# DESIGN OF ENCLOSED HARBORS TO REOUCE SEDIMENTATION

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## ABSTRACT

Sedimentation may be an important problem when quantities of suspended material are carried into an enclosed harbor on a flooding tide. In order to forecast future maintenance costs, two methods for predicting the sedimentation rate prior to harbor construction are proposed: 1) a sedimentation tank to be placed at the proposed harbor site, and 2) a mathematical model which uses sediment and hydraulic data collected at the harbor site.

Certain considerations in the design phase of a project may effect a reduction in harbor sedimentation. If feasible, the harbor may be sited in a region where suspended sediment concentrations are low and sediment sizes (settling velocities) are small. Proximity to river sediment sources may be a factor. Conversely, a harbor site in a clear-water river adjacent to a sediment-laden estuary may be desirable if bedload transport during freshets would not be a problem. Settlement of suspended material may occur in the channel which connects an enclosed harbor basin with navigable waters. This material may subsequently be resuspended and carried into the basin thereby increasing the sedimentation rate. To reduce that rate the channel should be designed as short as possible. A sill in the channel may also be used to reduce initial excavation costs and the sedimentation rate. Flotation for vessels in the basin will be provided at all times, but movement into and out of the harbor will be reduced to times of higher water. In high latitude areas where harbor use is limited to periods when ice cover is absent, the sedimentation rate may be reduced using a channel closure structure during non-use periods. Winter sedimentation rates can be predicted using the mathematical model for summer conditions, and when ice thickness is known.


## INTROOUCTION

Special attention to sedimentation problems is warranted in the design of an enclosed harbor sited in a high tidal range, sediment-laden coastal area. Large quantities of suspended material will likely be carried into the harbor each floodtide. Because of the relatively quiescent conditions in the harbor when compared to outside waters, a part of the suspended sediment will probably settle out of suspension before being carried out on the ebb tide. Two important considerations are to predict the sedimentation rate prior to harbor construction in order to forecast future maintenance costs, and to site and design the harbor

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to minimize sedimentation. These considerations are the subject of this summary paper. Deposition from suspension is assumed to be the only mechanism by which sediment infilling occurs. The only design criterion considered is that of minimizing the sedimentation rate.

In 1970, the Coastal Engineering Research Center (CERC) began a study for the U.S. Army Engineer District, Alaska, to address the problem of sedimentation in Alaskan small-craft harbors. Because of extremely high sedimentation rates and the attendant high dredging costs involved, the Alaska District requested that a means be developed to predict those costs before construction. It was noted that the feasibility of new harbor projects would, in some cases, hinge on maintenance dredging costs. The CERC study continued for 9 years. In that period, summer and winter monitoring of a prototype harbor at Dillingham, (Everts, 1976a) and measurements in Cook Inlet, Kenai River, and especially Knik Arm, Alaska, were made to identify and quantify the sediment and hydraulic mechanisms responsible for the harbor shoaling problem. A mathematical model (Everts, 1980) and a field measuring device (Everts, 1975) were developed to predict the sedimentation rate. Through the conduct of the study it also became apparent that certain considerations in the design of an enclosed harbor could effect a reduction in the sedimentation rate.

## HARBOR CHARACTERISTICS AND SEDIMENTATION PROCESSES

For application of the results described in this paper, harbor conditions should conform to those described in this section. An enclosed harbor connected to coastal waters by a navigation channel is considered (Fig. 1). Because of high-velocity, tide-driven currents, and severe ice conditions, the protection offered by enclosed harbors is a special requirement in some of coastal Alaska. A sill in the navigation channel is a possible added design feature. It may be at any elevation. A sill, usually sited at the basin opening (Fig. 1), is used in high tidal range areas to reduce basin excavation costs. While providing flotation for vessels at low tidal stages, a sill restricts navigation in and out of the basin to times of higher tidal elevations. Harbors in Alaska with such sills are called "half-tide" harbors.

The harbor basin and channel may be of any size and shape as long as the rise and fall of the water surface inside the basin is nearly in phase with and of the same amplitude at that outside the basin (Everts, 1980). This means the volume of water that enters the basin as the water surface rises is equal to the volume of the basin above the sill. Basin and channel sidewalls may be sloping or vertical. If a sill is present, the basin is assumed stagnant below sill elevation. Therefore, when a suspended-sediment particle settles below that elevation it is considered deposited, even though it has not yet reached the bottom. Horizontal circulation within the basin is of such magnitude that sediment, once deposited or once it has settled below the sill elevation, it is not resuspended.

Sedimentation results when suspended material settles from suspension. Bedload transport into the basin is assumed to be negligible. Sedimentation rates are assumed to be nearly equal throughout the basin; i.e., back eddies or other preferred depositional areas do not exist.

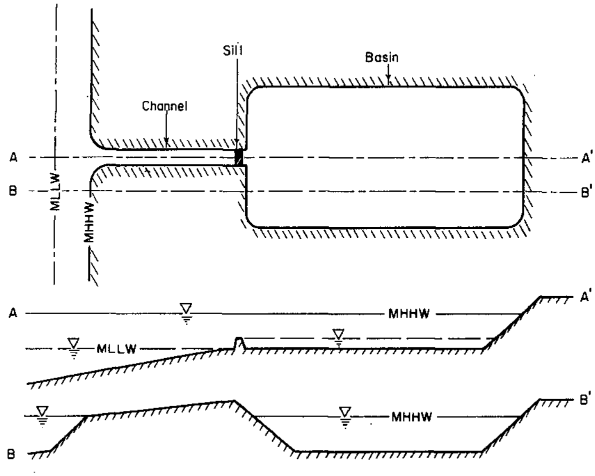


Figure 1. Definition sketch of an enclosed "half-tide" harbor illustrating major components: navigation channel, sill, and basin.

## PREDICTION OF SEDIMENTATION RATE

To plan maintenance expenses before harbor construction in areas where sediment is carried in suspension, it is necessary to forecast future sedimentation rates. Two means for doing this were developed in the study: (1) a sedimentation tank, and (2) a mathematical model.

### Prototype Harbor.

Dillingham Harbor, Alaska, was selected as the prototype on which to scale the tank and to test the model. Dillingham is located 500 km southwest of Anchorage, in the upper reaches of Nushagak Bay (Fig. 2). The local tidal range is 6 m and suspended-sediment concentrations vary from 50 to 1,500 mg/l of fine-grained material (1 to 100 micrometers). Local and transient fishing boats and commercial barges to 15-m long use the harbor. The harbor basin area is 21,500 $m^2$ at a project elevation of +0.6 m mean lower low water (MLLW). The sill elevation is +1.8 m MLLW and basin sidewall slopes are 1:5. Moorage is provided for 140 boats. Sedimentation has averaged almost 2 m/yr since the harbor was constructed in 1961. This requires nearly continuous dredging during the ice-free season.

June through September mean shoaling rates (5,400 $m^3$/mo) are almost twice the mean October through May rate of 3,100 $m^3$/mo (Fig. 3). Sediment infilling is nearly uniform throughout the basin when the basin bottom is below the elevation of the sill. An exception is a small region near the sill that is scoured during the lower stages of a flood-tide. The channel has been stable in plan view and cross section since slightly after construction.

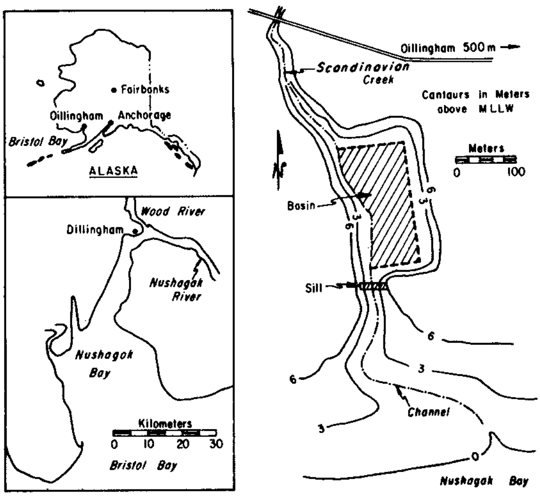


Figure 2. Location map of Dillingham Harbor, Alaska (Everts, 1976a). Discharge from Scandinavian Creek is negligible.

All sediment is transported into the harbor in suspension. At the sill, suspended concentrations are greatest as the rising tide initially passes over the sill (Fig. 4). More than 50 percent of the suspended material brought into Dillingham Harbor enters during the first hour of the 3-hour-long floodtide cycle in the basin. The concentration at any given time is nearly uniform from the sill to the water surface. At any specific time the concentration is also nearly uniform throughout the basin at the water surface (samples within the water column in the basin were not taken). The bulk density of deposited material in the basin is about 1.5 gm/cm$^3$.

Water velocities over the sill in the basin at any specific time are generally uniform from the water surface to the elevation of the sill. In the basin, the region below sill elevation appears to be near stagnant and a particle which settles below that elevation is not removed on an ebbtide. Velocities above sill elevation are low enough in most of the basin that resuspension after deposition on the sidewalls does not occur. The basin appears to be turbulance-free and movements of fluid into and out of it are directed in line with the nagivation channel.

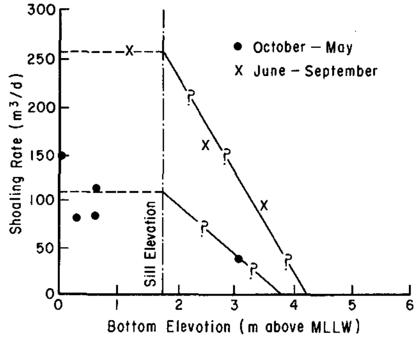


Figure 3. Shoaling rate in Dillingham Harbor, Alaska, as a function of bottom elevation in the basin (Everts, 1976a). Note the decrease in the shoaling rate as the bottom shoals above the sill elevation. This occurs because as the bottom elevation rises, less water and suspended sediment are carried into the harbor basin each floodtide, and consequently less sediment is deposited.

Sedimentation Tank.

A sedimentation tank was developed as an in situ instrument to obtain the shoaling rate as would be expected in an enclosed harbor (Everts, 1975). It was a hollow, upright cylinder fabricated of 5-mm steel, 9.1 m high and 3.7 m in diameter (Fig. 5). A narrow, vertical slot, 3 cm wide, 1.2 m long and of height sufficient to extend from the sediment-water interface to above the mean higher high water (MHHW) surface, was used to simulate the entrance channel. The tank was set in an excavated hole near the site of a proposed harbor in a tidal flat bordering Knik Arm, near Anchorage. The shoaling rate was obtained by monitoring the buildup of sediment within the tank during summer months of 1971 and 1972 (Fig. 6).

An important aspect of the study was to evaluate the tank. In most respects, depositional conditions within the tank were found to be similar to those at Dillingham Harbor. The study indicated the design could be modified to reduce fabrication, placement, and removal costs. The tank can not be scaled in its vertical dimension. However, it can be any plan shape or size, and a smaller plan area would serve the design purpose. Below the entrance slot the tank depth must be great enough to accommodate sedimentation expected during each field test. A critical aspect of the design is to provide an entrance which permits free exchange of water to or from the tank when the water surface rises or falls, but which inhibits in-tank circulation. The slot design (Fig. 5) worked well where waves were <0.6 m. In areas of higher waves the slot might be oriented away from the prevailing wave direction. The orientation, however, should be normal to the direction of the tidal current to inhibit direct current access. The slot simulated a harbor entrance channel, but did not account for channel deposition and resuspension that could affect the amount of material that would be expected to enter a half-tide harbor. The result could be an underprediction of the actual shoaling rate if the proposed harbor is to have a navigation channel.

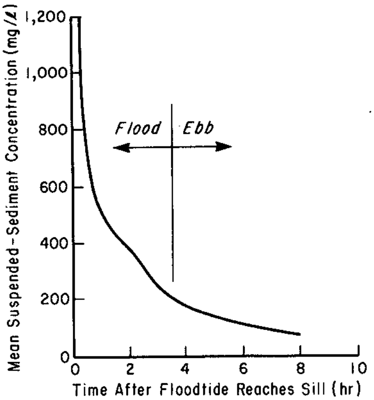


Figure 4. Suspended-sediment concentrations at the Dillingham Harbor, Alaska, sill over a harbor basin tidal cycle (Everts, 1976a). Concentrations are averaged through the water column and are based on sampling at the sill over five tidal cycles. Note the rapid decrease in concentration from the time the water level reached the sill until the time of high water.

Sedimentation Model.

Everts (1980) developed a model, posed in the Lagrangian representation, to simulate sediment shoaling. A mass of suspended particles is followed from the time and elevation at which it enters the basin in suspension until it is deposited or possibly removed from the basin during the outflow phase. The one-dimensional formulation has the essentials of the problem because the depositional process is assumed to be nearly uniform throughout the basin. The dependent variable is the mass of deposited sediment. Independent variables are the elevation and time - dependent mass of sediment discharged to the basin, the settling velocity distribution of that mass, and the harbor geometry. Data from the sedimentation tank and Dillingham Harbor were used to evaluate the model. In both cases the model results were between 10 and 12 percent less than the measured shoaling rate. Because of field sampling difficulties it is difficult to determine whether the errors are a result of an inadequacy in the model or are caused by sampling errors or omissions.

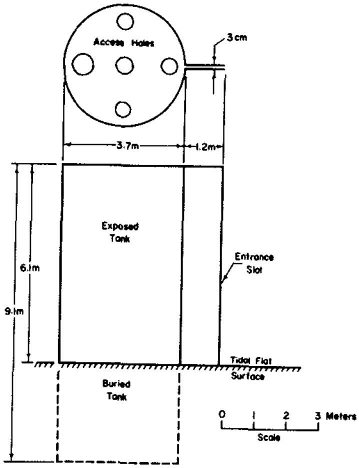


Figure 5. Side and plan view of sedimentation tank which was placed at half-tide elevation in a 500-m-wide tidal flat adjacent to Knik Arm near Anchorage, Alaska (from Everts, 1975). The median tidal range is 8.7 m. The entrance slot was oriented away from shore and normal to floodtide and ebb-tide currents.

The shoaling rate may be obtained in three steps: (1) Predict the total mass of sediment that will enter the harbor, (2) predict the part of that mass that will be deposited, and (3) predict the shoaling rate (bottom elevation increase).

(a) Step 1. During a rising tide the mass of sediment carried into a harbor is a function of the time-dependent concentration of entering suspended sediment, $c(t)$ time rate of water surface elevation, $\frac{dh}{dt}$ and the elevation-dependent plan area of the harbor basin at the water surface which is a function of time in the tidal cycle, $A(t)$. The total sediment mass which enters a harbor during a rising cycle, $M_e$, is

$$M_e = \int_{t_s}^{t_m} c \, A \frac{dh}{dt} \, dt \tag{1}$$

in which $t_s$ = time floodtide reaches elevation of sill, and $t_m$ = time floodtide reaches maximum elevation.

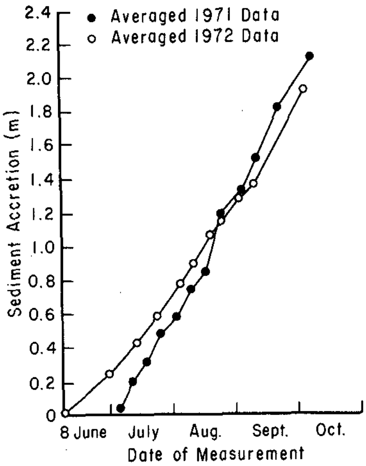


Figure 6. Sediment accretion in sedimentation tank in 1971 and 1972. Values are averages based on six measurement locations in tank. Note near-constant accretion throughout the summer and the 20 percent larger accretion rate in 1971.

(b) Step 2. That part of $M_e$ deposited in the harbor is primarily dependent upon the settling characteristics of the sediment, the distance the sediment has to settle to be deposited, the time during which the suspended material settles, and the sill elevation. Figure 7 shows the part of the suspended material, P, that will be deposited as a function of tidal range and particle size. For diurnal and semidiurnal tides, the settling characteristics of disaggregated material less than 1 micrometer in diameter are such that little will be deposited in the harbor. Most particles larger than 32 micrometers will be deposited. Figure 7 is based on the mathematical model discussed by Everts (1980). Because all natural sustems contain a range of sediment sizes, it is necessary to obtain $M_e$ and P for each size grouping, then sum the individual masses to obtain the total deposited mass, M. In intergral form this is

$$M = \int_{d_s=0}^{d_s=\infty} M_e P \, dd_s \qquad (2)$$

in which $d_s$= suspended-sediment particle size. Figure 8, obtained using the model, shows the mass of sediment deposited per tidal cycle when sill elevation, tidal amplitude, and particle size (fall velocity) are varied at the Anchorage sedimentation tank site.

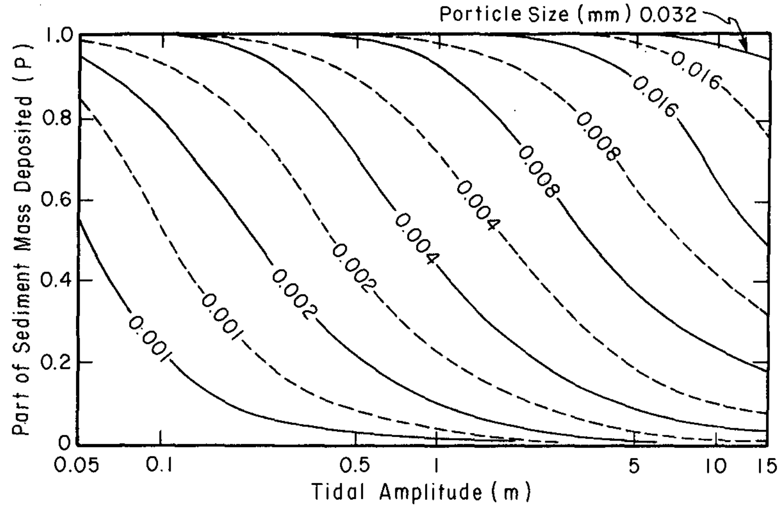


Figure 7. Part of sediment mass entering harbor basin which is deposited as a function of sediment particle size (based on sphere fall velocity in freshwater at 20°C) and tidal amplitude (from Everts, 1980). Solid lines are for a 12.4-hr. tidal period; dash lines are for a 24.8-hr. tidal period. Sill elevation is zero.

Sill elevation is not considered in Figure 7. At most, the increase in P will be 10 percent when the sill is at an elevation $A_0/2$ (half-tide elevation) and P = 0.7, where $A_0$= tidal amplitude. When sill elevation = $A_0/4$ and P = 0.7 the increase is only 5 percent. In using Figure 7, the concentration of suspended sediment entering the harbor is not assumed to vary with time. If concentrations are highest early in the tide cycle, P will be larger than shown in Fig. 7. Suspended-sediment fall characteristics are assumed to be constant through time.

Particle aggregation may be an important factor in increasing the settling velocity of suspended material, especially in a saline estuary environment. In south-central Alaska, clay minerals constitute less than 2 percent of the total suspended-sediment load. Even there, however aggregation plays an important role which must be considered in harbor sedimentation (Fig. 9). Unless the settling velocities are obtained in the fluid in which they are collected (versus distilled water used in some laboratory analyses) large errors in predicted sedimentation rates may result.

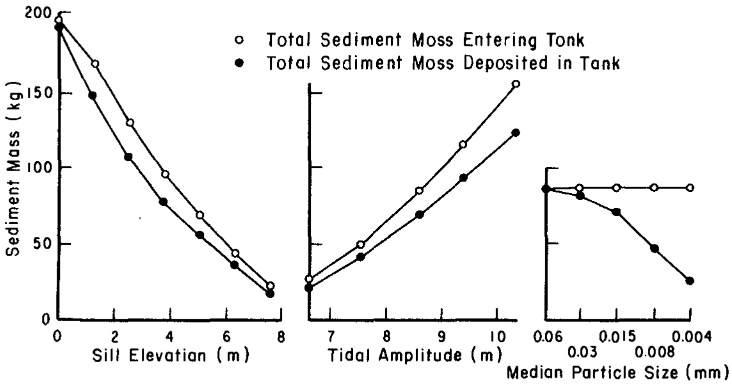


Figure 8. Sensitivity analysis of equations (1) and (2) using a mathematical model to predict sedimentation in a half-tide harbor (Everts, 1980). The model test basin was the sedimentation tank located in Knik Arm, Alaska. Predicted sediment mass entering and deposited in the tank is based on actual average values of all parameters except that shown.

The part of the sediment which enters the harbor and is subsequently deposited will probably be near constant from one tidal cycle to another, even though the total quantity which enters may vary widely (Everts and Moore, 1976; Everts, 1976a). Everts (1976a), for example, reported that the quantity carried into the basin at Dillingham Harbor varied by a factor of three between tidal cycles, but that the part deposited was near constant at 81 percent (range: 76 to 84.2 percent for five tidal cycles). Thus, to accurately predict $M_e$, a number of tidal cycles must be sampled to obtain representative concentration values.

(c) Step 3. If it is desirable to predict the rate of bottom elevation rise caused by sediment deposition, sediment mass deposited must be converted to sediment volume deposited. The part of a unit volume of deposited material with a density, $\rho_d$, which is composed of sediment of density, $\rho_s$, is $V_s$, given as

$$V_s = \frac{\rho_d - \rho_f}{\rho_s - \rho_f} \tag{3}$$

in which $0 \leq V_s \leq 1.0$, $\rho_f$ = water density. Then the mass of sediment per unit volume of deposited material, $m_v$, is

$$m_v = \rho_s V_s \tag{4}$$

and the shoaling rate (per tidal cycle), $S_r$, in the basin is

$$S_r = \frac{M}{F m_v} \tag{5}$$

in which f = plan view area of the basin bottom.

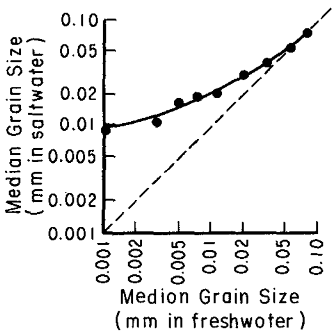


Figure 9. Comparison of median grain size, based on fall velocity, for duplicate samples of glacier-source sediment from Knik Arm using the hydrometer method with distilled water and with Knik Arm water (from Everts, 1976b). Sediment with a median grain size less than 0.075 mm settled at a faster rate in saltwater even though the clay mineral percentage was less than 2 percent.

## HARBOR DESIGN TO REDUCE SEDIMENTATION

In the course of the study, a number of possible means to reduce the shoaling rate became apparent. These are summarized in the following sections.

Harbor Siting.

If a number of harbor sites are considered, the site where sediment concentrations are lowest and sediment sizes are smallest, all other conditions being equal, will experience the lowest sedimentation rate (see eq. 1 and Fig. 7). The size and concentration of sediments suspended in the water column may vary throughout an estuary and this may be a consideration in where a harbor is sited. Temporal variations in size and concentration may also be a factor. For example, a decision to close a harbor during certain nonuse times of the year may hinge on the predicted sedimentation rate during the closure period versus that of the remainder of the year.

In estuaries such as Knik Arm, most of the suspended sediment is contributed by glacier-fed rivers. High concentrations in the estuary are clearly related to the summer influx of river-borne sediments, although a phase lag appears in the estuary where autumn concentrations remain high (Fig. 10). Everts (1976b) found suspended-sediment concentration to be related to water discharge for the two largest contributors (knik and Matanuska Rivers), but size was a function of water discharge only in the Knik River. A single year's water and sediment discharge record is not enough to predict average yearly suspended-sediment concentrations in a river-dominated estuary because yearly variations of 50 percent about the yearly mean may be expected. In addition, sediment discharge cannot be extrapolated from one river basin to another in glacial areas, even where the basins are adjacent. In south-central Alaska, river sampling during the 3 summer months (June, July, and August) is sufficient to determine the total yearly sediment load within 10 to 15 percent.

Floods may move a significant quantity of suspended material. In off-river harbors and harbors located near river mouths, the impact of flood discharge must be considered. A 2- to 5- day flood may discharge more than 50 percent of the yearly sediment contributed by a river. Sediment sizes carried by floodflows are considerably larger than the size carried during normal flow times.

Off-River Harbor Sites.

Siting a harbor beside or adjacent to a clearwater river may substantially reduce the sedimentation problem caused by fine-grained material. The reduction results because sediment-laden, landward-moving estuary waters are diluted by seaward-flowing, clear river waters. The decrease in suspended-sediment concentration, and in the predicted shoaling rate (eq. 5) can be obtained using data from a sediment sampling program during the time of floodtide incursion near the proposed enclosed harbor site. Temporal variations in river-borne sediment concentration and size must be considered.

Potential problems exist in using an off-river harbor. Caution is advised to ensure that deposition of river-carried bedload sediments, and the river sediment load during flood times, will not mitigate the savings.

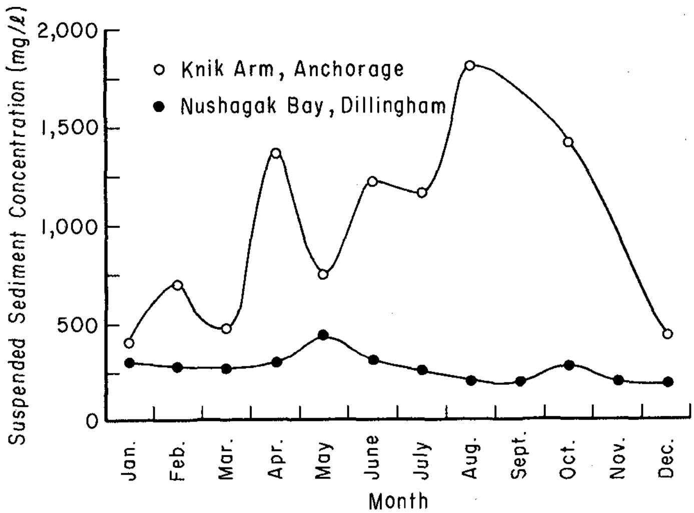


Figure 10. Average suspended-sediment concentrations in Knik Arm, an estuary in which much of the suspended material enters directly from glacier-fed rivers; and Nushagak Bay, an estuary where the material is continuously resuspended from the estuary bottom.

Channel Length.

Suspended sediment enters an enclosed harbor from two sources. The primary source is the adjacent estuary. An important secondary source may be the navigation channel between the harbor basin and estuary. At Dillingham Harbor, for example, current velocities in the channel are low when the tidal elevation is below the sill; consequently, suspended material settles in the channel during these times. As the next floodtide rises over the sill, channel currents increase rapidly to accommodate the increased water discharge required to fill the basin. At that time, when the submerged channel cross-sectional area is smallest, the velocities are greatest and material previously deposited in the channel is resuspended. The amount of sediment entering Dillingham Harbor from the channel source is 40 percent of the total amount brought in.

Economies can be achieved when an entrance channel is designed to reduce the accumulation of channel sediment. Usually, this will require that the channel length be designed as short as possible.

Sill Design.

Sedimentation within a harbor may be reduced if the mass of sediment carried in each floodtide is reduced. One way to effect this is by placing a permanent sill in the entrance channel at an elevation above the harbor basin bottom and MLLW (Fig. 8). This reduces the tidal prism.

The design consideration, therefore, becomes one in which initial harbor cost plus future maintenance expense is balanced against the percent of time navigation is restricted into and out of the basin.

The period of restricted navigation can be easily calculated using the tidal hydrograph and sill elevation based on a consistent datum, and the draft and clearance required of the vessels using the basin. The mass of sediment carried into the harbor versus sill elevation can then be established (eq. 1).

Changes in suspended-sediment concentration with time differ greatly from one location to another. Everts and Moore (1976) measured an increasing concentration toward high water at the sedimentation tank site in Knik Arm, while Everts (1976a) found the concentration to decrease through the tide cycle in the estuary at Dillingham Harbor. Concentrations in Knik Arm seemed to be related to current speed and direction; the highest concentrations were measured on an ebbtide, i.e., sediment was moving away from a major riverine source. At Dillingham the concentration is greatest near midtide in Nushagak Bay where the fine-grained sediment source is the bay bottom and tidal flats. The channel resuspension mechanism greatly increases the early high concentrations.

Basin Closure.

When harbor use is seasonal, a channel closure structure may be warranted during nonuse periods. The cost-effectiveness of the structure and its emplacement and removal is determined by calculating the sediment volume that would be deposited during the nonuse period and the attendant maintenance cost for its removal.

Ice and winter conditions restrict the use of many harbors in Alaska to 6 months or less. Summer sedimentation rates do not prevail during ice-cover conditions. The submerged ice volume reduces the discharge volume of water and suspended sediment to the basin. That reduction can be estimated. A reduction in the amount of water and suspended sediment in an ice-covered channel will reduce the sediment mass inflow from that source. The mass of sediment which enters a harbor may also vary seasonally, especially where river discharge is an important source, as it is in Knik Arm. Wide seasonal variations, however, are not always the case. In Nushagak Bay the average monthly concentration of suspended sediment is near constant year round (Fig. 10). Sediment in Nushagak Bay comes from the suspension and resuspension of bottom sediment, not river discharge.

Because sediment size, water viscosity, and particle aggregation affect the settling velocity of suspended material in the basin, these factors must be considered on at least a seasonal basis. At Dillingham, median particle size varied from 0.014 mm in the summer to 0.005 mm in winter. Temperature affects water viscosity, and hence the fall velocity of the sediment particles. For example, at $0^{\circ}C$ winter water temperature, the fall velocity of a particle 0.008 mm in diameter is about 70 percent the velocity it would be at $10^{\circ}C$. This must be considered. The effect of salt on the settling rate of clay minerals becomes distinguishable at seawater concentrations of about 1 to 2 parts per thousand (ppt).

Aggregation and hence the settling rate of the aggregated mass increase to seawater concentrations of 10 to 15 ppt. Suspended sediment in water samples with salt content of 0.5 ppt at Dillingham during the summer did not appear to aggregate. However, when the winter salinities reached 3 ppt, aggregation might have occurred.

At Dillingham, the winter shoaling rate (about 50 percent of the summer rate) was correctly estimated using these considerations. The major effects were decreased water and sediment discharge to the harbor because of the ice volume within the basin, and the reduction in sediment resuspended in the channel for which the ice cover was also responsible.

## SUMMARY

This paper results from a 9-year study of enclosed harbors in Alaska. Two methods to predict harbor sedimentation rates prior to construction are presented and a number of design considerations to reduce sedimentation are suggested.

## ACKNOWLEDGEMENTS

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## NOTATION

$P$ = deposited part of total suspended mass carried into harbor basin on floodtide

$c$ = suspended-sediment concentration

$h$ = water surface elevation

$A$ = plan area of harbor basin at water surface

$M_e$ = total sediment mass carried into harbor basin on floodtide

$t_s$ = time after low water that floodtide reaches sill elevation

$t_m$ = time after low water that floodtide reaches maximum elevation

$d_s$ = suspended-sediment particle size

$M$ = total mass deposited in harbor

$A_o$ = tidal amplitude

$V_s$ = sediment part of unit volume of deposited material

$\rho_d$ = density of deposited material

$\rho_s$ = sediment particle density

$\rho_f$ = water density

$m_v$ = mass of sediment per unit volume of deposited material

$S_r$ = harbor shoaling rate per tidal cycle

F = plan area of harbor at basin bottom elevation

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