

Managing Hydrotechnical Hazards for Pipelines Located Onshore or Within Coastal Zone Areas

API RECOMMENDED PRACTICE 1133
SECOND EDITION, DECEMBER 2017



AMERICAN PETROLEUM INSTITUTE

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Recommended Practice for Managing Hydrotechnical Hazards for Pipelines Located Onshore or Within Coastal Zone Areas

1 Scope

This recommended practice (RP) applies to new and existing hydrocarbon pipelines that transport gas and hazardous liquids. It is intended to apply to onshore waterways and coastal zones that may be susceptible to hydro-technical hazards. An onshore waterway is any man-made or natural channel through which water flows. Coastal zones extend offshore to a water depth of 15 ft and extend inland to include those areas of land influenced by tidal action, storm surge, back water flooding and other coastal hazards.

The RP provides guidelines and recommendations for identifying, assessing and managing risks to pipeline integrity associated with these hazards through the life-cycle of a pipeline. Except for the design and construction provisions in Section 7 of this RP which are strictly for new pipelines, this RP is for both existing and new pipelines.

2 Normative References

The following codes, standards, practices, specifications publications, and government regulations are incorporated in this RP.

API¹

API Specification 6D, *Pipeline Valves (Gate, Plug, Ball, and Check Valves)*

API Standard 1104, *Welding of Pipelines and Related Facilities*

API Recommended Practice 1109, *Marking Liquid Petroleum Pipeline Facilities*

API Recommended Practice 1110, *Pressure Testing of Steel Pipelines for the Transportation of Gas, Petroleum Gas, Hazardous Liquids, Highly Volatile Liquids, or Carbon Dioxide*

API Recommended Practice 1117, *Movement of In-service Pipelines*

API Recommended Practice 1160, *Managing System Integrity for Hazardous Liquid Pipelines*

AWS²

D1.1, *Structural Welding Code*

NASTT³

Guidelines for a Successful Directional Crossing Bid Package, 1996

OSHA⁴

29 Code of Federal Regulations Part 1926.650 through 1926.652 (Trenching and Shoring Code Only)

¹ American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070. www.api.org

² American Welding Society, 550 NW LeJeune Road, Miami, FL 33126. www.aws.org

³ North American Society for Trenchless Technology, 1655 N Ft. Myer Drive, Suite 700, Arlington, VA 22209. www.nastt.org

⁴ U.S. Department of Labor, Occupational Safety and Health Administration, 200 Constitution Avenue, NW, Washington, DC 20210. www.osha.gov. Note: OSHA Regulations are posted on, and can be downloaded from the OSHA website.

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purposes of this publication, the following definitions apply:

3.1.1

abandonment

A pipeline permanently removed from service that has been physically separated from its source of gas or hazardous liquid and is no longer maintained.

3.1.2

anchor frazil

Ice crystals carried to or formed on the channel bottom, which covers the channel bottom with a thick mass.

3.1.3

armoring

A facing layer (protective cover) or rip-rap consisting of very large stones placed to prevent erosion or the sloughing off of soil from an embankment.

3.1.4

avulsion

Rapid abandonment of a river channel and the formation of a new river channel.

3.1.5

bed-form migration

Features such as ripples and dunes on the channel/coastal zone bed resulting from bed material being moved by flowing water that can gradually move upstream or downstream depending on local hydraulic and sediment characteristics.

3.1.6

bending stress

Internal or compressive longitudinal stress developed in response to curvature induced by an external load.

3.1.7

check dams

A low, fixed structure, constructed of timber, loose rock, rip rap, masonry, or concrete, to control water flow in an erodible channel.

3.1.8

coastal zone

Area of coastal waters and the adjacent shore lands strongly influenced by each other and includes islands, transitional and intertidal areas, salt marshes, wetlands and beaches, and extends offshore to a depth of water of 15 ft as measured from the mean low water elevation.

3.1.9

cofferdam

A temporary structure built around a site to permit construction in (relatively) dry conditions.

3.1.10

commercially navigable waterway

PHMSA Pipeline Safety has elected to use the National Waterways Network database as the basis for identifying commercially navigable waters. This database includes commercially navigable waterways in open water (i.e.

offshore or in the Great Lakes) and those that are inland (rivers, canals, harbors, etc.) where a substantial likelihood of commercial navigation exists.

3.1.11

cross vanes

Structure typically constructed from timber or loose rock designed to guide flow away from channel banks to reduce bank erosion and promote local sedimentation.

3.1.12

cuttings

A mixture of drilling mud and soil that is generated during drilling operations.

3.1.13

degradation

The general lowering of the streambed by erosive processes, such as scouring by flowing water. The removal of channel bed materials and downcutting of natural stream channels.

3.1.14

deposition

The physical process by which sediments, soil, and rock are added to a landform.

3.1.15

depth of cover (DoC)

The distance between the top of the pipeline and the surface of the ground above the pipeline. It will typically vary across the waterway due to variations in the pipeline profile and the channel bottom topography. Minimum DoC represents the least amount of ground cover above the pipeline.

3.1.16

discharge

Discharge or stream/river flow, is the volumetric rate of flowing water which is transported through a given cross-sectional area. Discharge is typically described in cubic feet per second (cfs).

3.1.17

engineered span

A pipeline designed and engineered to cross a waterway at elevations above the channel bottom. Such spans differ from those that are the result of either channel bed erosion or bank erosion.

3.1.18

erosion

The wearing away or removal of soil or other material by the action of water or other agents.

3.1.19

fatigue

The phenomenon leading to fracture of a material under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

3.1.20

fetch

The distance over which waves are generated by a wind having constant speed and direction.

3.1.21**flood**

An unusual and rapid accumulation or runoff of surface waters from any source resulting in flowing water significantly greater than typically occurs and exceeds the capacity of the stream channel. Results in the partial or complete inundation of normally dry land.

3.1.22**floodplain**

A relatively flat area of land adjacent to a river or stream, formed mainly of river sediments and may become submerged by floodwaters.

3.1.23**fluvial geomorphology**

The science devoted to understanding rivers and streams, and the deposits and landforms created by them, both in their natural setting as well as how they respond to human-induced changes in a watershed.

3.1.24**frazil ice**

An accumulation of loose, spongy ice within a body of water or on its surface.

3.1.25**gabions**

Steel wire mesh baskets filled with stone used to prevent erosion.

3.1.26**gauging station**

A location used by hydrologists to monitor and test onshore and coastal water bodies. Measurements of water level surface elevation (stage) or volumetric discharge (flow), or both, are generally taken.

3.1.27**gas**

Natural gas, flammable gas, or gas which is toxic or corrosive.

3.1.28**geotextile fabrics**

Permeable fabrics typically incorporated into erosion control structures that separate, filter, reinforce, and protect soils from erosion.

3.1.29**hazardous liquid**

Petroleum, petroleum products, anhydrous ammonia, or ethanol.

3.1.30**high consequence area (HCA)**

High consequence areas, as defined in 49 CFR Part 195.450, include: 1) commercially navigable waterways; 2) high population areas; 3) other populated areas; and 4) unusually sensitive areas (e.g. drinking water supplies, ecological sensitive areas).

3.1.31**hydrograph**

A graph of the water level or rate of flow of a body of water as a function of time.

3.1.32**hydrology**

The science of Earth's water, its movement, abundance, chemistry, and distribution on, above, and below the Earth's surface.

3.1.33**hurricane**

An extremely large, powerful, and destructive storm with very strong winds that occurs especially in the western part of the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

3.1.34**incipient motion**

When a sediment particle or grain on the channel bottom first begins to move under the influence of flowing wind, water, or other agent.

3.1.35**land loss**

Transition of areas from land to open water as a result of beach and bluff erosion, and losses of wetlands around interior bays and estuaries.

3.1.36**matting**

Installing wood planks or other material in an effort to stabilize a work area, or route of ingress/egress.

3.1.37**meander**

A channel pattern characterized by a series of pronounced alternating bends formed by fluvial processes.

3.1.38**mean low water elevation**

The average of all the low water elevations observed at a location over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made to derive the equivalent datum of the National Tidal Datum Epoch (per http://tidesandcurrents.noaa.gov/datum_options.html).

3.1.39**microtunneling**

A remote-controlled, guided pipe-jacking process that provides continuous support to the excavation face.

3.1.40**mitigation**

Activities and plans to manage the risks of a particular pipeline system. Mitigation activities are broad ranging and are specific to a particular situation.

3.1.41**navigable waterway**

A waterway not identified as commercially navigable but has potential for motorized public boat traffic that represents a hazard to pipeline integrity.

3.1.42**near-bank stress**

The shear stress occurring near the bottom of the stream bank.

3.1.43**onshore**

The area landward of the established coastline in direct contact with the open sea, and landward of the line marking the seaward limit of inland coastal waters.

3.1.44**ordinary high water marks (OHWM)**

The ordinary high water mark is a line along the shore or waterway bank established by the fluctuation of water and indicated by physical characteristics. Details regarding identification of the ordinary high water mark is provided by 33 *CFR* Part 328.3(e).

3.1.45**ordinary high water width (OHWW)**

Per 33 *CFR* Part 328.3(e), the ordinary high water width defines the lateral extent of non-tidal streams and can be identified by ordinary high water marks (OHWM).

3.1.46**permeable dikes**

Structure extending from the channel bank into the channel designed to allow water to pass through the dike at a reduced velocity, thereby encouraging local sedimentation and reduced bank erosion.

3.1.47**rip-rap**

A permanent, erosion-resistant ground cover of large, loose angular stone used to line channels, stabilize banks, reduce runoff velocities, or filter out sediment.

3.1.48**rock riffle**

A type of grade control structure typically constructed from loose rock across a channel designed to reduce upstream flow velocity and promote local sedimentation.

3.1.49**sag-bend**

A bend in the pipeline in the vertical plane, often occurring near a river/stream such that the pipeline is buried under the channel bottom.

3.1.50**scour**

To abrade or wear away, as in the wearing away of a stream bed or surface by the erosive action of flowing water. Stream bed scour can be temporary or permanent. Also referred to as vertical channel movement.

3.1.51**shear stress**

Component of stress coplanar with a cross-section generated by fluids moving along the solid channel boundary.

3.1.52**stage**

A measured height of water above an arbitrary reference datum. Frequently used to describe the height of water in a stream, lake, well, canal or other water body. Stage and gauge height are equivalent terms. gauge height is usually measured at a stream gauge.

3.1.53**storm surge**

The piling up of water along a shoreline caused primarily by a storm's sustained winds—usually a hurricane.

3.1.54**Strahler number**

Numerical measure of a river network's branching or tributary complexity.

3.1.55**stream barbs**

A type of low rock sill projecting out from a streambank and across the stream's thalweg to redirect streamflow away from an eroding bank.

3.1.56**subsidence**

A lowering of the land surface in response to subsurface weathering, compaction, collapse or settlement.

3.1.57**swale**

A shallow trough-like depression that carries water mainly during rainstorms or snow melt.

3.1.58**thalweg**

The path following the deepest part of the streambed, i.e. the river bottom profile.

3.1.59**trenched crossing**

Method of installing pipe by which access is gained to the required elevation by excavating an open cut. After placing the pipeline, the excavation is then backfilled and the surface restored.

3.1.60**unsupported span length (USL)**

Continuous length of pipeline unsupported by soil material or the distance between vertical supports.

3.1.61**vortex-induced vibrations**

Motion induced on bodies interacting with fluid flowing around a cylinder.

3.1.62**vortex suppression devices**

Devices attached to a pipeline designed to reduce the occurrence of vortex-induced vibrations.

3.1.63**watershed (or drainage area/drainage basin)**

The geographic area that contributes runoff to a stream. It can be outlined on a topographic map by tracing the points of highest elevation (usually ridge crests) between two adjacent stream valleys. Watershed, drainage area and drainage basin are equivalent terms.

3.1.64**waterways**

A natural or man-made channel through which water flows. Waterway and watercourse are equivalent terms.

3.2 Acronyms and Abbreviations

For the purposes of this document, the following acronyms and abbreviations shall apply.

ADCIRC Advanced Circulation Model

BEHI	Bank Erosion Hazard Index
CO-OPS	Cooperative Observer Network
DoC	Depth of Cover
EC	Environment Canada
FEMA	Federal Emergency Management Agency
GEV	Generalized Extreme Value Distribution
GIS	Geographic Information Systems
GPS	Global Positioning System
HCA	High Consequence Area
HDD	Horizontal Directional Drilling
ILI	In-Line Inspection
IMP	Integrity Management Program
LN3	3-Parameter Lognormal Distribution
NBS	Near-bank Stress
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWIS	National Water Information System
NWS	National Weather Service
OFS	Operational Forecast System
OHWM	Ordinary High Water Marks
OHWW	Ordinary High Water Width
PHMSA	Pipeline and Hazardous Material Safety Association
PORTS	Physical Oceanographic and Real-Time Measurement System
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
USACE	United States Corps of Engineers
USGS	United States Geologic Survey

USL	Unsupported Span Length
VIV	Vortex-Induced Vibration
WHAFIS	Wave Height Analysis for Flood Insurance Studies

4 Overview of Hydrology and Hydrotechnical Hazards at Onshore and Coastal Zone Pipelines

Pipelines are static features within a dynamic environment with rivers, floodplains and coastal zones representing some of the most active areas within a landscape. Rivers can change course, migrate, deepen, and widen slowly over time or suddenly during large flood events. Coastlines and shorelines can retreat during hurricanes and, coastal land loss, particularly throughout coastal Louisiana, can cause pipeline exposure and suspension of previously buried pipeline segments. These hydrologic and geomorphic effects can put pipelines at risk for damage or failure. Understanding how rivers and coastal zones change and alter the landscape provides a framework for realizing the potential toll that hydrotechnical hazards can have on pipeline infrastructure and can increase the effectiveness in protecting the environment during the design, construction, operation, and integrity management of pipelines at river crossings, and throughout coastal zones. A brief description of riverine and coastal hydrology and hydrotechnical hazards is presented below.

4.1 Riverine Hydrology and Fluvial Geomorphology

The magnitude of hydrotechnical hazards and potential for damage to pipeline integrity is greatest at pipeline water crossings during flood events. Water depth is deepest and water velocity is typically fastest during floods. As a result, floods have the potential to carry large debris, impart significant bending stresses and vortex-induced vibrations on unsupported pipeline spans, and potentially remove sediment from river bottoms and soils from banks, thereby exposing previously buried pipelines to lateral water forces and impact from waterborne debris. Understanding a river's hydrology and geomorphology can help assist pipeline operating companies to better assess a river's potential for scour, channel migration, avulsion, etc. at pipeline water crossings. By evaluating the magnitude and frequency of flood events at water crossings, operators can efficiently direct resources to mitigate the potential hazards of floods and river erosion. Data describing the quantity, timing, and duration of both current and historic information regarding water levels and streamflow conditions for many streams and rivers is collected and published by various governmental agencies. The primary agencies responsible for collecting these data in North America include the U.S. Geological Survey (USGS) and Environment Canada (EC). Further details regarding publicly available data sources is provided in Annex A.

4.1.1 Overview—Flood Timing, Duration, Magnitude, and Frequency

The hydrology of a particular river or stream is defined by the timing, duration, and quantity of flowing water. The observed rise and fall of the water levels or discharge at a given point can be graphed over time; such a graph is called a hydrograph. The portion of a hydrograph where the water levels increase from base flow to the flood event's peak is termed the "rising limb". The portion of the hydrograph once the peak has passed and water levels return to base flow is defined as the "falling limb".

The timing of flooding describes when flood events typically occur throughout the year. For example, rivers draining the Rocky Mountains tend to have predictable springtime flooding in response to snowmelt. Conversely, rivers within the arid American southwest and mid-west tend to flood in response to large rainfall events which can potentially occur throughout the year. Timing of flood events is more predictable within areas dominated by snowmelt, and consequently, flood preparation and response planning is easier than in areas where flooding is dominated by extreme rainfall events.

The duration of typical flood events can vary across North America and understanding expected flood durations is important in flood preparation and planning. Snowmelt floods tend to build up slowly to a peak and then gradually decrease over time, often taking weeks to rise and fall. As such, pipeline operators often have time to prepare for

such floods, and implement appropriate operational controls to reduce related risks. Conversely, flood events caused by high intensity but brief rainfall often rise and fall within 24–48 hours, and the rapid rise to the flood peaks offers little time for pipeline operators to respond. The quantity of water during the peak of the hydrograph determines the size, or magnitude of flooding. The larger the flood, the more extensive the flooding may be; the deeper the riverbed scour may be, the more channel migration and bank erosion occurs. Further details regarding the timing, duration, and variability of flood events is provided in Annex B.

The magnitude of a particular flood event is often described in terms of a flood frequency or return period, that is, an “X year return period flood event”. The return period (“X” number of years) is the “recurrence interval” which represents the average interval of time expected before the next flood event of equal or greater magnitude can be expected to occur over the long-term and should not be viewed as the number or years between floods of a given size. The exceedance probability is another term used to describe the size of a flood event and is the mathematical inverse of the recurrence interval and equals the probability that a given flood of a given size will occur per year. Determining the flood frequency for a given location within a river system requires a statistical analysis using the recorded history of annual peak flood events from a particular location. Further details regarding flood frequency calculation is provided in Annex C.

4.1.2 Overview—Fluvial Geomorphology

The shape and size of a river and the extent and shape of a river’s floodplain is a key component in determining the depth of water and velocity during flooding, and therefore, the potential magnitude of channel bottom scour and erosion. Given similar flood flows, the larger a river’s cross section is, the lower the water velocity. During flood events that overtop a river’s channel banks, water can spill across the floodplain reducing the rate of increase in the water depth and velocity. Consequently, changes to a river’s floodplain can cause significant changes within the river itself. Construction of levees or roads across the floodplain can reduce the floodplain area and the amount of flood water that can flow across it, thereby increasing the depth and velocity of water within the channel during flood stage.

The rate at which the channel bottom and banks are scoured and eroded is also related to the types of sediment that make up the channel and the vegetation type, and density lining the channel. This channel erosion or scour has the potential to undermine and remove supporting soils, exposing buried pipelines to lateral water forces and impact from debris.

Channels can also migrate laterally across their floodplains due to the processes of erosion and deposition along its banks. Channel migration can occur gradually or shift abruptly to a new location which may happen during a single flood event, called an avulsion. In a meandering stream, channel migration typically occurs by erosion of the outer “cut” bank and sediment deposition on the inner bank or point bar. Channel migration can result in pipeline exposure and suspension, and potentially lead to pipeline damage.

4.2 Riverine Hydrotechnical Hazards

Flood hydrology and geomorphic processes have the potential to expose pipelines to a variety of hydrotechnical hazards. Understanding these processes provides a framework for realizing the potential risks that riverine changes can impose on pipeline infrastructure and can increase the effectiveness in protecting the environment during the design, construction, and operation of pipelines at river crossings.

Generally, two different types of hydrotechnical hazards can occur at pipeline waterway crossings and are classified as either vertical or lateral channel movement. Vertical channel movement is the result of channel bed scour during individual flood events or longer-term channel degradation, often resulting from changes within a river’s contributing watershed. Lateral channel movement is the result of gradual bank erosion, bank failure, or channel migration, and can also occur as a rapid shifting of the channel across the floodplain as an avulsion. Both vertical and lateral hydrotechnical hazards are discussed in greater detail in 4.2.1 and 4.2.2.

4.2.1 Vertical Channel Movement

Vertical channel movement, or scour, is often classified as either general or local scour and occurs in response to a given storm or flood event in contrast to lateral channel movement which typically occurs gradually over time. Both general and local scour can occur simultaneously within a particular cross section but are the result of different hydrologic and geomorphic processes. A variety of scour and erosion equations and models are available for predicting flood-related general and local scour (i.e., Shields 1936, Neill 1973, U.S. Bureau of Reclamation 1984, U.S. Army Corps of Engineers 1994, Melville and Coleman 2000, etc.). Equation and model complexity can vary greatly and the selection, application, and assessment of results should be done carefully. It should be noted that predictive models can often be conservative.

4.2.1.1 General Scour

With the rise in water level, or stage, during a flood there is an associated increase in water velocity, and subsequently the force of water acting on the channel bottom. As a result, the channel bed tends to scour during flood events. Buried pipelines can potentially become exposed or undermined while flood levels are increasing and then become re-buried when the flood levels recede. This occurs when water velocities slow down resulting in sediment carried from upstream are deposited back on the channel bottom (Figure 1). This phenomenon may not occur on every channel or during every flood and is dependent upon a variety of factors, including the flood duration and magnitude, the type of soils and sediment being carried, and how much sediment is supplied from upstream. For example, depending upon the depth and velocity of water during floods and the size of channel bottom sediments, erosion and scour may not occur until very large flood events. However, on other channels where the water velocity may be high, the sediments composed of smaller grains scour and erosion may occur during more frequent flood events. General scour can also be influenced, and typically increased, where the flow becomes confined as it passes through a narrow bridge opening or culvert which can increase water velocity and erosion potential. It is important to note that this increased scour potential occurs both at the confinement location and for some distance downstream from the confinement as the increased water velocity is maintained until the effect of the confinement dissipates as the channel returns to a wider and larger cross section shape.

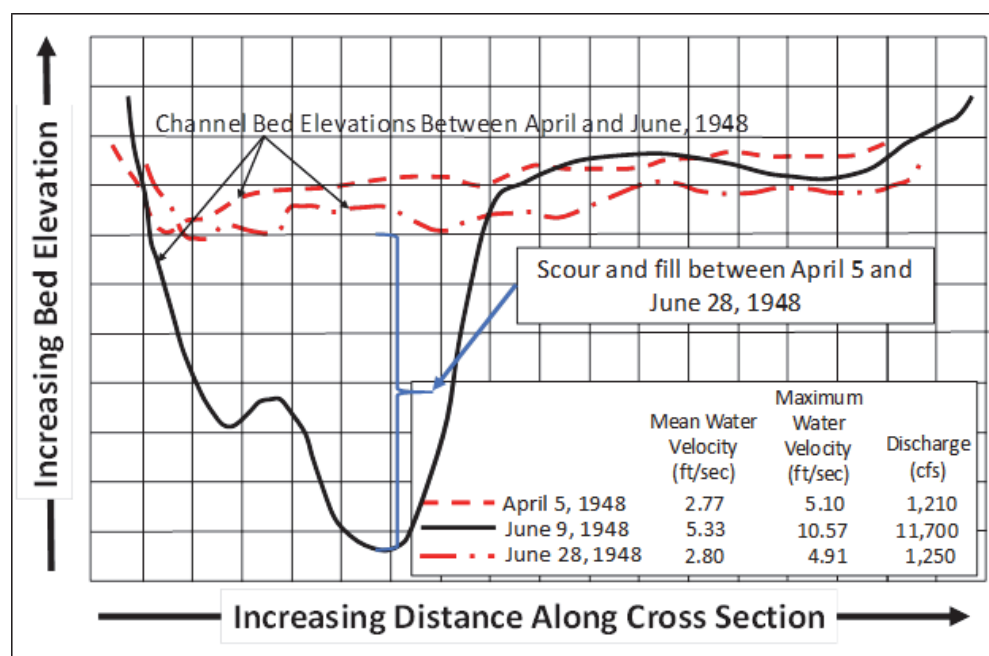


Figure 1—Streambed Profiles from the Rio Grande River at Albuquerque, NM, between April 5 and June 28, 1948 Illustrating Temporary Scour and Fill (after USGS Open File Report 1967). Not-to-scale

Another type of general scour is dune scour which generally only occurs in sand-bed streams and rivers. In sand-bed streams, bed-form migration, such as ripples and dunes, is a source of scour that can temporarily raise or lower the channel bed elevation as the trough or the crest of the ripple or dune passes over the pipeline crossing (Figure 2). The size of bed forms and the depth of dune scour relates to the size of the river. On average, observations indicate that dune heights can vary between 15 % and 50 % of the flow depth.

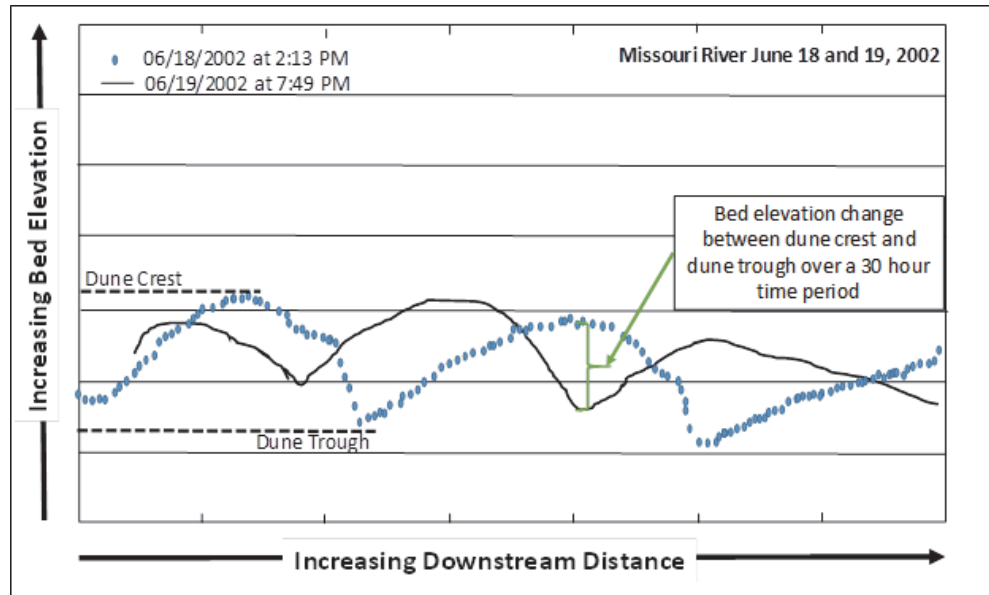


Figure 2—Streambed Profiles from the Missouri River at St. Charles, MO, between June 18 and 19, 2002 Illustrating Dune Scour (after USGS Scientific Investigations Report 2010-5091). Not-to-scale

4.2.1.2 Local Scour

Local scour results in the removal of sediment at a particular location in the channel induced by obstructions to the flow, such as around pipeline supports, bridge piers, abutments, rip-rap revetments, adjacent pipelines, and large woody debris. Local scour can also occur as the water accelerates around a channel bend or even at the confluence of two separate channels (Figure 3). Obstructions located upstream of a pipeline crossing can cause local scour that may extend downstream hundreds of feet and impact the crossing. Local scour depths are generally larger than general scour. Section 6.6.1 provides additional guidance on monitoring for features near pipeline water crossings that can cause local scour and increase risks to pipeline integrity.

4.2.1.3 Channel Degradation

Unlike temporary scour and fill that can occur during a particular flood event, channel degradation tends to occur over a longer period of time, over a longer reach of river, and tends to result in the permanent lowering of bed levels. Channel degradation typically results from an overall imbalance between the supply of water and sediment from a watershed. Such imbalances can occur with the construction of large flood control dams that trap a significant portion of the sediment. This loss of sediment results in an imbalance in the sediment supply, and the river will often respond by eroding and degrading its channel bed. Urbanization can both decrease the supply of sediment while also increasing the supply of water to a river system. As a result, rivers in urbanized settings will typically degrade their channel beds. Levee construction, removal of beaver dams, and channel straightening are common causes of channel degradation. Degradation is a common hydrotechnical hazard at pipeline water crossings.

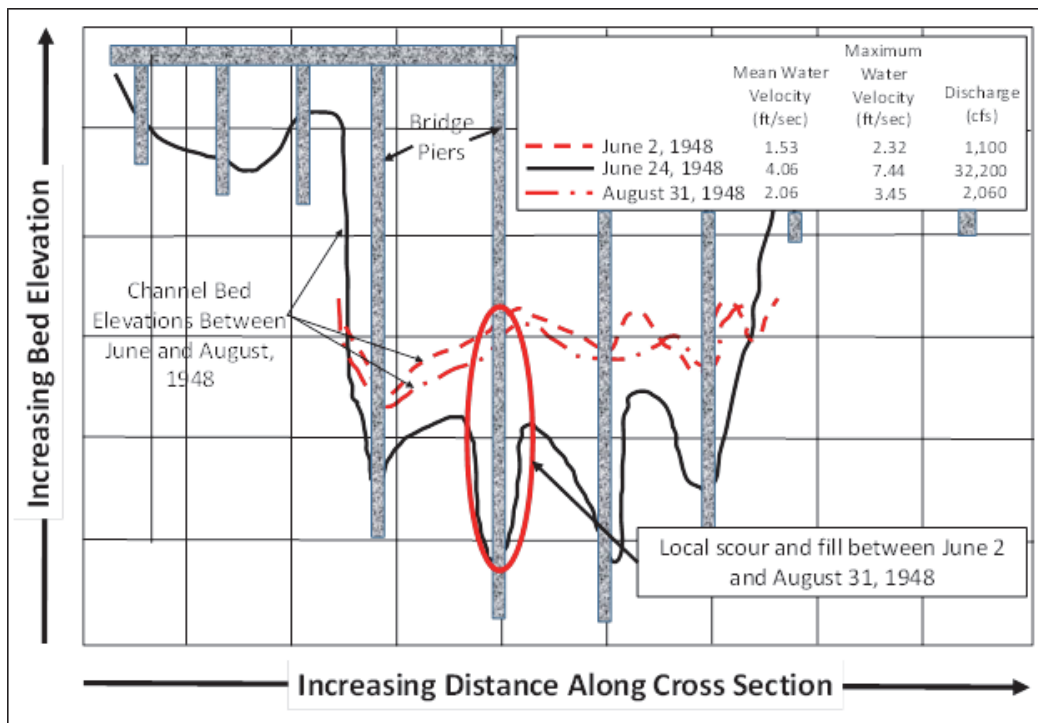


Figure 3—Streambed Profiles from the Arkansas River at Arkansas City, KS, between June 2 and August 31, 1948 Illustrating Local Scour and Fill around Bridge Piers (after USGS Open File Report 1967). Not-to-scale

4.2.1.4 Ice Scour

In cold weather climates, river ice can represent an additional form of scour. In fast moving water, ice crystals called frazil ice will form and may appear as thick porridge floating on the water surface. Ice crystals may also be carried to the channel bottom and cover the channel bottom with a thick mass called anchor frazil. Anchor frazil may float to the surface in large clumps during milder temperatures. Where the water velocity is lower, typically near the river banks, ordinary ice cover may form and at times break away and be carried downstream. It is also possible that the entire surface of a river or stream may freeze and form an ice cover. Under certain conditions, the floating frazil and chunks of ice that have broken away from the shoreline will interact with the ice cover, accumulate, and begin to form an ice jam. As this jam builds up, the flow of water is choked, the water is dammed up, and the water level rises upstream. As the water level rises, its velocity will decrease, so that the new ice slush that arrives can remain on the surface and add to the additional ice cover even farther upstream.

Under these conditions, the ice jam can divert water across the floodplain and potentially cause floodplain scour. In addition, as ice jams accumulate, the ice can directly contact the channel bottom and cause gouging of the bed or cause increased flow velocities and turbulence under the toe of the ice jam (Figure 4).

When air temperatures begin to warm, typically during springtime, the water temperature increases and the ice begins to melt or break up, or both, into large ice floes and potentially accumulate in ice jams. The floating ice can potentially erode channel banks or gouge the channel bottom. Ice jams may gradually break up into ice floes or potentially break up catastrophically resulting in large floods. Ice floes are of a particular concern to exposed and suspended pipelines as the ice can accumulate on the pipeline and thereby impart additional lateral loading on the pipeline. This additional loading may be sufficient to cause pipeline failure. Ice cover can also cap a river surface and cause increased water velocity under the ice, potentially causing increased channel bottom scour.

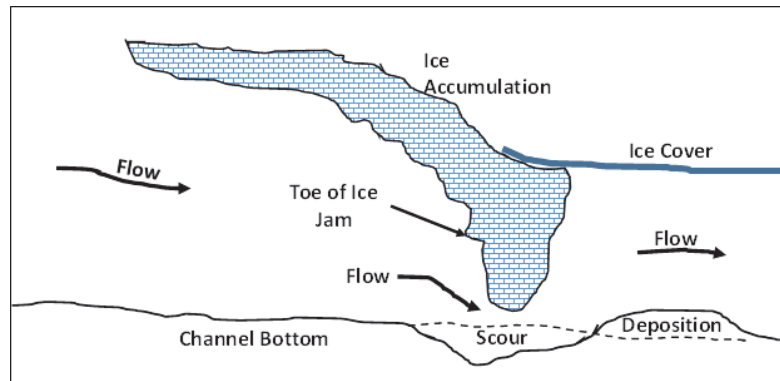


Figure 4—Schematic of Ice Jam Scour. Not-to-scale

4.2.2 Lateral Channel Movement

Lateral channel movement is the result of gradual bank erosion, bank failure or channel migration, or a combination thereof, over time or can occur as a rapid shifting of the channel across the floodplain in the form of a channel avulsion or as a result of floodplain ice-melt. One example of rapid channel movement caused by a channel avulsion occurred along the San Jacinto River in 1994 when new channels formed across the floodplain following 20 in. of rainfall and subsequent heavy flooding. A variety of equations and models are available for predicting lateral channel migration and bank erosion (Melville and Coleman 2000, Rosgen 2006). Equation and model complexity can vary greatly and the selection, application, and assessment of results should be done carefully. Trends in bank erosion or channel migration, or both, can also be estimated by comparing historic and current aerial photography.

4.2.2.1 Channel Migration and Bank Erosion

Lateral channel movement, usually channel migration, occurs through the preferential erosion of the outer “cut” bank and is accompanied by the deposition of sediment on the inner bank, or point bar (Figure 5). This preferential bank erosion and deposition causes the channel to migrate across its floodplain and, at a pipeline crossing, can result in exposure of the sag-bends and over-bends of the pipeline. Bank erosion is most common in meandering streams but can also occur along straight streams as well. In addition to debris accumulation and loss of pipeline support due to scour, bank erosion is one of the most recognizable of the hydrotechnical hazards at pipeline crossings.

Bank erosion and channel migration rates depend on the composition of the stream bank, e.g. soil type, presence/type/density of vegetation, water velocity and water depth, channel curvature, etc. In sand and gravel streams, bank erosion typically occurs through the loss of individual soil particles. Where banks are composed of cohesive sediments like clays and silts, failure of entire blocks of sediment, or slumping of the entire bank, is a more common form of bank erosion. Channel migration rates may be relatively constant over time or highly variable. In depth geotechnical analysis may be warranted where channel banks are susceptible to liquefaction and large scale bank failures.

Evidence of active bank erosion include loss of vegetation, tension cracks in the soil near the top of the bank as the soil pulls away, undercut banks, water seepage from banks, trees and shrubs that are not vertical indicating slope movement, loss of pipeline warning signs, bulging of channel banks, accumulation of debris at toe of slope, etc. Reviewing historical and current aerial photography of a pipeline water crossing is a useful means of determining bank erosion and channel migration rates.

Channel migration and bank erosion can result in pipeline exposure and unsupported spans through two different processes. For pipelines that cross waterways perpendicular to the flow, channel migration or bank erosion, or a combination thereof, can result in the river or stream gradually shifting across the floodplain and potentially exposing or suspending portions of the sag-bends. For pipelines that run parallel to a river or stream, channel migration or bank

erosion, or both, can result in the river or stream moving into the pipeline corridor, potentially exposing or suspending sections that were not within the channel banks. Paralleling pipelines or sag-bends that are near the existing channel banks are more at risk from channel migration or bank erosion, or a combination thereof.

Although the mechanism driving the movement of the channel toward sag-bends or paralleling pipelines may be similar, the hazard to the pipeline is usually different due to the orientation of the pipeline to the flow of the watercourse. If a paralleling pipeline becomes exposed due to channel migration or bank erosion, or both, a longer length of pipe may be exposed more quickly as an additional foot of bank erosion may expose several more feet of pipe along the corridor compared to perpendicular pipelines. However, pipelines situated parallel to flow can withstand longer free span lengths and are less susceptible to vortex shedding and impact loads.



Figure 5—2013 Aerial Photograph of the Leaf River, MS Illustrating Significant Bank Erosion and Channel Migration. Note: Red line indicates approximate location of river banks in 1996

4.2.2.2 Channel Avulsion

A channel avulsion is the rapid abandonment of a river channel and the formation of a new river channel across the floodplain and typically occurs where a meandering river has developed a channel slope too low to efficiently carry its water and sediment load (Figure 6). The channel avulsion results in a straighter, and steeper, river channel typically with greater erosion and scour potential than the abandoned channel. Channel avulsions can also occur when the existing channel migrates into an old relic channel or where a meander cutoff occurs. A meander cutoff is an example of a minor avulsion and occurs where a meander bend is sufficiently extreme that the two closest part of the meander merge together or the river cuts through the floodplain and abandons the meander bend to form a straighter, steeper channel. Ice-melt can also erode new channels within the floodplain, creating preferential paths for a channel avulsion. Ice jams can also direct floodwaters across the floodplain increasing the potential for a channel avulsion. Channel avulsions represent significant hydrotechnical hazards to pipeline integrity as the new channel formed through the avulsion process typically occurs where the depth of cover (DoC) is insufficient to protect the pipeline.

Additional material illustrating methods for computing general and local scour, channel degradation, and bank erosion or channel migration, or a combination thereof, is provided in Annex D.

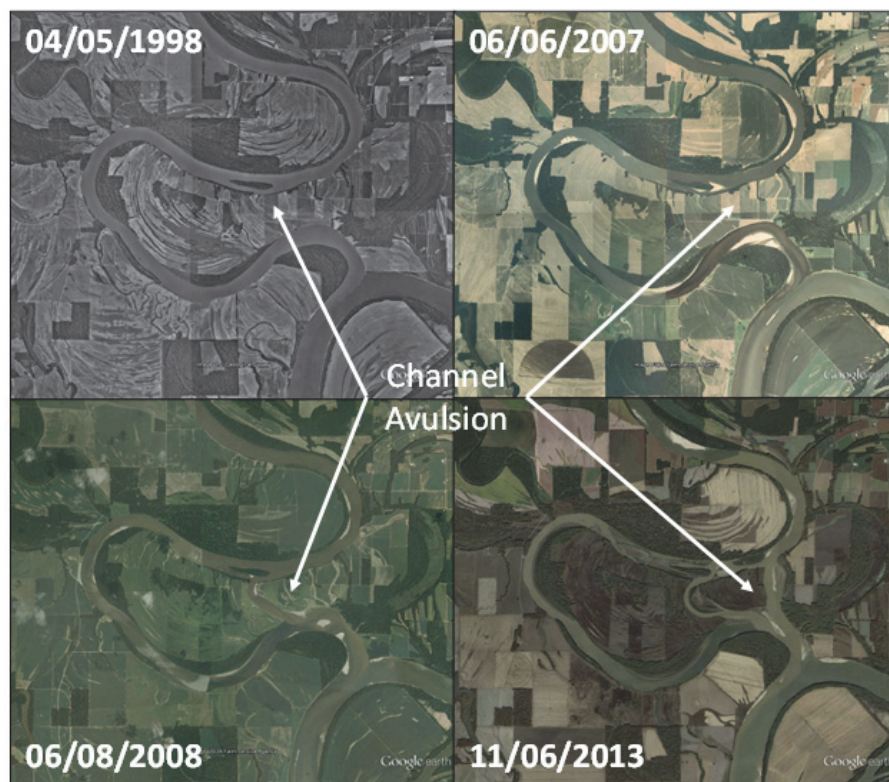


Figure 6—Time Series of Aerial Photography from April 1998 through November 2013 of the Wabash River, IN, Documenting the Development of a Channel Avulsion

4.3 Coastal Zone Hydrology

Unlike distinct riverine water crossings where only segments of pipeline located within the river channel are subject to flood-related hazards, the entire length of pipeline networks traversing coastal zones is potentially affected by land loss and scour from currents and waves associated with hurricanes, storms, wind, and daily tides. The magnitude of these natural processes will vary by location; hurricanes and their associated storm surges typically generate the greatest coastal zone hazards. It is important to note that much of the coastal zone is typically dry throughout the year and only inundated when storm surges push water inland. Therefore, a pipeline network located within the coastal zone, and not near a water body, may still be vulnerable to hydrodynamic hazards during overland flooding and large hurricane events.

Storm surges are produced by water being pushed toward the shore by the force of the cyclonic storm. The maximum potential storm surge for a particular location depends on a number of different factors and is sensitive to changes in storm intensity, forward speed, size, angle of approach to the coast, central pressure, and the shape and characteristics of coastal features such as bays and estuaries.

Other factors which can impact storm surge are the width and slope of the continental shelf. A shallow continental shelf slope will potentially produce a greater storm surge than a steep shelf.

NOTE A Category 4 storm hitting the Louisiana coastline, which has a wide and shallow continental shelf, may produce a 20 ft storm surge; while the same hurricane in a place such as Miami Beach, Florida, where the continental shelf drops off quickly, might

see an 8–9 ft storm surge. In the United States, the highest storm surge on record was generated in 2005 by Hurricane Katrina, which exceeded 27 ft, where it made landfall near the Louisiana/Mississippi border.

4.3.1 Tides, Currents, and Storm Surge

Various governmental agencies collect and publish data describing weather and tidal conditions within the near-shore environment as well as forecasting storm and hurricane path and intensity, to assist operators to better understand where threats to pipeline integrity are likely to occur. The primary agencies responsible for collecting these data in North America include National Oceanic and Atmospheric Administration (NOAA), the USGS, and the United States Army Corps of Engineers (USACE) (Annex A).

4.3.2 Variability in Hurricane Magnitude and Properties

A hurricane's strength is typically reported using the Saffir-Simpson Hurricane Wind Scale using a 1–5 rating based on a hurricane's sustained wind speed. This scale estimates potential property damage. However, depending on the properties of a particular hurricane, such as forward speed, angle of approach, central pressure, radius of maximum wind, etc., different types of hurricanes can produce similar storm surges. Conversely, a fast moving Category 3 hurricane will generate a very different hydrograph than a slow moving Category 3 hurricane, and therefore, different water velocities and water depths.

NOTE Federal Emergency Management Agency (FEMA) coastal flood maps describe the 10-, 50- and 100-year return period water levels associated with hurricanes and associated storm surge.

As potential scour depths and bank erosion rates are driven by many factors, this variability in storm surge hydraulic parameters across storms makes it difficult to predict scour and risks to pipelines for a given flood frequency. Spatial variability of storm surge water velocity and depth at a particular location can be estimated through detailed hydrodynamic modeling such as the ADCIRC, SLOSH, and WHAFIS models. Observations at tidal gauges can also provide a range of water velocities at points along the coasts. These observations or predictions, or both, can serve as inputs to scour and erosion models described in Annex D. In addition to using these models to evaluate the potential scour depths associated with future storms and hurricanes, these models can also be used to evaluate the impact of recent storms and hurricanes to assist in post-storm inspections and damage estimates.

4.3.3 Hurricane Return Period

Because hurricanes and their associated storm surges are highly variable in space and time along the coast, there are inadequate data to derive storm return statistics from the historical storm record. To overcome this limitation a methodology for computing hurricane storm risk was developed for FEMA (FEMA 2012) based upon numerical simulation of hundreds of hypothetical storm events. The hypothetical storm events are called synthetic storms and were developed from analyses of historic hurricanes. A set of synthetic storms were developed by altering storm tracks and other storm parameters to completely cover the coastal zones. The individual synthetic storms are assigned a probability and the flood risk along the coast is derived from the synthetic history, and from the probability of each storm's contribution to the ensemble result. Combining the surge results from the synthetic storms produces a data set dense enough to compute the 10-, 50-, and 100-year surge levels along the coast. The results of this analysis, as well as other types of assessments, have been used to generate FEMA coastal zone flood maps that identify the 10-, 50-, and 100-year surge levels along the pipeline. These data are available from FEMA and can be used to determine the inland extent of the coastal zone. See 4.3.4 for additional details regarding coastal zone boundaries.

4.3.4 Coastal Zone Boundaries

A variety of methods are available to determine if a particular pipeline network is located within a coastal zone and are potentially at risk from the impacts of land loss and scour from currents and wave forces associated with hurricanes, storms, wind, and daily tides. As stated earlier, the various magnitudes of these natural processes will vary by location.

In 2012, NOAA's Office for Coastal Management published a summary of the inland extent of Coastal Zones for all 35 coastal and Great Lakes states and territories (with the exception of Alaska) that participate in the National Coastal Zone Management Program (<https://coast.noaa.gov/czm/mystate/>). Figure 7 provides an example of a coastal zone as defined by the State of Louisiana. As described in Section 2, NOAA has also developed a Coastal Flood Exposure Mapper program. Across the East Coast and Gulf of Mexico, this program can assist pipeline operators in identifying pipeline segments potentially at risk from hurricanes and coast storm surge.

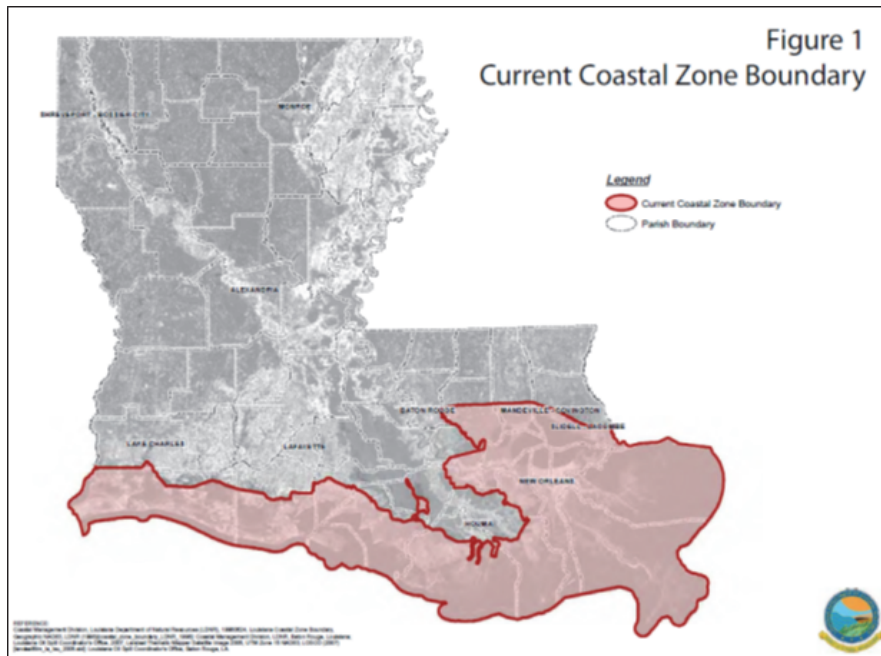


Figure 7—Map Illustrating State of Louisiana Coastal Zone Boundary
(Louisiana Department of Natural Resources, 2010)

4.4 Coastal Hydrotechnical Hazards

Similar to riverine hydrotechnical hazards, both general and local scour can occur within the coastal zone during hurricane storm surges, tropical storms, wind driven waves and tides. Unlike riverine scour, coastal zone scour can occur during both flood and ebb conditions. Shoreline retreat and land loss are unique coastal hydrotechnical hazards and can occur gradually over time through incremental loss of material from subsidence, daily waves, and tidal fluxes. It can also occur rapidly during a single large storm event.

4.4.1 Shoreline Retreat

Hurricane storm surge coupled with high winds and wind driven waves are one of the most common types of catastrophic natural disaster. During severe storms, damage is not just limited to flooding, but also involves shoreline erosion from increased wave activity. An efficient method for evaluating risk for shoreline erosion and coastal retreat is to compare publicly available historic to current aerial photography (Figure 8). Online sources provide easy access to aerial photography. The extent of erosion is related to a number of factors: composition of the shoreline (rock, sand, clay, marsh, or man-made structures), fetch, orientation to prevailing wind direction, and relative sea-level rise. Similar to channel migration and bank erosion, shoreline retreat can result in pipeline exposure where off-shore pipelines transition to on-shore.



Figure 8—2014 Aerial Photograph of the Louisiana Shoreline South of Lake Charles, LA Illustrating Significant Shoreline Retreat. (Note red line indicates location of shoreline in 1999.)

4.4.2 Land Loss

Coastal land loss occurs through the transition of areas from land to open water as a result of erosion and wetland losses around interior bays and estuaries. A variety of processes may be responsible for the land loss at a particular site, including erosion, reduced sediment supply to beaches and wetlands, subsidence, and coastal submergence. This land loss is significant as many pipelines were originally constructed across dry land that has since converted to open water. Areas of open water are also more susceptible to hurricane storm surge and likely experience great depths of water, greater water velocity, and potentially deeper scour during storm events. A pipeline located in a coastal area may experience increased hydrotechnical hazards resulting from loss of protective beaches and marshes.

NOTE Coastal Louisiana is particularly at risk from land loss. Louisiana wetlands are being lost at a rate of approximately 25-30 square miles a year naturally through compaction, sinking, saltwater intrusion that kills vegetation, hurricane and storm damage, wind and wave erosion, lack of sedimentation, and other processes. Man-induced losses occur from dredging and spoil disposal, levee building, canal digging, mineral extraction, agricultural practices, and industrial and urban expansion. From 1932-2010 the USGS estimates that coastal Louisiana has experienced a net loss in land area of approximately 1883 square miles (Figure 9).

5 Overview of Hydrotechnical Damage Mechanisms

Submerged pipelines, or buried pipelines that become exposed and/or suspended as a result of the hydrotechnical hazards described above are potentially subject to a variety of hydrotechnical damage mechanisms, including 1) hydrodynamic loading, 2) debris impact, 3) fatigue caused by vortex-induced vibration, and 4) dead loads associated with sagging due to erosion of supporting sediment. In addition to these hydrotechnical hazards, exposed/suspended pipelines within a waterway or coastal zone environment are at risk from third party damage such as direct impact from boats or anchors.

Hydrotechnical hazards need to be considered for any spans if they become submerged.

Similar to exposed and/or suspended pipelines within a waterway or coastal zone, in-channel pipeline supports are also subject to hydrotechnical and third party damage.

When evaluating the hydrotechnical damage mechanisms at a particular water crossing or pipeline segment within a coastal zone, it is important to understand that, although exposures are not desirable, simple exposure to

Threat interactions such as reduced wall thickness as a result of pipeline corrosion or from girth weld defects can cause unacceptable plastic strain levels to develop in a pipeline at lower velocities or at lower lengths of unsupported spans. Consequently, threat interactions can result in an increased risk of pipeline failure.

5.2 Debris Impact

Floating debris (i.e. wood, ice) or rocks transported by the flow could impact an exposed pipeline damaging the coating, denting the pipe, or causing a severe buckle, puncture, or rupture. Floating debris could be present in waterways or the coastal zone and may be comprised of woody debris such as trees and tree branches. Woody debris is often mobilized during flood events when water levels are sufficiently high to float fallen trees in the floodplain, or undermine trees on channel banks causing them to fall into the river (Figure 10). Hydraulically transported rocks or floating debris could potentially cause damage to an exposed pipeline if the transported objects are large enough and are moving quickly enough so that an impact would cause a load greater than the pipeline can withstand. Falling rip-rap may be a concern where existing armoring is undermined. In cold weather environments floating ice represents a significant risk for exposed/suspended pipelines.

Similar to hydrodynamic loading, threat interactions from reduced wall thickness or from girth weld defects may increase the risk of debris impact resulting in a pipeline failure.

The following examples are merely examples for illustration purposes only. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied, for reliance on or any omissions from the information contained in this document.



Figure 10—Example of Bank Erosion as a Source of In-channel Woody Debris

5.3 Vortex-Induced Fatigue

A pipeline span may be susceptible to fatigue damage from both cross-flow or in-line vortex-induced vibration (VIV) caused by vortex shedding. Vortex shedding can occur when water flows over and around pipeline at certain velocities. Under these conditions, vortices are created along the back of the pipeline and periodically detach, or are shed, from the pipeline. Each time a vortex is shed, it alters the local pressure distribution and the pipeline will tend to move toward the area of low pressure and will experience an induced stress. As the fluid flows around the pipeline, alternative low pressure vortices will be created above and below the pipeline causing it to vibrate up and down (Figure 11). The focus of the discussion here is on cross-flow VIV as they typically represent a more immediate risk to pipeline integrity. It is recognized that in-line VIV can also reduce the fatigue lifespan of a pipeline.

Depending upon the USL and the water velocity, interactions may arise between the vortex shedding mechanism and the pipeline movement. Under certain conditions, the pipeline may oscillate at or near its natural frequency, potentially resulting in large and destructive stresses. If a critical USL and flow velocity is reached, VIV may cause immediate failure. Figure 12 depicts the relationship of free span length and velocity for a set of specific pipe properties. For pipelines located within the coastal zone, velocity acting on the pipeline may be multi-directional during a single storm event, i.e. water flow inland versus off-shore during the flood and ebb tide, respectively. Further details and examples for computing allowable USL relative to cross-flow VIV is provided in Annex E. For an example calculation of in-line VIV, see DNV-RP-F105.

Integrity issues associated with pipeline wall thickness or girth welds, or both, can interact with the hydrodynamic forces acting on the pipe and reduce the pipelines ability to withstand VIV.

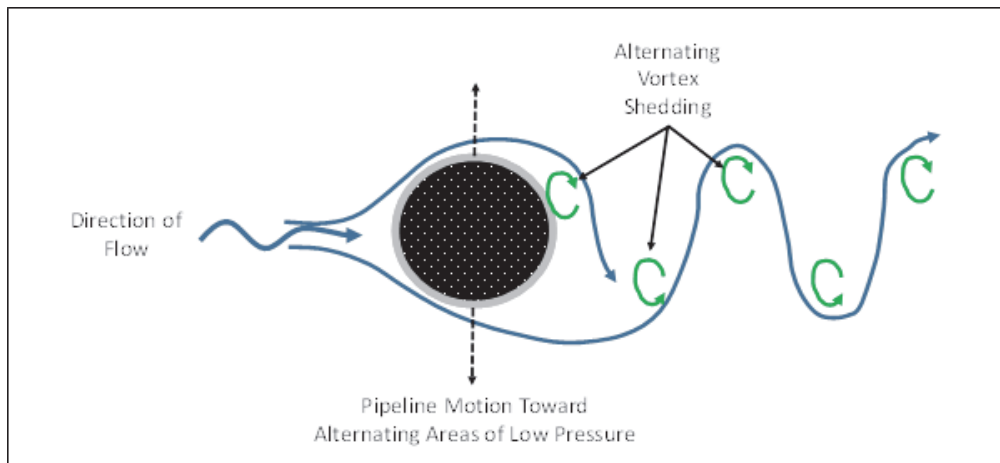


Figure 11—Schematic of Vortex-induced Vibrations

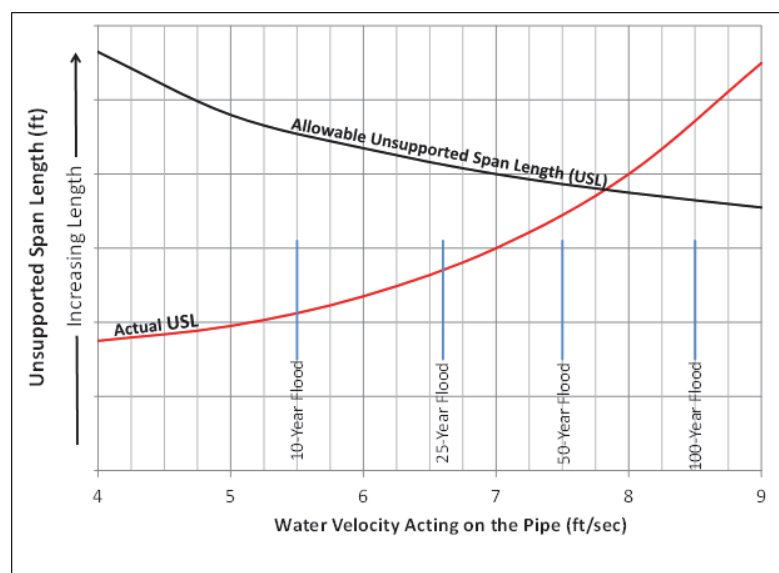


Figure 12—Example of Allowable and Actual Unsupported Span Length vs Water Velocity for VIV Damage Mechanism

5.4 Third Party Damage

Exposed and suspended pipelines are potentially subject to third party damage from ships/boats/anchors, as well as from anchor drag. Dredging is another source of third party damage. Though not specifically addressed by this RP, it is important to consider if third party damage is likely at the water crossing or coastal zone where exposed or suspended pipelines are located. Third party damage is of particular concern within commercially navigable waterways.

5.5 Dead Loads

Maximum allowable USLs are limited by the static loads acting on the pipeline depending on its weight, anodes, contents, and operating pressures. If the pipeline is submerged, buoyancy forces may counteract the pipe's weight. Similar to the analysis presented in 5.3, a comparison between the allowable USL to the actual USL is important to understand pipeline integrity risks from dead loads. To compensate for excessively long span lengths, aerial pipeline crossings are often supported over waterways or within the coastal zones by supports such as H-Braces (Figure 13). Supports are also subject to hydrotechnical hazards as discussed below.



Figure 13—Example of Engineered Span Supported by H-braces

5.5.1 Loss of Pipeline Supports

Aerial supports are often placed where the span length would otherwise be too long relative to the allowable lengths given the dead loads acting on the pipeline. During flood events local pier scour (see 4.2.1.2) can undermine the support structure of the H-brace and cause the pipeline support to fail. Pipeline supports often catch floating debris, particularly floating woody debris, which can increase the potential for local scour and also increase the hydrodynamic loading acting on the support during floods (Figure 14). Loss of pipeline supports, either through local scour or hydrodynamic loading, may result in longer USL that exceed allowable span lengths given the pipeline properties as described in 5.5.

5.5.2 Unrestrained/Unrestricted Pipeline Supports

Engineered spans supported by H-braces or other supports should be restrained both laterally and vertically on top of the support structure. If pipelines are unrestrained, it is possible that water levels within the stream, river, or coastal zone will overtop the support structure and may 1) force the pipeline off of the support structure or 2) deflect the pipeline beyond allowable deflection limits, or both. As with the loss of pipeline supports through local scour, if the