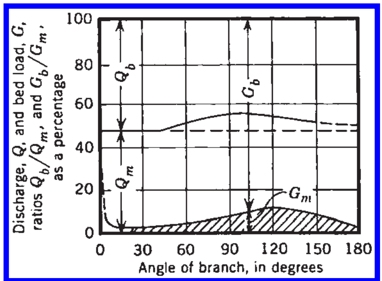
et al. (2005) both present results indicating that the horizontal exchange coefficient, and the diversion of stream flow and sediment into a harbor mouth (or branch channel), decrease with increasing downstream branch angle [Fig. 2-55(b)]. A reverse-oriented diversion flow greater than 90 deg produces the least amount of sedimentation (least amount of exchange with the side channel or basin), with the downstream angle of 120 deg appearing to be the most effective, as illustrated in Figs. 2-55(a) and (c).

The harbor entrance area also controls the extent of horizontal entrainment flow. As the ratio of the harbor entrance width to its basin length increases, the level of sedimentation into the harbor increases. Based on measured sedimentation rates observed in several European harbors, per Fig. 2-56, a basin that is twice as wide as long will suffer roughly 40% greater sedimentation than one that is twice as long as wide. Therefore, the entrance needs to be as narrow as possible consistent with navigation needs. This is also consistent with the requirements for improving water quality in the harbor basin.

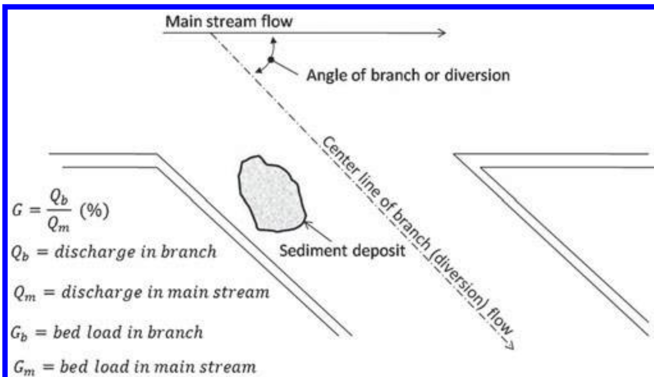
The mechanism of entraining sediment into a harbor is a product of flow moving past the harbor opening and setting up a circulation eddy inside the basin, which carries the sediment into the basin. In addition to sizing and orienting the harbor opening to minimize sediment entrainment, various passive schemes can be applied to disrupt or displace the basin eddy to limit how much sediment can be carried in. Figure 2-57 illustrates the basic principle. As flow passes an opening, a wake is formed, which diverts some of the flow into the side basin, creating an eddy. This eddy becomes trapped, pumping sediment into the basin, where it accumulates [Fig. 2-57(a)]. If a flow diversion structure is introduced, the eddy is pulled out of the basin, less entrainment of sediment occurs, and a secondary "internal" eddy may form in long, narrow basins [Fig. 2-57(b)].

Figure 2-58 illustrates some examples of how this understanding can be used to control sedimentation into a basin. In Fig. 2-58 (left panel), the addition of upstream and downstream spurs extended out into the main channel flow can be used to relocate the eddy downstream away from the harbor basin area. Figure 2-58 (right panel) offers an analogous solution by creating a secondary sediment trap downstream beyond the harbor entrance so that the normal siltation in the basin is diverted.

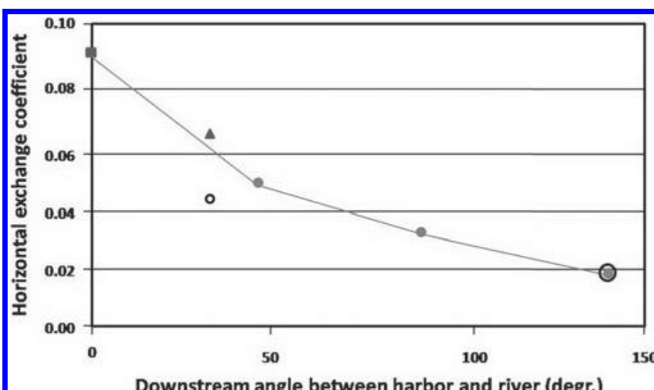
Figure 2-59 suggests other features that can be integrated at or within the harbor entrance to modify or disrupt the eddy. One technique is to modify the roughness or geometry of the downstream entrance wall to modify the entrainment flow pattern. The second is to introduce a counteracting current to break up the eddy. This might be particularly convenient if there is a constant flowing stream or outfall discharging nearby that could be diverted for this use. The third method is to reduce the velocity gradient between the channel and the basin by creating a separation channel, thus minimizing the wake. A porous groyne or an array of properly aligned piles situated upstream may accomplish this. By



(a)



(b)



(c)

Fig. 2-55. Diversion of sediment into a harbor as a function of entrance approach angle; (a) a reverse-oriented diversion flow greater than 90 deg produces the least amount of sedimentation (least amount of exchange with the side channel or basin), with the downstream angle of 120 deg appearing to be the most effective; (b) the horizontal exchange coefficient, and the diversion of stream flow and sediment into a harbor mouth (or branch channel), decrease with increasing downstream branch angle; (c) another example of a reverse-oriented diversion flow greater than 90 deg, with the downstream angle of 120 deg Sources: Vanoni (1975); Kuijper et al. (2005)

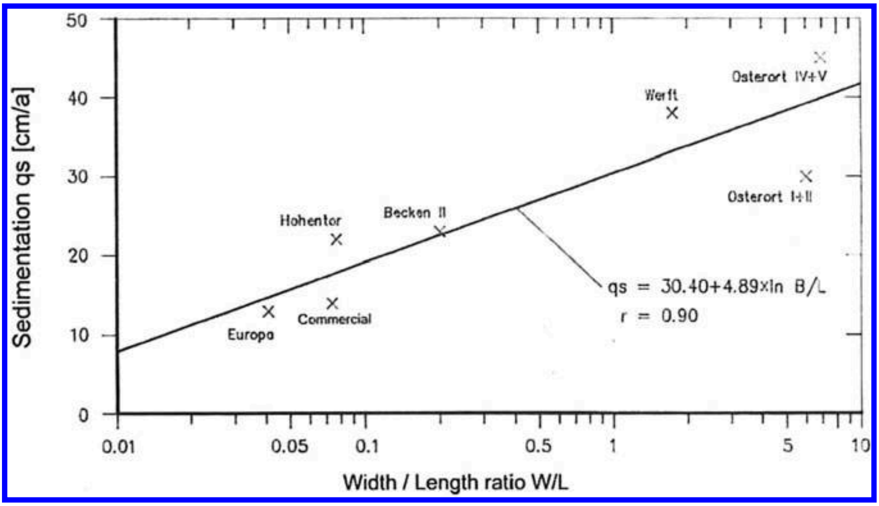


Fig. 2-56. Impact of basin aspect ratio on sedimentation
Source: Nasner (1992)

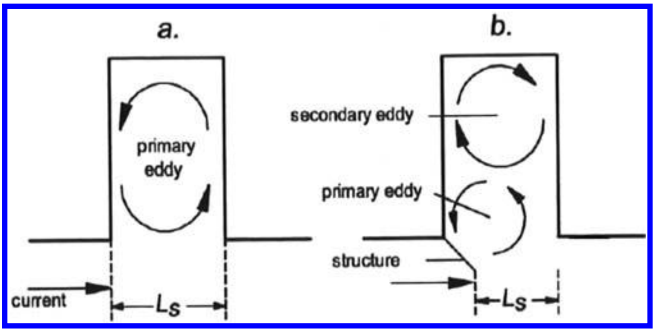


Fig. 2-57. Basic flow entrainment patterns past a basin

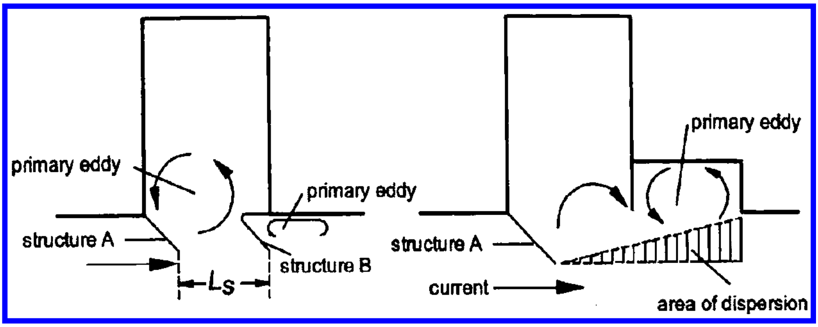


Fig. 2-58. Basic flow diversion techniques and stagnation eddy relocation
Source: Röhr (1934)

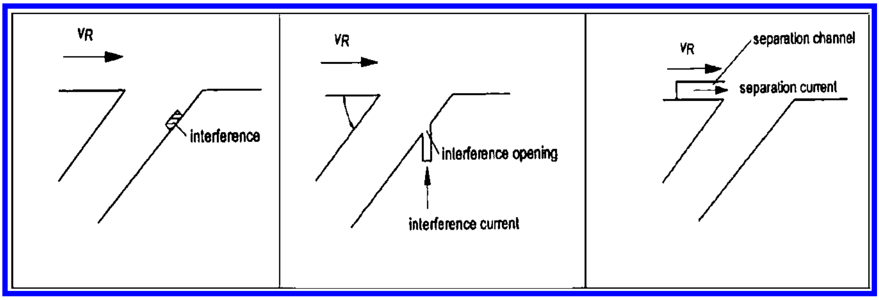


Fig. 2-59. Example interior basin enhancements to passively reduce sedimentation
Source: Vollmers (1963); Brinkman (1990)

smoothing the transition in velocity between river and basin, the exchange coefficient has been shown to be reduced by approximately 50% (van Schijndel and Kranenburg 1998).

Elements of the concepts described above have been aggregated into an actual passive sediment control system, and are detailed further in Fig. 2-60. A flow diversion device, commonly referred to as a *current deflecting wall* (CDW), a modified downstream wall geometry, and a submerged sill are combined for a case of bidirectional estuarine flow. The submerged sill functions similarly to the CDW, but for flow in the reverse and at a different tide level. Tests of such schemes have shown a reduction of flow entering the harbor basin of as much as 70%, with an associated decrease in sedimentation of at least 15% (Hofland et al. 2001).

To keep sediment moving along the bottom when the channel crosses the current, Krone (1987) recommends that the side slopes of the channel, or depression, be cut no steeper than $1V:10H$. This can easily be done by cutting the slope with 0.6-m (2-ft) terraces. This prevents large eddies from occurring near bottom, and the sedimentation that does occur simply fills the cuts to a smooth slope. By disrupting the bottom eddies due to flow separation over the dredge cut, cycle time for maintenance dredging can be extended.

Coasts

The principles for controlling sedimentation in a coastal setting are similar to those for a riverine setting, but the processes driving the siltation process are different. While riverine sedimentation is due entirely to gravity water flow, typically unidirectional on the open coast, the flow is either tidally driven (and therefore bidirectional), or may be induced by the pressure of the waves impinging on the beach. The latter is the

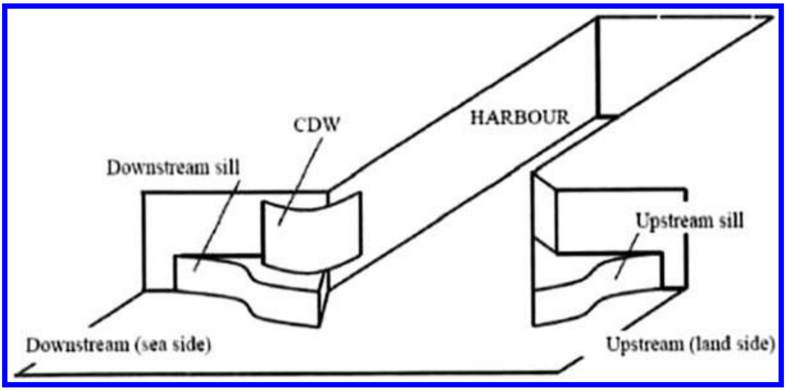


Fig. 2-60. Current deflecting wall and submerged tidal sill example

product of the waves reaching the beach at an angle to the shore. Although much of the energy of the wave is absorbed or redirected by the processes of wave breaking, wave reflection, and frictional dissipation, a percentage of the energy remains, applied in the along-shore direction of wave movement. This excess stress applied to the beach both triggers erosion of the material from the beach face and also induces drift of the beach material along the shore. The magnitude of the longshore sedimentation rate is a function of both the size of the waves and the relative angles that the approaching waves make with the beach. An expression for an estimate of the total sediment transport potential is given as:

$$I_1 \approx 0.1\left(\rho g H_b{}^2 C_b\right)\sin\alpha_b \cos\alpha_b \qquad (2\text{-}39)$$

where
H_b = the height of the wave at breaking
C_b = the speed of the wave at breaking
ρ = density of water
g = gravity
α_b = the angle the wave makes with the shore at the depth of breaking (Komar 1976).

Of this volume, approximately 20% is suspended load, i.e., material being carried in the water column. The remaining 80% is moving along the bed. Also recognize that this calculation is only instantaneous for a given wave height and a given wave angle. To determine the annual impact it is necessary to calculate the movement for every wave condition and duration, and combine them to give an annual number.

Note that this is a calculation for the *potential* amount of sediment to be moved, which may or may not be achieved, depending on whether there is sufficient sediment available to be moved. The total amount of transport that occurs, regardless of the direction of the movement, is referred to as the *gross transport*, while the offsetting movements of sediment up and down the beach are considered the *net transport*. It is very difficult to actually measure the sediment transport rate. If adequate wave and bathymetry data are available it is possible to perform reasonable calculations, though these estimates are often found to vary 50% from other measures of the transport rate. A commonly utilized estimate for transport is dredging records. Dredging does give an indication of the gross transport rate, if surveys carefully record how long it takes for a previously dredged hole to refill. However, dredging is typically done based on a preplanned maintenance, an emergency need, or a schedule, and as such may or may not capture the real time required for sediment to infill an area.

Although the net transport rate gives an indication of which direction the majority of sediment moves toward, which helps orient a harbor entrance, the gross number is a better indicator of the magnitude of material that might get captured by a harbor basin and entrance. Harbor entrances at open water sites have historically been protected against waves from a dominant storm direction, resulting in asymmetrical breakwaters. If the harbor is located in an area of strong bidirectional tidal currents or wave directions, this asymmetry can lead to an exacerbated sedimentation as sediment is driven into the entrance but there is no reverse flow pattern to transport it back away due to the shadowing effect of the overlapping breakwater.

In terms of harbor entrances, the greatest concern is for shoaling to occur across the entrance mouth. Some sediment will be ingested into the basin area; this was previously addressed in the following riverine discussion on how to minimize those impacts. However, for navigation purposes the concern is maintaining navigable depth during times of most critical maneuvering control needs. Beyond simply having adequate water depth to pass, the entrance needs to be protected to prevent sand bars from forming across the mouth. Sand bars are triggers to cause wave breaking, a potentially fatal occurrence to an unprepared or incapable vessel trying to transit through the entrance, as was shown in Fig. 2-11.

Practically, small craft using the harbor, either for berthing or refuge, will likely avoid leaving the harbor, or will try to get in off the open water, if waves have built to 2 m (6 ft) or higher. Wave breaking occurs when the wave height to water depth ratio is 60% or greater (USACE 2002a). To avoid wave breaking from occurring in the harbor entrance, the minimum depth anywhere in the entrance needs to be at least 3.3 m (10.8 ft) for safety. Given that sand bars may easily form 1 m (3 ft) tall or more, then the design water depth generally should never be less than 4.3 m (14 ft), and greater depth may be required if shoaling conditions dictate. This can be accomplished by either locating the entire harbor breakwater outside the breaker zone so that waves cannot break at the small craft harbor entrance, or jetties may be extended to deeper water to achieve a similar result.

There is a theoretical depth at which longshore transport ceases in any wave environment, given by the expression (Benassai 2006):

$$d_{LTo} = 2.28H_{So} - 10.9\left(H_{So}{}^2/L_o\right)(\text{units in meters}) \qquad (2\text{-}40)$$

where the subscripted parameters represent their deep-water values and an average error estimate of 0.5 m (Birkemeier 1985). To describe a limiting value, the H_{So} value that is exceeded only 12 hours per year, based on annual statistics, is typically used. For a 3-m wave of 8-sec period, the longshore closure depth is approximately 5.9 m. In this example, jetties would therefore need to extend to at least 6.5 m or greater water depth to ensure blockage of the sediment. However, in general, it is economically impractical to build the entrance of a small craft harbor far enough out to ensure no sediment passage.

The consequence of blocking the movement of sediment along the shore is typically a growth of the beach width on the updrift side of the harbor entrance, and a recession of the shoreline on the downdrift side. The latter is caused by the starvation of the beach of a continuous resupply of sand resulting from the harbor blockage. Looking along the beach, the shoreline alignment will be offset by the presence of the harbor. In locations where there is strong bidirectional wave or current action, growth of the beach immediately adjacent the harbor entrance on both sides may occur; however, typically a larger-scale offset will still be observed due to the net drift. In some very rare situations the harbor entrance might coincidently be located at a point on the shoreline where there is a net zero movement of the sediment. In this case the shoreline will not retreat; however, growth of a beach on either side is likely. If the gross movement is also zero, then the harbor is truly in an ideal, maintenance-free location.

To address the reality that some sedimentation will occur at the harbor entrance, various strategies may be employed. Some alignments of the breakwater flanks to the natural shoreline appear to be beneficial in promoting sediment transport around the harbor versus blockage. As in the case of flow across a dredged channel, the goal is to avoid "flow separation" from the flanks of the breakwater. Generally, a gross angle of 20 deg with the shore or less is best, with the curve tangent never deflecting more than 6 deg.

Rivers

On rivers, where and how to situate a marina basin or entrance to avoid or minimize sedimentation is strongly controlled by the behavior of stream flow. On straight segments of a river, the strongest flowing, and typically deepest portion of the channel (known as the *thalweg*) is generally near the center. However, at bends in the river the channel and higher-velocity flow shift to the outside of the bend. The flow pattern even becomes three-dimensional as it swirls, like a screw, as it passes around the corner. Figure 2-61 suggests this behavior, which is the mechanism for the outer bank in a curve to always erode away.

The severity of the bend in the river determines whether shoaling and sedimentation may occur on the inside of the bend where flow velocity is low. Shown in Fig. 2-62 are four bends with *relative turn radius* (ratio of the bend radius *R* to the width of the channel) ranging from 0.5 to 3.5.

The illustration suggests that when the curve is gentle (R > 3.5d), so that the flow fully fills the width of the channel, little sedimentation on the inside of the bend occurs. When the bend becomes more abrupt, the flow core is squeezed as it tries to turn, and more erosion occurs on the outside of the bend. Concurrently, large deposition occurs on the inside of the bend (Vanoni 1975). As general guidance for planning a marina basin, the basin entrance and approaches should never be located on the inside of a bend, where sedimentation will occur; also, they need to be located far enough downstream of the bend so that the flow can re-establish to smooth and full bank-to-bank.

Sediment Bypassing

If sedimentation cannot be avoided or diverted past the marina, then the most successful approaches are by active *sediment bypassing*, i.e.,

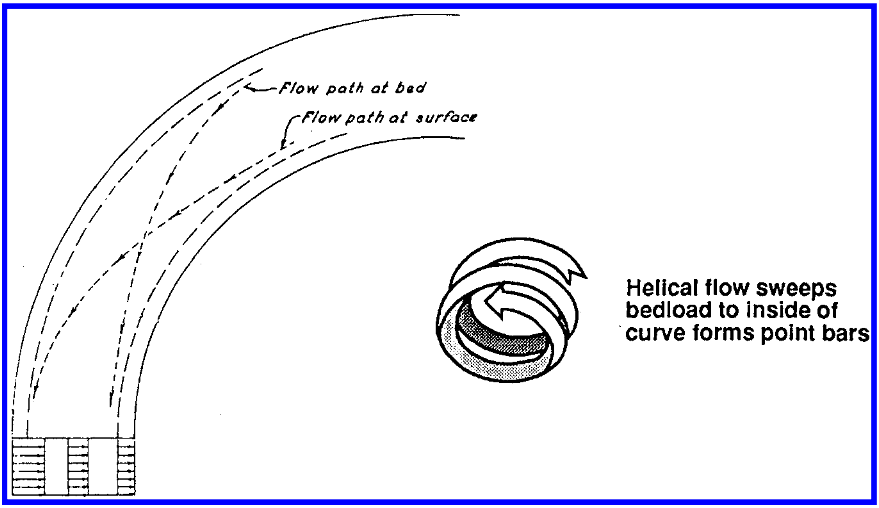


Fig. 2-61. Flow pattern of river at a bend

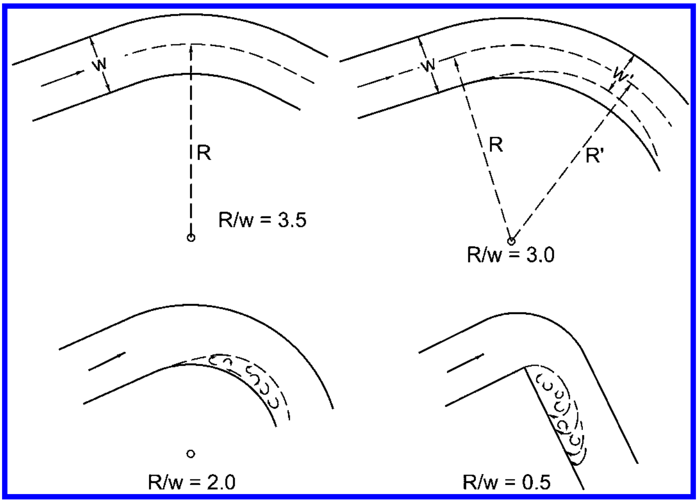


Fig. 2-62. Occurrence of sedimentation on inside flanks of bends

mechanically moving the sediment from one side of the entrance to the other. This has the added benefit of nourishing the downdrift shoreline, which is otherwise eroding back. If development exists on the downdrift shore, this step also protects the areas from erosion-based loss. The addition of a downstream pointing spur off the downdrift side of an entrance jetty or breakwater leg also aids in stabilizing that normally sediment-starved (eroding) shoreline area.

The bypassing of the sand might be performed in several methods. Land-based excavators can be used to physically dig up a portion of the beach and then transport the sand by truck to the other side, where it is then placed. A permanent sand bypassing pump system might be used to hydraulically collect sand and then pump it to the other side. If the entrance leaks more sediment, a third option is to use a dredge placed inside the shelter of the entrance breakwaters, which then captures the sand and pumps it or barges it out of the entrance. In this approach the entrance is best designed with an intentional "sediment trap" located out of the main navigation channel where the dredge can operate without affecting traffic. The trap area is selected and sized to capture sand moving around and into the entrance channel. If planning such a strategy, an extra-wide area needs to be dedicated in the entrance to allow room for this activity.

With any of the mechanical sand bypassing methods, special provisions need to be made to allow access to the sand removal and transfer areas. As a word of caution, sediment traps are very inefficient in capturing all the moving sediment, so large accommodation for variability should be provided. Usually, a moveable versus a fixed dredge or excavation system has proven the most efficient. The location of the discharge point downdrift is also important. If drift reversals occur, sediment just removed from a harbor entrance may be carried right back to the entrance from the opposing direction. Detailed study of the sediment patterns is required to understand where to best excavate the material and where to then place it.

The study of sediment behavior, whether riverine or coastal, is a complex problem and still not well understood in spite of extensive study efforts. Detailed computer and/or physical models are recommended as the best means of examining the sediment behavior and developing the appropriate mitigation for the site.

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