CHAPTER 99

MEASUREMENT OF BED FRICTION IN TIDAL INLETS

by

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ABSTRACT

The flow characteristics and the stability of a tidal inlet are governed, among other factors, by the channel bed friction. In order to determine the bed shear stress regime and the frictional characteristics, near-bed velocity profiles were obtained at the throat sections of two inlets, John's Pass and Blind Pass, on the Gulf Coast of Florida. A specially designed steel cage with five current meters in a vertical array was used to obtain the profiles in the bottom one meter of the flow.

The profiles were found to be logarithmic but it is noted that, especially near the times of slack water, the effect of inertia becomes significant. However, during the major part of the flood or ebb flow period, frictional effects are dominant. In the fully rough regime of flow, the bed-shear stress - velocity relationship is found to follow the square law, with a constant, characteristic friction factor and Manning's n for each inlet. This friction factor is used in hydraulic formulas, based on uniform, steady open channel flow relationships, to obtain the tidal prism - throat cross-sectional area ratio, which is then compared with that obtained from flow discharge measurements. Agreements and discrepancies in the comparison are discussed. The relationship between the bed shear stress at incipient motion and the grain size at the bed is reviewed, and it is noted that the observed relationship at the two inlets does not agree with the well-known correlation of Shields for uniform sandy beds.

INTRODUCTION

The hydraulic and sedimentary regime of a tidal inlet depends strongly on the friction characteristics of the channel bed. These characteristics are most commonly defined in terms of a friction factor, a Chézy coefficient or a Manning's n. Standard texts on hydraulics give values of these coefficients, particularly Manning's n, for rivers and canals of various geometries and vegetative cover. However, for tidal inlets, information of this sort is limited and is only derived indirectly from measurements of tides and currents, rather

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than through direct near-bed measurements. Correspondingly, the variation of the bed shear stress with the tidal cycle and its relationship to the motion of the sediment over the bed is also established indirectly.

Experience and observation have established that the most characteristic morphologic feature of a tidal inlet is its throat section, and that flow measurements at this location yield important information on the hydraulics and the stability of an inlet. A significant part of the frictional resistance to the flow occurs at the throat, and the cross-sectional area of the throat, among other parameters, seems to correlate uniquely with the tidal prism through the inlet (O'Brien, 1969, 1976). Moreover, it has been shown that there appears to be a correspondence between this prism-area relationship for stable inlets and the regime equations for rivers and canals in non-silting, non-scouring equilibrium (Mason, 1973, Bruun, 1974), despite the fact that the flow in an inlet is primarily oscillatory. The question arises as to whether the direct measurement of near-bed velocity profiles at the throat can yield a friction factor, or a Manning's n, which may be considered to be characteristic for the inlet in a manner similar to that in a canal. Furthermore, inasmuch as the regime of sediment transport is dependent upon the bed shear stress, the determination of the latter as a function of the stage of tide should correlate with the bed sediment motion at the throat. These considerations led to the planning of the field experiments described in this paper, with the following specific objectives:

(1) To measure the velocity distribution in the bottom one meter of the flow at the throat section of an inlet.

(2) To simultaneously record the state of bed motion at the throat.

(3) To determine characteristic friction coefficients from the measured data.

(4) To obtain the tidal prism-throat cross-sectional area ratio based on hydraulic formulas involving the above coefficients, and to compare this ratio with that obtained from flow discharge measurements and a survey of the throat.

(5) To establish the relationship between the critical shear stress for the bed grain motion and the grain size at the throat.

HYDRAULIC RELATIONSHIPS

The simplest method of analysing and testing inlet hydraulic data is that based on the generally accepted correspondence between inlet hydraulics and steady, uniform open channel flows. In the turbulent regime, the logarithmic profile for the flow velocity u is

$$\frac{u}{u^*} = B + \frac{1}{\kappa} \ln \frac{Z}{K} \tag{1}$$

where u^* = friction velocity, κ = Karman constant (= 0.40), $Z = zu^*/\nu$, $K = ku^*/\nu$ (wall Reynolds number), z = elevation above the theoretical bed, k = bed roughness and ν = kinematic viscosity of water. The depth-mean velocity $\bar{u}$ can be obtained from Eq. (1) for a depth of flow h (assuming $h >> z_o$)

$$\bar{u} = 2.5u^* \left[\ln\left(\frac{h}{z_o}\right)-1\right] \tag{2}$$

and Manning's n and k from

$$n = \frac{1.49h^{1/6}}{g^{1/2}} \frac{u^*}{\bar{u}} \tag{3}$$ [1]

$$k = (31.6n)^6 \tag{4}$$ [2]

Finally

$$B = 2.5\ln\left(\frac{k}{z_o}\right) \tag{5}$$

where z_o is the value of z at u = 0.

It can be shown that the sensitivity of Manning's n to the depth h may be expressed as

$$\frac{\Delta n}{n} = \left[\frac{1}{6} - \frac{1}{\left\{\ln\left(\frac{h}{z_o}\right) - 1\right\}}\right] \frac{\Delta h}{h} \tag{6}$$

Here Δn and Δh are small changes in n and h, respectively. The purpose of introducing Eq. (6) is to test the effect of changes in depth due to the tide on the computation of Manning's n. If this variation is small, it would be acceptable to ignore the range of tide in the inlet for the purpose of the hydraulic computations.

The bed shear stress τ_o $(=\rho u^{*2})$ is defined as

$$\tau_o = \frac{f}{4} \rho \frac{\bar{u}|\bar{u}|}{2} \tag{7}$$

where, in the fully rough range of flow ($K > 70$), the friction factor f depends solely on the ratio of the bed roughness to the depth of flow (for a wide channel).

$$\frac{1}{\sqrt{f}} = 2.34 + 0.87 \ln \frac{h}{k} \tag{8}$$

The foregoing relationships are strictly applicable to steady, uniform wide open channels only, but Eqs. (1) through (8) should be applicable to tidal inlets with the following characteristics:

(1) no significant density stratification, i.e. low fresh water discharge relative to the tidal prism

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[1] The foot-pound-second units are used in the computations thoughout this paper; metric units have been used in data presentation only.

[2] Eq. (4) is also known as Strickler's equation.

(2) low ratio of tidal amplitude divided by the mean depth of flow

(3) relatively large width to depth ratio

(4) negligible wave-induced turbulence

(5) negligible effect of the inertia of the mass of water in relation to frictional dissipation at the bed.

PRISM-AREA RELATIONSHIP

The tidal P is by definition related to the cross-sectional mean maximum velocity $\bar{\bar{u}}_{max}$ in an inlet according to

$$P = \frac{\bar{\bar{u}}_{max} A_c T}{\pi C_K} \tag{9}$$

where A_c = throat cross-sectional area below MWL, T = tidal period and C_K is a coefficient that accounts for the deviation from the sinusoidal variation of the velocity in the inlet (Keulegan, 1967). Keulegan and Hall (1950) found that $C_K \approx 0.86$ agrees well with most inlet data. In Eq. (7), at $\bar{\bar{u}} = \bar{\bar{u}}_{max}$, $\bar{\bar{\tau}}_o = \bar{\bar{\tau}}_{omax}$, and eliminating $\bar{\bar{u}}_{max}$ with the help of Eq. (9) yields

$$\frac{P}{A_c} = \sqrt{\frac{8}{f\rho}} \sqrt{\bar{\bar{\tau}}_{omax}} \frac{T}{\pi C_K} \tag{10}$$

If f, $\bar{\bar{\tau}}_{omax}$ and T are measured, P/A_c can be calculated and compared with a corresponding ratio in which P is obtained directly from volumetric flow discharge measurement and A_c determined by a survey.

By assuming a depth as well as width averaged velocity as in an open channel, and a relatively small ratio of the tidal amplitude a_c at the throat divided by the cross-sectional mean depth $\bar{h}$, Krishnamurthy (1974) obtained

$$\frac{P}{A_c} = 1.25 u^*_{cr} T \left(1 + \frac{2a_c}{\pi \bar{h}}\right) \left[\ln\left(\frac{10 \cdot 93\bar{h}}{k}\right)\right] \tag{11}$$

Here it is also assumed that the inlet is in a state of non-silting, non-scouring equilibrium, and that in such an inlet, on the average, the friction velocity $u^* = u^*_{cr}$, corresponding to τ_{ocr}, the critical bed shear stress for the incipient motion of the grains on the bed.

An agreement between the measured P/A_c and that derived from the above two equations, particularly Eq. (10), would clearly point to the relevance of the measured value of the friction factor at the throat.

THE INLETS

Two inlets, John's Pass and Blind Pass, shown in Fig. 1, were selected for the purpose of the measurements. These inlets connect the Gulf of Mexico to Boca Ciega Bay, near Tampa, Florida. Despite their relative proximity, the two inlets have disparate morphological characteristics, as seen from Table 1.

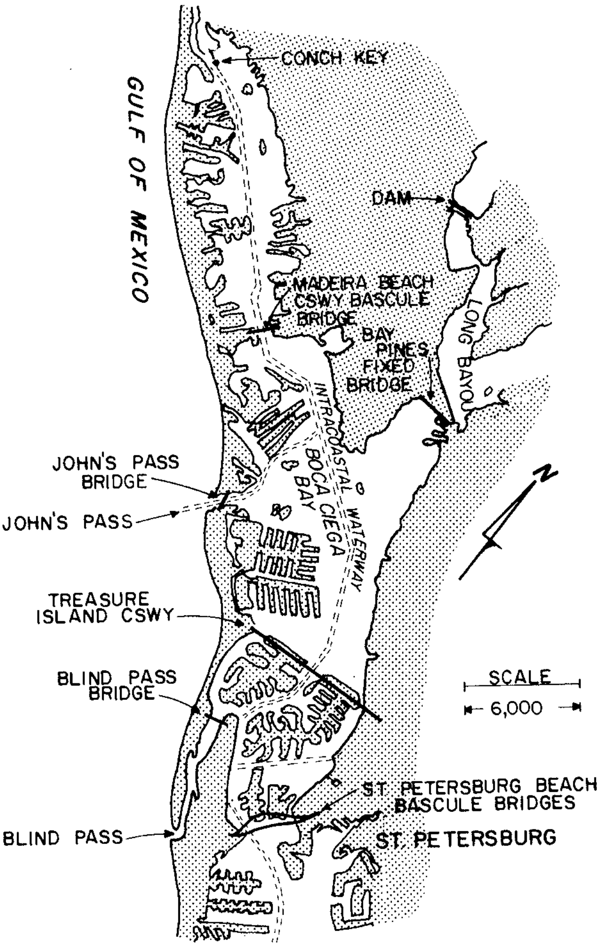

Fig. 1. John's Pass and Blind Pass Connect the Gulf of Mexico to Boca Ciega Bay. The City of Tampa (not shown) is due Northwest.

TABLE 1

Inlet	Mean Oepth $\bar{h}$ at the Throat below MWL (ft)	Throat Cross-section A_c below MWL (ft^2)	Length of the Channel (ft)	Jetties	Stability
John's Pass	16.0	9,500	2,200	one	Good
Blind Pass	5.2	440[3]	1,200	two	Intermediate

John's Pass is a stable inlet with no major problem of sedimentation. The 1,200 ft. long Blind Pass channel is followed by another 6,000 ft. long and relatively wider channel which enters Boca Ciega Bay. This second segment of the channel may, however, be considered to be a part of the bay itself, as currents in this channel are relatively low (Sanchez-Oiaz, 1975). The inlet cross-section has been decreasing steadily during the past century (Mehta and Adams, in press), and there have been some shoaling problems near the entrance, but the inlet has remained open. Figs. 2 and 3 give a closer look at these inlets, and indicate the locations of the throat sections. The penetration of ocean waves at these sections is minimal. Currents and salinity profiles indicated that the fresh water outflow at these inlets is rather small and that density stratification is not significant. The bed at the throat of John's Pass is laden almost entirely with relatively large pieces of shell. At Blind Pass, shells are found in patches surrounded by relatively fine sand.

EQUIPMENT

The essential equipment consisted of a vertical array of five ducted impeller current meters fitted inside a steel cage which could be lowered at the desired location from a specially designed A-frame on a barge. The following is a brief description of the current meter and the cage.

The current meter (Fig. 2): This consisted of a 3 in. o.d. and 6 in. long stainless steel duct containing an axially mounted impeller with six Epoxyglas blades. Two small magnets attached to the tip of two of the blades closed a reed switch mounted on the duct. The circuit was connected through a long insulated wire to a deck unit which could count the actuation caused through the rotation of the impeller. The counts were calibrated to yield the current speed (Byrne and Boon, 1973).

The cage (Fig. 2): This consisted of a framed cube, 4 ft. on the edge, constructed of 1 x 3/16 in. angle iron. For stability at the bottom of the inlet, the base of the cage was weighted with four 75 lb. lead weights fastened, one each, to the bottom corners of the frame. The vane assembly (which helped align the meters along the direction of flow) was fabricated from a 45 in. section of channel aluminum, modified to accept the mounting arms of five current meters, which were installed at 21.6, 36.2, 51.4, 75.6 and 103.6 cm above the base of the cage. Outputs from the current meters were monitored on a barge, anchored at a position close to the cage. A more detailed desciption of the equipment

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[3] Based on data obtained in 1974 prior to the construction of new jetties.

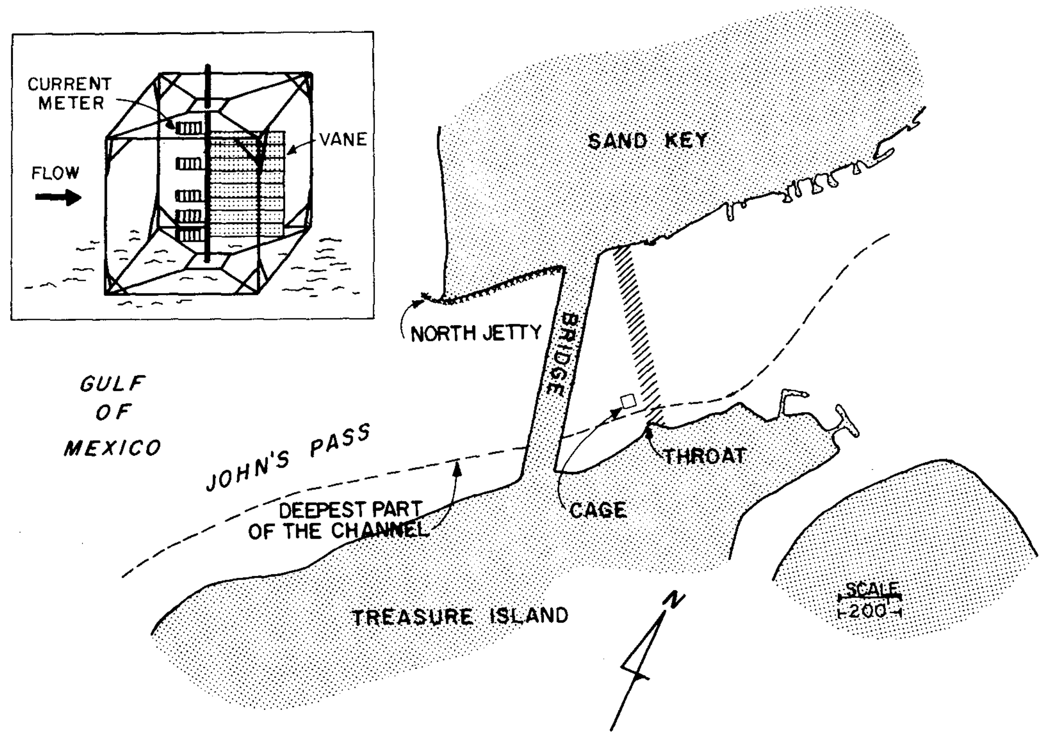

Fig. 2. John's Pass. The Inset Shows the Steel Cage with the Current Meters and the Vane Assembly.

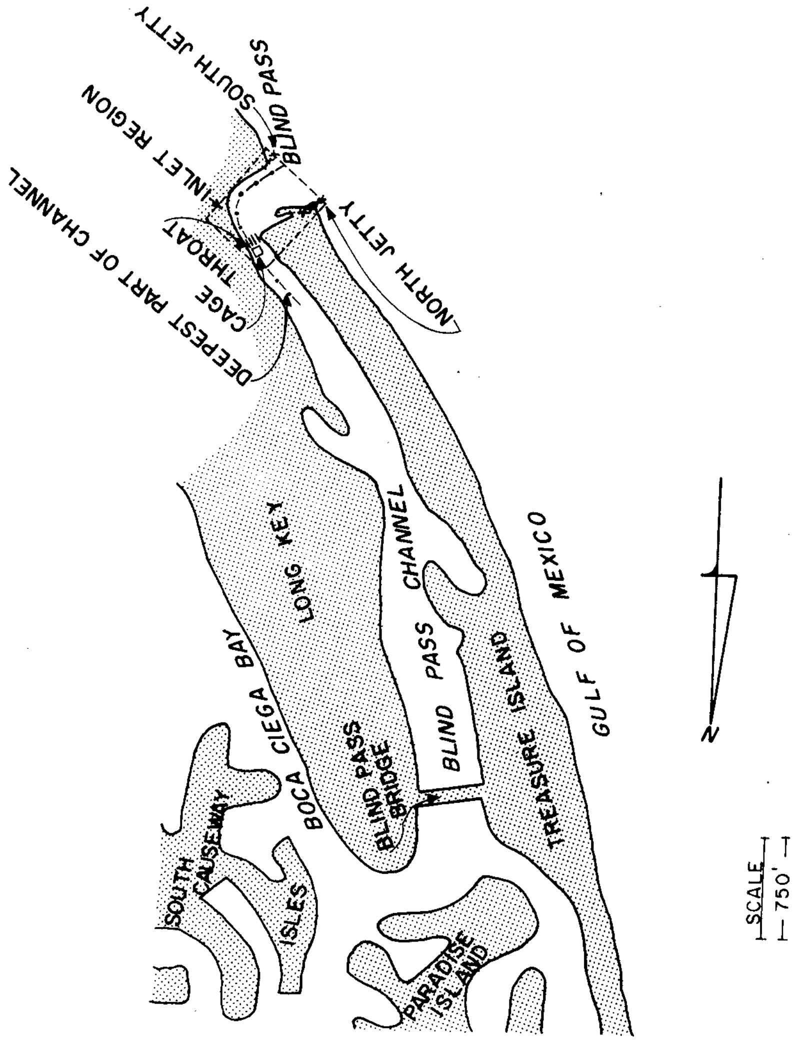

Fig. 3. Blind Pass. Note the Narrow Throat Section.

and its use may be found elsewhere (Mehta, Byrne and DeAlteris, 1975).

FIELD STUDY

The original plan was to obtain near-bed velocity profiles at a number of points across the throat by moving the cage from point to point, but time limitation and the presence of very heavy seaweed concentrations in the flow along certain parts of the channel at John's Pass permitted measurements at one location only, namely at the deepest part of the channel near the throat (Fig. 2). At Blind Pass, due to the narrow throat section, the measurements were also taken at one location only (Fig. 3) close to the deepest channel.

At John's Pass, data were collected on August 5, 6, 7, 8 and 9, 1974, and on August 14 at Blind Pass. On each day, counts corresponding to each of the five current meters were simultaneaously recorded from the deck units on the barge every few minutes, for a total time period ranging from slack to slack (one-half tidal cycle). At John's Pass measurements were obtained over floodtides and at Blind Pass over an ebbtide. The depth of water below MWL at the site of the cage was 25 ft. at John's Pass and 12 ft. at Blind Pass.

In addition to the near-bed profiles a single current meter at John's Pass obtained a few profiles over the entire depth. At Blind Pass, a current meter was installed near the throat to yield a continuous velocity measurement there. Tides were measured at both the inlets and a set of six stilling wells were installed at Blind Pass to measure the water surface slopes near the throat. Divers made observations on the state of sediment motion at the bed.

DATA ANALYSIS

Due to fouling by seaweed, divers had to clean the meters from time to time. For data analysis, any profile with less than four data points was considered unsuitable. As a result, for example, all the profiles obtained on August 6 had to be eliminated.

Fig. 4 shows examples of the velocity profiles obtained at John's Pass on August 9, and Fig. 5 shows profiles at Blind Pass on August 14. As in these examples, almost all the profiles were found to be logarithmic, according to Eq.(1). The ratios, a_c/h, of the average amplitude of tide to the depth of flow at the cage during the experiment were as follows: .

TABLE 2

Inlet	a_c (ft)	h (ft)	a_c/h (%)
John's Pass	0.76	25	3
Blind Pass	1.36	12	11

Thus at John's Pass, the tidal amplitude was 3% of the depth at the cage and at Blind Pass it was 11%. Using a typical value of z_o = 0.007 ft., and these percent changes in depth, Eq.(6) gives the corresponding $\Delta n/n$ as less than 0.1% at John's Pass and less than 0.2% at Blind Pass. It can be shown likewise, that the percent changes in $\bar{u}^2$ corresponding to the above changes in depths are also negligible. Thus in Eqs.(3) and (7), the effects of tidal

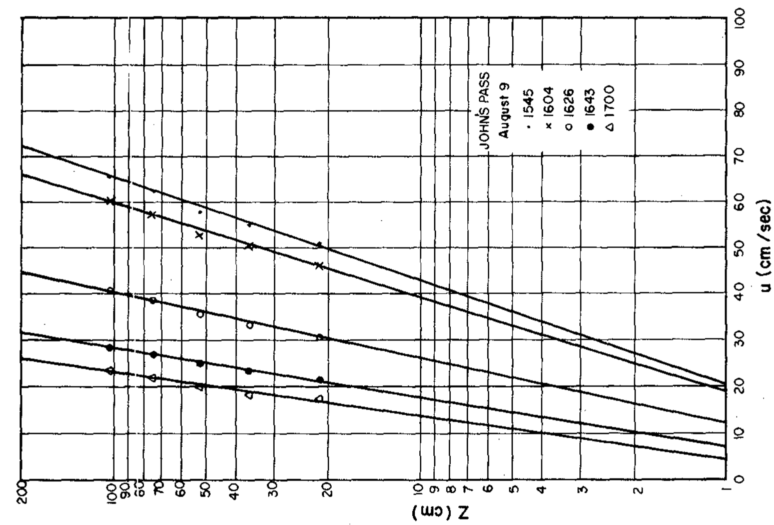

Fig. 4. Typical Examples of Near-bed Velocity Profiles at John's Pass, August 9, 1974.

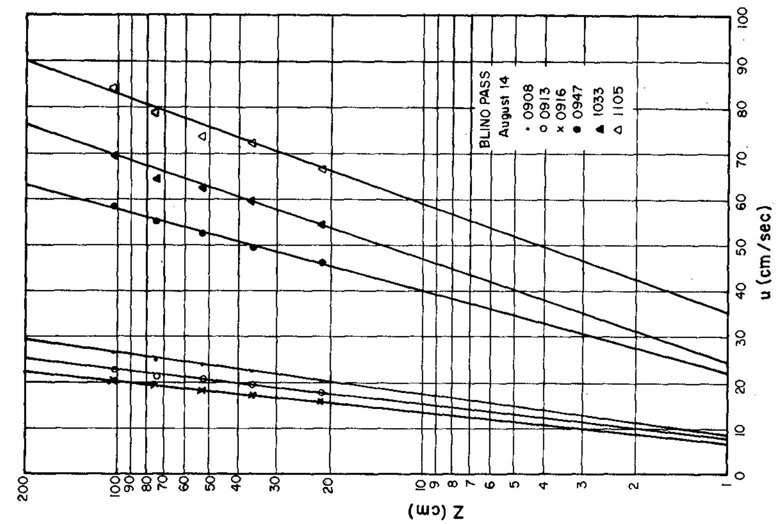

Fig. 5. Typical Examples of Near-bed Velocity Profiles at Blind Pass, August 14,1974.

variation on the value of n and f, respectively, may be ignored. In all computations, therefore, only the depth below MWL at the site of the cage was used.

The question of the effect of inertia was dealt with by observing the behavior of the coefficient M

$$M = \frac{\frac{\partial \bar{u}}{\partial t}}{\frac{f}{8h} \bar{u}|\bar{u}|} \tag{12}$$

which is the ratio of the temporal acceleration term divided by the friction term in the momentum equation.[4] In Fig. 6, $\bar{u}$ and M are plotted for the floodtide on August 9 at John's Pass. From slack to slack, the period of flood is 5 hr. 45 min. It is observed that at times of fluctuation in current speeds M becomes large, but its value is most significant close to times of slack water, where the inertia effect is clearly dominant. Consider for example the time period during which $|M|$ is equal to or greater than unity. Ignoring those times when this occurs for short intervals, and taking only the periods close to slack waters, the total time interval when $|M| \geq 1$ is 45 min., which is only 19% of the flood period. Measurements on other days at John's Pass yielded similar values, and at Blind Pass, on August 14, $|M| \geq 1$ only during 11% of the ebb. These observations tend to indicate that it is not unreasonable to use steady, uniform flow formulas for tidal inlet hydraulics although, clearly, phenomena close to slack water are likely to be strongly influenced by the effects of inertia.

In all calculations, $\bar{u}$, as computed from Eq. (1), was used instead of one which may be obtained from a measured velocity profile over the entire depth of flow. This is because only a few of the latter were obtained, and it was found that the average velocities obtained from these did not differ to any appreciable extent from those obtained from the near-bed profiles.

RESULTS

Fig. 7 is an example of the variation of the bed shear stress τ_o with time, on August 8, at John's Pass. From recorded diver observations on the state of bed motion, it is possible to determine the corresponding bed shear stress, as indicated on the figure.

In Fig. 8, τ_o is plotted against $\bar{u}$ on logarithmic co-ordinates for all the data points from John's Pass. Of particular importance here is the observance of the square law according to Eq.(7), with a constant friction factor f. The straight line gives f = 0.027, Manning's n = 0.026 from Eq.(3) and bed roughness k = 0.31 ft. from Eq.(4). Fig. 9 shows similar data for Blind Pass, with f = 0.021, n = 0.020 and k = 0.07. A few bed shear stress values obtained from surface slopes at Blind Pass were found to be nearly twice as large as those obtained from the velocity profiles, as these included losses at the channel bend (Fig. 3) as well (Mehta et al., loc. cit.).

In both, Figs. 8 and 9, at low velocities, the data points begin to

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[4] The temporal acceleration term is much more significant then the spatial acceleration term in the flow through the channel itself. The flow may therefore be considered to be uniform.

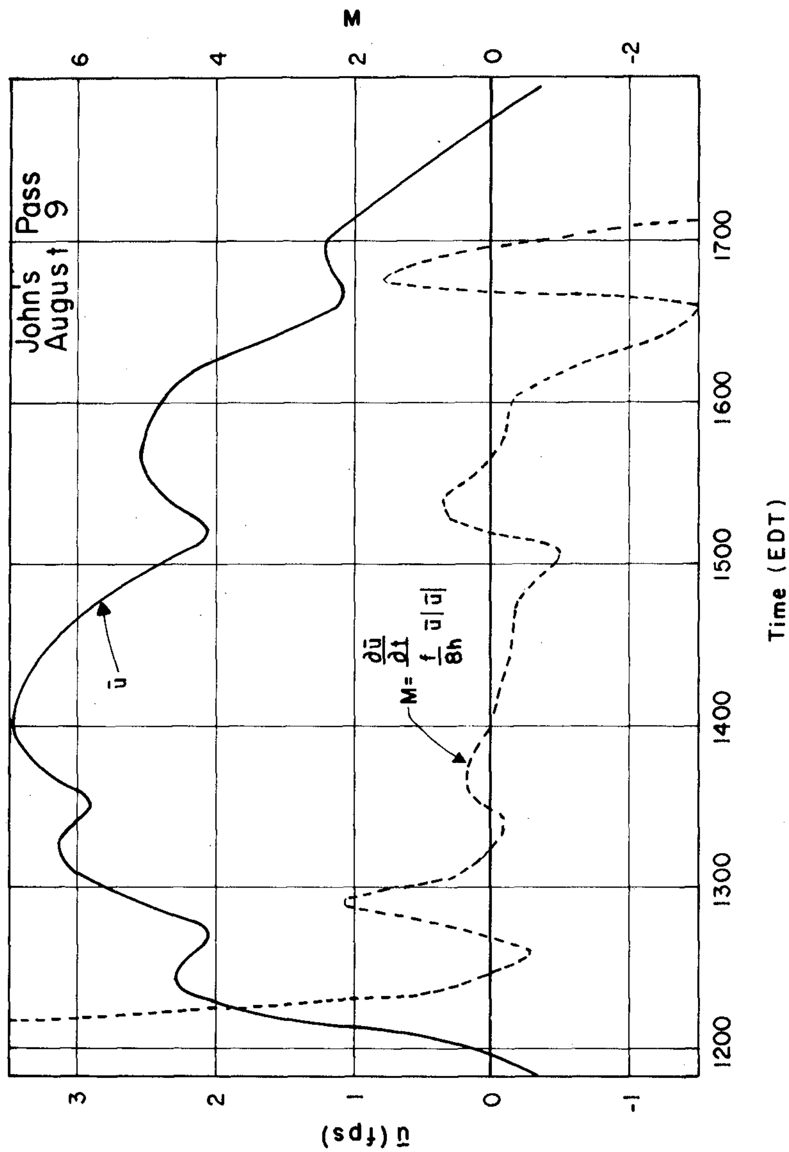

Fig. 6. Effect of Inertia Relative to Friction in Tidal Flood Flow through John's Pass, August 9, 1974.

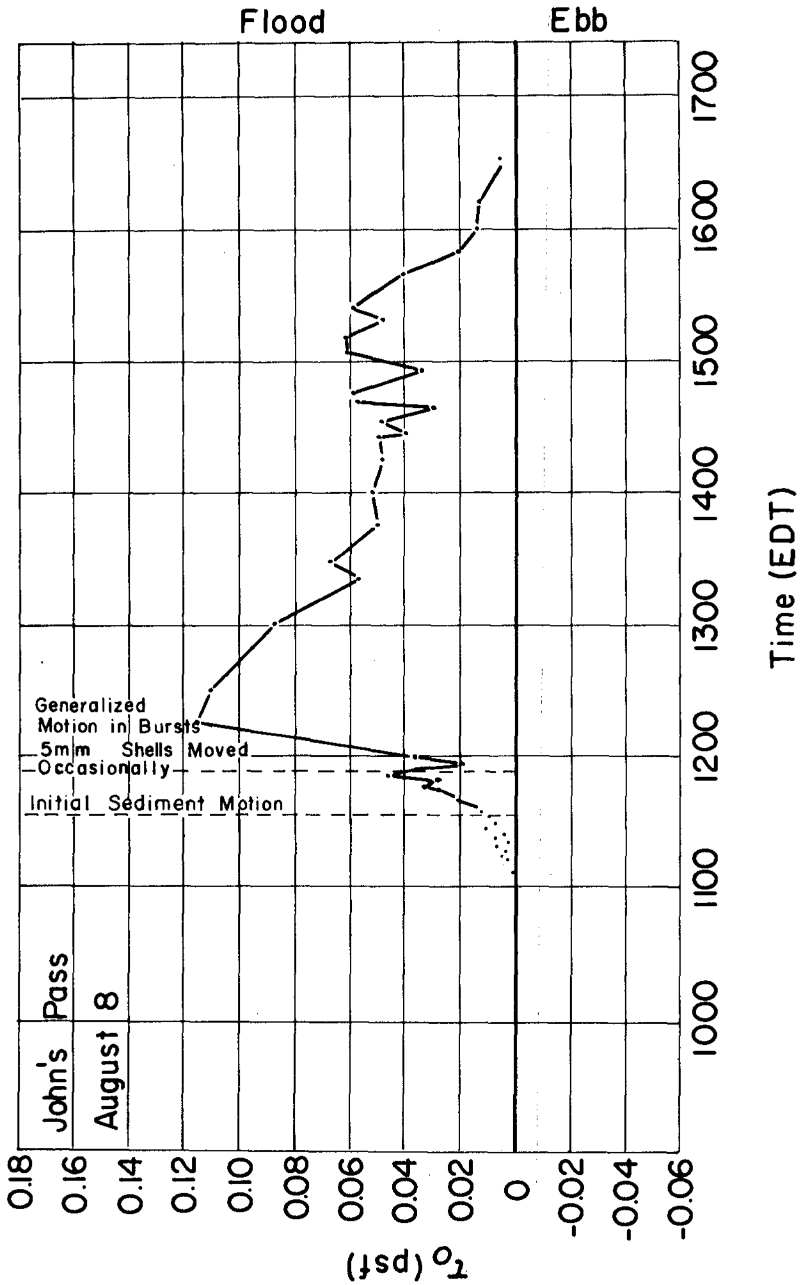

Fig. 7. Time Variation of τ_o at John's Pass, August 8, 1974.

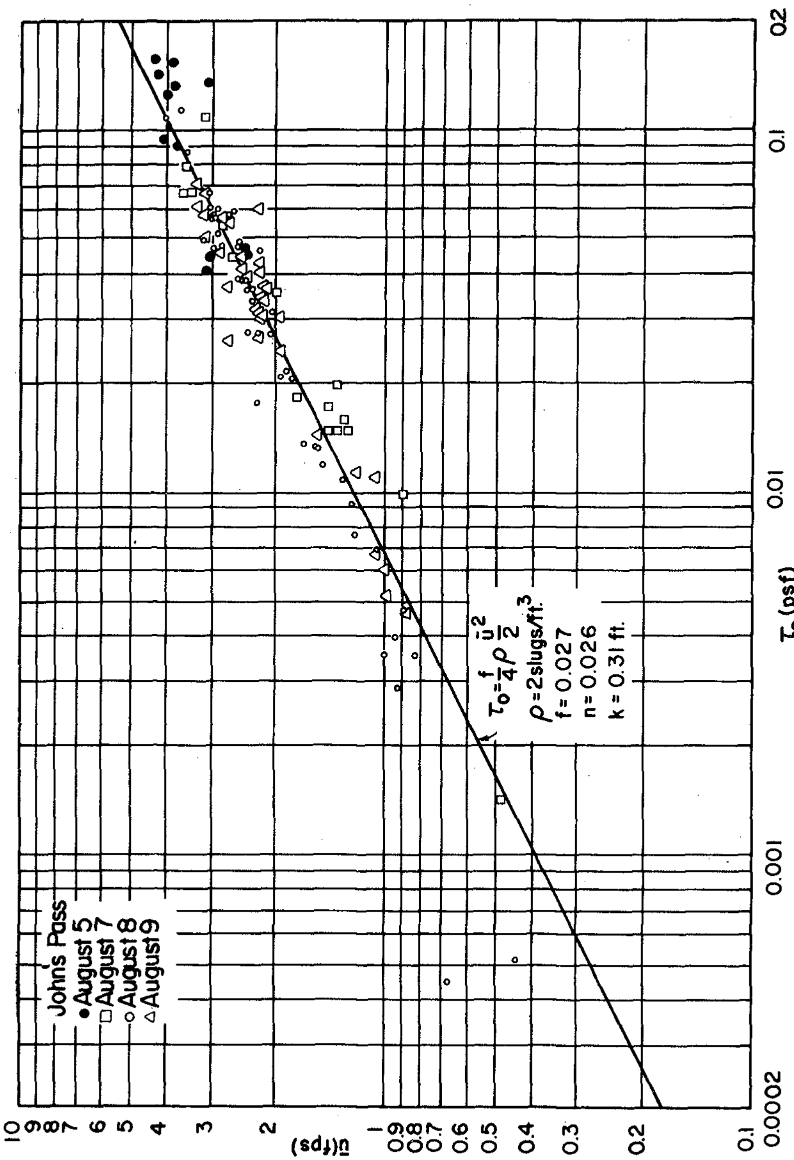

Fig. 8. Relationship between τ_o and $\bar{u}$, John's Pass.

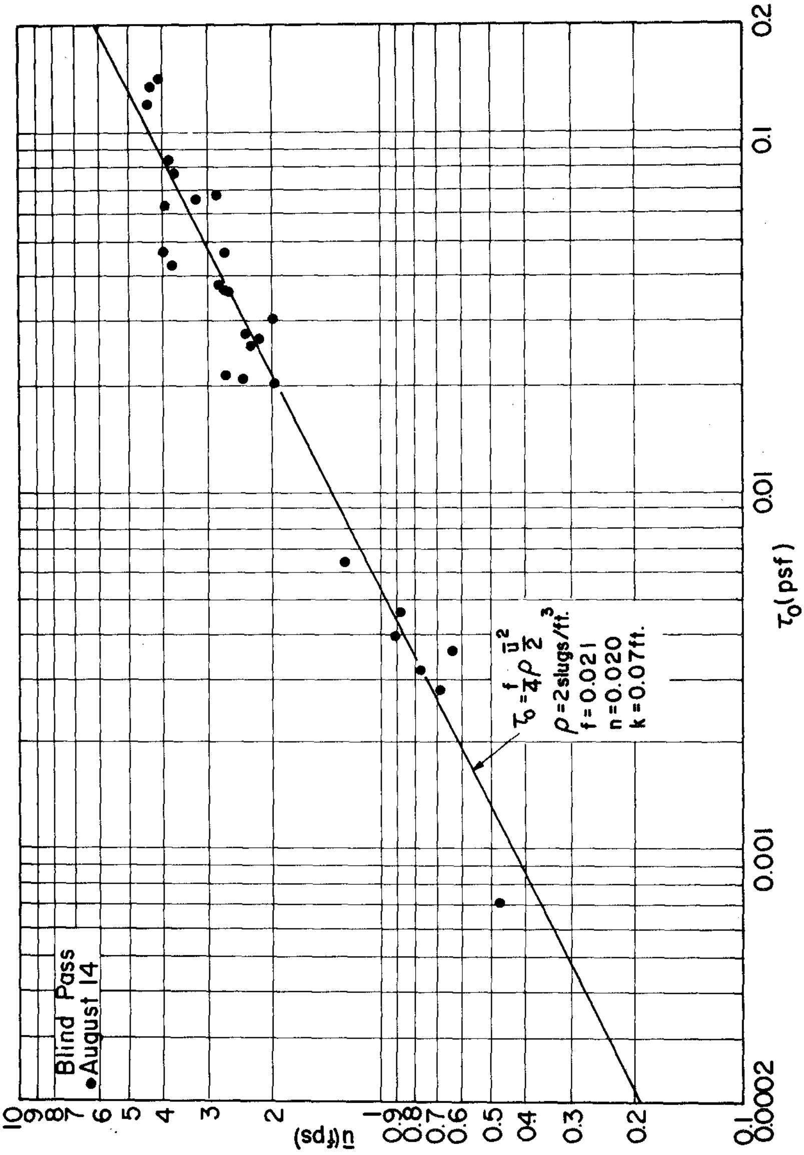

Fig. 9. Relationship between τ_o and $\bar{u}$, Blind Pass.

deviate systematically from the straight line, such that the measured shear stress is lower than that predicted by the line. This is, it can be shown, because these data points are in the transition range of flow, with $K < 70$ (Mehta, et al., loc. cit.). The friction factor f initially decreases in this range, as in an open channel, giving lower τ_o values.

At flow velocities near 4 fps and greater, another deviation from the straight line is observed in Figs. 10 and 11. This deviation is such that the measured friction factor f is greater than that predicted by the straight line, and is possibly due to a changing bed roughness associated with a re-orientation of the bed at these high velocities.

In Figs. 10 and 11, the coefficient B of Eq.(1) calculated from Eq.(5) has been plotted against K, for John's Pass and Blind Pass, respectively. A comparison with the well-known experimental relationship obtained by Nikuradse for beds of relatively uniform sand grain roughness shows that the B values from the two inlets are generally higher than those indicated by the curves. Furthermore, for high values of K, B indeed attains a constant value; B = 8.65 for John's Pass and 8.60 for Blind Pass, as opposed to 8.50 for the Nikuradse data. These higher values of B are most likely to be due to the non-uniformity of the bed material in the inlets (Yalin, 1972). Thus in the case of John's Pass, where the proportion of shell on the bed is greater than at Blind Pass, the B value is correspondingly larger. This fact is clearly reflected in the values of the bed roughness k as well.

Measured tidal prisms and the tide ranges at the two inlets are given in Table 3. The prism through John's Pass is an order of magnitude larger than that through Blind Pass. Indeed, the former inlet is primarily responsible for the flushing of the northern portion of Boca Ciega Bay.

TABLE 3

Date	Inlet	P (ft^3)	$2a_c$ (ft)
August 5	John's Pass	5.46×10^8	1.97
August 6	John's Pass	4.16×10^8	1.74
August 7	John's Pass	3.74×10^8	1.44
August 8	John's Pass	------	1.28
August 9	John's Pass	2.44×10^8	1.72
August 14	Blind Pass	3.77×10^7	2.72

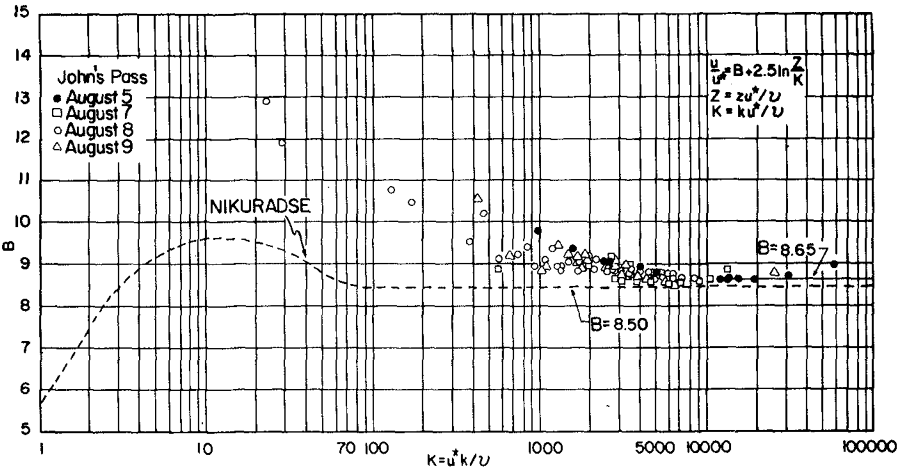

Fig. 10. Coefficient B of Eq.(1) Plotted against Wall Reynolds Number K, John's Pass.

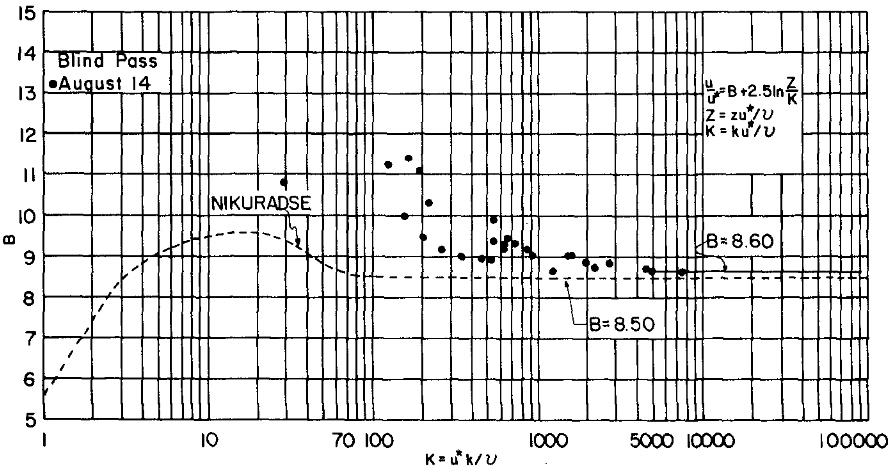

Fig. 11. Coefficient B of Eq.(1) Plotted against Wall Reynolds Number K, Blind Pass.

BED MOVEMENT

The motion of sand and shell was observed by the divers and is summarized in Table 4.

TABLE 4

Observation	τ_o (approx. range) (psf)
No detectable motion	0.000 - 0.010
Incipient motion of individual sand grain	0.010 - 0.015
Creeping motion of sand and "small" shells	0.015 - 0.045
Movement of individual "large" shells	0.045 - 0.060
Movement of the entire shell bed	0.060 -

Ranges of bed shear stress τ_o were determined by matching the times of observation with τ_o in plots such as Fig. 7. Since the diver observations were somewhat subjective, and the sediments in the two inlets are similar (the median, shell free sand diameter is 0.22 mm. at both the inlets), the classification of bed movement in Table 4 ignores any differences in bed motion between the two inlets. In the table, "small" refers to shell pieces less than approximately 5 mm. in diameter, and "large" to pieces larger than 5 mm. in diameter.

Because of the relatively small quantities of fine sand and shell pieces in motion at low flow velocities, attempts to collect the sediment in bed-load traps were not successful. Also, at high velocities, the divers were unable to enter the waters, and therefore could not make observations on the sediment motion when the currents were maximum.

OISCUSSION

A way in which the relevance of the friction factors derived from measurements at the throat may be determined is by testing Eqs.(10) and (11) against P/A_c determined from discharge measurements. Table 5 summarizes the calculations.

TABLE 5

	P/A_c (ft)	
	John's Pass	Blind Pass
Eq. (10)	5.12×10^4	8.81×10^4
Eq. (11)	3.04×10^4	4.26×10^4
Measured	4.08×10^4	8.54×10^4

The ratio for John's Pass represents a four day average (τ_{omax} = 0.16, 0.11, 0.10 and 0.06 psf at John's Pass and 0.13 psf at Blind Pass). In the estimation of τ_{omax}, a smooth curve was fitted to each of the τ_o-time curves, and the maximum was selected. A correction to this maximum was applied according to

$$\bar{\bar{\tau}}_{omax} = (\bar{\bar{u}}_{max} / \bar{u}_{max})^2 \tau_{omax} \tag{13}$$

to account for the transverse velocity profile. Here, $\bar{u}_{max}$ and τ_{omax} are values at the location of the cage, $\bar{\bar{\tau}}_{omax}$ and $\bar{\bar{u}}_{max}$ are the corresponding cross-sectional averages. It was found that $\bar{u}_{max}/\bar{\bar{u}}_{max}$ = 0.90 and 0.86, at John's Pass and Blind Pass, respectively. Also, measurements gave C_K = 1.0 and 0.84, respectively.

Table 4 indicates that Eq.(10) predicts a P/A_c which is larger than the measured value by 25% at John's Pass and 3% at Blind Pass. This implies that the appropriate value of the friction factor f in Eq.(10) should be 1.56 times the directly measured value (0.027) at John's Pass, but only 1.06 times the measured value (0.021) at Blind Pass.

It is interesting to note that, considering the assumptions involved, Eq.(11) (with $u^*_{cr} = \sqrt{\tau_{ocr}/\rho}$ = 0.079 fps) agrees reasonably with the measurements at John's Pass, but predicts a substantially lower P/A_c at Blind Pass. A possible explanation for this is that Blind Pass is not a very stable inlet. This is reflected by the rather large measured P/A_c value as well.

Another comparison can be made through Eq.(8). This equation gives f = 0.026 and 0.022, which is in excellent agreement with the measurements. These values are obtained by using the local mean depth h = 25 ft. and 12 ft., respectively, at the two inlets. If the cross-sectional mean depths $\bar{h}$ from Table 1 are used, f = 0.030 and 0.027 respectively, at John's Pass and Blind Pass.

It is worthwhile to compare, the observed relationship between the critical stress at incipient motion and the grain size, with the well-known relationship obtained by Shields for channels with sand beds in the fully rough range of flow:

$$\tau_{ocr} = 0.056\ (\gamma_s - \gamma)\ d_{50} \tag{14}$$

where γ_s is the unit weight of the sand grain (=169 lbs/ft^3), $\gamma = \rho g$ = 64 lb/ft^3 and d_{50} is the median grain size. Using d_{50} = 0.22 mm = 0.0007 ft. gives τ_{ocr} = 0.004 psf, whereas the observed value was close to 0.013 psf. It has been shown elsewhere (Mehta and Christensen, 1976) that this discrepancy is due to the presence of a rather large ratio of the bed roughness k to the diameter d_{50}, and also due to the differences in the velocity profiles from that in a channel with a uniform sand grain bed.

CONCLUSIONS

1. The velocity profiles in the bottom one meter of the flow near the deepest part of the channel throat section were found to be logarithmic at John's Pass and Blind Pass.
2. The effect of inertia was found to be important in relation to frictional dissipation near the times of slack water. Elsewhere, this effect may be considered to be relatively insignificant.
3. The bed shear stress and the depth-mean velocity derived from these profiles were found to be related by the square law in the fully rough range of flow, with a characteristic friction factor and a Manning's n for each inlet.
4. The velocity coefficient B was found to vary in a manner similar to that in a wide open channel, but B values were generally higher for the two inlets.

5. The tidal prism-throat cross-sectional area ratio, as determined from a hydraulic relationship, Eq.(10), agreed with the directly measured ratio at Blind Pass, but at John's Pass, there was a difference, indicating that f, as determined from the measurements, was 56% too low.
6. Shields' criterion for the incipient motion of sand grains predicted a critical shear stress which was about one-third of the observed value.

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