CHAPTER 200

PLANFORM INFLUENCE ON FLUSHING AND CIRCULATION IN SMALL HARBORS

by

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ABSTRACT

Laboratory data showing the influence of planform geometry on the tidal flushing characteristics of small harbors of simple surface shape. The tide ranges, water depths, and planform areas are typical of those encountered in small-boat marinas in Puget Sound, Washington. Each harbor investigated had a single, asymmetric entrance.

Flushing and circulation patterns within such harbors depend strongly upon the characteristics of the angular momentum established within the basin and upon the effective penetration distance into the basin of the stream of ambient water entering the harbor on the flood tide.

Experimental results confirm that best gross tidal flushing occurs when rectangular harbors have an aspect ratio L/B near unity, and that rounding interior corners of the basin has little effect on the gross tidal flushing but does improve local exchange. Aspect ratios L/B less than 3 lead to the creation of more than one circulation cell (gyre) within the basin.

INTRODUCTION

This paper reports on a laboratory study of tide-induced circulation in small, constructed harbors. Effects of wind and waves upon water motions within the harbors are not considered.

The study was keyed to the continuing demand for more small-boat marinas in Puget Sound, Washington. A common construction approach is to dredge the marina basin from a tideflat area, with the dredged material providing fill for parking lots, dry land work and storage areas, etc. A breakwater is provided on the seaward side, usually with a single asymmetric entrance located to provide best wave protection. Surface areas typically range from 10 to 30 acres, with provisions for from 200 to 800 boat moorages. Such marinas can truly be classified as "small" harbors.

Questions related to water quality are of considerable importance in

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the planning and design of such harbors. Of particular concern in the Puget Sound area is the potential impact of water quality in marinas on fish, particularly migrating junenile salmon. Poor tidal flushing can lead to detrimental algal growths and low dissolved oxygen contents, dangerous to the migrating fish. It becomes imperative in the design of new marinas, and in the design evaluation leading to the legal permission to proceed with construction, that both the gross tidal flushing and the local circulation patterns within the proposed basins be considered. The particular concern of the present study is the question of how much the basin planform geometry affects the overall exchange and the internal circulation patterns.

The approach followed has been to utilize physical models. Numerical modeling procedures have been employed to study flow fields in existing small harbors (e.g., Grubert (1)), but in order to predict actual water exchanges a convective-diffusion solution would have to be superimposed on the hydro-dynamic solution. Efficacy of the numerical techniques depends upon a valid determination of the separation streamline of the flood currents around the edges of the harbor entrance and on the time-and-space unsteady circulation cell which is initially engendered by this separation phenomenon, as well as upon the correct representation of diffusion coefficients. For designed but not built basins, the physical model approach has been considered the more economical and graphical approach to a combination of design tool and screen (2).

The laboratory tests described here utilized single-fluid vertically distorted models with a 10:1 distortion ratio. Such models do not properly scale diffusion-dispersion processes (3); therefore, the assumption must be made the convective transport is the dominant mode of water exchange and that diffusion <u>per se</u> is of less significance, allowing the use of tracer dyes in the model. This assumption has been used in a number of specific model studies of tidal exchange in small harbors subject to fairly large tides, where tidal currents are the dominant circulation feature (2). Field verification studies of water exchange are still needed; the models do reproduce depth-averaged velocities in the small harbors (4).

Because the tidal currents are indeed quite strong in the basins modeled it is safe to ignore Coriolis as well as wind and wave effects, and because the basins are relatively short and deep the absence of a friction calibration is not viewed as a major concern. Results are restricted to non-stratified harbors having no fresh water inflow; this is indeed the situation for the well-mixed water bodies which have been investigated so far in the Puget Sound marina studies. These limitations are listed here because they do restrict the generality of the results.

RANGE OF TESTS

The laboratory studies were treated as model studies of idealized basin shapes. The scale ratios were 1:500 horizontal, 1:50 vertical. Tides were restricted to repetive, sinusoidal tides of constant period of 10.52 minutes in the model corresponding, via Froude law scaling relations, to a 12.4-hour semi-diurnal tide. Gross water exchange (flushing) was deterined by measuring changes in the concentration of fluorescent dye Rhodamine-WT in the basin over a number of cycles. Ink dye was used for visual observation of internal circulation patterns. Laboratory techniques and details of the tidal model basin used have been described previously (2,4).

Flushing data are presented in terms of E, the average per-cycle exchange coefficient, defined as that fraction of the water in the basin at high water slack which is removed from the basin and replaced by ambient water during the cycle ending at the next high water slack. The choice of selecting the period from high-water to high-water is arbitrary, but leads to a simple comparison with the tidal prism ratio, defined conventionally as

Tidal Prism Ratio(TPR) = (Basin Vol. at High Tide)-(Basin Vol.at Low Tide) Basin Volume at High Tide

where the numerator is known as the "tidal prism." A "flushing efficiency" is defined as

$$\eta = \frac{E}{TRR} \times 100$$
, percent

and compares measured water exchanges with those predicted by the simple tidal prism theory.

Three planforms--rectangular, rectangular with rounded corners, and circular--were investigated. For simplicity, vertical walls and horizontal basin bottoms were used in all cases. The basin planforms and notation used are shown in Figure 1. Semi-circular "jetties" were used at the entrance in each case.

The basin area was maintained at 1.25×10^6 square feet (28.7 acres). The equivalent L/B = 1.00 basin (which was not tested) has a side length of 1180 feet, or approximately 0.2 mi. The mean depth d within the barbor was 16 feet, taken at mean water level. The three tide ranges used in the tests were: neap, 4 feet; mean, 8 feet; spring, 12 feet. These values are representative of small boat basins in Fuget Sound. The range of L/B in the rectangular basin tests varied from 0.20 to 5.00, more than spanning the usual range of aspect ratios found in such small harbors with single entrances aligned with one side wall. Entrance widths w were 125, 250, and 500 feet; the first is the most representative of field dimensions, and is emphasized most in following results. Data are presented in terms of equivalent prototype dimensions.

TIDAL FLUSHING

Essentials of the flushing (water exchange) test results are summarized in Figure 2 on which are shown data for three entrance widths w, three tides H, for rectangular basins over the aspect ratio L/B range 0.2 to 5.0. No data points are shown on Figure 2; a representative set is shown on Figure 3, illustrating the degree of experimental scatter which can be obtained in the rather sensitive exchange tests.

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A few conclusions are apparent. Over the range of L/B from 2/3 to 3.2 there is relatively little variation in exchange coefficient E for a given tide range H. The overall flushing falls off markedly for L/B less than 1/3 and greater than 3. This trend holds for the narrow entrance widths w. The dip in the E-curve near L/B = 1.0 is confirmed by the test points in Figure 3. At the larger tides H, the narrower entrance generally produces better overall flushing. As H decreases, the flushing efficiency n increases; this behavior has been noted on model studies of specific marinas having the very short entrance channel lengths used in the present tests.

Effects of L/B and w noted above are linked to the angular momentum of the complex flow within the harbor. The preservation of this angular momentum, associated with the deflection of flood tide flows through the entrance, is especially important to the internal circulation and, hence, harbor flushing. Circulation cells, or gyres, are created on the flood tide flow by moments of effective stresses associated with flow separation past the breakwater. These cells grow in both circulation strength and in size until they occupy a significant part of the basin, and may persist well into the ebb phase of the tidal cycle. As a consequence of the angular momentum established within the basin, even in the absence of longshore currents ebb flows are often skewed instead of leaving the basin in a direction parallel to the entrance axis. Higher velocities occur near the basin perimeter, and lower velocities near its center. These conditions in some respects are comparable to those occurring when tangential entrance jets of small size are used to produce a slow-moving large-scale circulation in water supply reservoirs (5). This angular momentum allows the inflowing ambient water to sweep past a major portion of the interior boundaries of the basin without losing its identity through diffusion. Thus, factors which contribute to increased angular momentum would be expected to improve overall flushing.

A preliminary simple angular momentum control volume analysis was made which considered shear forces on the walls and bottom of the basin and pressure forces on the walls; these would enter calculations of angular momentum about a vertical axis at the basin center. While details of these forces were not considered because interior velocities were not known, it was demonstrated that the optimum rectangular planform for maximizing the interior velocities at any instant of time is a square, L/B = 1.0 (6). For a constant surface area A the square planform has the minimum boundary perimeter, so that for a given H, w combination there is the greatest possibility in such small harbors that the ambient water entering as a two-dimensional jet will be able to circumnavigate the basin. Water which so completes the circuit around the boundary has a velocity component along the breakwater side of the basin as it approaches the entrance from within (clockwise, in Figure 1); if this not fully mixed ambient stream reaches the entrance at about high water slack some of it will be deflected back into the basin but some will exit the basin and not accomplish any effective exchange. The dips on the E-curves near L/B = 1.0 on Figures 2 and 3 reflect this phenomenon.

The 125-foot entrance width w is narrow enough to lend itself to the above reasoning over the full L/B range tested, and the 250-foot width nearly so. For the 500-foot width, tested for the 8-foot tide only, at small L/B the entrance width approached L and for large L/B for the constant surface area the width w approached B, and in neither case do the foregoing angular momentum considerations apply. Actual entrance widths are seldom much less than

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the smallest (125 feet) value tested, due to navigation considerations.

The reason for the fall-off in E for L/B less than 1/3 and greater than 3 will be discussed in the next section.

Figure 4 shows there is little difference in gross flushing performance between the rectangular and rounded-corner basins of equal aspect ratio. The benefit of the rounded interior corners is that local separation zones, hence areas of relatively stagnant water, are eliminated; this is a point of concern to fisheries resource managers.

Figure 5 reflects the data of Figure 2, and indicates more clearly that the flushing efficiency for these short-entrance basins increases as the tide range H decreases. This is contrary to what can happen if entrance channels are longer or if exterior constraints such as a detached breakwater located athwart the channel axis impede the free exchange of basin and ambient waters, so that at the smaller tide ranges some of water exhausted from the basin on the ebb is returned to the basin on the flood.

Figures 6 and 7 indicate very little difference in the flushing performance of rectangular and rounded-corner basins with L/B = 1.0 and of a circular basin of the same surface area. At the "mean" tide of 8.0 feet flushing coefficients are nearly identical, and all exchange coefficients are above 80 percent. Extrapolation of these results to tide ranges of less than 4 feet may not be safe. It also is pointed out again that the combination of A, H, and d tested apply to limited geographical areas.

CIRCULATION PATTERNS IN HARBOR

Insight into the mechanisms of the tidal flushing process can be gained be considering the path and distance penetrated into the harbor on the flood tide by the inflow stream of ambient water and by relating this distance to the planform geometry of the basin. This section deals with a simple correlation of these quantities.

Experimental results are shown in Figure 8 for two tidal ranges for each of four harbor geometries. Small tubular drogues, weighted to provide adequate vertical penetration so that the drogues move with the local depthaveraged velocity, were released at the center of the entrance at the time of mean water level crossing and were tracked through the basin for the subsequent one-quarter cycle to high water slack. The locations of the drogues at one-eight and one-fourth of the tidal period T after release are indicated, as well as the paths followed. The effect of doubling the range H from 4 feet to 8 feet is apparent.

For the elongated basins of L/B = 3.20 and L/B = 0.31, the drogue paths indicate how two circulation cells are developed in the harbors. For the inlet orientation shown the cell near the harbor entrance is clockwise in each case, while that in the rear portion of the harbor is counterclockwise. The drogue pathlines for these two configurations do not show that part of the ambient water stream does not follow the plotted pathline into the rear section of the harbor but rather moves into the gyre in the front section of the harbor. Figure 8 indicates pathlines for water entering at the time of mean water level crossing. Ambient water entering the basin prior to this time on the flood tide has followed much the same path after initial development of the cell inside the harbor entrance; as a consequence, at the time of high water slack there are currents moving along the walls of the harbor and toward the mouth.

For purposes of comparison, a penetration distance p has been defined as the distance traveled along its pathline by a particle of water which enters the basin at the time of the mean sea level crossing, which for practical purposes in an entrance of the type used in the present study is the time of maximum velocity of the flood tide current. The flood current has maximum or near-maximum momentum at this arbitrarily selected but convenient time, and from consideration of conservation of m mentum of the inflow "jet" it possesses the capability of penetrating a maximum distance into the basin in a finite time. The following simple analysis considers the penetration distance p at high water slack, a time T/4 after water entrance into the basin. Notation is shown in the definition sketch, Figure 9. The rounded jetties used in the tests minimized contraction of the inflow as it passed through the inlet, so that a one-dimensional condition of uniform velocity V_0 over the entrance area wd could be a reasonable assumption.

The inflow stream initially flows parallel to one wall in the harbor planforms studied, but in all cases ultimately deflects from its initial direction. The choice remains, in a simple momentum correlation, whether to employ a wall-jet analysis or a slot-jet analysis. In either case, neither of which matches the physics of the tidal currents in the small harbors, the expression for the velocity v along the streamline of maximum velocity is

$$\frac{v}{v} = C\left(\frac{x}{w}\right)^{-1/2}$$

Values of the constant C are 3.45 for the wall-jet (7) and 2.28 for the slotjet (8), respectively. Assuming that the steady flow relations can be applied to a water particle moving along this streamline, integration of the expression v = dx/dt along the initial direction of motion, x, gives

$$x \approx \left(\frac{3}{2} C\right) = \frac{2/3}{V_0} \frac{2/3}{W_1} \frac{1/3}{2} \frac{2/3}{2} \frac{1}{3} \frac{2}{3} \frac{2}{3} \frac{2}{3} \frac{2}{3} \frac{1}{3} \frac{2}{3} \frac{2}$$

It remains to relate $V_{\rm O}$ to the tidal range and to the basin geometry. Applying the simple one-dimensional continuity equation for a sinusoidal tide of range H and period T to the basin of planform area A and inlet cross-sectional area wd at the mean water level, $V_{\rm O}$ at this time is given by

$$V_o = \frac{\pi H}{T} \frac{A}{wd}$$

Interchanging the penetration distance p for the distance along the x-direction gives

$$p = \left(\frac{3}{2} \pi C\right)^{2/3} \frac{H^{2/3}}{m^{1/3}} \left(\frac{A}{d}\right)^{2/3} \left(\frac{nT}{T}\right)^{2/3}$$

where n = the fractional part of the tidal cycle after t = 0 at which p is evaluated.

The results of Figure 8 have been replotted in Figure 10, in which the maximum value n = 1/4 represents conditions at high water slack. The slot-jet value of C = 2.28 was used because it correlates more closely with the experimental observations; the wall-jet empirical constant C over-predicts the penetration. Numerical agreement with the jet models considered could not be expected, but the test results do show agreement in the form of the penetration distance vs. time relationships. Therefore, the form of the last equation given above can be used to predict changes in the ambient-water pene-. tration into a harbor with variations in tidal range H or in harbor geometry parameters A, d, and w.

CONCLUSIONS

The effect of planform geometry upon the tidal flushing characteristics of small harbors with single asymmetric entrances has been studies for simple, rectangular basins in which wind and stratification effects are negligible and tidal action is the dominant flow-producing mechanism. When harbor aspect ratios exceed 3 or are less than 1/3, multiple circulation cells exist within the harbor and the basin-average tidal flushing is reduced. So long as the aspect ratio is kept within these limits there is relatively little variation in the tidal exchange coefficient, E, with L/B for a given tidal range H, although best flushing occurs when the aspect ratio is close but not necessarily equal to unity, the value predicted by simple considerations of angular momentum of the internal tidal currents.

The experimental data indicate that rounding interior corners of the harbor does not improve the gross flushing. The elimination of sharp interior corners does, however, eliminate local stagnation zones and thus improves local water exchange and local water quality. This latter consideration is important to the safety of fish which pass through or temporarily reside in small-boat basins of the size range tested. In the Puget Sound area of Washington, this point is of particular concern in the safe migration of juvenile salmon. Figure 11 illustrates changes in typical marina planform shapes for small-boat basins in the Puget Sound region which have in some part been brought about by considerations of tidal flushing and internal circulation patterns, particularly the latter.

Results of this study may be used to answer some of the hydraulic questions considered in the design of such harbors and may reduce the need for individual model studies on a case-by-case basis.

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REFERENCES

- Grubert, J. P., "Numerical Computation of Two-Dimensional Flows," Journ. of the Waterways, Harbors, and Coastal Eng. Division, ASCE, 102, No. WW1, February 1976, pp. 1-12.
- Nece, R. E. and E. P. Richey, "Application of Physical Tidal Models in Harbor and Marina Design," <u>Proceedings of the Symposium on Modeling</u> <u>Techniques</u>, ASCE, San Francisco, California, September 1975, pp. 783 -801.
- Harleman, D. R. F., "Pollution in Estuaries," Chapter 14 in <u>Estuary and</u> Coastline Hydrodynamics (A. T. Ippen, Ed.), McGraw-Hill, 1966.
- Nece, R. E. and E. P. Richey, "Flushing Characteristics of Small-Boat Marinas," <u>Proceedings of the Thirteenth Coastal Engineering Conference</u>, Vancouver, Canada, July 1972, pp. 2499-2512.
- Sobey, R. J. and S. B. Savage, "Jet-Forced Circulation in Water-Supply Reservoirs," <u>Journal of the Hydraulics Division</u>, ASCE, <u>100</u>, No. HY12, December 1974, pp. 1809-1828.
- Falconer, R. A., "Tidal Circulation Effects in Rectangular Harbors," MSCE Thesis, University of Washington, Seattle, Washington, 1974, 97 pp. (unpublished).
- Rajaratnum, N., "The Hydraulic Jump as a Wall Jet," <u>Journal of the</u> Hydraulics Division, ASCE, 91, No. HY5, September 1965, pp. 107-132.
- Albertson, M. L., Y. B. Dai, R. A. Jensen and H. Rouse, "Diffusion of Submerged Jets," <u>Transactions ASCE</u>, <u>115</u>, 1950, pp. 639-664.





Plan - Rectangular Basin (Note: r=250', all cases, Rounded Corner Basin)

Plan - Circular Basin (Note:Surface Area = LB)



Vertical Wall, Level Bottom Basin:

$$TPR = \frac{H}{d + \frac{H}{2}}$$
$$\eta = \frac{E}{TPR} \times 100$$

FIGURE 1. Definition and notation diagram.



FIGURE 2. Flushing data summary, rectangular harbor.











FIGURE 5. Variation of flushing efficiency with tide range, regular basin, w = 125 feet.

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FIGURE 7. Flushing efficiency, circulat and "square" basins.





FIGURE 8. Inlet jet paths and penetration distances for four harbor planforms.



FIGURE 9. Definition diagram, jet penetration analysis.



FIGURE 10. Jet penetration measurement data.



achieve improved internal circulation.