HYDRAULIC CIRCULATION PERFORMANCE OF A CURVILINEAR MARINA

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INTRODUCTION

An innovative coastal engineering concept has been developed to maximize the hydraulic circulation and water quality of dredged backshore harbors and boat basins. The concept represents a radical departure from the hydraulic design of existing artificial boat basins in that the basin geometry and entrance channel are primarily sized for hydraulic purposes rather than navigational access. Specific elements of the concept are described below.

CONCEPT

Past design practice of backshore-dredged harbors, basins, and marinas has concentrated primarily on optimizing the dredged geometry to develop maximum maneuvering space and moorage area. Typically, little or no thought was given to water circulation and water quality within the artificial harbor. However, recent environmental studies have shown that rectangular dredged basins can have limited water circulation and flushing, resulting in the formation of stagnant zones throughout the harbor (Nece and Kroll, 1974, and Nece et al., 1976). Limited water circulation, in turn, can result in poor water quality levels in the harbor. Typically, water temperatures rise and dissolved oxygen levels decrease in basins with poor circulation. These changes can have profound effects on the flora and fauna inhabiting the harbor.

To overcome the above problems associated with limited hydraulic circulation, a new design concept was developed by the author in conjunction with Professors E. P. Richey and R. E. Nece of the University of Washington, Seattle.

The concept revolves around the use of a properly sized offset entrance coupled with a rounded basin shape. The curvilinear geometry allows "new" water entering the marina to move freely around the entire basin perimeter and mix with "old" basin water without forming isolated dead spots. Similarly, during ebb tide, the basin's shape minimizes restrictions to the potential flow field, eliminating stagnant zones. Specific elements of the concept are as follows:

- Conventional rectangular geometry of backshore-dredged basins is replaced with curvilinear

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geometry. Rounded corners of the basin reduce sideslope friction and eliminate stagnant zones common to sharp-edged rectangular corners.

- The rounded basin geometry is coupled with a single narrow entrance channel. This channel is hydraulically designed to produce a flooding tidal jet that possesses sufficient momentum to create large-scale rotating vortex systems within the curvilinear basin.

Through the above process a strong tidally driven basin circulation current system can be created. This current system is capable of maintaining water quality levels within enclosed harbors at near-ambient open water levels. Physical hydraulic model testing and post-construction prototype monitoring have verified the concept (discussed below).

THEORY

Figure 1 illustrates a plan view of a typical small-craft harbor. The principal elements of the harbor's geometry consist of a wide entrance channel coupled to a large square or rectangular moorage basin. The efficiency at which the interior "old" basin water mixes with "new" incoming offshore water is directly affected by the velocity of the flooding tidal jet as it flows through the harbor entrance. For weak entrance channel currents, which are characteristic of wide channels, the flooding tidal jet may not possess sufficient momentum to allow the incoming water to penetrate to the farthest reaches of the basin. This can result in the formation of hydraulically stagnant zones in the harbor. For harbors with linear geometry, the stagnant zones commonly form in corner areas. This poor mixing action of tidal water can result in degradation of water quality as previously described.

To improve the circulation and mixing action of a harbor, two basic approaches are available:

1. Induce artificial circulation in stagnant zones with mechanical devices such as pumps or ducted propellers (Dunham, and Finn, 1974).
2. Redesign the geometry of the harbor basin and entrance channel to allow natural tidal action to improve hydraulic circulation and mixing.

The first method described above is a remedial solution. Reliance on mechanical devices (and the human personnel required to operate them) to work continually in a marine environment is questionable at best. Typically, mechanical systems corrode, become biofouled, and experience general electrical and mechanical problems such that they cannot be relied upon 100 percent. As an example, if a mechanical system used to induce circulation in a harbor fails at a critical period, such as during a prolonged hot spell in the summer season, solar heating of the stagnant basin water

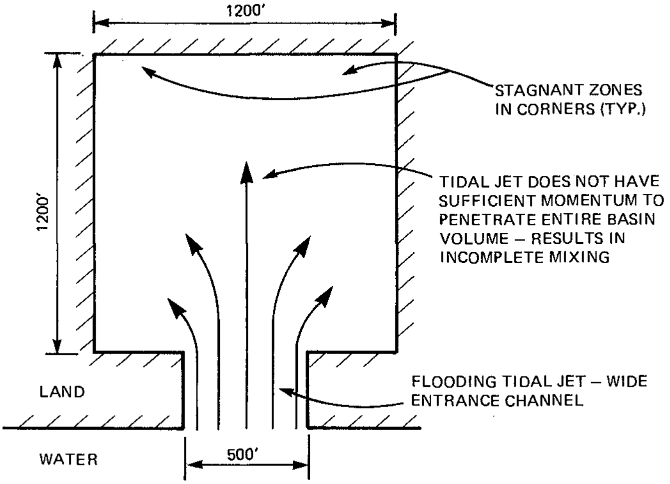

FIGURE 1
CONVENTIONAL RECTANGULAR BASIN

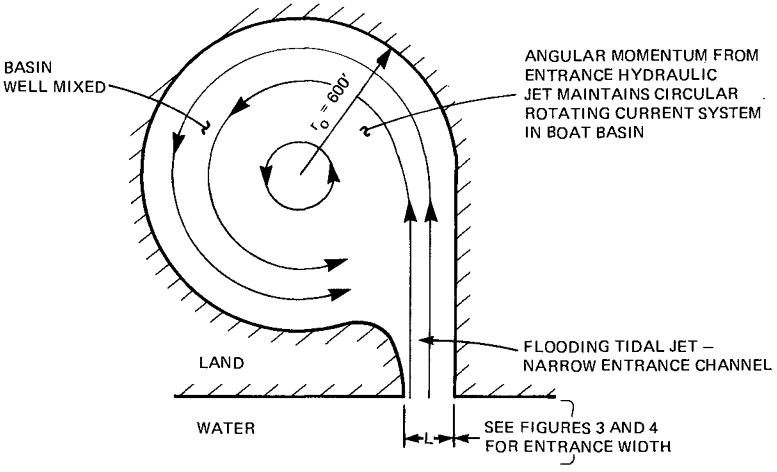

FIGURE 2
CURVILINEAR BASIN

could increase ambient temperatures to levels that are lethal to resident and migratory fish populations.

Because of poor reliability of mechanical systems, most governmental agencies responsible for issuing permits related to marine water quality are extremely reluctant to approve artificial circulation devices. The agencies prefer natural systems that do not require constant monitoring and maintenance. Thus, the use of artificial circulation systems in harbors to maintain water quality is generally not an acceptable solution.

As an alternative to mechanical systems, harbor geometry can be modified to allow nature, through the action of the tides, to produce sufficient hydraulic circulation to eliminate or minimize potential water quality problems. Such a modification of a conventional harbor is shown in Figure 2. The linear geometry of the square basin of Figure 1 has been replaced with curvilinear geometry to eliminate sharp corner areas. In addition, the entrance channel has been reduced in size and offset along one side of the basin. These simple changes in geometry result in the formation of a strong flooding tidal jet that now possesses sufficient angular momentum to carry new incoming offshore water throughout the entire volume of the basin. This naturally induced momentum results in excellent internal circulation and mixing witin the harbor. To illustrate the angular momentum concept, an example problem is provided below.

DESIGN EXAMPLE

It is desired to dredge a small-boat harbor and entrance channel in a low-lying area landward of an existing shoreline (see Figure 2). To be economically justifiable, the basin must have sufficient area for 1,000 moorage berths, and the entrance channel should be wide enough to safely allow two-way boat traffic. Also, property boundary constraints require the entrance to be positioned to the right side of the basin. Environmental restrictions placed on the site to protect migrating salmon fry limit increases in basin water temperature to no more than 1-1/2 degrees C above ambient offshore waters. Also, the use of artificial circulation devices is prohibited. The mean tide range is 6 feet, and the mean tide level is 6 feet above mean lower low water (MLLW = 0). Size the basin and entrance channel to meet the above conditions.

Basin Size

Through the use of standard marina berth layout parameters (Dunham and Finn, 1974) and the use of a curvilinear boat basin geometry (Figure 2), it is determined that a circular basin with a radius of 600 feet will provide sufficient space for 1,000 small craft. Similarly, calculations of solar-heated basin water mixing with ambient offshore water over a tidal cycle show that basin temperatures will not exceed the 1-1/2 degrees C increase limit if the boat basin is well mixed. A complete rotation of the entire basin's water mass over the flooding cycle is calculated to provide the necessary mixing. The problem now becomes to size the entrance channel such that the flooding tidal jet will produce the desired rotation of the basin water.

Entrance Channel Size

To size the entrance channel, consider the water within the circular basin of Figure 2 as a cylinder. Allow this water body to be given sufficient angular momentum to move with "solid-body" rotation, overcoming frictional resistance of the basin's bottom and sides. From the discussion above, assume that one complete revolution of the water body during a flooding tide period (approximately 6 hours) is sufficient to induce the necessary circulation. To produce this rotation, the entrance channel must be sized to transmit sufficient tidal jet momentum to the basin waters. The following describes procedures to calculate the required tidal jet energy.

Treat the basin as a cylindrical body with a 600-foot radius. Assume a uniform friction coefficient of 0.005 for all boundaries (Nece and Richey, 1975). The problem now becomes one of estimating the required torque of the solid-body water mass to overcome the bottom and sidewall frictional resistance of the basin. To calculate the resisting frictional torque exerted on the rotating water mass by the bottom, Nece and Richey (1975) suggest the following:

$$T_b = \int_0^{r_o} c_f \frac{\rho}{2} (\omega r)^2 \, 2\pi \, r r d_r \tag{1}$$

$$= c_f \frac{\rho}{2} \omega^2 \, 2\pi \, \frac{r_o^5}{5} \tag{2}$$

where T_b = bottom torque (ft-lb)

c_f = friction coefficient = 0.005

ρ = mass density (2 slugs/ft^3 for seawater)

ω = angular velocity for one rotation of boat basin water duing one-half tidal cycle

$$= \frac{2\pi}{(6.2)(3600)} \quad \frac{\text{radians}}{\text{sec}}$$

r_o = radius of basin = 600 feet

For the example problem a friction bottom torque of 38,600 foot-pounds is calculated.

For the sidewall torque, Nece and Richey (1975) suggest treating the basin perimeter as a cylindrical surface of revolution. The resulting peripheral torque is calculated as follows:

$$T_p = c_f \frac{\rho}{2} (\omega r_o)^2 \; 2\pi \; r_o h r_o \qquad (3)$$

where T_p = peripheral torque (ft-lb)

h = water depth corresponding to distance from mean tidal level to basin bottom. (For example, basin dredged to -10 with mean tide of 6 feet, h = 16 feet)

For the example problem a peripheral torque of 5,150 foot-pounds is calculated.

Combining the bottom and peripheral torque results in a net torque to be overcome by the entrance jet of approximately 43,750 foot-pounds. Startup, or inertial, effects have been neglected and are considered minor because of long tidal periods. Also, the current deflecting effects of the Coriolis force have been neglected because of the overriding influence of basin geometry on current direction. (It should be noted, however, that, if harbor geometry allows placement of the entrance channel on either side of the basin, it is preferable to place the entrance on the left side in the Northern Hemisphere. This will allow the Coriolis force to help augment the resulting clockwise circulation. For the Southern Hemisphere, a right-hand entrance is preferred.)

Assuming that all of the torque to overcome the net frictional torque of 43,750 foot-pounds is provided by an entrance channel hydraulic jet offset a distance of r_o to the side of the boat basin, the required entrance momentum can be calculated as follows:

$$Q\rho V r_o = T_b + T_p \qquad (4)$$

where the entrance channel provides a volumetric flow rate of Q (ft^3/sec) with a jet velocity of V(ft/sec).

For the example problem, a momentum flow of QV = 36.5 is required. To determine both Q and V, the following procedure is used:

$$\text{Average } Q = \frac{\text{basin tidal prism volume for mean tide level}}{\text{half-tidal cycle time period}} \qquad (5)$$

$$= \frac{(6.0)(\pi)(600)^2}{(6.2)(3600)}$$

$$= 304 \text{ cubic feet per second}$$

The required average velocity of the entrance jet can then be calculated as follows:

$$V = \frac{36.5}{Q} = \frac{36.5}{304} = 0.12 \text{ foot per second} \qquad (6)$$

Thus, the entrance channel must be designed to provide an average flooding entrance channel velocity of 0.12 foot per second. It should be noted that the actual entrance channel velocity will vary as a function of time and tidal height such that peak velocities are two to four times higher than the average velocity and minimum velocities approach zero. However, the average velocity of 0.12 foot per second represents the same net momentum input to the basin when peak and minimum velocities are combined.

To estimate the required cross-sectional area of the channel, the continuity equation is employed:

$$Q = VA \tag{7}$$

where V = average tidal velocity (feet per second)
A = average area of entrance channell (square feet)

$$\text{Therefore, } A = \frac{Q}{V} = \frac{304}{0.12} = 2{,}500 \text{ square feet}$$

Thus, for the example problem, the entrance channel must have a cross-sectional area less than or equal to about 2,500 square feet.

Figures 3 and 4 illustrate two entrance channel configurations that are sized to produce an average tidal jet velocity of 0.12 foot per second. Both channel types are sufficiently wide to allow two-way vessel traffic into and out of the harbor.

Factor of Safety

To account for possible inaccuracies in the procedures described above (e.g., selection of friction coefficient, neglecting inertial forces), it is recommended that for design purposes the calculated minimum entrance channel velocity be increased by at least a factor of 1.35. This results in a reduction of the required entrance channel area by about 25 percent.

HYDRODYNAMIC ASYMMETRY

Angular momentum within a harbor basin will persist for sometime after flooding stops and ebbing tide begins. This sets up a flow condition where rotating basin eddies encounter the potential flow regime of the ebbing tide. Thus, two different flow conditions occur at the same instance, producing hydrodynamic asymmetry. This is advantageous because it helps to further increase mixing action within the basin.

PROTOTYPE EXAMPLE

The concept described above was developed as a result of the design of a large marina located in northern Puget Sound at Point Roberts, Washington. Analytical studies, field measurements, and physical modeling efforts were all utilized in the hydraulic design of the marina's basin and entrance channel. Calculations presented in the example problem were based, in part, on the design of the marina. A brief description of the marina is provided below.

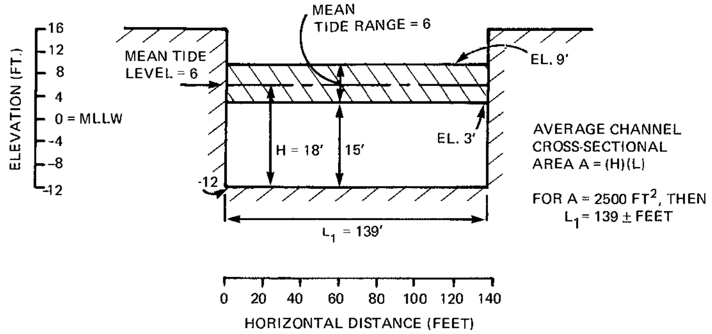

FIGURE 3
RECTANGULAR
ENTRANCE CHANNEL

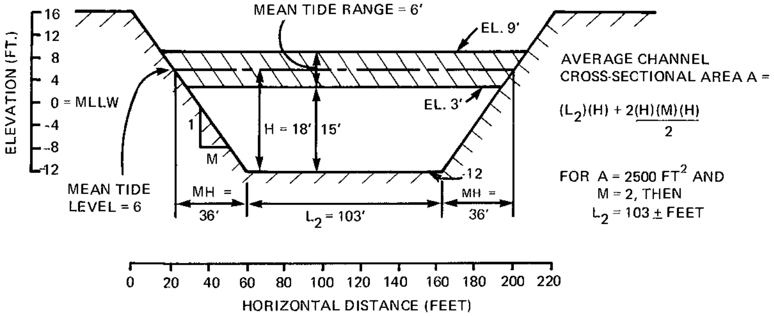

FIGURE 4
TRAPEZOIDAL
ENTRANCE CHANNEL

Point Roberts Marina

The 1,000-berth Point Roberts Marina is one of the largest privately owned coastal engineering developments on the Pacific coast of the United States. Construction of the marine portions of the $6 million marina began in November 1976 and were completed in August 1978. The marina is located on the south shore of Point Roberts, a small peninsula politically part of the State of Washington, USA, but physically connected to British Columbia, Canada. The marina site encompasses approximately 140 acres and includes nearly 8,000 linear feet of marine shoreline (Layton, 1979).

Figures 5 and 6 present aerial views of the completed marina showing the relationship of the entrance channel to the backshore curvilinear boat basin. This configuration was found to maximize hydraulic circulation within the marina's 40-acre boat basin, which in turn resulted in acceptable water quality levels. Construction of this marina represents the first application of the above-described concept and is representative of the state of the art in marina and harbor basin hydraulic design.

Hydraulic Model Study

Prior to construction of Point Roberts Marina, a hydraulic model of the proposed marina was constructed and a series of tracer dye tests conducted to predict the circulation performance (CH2M HILL, 1976, and Nece, 1976). Results showed that the marina would have excellent internal hydraulic circulation. A large counterclockwise rotating vortex system was found to occur in the boat basin during all ranges of flood tides. No stagnant zones were observed and the basin was found to be well mixed. Figures 7 and 8 illustrate typical circulation patterns of the boat basin and offshore waters during ebb and flood tide conditions.

Prototype Studies

After contruction of the marina, several hydraulic and water quality studies have been conducted to determine the overall performance of the design concept. Figure 9 illustrates the results of one test where a drogue was used to trace the path of water mass movement in the basin during a typical flood tide. Of importance to note is that the drogue traveled from the entrance channel over 2,000 feet to the head of the boat basin. This verified the hydraulic model tests and demonstrated that the concept of curvilinear boat basin geometry coupled with a hydraulically designed entrance channel is effective in producing strong internal circulation.

Remote aerial sensing studies conducted by the U.S. Environmental Protection Agency in June 1978 also showed that the Point Roberts Marina basin has excellent thermal mixing. Comparison of thermal imagery of other conventional rectangular marina basins in Puget Sound clearly illustrated the superior mixing action of the curvilinear basin.

FIGURE 5
OBLIQUE AERIAL VIEW
OF POINT ROBERTS MARINA

FIGURE 6
PLAN VIEW OF POINT ROBERTS MARINA

FIGURE 7A
MOVEMENT OF DYE FROM ENTRANCE
CHANNEL TO BASIN DURING FLOOD TIDE

FIGURE 7B
DISTRIBUTION OF DYE IN BOAT
BASIN AT END OF FLOOD TIDE

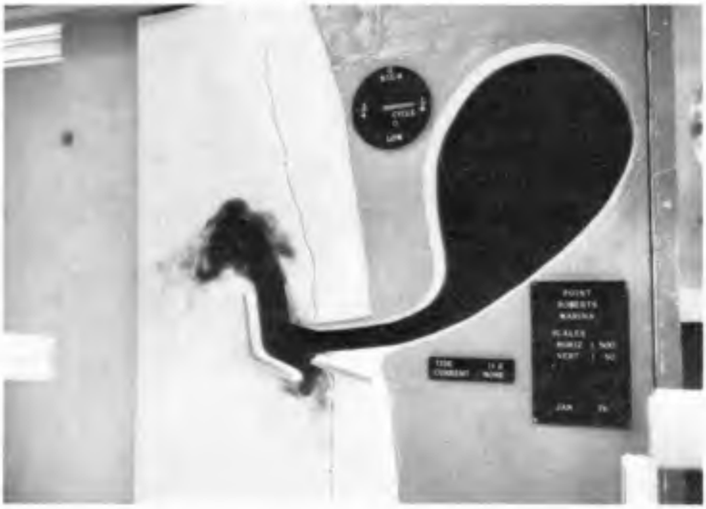

FIGURE 8A
DISCHARGE OF DYE FROM MARINA
DURING EBB FLOW (NO LONGSHORE CURRENT)

FIGURE 8B
DISTRIBUTION OF DYE AT END
OF EBB TIDE (NO LONGSHORE CURRENT)

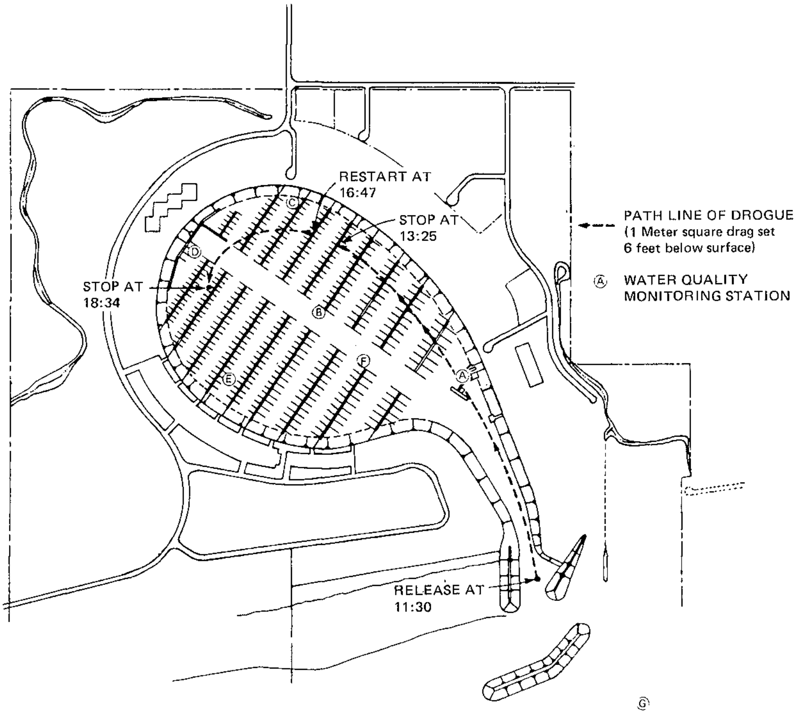

FIGURE 9
TYPICAL PATHLINE OF DROGUE RELEASE
ON OCTOBER 13, 1978

In addition to the above prototype studies, a water quality monitoring program was conducted at the marina during 1978. Table 1 presents a typical set of water temperature measurements recorded in the constructed boat basin. The results indicate that the interior of the boat basin has a fairly uniform temperature distribution with basically very little variation from ambient water temperature conditions in the Strait of Georgia.

Table 1
WATER TEMPERATURE MEASUREMENTS IN
POINT ROBERTS MARINA, October 12, 1978

Station*	Time	Depth (meters)					
		0	1	2	3	4	5
		Temperature °C					
A	1540	12.5	12.2	11.8	11.6	11.5	11.5
B	1600	12.4	12.1	11.8	11.5	11.2	11.2
C	1703	12.4	12.0	11.7	11.5	11.4	11.3
D	1728	11.9	11.8	11.6	11.4	11.4	11.3
E	1752	12.2	12.0	11.6	11.5	11.4	11.4
F	1815	12.1	12.0	11.6	11.4	11.2	11.2
G	1403	12.2	12.2	12.0	11.8	11.7	11.5

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* See Figure 9 for station locations.

CONCLUSIONS

A new concept in the design of dredged backshore basins for maximizing hydraulic circulation and water quality has been described. The concept employs the use of curvilinear basin geometry coupled with a single offset entrance channel. This combination produces a flooding tidal jet that can have sufficient momentum to penetrate all portions of the basin, producing a well-mixed, stagnant-free water mass. The concept was employed in the design of a large marina, and subsequent post-construction monitoring has verified the concept.

ACKNOWLEDGEMENT

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