Bridge Scour in Tidal Waters

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Sediment scour near bridges in tidal waters is discussed. A brief overview of the coastal processes that influence bridge scour is presented and followed by a discussion of the various types of scour. The complexity and unsteady nature of tidal flows complicate the scour processes and make them difficult to predict. Existing scour prediction methods and equations were developed for steady, homogeneous, unidirectional flows that are significantly different from those found in the coastal zone. Some of the unique features of bridge scour in the coastal zone are discussed, and areas in which research is needed are delineated.

This paper discusses sediment scour near bridges in waters that are strongly influenced by astronomical tides. In general, this refers to rivers and estuaries along the coast. Depending on the terrain, range of tide, and river discharge, astronomical tides can have a significant influence many miles inland. For the purposes of this paper, locations where spring tidal currents are at least half of the total current will be considered as tidal waters. Even though this region is defined by the tide, tidal currents are by no means the only coastal process that influences scour at bridges in this area. Such quantities and processes as mass density stratification, water salinity, longshore (sediment) transport, surface waves, and tidal inlet instability can all play a significant role in bridge scour. The closer the location of interest is to the open coast, the larger the influence of these quantities. A brief discussion of how bridge scour is affected by these quantities is presented in this paper.

Sediment scour at bridges spanning inland streams and waterways has been divided into three major categories: (a) local, (b) contraction, and (c) aggradation and degradation. These same classifications can be used for tidal waters even though the scour mechanisms are, for the most part, different.

The paper is organized such that a brief review of the salient coastal processes is followed by a discussion of how these processes affect both the scour and the manner in which it is predicted.

COASTAL PROCESSES

Coastal processes are defined as the hydrodynamic and sediment transport processes that take place on open coastlines and in the adjoining bays, estuaries, river mouths, and tidal inlets. These processes are primarily driven by wind, wind waves, and astronomical and meteorological tides, although mass density stratification can be a forcing function as well as a process-modifying agent.

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Tides

Astronomical tides are the result of gravitational and centrifugal forces between the ocean waters and the sun and planets in the universe, the most significant being the sun and the earth's moon. Components of this tide have many frequencies ranging from 0.857 to 2.90 cycles per day (cpd), but the frequencies of the dominant components are 1.932 (M_2), 2.000 (S_2), 1.076 (O_1), and 1.003 cpd (K_1). Even though they are generated by gravitational and centrifugal forces, these long waves, known as astronomical tides, are influenced by Coriolis accelerations (resulting from the earth's rotation about its axis), shoaling, refraction, diffraction, bottom friction, interaction between different frequencies, and resonance.

Meteorological tides are alterations of the water surface due to wind-generated mass transport in the ocean. These tides are most noticeable during long-duration winter storms and subtropical storms or hurricanes. An interesting aspect of the net wind-driven mass transport in deep water is that it is (according to Ekman's theory) at right angles to the wind direction as a result of Coriolis acceleration. As viewed from above, the net transport is to the right of the wind direction in the northern hemisphere and to the left in the southern hemisphere. These tides and the waves that usually accompany them are agents of mass destruction along the coasts and in the coastal zone.

In this discussion, wind-driven currents are treated separately from meteorological tides even though they are both generated by wind shear on the water surface. Meteorological tides (sometimes called storm surge) are the change in water elevation resulting from the net movement of water by the wind and changes in barometric pressure. Wind-generated currents are the actual water movements that create the changes in water elevation. Both are important in sediment scour processes. For bodies of water connected to the ocean at more than one location, such as bays separated from the ocean by barrier islands, the design conditions for scour could very well be created by wind-generated currents rather than meteorological tides.

Waves

Surface waves play a major role in coastal processes. One convenient way of classifying surface waves is according to their period (or frequency). Table 1 gives such a breakdown ranging in periods for small ripples to the long periods associated with tsunamis (i.e., seismically generated waves) and astronomical tides. As waves propagate through water, the water particles undergo an orbital motion that extends to a depth of approximately half the length of the wave. Therefore,

TABLE 1 Classification of Ocean Surface Waves by Period

Classification	Range of Periods
Ripples	0 sec < T < 1 sec
Chop	1 sec < T < 4 sec
Sea	5 sec < T < 12 sec
Swell	6 sec < T < 25 sec
Surf Beat	1 min < T < 3 min
Tsunamis	10 min < T < 20 min
Tides	6 hr < T < 24 hr

when waves approaching the beach from offshore reach a water depth of less than approximately half their length, they begin to exert an oscillating shear stress on the bottom. This, coupled with a current (generated by any one or more of a number of possible mechanisms), can cause sediment movement.

Perhaps more important, however, are the indirect effects of waves on erosion and deposition of sediment. When large-amplitude swells generated by distant storms (perhaps combined with locally generated sea) approach a sandy beach coastline at an angle, a strong longshore current is generated. This current is bounded by the shore on one side and the edge of the breaker zone on the other. The width of this current can range from tens of meters for a steep-sloped near-shore beach face to a few hundred meters for a flat-sloped beach face. Breaking waves place sediment in suspension and fluidize the bed, enabling the longshore current to transport vast quantities of sand along the coast. This process is known as longshore transport. Estimated net transport rates for the continental U.S. coastline are shown in Figure 1.

The significance here is not so much what is happening along the open coast, but rather what happens to this "river of sand" when it reaches a tidal inlet or a river delta where a bridge might be located. What does happen depends to some degree on the nature of the inlet and bay system and the existence of manmade or natural structures nearby. Consider the so-called unimproved inlet shown as Inlet 2 in Figure 2 (i.e., an inlet that does not have a jetty system or hardened shorelines). During flood tide (flow from the ocean to the bay), a large percentage of the sediment transported along the coast moves into the bay and forms bars and shoals known

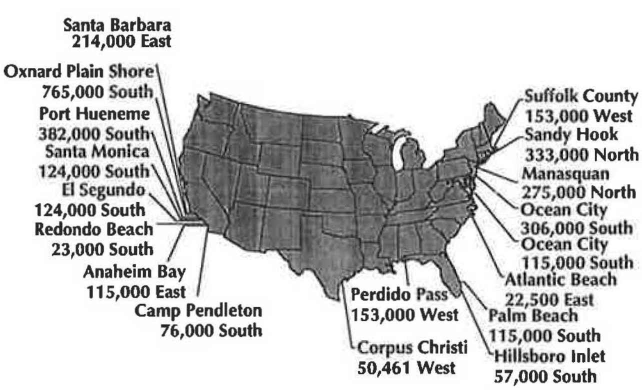

FIGURE 1 Approximate net longshore sediment transport rates along U.S. coastline (m^3/year).

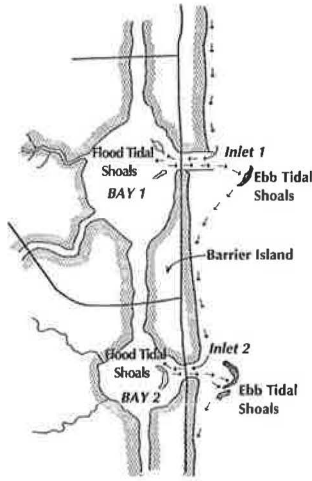

FIGURE 2 Schematic drawing of coastline with barrier islands and tidal inlets.

as flood shoals. Under ebb tide conditions (flow from the bay to the ocean), a portion of the sediment from the flood shoals is transported to offshore or ebb shoals (also shown in Figure 2). From there the sediment is transported to the downdrift shore and on down the coast. When jetties exist (see Inlet 1 in Figure 2) the sediment movement is similar to that for the unimproved inlet except a portion of the sand is trapped by the updrift jetty and there is generally less transport into and out of the inlet.

If on an annual basis there is a net transport in one direction along the coast (due to larger or more persistent waves approaching the coast from that direction), sand will accrete near the updrift jetty and erosion will occur downdrift of the inlet. The significance of these processes on the different types of bridge scour is discussed later in the paper.

Mass Density Stratification

Mass density stratification and salt wedges can have a dramatic effect on the flow in an inlet or coastal channel. This effect can alter both sediment scour and the manner in which scour depths are predicted. Salt wedges occur when the denser and more saline ocean water enters a river mouth or tidal inlet to a bay or estuary where there is significant freshwater runoff (see Figure 3). The interface between the fresh and salt water has a wedge shape, thus the name salt wedge. Typical velocity profiles in the water column through a wedge are shown in Figure 3. Note that with flow reversal in the water column, the depth average velocity can be very small even though the velocity near the bottom (and the bottom shear stress) is large. A local scour prediction based on average velocity for this case would be meaningless.

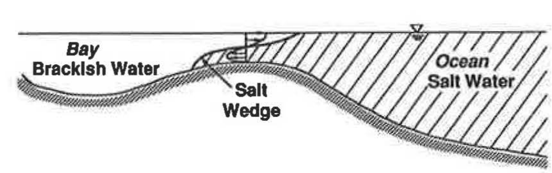

FIGURE 3 Profile of salt wedge.

Salinity

The direct effects of salinity on sediment transport processes can also be significant. This is particularly true when cohesive (fine) sediments are present. The deposition and consolidation of fine sediments is greatly influenced by the ions present in saline water. Thus the "erodible characteristics" of the sediment near bridge piers will be different in saline than in fresh-water systems.

General

Even though a wide range of geological conditions exists around the coast of the United States and each situation is somewhat unique, some general comments about shoreline and inlet stability can be made. Portions of the coast on the eastern continental United States and the Gulf of Mexico are lined with barrier islands. These islands are very dynamic in that they migrate normal to and along (perpendicular to and parallel with) the coast. The tidal inlets that connect the bays and estuaries behind these islands to the ocean or gulf are equally unstable. Despite the unstable nature of barrier islands and their vulnerability to severe storms, many have become heavily populated, thus creating the need for elaborate road systems and bridges in these areas.

Changes in these coastal features take place on time scales that range from hours to hundreds of thousands of years. Even though the long-term (geological time) changes taking place at a particular location are important to the overall understanding of the situation, the changes that will occur over the life of the bridge that are of most interest to the design engineer. This time span is on the order of 60 years.

Armed with an understanding of the geology of the area; local historic charts and maps; aerial photographs; information on planned modifications to the system to which the inlet of interest belongs (in the form of proposed dredging of existing or new channels, reclamation of land, construction of dams on rivers leading into the system, etc.); knowledge of the nature, frequency, and intensity of storms in that area; and output from the appropriate hydrodynamic models, the coastal engineer can estimate with some degree of certainty what the inlet will do over the life of the bridge. This estimate is based on the quantities listed earlier and is, of course, subject to the accuracies of these projections, forecasts, and computations.

All flows in nature are unsteady. Some, however, are more unsteady than others, in both the frequency with which changes occur and the magnitude of the variations. In general, tidal flows undergo much higher frequency changes than inland river flows. In most cases the changes are not only in magnitude but in direction as well. In locations where the maximum tidal currents are sufficiently large, the bottom roughness can undergo large changes during a tidal cycle, ranging from sand ripples to dunes to a flat bed, thus making flow and sediment transport computations much more difficult than for steady flow situations. Also, the duration of extreme events in tidal waters is different than those for inland waters. Figure 4 shows a storm hydrograph for an inland river situation and a computed hurricane storm surge (meteorological tide) for a location on the east coast of Florida. Note the dramatic

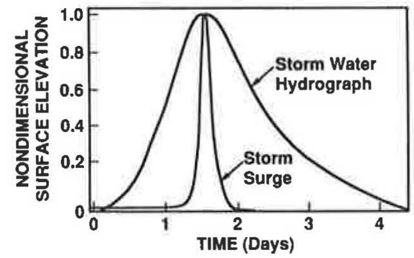

FIGURE 4 Schematic of typical storm water hydrograph and hurricane storm surge.

differences in the rates of rise and fall of water elevation and the overall duration of the events.

Another characteristic of tidal inlets that adds to the complexity of the scour processes is the strong tendency for the ebb channel to be different from the flood channel—that is, the dominant flow from the ocean to the bay is at a different location in the inlet channel than the dominant flow from the bay to the ocean. This can result in different phases of tidal flow occurring at the same time at a channel cross section. For example, slack water may exist over a portion of the channel while ebb or flood flow exists over the remainder of the channel. A one-dimensional hydrodynamic model, calibrated for this particular inlet, might give reasonable values for the discharge and the average velocity in the inlet, but using the computed average velocity for local scour prediction may not be appropriate.

LOCAL SCOUR

The processes governing local structure-induced sediment scour due to steady flows are reasonably well understood. Detailed descriptions of these processes can be found in any number of review articles on the subject (*1–9*); therefore, only a brief summary will be presented here.

The conditions under which sediment movement is initiated are not thoroughly understood, but it is generally accepted that movement occurs once the bottom shear stress exceeds a certain value. Bottom shear stress depends on both the mean flow and the level of turbulence near the bottom. Steady flow around a bluff structure that is embedded in the bottom results in several mechanisms that produce bottom shear stress. If the (open channel) flow is fully developed, the boundary layer will reach from the bottom to the water surface. When this flow, whose velocity increases with distance from the bottom, impinges on the structure, a vertical pressure gradient along the leading edge of the structure is formed. This produces a downward flow that results in a vortex that wraps around the structure and trails off downstream. When viewed from above this vortex looks like a horseshoe, thus the name horseshoe vortex.

The flow is also accelerated to higher velocities as it moves around the structure. Once the flow reaches a sharp corner or a region of increasing pressure (i.e., an adverse pressure gradient), flow separation occurs and a wake region forms. Flow in the wake region is more turbulent than the surrounding flow and contains strong vertical vortices that are attached or shed from the structure. All three of these flow mechanisms enhance the bottom shear stress in the neighborhood of the structure. The complexity of this flow and the associated sediment transport processes have hampered progress in the analytical and numerical treatment of these problems.

These flows are inherently three-dimensional and turbulent and require full three-dimensional turbulent flow equations for their modeling. Even if turbulence (math) models were available for these flows, they would require substantial amounts of supercomputer time for their solution. Recent attempts by the author to explore the possibilities of estimating local scour by combining a three-dimensional laminar Navier-Stokes equation solver with a sediment transport model for the flow in the vicinity of a single vertical pile led to the conclusion that additional research is needed before this approach can be used to solve practical problems. For these reasons much of the success in predicting local scour depths (and volumes) has been with empirical equations.

Empirical equations have been invaluable to engineers over the years in providing tools for analyzing complex situations before analytical and computational models could be developed. They are, however, very dependent on the data used in their creation and as such not easily extended to situations different from those for which they were developed. Care must be exercised in using empirical local scour prediction equations—which are based primarily on steady, homogeneous flow laboratory data—for unsteady tidal flow situations.

The duration of hurricane storm surges is much shorter than river flood hydrographs (see Figure 4). The effect of this time difference on local and contraction bridge scour is not known since there are very few data on rates of scour (*1,5,10*). Because the duration of scour-producing events for most inland rivers is longer than the time to reach equilibrium, there has been little interest in scour rates in the past. Shen (*1*) plotted data from Chabert and Engeldinger (*11*) on coordinates of velocity squared (V^2) versus time to reach 75 percent of maximum scour depth. Even though there is considerable scatter in the data, the plot does show that the rate of scour increases with decreasing grain size. Baker found that the time required to reach equilibrium scour depth increased as the velocity was increased to the transition from clearwater to live bed conditions, then decreased as the velocity was increased further (*5*). Clearly, more data and analysis on the time dependency of scour, especially in reversing tidal flows, are needed.

Those responsible for specifying the local scour design equations wisely have made them conservative to account for uncertainties in the equations and the input data. As long as sufficient care is taken in arriving at the input quantities, these equations should be used in tidal waters until questions regarding their applicability to these conditions are resolved. It is likely, however, that these equations will prove to be too conservative for most coastal situations.

CONTRACTION SCOUR

Contraction scour occurs in erodible inland rivers and streams when there is a natural or manmade obstruction to the flow. When a bridge causes the obstruction, it usually means that under flood conditions the river is out of its banks upstream and perhaps downstream of the obstruction but is forced into the main channel at the bridge. Channel scour will occur at the bridge until the sediment transport entering the bridge cross section equals that leaving the section. The flow driving mechanism at the bridge is the water elevation difference (i.e., the head difference) across the bridge. The water elevation upstream of the bridge will simply rise until the velocity and cross section are such that the river discharge is accommodated.

Once the river overflows its banks, the width of the stream usually increases rapidly (i.e., the area adjacent to the main channel is usually relatively flat and in many cases vegetated). This means that velocities in the overbank flow region are smaller than in the main channel, resulting in little or no sediment transport in that part of the flow. With the increased flow velocities at the bridge and the sediment transport into that section coming primarily from the main channel upstream, scour at the bridge will occur until sediment transport equilibrium is reached—that is, when the sediment transported out of the bridge area equals that entering the region. Larsen's equation (*12*,Ch.4) appears to either directly or indirectly take most of these mechanisms into consideration for this flow situation.

In tidal waters, where the design storm event is usually produced by a hurricane storm surge, the situation is somewhat different. Unlike the design flood condition, the ocean water level at the inlet is essentially unaffected by the flow through the inlet (i.e., the ocean water level is only slightly modified by the presence of the inlet). Therefore, at least during the flood stage, the head difference across the bridge and average velocity are limited by the storm surge height, not by the obstruction. For the inland river situation the head difference and velocity will increase with increasing constriction until the hydrograph peaks or overtopping occurs.

The quantity of bedload and suspended sediment entering the inlet during the flood phase of a severe storm event can be substantial (due to large longshore transport). This can have a major impact on local as well as contraction scour by modifying the near-bottom flow and shear stress and, because of the high sediment concentrations, the ability of the flow to transport additional sediment.

AGGRADATION AND DEGRADATION SCOUR

Aggradation and degradation result from channel movement in the vicinity of the bridge. In general, the bridge plays only a minor role in this process. This is not to say that under certain circumstances the bridge will not retard or accelerate the migration, but for the most part it is a separate process driven by mechanisms unrelated to the bridge. In tidal waters aggradation and degradation occur when (a) the deeper channels in a bay or estuary migrate as a result of natural or manmade alterations to the system, and (b) tidal inlets become unstable.

The term "system" is used here to denote bodies of water along the coast connected by rivers, navigation channels, and such. These bodies are usually connected to a gulf or ocean by one or more tidal inlets. For a location to be part of the system associated with a particular point of interest, a physical alteration at the location must result in a measurable physical change at the point of interest. For example, the system associated with a bridge connecting the mainland to a barrier island might include the bay spanned by the bridge, rivers, and streams running into the bay, a manmade navigation canal connecting this bay with the adjoining bay, and the two or more tidal inlets connecting these bays to the ocean. Modifications of the system that influence aggradation and degradation at the bridge in question include dredging of an inlet or canal, addition of a marina in one of the bays, dredging of finger canals for a housing development, reclamation of land to extend a runway for an airport, changes in land use that affect runoff in the bays and rivers, coastal construction in the bays and at the inlets (seawalls, revetments, bulkheads, jetties, groins, etc.), and construction of other bridges.

SEDIMENT SCOUR DESIGN CRITERIA

In some types of structural design not much emphasis is placed on environmental design conditions (i.e., on the prediction of the loading on the structure due to the environment). Sometimes this is completely justified, because other types of loading far exceed the anticipated environmental loads. In other situations this lack of emphasis appears to stem from a lack of appreciation for the possible magnitude of these loads. The return interval for design events—say, 50, 100, or even 500 years—makes it unlikely that the design engineer has personally experienced such conditions in his or her lifetime. Thus, the loading predicted for such an event may appear to be unreasonable when in fact it may be correct.

On the other hand, sufficient resources, time, and effort must be devoted to establishing accurate environmental design criteria to ensure that they neither under- nor overpredicts design load conditions. Overprediction can result in unnecessary construction costs that are orders of magnitude greater than the costs of studies needed to establish more accurate design criteria. Underprediction is more rare but can be costly as well in terms of risk to lives and property.

The offshore industry (consisting primarily of the major oil companies) spends large sums of money each year for environmental data collection and analysis, sophisticated analytical and computer model development and execution, elaborate wind, wave, and current hindcast and laboratory testing, all for the purpose of establishing environmental design criteria for near- and offshore locations around the world. Sediment scour near bottom-mounted structures in bays and in the more shallow waters on continental shelves is one of the design parameters examined. Sediment scour in tidal waters is a difficult quantity to predict for the reasons just given. The methods used for predicting bridge scour for inland rivers and waterways may not be sufficient for tidal waters because of the complexity of the flows, the effects of waves, density stratification, longshore transport, wind-generated currents, and so forth.

A general methodology should be developed that applies to the wide range of conditions found in the coastal zone around the United States. The weighting and details of the various procedures would vary with the local geology, sediment types, tidal range, nature of extreme storm events, and so on, but the basic approach would be the same. This approach could benefit from techniques developed by the offshore industry over the past 20 years. The resulting product could be a procedures manual that outlines the processes that must be considered. The procedures might start with a determination of whether sediment scour is possible. If an erodible substrate is present and scour is deemed possible, then the procedures manual would guide the user through the necessary steps to obtain design scour depth predictions. In most if not all cases, the prediction of local and contraction scour would include the application of the appropriate computer flow models. The particular model needed will change depending on the local conditions, but for particular situations the guidelines can address the procedures that the model should include. If the location and conditions are such that surface waves are important, then they must be predicted as well. Local scour prediction, at least for now, needs to use the appropriate empirical scour relationships that have been and are being developed from laboratory experiments. The prediction of inlet instability and channel migration (aggradation and degradation scour) requires a rather complex analysis based on information and data produced by a variety of computer programs, historical charts and photographs, projected construction and activities in the area, and the like.

SUMMARY AND CONCLUSIONS

In summary, the environmental conditions in tidally influenced waters can be significantly different from those in inland streams and waterways. The effects of reversing flows, density stratification, longshore sediment transport, waves, inlet instability, short duration, and rapidly changing storm hydrographs, among other characteristics, on bridge scour in this zone can be great. Present scour prediction schemes and formulas were not developed for these conditions and as such may not be applicable. These equations are, however, designed to give conservative estimates of scour depths and therefore should be used in the coastal zone until questions about their appropriateness for these conditions have been resolved. As pointed out, it is more likely that further research will prove them to be too conservative in their predictions for most situations found in the coastal zone.

A field measurement program that is well-conceived and -executed is needed to obtain the data required to test existing scour prediction techniques and equations and develop new approaches and equations where needed. The payoff for the greater emphasis on the development of environmental design criteria will be better, safer, and more efficiently designed bridges that require less maintenance.

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