietary barrier systems are available for use on marine projects. Some commonly available systems consist of water-filled bladders and membrane-covered support frames (Figure 28). These systems are typically limited to waters less than 10 feet deep, having minimal currents and firm riverbeds with low permeability.

Figure 28. Photo. Example of proprietary barrier systems (Source PLC Construction).

CHAPTER 5.
EQUIPMENT FOR UNDERWATER REPAIR

This chapter is intended to provide general information only, and its contents should not be construed as a FHWA recommendation. Professionals in this area should be consulted for guidance regarding the information found in this chapter.

5.1 INTRODUCTION

Underwater construction requires specialized equipment and experience. Many construction activities performed above water can be performed below water with proper planning. Construction performed underwater requires unique equipment, takes considerably more time, and is normally at a higher cost than similar activities above water. The equipment typically used to complete underwater bridge repairs is discussed further in Sections 5.4 through 5.8.

5.2 DIVING SYSTEMS

Surface-supplied diving equipment may have some safety advantages over SCUBA equipment, including:

- Hardwire direct communication between the diver and surface support team through diver umbilical.
- Breathing gas is provided by a compressor or high-pressure bank at the surface.
- A pneumofathometer for precise depth measurements at the work site.
- A strength member integral with the diver umbilical for safety.
- Improved diver head protection and safety.
- Option for hard wire video monitoring of the underwater construction site.
- Option to integrate a hot or cold-water system into the diver umbilical to regulate diver comfort.

In addition to the advantages listed above, surface-supplied equipment can improve project production rates once the equipment is set up and diving activities begin.

5.3 ABOVE WATER SUPPORT

A wide variety of topside support equipment is used when performing underwater repairs (Figure 29). In addition to the standard construction equipment needed to support the site, a separate area is needed to safely set up and conduct diving operations. Close communication and advanced coordination are necessary between the dive team supervisor and all topside equipment operators to ensure a safe work environment. Lockout/tagout procedures may be needed to safely secure equipment that could harm divers. Refer to 29 CFR 1910.147 for OSHA lockout/tagout regulations.

Figure 29. Photo. Dive team and support equipment on a construction site. (Source Global Diving and Salvage).

5.4 UNDERWATER TOOLS

Common tools without a motor that are used above water are typically used for underwater construction. These may include hammers, pliers, wrenches, screwdrivers, hack saws, knives, etc., However, special care to protect the tools from corrosion due to submersion in the water is suggested to help ensure long-term durability.

5.4.1 Pneumatic Tools

Pneumatic tools designed for above-water use typically can be used underwater in shallow depths. A pneumatic tool's maximum effective depth is typically less than 30 feet. This category of tools includes nail guns, staplers, drills, grinders, and hammer guns, to name a few. The limiting factor is the tools' operating air pressure, which should offset the hydrostatic pressure at the underwater worksite. When pneumatic tools are used underwater, they should be thoroughly lubricated after use to prevent premature failure and ensure longevity. Figure 30 shows commonly used pneumatic underwater tools.

Figure 30. Photo. Commonly used pneumatic underwater tools. (Source Global Diving and Salvage).

5.4.2 Hydraulic Tools

Hydraulic tools have been specially designed for use underwater. These tools normally use a special environmentally friendly hydraulic fluid to prevent contamination if the hydraulic fluid bleeds out during use. Underwater hydraulic tools include chainsaws, drills, chisels, grinders, coring machines, and rebar cutters.

There are also a variety of attachments designed for use underwater for a specific task. For example, special attachments are available for cleaning marine growth from structures, which is normally outlined in the scope of work for surface preparation before repairs. Figure 31 illustrates one such attachment for a hydraulic grinder. Tools designed to remove marine growth can also remove the coating system from steel bridge components, so care should be taken to prevent damage to the protective coating.

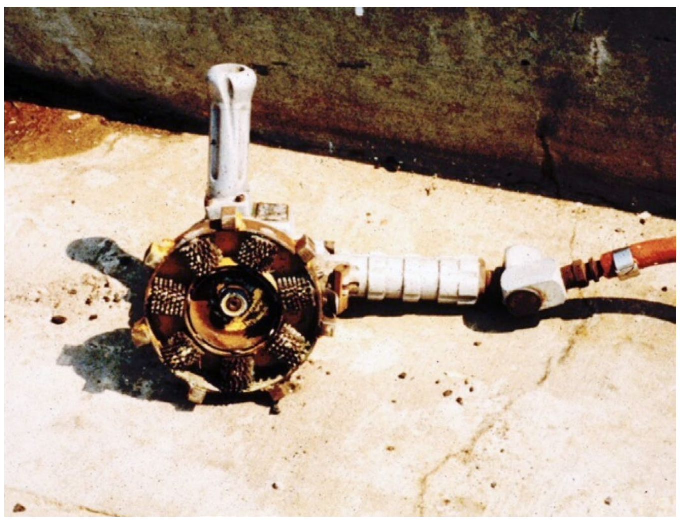


Figure 31. Photo. Grinder attachment used to remove marine growth. (Source FHWA).

5.5 EXCAVATION METHODS

Available excavation methods will depend on the water depth at the excavation site and the extent and type of material being excavated. Multiple excavation techniques may be required as construction advances.

5.5.1 Mechanical Excavators

Excavators used for above-water projects can also be used underwater when access and depth allow. These include backhoes and cranes with clamshell buckets or drag lines. Depending on the site location, these excavators can work from a barge (Figure 32) or on shore. All attachments available above water will work underwater. Additional maintenance may be needed to keep all systems operational due to the harsh marine environment.

Figure 32. Photo. Excavator mounted on a barge. (Source FHWA).

5.5.2 Airlifts

Airlifts work using a differential density principle. Air is introduced at the intake point of a pipe and mixes with the water inside, creating a lower-density mixture that rises to the pipe outlet near the surface. The amount of material moved by an airlift depends on the pipe's size, water depth, air pressure and volume, and material being moved. Airlifts are most effective when excavating mud, sand, silt, clay, and cobbles. The optimal working depth is from 30 to 75 feet when material only needs to be moved a short distance from the excavation location.

The airlift is diver-operated, with a control valve installed 20 to 30 inches up from the pipe intake. A handle is installed near the intake allowing a diver to control the location of the inlet in the excavation location. Refer to the illustration in Figure 33 of an airlift assembly. Communication with the diver is essential for an airlift to be operated safely since the diver is controlling the intake valve.

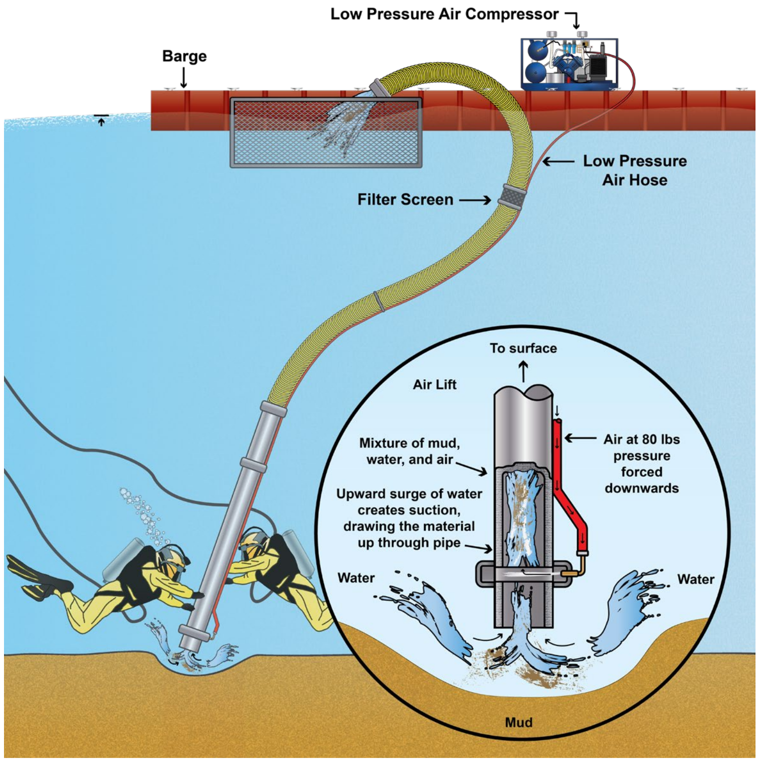


Figure 33. Illustration. Airlift system.

5.5.3 Jetting

Jetting is the process of moving material by forcing pressurized water through a nozzle operated by a diver (Figure 34). Jetting can be performed at any depth provided the pump can produce a flow rate needed, typically 100 gpm, and discharge pressure needed, typically 50 to 150 psi over the work location water pressure. Jetting can move large quantities of mud, sand, and silt. A jetting nozzle will produce back thrust, which the diver should resist to maintain nozzle control. Most nozzles designed for jetting have balancing jets to help counter back thrust, as illustrated in Figure 35. Jetting nozzles can also be fitted with an air manifold near the nozzle, which can help float sediment and debris out of the immediate work area to help improve visibility and diver productivity.

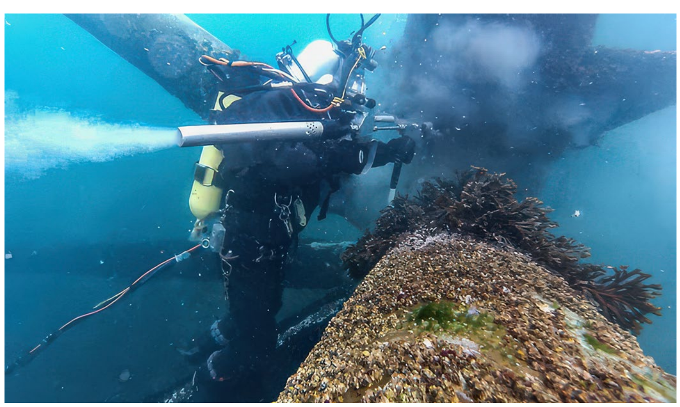


Figure 34. Photo. Diver operating a water blasting system. (Source Global Diving and Salvage).

Figure 35. Photo. Tee nozzle. (Source FHWA).

5.5.4 Dredging

Underwater diver-operated dredging can move large quantities of sand, gravel, and mud bed material when water is too shallow for an airlift. Dredges can be operated at any depth. There are two general types of diver-operated dredges. The first type of diver-operated dredge is an eductor dredge. This configuration uses a lightweight tube with a 30-degree bend at the intake, as illustrated in Figure 36. A water jet is installed at the bend and directed to the discharge end of the tube. The water jet moves water through the tube, creating suction at the intake. A diver-operated kill switch should be installed at the location just behind the bend, and a screen should also be installed at the intake for safety.

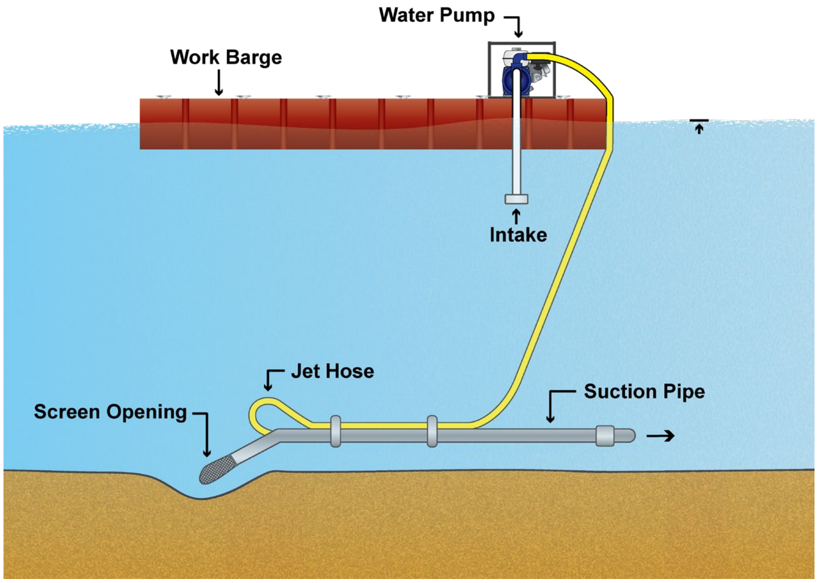


Figure 36. Illustration. Eductor dredge system.

The second type of diver-operated dredge is a suction dredge. This configuration uses a flexible suction hose connected to a dredge pump on the surface. A nozzle or suction pipe with a safety screen is connected at the intake end of the flexible pipe. As with the educator tube dredge, a diver-operated kill switch should be provided where the diver manipulates the inlet location (Figure 37). Table 8 lists typical suction pipe, jet pipe, and pump sizes.

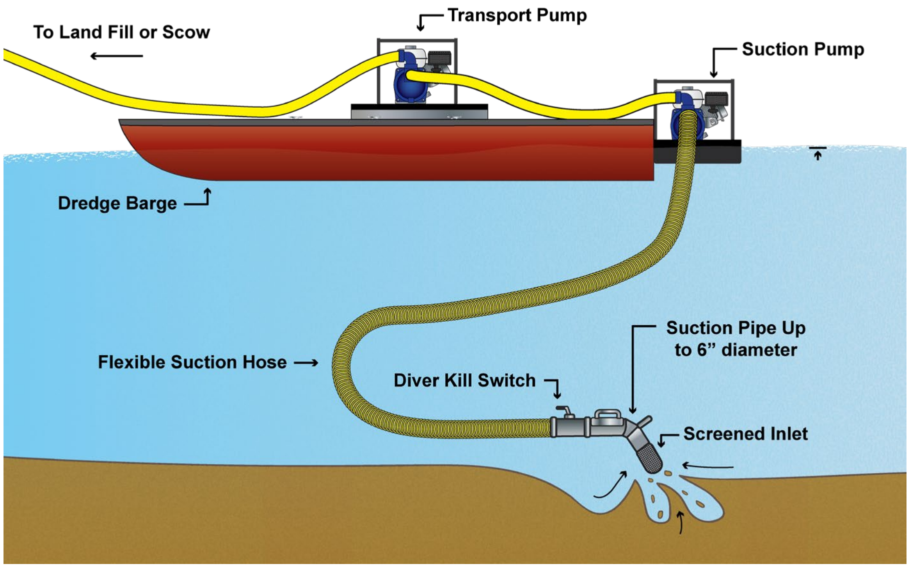


Figure 37. Illustration. Suction dredge system.

Table 8. Suggested selection guide for underwater dredge suction pipe, jet pipe, and pump. (Source: Naval Facilities Engineering System Command AVFAC P-990, Section 2.6.3)

Suction Pipe (id)	Jet Hose (id)	Min. Pump Output
2 in.	1 in.	55 gpm
3 in.	1 in.	100 gpm
4 in.	1.5 in.	125 gpm
6 in.	1.5 in.	300 gpm
8 in.	3 in.	500 gpm

5.6 CONCRETE PLACEMENT EQUIPMENT

5.6.1 Tremie

A tremie is a 4-to-10-inch diameter steel tube or rigid rubber hose with a hopper at the top that allows it to be filled with concrete (Figure 38). Tremie systems are used when direct access above the submerged work site allows the tremie to be held in position with a crane, as previously illustrated in Figure 11. A plug is used when concrete is first placed in the hopper to maintain a barrier between the water and the concrete as it moves through the tube. The concrete forces the plug out of the bottom of the tub, and a mound of concrete is formed. The discharge end of the tremie should be maintained several feet inside the concrete mound to protect the fresh concrete from contact with water. The concrete slump should be between 6 and 9 inches to allow the concrete to flow to all areas of the form because the concrete should not be vibrated into position. For more information on placing concrete underwater using a tremie, refer to Section 3.2.4.

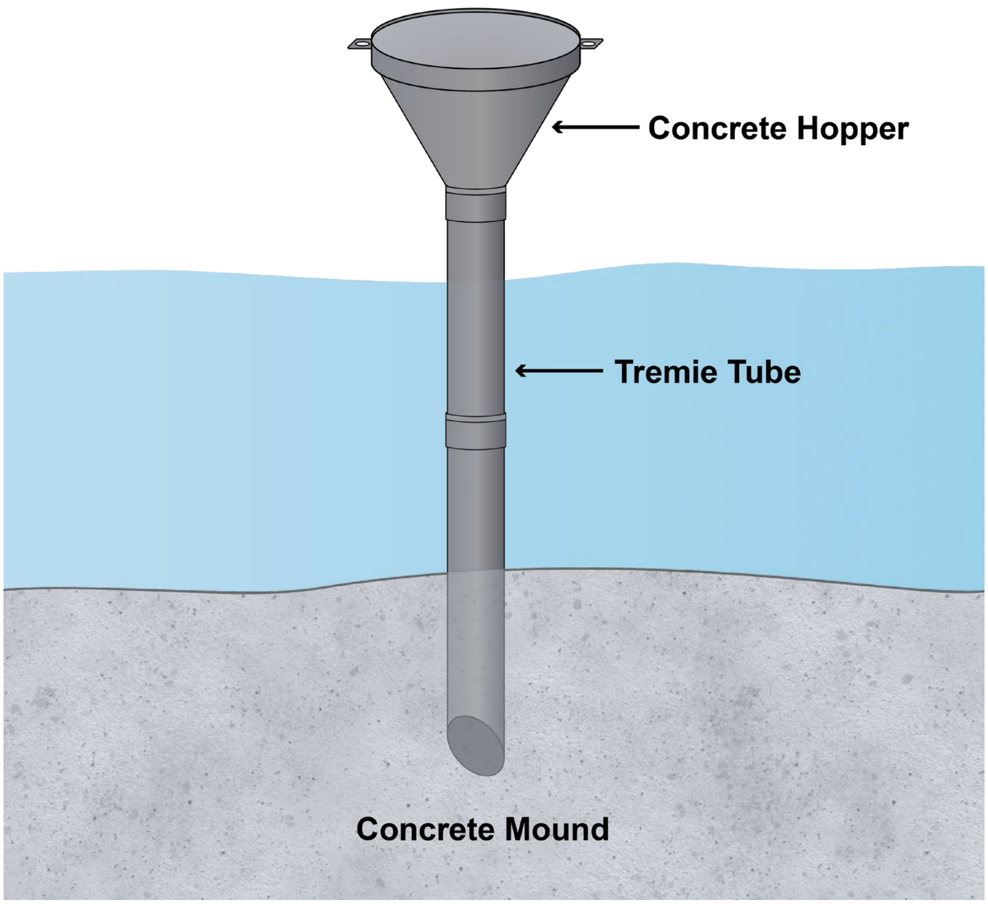


Figure 38. Illustration. Tremie system

5.6.2 Pumps

Concrete or grout pumps (Figure 39) are used to place concrete or grout when access to the repair location is limited. Pumps are generally preferred over tremie placement because they allow more control of the process. Forms should be filled from the bottom up and ports installed at the top of the formwork to allow water to escape as the pumped concrete displaces it. Like a tremie, a plug is initially inserted into the concrete hose at the pump to keep the concrete separated from the water when pumping begins.

Figure 39. Photo. Grout pump. (Source JF Brennan Company).

5.7 SPECIAL EQUIPMENT

5.7.1 Acoustic Imaging

Acoustic imaging technology helps identify diving hazards before divers enter the water and documents conditions at the construction site.

2D images are collected utilizing a single beam sonar. The sonar head, consisting of a transducer and receiver, is mounted in a fixed location. The sonar head rotates, collecting data at numerous iterations through the rotation to construct a visual representation of the structure and channel bottom below the water. Refer to Figure 40 for an example of a 2D acoustic image of the submerged portion of a bridge pier combined with a photo of the above-water portion.

During data collection of 2D imaging, the sonar head should remain stationary, as any movements would create inaccurate images. Stabilizing the sonar head can typically be accomplished by rigidly attaching it to a vessel, bridge pier access equipment, or other stationary objects throughout the duration of a single scan. However, when wave action is created by wind or high currents, it becomes difficult to maintain the sonar head in a stationary position to record accurate data. Additionally, air bubbles near the sonar head during high flow also deteriorate the quality of the collected images.

Figure 40. Graphic. Combined 2D acoustic image of a bridge pier.
(Source FHWA).

Multi-beam sonar, or 3D imaging, is used to create a 3D model of a construction site. The multi-beam sonar system consists of a sonar head, an inertial reference unit, and two GPS antennae. The system is typically mounted to a vessel, with data collection occurring while the vessel is underway. Depending on the multi-beam sonar system, a few hundred to several thousand data points are collected multiple times per second to build a point cloud of geo-referenced points. Since this system collects data while the vessel is in motion, it can collect accurate data when there is wave action and higher water velocities. However, air bubbles created in the sonar head's vicinity will still significantly distort the data.

With every data point collected being geo-referenced with an X, Y, and Z coordinate, very accurate data can be obtained regarding footing exposure, seal exposure, and volume of scour holes around bridge piers. Refer to the example in Figure 41.

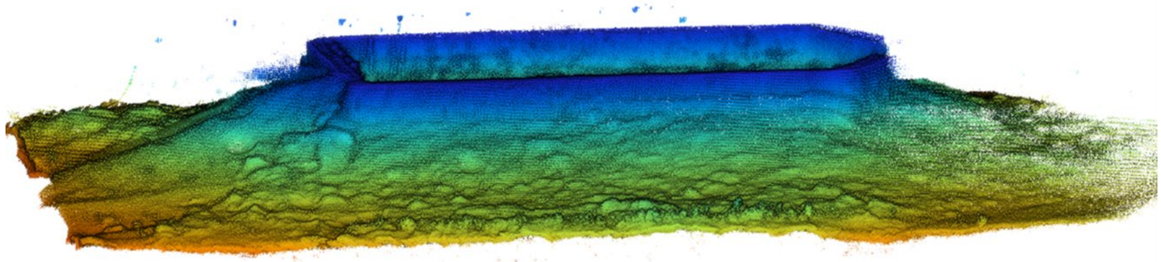


Figure 41. Graphic. 3D sonar image of a bridge pier.

5.7.2 Remotely Operated Vehicles (ROV)

Remotely operated vehicles are underwater robots controlled by an operator on the surface using a console with a video feed from the ROV. There are a variety of sizes available, ranging from a shoebox to the size of a small automobile. ROVs can also be fitted with tools and arms to manipulate objects and complete work depending on the project's needs. Figure 42 shows an example of an industrial ROV at work.

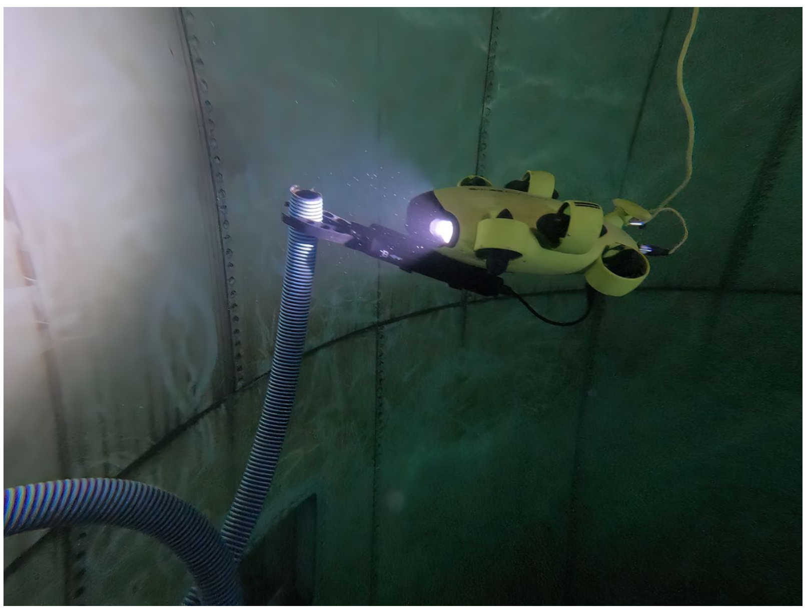


Figure 42. Photo. Remotely operated vehicle (ROV) used in construction. (Source FHWA).

5.7.3 Lift Bags

Lift bags are used below water by divers to lift heavy objects. There are a variety of sizes and configurations available, including bags with open bottoms and those that are closed. Lift bags are filled with air from the diver's pneumofathometer or other independent air sources to provide a buoyance force to lift an object. When divers are lifting an object with lift bags, they should be careful not to ride the load as it moves up through the water column for safety reasons. On any open bottom lift bag, it is suggested to use a counterweight, or deadman anchor, to help control the ascent and prevent lift bag runaway. For example, suppose an open-bottom lift bag accelerates to the surface too quickly. A large amount of air may be lost suddenly, increasing the likelihood of the lift bag losing buoyancy and rapidly returning to the bottom. Lift bag runaway can cause damage and possible personnel injury. Refer to Figure 43 for a view of a diver operating a lift bag.

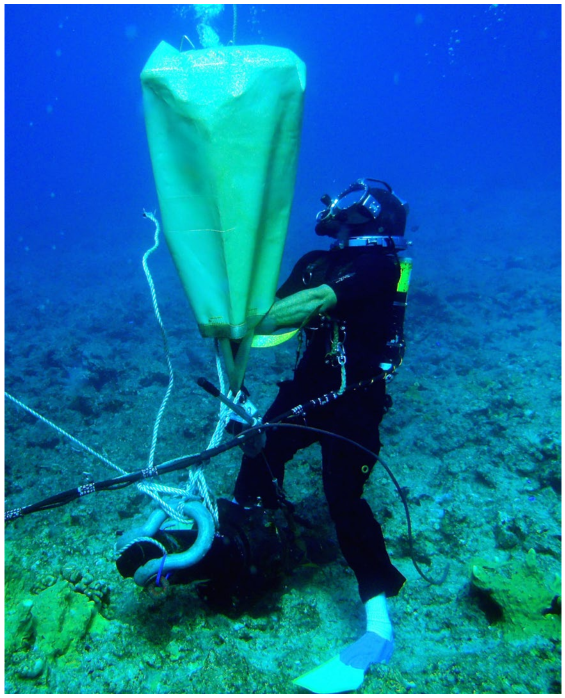


Figure 43. Photo. Diver using a lift bag. (Source SubSalve USA).

5.8 UNDERWATER WELDING AND CUTTING

5.8.1 Introduction

Underwater welding was first accomplished in 1917 during World War I to stop leaks on the seams and rivets in ships' hulls. In 1965, the first dry hyperbaric weld was performed offshore in the Gulf of Mexico on a 6-inch branch line in 80 feet of seawater (fsw). In 1971, the first major underwater structural weld was performed on an offshore oil rig in the Gulf of Mexico in 130 fsw.

5.8.2 Methods

Several methods can be used to perform underwater welding for bridge repairs. Some are described below:

- Dry welding in a dry habitat at depth pressure out of dive gear—A hyperbaric weld is performed by enclosing the work with a steel structure. Depending on the depth, the diver enters the structure and displaces (evacuates) the water with air or other suitable breathing gas mixture. The diver then works in-the-dry.

- Dry welding in open bottom cofferdam at depth pressure—Air is pumped into the cofferdam to displace the water in the area to be welded. The diver works in dive gear and is dry above the waist, and the welding work is performed in-the-dry.
- Dry welding inside a closed-bottom open-top cofferdam at 1 atm—The cofferdam is open at the top, and the welder is inside the cofferdam performing the repairs in-the-dry.
- Wet welding at depth pressure—Performing a weld without any barrier between the welding arc and the surrounding water.

Many bridge repairs use the “wet welding” method for welding projects on anodes, steel pile, or steel sheet pile. As repairs become more complicated in deeper water, using a dry habitat would lend itself to a more satisfactory repair. Open-top and closed-bottom cofferdams are sometimes used on sheet pile and pile repairs.

5.8.3 Specifications

Several weld specifications are available depending on the type of weld being performed and the type of structure. The following represents some of them. It should be noted that these are not Federal requirements.

- American Welding Society (AWS) D3.6M:2017 Specification for Underwater Welding
- AWS D1.1:2020 Structural Welding Code
- AWS D1.5M/D1.5:2020 Bridge Welding Code
- American Petroleum Institute (API) RP2A & API Std 1104 Welding of Pipelines & Related Facilities

5.8.4 Weld Design

Welds are typically designed for specific applications and meet bridge owner’s requirements. Common applications for underwater welding include:

- Patchwork on steel sheet pile
- Doubler plates for section loss to sheet pile, pipe, or HP piles
- Bracing connections
- Zinc anodes

Typically, underwater welds are categorized into three “classes”:

- Class “A” welds are intended to be suitable for applications and design stresses underwater that are comparable to their conventional surface welding counterparts.
- Class “B” welds are intended for limited structural applications, and their suitability is based on a “fitness for purpose” as determined by the weld design engineer. The designer should provide the required strength for the completed welds.
- Class “O” welds are used to conform to meet the bridge owner’s or engineer’s specific specification.

5.8.5 Effects of Wet Welding Versus Dry Welding

There are major differences between welding in-the-dry and welding in-the-wet. The biggest difference is the wet environment surrounding the diver and the welding arc. Heat and electricity generated by the welding arc cause the water near the arc to disassociate into its basic components—oxygen and hydrogen. This hydrogen gas is then available for infusion into the weld, leading to possible hydrogen embrittlement. Hydrogen gas can also accumulate and pose a safety risk if not properly vented and allowed to reach the surface. When conducting welding in a dry habitat or enclosed space, atmospheric conditions should be continuously monitored even if there is mechanical ventilation, or the welder is on self-contained breathing apparatus (SCBA).

5.8.6 Underwater Wet Welding

Underwater wet welding can be fast and economical; however, it has an increased list of variables, especially when exact structural specifications need to be met. It is important to use quality electrodes that are specifically designed for “wet” or in-water use. Specially formulated fluxes and waterproofing help mitigate hydrogen embrittlement and repel the harsh atmospheric effects during the welding process. The electrode holder or stinger should also be manufactured specifically for underwater use.

Proper equipment and use are important for personnel safety and quality wet welds. A dual pole knife switch or breaker box should be used to terminate both the positive and negative sides of the circuit. All welding leads should be free of contaminants and damage. Splices and connections should be waterproofed to mitigate voltage loss and stray electrical currents underwater. Ensure all cable connections are tight and the welding machine is free from damage and properly grounded. Refer to the illustration in Figure 44 of a basic underwater wet welding setup.

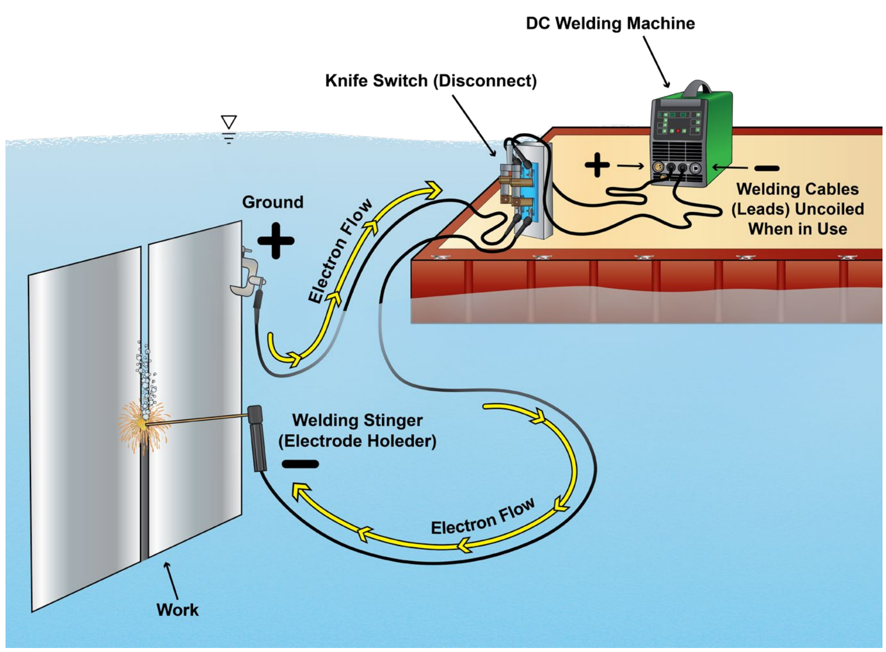


Figure 44. Illustration. Basic underwater wet welding setup.

Additional factors affecting underwater wet welding are listed below:

- Magnetism—Electromagnetic fields exist around all electric current and are especially present underwater during wet welding. Magnetism can cause issues such as arc blow and arc wander.
- Penetration—The water around the welding arc creates a faster cooling rate which causes reduced penetration into the base material. In conjunction, the rapid quenching of the weld results in a loss of ductility and tensile strength.
- Visibility—The diver's visibility should be adequate to perform the work in the wet. Visibility should be no less than 2 feet.

5.8.7 Underwater Cutting or Burning

Burning may be specified to cut out damaged sheet piles or steel bridge piles to initiate underwater welding repairs. Similar equipment used for underwater welding is also used for underwater burning. Although both wet welding and burning produce dangerous gases that should be vented, underwater burning poses more danger. Since most manufacturers' rods use oxygen in the burning process, there is an increased risk of explosion. Regardless of whether oxygen is used, there is still an explosion risk with hydrogen build-up that may combine with gases other than oxygen to cause an explosion. (Figure 45).

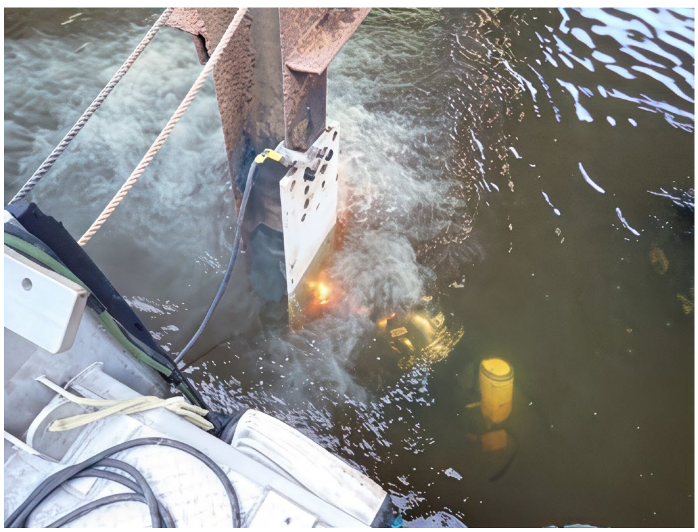


Figure 45. Photo. Diver cutting steel underwater with dangerous gasses forming on the surface. (Source FHWA).

There are several underwater burning methods, but the most conventional method for bridge repair applications is exothermic or oxy-arc rods. Refer to the illustration in Figure 46 of a basic underwater cutting and burning setup.

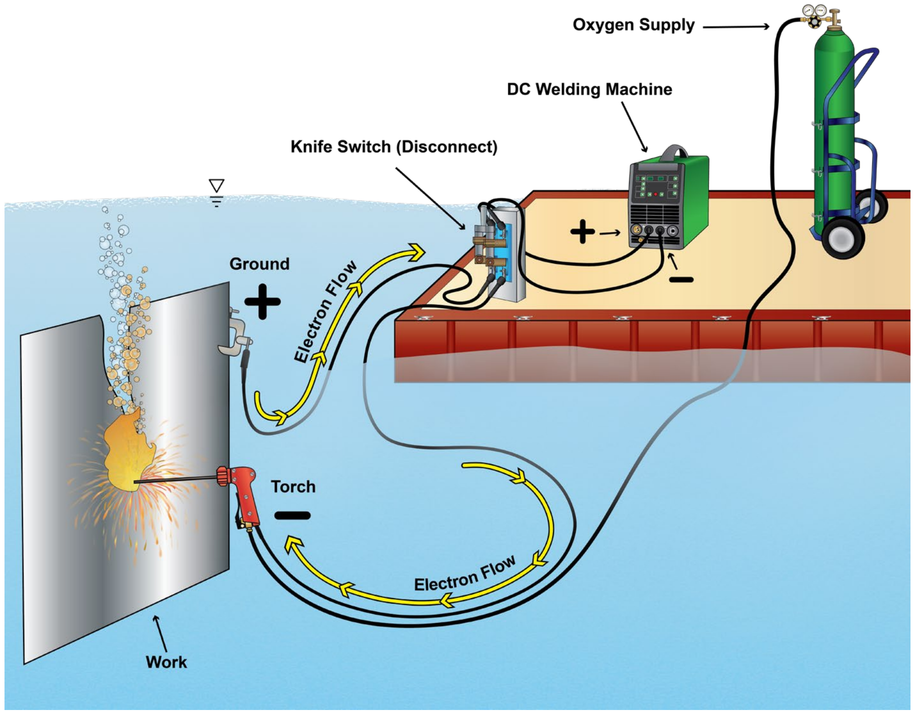


Figure 46. Illustration. Basic underwater cutting and burning setup.

Exothermic cutting allows trained operators to melt (cut), pierce, or gouge any metal (ferrous or non-ferrous) and some types of masonry by flowing pure oxygen through a steel-alloy tube or rod. Direct Current (DC) is only used to initiate the exothermic reaction, to which the current is then terminated or made “cold,” allowing the oxygen to freely react with the fuel rod for efficient cutting.

Oxy-arc cutting allows trained operators to use the exothermic reaction in conjunction with constant current (DC only). Current is used continuously throughout the cutting process and made “cold” only at the end of each cut. Depending on project size and depth, typically 300–600 amps would be used.

CHAPTER 6.
PIER AND CULVERT REPAIRS

6.1 INTRODUCTION

Bridge piers and culverts are predominately constructed of reinforced concrete, and repair techniques utilized for underwater repairs are similar to those used above water. Common types of deterioration requiring repair include material degradation, impact damage, and undermining. Deterioration mechanisms are covered in the *Underwater Bridge Inspection Reference Manual*. Much of the information presented in this chapter on formwork, concrete placement, and polymer injection is applicable to all concrete structures.

6.2 FORMING SYSTEMS

Formwork is grouped into three broad categories: rigid, semi-rigid, and flexible. Form pressures below water are reduced due to the water pressure outside the form countering the concrete pressure within the formwork. Forms should be tight-fitting and sealed to prevent concrete from seeping into the water and minimize concrete washout when placed in flowing water. Forms are generally preassembled above water, when possible, to minimize work by divers.

6.2.1 Rigid Formwork

Rigid forms are stiff and maintain their shape during concrete placement and can consist of plywood, timber, polymer-based materials, precast concrete, and steel (Figure 47). Proprietary modular forming systems are available, as are custom-built forms. Most forms available for above-water use can be adapted to work underwater.

Figure 47. Photo. Rigid formwork. (Source FHWA).

Rigid forms are typically removed after the concrete cures adequately. However, sometimes they are left in place due to the high cost of removing underwater formwork. Formwork left in place can make inspection of the repair difficult and may also present hazards to future inspectors. Corroded edges of steel formwork can become sharp and jagged, presenting an entanglement or impalement hazard to future inspectors. Additionally, abandoned formwork can conceal construction-related defects, such as voiding from poor consolidation or exposed reinforcement due to insufficient concrete cover. Defects concealed by left-in-place forms may not be addressed and lead to more extensive deterioration of the bridge member.

There can also be advantages when the formwork is left in place, such as providing a barrier against abrasion and other deleterious environmental conditions. Owners should carefully consider the advantages, disadvantages, and long-term durability when forms remain in place after construction.

Certain formwork systems may be better left in place than others. For example, stay-in-place metal formwork or precast formwork systems can be effective in underwater applications due to their durability and ease of installation. On the other hand, traditional wood formwork may not be as well-suited for underwater applications, as it can be susceptible to rot and decay in moist environments.

6.2.2 Flexible Formwork

Flexible forming systems are available in a wide variety of materials, such as synthetic fiber fabric, burlap, nylon, and membrane plastic. Unlike rigid formwork, flexible forms do not maintain a geometric shape because they lack bending stiffness. Flexible forms take on a more organic shape as they are filled with concrete or grout.

Flexible forms are often utilized for pile jackets or as bags that are filled with grout for undermining repair or riprap replacement. Flexible forming systems normally remain in place after construction (Figure 48).

Figure 48. Photo. Flexible formwork installation. (Source FHWA).

Advantages of flexible forms include low cost, lightweight, and the ability to conform to gaps or voids when filled with concrete or grout. Disadvantages include difficulty handling them in flowing water and the undesirable irregular surfaces that can occur when concrete or grout is placed inside them. Additionally, flexible form materials can degrade in sunlight, and bleeding may occur with fabric forms creating environmental concerns.

The fabric used for flexible forms typically has a tensile strength ranging from 200 to 400 psi. The form material may stretch as much as 10 percent under loads of 50 percent of the fabric's tensile strength. Thus, allowance in computing concrete or grout volumes should consider this relationship.

6.2.3 Semi-rigid Formwork

Semi-rigid forms have features of both rigid and flexible formwork. Semi-rigid forms are flexible enough to be shaped around bridge elements, yet stiff enough to maintain a desired shape and can be designed as thin-shell free-standing units. The forms are typically made from thin-walled steel pipe, waterproof cardboard, fiber-reinforced polymer (FRP), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and acrylonitrile-butadiene-styrene (ABS).

The flexibility and structural qualities of semi-rigid forms make them particularly well-equipped to serve as repair formwork. While semi-rigid forms are generally used for forming cylinders such as pile jackets, they can be molded into nearly any geometric shape, leading to a wide array of applications. Due to the form's ability to be molded tight to a structure, the amount of annular space between the concrete and the form can be greatly reduced. The forms are often prefabricated monolithically or fabricated into multiple pieces or panels spliced together to lengthen the overall shape.

During installation, the form can be wrapped loosely around the structure element from the surface. The diver pulls the form into place, where it is tightened and firmly attached to the structure.

6.2.4 Concrete Preparation

The concrete undergoing repair should be properly prepared prior to the installation of any formwork. Preparation includes removing loose and deteriorated concrete to the maximum extent possible and ensuring there is an appropriate gap under exposed rebar, typically at least 1 inch, so the new concrete can properly bond to the repair area (Figure 49). Repair edges should be saw cut or chipped to provide a vertical or slightly undercut edge around the repair area. Where closed forms are used, forms should have vent pipes at the high point to prevent displaced water from being trapped inside the repair area.

Figure 49. Photo. Concrete repair preparation. (Source FHWA).

6.3 REINFORCING

Concrete repairs usually include additional reinforcing steel to restore the steel cross-section of the original member, provide increased strength, or control cracking and improve anchorage of the repair to the substrate.

6.3.1 Design Considerations

Concrete deterioration is often the result of the internal reinforcing steel corroding. When the repair includes adding reinforcing steel to restore the cross-section, it should be designed to provide adequate splice and steel development length. Sound concrete is often removed to provide access to the original reinforcing to meet design requirements. Mechanical splices and smaller diameter reinforcing steel can minimize the amount of sound concrete that needs to be removed to provide development and splice lengths. Welding should not be used to attach reinforcing steel underwater.

Adding reinforcing steel to the design can improve surface concrete repair durability. For example, No. 3 hooked dowel bars spaced 18 to 24 inches on center can be drilled and grouted into the substrate concrete to improve anchorage. Additionally, a 12- to 18-inch grid of No. 3 reinforcing bars included in the design of a surface repair can reduce cracking.

When adding reinforcing steel as part of the repair, the minimum concrete cover outlined in the repair design should be followed. Insufficient concrete cover can result in rapid deterioration of the reinforcing steel and premature failure of the repair.

6.3.2 Surface Preparation

Existing reinforcing steel should have corrosion byproducts removed before attaching the new reinforcing steel. This preparatory step can be accomplished by using high-pressure water or abrasive cleaning using a wire brush attached to an underwater power tool. Additionally, at least 1 inch of clearance is recommended behind all steel remaining or used in a repair to provide adequate bonding of the repair concrete (Figure 50).

Figure 50. Photo. Reinforcing steel prepared for repair. (Source JF Brennan Company).

6.3.3 Anchorage

Concrete repairs often utilize forms anchored to the concrete surface of the structure being repaired. Forms can be anchored using mechanical or grouted anchors. Anchor systems used underwater are installed in a manner like those used above water.

Drilling a hole in concrete underwater is more challenging than drilling a similar hole above water (Figure 51). A lack of diver leverage and water flow creates unique issues. A system of ropes is usually required to anchor the diver in position to apply enough force to a drill underwater. Alternatively, an underwater drill press can be temporarily anchored to the concrete surface to better control drill progress. Because of the challenges of drilling underwater, grouted anchors are normally used to account for variations in drill hole quality.

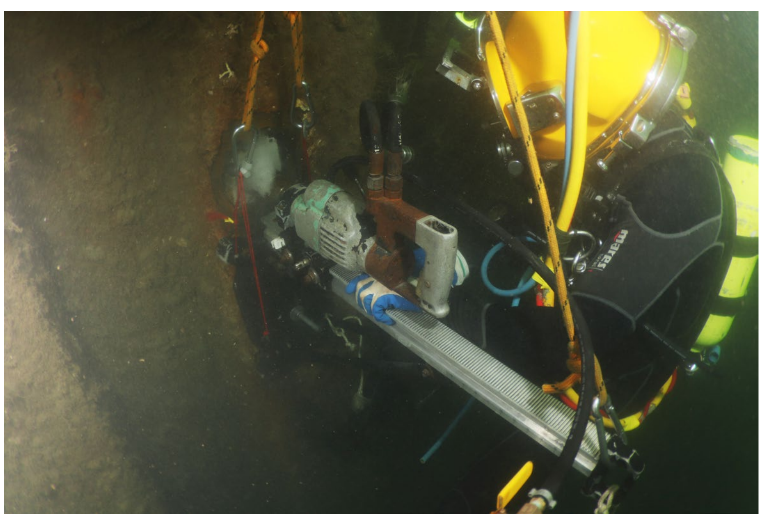


Figure 51. Photo. Diver drilling anchor holes in bridge foundation. (Source FHWA).

Grouted anchors are typically set using epoxy grouts. Special underwater epoxies are available for use underwater. Each manufacturer provides installation instructions for their proprietary system when used underwater.

6.4 CONCRETE PLACEMENT METHODS

When concrete is placed underwater, it is important to minimize contamination of the freshly placed concrete by carefully controlling the process. Concrete placement by tremie and pump systems are discussed in detail in Section 5.6. Other concrete placement methods for underwater applications are discussed in this section. When possible, forms should not be removed until the concrete is fully cured, typically 28 days.

6.4.1 Hand Patching

Hand-applied patches can be used for shallow repairs with a limited surface area. Underwater patch material can be either epoxy, hydraulic, or portland cement.

Before applying any of the proprietary underwater patch systems, the area that the patch is applied to should be cleaned of all marine growth, contaminants, and deteriorated concrete. The materials are mixed above water and taken below water in a manageable quantity, such as a 5-gallon bucket. A diver typically applies the repair material using a gloved hand or a trowel (Figure 52).

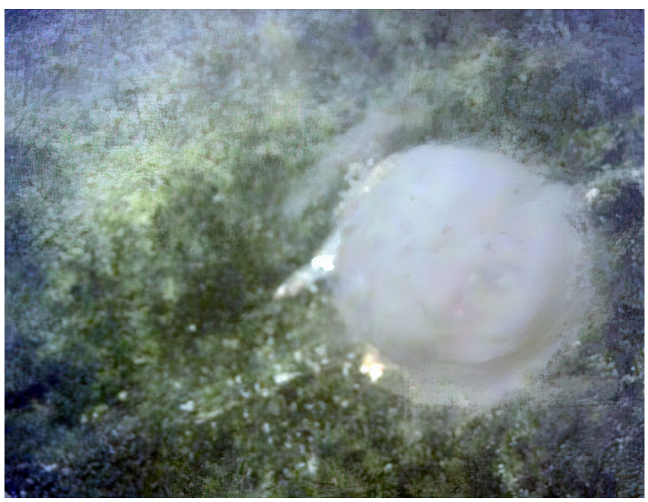


Figure 52. Photo. Hand patch applied underwater at a coring site. (Source FHWA).

6.4.2 Preplaced-Aggregate Concrete

Preplaced-aggregate concrete (PPA) is a two-step process in which aggregate is first placed into the forms, and a cement grout is then pumped into the aggregate, producing in-place concrete. PPA has been used for many years and is well-suited to underwater construction. PPA can be used for most repair applications where the repair thickness is greater than two inches.

Mix proportioning for PPA differs from conventionally placed concrete in that it has a higher percentage of coarse aggregate. Since the coarse aggregate is hand placed, its size is not controlled by the diameter of pump lines or tremie pipes. Grouts used for PPA are most often prepackaged materials formulated specifically for PPA use. Grout must be easily placed and have minimal bleeding. Grout flow is measured using the flow cone method. Typically, a flow of 20 to 24 (±2) seconds is used underwater placement.

Formwork should fit tightly to contain the fluid grout and be substantial enough to withstand grout injection pressures. Edges against existing concrete can be sealed with mortar, caulking rope, or compressible materials. Grout inlets and vent ports are provided in the formwork, typically made of 1½-inch to 2-inch PVC pipe. Each inlet or port is equipped with a valve. When practical, a vent pipe should be provided which extends above water.

After the repair area is properly prepared and any reinforcing steel placed, the forms are set, and the void area is filled with coarse aggregate. Forms for larger repairs are set vertically in sections to facilitate aggregate placement. Formwork for smaller repairs can be provided with temporary openings, "windows," for aggregate placement. After the aggregate is placed and the formwork is sealed, grout placement starts by pumping through the bottom port and progressing upward as needed (Figure 53). Grout preparation and pumping are performed above water and supplied to the divers through a pump line. Pump pressures are typically 10 psi above the static water head at the repair.

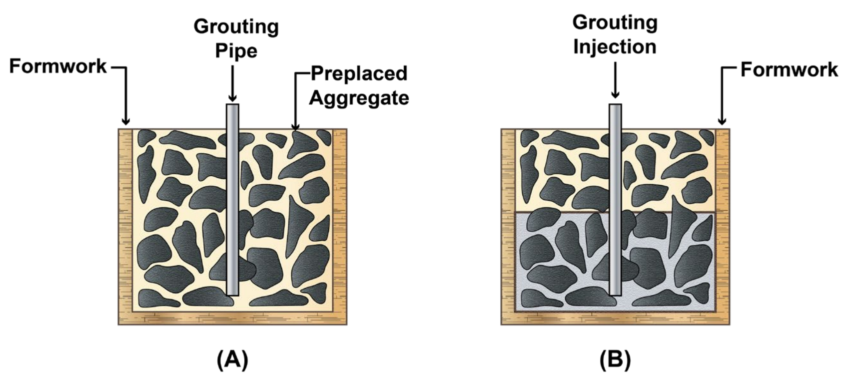


Figure 53. Illustration. Cross-section of PPA setup (A) prior to grout placement and (B) after partial grouting injection.

6.4.3 Bottom Dump

Placement of concrete underwater by bottom dump or free dump is sometimes used to fill eroded areas or for casting concrete slabs. Covered skips or bottom dumping buckets are used to deliver concrete to the point of underwater placement, where the bottom is opened, and the concrete is allowed to free fall to its final location. Concrete for bottom dump placement should be proportioned to be cohesive and should contain anti-washout admixtures. The freefall distance of concrete during placement should be limited to approximately 1 foot.

The application of bottom dump placement for bridge substructure repair is limited but may be practical in filling scour holes or placing thick channel linings. The method should not be used when significant currents are present.

6.5 CRACK REPAIR

Crack repairs can be either structural or nonstructural. Nonstructural repairs are typically performed using a flexible material, while structural repairs use rigid materials.

6.5.1 Routing and Sealing

The purpose of routing and sealing a crack is to prevent or reduce water intrusion, which can cause increased deterioration. Routing and sealing are only used on nonstructural cracks. The crack is enlarged and filled with a flexible sealant which is applied using the manufacturer's instructions. This technique is normally used above the mean low waterline on bridge substructures.

6.5.2 Epoxy Injection

Crack repair in a splash zone and underwater by epoxy injection has been successfully performed since the 1960s. Epoxy crack injection (Figure 54) is used to restore the concrete structural integrity by bonding the crack surfaces together and filling small void and honeycomb areas. The physical properties of concrete repaired with epoxy injection are like the original concrete, but do not provide any increased strength. Only non-moving cracks should be repaired by epoxy injection. A low-viscosity resin may penetrate cracks as narrow as 0.015 inches.

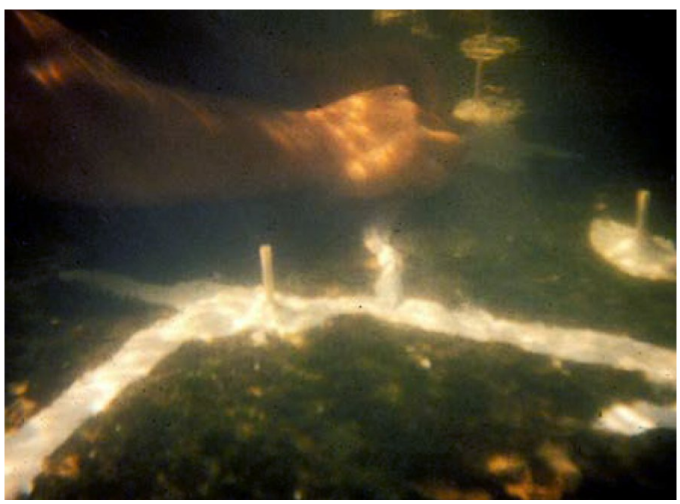


Figure 54. Photo. Epoxy injection. (Source FHWA).

Epoxies used for resin injection are 100 percent solid with low curing shrinkage. Materials will be able to cure underwater and bond to water-filled saturated cracks in fresh or salt water. Epoxy materials for the seal coat and injection resin should be capable of being placed and cured in water temperatures experienced at the repair location. Cold water increases resin viscosity and slows, or can even halt, resin curing. When injecting resins underwater, the resin mixing and pumping equipment are placed and operated above water. This arrangement can result in long hoses running to the injection point and cause concerns when resin viscosity is high.

Underwater and above water injection repairs are installed in a similar manner. Cleaning the crack area by mechanical methods such as hydraulic-operated needle scalers or by high-pressure water is necessary to remove contaminants and allow seal coat bonding. Underwater cracks may contain dissolved mineral salts, silt and clay, corrosion products, and water. These materials will reduce the bond and may not be able to be removed completely. Flushing of cracks with fresh water injected through the ports after installing the seal may partially clean the crack surfaces. The surface seal may be an epoxy or a hydraulic cement material. Selection should be made based on water temperature, currents, set time, and experience. The installation method and spacing of injection ports will vary with the resin supplier's requirements. The epoxy is injected starting at the lowest injection port. Resin is injected at that port until clean resin exits the next higher point, at which time the lower port is sealed, and injection starts at the next higher port. This process continues until the whole crack is filled. Injection pressures of 20 to 150 psi over ambient water pressure are commonly used. Seal coats and injection ports are left in place unless they are visually unacceptable where a repair extends above water.

6.6 MASONRY REPAIR

Masonry piers are often repaired using cast-in-place concrete. Individual stones or large areas of the masonry can be completely replaced with cast-in-place concrete or grout (Figure 55). Exterior formwork can be designed to match the existing stone texture. Typically, the concrete or grout is pumped into the void using ports in the formwork.

Figure 55. Photo. Concrete masonry repair. (Source FHWA).

If required for aesthetic or historic preservation reasons, individual stones can be replaced on masonry piers and mortar joints restored by repointing. Stone replacement starts with the removal of the old stone, taking care not to damage adjacent stonework. All old mortar is cleaned from the surfaces of the stone cavity, and the new stone is placed using shims to provide mortar joint space. The joints are then filled with mortar.

Extensive stone deterioration around the waterline can be repaired by constructing a concrete encasement around the pier. The encasement should be fully reinforced to provide appropriate strength and durability. The top should be sloped so water drains away from the pier shaft.

Repointing of masonry joints is performed where mortar loss has occurred. Mortars containing high amounts of lime tend to leach the lime from the mortar over time. Mortars containing a higher proportion of portland cement provide improved resistance to erosion, but hardness may cause local spalls when combined in joints of softer mortars. Repointing involves the removal of loose mortar using a joint rake or high-pressure water and applying new mortar well compacted into the joint. Mortar used to repoint usually consists of hydraulic cement and sand, which is mixed above water and carried underwater in plastic bags for placement. Large repointing projects may use grout pumped through a metal nozzle to pressure-grout the prepared joints.

6.7 UNDERMINING AND LOCAL SCOUR REPAIRS

Numerous techniques are used to repair foundation undermining and scour at bridges. Several of the more commonly used techniques are discussed in this section. Repairs are undertaken in response to observed conditions that may not represent the maximum scour the site could cause. Therefore, prior to executing scour repairs, an in-depth scour analysis should be completed to guide the design team.

References for scour and scour countermeasure analysis include the following:

- Hydraulic Engineering Circular No. 18 (HEC 18), *Evaluating Scour at Bridges*
- Hydraulic Engineering Circular No. 20 (HEC 20), *Stream Stability at Highway Structures*
- Hydraulic Engineering Circular No. 23 (HEC 23), *Bridge Scour and Stream Instability Countermeasures: Experience, Selection, and Design Guidance*
- National Cooperation Highway Research Program (NCHRP) Report 568, *Riprap Design Criteria, Recommended Specifications, and Quality Control*

6.7.1 Undermining Repairs

The purpose of an undermining repair is to restore full bearing of foundation loads to the bearing soil with non-erodible material. One approach is to dewater the area using a cofferdam and form and place concrete to fill the undermined area. Repair methods that do not require dewatering include grout bags, concrete fill, and grouted stone.

When replacing eroded material below spread foundations with concrete or grout, the new material should be at least as strong as the lost material to restore bearing capacity. Actual load distribution may be impacted by the added stiffness of the new material or redistribution of forces from the bridge due to the undermining. Such aspects should be carefully considered as part of the repair design.

Where piles are exposed in the undermined area, the piles can be wrapped with polyethylene sheeting or similar debonding material to prevent the grout from adhering to the exposed piles. If the grout bonds to the piles, the added dead load from the grout could reduce the pile capacity.

6.7.1.1 *Grout Bags*

Grout or cement-filled bags are often used to repair undermining due to their ease of placement, ability to conform to irregular spaces and relatively low cost. An example of grout bag placement to repair undermining at a pier footing is shown in Figure 56. Below are typical procedures for grout bag selection and installation:

- Grout bags are typically made of high-strength water-permeable material and outfitted with a self-closing inlet valve to accommodate concrete hose insertion.
- Bags are typically no larger than 3 feet wide, 4 feet long, and 1 foot thick.
- Bags will be filled approximately to two-thirds capacity to avoid overfilling.

- Each bag will be snugly butted against adjoining bags and the substructure unit.
- Bags will typically have overlap joints with bags of preceding layer when multiple layers are needed.

Figure 56. Photo. Grout bags used to repair undermining. (Source FHWA).

When properly installed, the grout bags act as a form along the undermined portion of the footing so the grout can be pumped into the void area. Refer to Figure 57 for an illustration of grout bags in use to repair undermining at a bridge pier. The sequence for grout bag installation and grouting of undermined pier or abutment footings generally follows the steps below:

1. Remove debris and other unstable material from the undermined area.
2. For pile-supported footings, debonding material should be applied to all piles with more than 3 feet of vertical exposure.
3. Set vent and fill pipes into the undermined area at a maximum spacing of 4 feet. PVC pipe, or similar, is generally used with a 4-inch minimum diameter.
4. Place grout bags along the face of the footing where undermined and fill each bag with grout. Add additional layers of grout bags as needed until the top layer is at least 1 foot above the bottom of the footing.
5. Grout bags should extend 6 feet or twice the footing width, whichever distance is greater up to 12 feet, from the face of the footing (Figure 57).
6. Once the vent and fill pipes have been installed and the bags are filled, pump grout through the fill pipe until all water in the undermined area has been displaced through the vent pipe.
7. Remove vent and fill pipes or cut flush with the top of grout bags. Pipes left in place can result in debris buildup and cause additional scour.

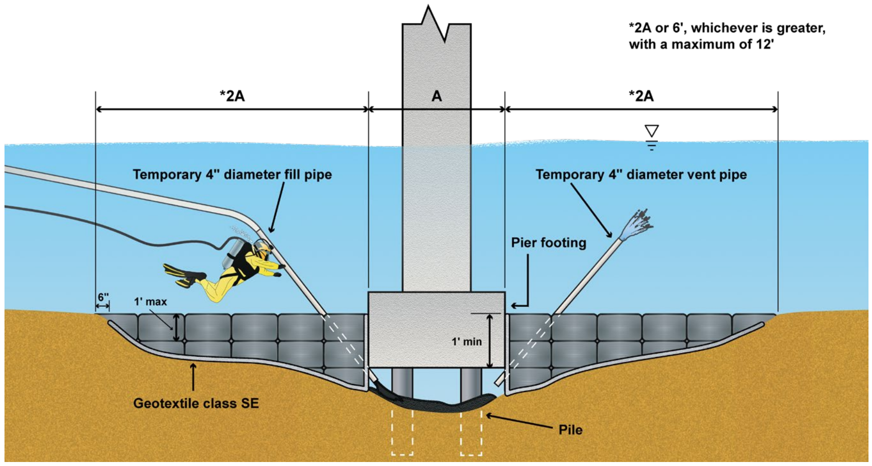


Figure 57. Illustration. Grout repair of an undermined pier.

A typical grout mix includes 850 pounds per cubic yard of cement (Type II if in seawater), fine aggregate, a water-cement ratio of 0.80, air entrainment, and anti-washout admixture. A minimum specified compressive strength of 3,500 psi is commonly used. Grout may contain 3/8-inch coarse aggregate. The leakage of cement fines and alkaline waters from the fabric should be assessed for environmental effects.

6.7.1.2 *Sheet Piling*

Undermined areas can also be filled with concrete placed inside rigid forms. Driven sheet piling can be used as formwork and can also provide long-term scour protection if driven to an adequate depth. The sheet piles may be driven 1 or 2 feet outside the footing to provide space for tremie placement of concrete. Sheet piling, or any other permanent formwork, should not extend above the top of the footing or pile cap.

6.7.1.3 *Grouted Stone*

Grouted stone is another technique used in filling undermining and adjacent scour holes. Grouted stone is like a very large aggregate PPA placement. A relatively large stone is placed in the undermined and scoured area, along with grout fill pipes at the bottom of stone placement and vent pipes at the top. Grout is then pumped into the stone, solidifying the mass. The corresponding grout mix was one part cement to two parts sand, a water-cement ratio of 0.70, and admixtures. A pump pressure of 5 psi over water pressure has been used successfully. Grout placement should be controlled and monitored by divers to ensure it does not begin flowing into the waterway.

6.7.2 Scour Countermeasures

HEC 23 provides design information for various scour countermeasures. Scour countermeasures for bridge piers and abutments are detailed in *Design Guidelines 8* through *15* in HEC 23. These design guidelines are based on extensive research in both laboratory and field settings. The scour countermeasures addressed below are some more common techniques used for local pier or abutment scour.

6.7.2.1 *Rock Riprap*

Rock riprap is perhaps the most common countermeasure employed for local scour protection. HEC 23 *Design Guideline 11* (DG11) provides detailed information for design criteria, specifications, and quality control of riprap countermeasures. Typically riprap scour protection will be monitored and inspected during and after each high-flow event to ensure it remains effective.

A riprap system should be well-graded, adequately sized, and properly installed for stable performance. Rocks used for riprap should be durable and subangular to angular, with a length-to-thickness ratio of three or less. The ten classes of riprap based on the median particle diameter (d_{50}) are shown in Table 9.

Table 9. Typical minimum and maximum allowable particle size in inches. (HEC 23, Table 4.1)

Nominal Riprap Class by Median Particle Diameter		**d_{50}**	
Class	Size	Min	Max
I	6	5.7	6.9
II	9	8.5	10.5
III	12	11.5	14.0
IV	15	14.5	17.5
V	18	17.0	20.5
VI	21	20.0	24.0
VII	24	23.0	27.5
VIII	30	28.5	34.5
IX	36	34.0	41.5
X	42	40.0	48.5

Riprap systems typically include a filter layer placed between the riprap and channel bed. The filter helps retain the subsoil while allowing water infiltration and exfiltration. Filters can be a geotextile fabric, a granular filter consisting of sand or gravel, or a composite filter consisting of both granular and geotextile. The type of filter selected is based on compatibility with the subsoil. Filter design is detailed in HEC 23, *Design Guideline 16*.

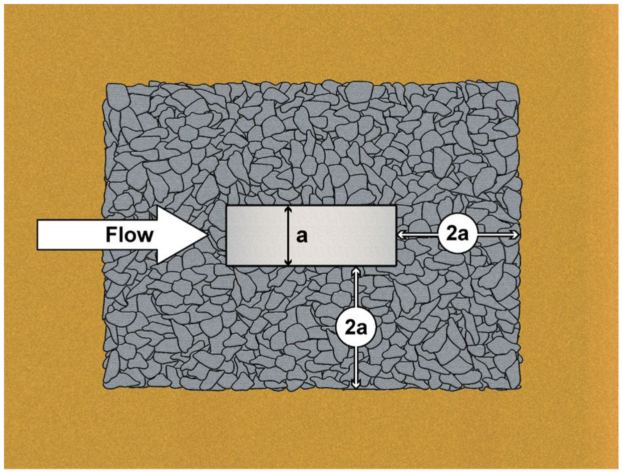


Figure 58. Illustration. Plan view of riprap scour countermeasure at bridge pier.

Riprap should extend perpendicular to the pier to a distance of at least two times the pier width in all directions (Figure 58). The area to receive riprap is first excavated to the calculated depth. After excavating, the filter layer is placed snugly around the pier and should extend two-thirds of the distance to the edge of the riprap (Figure 59). A geotextile filter may be difficult to place underwater unless flow is negligible. The filter fabric should be precut above water, then rolled out on the streambed, and secured with sandbags prior to riprap placement. The fabric should be loosely laid with generous overlaps at the edges. Riprap should be carefully placed to prevent the filter from tearing. Riprap placed on an embankment slope at an abutment (Figure 60) should have the toe buried beneath the streambed, though an alternate installation places a mound of stone along the toe rather than burying it.

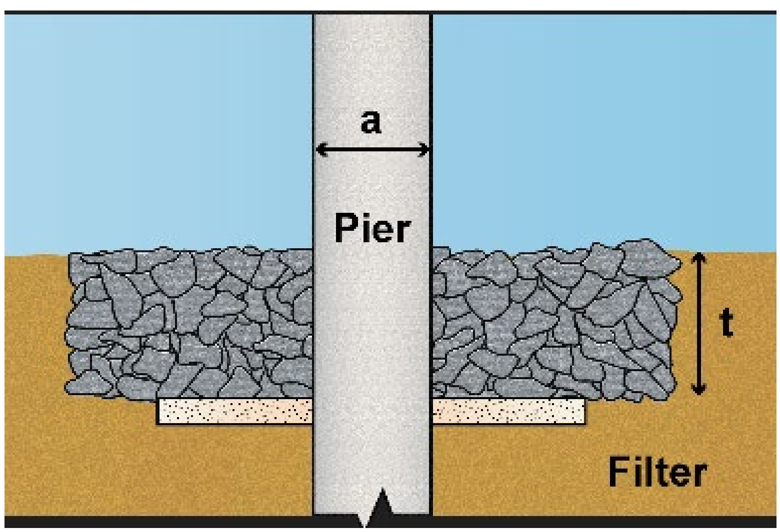


Figure 59. Illustration. Elevation view of riprap scour countermeasure at bridge pier.

Figure 60. Photo. Riprap along bridge abutment.

6.7.2.2 *Partially Grouted Riprap*

Partially grouted riprap is used for bank protection as well as a scour countermeasure for piers and abutments. *Design Guideline 12* (DG12) in HEC 23 offers design and placement details for partially grouted riprap. When periodically inspected and maintained, properly designed partially grouted riprap can offer lasting protection.

Partial grouting is preferred over rigid systems, such as fully grouted riprap because partially grouted riprap maintains permeability and flexibility. The grout should fill between one-third to one-half of the riprap matrix void space to create conglomerates of rock throughout the system. Permeability is maintained since less than 50 percent of the riprap matrix void space is filled with grout. If the riprap matrix fractures from differential settlement or hydraulic loading, the system is designed to fracture into conglomerate-sized pieces. These conglomerate particles maintain excellent interlocking between particles after fracturing occurs.

The rock selected for this system should adhere to the same specifications outlined in Section 6.7.2.1. However, only Classes II, III, and IV from Table 9 may be used in a partially grouted riprap system (DG12). These classes are used to provide the appropriate void space for grout penetration between the rocks. Riprap smaller than Class II creates voids too small for the grout to penetrate to an effective depth, while riprap larger than Class IV creates voids too large to retain the grout.

For partially grouted riprap to function correctly, DG12 specifies a portland cement-based grout must be used. Additionally, the grout mix should result in a wet grout density between 120 to 140 lb/ft^3. Wet densities not within this range should be rejected and the grout mix reevaluated. A basic grout mix for partially grouted riprap applications is provided in Table 10.

Table 10. Suggested grout mix (1 yd^3) for partially grouted riprap application.

Material	Quantity by weight (lbs.)
Ordinary portland cement	740 to 760
Fine concrete aggregate (sand), dry	1,180 to 1,200
¼ inch crusher chips (very fine gravel), dry	1,180 to 1,200
Water	420 to 450
Air entrained	5 to 7%
Anti-washout additive (used only for placement underwater)	6 to 8

The riprap and filter installation procedures outlined in Section 6.7.2.1 are similar for partially grouted riprap. However, the extent of riprap placement is 1.5 times the pier width versus two times the pier width. Additionally, the rock should be thoroughly rinsed before placement for a partially grouted riprap system. If clay, organics, or other particles remain on the rock, it could result in poor bonding between the grout and rocks.

The grout can be placed once the filter layer and riprap are installed. An anti-washout additive should be used for underwater applications to prevent the segregation and dispersion of fine particles. The grout can be placed using a flexible hose attached to a concrete pump, boom, or by tremie. Depending on the riprap size class, application quantities should range from 2.0 to 4.1 ft^3/yd^2 for effective grout distribution. Proper grout distribution and coverage are key to a successful installation. Therefore, prior to placement, application rates should be established on test sections and adjusted based on grout consistency and nozzle size. Exceeding the recommended application quantities can reduce the permeability and flexibility of the system, resulting in an ineffective scour countermeasure or premature failure.

When placing grout, distribution within the riprap matrix should result in two-thirds of the grout remaining in the upper half of the grout layer, with only one-third penetrating to the lower half. Proper grout distribution should result in riprap conglomerate particles throughout the system. For areas along vertical faces where void space is higher, such as the pier, the riprap should be fully grouted.

6.7.2.3 *Articulated Blocks*

Articulated concrete block systems (ACBs) consist of precast concrete units that interlock or are tied together by cables so that they act as a continuous mat system. These systems have predominately been used for slope protection (Figure 61) but are also applicable to pier and abutment scour protection. System design is detailed in HEC 23, *Design Guideline 8* (DG8). Design parameters are developed by manufacturers based on product testing.

Figure 61. Photo. Articulating concrete block system used as scour countermeasure. (Source FHWA).

When using ACBs for scour protection, mats that are preassembled and secured by cabling are recommended. Installation guidelines of ACBs for pier scour protection include the following:

- The ACB mat should extend at least 2.5 times the pier width in all directions.
- The top of the mattresses should be even with the streambed. The upstream edge of the mat should be turned down and buried.
- A filter layer should be used below the ACBs.
- No gaps should be left between individual ACB mattresses.
- Mats should be sealed at the pier. Techniques used to provide a seal include grouting or concreting the gap, placing grout bags at the joint, and sealing filter fabric to the pier (or pile) with banding.
- Installation of anchors through the mat into the streambed around the mattress edges counteracts any tendency of the mattresses to be lifted by currents. Duckbill anchors placed at 8 feet spacing and corners have been used by the Minnesota Department of Transportation (HEC 23, Sec. 8.5). Screw-in anchors can also be used.

As with riprap, ACB systems should be inspected following high-flow events to ensure proper performance.

6.7.3 Culvert Undermining Repair

A culvert is a conduit that conveys stream flow through a roadway embankment. Culverts are most commonly constructed of concrete, corrugated metal, masonry, or plastic and are generally categorized as closed or open bottom. Common shapes are pipe arch, box (rectangular), circular, or elliptical.

Culvert undermining can result in a catastrophic failure if unchecked. Undermining can occur at the inlet or outfall of a closed culvert. If not remediated, undermining can progress throughout the entire length of the culvert, commonly referred to as "piping," since it creates a hollow void, similar to a pipe. Although piping frequently starts by scour at the inlet end, around, or under the entrance features, it may occur because of scour of the embankment above the culvert. Piping can also occur because of water seepage through open joints. The repair methods discussed in Section 6.7.1 for pier undermining can also be applied to closed culverts. A common method to repair culvert undermining is the installation of appropriately sized riprap (Figure 62). *Design Guideline 18* in HEC 23 offers detailed guidance and specifications for installing riprap protection for bottomless culverts.

Figure 62. Photo. Riprap used to repair undermining at culvert. (Source FHWA).

The FHWA's *Culvert Repair Practices Manual* (Publication No. FHWA-RD-94-096) also provides rehabilitation techniques for undermined culverts; some of the techniques include the following:

Underpinning Grout Injection: This method involves injecting cementitious grout into the voids around the culvert to fill the voids and stabilize the soil. Grout injection can be done using either low-pressure or high-pressure injection techniques, depending on the extent and depth of the undermining. Chemical grouting can also be used for the injection, which is usually polyurethane; this grout expands into inert foam, filling irregular and hard to reach voids.

Soil Replacement: This method involves excavating the undermined soil around the culvert and replacing it with suitable backfill material such as crushed stone or concrete. The backfill material is compacted to provide stability and support to the culvert.

Reinforced Soil Structure: This method involves constructing a reinforced soil structure around the culvert to provide additional support and stability. The structure is constructed by placing layers of geotextile fabric and compacted soil in a predetermined sequence.

Culvert Replacement: If the culvert has sustained significant damage due to the undermining, it may need to be replaced. The replacement culvert should be sized to accommodate the flow of water and sediment in the stream and designed to withstand the hydraulic and structural loads. If possible, an apron with a cutoff wall should be added to minimize the potential for future scour.

6.8 FOUNDATION MODIFICATIONS

6.8.1 General

Existing bridge foundations may require modification to support added loads or as a scour countermeasure. Foundation modifications most often include new pile or drilled shaft installation, footing enlargement, and pile cap or pier shaft extension.

6.8.2 Adding Piles and Drilled Shafts to a Pile Supported Footing

Driven piles and drilled shafts can be used to increase foundation capacity because of increased loads or to repair local scour. Installation typically requires overhead access; therefore, installations also result in a cap extension or modification. Figure 63 and Figure 64 illustrate the construction sequence of a scour repair which required additional drilled shafts and a footing extension of an existing pier.

Figure 63. Photo. Drilled shafts were installed to strengthen the existing pier. (Source FHWA).

Figure 64. Photo. Reinforcing to extend footing and tie-in new drilled shafts. (Source FHWA).

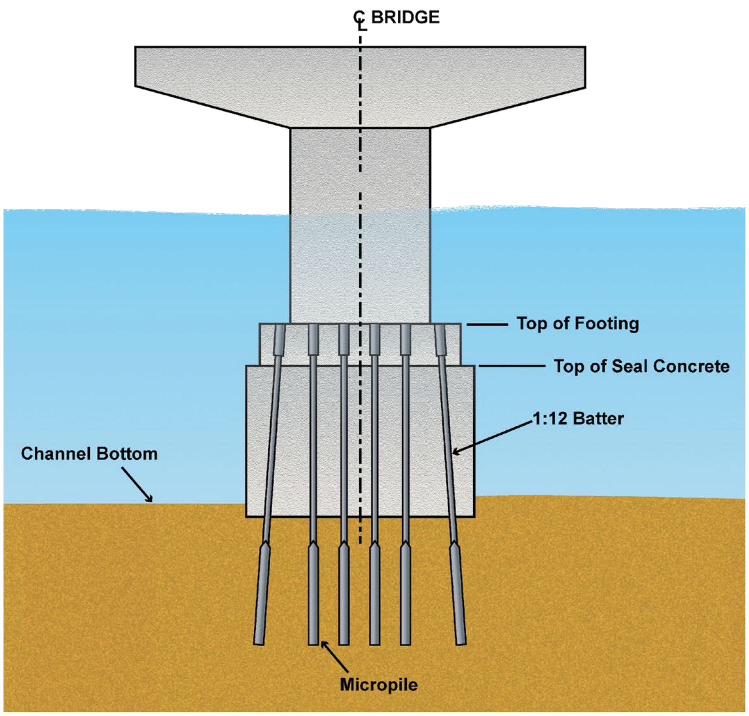
6.8.3 Adding Piles to a Bent

Piles can be added to a pile bent to restore capacity lost due to pile deterioration or scour. The bent cap can be extended to encompass the new piles, or the bent cap can be supplemented with external members creating a crutch bent to provide additional support. An example of a crutch bent is shown in Figure 65.

Figure 65. Photo. Steel pipe pile crutch bent. (Source FHWA).

6.8.4 Micropiles

When site conditions do not allow for traditional pile or drilled shaft installation, micropiles are an alternative method to strengthen a spread footing. Micropiles are typically less than 10 inches in diameter and are cored through the footing into suitable bearing material. They typically have a steel casing or reinforcing steel added for strength. Figure 66 illustrates micropiles installed on a bridge pier that had a foundation comprised of a spread footing founded on a structural, unreinforced mass concrete seal.



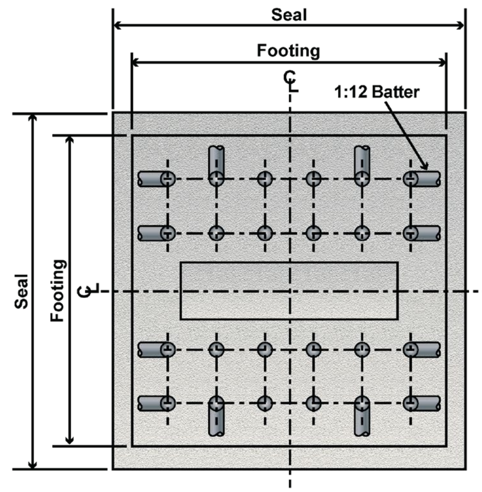


Figure 66. Illustration. Elevation view (left) and plan view (right) of micropile strengthening of a bridge pier.

6.8.5 Footing or Pile Cap Extensions

Pier geometry modifications are structural scour countermeasures that can be applied to reduce flow resistance and mitigate local scour. Extensions are typically constructed on the upstream side of a pier and extend above the maximum flood elevation (Figure 67). The extension should have a sharp or rounded nose streamlined into the approach flow.

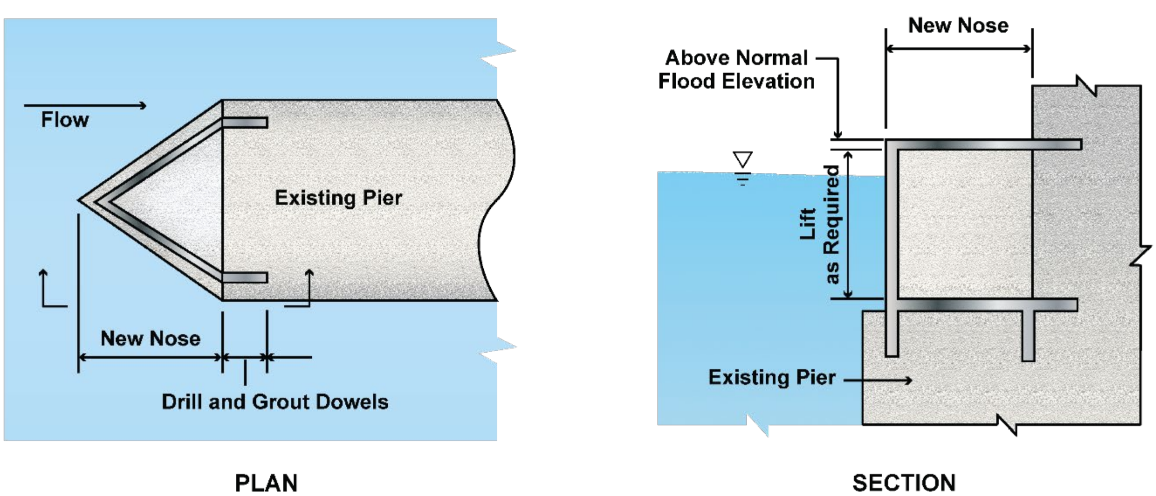


Figure 67. Illustration. Plan view (left) and section view (right) of footing extension.

The existing surface should be cleaned to remove all marine growth, loose or degraded concrete, and other contaminants. Rigid panel forms or stiffened fabric forms, which may remain in place, can be used to form the extension. Drilled and grouted reinforcing steel is installed into the existing pier to secure the new extension. Reinforcing steel should be assembled on the surface and lowered in place. Once the formwork and reinforcing steel are secured to the existing pier, concrete can be placed by pumping or tremie.

CHAPTER 7.
PILE AND SHEET PILE REPAIRS

7.1 INTRODUCTION

Pile-supported bents are a common type of bridge substructure. Piles can be made of steel, timber, or concrete. Sheet piles are used to construct channel walls and bridge protective structures. Pile repair techniques include full and partial replacement, strengthening, and protection. Good repair performance requires the careful selection of repair techniques and the use of proper installation methods.

7.2 PILE REPAIR

Pile repairs are often a condition-based preventive maintenance activity. The repair method is selected based on several factors, including pile material, type and extent of deterioration, condition of adjacent piles, and cost. Repairs are implemented as a cost-effective means to prolong the bridge's life. There are four primary categories of pile repairs:

- Preservation
- Strengthening
- Partial replacement
- Replacement

Preservation is used when the substructure has adequate capacity to support design loads and has active deterioration that can be arrested. Cathodic protection and pile wrapping are two techniques used to preserve in-service piles.

Strengthening involves installing additional structural elements to an in-service pile through encasement or attachment of structural elements (Figure 68). Bridges that are good candidates for pile strengthening have deck and superstructure elements that are in at least fair condition and can have their service life significantly extended by strengthening the substructure components.

Partial replacement involves removing and replacing the damaged portion of a pile. Steel and timber piles with isolated areas of deterioration are good candidates for partial replacement.

Replacement is required when the structural capacity of a pile within a pile bent is reduced to the point that a substructure cannot support the design load, and other repair options are not possible. Replacement of a pile is typically the last resort in the hierarchy of pile repair options.

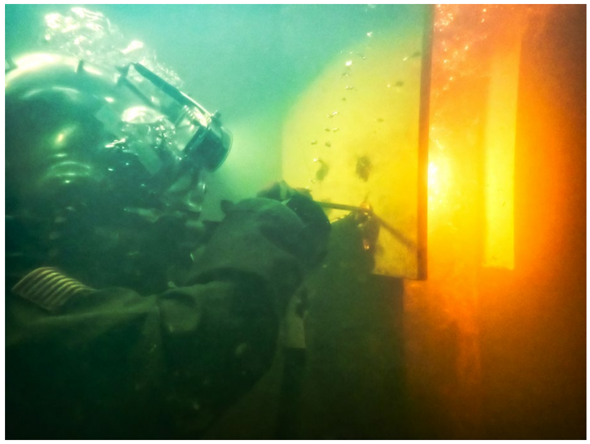


Figure 68. Photo. Diver strengthening a steel pile by attaching a steel plate to the flange. (Source FHWA).

7.2.1 Pile Preservation

Pile preservation is a viable option when adequate pile capacity remains, and the primary goal is to prevent further loss of capacity. The two methods used to protect piles are pile wraps and pile jackets.

7.2.1.1 *Pile Wraps*

Pile wraps are used when a pile has adequate capacity and deterioration can still be arrested. Pile wraps prevent oxygen or other contaminants from reaching the pile surface, effectively preventing further deterioration if they are designed correctly. Pile wraps can be installed on timber, steel, and concrete piles.

The primary advantage of a pile wrap is the lower cost when compared to other repair options. Pile wraps are like other encasement systems regarding the level of effort needed to prepare the pile being repaired. Both pile wraps and pile encasements require extensive cleaning to remove all biofouling and damaged materials from the surface of the pile (Figure 69 and Figure 70).

Figure 69. Photo. Timber pile wrap. (Source FHWA).

Figure 70. Photo. Steel pile wrap. (Source FHWA).

There are several disadvantages to pile wraps. The main disadvantage is that the pile wrap may require periodic removal or partial removal to assess the conditions of the wrapped pile to determine effectiveness. Pile wraps can also be damaged by floating debris or become loose over time due to water flow.

Various proprietary pile wrap systems are available, and installation instructions should be followed as described in each manufacturer's technical literature. Some manufacturers provide substrate materials that can be installed around the pile base material prior to wrap installation to enhance performance.

7.2.1.2 *Pile Jackets*

Pile jackets provide a robust structure to cover the damaged pile. A pile jacket uses grout or concrete (Figure 71) to encapsulate the deteriorated portion of the pile. If properly constructed, the grout or concrete will form to the cross-section of the pile, effectively preventing oxygen or other contaminants from reaching the pile.

Figure 71. Photo. Concrete pile jacket. (Source FHWA).

Pile jackets can include reinforcing steel to improve or restore the structural capacity of the pile system, as discussed in Section 6.3. A wide variety of pile jacket systems are available. Jacket manufacturers typically provide technical support to ensure their system is effective for site-specific conditions.

The primary advantage of using pile encasements as a strengthening method is they can often be completed without removing the bridge from service. Disadvantages include the increased weight of the encasement system on the pile and that the concrete encasement can stiffen a pile and reduce its performance during a seismic event.

7.2.2 Pile Strengthening

Pile strengthening involves adding structural elements to a pile by either attaching them directly to the pile in the case of steel or timber piles or encasing a concrete pile in a pile wrap with supplemental reinforcing steel.

Strengthening steel and timber piles by attaching supplemental members to them is typically the most economical alternative for repair. Often these repairs do not require shoring of the structure, and they can be performed while the bridge remains in service after confirmation that construction activities can be performed safely.

7.2.2.1 *Steel Pile Strengthening*

Supplemental steel members can be bolted directly to steel H-piles where deterioration exists. Figure 72 shows an engineer creating holes using an electromagnetic drill press to facilitate bolted connections for repair. Designers should ensure adequate steel thickness is present to allow a secure attachment of the additional section. A protective coating should be applied in the shop after the fabrication of the supplemental members to provide the best results.

Figure 72. Photo. Electromagnetic drill press used to facilitate repair connections. (Source FHWA).

Welding supplemental steel is also a viable option, provided site conditions support underwater welding operations. Underwater welding is discussed in detail in Section 5.8 of this manual.

7.2.2.2 *Timber Pile Strengthening*

Timber piles can be strengthened by attaching additional timber members to the pile with through bolts. The through bolting technique is illustrated in Figure 73. Members are sized to provide additional cross-section during the design process and can be installed by relatively inexperienced personnel. The location where through bolting is performed should be in sound timber with no internal or external decay. Bolt holes drilled in the field should be treated with a preservative prior to installation on the affected pile.

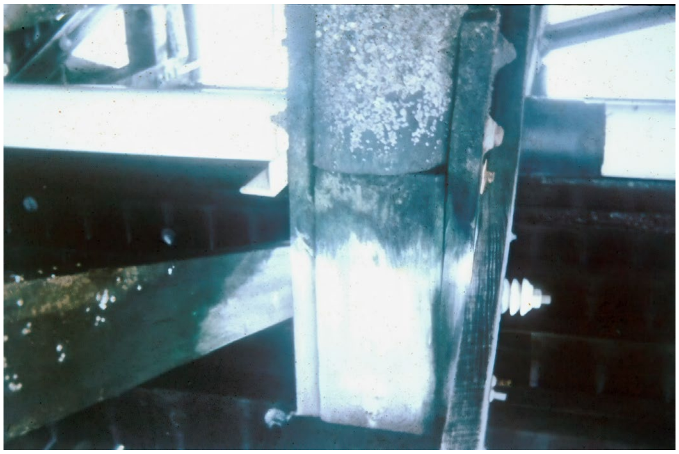


Figure 73. Photo. Timber pile with strengthening members attached. (Source FHWA).

7.2.2.3 *Concrete Pile Strengthening*

Concrete pile strengthening involves encasing the damaged pile in a concrete encasement with reinforcing steel to restore structural capacity. The design process determines the configuration and amount of reinforcing steel needed to restore the pile capacity to the desired level.

There are several structural encasement systems available. Figure 74 shows one example of a concrete pile encasement system.

Figure 74. Photo. Concrete pile being strengthened with a structural jacket. (Source FHWA).

7.2.3 Partial Replacement

Partial pile replacement or splicing can be used when a localized area of the pile is severely damaged. Partial replacement has predominately been applied to timber piles though it is used to a limited extent on steel piles.

In any partial replacement, lateral load transfer should be provided through bent bracing or other application-specific details. When performing partial pile replacements, a detailed analysis of the pile bent where work is performed should be completed. In the absence of a detailed analysis, it is recommended that no more than 25 percent of the piles in a bent be repaired with partial replacement. Temporary support may also be required during construction to ensure load transfer when sections of piles are removed.

Figure 75 shows one technique for the partial replacement of a steel pile. The damaged area is cut off, and a bearing plate is installed atop the remaining lower pile section. The bearing plate can be bolted or welded to the existing pile. The new upper portion is installed by bolting or welding to the bearing plate installed on the lower pile section. The replaced pile portion is fabricated to be shimmed at the existing pile cap to account for installation clearances. The pile may be preloaded by jacking the pile against the cap prior to shimming.

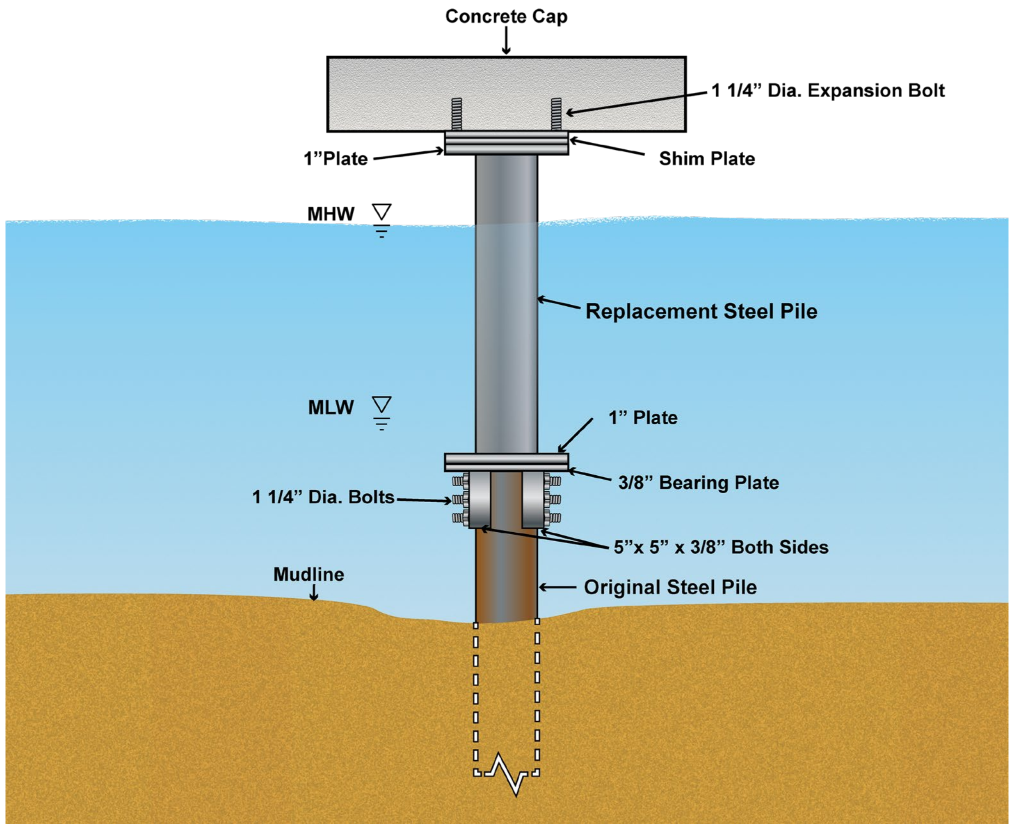


Figure 75. Illustration. Steel H-pile partial replacement.

A method for splicing a portion of timber pile is illustrated in Figure 76. A steel sleeve is set over the remaining bottom section of the pile to receive the new section. This sleeve is secured with spikes and grout and placed between the pile sections to aid in the transfer of load from the new section to the existing pile section. The top of the replacement section is shimmed tight. Various fasteners or epoxy grout could also be used at the top connection. Another method of splicing in a new pile section using splice plates, or "fish" plates, is shown in Figure 77.

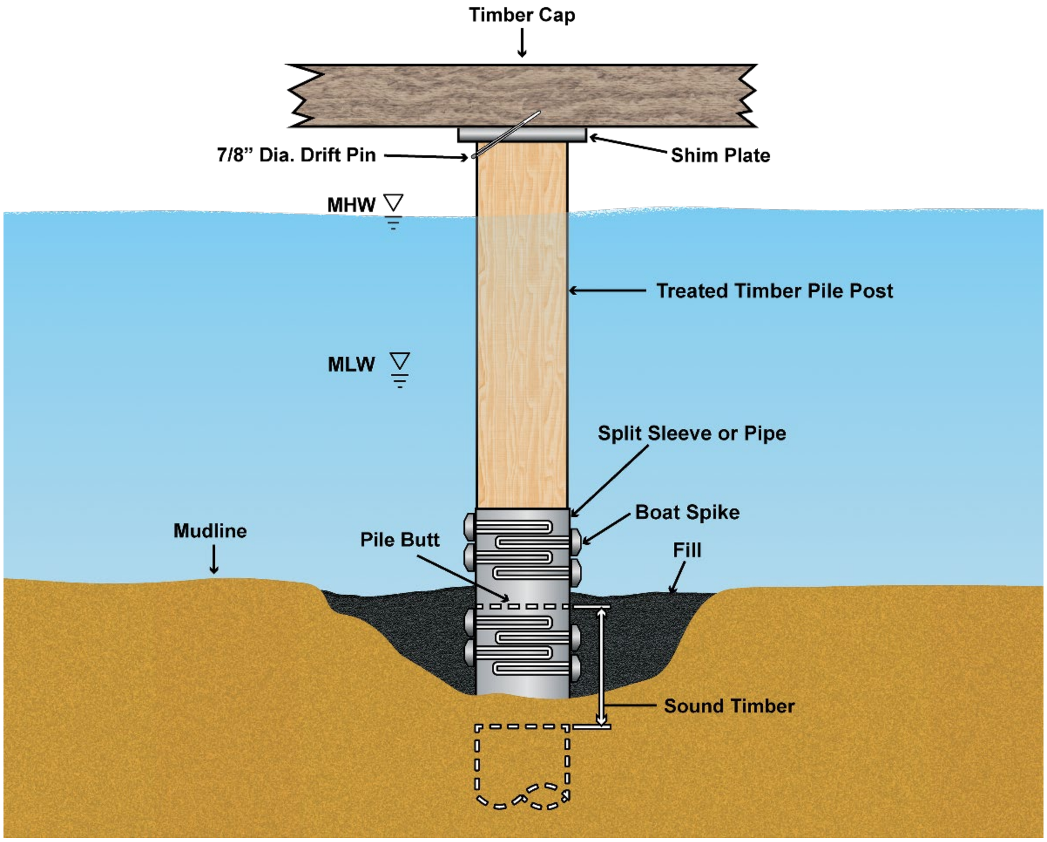


Figure 76. Illustration. Timber pile partial replacement.

Figure 77. Photo. Fish plates used for partial pile replacement. (Source FHWA).

7.2.4 Pile Replacement

Piles with severe physical damage are candidates for replacement. Replacement is typically the most expensive alternative and is normally the last resort. Direct pile replacement is often not possible due to the difficulties of removing the existing pile and inserting a new one. Most commonly, the new pile is installed adjacent to the damaged pile, and the cap is extended to transfer loads to the new pile, effectively abandoning the old pile (Figure 78). One exception to this is bridge protective systems, where pile removal and replacement may be readily accomplished. Generally, replacement piles are of a similar type to those they replace.

Figure 78. Photo. New timber piles driven adjacent to deteriorated piles. (Source FHWA).

Supplemental pile bents, often called crutch bents, can be used where the existing pile cannot be directly replaced. Crutch bents are discussed in detail in Section 6.8.

7.3 QUALITY ASSURANCE

All underwater repairs should be monitored during installation to ensure the quality of the repair. A test installation may be required on larger projects to ensure the repair can be executed as required by the engineer and product manufacturer.

Test installation is a common practice in larger construction or engineering projects where installation or repair of a complex system is needed. The purpose of the test installation is to ensure that the repair or installation can be executed in accordance with the product manufacturer or engineer’s recommendations before moving forward with the entire project.

Typically, a test installation involves the installation of a smaller, scaled-down version of the system or component. This step allows installation methods to be evaluated, identify any potential issues, and make any necessary adjustments before committing to the rest of the project.

7.4 CRACK INJECTION

Crack injection can be used for the repair of cracks in concrete piles. Crack injection materials and processes are presented in Section 6.5. Only dormant cracks should be injected.

7.5 COATINGS

There are commercially available coatings formulated for underwater and splash zone applications. These coatings are most often used on steel H-piles, pipe piles, and sheeting but may also be used on concrete. They form a barrier coating to prevent contact with the water. When used on concrete, coatings should be applied before the chloride level at the reinforcements reaches the critical value to initiate corrosion. These coatings are generally epoxy or polyester formulations. Some materials are quite viscous and are applied by gloved hand or trowel. Others can be applied by brush or roller. Coatings can be applied to concrete or steel.

Surfaces to receive underwater applied coatings should be prepared by abrasive blasting to remove all deleterious material and provide a surface profile to maximize adhesion. The materials are mixed and taken underwater in a bucket, though pressurized hoses feeding a roller have been developed. Material application by gloved hand or trowel typically results in a coating thickness of 0.125 to 0.200 inches. Brush or roller-applied coatings are typically 0.03 to 0.04 inches thick. Coating materials should be free of harmful chemicals that could enter the water. A documented history of successful use should be required from the product manufacturer and applicator.

Coating inspection should include verification of surface preparation, materials preparation and application, and selected coating thickness readings of the completed work. Magnetic coating thickness gauges may be used underwater.

7.6 SHEET PILE REPAIRS

Sheet piles are often used as channel protection or abutment retaining walls. Sheet piles can be concrete, timber, or steel. When sheet pile walls fail, backfill can spill out from behind the wall and cause failure of an approach roadway.

Minor corrosion without significant section loss can be repaired by applying a splash zone or underwater coating. When site conditions allow, temporary cofferdams can be used to accommodate the completion of repair and coating application in dry conditions. Some specialized limpet cofferdams have been constructed to fit sheeting profiles. Cathodic protection may also be installed, which is discussed in Section 8.3.

Local areas of severe damage resulting in holes can be repaired by installing patch plates on steel or using hand-placed grout patches on concrete. Extensive deterioration may require replacing the wall or installing a new wall immediately in front of the existing wall, as illustrated in Figure 79.

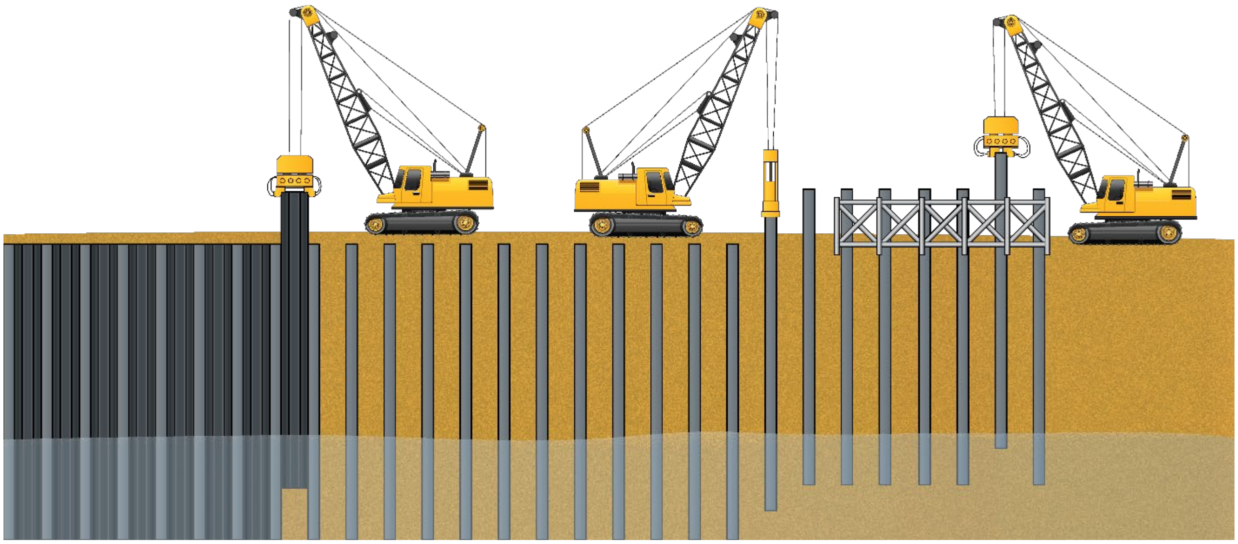


Figure 79. Illustration. New sheet pile wall being installed.

CHAPTER 8. CATHODIC PROJECTION FOR SUBSTRUCTURES

8.1 INTRODUCTION

Modern construction methods seek to protect bridge substructures from corrosion damage by preventing or delaying the onset of steel corrosion. Bridge members can be protected by using steel coating systems, high-performance concrete (HPC), or the use of corrosion-resistant materials like stainless steel and FRP. Cathodic protection systems can be effectively implemented on older structures to extend their life by arresting further deterioration.

8.2 FUNDAMENTALS OF CATHODIC PROTECTION

Environmental corrosion primarily affects metal in contact with soil or water and is caused by the formation of a corrosion cell. The four components used to form a corrosion cell are shown below:

- Anode
- Cathode
- Electrolyte (ionic path)
- Metal path

The anodic site is the location of visible corrosion (oxidation), while the cathodic site is the location of the reduction reaction driven by activity at the anode. The steel member or reinforcing provides the metallic path, and the water provides the ionic path. Oxygen, which is essential for the corrosion process to occur, is generally supplied from the atmosphere. The presence of salts or other electrolytes in the water facilitates the movement of electrons and increases the corrosion rate. Refer to the diagram of a corrosion cell in Figure 80.

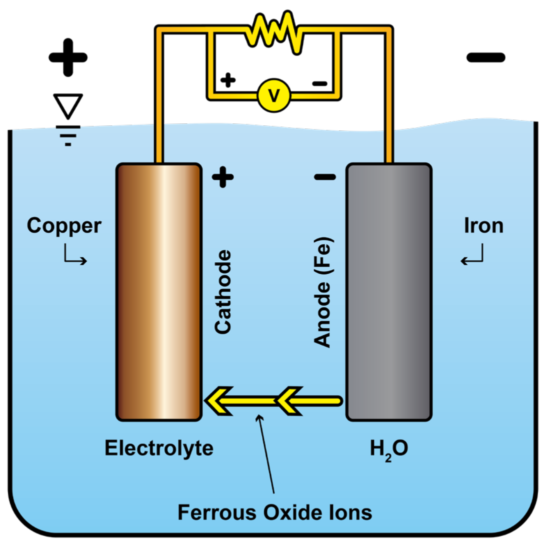


Figure 80. Diagram. Electrochemical corrosion cell.

Cathodic protection systems suppress corrosion activity by providing sufficient electrical current from an external source to exceed the local environment's corrosion threshold, overcoming the structure's ongoing corrosion current. The anodic reaction stops, halting corrosion. Cathodic protection systems are classified as impressed current (active) systems, which use an external power source for current, or as galvanic (passive) systems, which use current generated by a sacrificial anode such as zinc.

8.3 CATHODIC PROTECTION SYSTEM

Cathodic protection systems fall into two main categories: passive (galvanic) and active (impressed current) systems. Both have distinct characteristics which should be evaluated during the design phase.

8.3.1 Passive Systems

Passive systems operate based on dissimilar metal corrosion and the relative position of specific metals in the galvanic series. When two metals are electrically connected, the metal with higher electrical potential (corrosion potential) will sacrifice itself to protect the other metal. Therefore, a passive system involves attaching a sacrificial anode to the steel to be protected. The anode will be consumed over time and should be periodically replaced. Table 11 is a partial list of electrical potentials of common metal. The material with the higher electrical potential is at the top.

Table 11. A partial list of electrical potential for materials.

Material	Electrical Potential (V) [1]
Zinc	-1.10
Carbon Steel	-0.68
Copper	-0.43

[1]All values with respect to copper-copper-sulfate half-cell.

Sacrificial anodes are typically made of zinc, aluminum, or magnesium. Zinc is the most common due to a combination of good performance and low cost. Aluminum anodes are alloyed with zinc. Science has shown that magnesium anodes are poorly suited for use in seawater due to magnesium's tendency to self-corrode in low-resistivity seawater. Additionally, the science has shown that zinc anodes are well suited to the seawater environment when sufficient exposure to moisture maintains lower resistance, and the availability of chloride ions keeps the zinc active. Table 12 presents the advantages and disadvantages of a passive cathodic protection system.

Table 12. Advantages and disadvantages of a passive galvanic system.

Advantages	Disadvantages
Simple system No monitoring Limited maintenance Self-adjusts current output as structure's potential varies Minimal risk of hydrogen embrittlement on prestressing steel	Limited anode life Limited current output

8.3.2 Impressed Current Systems

Impressed current systems drive a low voltage direct current from an inert anode through the electrolyte to the structure to be protected. Sufficient direct current is provided to overcome the anodic reaction on the steel surface. An external power source supplies direct current. Figure 81 shows typical components of an impressed current system. Coatings should be used above and below the water when impressed current systems are used on steel structures. No cathodic protection is provided to those portions of the structure located above water.

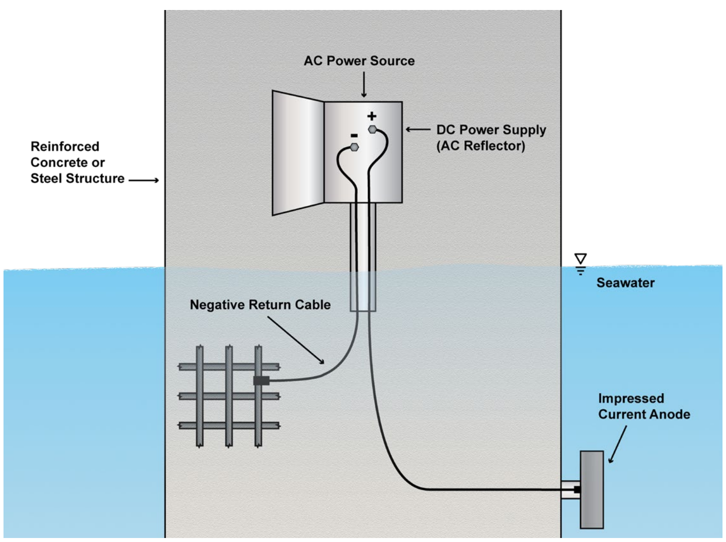


Figure 81. Illustration. Impressed current system.

Power for impressed current systems has traditionally been supplied by commercial utilities as power runs through a rectifier to produce direct current. Solar power and special batteries have also been used. Anodes are commonly made of cast iron, graphite, and special alloys. The negative side of the various protected components is connected back to a grounding system.

Impressed current systems should be regularly monitored and current output adjusted as needed. A higher current may be needed to polarize the structure initially. If the current is too high, there is a potential for hydrogen to be produced from the reduction of water into hydrogen and oxygen.

The hydrogen may cause embrittlement of steel, resulting in cracking. Table 13 outlines several advantages and disadvantages of an impressed current system.

Table 13. Advantages and disadvantages of an impressed current system.

Advantages	Disadvantages
Applied current can be controlled and varied Can protect a more extensive area Suitable for high resistivity electrolytes Requires fewer anodes than galvanic systems	Requires external power source Potential monthly power charges Initial costs are higher than galvanic systems Requires regular adjustment and maintenance Anodes are long life

8.4 EXAMPLE SYSTEMS

A variety of systems are supplied by different manufacturers. They generally fall into several categories, such as pile jacket systems, surface applied systems, and embedded systems.

8.4.1 Pile Jacket-Anode Passive System

Fiberglass pile jackets incorporating an integral zinc mesh sacrificial anode are used to rehabilitate and protect concrete piles in the tidal and splash zones from further deterioration. The system does not restore structural capacity. Prior to jacket installation, loose concrete is removed, but no pile repairs are completed. The pile jacket mesh system is installed, and a sand cement grout is used to fill the space between the pile and jacket (Figure 82). The grout absorbs water and provides a path for current flow from the mesh. A connection between the zinc mesh and pile reinforcing is made by drilling into the pile and attaching a conductor to the internal reinforcing. Electrical continuity between reinforcing steel within the pile should be verified. In the case of prestressed piles, it may be necessary to electrically connect all the prestressing strands together.

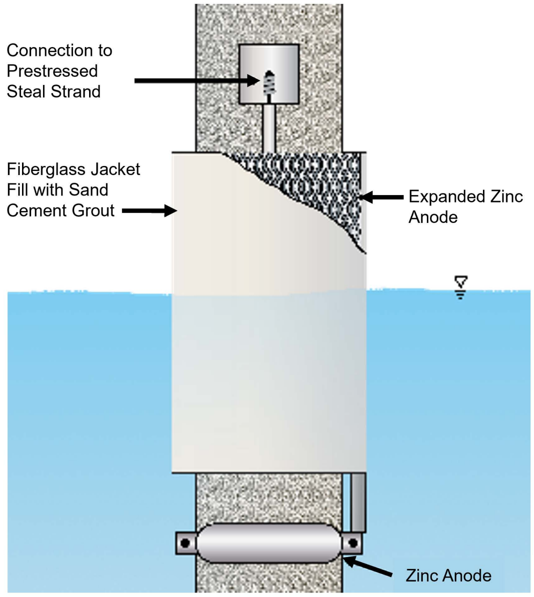


Figure 82. Illustration. Zinc mesh pile jacket system.

To prevent rapid depletion of the zinc mesh near the bottom of the jacket (attempting to protect the pile outside the jacket), a bulk 45-pound zinc anode is attached to the pile below the jacket. This anode should also be electrically connected to the pile reinforcing steel or prestressing strands.

8.4.2 Surface-Applied Systems

Surface-applied systems are expensive and require frequent inspection and maintenance because they are exposed to harsh environmental conditions near the tidal zone.

8.4.2.1 *Arc-Sprayed Zinc*

Arc-sprayed zinc and luminous zinc indium alloy are two systems used to protect steel from corrosion from the splash zone up. The sprayed zinc is applied directly over cleaned exposed steel after all deteriorated material is removed (Figure 83). It is applied during periods of low water. Performance is best where the area is wetted periodically. Arc-sprayed zinc can be used as part of an active or passive system. Installation should follow specific manufacturers' instructions.

Figure 83. Photo. Sprayed zinc is applied to a bridge substructure. (Source FHWA).

8.4.2.2 *Titanium Mesh System*

A titanium mesh-impressed current system can be installed over a patched concrete surface, normally in the tidal and splash zones. Power is supplied to mesh distributor bars from a power source on or near the bridge. The mesh is normally covered with sprayed conductive mortar after installation. Refer to Figure 84 for an example of an installed titanium mesh system.

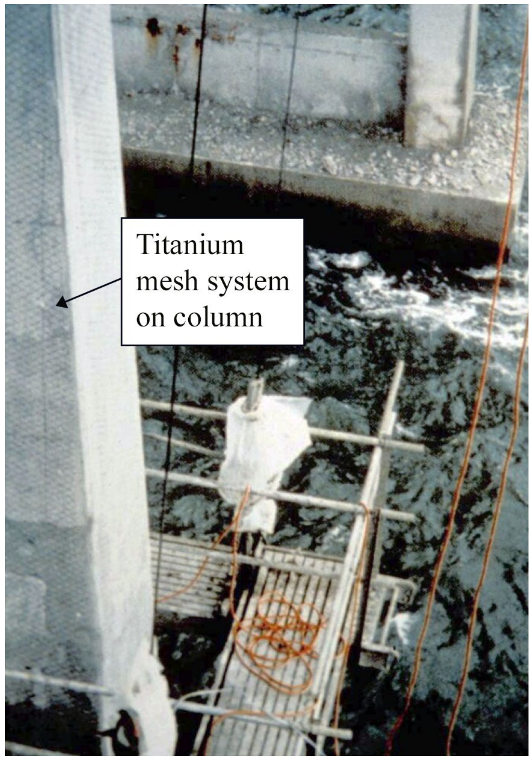


Figure 84. Photo. Titanium mesh system installation. (Source FHWA).

CHAPTER 9.
UNIQUE CHARACTERISTICS OF UNDERWATER CONSTRUCTION

9.1 INTRODUCTION

Underwater repair and rehabilitation of bridges can be an important part of a comprehensive bridge management program. Underwater construction activities have unique characteristics. The following information is provided to highlight some of these unique characteristics. Except where required in statute or regulation, these are not federal requirements and only provided to inform the reader.

9.2 CONSTRUCTION INSPECTIONS

Construction inspection of underwater repairs is critical for a successful project. This inspection is frequently overlooked since work is often not visible from the surface.

9.2.1 Inspection Options

To help ensure quality in the construction process, the owner may implement a program to ensure compliance with construction documents. There are several ways that are typically used to accomplish this for underwater repair projects. The owner can utilize in-house (owner-provided) inspections, contractor-provided inspections, or inspections through a third party. There are advantages and disadvantages to each option.

9.2.1.1 *Contractor Provided Inspections*

The owner may write the contract so that the contractor has full responsibility for quality control and the inspections during and after construction. The advantage of this agreement is that the owner has to only engage one firm. This may be helpful where the owner may have limited options with other diving sources in a specific geographical area or specific qualifications required of the divers to enter the worksite. However, this scenario typically puts the contractor in control of construction techniques and reviews, not providing that independent inspection of the work.

9.2.1.2 *Owner Provided Inspections*

Many government agencies utilize internal resources to provide in-house inspections. The obvious advantage to this option is that the owner can ensure quality construction and is able to work closely with the contractor to ensure all requirements of the construction documents are met.

9.2.1.3 *Third-Party Inspections*

An independent third-party inspection is typically an ideal approach to performing quality control inspections when owner provided inspections are not available. The inspection organization will report inspection results to the owner, the engineer, and the contractor.

9.2.2 Acceptance and NBIS Inspection

In conjunction with the final acceptance inspection, it is helpful to perform an underwater inspection, required by the NBIS. This inspection will not only help determine if the contractor has performed everything correctly, but while the divers are in place, an updated NBIS inspection can provide details of any needed updates to the NBI or element quantities. This inspection can also verify the as-built drawings so that they are accurate going forward.

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