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A REVIEW OF THE CHARACTERISTICS, BEHAVIOR AND DESIGN REQUIREMENTS OF TEXAS GULF COAST TIDAL INLETS

Prepared by

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ABSTRACT

This paper is intended to provide the reader with a background in the design of tidal inlets. In order to adequately achieve this end, an effort is made to present the hydraulic equations generally used to describe the flow in a tidal inlet along with an explanation of the simplifying assumptions normally made. Consequences of these assumptions as well as relative sizes of the terms deemed negligible are included.

Consideration is given to the response of tidal inlets to such outside influences as wave action, littoral drift and tides. Presently accepted methods for determination of inlet stability are included, and the necessary parameters for an effective inlet design are presented.

Finally, a bibliography containing the foremost publications in the field of tidal inlets is presented. Materials on specific topics are listed under categories deemed appropriate by the writers.

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NOTATION

A = minimum flow cross-section of entrance channel measured below mean sea level,

A_B = surface area of the bay,

A_{cs} = cross-sectional area of the channel,

a_b = amplitude of bay above datum,

a_s = amplitude of sea above datum,

c = wave celerity,

C = Chezy's coefficient,

d = water depth below Mean Sea Level,

f = friction factor,

g = acceleration of gravity,

H = mean tidal variation in feet,

h_ℓ = head loss in feet,

K = Keulegan's coefficient of repletion,

K_{en} = loss coefficient at entrance,

K_{ex} = loss coefficient at exit,

ℓ = channel length,

m = coefficient resulting from velocity distribution,

n = Manning's "n",

P = pressure,

p = wetted perimeter,

Q = discharge,

R = hydraulic radius,

T = tidal period,

u, v, w = velocity components in the cartesian coordinate system,

V, v_c = mean velocity in channel,

v_s = velocity of flow in the sea,

v_b = velocity of flow in the bay,

ρ = water density,

τ_v = viscous and turbulent shear stresses,

Ω = tidal prism, and

γ = specific weight.

INTRODUCTION

The usefulness of natural and artificial tidal inlets has become increasingly apparent in recent years. Aside from the obvious advantage of increased navigational access to coastal waterways, wise use of artificial inlets can enhance tidal regions in other ways. Through salinity and pollution control, an ecologically balanced region for fish migration and spawning can be provided. With proper management, tidal inlets can be used to increase the value of recreational facilities in the coastal zone and enhance the possibilities for sport and commercial fishing in a given region.

At present a need exists in Texas Coastal regions for increased interaction between Gulf and lagoon waters. Various bays suffer from either high or low salinities which might be remedied by addition of properly placed artificial inlets. For example, the Laguna Madre often suffers from excessive salinities due to the high evaporation and low precipitation in the area. Galveston Bay, on the other hand, is plagued by unusually low saline content after heavy rains.

Along the Texas coastline, there are six major natural passes which have remained open for over a hundred years. Four of these have been stabilized with jetties (46). In addition a number of river mouths open into the Gulf and approximately eight other passes have functioned intermittently. At this writing four artificial inlets also serve the Texas Coast: the channel to Port Mansfield, Corpus Christi Fish Pass, Matagorda Bay Channel, and Rollover Fish Pass. The primary function of the first two is to provide navigational access to inland waters. Rollover Fish Pass and Corpus Christi Fish Pass were designed to provide for fish migration as well as salinity control for East Bay and Corpus Christi Bay respectively.

A number of other attempts have been made to provide access routes between the Gulf of Mexico and the bays along the Texas Coast. The Texas Game, Fish and Oyster Commission (now Texas Parks and Wildlife Commission) introduced a series of artificial cuts over natural washovers at several locations along the coast. In all but one case, Cedar Bayou, siltation rapidly closed the channels (33). In most of these cases no design criteria were applied while in others poor or insufficient design resulted in a variety of undesirable side effects.

A hydraulically unbalanced inlet can result in excessive scour as in the case of Rollover Fish Pass (50) or it may result in siltation as in the case of early attempts to dredge a pass at Corpus Christi (46) and several other locations. Should an artificial inlet remain open its interference with littoral drift makes downcoast erosion possible. Indescriminate cutting of tidal inlets may result in an undesirable alteration of tidal flow or circulation patterns in the bay system. Addition of a pass or enlargement of an existing navigation route may cause drastic changes in otherwise stable channels which connect the same bay system to the open sea. For instance, the enlargement in the channel opening at Aransas Pass in the early 1930's caused Corpus Christi Pass to be closed by littoral drift (46).

Present scientific and engineering principles can be applied to obtain a rational design for an artificial or semi-artificial tidal inlet. Currently there are several methods available to obtain an approximation to the stability of tidal inlets. A certain amount of initial investigation is necessary in order to effectively apply the present degree of sophistication to achieve an adequate design. However, a relatively small amount of field investigation and theoretical analysis may allow the design of an inlet to be carried out with the same degree of certainty as other hydraulic systems and could result in significant long term savings from an economic as well as environmental standpoint.

A good deal of work has been done in recent years in studying the stability and impact of natural and artificial inlets on their surroundings. A large amount of material is available. However, there is a real need for presentation of this information and background material in a condensed form. The objective of this report is to fill this need with specific reference to the Texas Coastal Zone.

CHARACTERISTICS OF NATURAL INLETS

Sandy beaches found on a large number of ocean shorelines are generally in a state of dynamic equilibrium. A continuous process of erosion and deposition motivated by wind, wave action, tides and currents is carried on in the coastal zone. Seasonal variations are a common occurrence along sandy coasts with material moving up the beach face during the periods of relative calm and being removed to offshore bars during storms (34). Short term variations can often be found after the passage of hurricanes or natural phenomena of similar magnitude. The majority of the time actual equilibrium conditions will never be fully attained due to the extreme variability of the factors influencing the coastal sediment processes. However, if the beach does not exhibit excessive erosion or accretion over a period of years, it can, for engineering purposes, be considered stable.

Along a coastline such as Texas', characterized by barrier islands and enclosed lagoons, a number of tidal inlets can be found. Some are natural, others artificial, but all have several characteristics in common. Generally, the most active area along a coast consisting of a series of barrier islands can be found in the vicinity of tidal inlets. The rapid variations in the flow regime of the inlet induced by tidal fluctuations can cause relatively rapid changes in the coastal geometry of a given region. Consideration of the behavior of natural inlets is helpful in avoiding difficulties in the design of a completely artificial cut or the stabilization of an existing pass.

a) Inlet Formation

Bruun and Gerritsen (17) suggest that natural tidal inlets can be categorized into three types according to method of origin: geological, hydrological, and littoral drift.

Those inlets with geological origins such as the fjords of Norway or San Francisco's Golden Gate are formed by processes other than erosion and do not strictly follow the patterns for alluvial channels. Although they are not considered herein, it should be noted that some characteristics of coastal inlets in general may still exist.

River mouths discharging to the sea cause the formation of inlets with hydrologic origins. The flow regime may be considerably different from that in a tidal inlet with complexities introduced by the intrusion of saline water into fresh water from the river's discharge. Basic characteristics found in tidal inlets may also be found in river mouths, and application of the basic theories can be made to these channels. An example of this type of inlet found along the Texas Coast is the mouth of the Brazos River.

The third type, and the ones of primary importance herein, are those whose origins are intimately related to littoral drift. Some are the result of the formation of a littoral barrier across a bay or river mouth (16). Longshore transport causes deposition of material in the entrance of a river or bay. If flow velocities at ebb tide are insufficient to cause scour of the sediment and a continuous supply is available, a spit or bar forms across the body of water. Growth continues up to an equilibrium condition in which all the material deposited at the inlet is scoured from the channel during the tidal cycle. East Rockaway Inlet, New York, is an example of a tidal pass formed in this manner (17).

Formation of inlets through barrier islands can also be the result of breakthroughs. The majority of natural tidal inlets in alluvial material can be attributed to this method of formation (17).

Two methods of breakthrough of tidal inlets in existing barrier islands have been given. Johnson (9) suggests that wave action on the ocean side of the island during high water caused by the passage of a large storm washes water over the low parts of the barrier. The water scours a channel and an inlet is formed. A second theory proposed by Shaler (62) holds that tide levels in the lagoon rise sufficiently to allow water to pour over the low points of the island and scour an inlet. Pierce (60) in a discussion of formation of natural inlets suggests that a sudden shift in winds to an offshore direction causes large quantities of water built up in the lagoons by storm tides, to be forced against the barrier islands. The result is a breakthrough in the low-lying areas.

Each explanation appears to have some validity. However, it is likely that some combination of these effects causes the breakthroughs which result in tidal inlets. Wave action on the ocean side brought high onto the beach by storm tides washes away dune formations protecting the island. Waves supply the energy to suspend the material and water spilling over the low points from the bay or ocean side washes away the suspended sediment and forms a channel.

Natural inlets usually form in an area conducive to their own maintenance. However, the majority of inlets caused by breakthroughs are quickly choked by littoral deposits. Their purpose is to aid in draining unusually high storm tides and runoff from the bay, and when this task is completed, the quantity of flow necessary to maintain their hydraulic efficiency is no longer available.

The majority of inlets formed by breakthroughs occur during the passage of large storms. Hurricanes passing the Texas Coast cause numerous tidal passes of this type to appear. Brown Cedar Cut and Cedar Bayou are examples.

Hurricanes can also serve the purpose of helping to maintain existing channels. The increased water levels cause higher flow rates in tidal inlets and as a result a great deal of material is scoured from the channel. Heavy rains from local storms have a similar effect, especially in estuaries which serve a large drainage basin. Strong winds, often associated with the movement of large frontal systems, contribute to the maintenance of coastal passes. These processes are of extreme importance along the Texas Coast where the normal astronomical tide range is low. Many natural inlets in the region have a slight tendency toward siltation. Over a period of years, the deposition seeking to close off the pass would succeed if strong north winds, periodic hurricanes, and occasional heavy rains did not clean out the channel.

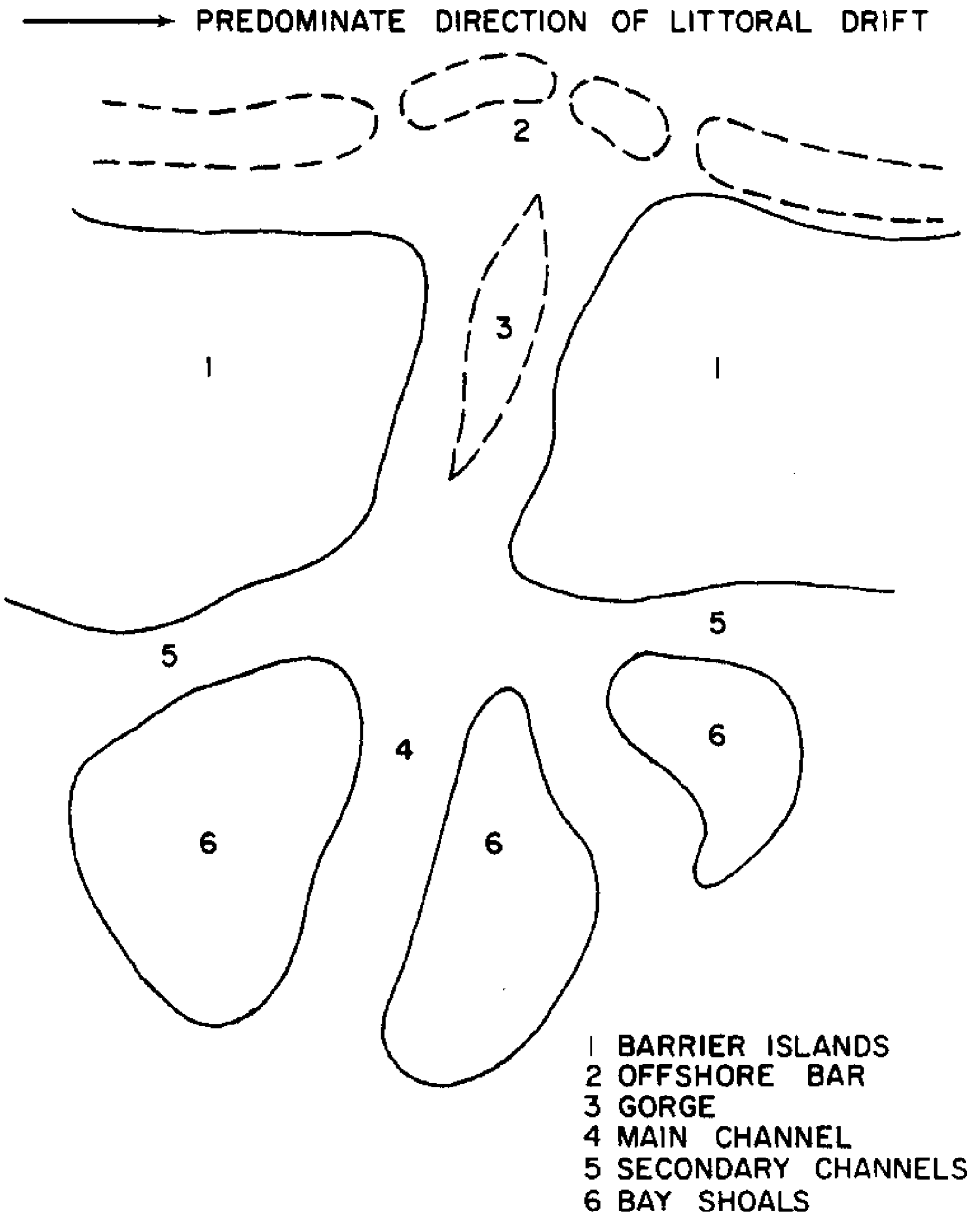
On the other hand, the passage of a hurricane over an existing inlet can have a detrimental effect. Although a great deal of material is removed from the channel, the storm causes abnormally high littoral transport rates. Large quantities of material can be deposited on the shoal areas discussed below and hasten the closure of the pass. The storm can also cause an extreme widening of the channel which results in a hydraulically inefficient flow regime during normal tidal flow. Closure may result.

Figure 1 presents a sketch of a natural tidal inlet such as might be typical of barrier beach coastlines.

b) Shoal Areas

Characteristically, the geometry and behavior of tidal inlets are intimately related to the direction and magnitude of littoral drift in a given area. Littoral currents induced by waves approaching the shore obliquely are the primary mode of sediment movement along the coastline. Longshore transport or littoral drift has been studied by several investigators (38,54,55). It has been found that material is moved in a zig-zag motion along the beach face as well as in the breaker and surf zones by the longshore current. Waves not only provide the power to keep material in suspension, but also force sediment up the slope in their direction of travel. Gravity and return flow cause it to move down the beach face and the material is transported slowly down the coast. The sediment can be supplied from updrift beaches, from sediment load of streams and rivers discharging into the coastal waters, from erosion of coastal landforms or from the net onshore movement of sediment from the open sea. The major sources of beach sand in Texas are the Brazos, Colorado and Rio Grande Rivers, and erosion of beaches.

Tidal inlets act as partial restrictions to littoral drift. A complete reversal of flow in the pass occurs over the period of one



- FIGURE 1 -
TYPICAL TIDAL INLET

tidal cycle. During the flood tide, the inlet acts as a trap for sediment attempting to pass on its way down the coast. The material is drawn into the inlet with the flow and is discharged into the bay. The relationship between sediment size distribution and current velocity will be discussed below. Suffice it to state at this point that sediment suspended by wave action and drawn through the inlet by a given current may not be carried out of the estuary by a reverse flow having the same magnitude current. Wind-blown sediment as well as sediment supplied from such sources as dredge spoils, combined with the overall tendency toward siltation behind the channel, cause the formation of bay shoals characteristic of the majority of tidal inlets.

Bay shoals may have one or more channels passing through them. For the most part, the channels are easily identifiable and maintain a constant position with time. Since bay shoals are not generally exposed to severe wave or current action, they tend to gain appreciable size and take on the lobate shape of common deltas (24). Due to the predominance of flood tides, bay shoals are a prominent feature of Gulf Coast inlets.

Along the Pacific Coast of the United States offshore shoals are generally more prominent than bay shoals. The predominance of ebb flow accounts for this situation. This flow carries some of the material deposited on the flood tide out of the bay and may jet it beyond the breaker zone where it is deposited offshore (17). Some of the material returned to the ocean may be delivered to the downdrift beach eliminating or decreasing leeside erosion (17). During the slack flow material is free to move along the coast and is deposited in the mouth of the channel.

c) Offshore Bar

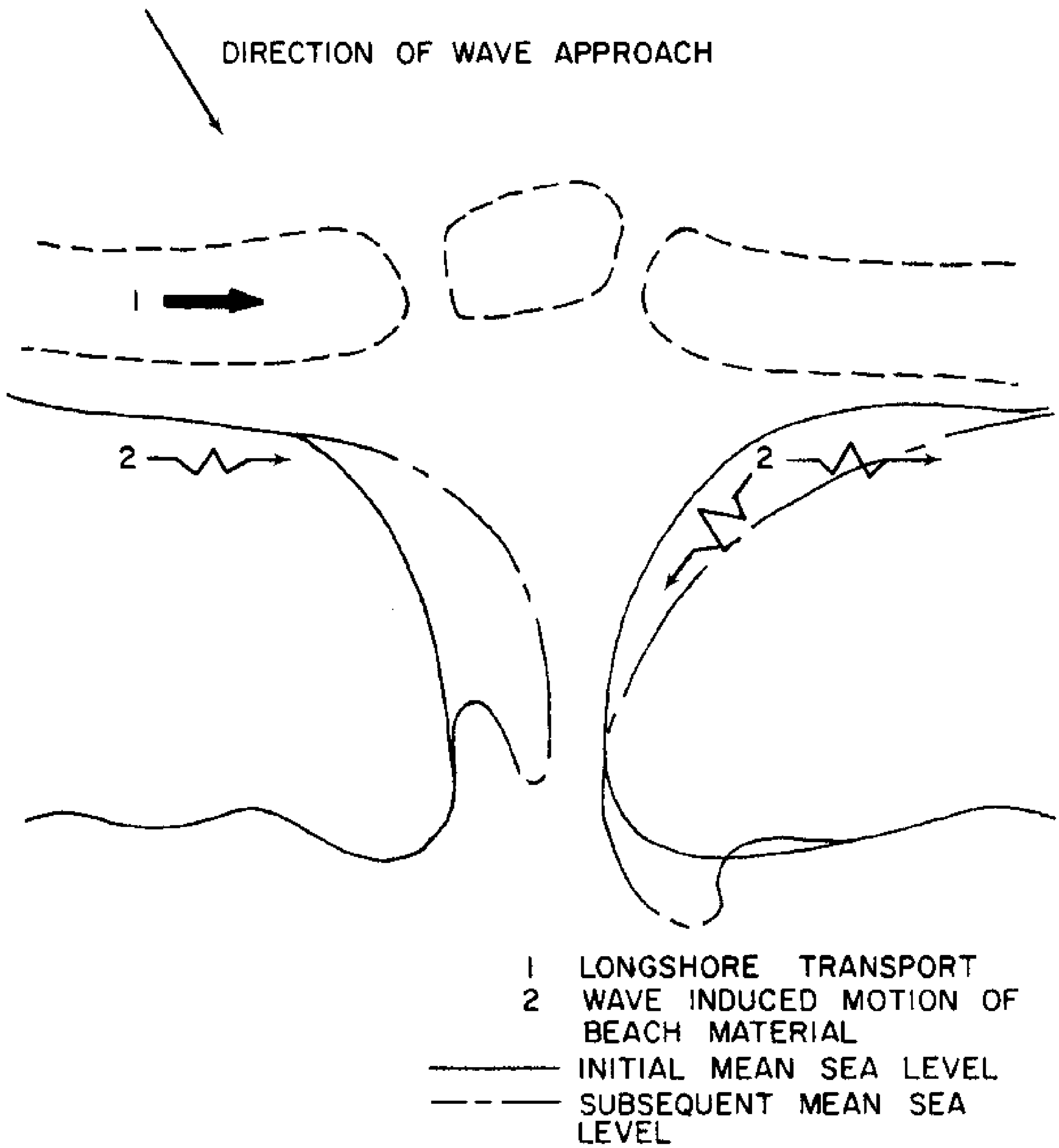
The offshore bar characteristic of tidal inlets is a mechanism for natural inlet bypassing. Generally, the bar across the mouth of the inlet is merely an extension of the bar found along the majority of sandy coasts. The jetting action of the flow during ebb tide causes the bar to be slightly bowed in front of the inlet, with one or more channels allowing access to the sea. To accomplish its function of natural bypassing, the bar must occur in fairly shallow water. In such a position, it takes advantage of the ability of waves as well as currents to transport sediment.

Since the offshore bar and shoals suffer more exposure to wave and current action, their growth tends to be limited compared with that of bay shoals. The relatively complex shape of the bay shoals is not usually found in the offshore formations.

d) Spit Formation and Channel Migration

Along with the interference with longshore transport in the breaker zone, tidal passes also disrupt the wave induced motion of sand particles along the beach face. Wave action carries the particles downcoast to the inlet. As the particles move into the cut, the wave action is no longer sufficient to cause their continued progress. The deposition at the upcoast side of the inlet causes formation of a recurved spit.

On the downdrift side of the inlet predominant wave action causes the zig-zag motion of the beach material to be in opposite



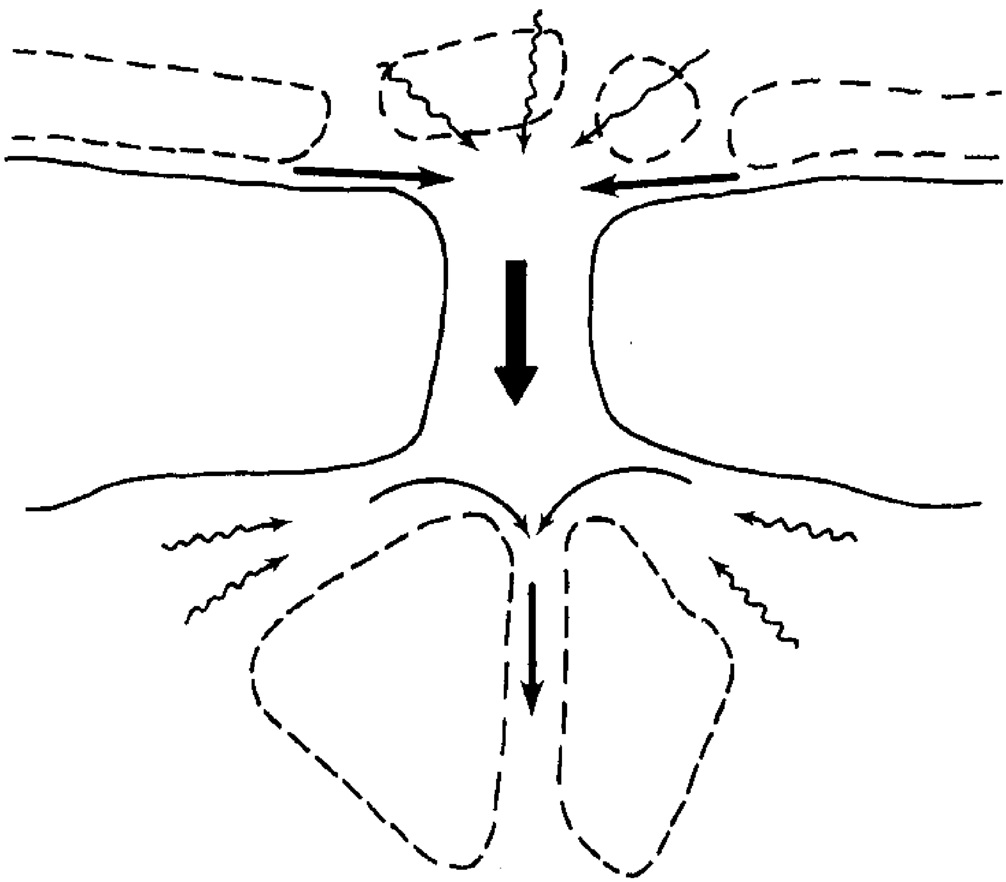
- FIGURE 2 -
SEDIMENT MOVEMENT AND SUBSEQUENT SHORELINE CHANGES

directions as indicated on Figure 2. This movement of particles causes a general erosion of the point of the barrier island.

The combined effect of the spit formation and erosion of the opposite side of the channel is a marked tendency on the part of the mouth of a natural inlet to migrate in the predominant direction of littoral drift. A change in inlet cross-section accompanies this migration. The gorge is forced against the downcoast side of the inlet while the channel can lengthen to a point where hydraulically efficient flow is no longer possible. Complete closure often results. Occasionally nature heads off this process and a change in wave climate reverses the procedure prior to a complete blockage. Storms of sufficiently large magnitude may flush the pass, or, if closure occurs, a new breakthrough may result.

e) Secondary Channels

From elementary fluid mechanics considerations, flow through tidal inlets causes a jetting action to occur. The result is that a main channel may be found in the bay shoals as a result of flood tides; and a primary channel through the offshore bar is generated by the ebb tides. Secondary channels are generated along the shoulder of the cut on the ocean side by the flood currents and on the bay side by the ebb flow. High velocities may occur in these channels on the ocean side of the inlet on the flood tide, and cause a large quantity of sediment to be washed into the inlet and deposited on the bay shoals. Jetting action on the ebb tide generates eddies on each side of the inlet, causing a flow toward the channel along the



- FIGURE 3 -
FLOW IN SECONDARY CHANNELS AT FLOOD TIDE

shoulders. The result is a continual flow toward the pass in the secondary channels as illustrated in Figure 3.

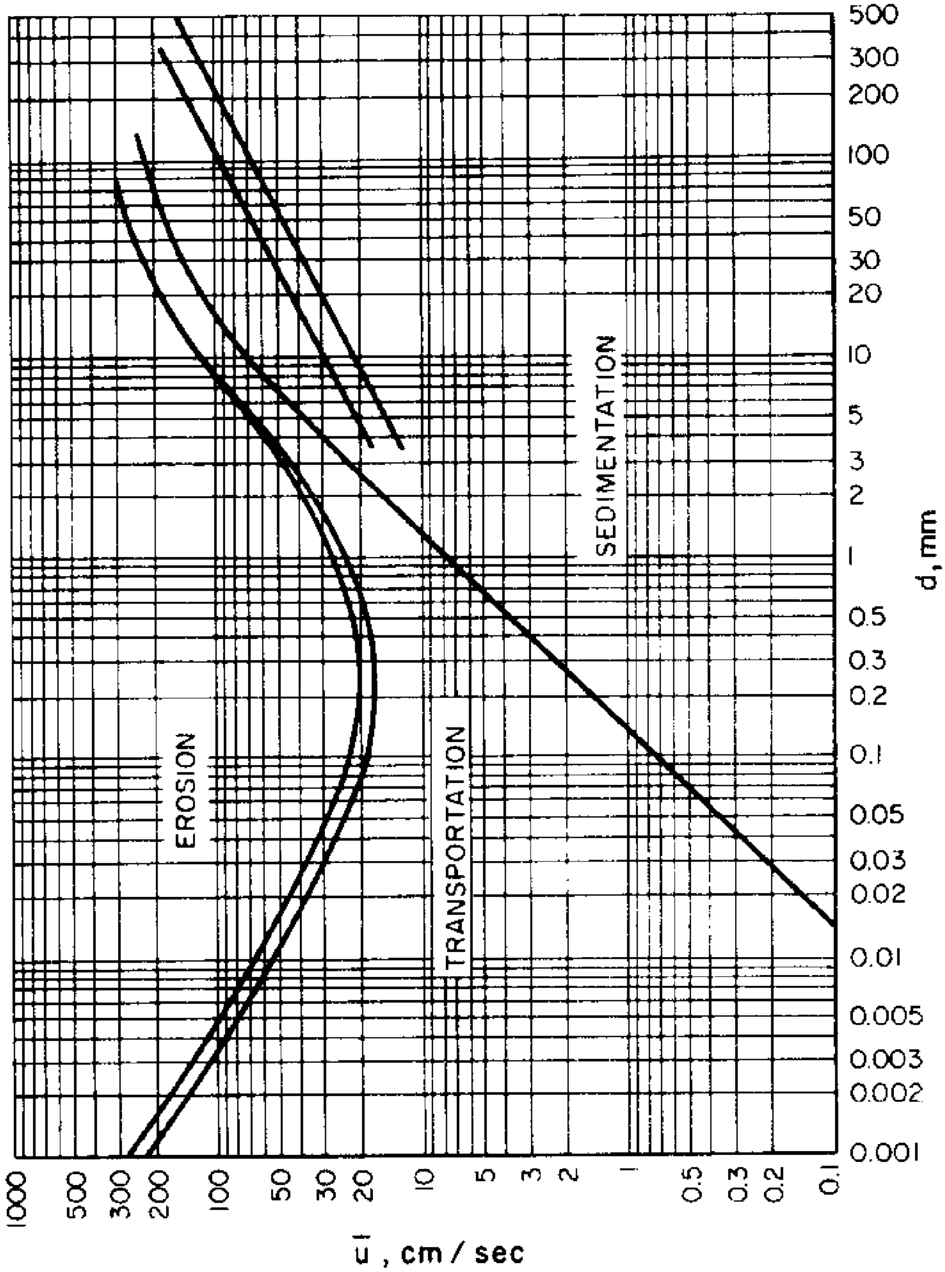
f) Sediment Size Distribution

Sediment size distribution has been documented in several field studies of tidal inlets (49,50,65). From the standpoint of initiation of motion, the larger, heavier particles will be found in areas of high flow velocity and turbulence. The highest velocities in a tidal inlet occur in the gorge and channel and, as expected, the sediment in these areas is relatively large. A natural armoring comprised of shells may cover the channel bottom (50).

The offshore bar, also an area of great turbulence, is made up primarily of coarse sand and shell. Any fine sediments are suspended by breaking waves and carried away.

On the ebb tide a certain amount of material is flushed from the bays. As the flow energy is dissipated in the open sea, the heaviest of the sediment particles is lost from suspension first. Any offshore shoals found in the area of the inlet exhibit finer sediment sizes further from the inlet mouth.

The finest sediment sizes in the area of a tidal cut can generally be found on the bay shoals. This distribution is the result of several causes. Figure 4 shows a plot of erosion-deposition criteria



- FIGURE 4 -
EROSION-DEPOSITION CRITERIA FOR UNIFORM PARTICLES
[After Hjulstrom (53)]

for uniform particles (53). Several interesting phenomena can be seen upon examination of the curves. The highest average velocities are required to initiate motion of a given sediment size. However, once the material is suspended, it can be transported at lower velocities. As a result, material churned up by wave action along the coast and sucked into the pass may be deposited inside the estuary. However, if the same velocity of flow occurs on the ebb tide, it may be insufficient to cause erosion of the particles originally carried on the same velocity flow. Also, due to the jetting action, the flood velocities can often exceed the ebb velocities in the bay shoal region.

It is also interesting to note that the most difficult sizes to erode are found at either end of the material spectrum - the fine and heavy sediments. Along the Texas Coast common beach sand lies in the range of sizes most easily moved, around 0.1 mm to 0.2 mm. The larger, heavier materials require nearly as much energy to transport as to erode, and if they are carried through the inlet by a given flow, they will probably be removed by a reverse flow of the same magnitude. The fines, on the other hand, require much less energy to transport than to suspend. Consequently, the particles may be suspended by wave action and washed through the inlet on the flood tide. As flow energy dissipates the particles are deposited. Generally, sufficient wave energy is not available on the bay side to resuspend the material, and flow velocities on the ebb tide are not high enough to scour the material. Even if flow velocities reach a sufficiently high value to cause erosion, this occurs only at or near the peak of the ebb tide. The result is an overall deposition. Fine materials deposited in the estuary by rivers and wind action also contribute to the particle distribution found on the bay shoals.

g) Regional Peculiarities

Aside from the general characteristics of tidal inlets, regional peculiarities may be found in passes along some coastal areas. The predominance of common characteristics such as bay shoals along the Gulf Coast have been previously mentioned. Other regional differences are worth noting in that the combination of factors leading to a given condition in a certain area will also act on artificial or stabilized passes in the same area.

Price noted that the orientation of Texas coastal inlets is generally in a North-South direction. It has been hypothesized that this is a result of water flowing out of the bays on the strong North winds during the winter months (33). Regardless of the motivation, it seems valid to assume, then, that an artificial pass introduced along the Texas Coast will attempt to orient itself in a North-South direction. Due consideration should be given this probability in the design stages of channels or stabilization works in the region.

Galvin (51) points out that the centerlines of the barrier islands on either side of most tidal inlets do not coincide. An explanation of several types of these offset inlets is offered in terms of their relationship to littoral transport rates and wave climate. According to a survey of inlets along the Atlantic and Gulf coasts of the United States, Galvin categorized tidal passes into four groups according to the type of offset found: overlapping, updrift, downdrift and negligible. Overlapping and updrift offsets result where an adequate supply of sediment is available updrift of the inlet. Overlapping occurs where the gross littoral transport is approximately equal to the net littoral transport; updrift offset results if gross transport is slightly greater than the net transport. Downdrift offset is found in areas where the gross transport exceeds the net transport, but an insufficient supply of material is available to the updrift side of the inlet. Negligible offset occurs when the net drift in a region is zero.

The major stable inlets along the Texas Coast are generally downdrift offset in nature. Along the Texas shoreline beach erosion is the principle source of material for littoral transport. The result is a transport capacity somewhat greater than the available material. Consideration of littoral drift in the region shows that gross transport rates are greater than net transport. As would be expected from Galvin's hypothesis, Galveston, Pass Cavallo, and San Luis Pass are all examples of inlets with a downdrift offset.

h) Selected Texas Inlets

Examination of Texas coastal inlets serves to illustrate many of the characteristics described above. Thus, a brief look at their history and present status can be worthwhile.

The map found in Appendix A indicates the location of many of the inlets which function either continuously or intermittently along the Texas Gulf Coast. Table A 1 provides a listing of these inlets along with a statement as to their present status.

Figure A 2 is a photograph of a recently closed washover, any number of which might be seen on the barrier islands after the passage of a hurricane. It is likely that a small channel will be found in the area after the passage of any large storm. Since the volume of water drained from the estuary during normal conditions is insufficient to maintain the hydraulic efficiency of the cut, a slow process of littoral deposition seals off the channel. Photographed in November, 1970, this washover was probably last opened by hurricane Celia which passed over Corpus Christi from the east early that year.

Several artificially stabilized inlets of various sizes may be found along the coast. Rollover Fish Pass, Figure A 5, is a totally artificial channel opened by dredging in January, 1955 (50). From the outset Rollover Pass had an extreme tendency towards erosion. Due to insufficient application of design criteria, installation of sheet pilings, stone rip rap, and sheet pile weirs was necessary to control the channel. The purpose of the pass was to provide an access route for fish migration to East Bay as well as to improve biological factors in the bay. Erosion of the pass resulted in serious loss of property and considerable beach erosion on the east side of the cut. Final cost far exceeded original estimates, and its effectiveness has been severely limited by the weir installed just south of the bridge. Channel migration is deterred by the sheet piling found along both sides of the inlet. Prather and Sorensen (50) in a study of the pass indicate that the stabilization works have been successful and the downcoast beaches seem to have reached some form of equilibrium.

Brown Cedar Cut is a naturally occurring tidal inlet which serves East Matagorda Bay. In a study of the cut, Mason and Sorensen (49) note that historically Brown Cedar Cut has exhibited an extreme instability. The cut opens and closes periodically in response to environmental parameters. Appendix B provides a series of photographs of Brown Cedar Cut that portray a cycle in the life of a natural tidal inlet. Figure B 1 shows the inlet as it appeared in October of 1966. It appears that widening of the inlet by hurricanes Carla and Cindy resulted in its ultimate closure in 1964 (49). Several attempts to artificially open an inlet by local inhabitants during this period led to abject failure. The remnants of two of these may be seen on either side of the photograph. The one on the left was excavated with a bulldozer and dragline dredge in 1965, and is reported to have been closed by littoral transport in about one week.

Brown Cedar Cut was reopened by Hurricane Beulah in 1967 (49). Mason reports that no post-Beulah photographs were available, but no significant change in geographic location occurred prior to Figure B 2 taken in February, 1969. Attention is called to the extensive bay shoals and shoal areas along the sides of the inlet indicated by whitecaps in the photograph. Breakers also indicate the existence of a crescent shaped bar across the mouth of the inlet.

Figure B 3 is a photograph of the inlet as it appeared in July, 1971. Breakers at the lower left of the picture indicate that the gorge has migrated to the left side of the channel. The spit formation on the left side of the pass indicates a temporary change in the littoral transport from its normal East-West direction. Extensive bay shoal formations are apparent.

The next photo in the series, Figure B 4, shows the inlet as it appeared in June, 1972. Significant migration of the channel has occurred since the previous photo. Migration has been caused by the development of spits, the indications of which can be seen on the right of the inlet. At present, it seems that Brown Cedar Cut is well on its way to total closure and completion of its life cycle.

The final figure in the series shows the migration of the gorge of Brown Cedar Cut. The preliminary profile was estimated by Mason and Sorensen (59). Subsequent profiles were taken on the dates indicated. Migration of the channel gorge in a westerly direction is apparent.

The two natural passes found at Corpus Christi are also historically unstable. Considerably longer than Brown Cedar Cut, they are subject to meandering of the channels; however, since the net littoral drift in the area is approximately zero, they suffer little or no migration of the mouth. Subject to long periods of insignificant flow and closure, several attempts have been made to dredge a channel open at their location (46).

Construction has recently been completed on an entirely artificial pass on Mustang Island just north of the natural passes at Corpus Christi. Figure A 4 depicts the channel as it appeared in August, 1972. Corpus Christi Fish Pass will be discussed in more detail below, however, it should be noted here that the presence of this jettied fish pass makes the future of the natural passes questionable. At present the natural passes are barely open and with the additional quantity of flow removed by the Fish Pass, the decrease in their flushing ability may result in complete closure.

TIDAL WAVE PROPAGATION

The propagation of the tidal wave through an estuary system and the hydraulic characteristics of an inlet dictate the water level differential across the tidal inlet, and consequently the duration and magnitude of the resultant flow. The majority of the derivations concerned with the hydraulics of coastal passes assume that the tidal level in the bay rises and falls uniformly, i.e. the tidal wave travels throughout the bay in an insignificant amount of time as compared to the period of the wave.

Assuredly, the assumption may be valid under select circumstances, for instance a small, deep bay. However, complications are introduced in most naturally occurring situations.

Since the tidal wave in an estuary is a shallow water wave, its velocity is related only to the depth as dictated by the relationship

$$c = \sqrt{gd}$$

in which c = wave celerity, g = gravity, and d = total depth.

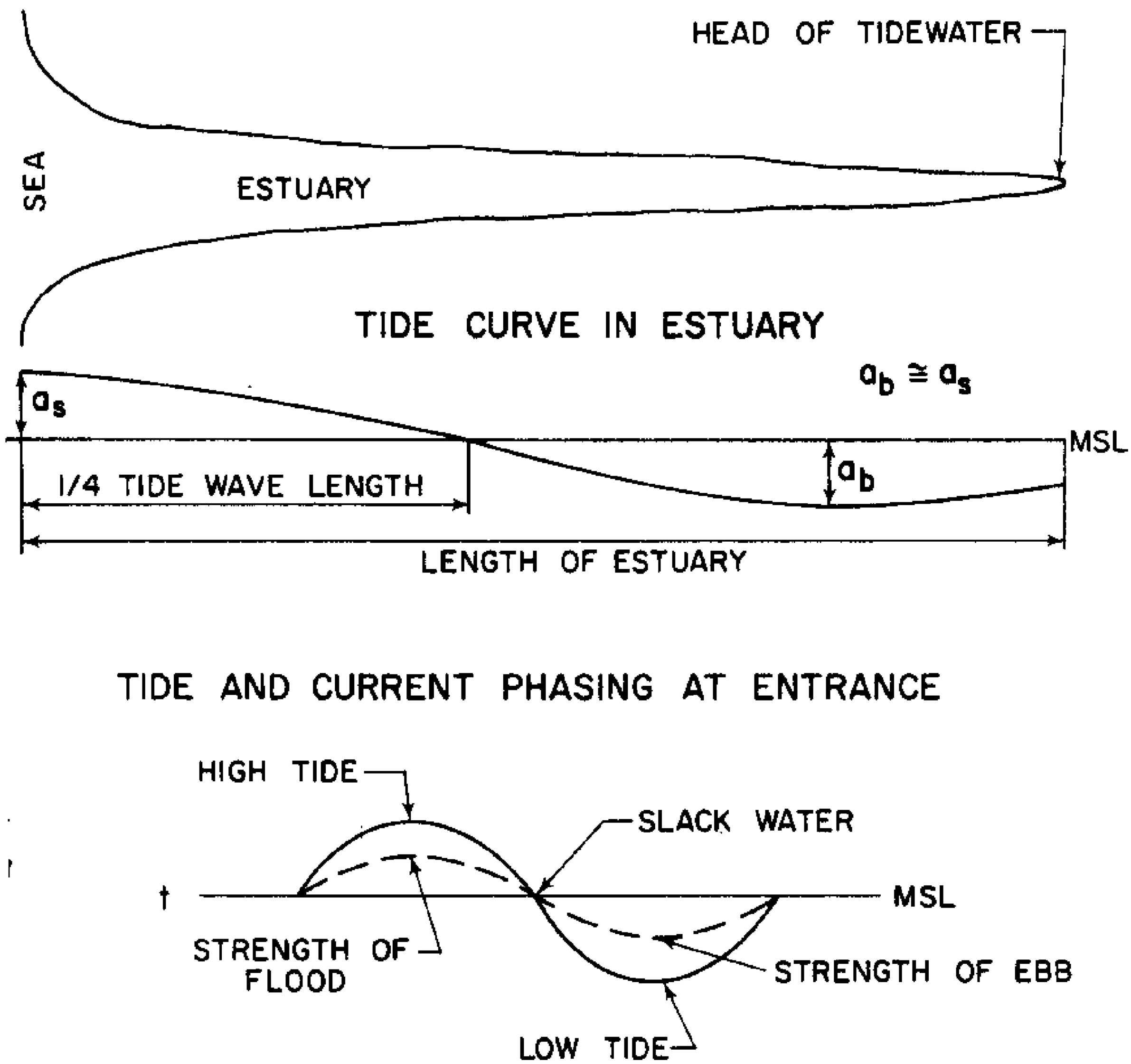
In relatively large, shallow bays as commonly seen along the Texas Coast, it may take several hours for the tidal wave to reach the far ends of the system. For example, from calculations based on an average depth in East Bay, a tide wave impressed at the Galveston jetties takes 3.7 hours to reach Rollover Fish Pass (50).

Tidal wave interaction with the bottom results in frictional dissipation of wave energy. From classical wave mechanics considerations, this results only in a decrease in wave amplitude, and consequently partially accounts for differences in maximum and minimum tide levels in the sea and the basin.

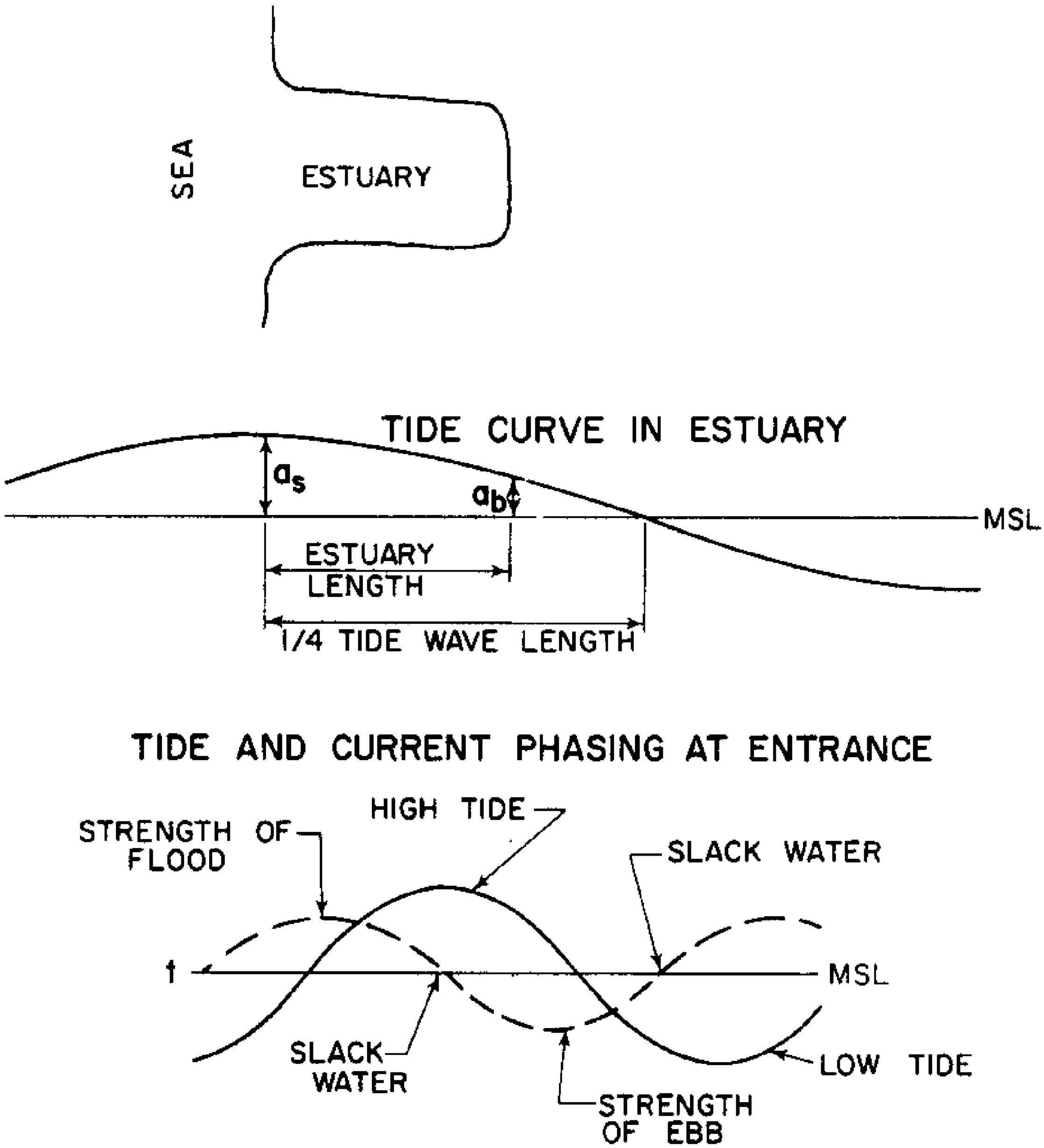
Since the frictional resistance in the connecting channel varies as the square of the velocity, frictional effects in the channel result in a distortion of the wave form found in the bay. If a sinusoidal wave form is impressed on the ocean side, the resulting wave form on the bay side may be periodic, but not necessarily sinusoidal. Due in part to frictional effects, then, the maximum differential does not necessarily coincide with the maximum tides as is illustrated in Figure 5 through 7.

Basin geometry also has a significant effect on propagation of the tidal wave in an estuary system. Changes in water depth and cross-sectional area result in increases or decreases in amplitude as the circumstances dictate. Reflection of the tidal wave may occur and further complicate the situation. Resonance effects in the bay system could result in a tidal fluctuation in the estuary being considerably greater than that in the ocean. The Bay of Fundy is a classic example of this phenomenon.

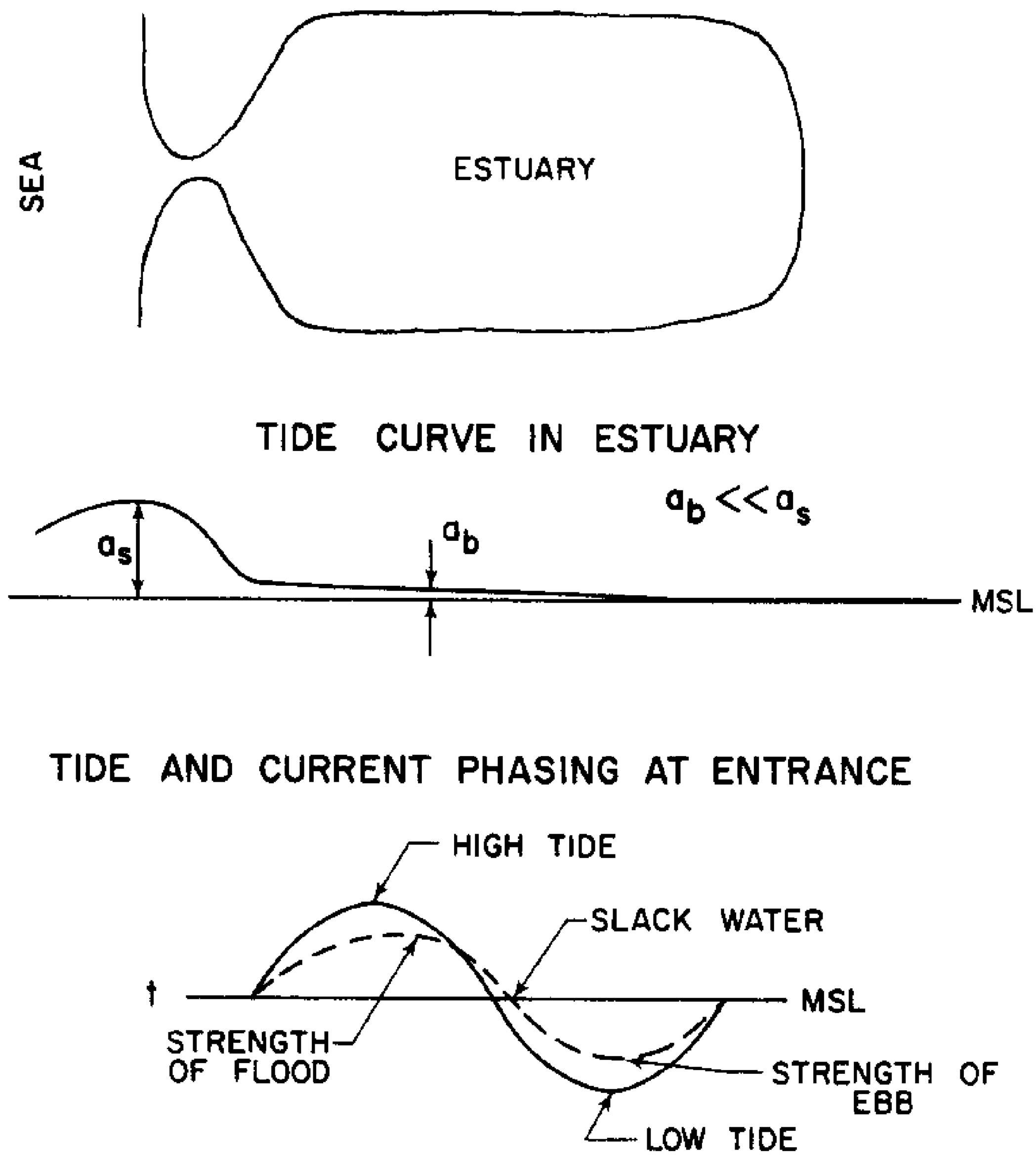
In a paper on tidal currents in inlets Caldwell (18) deals with the effect of basin geometry and inlet size on tidal propagation and consequently inlet currents. Working on the premise that the "relation of tidal current to tide is not constant, but varies from place to place", Caldwell delineates three types of inlets according to the ratio of estuary length to length of the tidal wave. These three types are used to describe the extreme conditions and are illustrated in Figures 5 through 7.



- FIGURE 5 -
SCHEMATIC DIAGRAM OF CLASS 1 ENTRANCES
[After Caldwell (18)]



- FIGURE 6 -
SCHEMATIC DIAGRAM OF CLASS 2 ENTRANCES
[After Caldwell (18)]



- FIGURE 7 -
SCHEMATIC DIAGRAM OF CLASS 3 ENTRANCES
[After Caldwell (18)]

The first class assumes a uniform channel gradually decreasing in cross-sectional area and depth from the sea to the extreme of the basin. The length of the estuary is considered to be greater than one-quarter the wave length of the tide. Under this set of circumstances the tidal wave propagates up the estuary with a relatively small change in form at the inlet. The tidal waters enter the estuary coincident to the phasing of the tidal wave, i.e., the velocities are in phase with the tidal cycle.

In the second class the estuary is shorter than one-fourth the wave length. If there is no constriction at the mouth of the bay, the form of the wave at the inlet is altered by the fact that water reaching the headwater of the estuary tends to "back-up" to the mouth. The result is that the inlet is basically filled by the time the high tide reaches the mouth, and a slack flow occurs at the peak of the tidal cycle, that is, the velocities in the inlet are 90° out of phase with the tidal wave.

The third type of system may be defined as having a large deep bay with an extremely constricted inlet. A maximum differential across this type of pass occurs at high and low tides. The result, as in class 1, is that the velocities are in phase with the tides. Unlike class 1 inlets, however, the amplitude of the tide in the bay system for this type of inlet is substantially lower than in the sea.

Extensive littoral deposition may result in the alteration of a class 1 or 2 inlet into a class 3 pass. If velocities developed are not sufficiently high, the pass may ultimately be sealed off.

Complications are introduced in a situation where more than one inlet allows access to the bay. The tidal wave propagating through a larger cut can influence the differential across a smaller channel. The relationship between Galveston Entrance and Rollover Fish Pass is an example of this type of situation.

Caldwell does not consider resonance effects, reflection, or fresh water inflow. He points out that both Galveston entrance and Aransas Pass are examples of class 3, or inadequate, inlets, and, in considering a total of 52 inlets along the coast of the United States, he found that 44 fell directly into one of the three classes. It is specifically pointed out that no inlets with a sufficient amount of fresh water inflow to distort the tidal cycle were considered. However, Caldwell's classification provides a rudimentary connection between a variety of inlets previously treated primarily on an individual basis.

PERTINENT FACTORS INFLUENCING INLET STABILITY AND CONFIGURATION

As with most natural systems, the response of a tidal inlet to a given set of environmental conditions is a complex phenomenon. In striving to understand the outside influences which need be considered in the design or stabilization of coastal inlets, not only is it necessary to have an appreciation of the parameters which affect the unit directly, but it is also imperative to recognize the inter-relationships of the various factors.

On an extremely simplified level, the geometric and geographic stability as well as the configuration of a tidal cut are governed by a balance between two factors: littoral transport and flow velocity in the inlet. In order to be in perfect balance, the amount of material delivered to the updrift side of the inlet during a tidal cycle must be passed to the downdrift side (or offshore) during that tidal cycle. The implication is that the flow velocity and duration are sufficient to scour all material deposited in the channel or on the shoals during the tidal cycle and return it to the normal flow of littoral material. The idealization is a poor one as can be seen from the formation of large shoal areas commonly found in natural inlets. However, over a period of years an inlet's channel and shoal areas may indeed be stable. Once that situation is achieved any change in littoral drift rate or flow velocity may upset the balance and the inlet will strive to achieve a newly balanced position.

Wave climate in a given region also effects the configuration of tidal inlets. As previously described, wave action is the primary cause of spit formation and subsequent channel migration in tidal inlets. Changes in predominant wave direction cause changes in the area subjected to deposition or erosion by the wave climate. If the wave climate was such that the direction of approach varied around the inlet during a sufficiently short period no migration of the channel would occur. It should be noted that changes in the wave climate also cause a change in the direction and magnitude of littoral drift.

A series of factors collectively control the flow velocity in an inlet. The first and most obvious is the discharge rate. From simple continuity considerations, the greater the overall discharge, the higher the average velocity.

The discharge rate in the inlet is related to the tidal fluctuations at sea and in the estuary. The quantity of water which flows through the inlet during one half tidal cycle is called the "Tidal Prism". In certain regions, the input of fresh water due to precipitation or runoff may have a significant effect on the tidal prism in an estuary or bay system. Changes in the tidal prism result in subsequent changes in inlet cross-sectional geometry and area. Therefore, the tendency may be for a widening or deepening of a channel during the rainy season and a decrease in cross-section may occur during the dry portions of the year.

Size of the bay shoals also affect flow velocity in an inlet. Expansion of the bay shoal areas behind a tidal inlet can result in a lengthening of the channel and an increase in the frictional dissipation of energy. Shoal deposits also decrease the bay storage capacity and thus the tidal prism. The result is a decrease in the flow velocity and, consequently, the energy available to flush the inlet. A decrease in channel cross-section ensues, and if the shoal areas increase to a sufficiently large size, complete closure of the inlet may occur.

Velocity of flow in an inlet is also related to the hydraulic efficiency of the inlet channel. The presence of such formations and dunes or ripples on the bottom affect the roughness parameter of the unit with a resultant decrease in efficiency. Changes in hydraulic radius, i.e. the ratio of cross-sectional area to wetted perimeter, also affect the overall efficiency of the channel. If the wetted perimeter is large compared to the cross-sectional area, a great deal of energy is dissipated to bottom friction. Therefore, a widening of the channel or a splitting of the pass into two separate channels results in a decrease in efficiency and may lead to closure.

The final controlling factor on the velocity of flow in tidal cuts is the position and size of the offshore bar. The bar provides an automatic mechanism for the control of the transport capacity of a tidal inlet (31).

Duration and magnitude of the peak velocities in the pass is critical to maintenance of the channel. Since the flow is generated as a result of a differential across the cut caused by tidal fluctuations, the propagation of the tidal wave in the estuary is crucial. Consequently the inlet and basin geometry, which control the propogation of the tidal wave, must be considered in their influence on inlet stability and configuration.

The final two parameters which need be considered with respect to their direct influence on tidal inlets are best treated concurrently.

They are bottom shear and sediment load. A requirement for stability of the channel bottom is that the median shear stress during a tidal cycle approximately equals the critical stress for initiation of motion (i.e., the flow conditions result in zero net transport in the section). Bottom shear and sediment load affect the flow conditions of the inlet. Bottom shear dissipates energy in the flow and consequently reduces the average velocity. Sediment load dampens the turbulence found in the flow and results in a decrease in energy loss due to turbulent shear stress.

In summary, the stability and configuration of natural and artificial tidal inlets may be affected by a variety of factors. However, the degree of influence of each individual parameter may vary with the specific circumstances. In general, the pertinent factors influencing inlet stability are:

A. Littoral drift

B. Wave action

C. Current velocities in inlet

D. Inlet and estuary geometry

E. Bottom shear

F. Sediment load

G. Fresh water input

    1. Precipitation

    2. Runoff

INLET HYDRAULICS

It is not the purpose of this paper to provide a detailed derivation of the hydraulic equations necessary to describe the flow in a tidal inlet. The equations are presented and treatment is given attempts by several authors to obtain a viable solution to these equations.

The relationship between flow characteristics in the vicinity of an inlet and the stability of the channel has been detailed by a number of authors. The velocities which must be developed to maintain cross-sectional stability are governed to an extent by a balance between the littoral drift moving into the inlet and the ability of the inlet currents to move the sediment (18).

In order to fully describe the flow regime of a tidal inlet, it is necessary to consider the equations of energy or motion and continuity in the tidal cut. Unlike simple flow in an open channel complexities are introduced due to the variations in the water level caused by the tides. These non-sinusoidal tidal fluctuations are the primary forcing function which generates flow through the inlet by producing a differential across the pass. Wind set-up in the bay or sea can also effect the difference in water elevation across the pass.

In writing the hydraulic equations for a tidal inlet, the goal is to define the flow velocities in the channel as well as actual water surface elevation in the estuary at a given time. There is general agreement as to the original form of the equations needed, and these will be presented below. However, a variety of approaches have been taken to obtain solutions to them.

Numerical step-type calculations are useful; however, they are time consuming and extremely tedious (22). Generally, the mathematical approaches work on the premise that in order to obtain a quantitative analysis of the problem a series of simplifying assumptions may be introduced without seriously hampering the end result. Effectively, idealization of the flow results and the actual deviation from reality can be considerably greater then originally anticipated.

Figure 8 is a definition sketch of an inlet connecting an ocean and a bay. The equation of motion through the inlet if the level of the sea is greater than that in the estuary yields, in the x-direction:

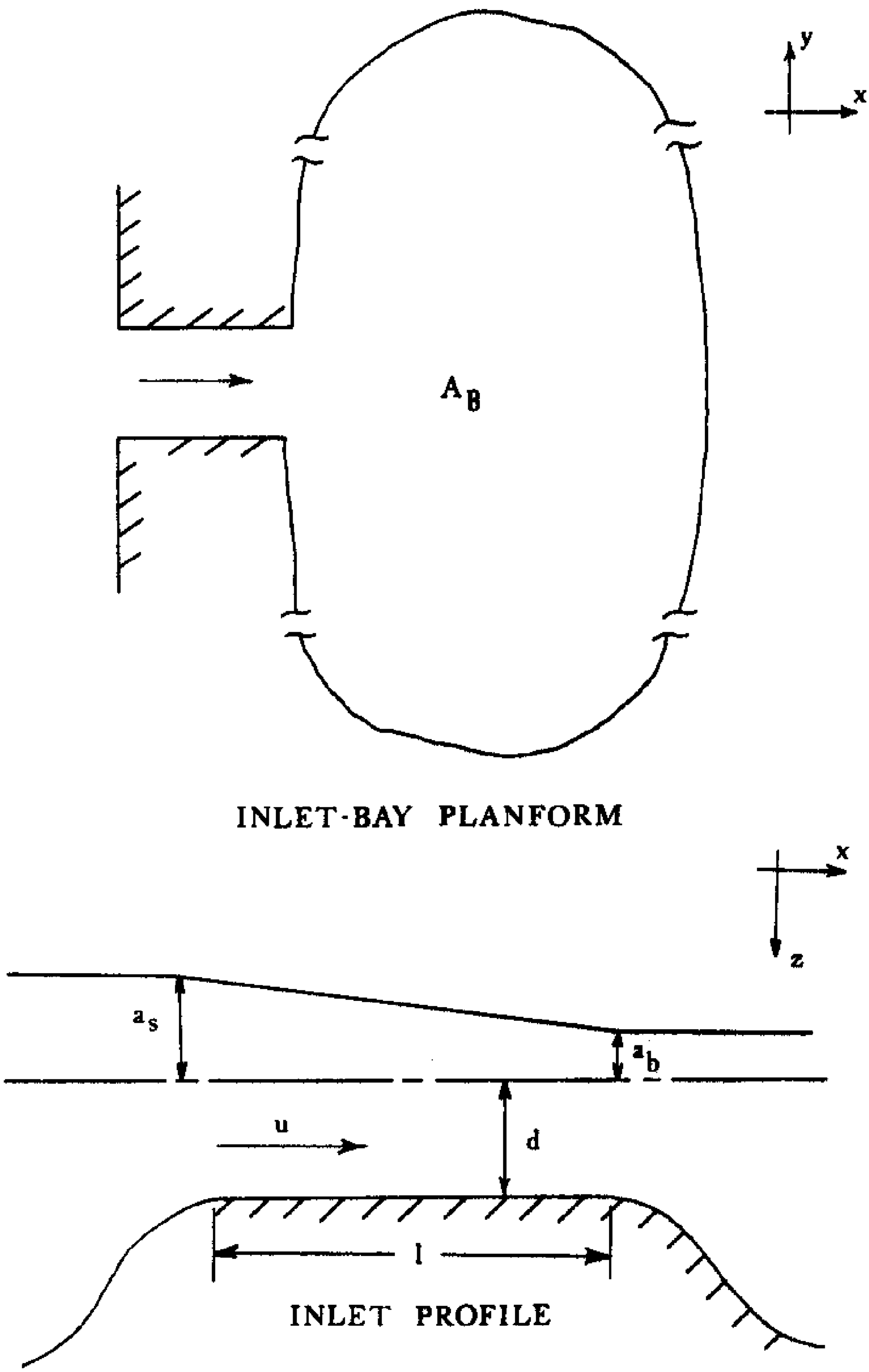
$$-g \frac{\partial h}{\partial x} - \frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_v}{\partial x} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \qquad (1)$$

where u is the inlet velocity, P is the pressure, ρ is the water density and τ_v is the viscous and turbulent shear stresses.

Equation (1) results from the application of Newton's second law to the system, equating a balance in pressure forces per unit mass across the inlet, shear stresses per unit mass in the channel, and convective and local accelerations.

Considering the channel to have a horizontal bottom and zero gravitational force in the direction of flow, the equation becomes:

$$-\frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_v}{\partial x} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \qquad (2)$$



- FIGURE 8 -
DEFINITION SKETCH OF INLET BAY SYSTEM

Bruun and Gerritsen (17) in their treatment of tidal hydraulics list five simplifying assumptions most commonly used to facilitate the solution of the basic equations. These assumptions are:

1. Average elevation of water surface constant along horizontal channel
2. Simple harmonic tide
3. Friction term is linearized
4. Constant channel cross-section
5. Non-linear terms in the differential equations neglected.

The ramifications of these assumptions should be noted in the interest of understanding. The constant average elevation along the horizontal channel eliminates the possibility of convective accelerations in the x-direction while the stipulation of constant channel cross-section and horizontal bottom allows for the deletion of the other two convective accelerations since v,w = 0. The use of a simple harmonic tide simplifies the solutions in that it is not necessary to use a Fourier expansion to describe the forcing function. Linearization of the friction term results, primarily, in the simplification of the mathematics involved and finally neglecting the non-linear terms in the equations allows for an explicit solution to be obtained.

One of the first solutions to the tidal flow problems was by Parson's harmonic theory which used all of the above assumptions (17).

Application of the above simplifications results in the following equation of motion:

$$\frac{\partial P}{\partial x} = \frac{\partial \tau_v}{\partial x} \qquad (3)$$

or assuming a hydrostatic pressure distribution

$$a_s - a_b = \frac{\partial \tau_v}{\partial x} \tag{4}$$

where a_s is the amplitude of the sea above some datum, a_b is the amplitude of the bay above that datum.

It is important to note that the removal of the $\frac{\partial u}{\partial t}$ term results in the elimination of the time dependency of the equation. Therefore, the instantaneous rate of change of velocity is neglected as well as the wave characteristics of the forcing function. As a result the equations define the flow only at an instant.

If the energy equation is written neglecting local acceleration terms:

$$a_s + \frac{v_s^2}{2g} = a_b + \frac{v_b^2}{2g} + \Sigma h_\ell$$

where: v_s = velocity of flow in the sea

v_b = velocity of flow in the bay

Σh_ℓ = total energy dissipated to the flow

Assuming that the area of the ocean and bay are large so that $v_b = v_s = 0$

$$a_s - a_b = \Sigma h_\ell \tag{6}$$

The term Σh_ℓ may be used to take into account a variety of losses for specific inlets. For instance, the loss caused by the weir across Rollover Fish Pass or the dogleg in the Corpus Christi Fish Pass.

If the flow is assumed to accelerate in the ocean and out into the bay, but maintains constant velocity in the channel, the Darcy-Weisbach equation may be used to determine shear resistance. Presuming that one velocity head is lost at the exit and some portion, K_{en}, of one velocity head is lost at the entrance, the energy equation becomes

$$a_s - a_b = (K_{en} + 1 + \frac{f\ell}{4R}) \frac{{v_c}^2}{2g} \qquad (7)$$

in which ℓ = channel length,

R = hydraulic radius of the channel,

g = acceleration of gravity, and

v_c = velocity in the channel.

The value of K_{en} is dependent on the streamlining of the inlet entrance. A more streamlined entrance will have a lower value of K_{en}. Suggested values range from 0.05 to 0.25 (19).

The equation of continuity for a single inlet serving an enclosed bay (Fig. 8) may be written in differential form.

$$Q = V\ A_{cs} = \frac{\partial a_b}{\partial t}\ A_B \qquad (8)$$

where A_B = surface area of the bay.

Brown (16) in a classic treatment of tidal inlets introduced a series of assumptions beyond those listed above and the equation of motion which resulted in an equation identical to the Chezy equation.

$$V = C\sqrt{RS} \qquad (9)$$

This implies that $\frac{\partial u}{\partial t}$ and $u\frac{\partial u}{\partial x}$ from equation (2) are zero. That is, the time dependence is eliminated from the equation. However, Brown carried the derivation a step further and defined the slope of the water surface in terms of the tide level on the ocean side, the tide level in the bay and a lag caused by the limited capacity of the inlet. Equation (9) then became:

$$V = C\sqrt{R/2L}\ \sqrt[4]{a_s^2 - a_b^2}\ \cos 2\Pi\ (\frac{t - \delta}{T}) \qquad (10)$$

Reasoning that the maximum velocity occurs when the lag, δ, is equal to t, the equation takes the form:

$$V_{max} = C\sqrt{R/2L}\ \sqrt[4]{a_s^2 - a_b^2} \qquad (11)$$

The equation of continuity is derived from

$$dg = A_{cs} V\ dt \qquad (12)$$

using the previously determined expression for V. That is,

$$dg = C\ A_{cs}\sqrt{R/2L}\ \sqrt[4]{a_s^2 - a_b^2}\ \cos 2\Pi\ (\frac{t-\delta}{T})\ dt \qquad (13)$$

The expression is integrated over one half tidal cycle, or

$$Q = \frac{\delta \pm T/4}{\delta - T/4}\ C\ A_{cs}\sqrt{R/2L}\ \sqrt[4]{a_s^2\ \ a_b^2}\ \cos 2\Pi\ (\frac{t-\delta}{T})\ dt \qquad (14)$$

The mathematical manipulations yield

$$Q = 2.3962\ \frac{TC\ A_{cs}}{2\Pi}\ \sqrt{R/2L}\ \cdot\ \sqrt[4]{a_s^2 - a_b^2} \qquad (15)$$

Brown considered the estuary to be in a pumping mode. That is, the rise and fall of the tide occurs equally in all sections of the estuary at a given time. He greatly simplified the solutions in eliminating the time dependence and, therefore, the wave characteristics of the response. Calculations could be carried out in a step-type fashion

TABLE 1

Terms From the Equation of Motion --
Relative Orders of Magnitude
For Two Hypothetical Inlets

	CASE 1	CASE 2
Length:	5000 ft	1000 ft
Width:	500 ft	500 ft
Depth:	8 ft	1.56 ft
Maximum Differential:	1.0 ft	1.0 ft
Tidal Period:	24 hrs	24 hrs

Term	$\frac{1}{\rho}\frac{\partial P}{\partial x}$	$\frac{1}{\rho}\frac{\partial \tau}{\partial x}$	$\bar{u}\frac{\partial \bar{u}}{\partial x}$	$\frac{\partial \bar{u}}{\partial t}$	$\bar{v}\frac{\partial \bar{u}}{\partial y}$	$\bar{w}\frac{\partial \bar{u}}{\partial z}$
Case 1	.0065	.0063	.0004	.0002	0	0
Case 2	.033	.033	.008	.0001	0	0

and an approximation of the flow obtained. Brown's solutions are commonly used to obtain a rough estimate of inlet hydraulics, but are not generally accepted in design work due to their relative inaccuracy.

Brown himself noted that his equations should be used with "due regard to their limitations" (16). Indeed, this statement is applicable to any set of equations and it is interesting to note, for instance, the relative sizes of terms in the equation of motion which are very often neglected. Some terms deemed negligible, at least at certain points in the tidal cycle, are not sufficiently small to be neglected. However, due to inherent difficulties in solving the equations with these terms intact, it is necessary to delete them. Table 1 presents the order of magnitude of terms in the complete equation of motion for two hypothetical inlets.

The length and width characteristics of these inlets were arbitrarily chosen as typical of passes found along the Texas coast. Depth of the pass is based on a stability shear stress of 0.1 pounds per square foot (25). The channel is assumed to be clean and straight, in alluvial material. The maximum differential across the pass, for practical purposes, is based on data obtained by Carothers and Innis (31) at several inlets along the Texas coast. It can be argued that the above characteristics are somewhat unrealistic, however, they are sufficient for illustrative purposes.

In both cases, the values of terms $\overline{v}\,\frac{\partial \overline{u}}{\partial y}$ and $\overline{w}\,\frac{\partial \overline{u}}{\partial z}$ are zero since $\overline{v}$ and $\overline{w}$ are zero. As expected, the shear and pressure terms dominate in both cases, however, the relative order of magnitude of the $\frac{\partial u}{\partial t}$ and

$\bar{u}\frac{\partial\bar{u}}{\partial x}$ terms vary with the individual circumstances. In Case 1 they amount to roughly 8% of the pressure or shear terms. Based on the accuracy of the input data, it may be assumed that these terms are indeed negligible. Case 2 presents a different situation. Shortening of the channel and the decrease in depth result in an increase in the magnitude of the terms generally deleted from the equation of motion. $\frac{\partial\bar{u}}{\partial x}$ is approximately 25% of the magnitude of the pressure and shear terms. A question arises as to the negligibility of this term.

Further complications arise in actual inlets due to the introduction of further acceleration terms as a result of changes in channel geometry. An increase in the $\frac{\partial u}{\partial t}$ term results in areas with a tidal period of 12 hours.

A variety of attempts have been made to obtain a solution to the equations of motion and continuity for tidal inlets. W.D. Baines' (15) treatment of the subject differed from that of Brown in that he considers a phase shift in the tidal fluctuations of the bay and ocean by inclusion of a frictional term in the equation of motion. Baines also introduces an attenuation factor functionally related to frictional effects and the response of the basin to the impressed tidal wave. He notes that the tidal fluctuations in the bay may be greater than those in the sea. As is common to many available solutions, Baines linearizes the friction term which results in equation (7) being rewritten as:

$$a_s - a_b = (K_{en} + 1 - \frac{f\ell}{4R}) \frac{V\,|V|}{2g} \qquad (16)$$

A value of the absolute value of V is assumed depending on the best overall accuracy desired or the portion of the tidal cycle where the coefficient resulting from the velocity distribution and f is a friction factor.

Deriving the relationship between Manning's n and the friction factor f to the form,

$$\sqrt{f} = \frac{n\sqrt{2g}}{1.48\ R^{1/6}} \tag{18}$$

and assuming the velocity distribution at the channel entrance is uniform, equations (17) and (18) may be combined to yield:

$$\frac{A_B\ K\ \sqrt{H}}{A_{cs}} = \frac{T\sqrt{2g}}{2}\ \frac{R}{f\ell + R} \tag{19}$$

Some numerical values relating f to n and R are seen in Table 2 as found in Keulegan's paper. Table 3, also from Keulegan, contains computed values for the right side of equation (19) for a variety of values of n, channel depth, and channel length. Tidal period is assumed at 12 hours.

Values of the coefficient of repletion will vary widely depending on a given situation. Dean (19) notes that an inlet/bay system with a large value of K will be most efficiently filled. The resultant bay tide will be approximately equal to that in the sea. Small values of K are found in less efficient systems, with the tide range in the sea being considerably greater than that in the bay. Dean points out that for K > 1.0 the bay tidal range will be greater than 86% of the ocean range while for K < 0.1 bay tides will be less than 12% of the ocean tidal range. If there is more than one inlet connecting a given bay system to the sea, K for the system equals the sum of the K's for the

TABLE 2

Relation Between the Coefficient of Friction f and Manning's n

	$f \times 10^4$			
R , ft	n = 0.02	n = 0.03	n = 0.04	n = 0.05
5	68.04	153.26	272.58	425.18
10	54.02	121.66	216.38	337.82
15	47.22	106.29	189.06	295.15
20	42.93	96.63	171.87	268.30
30	37.45	84.33	150.06	234.09
40	34.05	76.67	136.42	212.87
50	31.62	71.18	126.56	197.68
60	29.72	66.93	119.02	185.78
70	28.25	63.60	113.21	176.62
80	27.02	60.82	108.16	169.00
90	25.97	58.49	104.04	162.31
100	25.05	56.43	100.00	156.75

TABLE 3

Tabular Values of the Coefficient of Repletion for T = 12 hr and n = 0.02, 0.03, 0.04, and 0.05

R	$(A_B K \sqrt{a_s/A_{cs}}) \times 10^{-4}$					
	$\ell = 0.1 \times 10^4$	$\ell = 0.2 \times 10^4$	$\ell = 0.5 \times 10^4$	$\ell = 1.0 \times 10^4$	$\ell = 2.0 \times 10^4$	$\ell = 4.0 \times 10^4$
			n = 0.02			
5	3.697	2.859	1.974	1.443	1.112	0.741
10	4.557	3.825	2.867	2.180	1.606	1.160
15	4.810	4.364	3.437	2.708	2.042	1.495
20	5.004	4.611	3.830	3.110	2.397	1.780
30	5.293	5.018	4.637	3.722	2.952	2.254
40	5.295	5.120	4.618	4.053	3.209	2.626
60	5.383	5.327	4.938	4.537	3.909	3.195
80	5.426	5.338	5.101	4.770	4.262	3.596
100	5.449	5.383	5.195	4.925	4.500	3.899
			n = 0.03			
5	2.734	2.064	1.365	0.980	0.699	0.496
10	3.704	2.975	2.098	1.519	1.097	0.783
15	4.219	3.548	2.589	1.939	1.416	1.019
20	4.528	3.933	2.984	2.284	1.689	1.223
30	4.871	4.414	3.556	2.825	2.290	1.577
40	5.051	4.688	3.941	3.230	2.508	1.873
60	5.233	4.985	4.422	3.794	3.067	2.358
80	5.323	5.140	4.696	4.154	3.473	2.743
100	5.366	5.228	4.870	4.406	3.778	3.055

TABLE 3 (continued)

Tabular Values of the Coefficient of Repletion for T = 12 hr and n = 0.02, 0.03, 0.04, and 0.05

R	$(A_B K \sqrt{a_s/A_{cs}}) \times 10^{-4}$ $\ell = 0.1 \times 10^4$	$\ell = 0.2 \times 10^4$	$\ell = 0.5 \times 10^4$	$\ell = 1.0 \times 10^4$	$\ell = 2.0 \times 10^4$	$\ell = 4.0 \times 10^4$
			n = 0.04			
5	2.171	1.598	1.038	0.740	0.525	0.385
10	3.101	2.389	1.604	1.158	0.828	0.589
15	3.732	3.264	2.040	1.495	1.077	0.769
20	4.044	3.344	2.397	1.780	1.292	0.927
30	4.504	3.900	2.948	2.245	1.662	1.184
40	4.761	4.252	3.328	2.626	1.971	1.441
60	5.037	4.665	3.909	3.191	2.473	1.846
80	5.175	4.894	4.262	3.596	2.866	2.180
100	5.261	5.035	4.500	3.894	3.182	2.460
			n = 0.05			
5	1.793	1.311	0.836	0.594	0.422	0.298
10	2.675	1.979	1.303	0.935	0.666	0.473
15	3.202	2.668	1.675	1.213	0.869	0.637
20	3.603	2.873	1.985	1.452	1.036	0.745
30	4.133	3.447	1.580	1.858	1.353	0.973
40	4.454	3.837	2.881	2.194	1.615	1.168
60	4.819	4.336	3.452	2.726	2.055	1.512
80	5.012	4.622	3.843	3.128	2.412	1.796
100	5.123	4.815	4.131	3.392	2.713	2.046

individual inlets. Keulegan's treatment is widely used and the reader is referred to the original document for a thorough consideration.

Jacobus van de Kreeke (22) produced a mathematical model in order to obtain a solution to the hydraulic equations of a tidal inlet in which he maintains the quadratic friction term and introduces the effects and friction in the bay, but obtains a solution compatible with numerical solutions and that of Keulegan.

All of the above solutions deal only with sinusoidal oscillations in the bay and the majority neglect flow accelerations in the inlet. In what may be the most comprehensive solution to date, Shemdin and Forney (23) include acceleration of flow in the inlet, the quadratic friction term, and a non-sinusoidal tidal oscillation in the ocean. An approximation of a periodic tidal wave is achieved through the use of a series of circular functions.

From continuity considerations, if more than one tidal pass provides access to the sea, it may be questionable as to the actual surface area of the system which contributed to the flow through a particular inlet. Rollover Fish Pass is a case in point. Prather and Sorensen (50) in their study of the inlet encountered difficulties in predicting the source of the tidal wave at given points in the bay system. As a result a question arose as to the validity of the assumption that the inflow and outflow of the pass were identical.

Determination of the volume of water contributed through several inlets to a given bay system may be made through the use of a numerical model such as that of Reid and Bodine (61). The drawback to the use of these models lies in the extensive amount of field data needed to properly calibrate the model as well as the computer time necessary to calculate the final results.

Treatment of the hydraulic equations involved in flow through tidal inlets may be approached from a variety of viewpoints. Fresh water inflow, shape of the tidal basin, resistance in the channel, number of interconnected basins, or shape of the tidal wave impressed may be the dominant factor in a given situation. In an attempt to obtain a solution for the equations a number of simplifying assumptions are introduced. Validity of these assumptions and the consequences of them differs for an individual inlet and the limitations of a given solution with respect to a specific inlet must be considered. To date an exact solution to the complete hydraulic equations has not been found. However, with proper consideration given their limitations, adequate results may be obtained from the available methods.

STABILITY CRITERIA

A number of attempts have been made to define criteria for the stability of tidal inlets. The criteria suggested have met with varying degrees of success, and several are discussed below.

The stability of channels in alluvial material has been the subject of an extensive amount of research. There are several obvious factors which influence the stability of tidal inlets and are not generally of consequence in alluvial channels. However, Bruun (17) points out that several interesting similarities are apparent when the results of studies of alluvial channels are compared to the results of studies of tidal inlets. For instance, in 1930 Gerald Lacey (57) developed an equation which relates the wetted perimeter of an alluvial channel only to the discharge. As will be seen below, O'Brien observed a similar relationship in tidal inlets.

In an early attempt to define the stability of tidal inlets, O'Brien (28) theorized that a relationship exists between the tidal prism of an estuary and the cross-sectional area of this inlet. From data available on Pacific Coast inlets, O'Brien suggested the empirical relationship for inlets without jetties:

$$A = 4.69 \times 10^{-4} \, \Omega^{0.85} \qquad (20)$$

in which A = minimum flow cross-section of the entrance channel measured below mean sea-level, and Ω is the tidal prism corresponding to the diurnal or spring range of tide in cubic feet. Subsequent analysis of a variety of other inlets yielded the linear relationship:

$$A = 2.0 \times 10^{-5} \Omega \tag{21}$$

O'Brien himself points out that the close agreement of the data appears to be fortuitous for a variety of reasons. The available data on tidal prisms was somewhat crude. The effect of bottom material size in the inlet channel is not accounted for. Jetties found at the mouth of the inlet also seem to have little effect on the relationship. Such variables as wave climate and littoral drift rate, according to O'Brien's hypothesis, are not directly involved. O'Brien indicated a suspicion that the area-tidal prism relationship provided an approximation of a more complex function which accounted for such factors as material size, exposure to wave action, and artificial stabilization.

Although O'Brien's relationship is not regarded as sufficiently precise for design work, it is still used to obtain a first approximation for the size of a stable inlet. His work is of particular significance because it epitomizes the school of thought which visualized the stability of tidal inlets as a balance between the flow available for flushing the inlet, and the amount of material deposited in the inlet channel (17).

Francis Escoffier in a work subsequent to that of O'Brien suggests a graphical means of determining the stability of a tidal cut. Based on equations derived by Brown (16), Escoffier obtains a relationship for the mean velocity of flow in a tidal inlet as:

$$V_m = C \left(\frac{A_{cs} H}{2p\ell}\right)^{1/2} \{(1 + r^2)\ 1/2 - r\}^{1/2} \qquad (22)$$

where: $r = \left(\frac{12054c}{A_B}\right)^2 \frac{g^3}{2pH\ell}$

A_{cs} = cross-sectional area of the channel in square feet,

C = Chezy's coefficient in $(\text{feet})^{1/2}$ per second,

p = wetted perimeter of channel cross-section in feet,

H = mean tidal variation of the sea in feet,

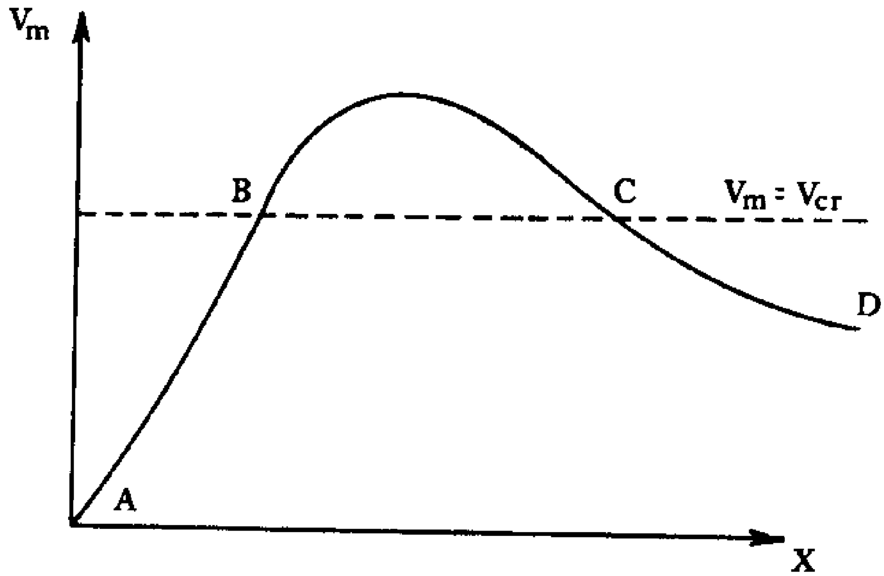
ℓ = length of channel in feet, and

A_B = water surface area of bay in square feet.

Escoffier assumes that the Chezy coefficient, the mean tidal variation of the sea, the water surface area of the bay, and the length of the channel are constant. This leaves the cross-sectional area of the channel and the wetted perimeter as the only variables which can be related to the hydraulic radius, R. The result is that the mean channel velocity is related only to R and a plot, seen in Figure 9, of V_m versus R may be drawn.

Working under the added premise that the balance between mean velocity and the critical velocity required for initiation of motion of the bed particles determines the cross-sectional stability of an inlet, a line of $V_{cr} = V_m$ is drawn.

Examination of the sample plot in Figure 9 is of interest. The intersections of the line $V_m = V_{cr}$ with the curve ABCD indicate the roots of the equations relating the previously mentioned variables. A channel with a mean velocity greater than the critical velocity will



- FIGURE 9 -
ESCOFFIER'S CURVE FOR DETERMINING
THE STABILITY OF A TIDAL INLET

have a tendency towards erosion; if the mean is lower than the critical velocity in the channel siltation results. It can be seen that a channel with a hydraulic radius which places it on the curve between B and A, will close; between B and C, will erode to the size at C; and between C and D, will silt to the size at C. Therefore, of the two roots, B and C, only one is stable. From an engineering standpoint only the root at C is of value. This should then be the stable channel wetted perimeter for the conditions given. On the Texas coast a number of attempts to create tidal inlets by dredging a small opening across a barrier beach have failed. It was assumed that the opening would scour to stable channel dimensions. However, most attempts were probably in the region A-B of Fig. 9 leading to closure of the cut.

Variation of the terms originally held constant in determining the curve, result, obviously, in variations of the curve. For example, an increase in the effective length of the channel results in an overall lowering of the curve while the critical velocity remains approximately constant. It can be seen that the curve may ultimately fall completely below the line of critical velocity and the inlet will close. Mathematically, just one unstable root may exist, or no roots at all. Generally, Escoffier suggests that a mean velocity of approximately 3 ft/sec will result in a stable channel.

E.W. Lane (32) presents a theory based on limiting tractive force for a stable channel design. Basically, Lane strives for a distribution of shear force in the channel which prevents deposition at all points while at the same time avoiding excessive scour. From experimental data, Lane presents values for the limiting tractive force based on size of bed material. Lane's theory is limited due to the fact that it is based on clearwater conditions.

In a later development, Carothers and Innis (31) suggest the use of a design velocity equal to the saltation velocity of the particles found on the beach or in the littoral transport in the area. For well sorted sands, the median diameter is used as a basis. The velocity of flow in the channel is determined using Manning's equation and the design velocity is taken as the flow velocity at the median tidal differential. The result is an inlet sized such that it tends equally to deposition and erosion. Carothers corroborates his thesis with data obtained from Texas coastal inlets.

Bruun and Gerritsen (17) present a set of equations to predict inlet stability based on a balance of littoral material moving into and out of a coastal inlet on a tidal cycle. However, due to the lack of sufficient knowledge of the relationship between sand transport and tidal flow, application of these equations would be difficult. If the necessary relationships can be established, similar equations may also prove useful for determining the stability of flood and ebb channels as well as the single primary channel normally considered.

Compilation of field data led Bruun and Gerritsen to suggest a stability criterion based on the ratios of tidal prism, Ω, and maximum discharge at spring tide, Q_m, to annual gross littoral drift rate, M. It was determined that inlets with a value of $\Omega/2M$ greater than 300 tended to be highly stable while those with a value less than 100 were generally unstable. Values of Qm/M less than .01 usually indicated a more stable configuration than values greater than .01.

Due to the inherent difficulties in determining gross littoral drift rates at a site, Bruun and Gerritsen suggest what may be a more practical approach to the problem. They picture a tidal channel as possessing a "rolling carpet" of sediment on the bottom. Material is worn off both ends as the carpet moves back and forth along the bottom. A stability shear stress of approximately 0.1 lbs/sq.ft. is suggested for stable inlets.

In applying the above stability criteria to Brown Cedar Cut (49) and Rollover Fish Pass (50), the majority adequately predicted the behavior of these passes. Mason found that O'Brien's criterion provided erroneous results and notes that the difficulties may be caused by the extensive shoal formations behind the pass.

However, Prather (50) points out that wide discrepancies result from attempts to determine a stable cross-section. Without further study, any statement as to the preferability of one of the above criteria would be mere conjecture. A degree of familiarity with the equations and their limitations combined with sound engineering judgment hopefully will yield a rational design for a given situation. What the authors feel is a valid design procedure is treated in a subsequent section.

ARTIFICIAL STABILIZATION

For many applications, the natural tendencies of tidal inlets toward shoaling and migration may be extremely undesirable. The movement of a navigation channel and formation of large shoal areas in and around that channel, for instance, could have disastrous effects on shipping. Consequently, a number of modifications to natural inlets and improvements to artificial passes have found wide use over the years.

Jetties are the most common form of structure found on coastal inlets. Their purpose is to channel the flow and induce more efficient flushing, restrict the movement of littoral material into the inlet, eliminate migration of the channel mouth, and provide the channel mouth with protection from storm waves and cross currents. In order to effectively accomplish such aims, the design and construction of such jetties must be undertaken with great care. This subject is treated in some detail in Shore Protection Planning and Design (34).

An alternate solution to the problems incurred as a result of littoral transport is maintenance dredging. Periodic dredging can be used to remove shoal areas in the channel as well as in the surrounding areas, and to eliminate the spit formations and migration of the mouth. In areas of high littoral drift, the cost of the dredging operations may be prohibitive and the construction of jetties may prove more economical from a long term standpoint.

Jetties constructed in the vicinity of a tidal inlet act as a trap for littoral material moving along the coast. Natural inlets develop a bypassing system as previously described. However, the formation of the necessary offshore bar is generally undesirable in improved inlets. Jetties are constructed to trap as much as possible of the material attempting to move past the inlet. The result is excessive downcoast erosion. After a certain period of time, the material building up on the upcoast side of the jetty will circumvent the structure and partially defeat the purpose of the jetty. The solution is a system of artificial sediment bypassing.

Several methods of artificial bypassing are available, ranging from completely portable installations to permanent fixtures. The desirability of a particular method is dependent on the situation. In areas where the net drift rate approaches the gross drift rate and the quantity of material is great, a permanent installation is acceptable. Areas where the drift rate is approximately equal in both directions require that the bypassing system be at least semi-portable. In areas where the drift rate is relatively small, the occasional use of a floating dredge may be sufficient. For a more thorough treatment of artificial sediment bypassing the reader is referred to the available literature, some of which is listed under "Selected References".

A series of other less extensive measures may be taken to combat specific problems in tidal inlets. The installation of sheet metal pilings along the sides of the channel to forestall excessive erosion, stone rip rap on the bottom of the channel to dissipate energy and aid in maintaining channel stability, sheet piling weirs to inhibit flow, sills and various other devices may be used to maintain the geographic and geometric stability of a given channel.

AVAILABLE DESIGN PROCEDURES

Presently, there are at least two procedures available for the design of stable coastal passes. The first to be discussed herein was formulated by Bruun and Gerritsen (17), the other by Carothers and Innis (31). In both cases, the procedures are intended to facilitate the design of naturally maintained tidal inlets eliminating the use of stabilization works and maintenance dredging as much as possible.

Bruun and Gerritsen (17) extend the work carried out by O'Brien (28), who suggested a linear relationship between the cross-sectional area of the inlet and the tidal prism as follows:

$$A_{cs} = 2.0 \times 10^{-5}\ \Omega \qquad (23)$$

or

$$\frac{\Omega}{A_{cs}} = 0.5 \times 10^{5} \qquad (24)$$

where A_{cs} is the cross-sectional area and Ω is the tidal prism. Using the Chezy equation in the form

$$Q = A_{cs}\ C\ \sqrt{RS} \qquad (25)$$

and

$$\tau = \gamma RS \qquad (26)$$

where τ = shear stress,

γ = specific weight,

R = hydraulic radius, and

S = slope of bottom.

Bruun evaluates a "stability shear stress" for a series of coastal passes. From the above equations:

$$\frac{Q}{A_{cs}} = C \sqrt{\tau_s/\gamma} \tag{27}$$

Realizing that the relationship between average discharge and the tidal prism, for Texas coastal passes is

$$Q \times 12.25 \text{ hrs} = \Omega \tag{28}$$

Substitution in equation (27) yields:

$$\frac{\Omega}{A_{cs}} = 12.25\ C \sqrt{\tau_s/\gamma} \tag{29}$$

Bruun and Gerritsen, calculating the average stress for spring tides at a number of stable inlets found that the stability shear stress varies from .072 lbs/sq.ft. for light sediment loads to 0.103 lbs/sq.ft. for heavy sediment loads.

This procedure also includes stability checks by means of the ratios of discharge to littoral drift rate and tidal prism to littoral drift as discussed in a previous section. A shape factor based on the cross-section of the channel is also included.

Difficulties arise in determining a valid Chezy coefficient, as well as a shape factor for the channel. In the final analysis, Bruun and Gerritsen point out the importance of model tests in achieving an adequate design.

In what seems to be a somewhat more practical approach to the problem, Carothers and Innis (31) base their design procedure on stability criteria set forth by a number of authors. The initial cross-sectional area of the channel is evaluated from O'Brien's equation, subsequently checked based on work by Carothers and Innis, and finally sized according to ratios of maximum discharge and tidal prism to littoral transport rate as determined by Bruun and Gerritsen.

The procedure as presented by Carothers and Innis (31) for the design of an artificial pass is as follows:

1. "Secure and analyze hourly tidal differentials across the barrier island,
2. Compute the first approximation of potential cross-sectional area of the inlet and potential water interchange,
3. Sample and determine size distribution of the littoral material,
4. Make the first trial balance in design by sizing the inlet channel so that the velocity estimated from the median differential is equal to the design velocity,
5. Adjust the tidal differentials where appreciable change in bay tides is expected, then rebalance,
6. Estimate from wave energy the total littoral transport intercepted from both longshore directions by tidal flow through the inlet,
7. Rebalance the design to equate sediment transport capacity of inlet channel with the intercepted littoral transport,
8. Secure final dynamic balance by use of the highly variable mechanism of the Gulf bar,
9. Design stabilization works as necessary to control the Gulf bar mechanism to support imbalance where, for many reasons, complete natural operation is not achieved.

10. Evaluate relations of rainfall, runoff, and evaporation for the bay,
11. Evaluate the nature and effects of salinity or density currents on water interchange,
12. Estimate efficiency of mechanical mising between Gulf and bay waters, and
13. Provide sufficient water interchange for the desired or most feasible salinity control."

Inspection of the above procedure shows that a certain amount of field data is necessary to achieve an adequate design. In the initial planning stages it is imperative that the designer have access to hourly tidal differentials across the island. This can be accomplished by the installation of tide gauges on either side of the island at the site of the proposed pass.

Carothers points out that the tides along the Texas Coast are primarily influenced by the declination of the moon, the cycle repeating itself every 27 1/3 days. Therefore, it is necessary to obtain a record of tidal differentials for a minimum of one tropical month (31). Additional tide records taken during periods of strong north winds, storms, and calm will also prove helpful. Records during selected tropic months or continuous months increase the probability of obtaining an adequate design.

Overall, the step by step procedure suggested by Carothers and Innis seems adequate. However, the designer must realize that it is, after all, an approximation. The accuracy of the final product will be based on the accuracy of methods involved in stability calculations as well as the input data available.

CONCLUSIONS

A basic understanding of the characteristics and behaviour of natural inlets is helpful in achieving an appreciation for the factors involved in maintaining an artificial cut. Application of the present state of knowledge to the design of artificial tidal inlets can effect an adequate result.

At present the possibility of achieving a naturally maintained inlet without the aid of artificial stabilization or occasional maintenance is doubtful. Procedures available for the design of tidal inlets can be extremely useful in achieving the desired end result. However, a variety of criteria have been put forth to determine the stability of tidal inlets and several of these should be applied in the hope of obtaining an adequate design.

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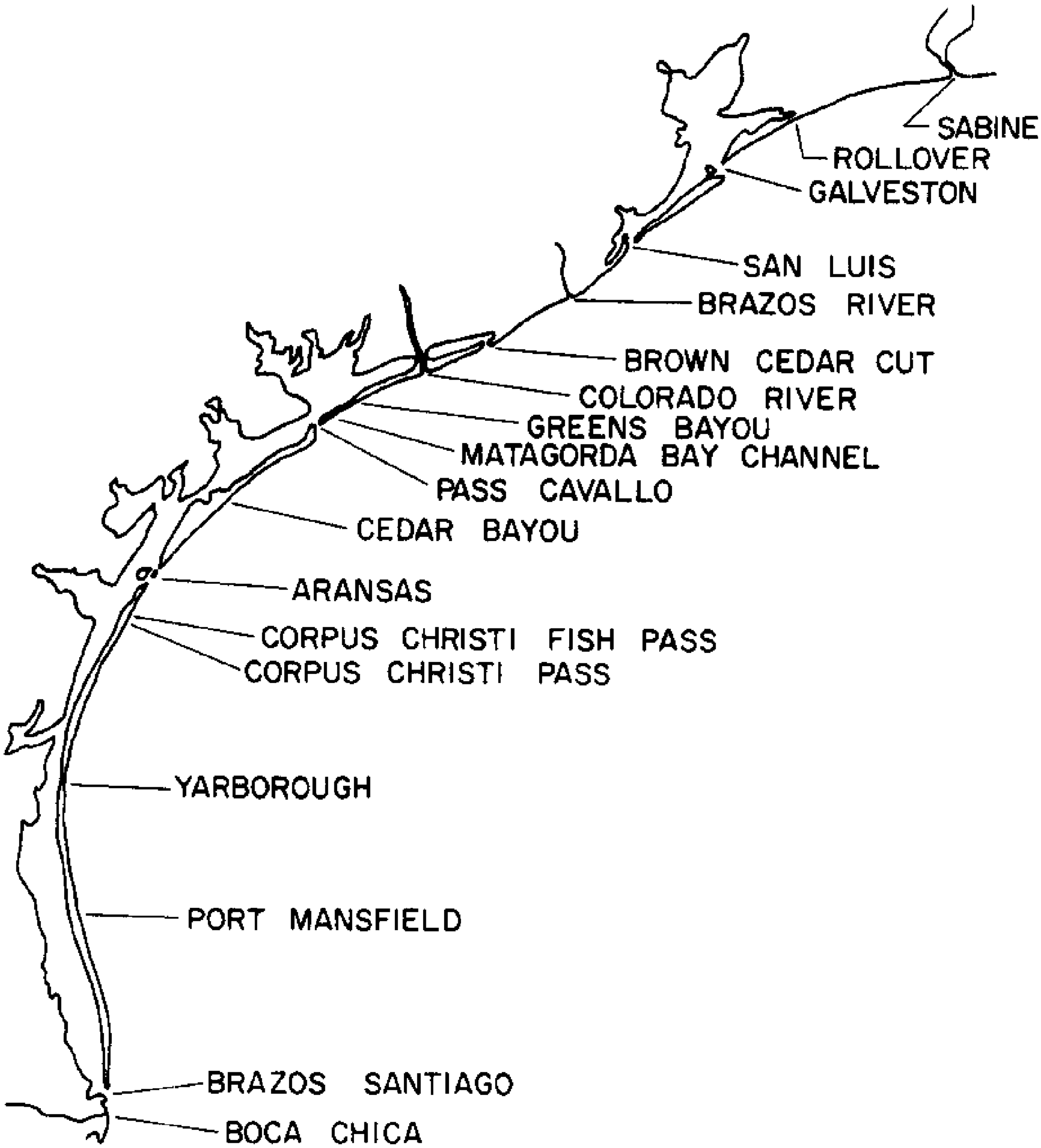
APPENDIX A

TEXAS COASTAL INLETS



- FIGURE A 1 -
GEOGRAPHIC LOCATION OF TEXAS COASTAL PASSES

TABLE A 1

TEXAS COASTAL INLETS

Inlet	Present Status	Comments
Sabine Pass	Open	stabilized navigation route
Rollover Fish Pass	Open	controlled, completely artificial fish pass
Galveston Entrance	Open	stabilized navigation route
San Luis Pass	Open	stabilized navigation route
Freeport Harbor Entrance	Open	stabilized navigation route
Brazos River	Open	direct entrance to Gulf - large delta formation
Brown Cedar Cut	Open	periodically open natural inlet - presently in danger of complete closure
Colorado River	Open	completely filled in its estuary and now empties directly to the Gulf
Green's Bayou	Closed	rarely open, natural inlet
Matagorda Ship Channel	Open	completely artificial navigation route maintained by dredging and stabilization works
Pass Cavallo	Open	unstabilized natural pass - main water exchange for Matagorda Bay
Cedar Bayou	Closed	occasionally provides Gulf water interchange with Mesquite Bay
Aransas Pass	Open	stabilized navigation route
Corpus Christi Fish Pass	Under Construction	design for fish migration and salinity control in Corpus Christi Bay - stability questionable nearing completion

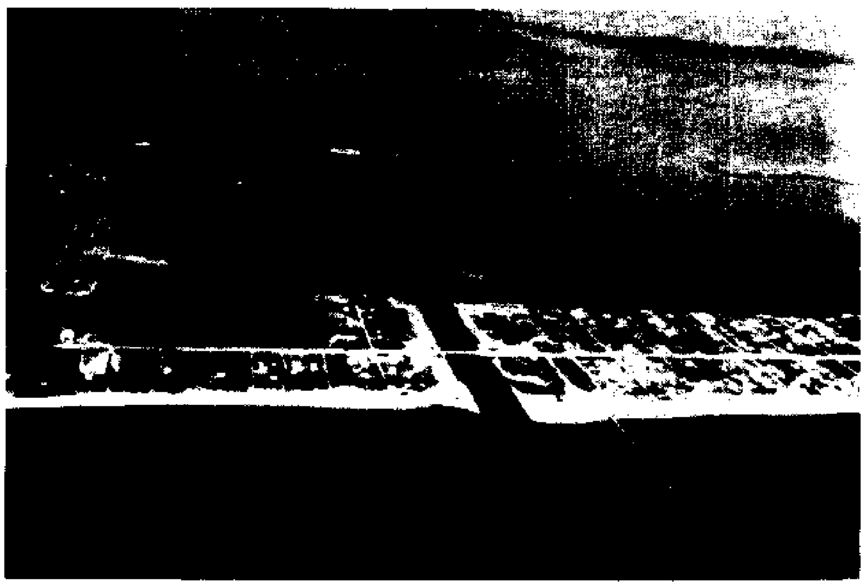
TABLE A 1
(continued)

Inlet	Present Status	Comments
Corpus Christi Passes	Open	natural unstabilized passes presently in danger of closure
Yarborough Pass	Open	artificial inlet - completely closed for some time
Port Mansfield Channel	Open	completely artificial - stabilized
Brazos Santiago	Open	stabilized - affords access to lower Laguna Madre

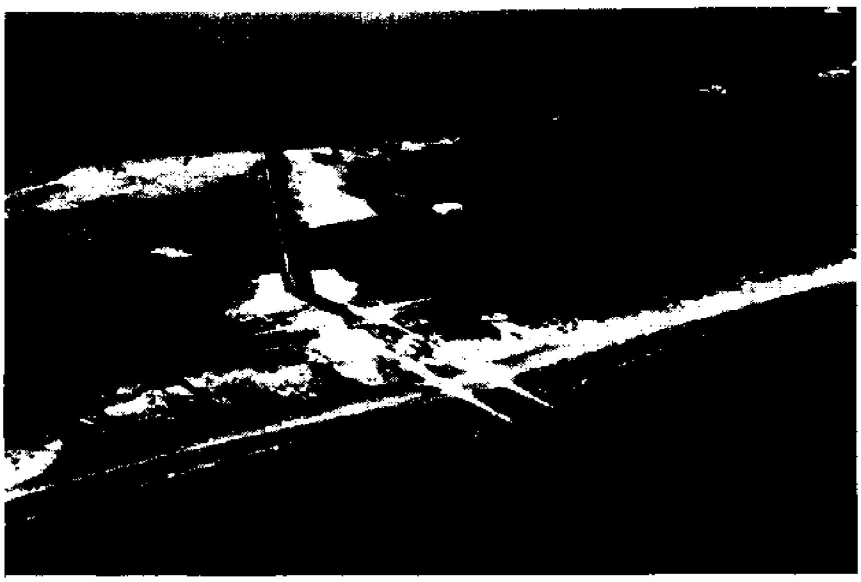
– FIGURE A 2 –
RECENTLY CLOSED WASHOVER ALONG THE TEXAS COAST
November 1970

- FIGURE A 3 -
NATURAL PASSES AT CORPUS CHRISTI
February 1972

- FIGURE A 4 -
NORTH BRANCH OF CORPUS CHRISTI PASS
February 1972



- FIGURE A 5 -
ROLLOVER FISH PASS
January 1971



- FIGURE A 6 -
CORPUS CHRISTI FISH PASS
August, 1972

- FIGURE A 7 -
ARANSAS PASS
February 1972

APPENDIX B

MIGRATION OF BROWN CEDAR CUT

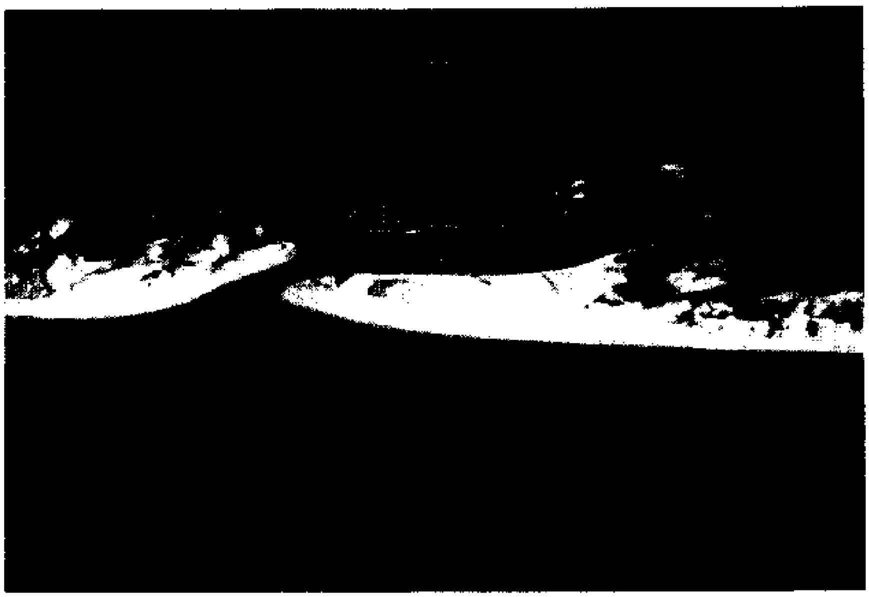
- FIGURE B 1 -
BROWN CEDAR CUT COMPLETELY CLOSED PRIOR TO HURRICANE BEULAH
1966

- FIGURE B 2 -

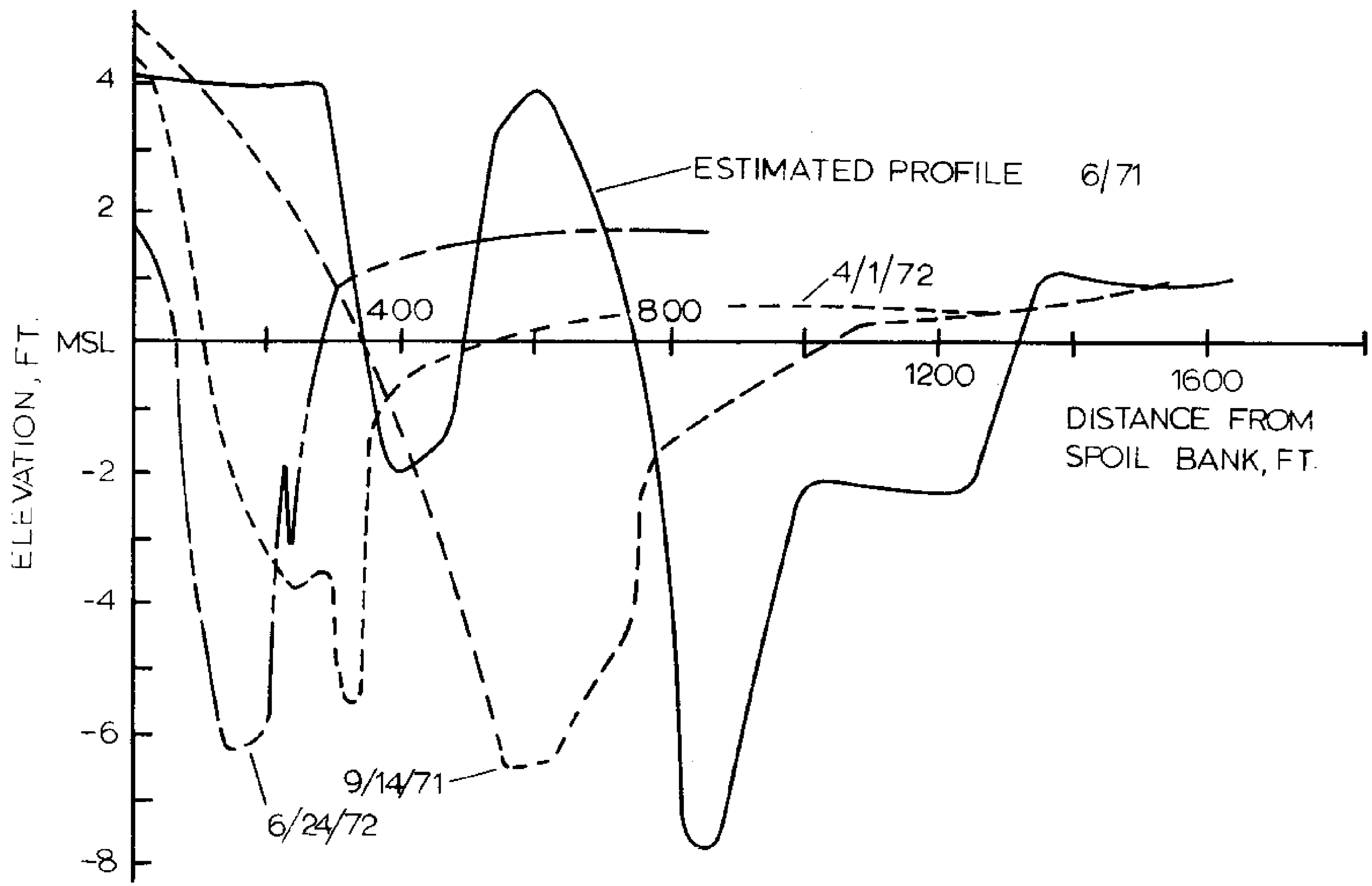
February 1969

- FIGURE B 3 -

July 1971



- FIGURE B 4 -
BROWN CEDAR CUT SUFFERING FROM EXTENSIVE MIGRATION
June 1972



- FIGURE B 5 -
PROFILES ACROSS BROWN CEDAR CUT