CHAPTER 90

HYDRAULIC CONSTANTS OF TIDAL ENTRANCES

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ABSTRACT

Data contained in the Tide Tables, Current Tables and navigation charts of National Ocean Survey pertaining to tidal entrances along the coasts of the continental United States are analyzed to obtain flow coefficients defined by a simple hydraulic equation. The evaluation of the published data indicates that the data are sufficiently accurate and representative, despite some unexplained anomalies, to permit determination of the approximate discharge coefficients and, more importantly, to identify categories of flow regimes of inlets. A few conclusions are:

1. The Keulegan approach and similar analyses of inlet hydraulics provide a useful qualitative framework for ordering data but they apply quantitatively only to small inlets and lagoons with simple inlet channel geometry.

2. The lag of slack water in the entrance channel after HW and LW is a powerful tool in the analysis of the hydraulic regime. It is easily measured in the field and should become an identifying characteristic of each entrance.

3. The resistance coefficient F represents the overall impedance and exit losses, reflections from the lagoon shore, fresh water discharge and the configuration of the channel between the inner and outer bars. It may be determined from measurements of lag and maximum velocity at the throat and the range of ocean tide.

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1. The tide in the lagoon continues to rise after high water in the ocean. Slack water occurs when the two curves intersect, and high waters and low waters around the lagoon occur at the same time. With reference to the definitions of Figure 1 the relevant equations are:

$$\eta_o = \text{elevation of ocean tide} = a_o \cos \sigma t \tag{1}$$

$$\eta_B = \text{elevation of tide in lagoon} = a_B \cos (\sigma t - \varepsilon) = a_o \cos \varepsilon \cos (\sigma t - \varepsilon) \tag{2}$$

$$2a_B = \text{range in lagoon} = 2a_o \cos \varepsilon \tag{3}$$

Here, a_o and a_B are the ocean and lagoon tidal amplitudes and $\sigma (= 2\pi/T)$ is the angular frequency of the tidal period T.

2. The driving head at any time t during the tidal cycle is:

$$\eta_o - \eta_B = a_o \cos \sigma t - a_o \cos \varepsilon \cos (\sigma t - \varepsilon)$$

$$= a_o [\cos \sigma t - \cos \varepsilon \cos (\sigma t - \varepsilon)] \tag{4}$$

Slack water occurs at $\sigma t = \varepsilon$
Maximum head occurs at $\sigma t = \varepsilon + \frac{\pi}{2}$
Maximum head = $(\eta_o - \eta_B)_{max} = a_o \sin \varepsilon$

These relationships follow directly from the assumption that the tide curves in the lagoon and the ocean are sinusoidal. If the friction loss in the entrance channel is quadratic, the maximum value of the velocity, averaged over the flow area, A_c, becomes

$$\overline{V}_{max} = \left[\frac{2g\, a_o \sin \varepsilon}{F}\right]^{1/2} \tag{5}$$

where

$$F = k_i + k_e + \frac{fL_c}{4R_c} \tag{6}$$

Here, k_i and k_e are the inlet entrance and exit loss coefficients respectively, f the Darcy-Weisbach friction coefficient, R_c the hydraulic radius for the flow area, A_c and g is the acceleration of gravity.

The entrance and exit loss coefficients approximate unity. The quantity, L_c, is the length of a channel of area A_c which would have the same overall friction loss as the real channel. If the real channel with a length X_L has reasonably well defined boundaries, a value for L_c may be estimated as

$$L_c = \int_0^{X_L} \left(\frac{R_c}{R_x}\right)\left(\frac{A_c}{A_x}\right)^2 dx \tag{7}$$

$$f = (F - 1)\frac{4R_c}{L_c} \tag{8}$$

$$n = 1.48\, R_c^{1/6} \left(\frac{f}{8g}\right)^{1/2} \text{(Manning's coefficient)}. \tag{9}$$

Keulegan (1967) recognized that quadratic friction causes the tide curve in the lagoon to depart from sinusoidal. He represented his results as functions of a repletion coefficient K defined as

$$K = \frac{T}{2\pi a_o}\frac{A_c}{A_B}\left(\frac{2ga_o}{F}\right)^{1/2} \tag{10}$$

where A_B is the surface area of the lagoon. The quantities comprising K are the primary variables which must be known in order to determine the flow conditions in an inlet.

The quantity F, computed from Equation (5) employing measured values of $\overline{V}_{max}$, ε, and a_o, represents the effect of all influences restricting the flow and not merely the entrance and exit losses and the bottom friction. It should thus be regarded as the overall impedance of the inlet.

SOURCES OF DATA

Ideally, the data used to determine the hydraulic constants should include:

1. Measurements of the velocity across the throat section (representing the minimum cross-sectional area of the inlet) to fix the time of slack water after HW and LW and the average velocity over the throat area A_c at the time of strength of flood and ebb.

2. Concurrent measurements of the tide in the ocean sufficiently far from the inlet to avoid the effect of local drawdown.

3. Survey of the inlet channel at the time of velocity measurements.

There are very few entrances for which such complete sets of concurrent data are available.

The NOS (National Ocean Survey) Tide Tables and Current Tables are intended primarily as aids to navigation. They include the tide at only a limited number of stations on the open coast. Current data pertain to the navigation channel, usually the deepest part of the cross-section; however, the location of this current measurement may not have been at the throat. Evidently, these data are not ideal for determining the hydraulic coefficients but they do have virtue of representing the results of extended periods of measurement and of rigorous processing to obtain representative average values.

The tabulated tide and current data were analyzed as follows:

1. The tabulated strengths of ebb and flood currents (V_{max}) were averaged and multiplied by 0.85* to obtain $\overline{V}_{max}$, the maximum average velocity over the inlet cross-section.

2. The tide ranges at stations on the open coast were plotted against distance along the coast, and the ocean tide range applicable to each inlet was obtained by interpolation.

3. The times of HW and LW at the throat section were obtained by applying the tabulated time differences from the reference station.

4. The lags of slack water after HW and LW were determined by combining the data in the Tide Tables and Current Tables. At the primary stations, the lags were averaged over a period of one month; at the secondary stations, over a period of one week. The characteristics of the entrances selected for study are listed in Tables 1 and 2.

Equation (5) was employed to compute two sets of values of F as follows:

a. F was based on the mean range of tide, the average lag of slack water after HW and LW, and the average of the strengths of flood and ebb currents.

b. Daily predictions of tides and currents were used to determine the range, the strength of current, and the lag for the flood and ebb phases separately, in order to obtain values F_F (flood) and F_E (ebb) for each tidal cycle. Tables 3 and 4 show values of F_F and F_E averaged over a number of tidal cycles.

Entrances on the coast of the Gulf of Mexico were studied, and some data pertaining to them are included in the tables. However, the variability of tide range and the lag of slack water were too great to permit calculation of the hydraulic constants using the velocity data given in the Current Tables.

EVALUATION OF RESULTS

Friction Coefficients

Unfortunately, there are few entrances which have sufficiently regular channels to justify calculation of L_c, from Equation (7) and f and n from Equations (8) and (9). The seven entrances listed in Table 5 are the only entrances included in this study for which the configuration of the channel seemed to justify calculation of L_c.

*An estimate based on measurements in unidirectional open channel flow.

TABLE 1

ENTRANCE GEOMETRY AND TIDES FOR REFERENCE STATIONS

ENTRANCE	JETTIES	OCEAN TIDE MEAN RANGE $2a_o$ (ft)	THROAT SECTION				RATIO OF WIDTH TO HYDR. RADIUS W/R_c	BAY (LAGOON) AREA (MWL) A_B (ft^2)	BAY TIDE MEAN RANGE $2a_B$ (ft)
			AREA (MWL) A_c (ft^2)	WIDTH W (ft)	MEAN DEPTH (ft)	MAX. DEPTH (ft)			
NARROWS	Bridge	4.5	305920	5000	61	103	82	N. A.	4.5
DELAWARE		4.4	2454900	64300	38	N. A.	1683	N. A.	4.9
CHESAPEAKE	Bridge	3.5	1890000	76000	25	60	3065	N. A.	2.4
CHARLESTON	2 Jetties	5.2	73450	2800	26	38	107	N. A.	5.2
SAVANNAH	2 Jetties	6.9	41050	1670	26	39	65	N. A.	7.4
ST. JOHNS R.	2 Jetties	5.4	49230	1580	31	36	51	N. A.	4.5
MIAMI	2 Jetties	2.5	18690	950	20	33	48	N. A.	4.5
MOBILE	Natural	1.3[a]	228000	15300	15	60	1040	1.34×10^{10}	1.5
GALVESTON	2 Jetties	2.1[b]	232920	6875	34	38	203	1.60×10^{10}	1.2
GRAYS	2 Jetties	6.4	262520	10200	26	48	397	(1.89×10^{9})	7.2
HUMBOLT	2 Jetties	4.3	51900	2200	34	42	134	(5.67×10^{8})	6.8
SAN FRANCISCO	Bridge	4.2	(931000)	(5270)	(177)	N. A.	30	N. A.	4.2
SAN DIEGO	1 Jetty	3.7	63670	1855	41	48	47	(4.75×10^{8})	4.0

N. A. - Not Available ( ) - Data from other sources a - Diurnal

b - Mixed

TABLE 2

ENTRANCE GEOMETRY AND TIDES FOR SECONDARY STATIONS

ENTRANCE	JETTIES	OCEAN TIDE MEAN RANGE $2a_o$ (ft)	THROAT SECTION				RATIO OF WIDTH TO HYDR. RADIUS W/R_c	BAY (LAGOON) AREA (MWL) A_B (ft^2)	BAY TIDE MEAN RANGE $2a_B$ (ft)
			AREA (MWL) A_c (ft)	WIDTH W (ft)	MEAN DEPTH (ft)	MAX. DEPTH (ft)			
FIRE ISLAND	1 Jetty	4.1	36500	2600	14	18	188	2.45×10^9	0.7
SHINNECOCK	2 Jetties	3.0	5520	800	7	N. A.	116	3.14×10^8	N. A.
JONES	1 Jetty	4.2	28900	2500	13	24	195	4.78×10^8	2.4
E. ROCKAWAY	1 Jetty	4.5	10735	680	14	22	50	N. A.	3.9
ROCKAWAY	1 Jetty	4.5	82300	3060	27	48	114	6.27×10^8	5.2
MANASQUAN	2 Jetties	4.3	3530	360	10	N. A.	37	5.80×10^7	3.3
BARNEGAT	2 Jetties	4.3	12700	950	13	28	71	N. A.	0.6
INDIAN R.	2 Jetties	4.1	(5300)	500	11	N. A.	47	N. A.	0.9
HATTERAS	Natural	3.6	43050	8800	5	N. A.	1796	N. A.	<0.5
OCRACOKE	Natural	3.6	82200	6750	12	53	553	N. A.	<0.5
NEW RIVER N.C.	Natural	3.7	7950	600	11	N. A.	57	1.01×10^9	<0.5
ST. MARYS	2 Jetties	5.8	111440	3400	33	71	104	8.89×10^7	6.0
PORT ROYAL	Natural	6.4	513020	12830	40	60	321	N. A.	7.1
FT. PIERCE	2 Jetties	3.1	8950	900	10	23	91	1.27×10^9	0.7
LAKE WORTH	2 Jetties	2.8	19300	870	21	33	42	4.00×10^8	2.6
PORT EVERGLADES	2 Jetties	2.6	16500	800	27	N. A.	30	7.53×10^7	2.3
PENSACOLA	Natural	1.2[a]	82850	2400	35	52	70	3.34×10^9	1.5

TABLE 3

INLET HYDRAULICS FOR REFERENCE STATIONS

ENTRANCE	$\bar{V}_{max}$ (NOS Current Tables) FLOOD (ft/sec)	EBB (ft/sec)	TIDAL PRISM HYDRAULIC - P_H (ft^3)	TIDAL PRISM VOLUMETRIC - P_V (ft^3)	LAG OF SLACK - ϵ (°) ϵ_F	ϵ_E	ϵ_{AVG}	IMPEDANCE - F F_F	F_E	F_{AVG}
NARROWS	2.87	3.38	1.43×10^{10}	N. A.	67.1	66.8	67.0	22.9	16.4	19.2
DELAWARE	3.04	3.21	9.29×10^{10} (11.1×10^{10})	N. A.	35.5	42.8	39.2	13.3	13.5	13.4
CHESAPEAKE	1.69	2.54	6.30×10^{10}	N. A.	110.2	113.8	112	51.6	20.7	31.0
CHARLESTON	3.04	3.04	2.71×10^{9}	N. A.	27.8	27.0	24.4	7.4	6.3	6.8
SAVANNAH	2.70	4.39	1.76×10^{9}	N. A.	29.8	40.9	35.3	21.4	10.9	14.6
ST. JOHNS R.	3.21	3.89	3.03×10^{9}	N. A.	92.2	93.4	92.3	20.9	14.9	17.5
MIAMI	3.21	3.55	9.12×10^{8}	N. A.	55.1	58.1	56.7	9.3	7.0	8.0
GRAYS	3.21	4.73	1.26×10^{10}	1.36×10^{10}	15.1	20.3	17.7	7.9	5.1	6.0
HUMBOLT	2.70	3.80	2.50×10^{9}	3.86×10^{9} (3.03×10^{9})	11.5	18.4	14.9	4.6	5.5	5.1
SAN FRANCISCO	4.90	5.75	6.00×10^{10}	N. A. (5.1×10^{9})	49.5	64.4	56.9	5.7	5.2	5.5
SAN DIEGO	2.03	2.54	1.97×10^{9}	1.90×10^{9}	8.5	13.9	11.2	6.2	7.0	6.7

( ) - Data from other sources

TABLE 4

INLET HYDRAULICS FOR SECONDARY STATIONS

ENTRANCE	$\bar{V}_{max}$ (NOS Current Tables) FL000 (ft/sec)	E8B (ft/sec)	TIDAL PRISM HYDRAULIC - P_H (ft^3)	VOLUMETRIC - P_V (ft^3)	LAG OF SLACK (°) ϵ_{AVG}	IMPEDANCE F_{AVG}
FIRE ISLANO	4.06	4.06	2.42×10^9 (2.23×10^9)	1.72×10^9	93.5	16.0
SHINNECOCK	4.23	3.89	3.15×10^8 (3.06×10^8)	N. A.	78.9	11.5
JONES	5.24	4.39	2.03×10^9	1.15×10^9 (1.5×10^9)	48.7	8.8
E. ROCKAWAY	3.72	3.89	5.79×10^8	N. A.	31.7	10.5
ROCKAWAY	3.04	4.56	4.13×10^9	3.26×10^9	17.9	6.2
MANASQUAN	2.87	3.04	1.52×10^8 (1.74×10^8)	1.91×10^8	50.6	16.9
BARNEGAT	3.72	4.23	7.40×10^8	N. A.	94.9	12.1
INOIAN R.	3.04	3.55	2.96×10^8	N. A.	65.8	15.3
HATTERAS	3.55	3.38	2.23×10^9	N. A.	103.8	13.0
OCRACOKE	2.87	4.06	4.26×10^9	N. A.	96.9	13.3
NEW RIVER, N.C.	1.86	3.04	2.90×10^8	$<5 \times 10^8$	112.4	24.4
ST. MARYS	3.89	4.39	5.58×10^9	5.33×10^9	30.2	7.6
PORT ROYAL	3.04	3.04	1.89×10^{10}	N. A.	31.3	16.6
FT. PIERCE	4.39	5.24	6.42×10^8	8.89×10^8	87.3	7.2
LAKE WORTH	4.06	6.08	1.34×10^9	1.04×10^9	57.7	5.9

TABLE 5

ENTRANCE FRICTION COEFFICIENTS

ENTRANCE	L_C (ft)	R_C (ft)	F	f	n
FIRE ISLAND	33100	13.8	16.0	0.025	0.022
E. ROCKAWAY	11100	13.7	10.5	0.047	0.022
INDIAN R.	4200	10.6	15.3	0.143	0.051
ST. MARYS	15200	32.8	7.6	0.057	0.039
LAKE WORTH	1900	20.9	5.9	0.220	0.071
HUMBOLDT	2690	17.9	5.1	0.110	0.049
SAN DIEGO	18860	40.9	6.7	0.049	0.038

The values of f and n listed in Table 5 are high as compared with the values frequently assumed in calculating hydraulic friction losses in tidal waterways. In this connection, the data for Indian River Inlet are of particular interest because Keulegan (1967) found f = 0.098 and n = 0.046 from velocity and surface elevation measurements there in the relatively uniform channel between the ends of the jetties and the seaward side of the bridge. The values listed in Table 4 (f = 0.143; n = 0.051) for Indian River Inlet include the losses at the jetty ends, through bridge piers, and in the irregular channel between the bridge and the bay, in addition to the losses in the channel where Keulegan obtained his data. The value of f obtained is inversely proportional to the computed value of L_c which is subject to considerable error because the end-points are seldom well defined.

Tidal Prism

An indication of the validity of the values of $\overline{V}_{max}$ used in determining F is provided by a comparison of the tidal prism computed from:

a. The surface area and range of tide in the lagoon.

b. Integration over the ebb or flood phase of the average velocity times the flow area, as given by Keulegan (1967):

$$P_H = \frac{\overline{V}_{max} \cdot A_c \cdot T}{C_K \cdot \pi} \qquad (11)$$

The value of C_K as a function of K ranges from 0.81 to unity. Keulegan and Hall (1950) found that C_K = 0.86 gave good agreement with tidal prisms determined by velocity measurements. Applying this equaiton, the tidal prisms in Table 3 and 4 were computed. Comparison of the value of P_H with that determined volumetrically, P_V, gives:

Location		P_H/P_V
St. Marys		1.04
San Diego		1.04
Grays Harbor		0.93
Manasquan	(0.91)	0.79
Rockaway		1.26
Lake Worth		1.29
Fort Pierce		0.72
Mobile		0.63
Galveston		1.36
Fire Island	(1.30)	1.40
Humboldt Bay	(0.83)	0.65
Jones Inlet	(1.35)	1.77
Average	(1.06)	1.07

The values in parentheses are data from sources other than the Current Tables and Tide Tables, believed to be valid. The large discrepancy in the case of

Jones Inlet has not been explained; using a value of P_V supplied by the Long Island State Park Commission this ratio would become 1.35.

The average difference of 7 percent in the preceeding table is perhaps of little significance since P_H and P_V differ in some cases by as much as a factor of two. However, the sources of errors in each quantity should be recalled in assessing the results.

Regarding the accuracy of P_H, the velocity in the Current Tables (V_{max}) was multiplied in all cases by 0.85 to obtain the average velocity; the velocity may not have been measured at the throat section; and the flow area may have changed between the times of the survey and of the current measurements. For example, the flow area at the throat at Humboldt Bay entrance changed as follows:

Year	A_c
1911	51900 ft^2
1917	46480 ft^2
1935	66840 ft^2
1937	56510 ft^2

The ratio of the maximum (1935) to minimum (1917) area is 1.44.

The tidal prism based on lagoon area and tide range (P_V) is subject to considerable error because of the difficulty in determining the surface area at LW. The line of HW is clearly delineated on the charts but its position may be in error where the surveyor interpolated between tide gages - especially in flat terrain and with a decreasing tide range away from the inlet. Not all of the inlets studied could be included in this list, either because the low water area was ill defined or because of interconnections between lagoons.

Ratio of Ranges

The usual assumptions made in the hydraulic analysis of inlets include a sinusoidal ocean tide and a horizontal water surface in the lagoon. If these assumptions are satisfied, the ratio of ranges (a_B/a_O) should equal the cosine of the average lag of slack water (Equation (3)). A measure of the degree to which this assumption is satisfied is the difference in these quantities

$$\Delta = \frac{a_B}{a_O} - \cos \epsilon \qquad (12)$$

Figure 2 shows these data. The absolute size of the entrance is represented by the dimensionless ratio (A_c/a_O^2).

For small entrances, the values of Δ scatter around zero randomly, but there is an upward trend (dashed line) with absolute size and all of the large entrances show large positive values of Δ. Noteworthy is the fact that the range of tide inside but adjacent to the inlet equaled or exceeded the ocean range in a large number of the entrances studied. This

phenomenon was observed at the Narrows, Rockaway Inlet, Delaware Bay, Charleston Harbor, Savannah River Entrance, St. Marys River Entrance, Port Royal Sound, Pensacola Bay, Mobile Bay, Grays Harbor, Humboldt Bay, San Francisco Bay and San Diego Bay. This list includes entrances covering a wide range in absolute size, range of tide, overall resistance coefficient (impedance), and configuration of the inlet channel.

In all cases where the ratio of ranges (a_B/a_o) equaled or exceeded unity, cos ε did approach unity with the following exceptions:

Location	cos ε
The Narrows	0.39
Delaware Bay	0.77
San Francisco Bay	0.55

If the lag of slack water approaches 90°, the range of tide inside should approach zero, according to the hydraulic theory. Examples of entrances where the flow conditions differ markedly from this relationship area:

Location	Lag ε (deg)	cos ε	a_B/a_o
Chesapeake Bay	112	-0.37	0.68
St. Johns River	92	-0.04	0.83

Clearly, these entrances follow a regime differing fundamentally from that assumed in the hydraulic theory.

Times of HW and LW in Lagoon

If the water surface in the lagoon remains approximately horizontal during the tidal cycle, high waters should occur at the same time at all tide stations at the shores of the lagoon and concurrently with slack water after HW in the inlet channel; this same statement should be true for the times of LW. Examination of the data in Tide Tables shows that this phase relationship occurs at very few inlets, and that the usual situation is one in which the tide is not in phase across the lagoon. Consequently, the effective elevation of the water surface in the lagoon, a_B, differs from that obtained from continuity assuming a level surface. Compuations of the tidal prism on the basis of surface area and tidal ranges would require consideration of these phase differences.

Tractive Stress

An estimate of the maximum average tractive stress may be made for inlet channels which are sufficiently regular to permit computation of Manning's n as follows:

$$\tau_{max} = \gamma RS = \gamma \frac{\overline{V}^2_{max}}{C^2}$$

$$= \frac{\gamma}{2.21} \cdot \frac{n^2 \overline{V}^2_{max}}{R^{1/3}} \qquad (13)$$

Values of maximum tractive stress τ_{max} (where γ is the specific weight of water, C the Chézy coefficient, R the hydraulic radius and S the slope fo the enrgy grade line at the time of maximum velocity) computed by Equation (13) are:

Location	$\overline{V}_{max}$(ft/sec)	n	τ_{max}(lb/ft^2)
Fire Island	3.45	0.022	0.07
East Rockaway	3.23	0.022	0.06
Indian River	3.29	0.510	0.37
St. Marys	3.52	0.039	0.17
Lake Worth	5.07	0.071	1.37
Humboldt	3.25	0.049	0.28
San Diego	1.94	0.038	0.05

Reported values of the maximum tractive stress in the main channels of estuaries are in the range of 0.03 to 0.20; at the throat section, somewhat higher values probably occur. At Lake Worth entrance, the maximum tractive stress is high but this is so because the maximum velocity there is unusually strong. The other values seem reasonable, considering the nature of the data employed and the fact that effects other than friction resistance are lumped into Manning's n as determined in this study.

CATEGORIES OF ENTRANCES

The configuration of entrances on sandy coasts represents a dynamic equilibrium in response to influences which vary seasonally, annually, and over long periods. Wave climate, littoral transport, river sediment, range of tide, fresh-water runoff, wind drift, and even biological growth, superimpose shifts in this configuration upon the long range geological trend of change due to subsidence, uplift and sea-level change. Engineering works - jetties, dredging, river regulation, new inlets - initiate the approach to new equilibrium conditions. In a sense, each inlet is unique in its hydrodynamic and morphological regime, and generalizations about details of inlet behavior are dangerous - at least in the present state of our knowledge. However, this study has identified a few characteristics which permit a rough classification of inlets. Some examples of inlets in these categories will illustrate this point.

Inlets Exhibiting Simple Hydraulic Flow

The two inlets used to illustrate the analysis of the hydraulic flow regime - Absecon by E. I. Brown (1928) and Indian River by Keulegan (1967) - were very different in configuration and hydraulic characteristics. The approach developed in this paper will be applied both to compare the methods

and the quantitative results.

Absecon Inlet is not listed in the Current Tables, and this analysis is based on Brown's measurements. Brown determined the tidal prism, the maximum velocity, and the lag of tidal events in the lagoon by current measurement and found that the measurements agreed closely with his predicted values.

The ratio of the ranges of lagoon and ocean tides, assumed by Brown to be effectively the same for both channels, was 0.74; the theoretical values, equal to cos ε, were 0.70 for Absecon Channel and 0.74 for the Main Channel.

Absecon Inlet connects the ocean to a highly irregular system of channels and bays. At the time of Brown's study the inlet was unimproved and consisted of two channels - the Main or Thorofare Channel and the Absecon Channel. Quantities scaled from charts or measured at the throat section were:

	Absecon Channel	Main Channel
A_c (ft^2)	17,750	12,000
R_c (ft)	19.5	6.62
ε (°)	46.6	42.4
$2a_o$ (ft)	3.8	3.8
$2a_B$ (ft)	2.8	2.8
$\overline{V}_{max}$ (ft/sec)	3.00	2.46
L_c (ft)	35,000	10,000

The calculated resistance characteristics are:

	Absecon Channel	Main Channel
F	9.65	13.54
f	0.019	0.033
n	0.020	0.020
C (Chézy)	121	92

These values seem reasonable. Brown used C = 116 for the Absecon Channel and C = 85 for the Main Channel in calculating the tidal prism.

Indian River Inlet connects the ocean to Indian River Bay, which in turn is connected to Rehoboth Bay. The inlet channel is stabilized by two jetties, 1530 ft. in length; bridge piers obstruct the channel 1400 ft. from the seaward ends of the jetties. The study by Keulegan (1967) of this inlet was based on surveys and current measurements made prior to 1950. The data in the tide and current tables and published charts are of uncertain but later dates. There has been considerable shoaling in the inlet channel since Keulegan's study.

Oata listed in the 1973 Tide Tables and Tidal Current Tables and the derived coefficients are:

$\overline{V}_{max}$ = 3.30 ft/sec (average of flood and ebb)
ε = 65.8°
$2a_o$ = 4.1 ft
F = 15.30
f = 0.143
n = 0.051

These values of f and n are high as compared with other inlets, but they do include the loss through the bridge piers. If F and ε are constant characteristics of an inlet, the equation for $\overline{V}_{max}$ may be simplified for each inlet; for Indian River Inlet, $\overline{V}_{max} = (2ga_o \sin \varepsilon/F)^{1/2} = 0.24 \sqrt{2ga_o}$. This coefficient is exactly the same as that obtained by Keulegan. As noted previously, Keulegan computed the values of f and n for the channel between the ocean and the bridge, not including the friction and shock losses through the bridge piers using current measurements made from the bridge and tide records on the seaward side of the bridge. He obtained f = 0.098 and n = 0.046. These values are in reasonably close agreement with those obtained in this study.

Abnormal Tide Ranges in the Lagoon

As noted earlier, if the lagoon fills by "hydraulic flow", the ratio of the amplitude in the bay to that in the ocean should follow the relationship $a_B/a_o = \cos \varepsilon$ from Equation (3). This ratio should always be less than unity if the assumptions underlying the theory are fulfilled. Figure 2 shows that the discrepancy between a_B/a_o and cos ε is substantial at a majority of the inlets studied; in fact, few inlets exhibit good agreement in this respect.

There are many entrances and lagoons at which the range inside exceeds that in the ocean. One example of this effect is San Francisco Bay where the tide range at all points around the Bay proper exceeds that in the ocean. A smaller entrance showing the same effect is St. Marys River Entrance on the border of Florida and Georgia, where the ranges are as follows:

Location	Range	Oistance from Throat (n.m.)
Ocean	5.8	-
St. Marys	6.0	7

The hydraulic coefficients of this entrance are not unusual.

The cause of this behavior has not been determined. Convergence and shoaling of the channels, and resonance are possible causes. In any event, tide ranges in the lagoon exceeding the range in the ocean are a clear warning that the hydraulic regime does not conform to the "hydraulic flow" relationships; if the range in the lagoon is less than that in the ocean, this

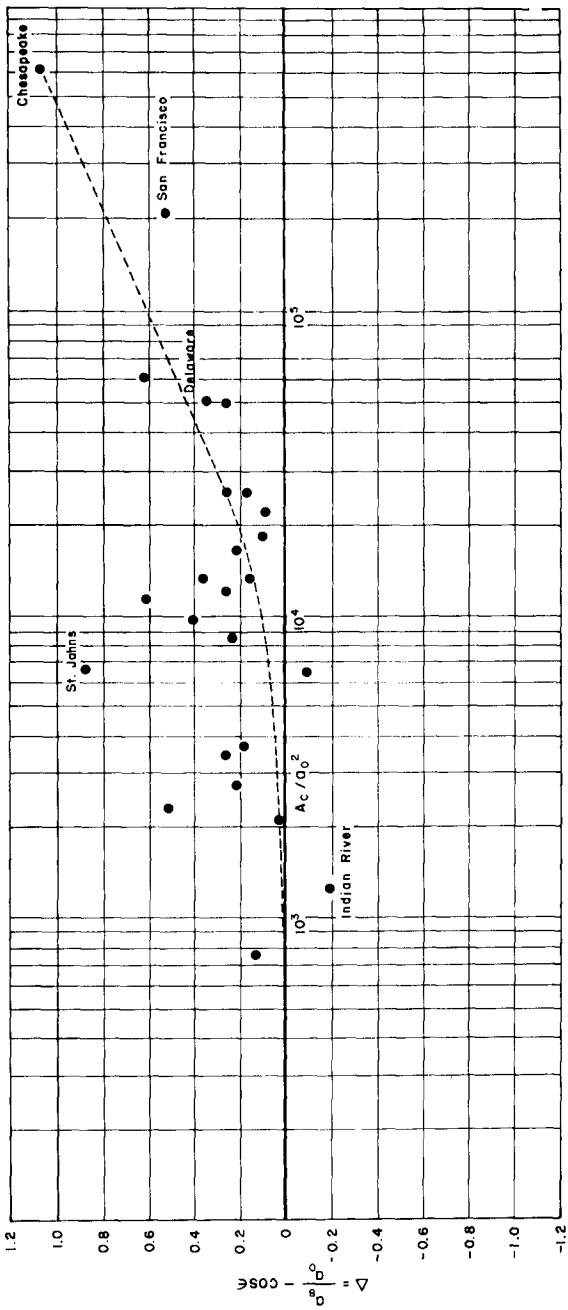

Figure 2 Degree of Deviation from "Hydraulic Flow" Represented by Δ, as a Function of A_c/a_o^2.

effect may nevertheless be present and may increase the range above the theoretical value.

These facts lead to the conclusion that the ratio of ranges is not, in general, a reliable indicator of the flow conditions in an entrance.

Very Large Lagoon Area

If the ratio of the surface area of the lagoon to the flow area of the inlet (A_B/A_C) is very large, the repletion coefficient (Equation (10)) should be small, the lag of slack water should approach 90 degrees, and the range of tide in the lagoon should approach zero. The effective surface area A_B may be only a fraction of the total surface area of the lagoon if the lagoon is shallow; each element of the tide wave advances across the lagoon at the celerity $\sqrt{gh}$ (where h is the depth) and the tidal prism is bounded by the amplitude a_B and a horizontal dimension equal approximately to $T\sqrt{gh}/4$. Flow through the inlet is limited by a backwater effect induced by the limited depths.

The inlets to Pamlico Sound (Oregon, Hatteras, Ocracoke, and others) exemplify this type of flow regime. The hydraulic characteristics of two of these inlets are:

Location	Mean Ocean Range (ft)	Lagoon Range (ft)	$\overline{V}_{max}$ (average flood and ebb) (ft/sec)	ε (deg)	F
Hatteras	3.6	<0.5	2.05	104	13
Ocracoke	3.6	<0.5	2.05	97	13

These two inlet differ greatly in width and depth.

Flow Through the Entrance as a Shallow Water Wave

Under the assumption of hydraulic flow through an entrance, the range of tide inside should decrease as the lag of slack water after HW increases towards 90 degrees. Conversely, if the propagation of the tide through an entrance has the properties of a shallow-water wave, the lag of slack water should be approximately 90 degrees, and the range should not be reduced in passing through the inlet; strength of current should occur at approximately HW and LW.

St. Johns River Entrance (Florida) is an example of flow through an entrance which is of a fundamentally different character from the "hydraulic flow" usually assumed. The width and depth of the river for some miles above the mouth are approximately constant; apparently, the tide advances through the entrance as a wave with the strength of ebb and flood currents occurring at LW and HW almost exactly.

As Figure 2 shows, the degree of departure from hydraulic flow increases with absolute size of the entrance. Probably, all but the smallest entrances exhibit a mixed flow regime with both "tide-wave" and "hydraulic" effects present in the current velocity tide range relationships.

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