CHAPTER 12

INTER-RELATIONS BETWEEN JET BEHAVIOR AND HYDRAULIC PROCESSES OBSERVED AT DELTAIC RIVER MOUTHS AND TIDAL INLETS*

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Price (1951) has stated:

"(In) geological oceanography as practiced today there is constant emphasis on quantitative measurement and quantitative theoretical development."

As a demonstration of this geophysical approach to geological problems the authors have studied the theory of processes involved when sediment-laden water flows into a currentless, tideless, wave-free basin. The theoretical concepts developed have then been tested against the actual occurrences in nature. The result is that it is possible to propose a comprehensive theory of delta formation which may explain many of the features observed near mouths of rivers. According to this theory, there are three distinct and basic types of river inflow into a still basin, as shown in Figure 1:

a. "Hyperpycnal" inflow (inflow more dense) which results in a turbidity (density) current forming a submarine delta far below the water's surface at the foot of reservoirs and submarine canyons.

b. "Homopycnal" inflow (inflow equally dense) under appreciable hydraulic head. (Result is that a vertical frontal boundary forms between river and basin water and slowly spreads radially from the orifice, thereby causing an extremely rapid decrease in issuing velocity and the deposition of most of the sedimentary load within a distance of one diameter from the orifice. This depositional pattern results in the classical delta of geological textbooks with its well developed

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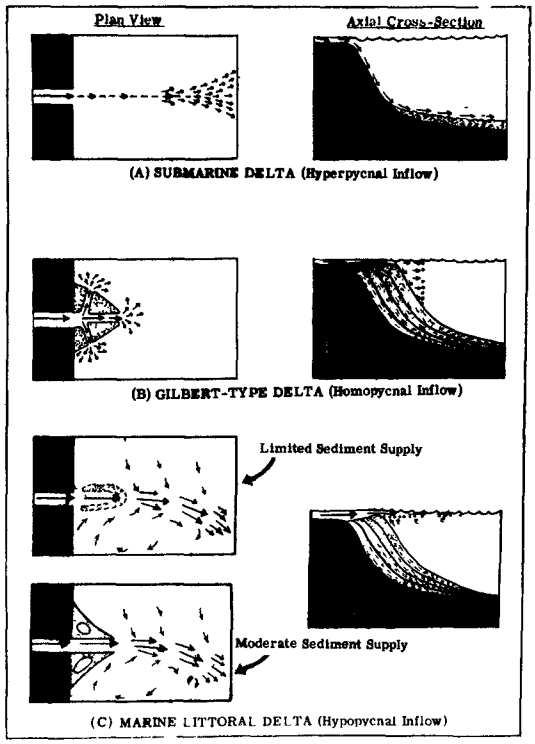

Fig. 1. Three basic methods by which sediment-laden water enters basins filled with water of differing densities.

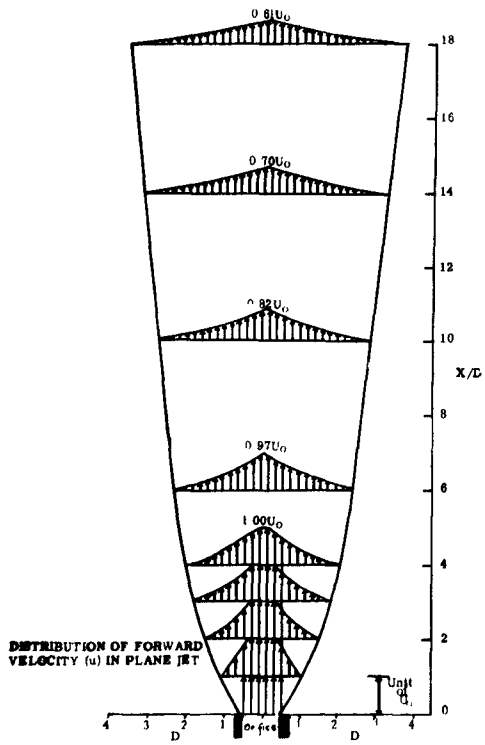

Fig. 2. Plan view of forward velocity vectors in a plane jet of the Tollmien type.

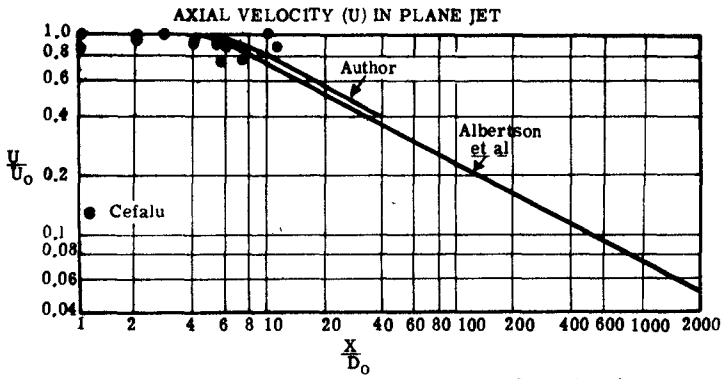

Fig. 3. Distribution of axial velocity in a plane jet according to theory and observation.

top-set, fore-set, and bottom-set beds. This frontal theory also explains the flow of Mississippi River water through Lake Ponchartrain when the Bonnet Carre Spillway is opened just above New Orleans).

c. "Hypopycnal" inflow (inflow less dense) with sediment-laden water flowing into a basin filled with water of greater density, such as a river emptying into an ocean.

The first two phases of this theory will be fully discussed in a forthcoming paper entitled, "A Rational, Quantitative Theory of Delta Formation". However, because of the interest of the coastal engineer in hypopycnal inflow, the general behavior of this type of inflow will be described in some detail here. In this particular case, a tongue of outflowing brackish or fresh water entering the ocean is, as it loses its hydraulic head, continually buoyed up by the salt-water below so that issuing velocity is maintained for appreciable distances beyond the orifice. This flow pattern strongly suggests that of the plane jet. Tollmien (1926) has developed a theory for the behavior of a turbulent plane jet moving solely under its own inertia and entering and entraining homogeneous fluid identical with that composing the jet.

By assuming that mixing length was a function only of distance away from the orifice, that profile similarity* existed throughout the jet, and that an expression could be applied from the Prandtl theory for turbulent shear stress, Tollmien obtained a theoretical streamline pattern for two-dimensional flow. Förthmann (1934), Peters and Bicknell (Rossby, 1936), and Albertson, Dai, Jensen and Rouse (1948) have found for plane jets that there is satisfactory agreement between the results of this theory and actual experiment. Even more extensive and just as successful experimentation has been done with the three-dimensional, axial jet by such aerodynamicists as Ruden (1933), Kuethe (1935), and Corrsin and Uberoi (1949), by chemical engineers (Taylor, 1950), and heating engineers (Nottage, Slaby, and Gojsza, 1952), to name but a few. All of the above workers assumed that the cross-sectional area of the jet must continue to increase continually downstream; however, Goldstein (1938) was able to prove that in the plane jet, the lateral streamlines eventually became nearly parallel downstream so that the boundary of this two-dimensional jet is parabolic. Such parabolic tongues are readily visible on aerial photographs of the outflow patterns of the Mississippi River and off tidal inlets of the Louisiana Coast. A typical velocity pattern is shown in Figure 2 based on the plane jet theory. The boundary of this jet is based on the parabolic margin of flow issuing from South Pass of the Mississippi River on October 14, 1940, during very low river stage when hydraulic head effects are at a minimum.

*Similarity in the curve velocity $\propto \sqrt{\text{distance from orifice}}$.

The general equation for this parabolic boundary is:

$$y^2 = \frac{3}{4} x$$

In this jet, a zone of strong lateral shear forms a fraction of a diameter away from the orifice and extends outward to a distance of at least four diameters from the orifice. Leighly (1934) has pointed out that sediment is deposited parallel to these threads of high shear; thus, natural levee formation can be expected to begin a short distance out from the orifice and to parallel the core of high-speed flow. Theory and experiment both indicate that up to a distance variously reported as falling between 4.0 and 5.0 diameters from the orifice, the center-line velocity remains the same as the issuing speed and hence there is no pronounced deposition of sediment. Beyond this critical region, however, lateral turbulence from the flanks of the jet penetrates to the very core of the jet and the center-line velocity thereafter decreases exponentially. It is interesting to note that as long as the flow is turbulent, this fall-off rate is essentially independent of Reynold's number and it makes no difference whether the jet and entraining material is a gas or a liquid if the material's viscosity is low. Of the many possible sets of available distribution of axial velocity data for this type of velocity distribution in plane and axial jets, Figure 3 shows the findings of Albertson et al (1948) for a two-dimensional slot compared to values obtained by converting the three-dimensional values of Corrsin and Uberoi (1949) to the two-dimensional case, as well as to observations by Cefalu (1918) made with floats at the mouth of Southwest Pass of the Mississippi River. The conversion of the three- to the two-dimensional case was accomplished by changing the curve of U/U_o from a function of D/x to a function of $D/\sqrt{x}$ in accordance with Rossby's (1936) discussion of this general subject. The terminology in this particular case is is that "U" represents the center-line velocity at any point, "U_o" the issuing center-line velocity, "D" the width expressed in diameters of a circular orifice or the width of a slot, and "x" the distance expressed in forms of D and measured along the jet's axis, the point of origin being the mouth of the orifice or slot. Geologically speaking, the agreement is good between these two distinctly different approaches to the same problem. Thus, deposition of suspended material may be theoretically expected to begin on the center-line of the jet somewhere in the zone of four to five diameters out from the slot, thereby creating a horizontal bar which links the two natural levees forming along the flanks of the jet. Such a pattern of deposition gives the familiar lunate bar observed in nature.

Interestingly enough, the principle that deposition in the path of the jet becomes important only when the above distance is reached out from the channel opening appears to operate in practically all cases of well-defined channels. Figure 4 illustrates only a few of the supporting examples contained in the files of the authors. In the case of the 4-foot road culvert near Bryan Beach, Texas, the scour-pit extended about 4.5 dismeters out from the culvert; the Golden Gate has the crest of its famous bar 3.8 diameters out; and according to a survey made in 1871 before man constructed jetties,

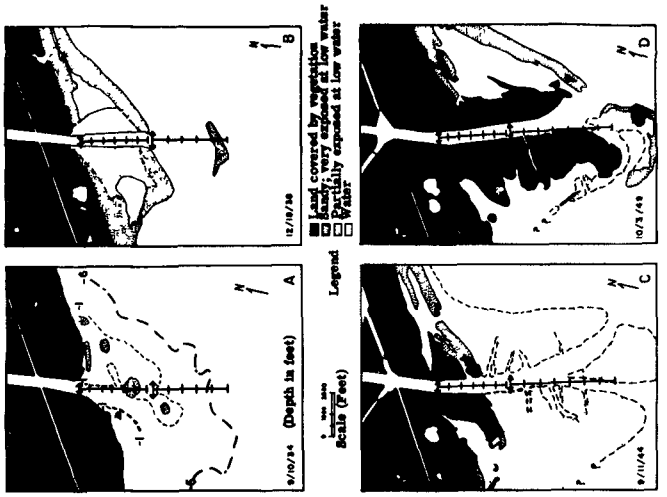

Fig. 5. Four stages of delta formation at the mouth of the Brazos River, Texas, following dredging of a new channel to the Gulf of Mexico in 1929.

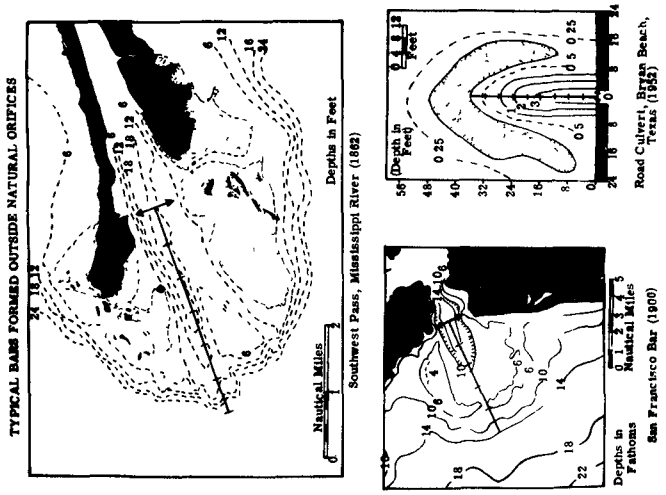

Fig. 4.

the bar of the Mississippi's Southwest Pass formed about 3.5 diameters out from a line drawn between the seaward ends of high-water-marks on opposing river banks. In the latter case, it is most surprising that such a high-water mark is an important feature in defining the morphology of a river's mouth, but it may well be that the end of the high-water mark represents the orifice of a confined channel.

However, the formation of Δ-shaped deltas without distributaries, i.e., the cuspate delta described by Johnson (1919, p. 409), can likewise be shown to be a direct outgrowth of the depositional pattern associated with the Tollmien jet. The history of the rapidly-building delta of the new Brazos River near Freeport, Texas, is an excellent demonstration of the operation of this principle. The new channel was cut in 1929 and a hydrographic survey by the U. S. Corps of Engineers in July, 1931, shows a well-developed submerged bar whose crest formed about 5 diameters out from the river's mouth. Waves and high meteorological tides from hurricanes markedly affected this region in August, 1932, September, 1933, and July, 1934. The protruding mass of deltaic sediments was subjected to a marked concentration of wave energy because of wave refraction effects, so that by October, 1934, the bar had become roughly triangular in shape, linked to the land, and various portions stood above low water (Figure 5-A). In fact, the bar thereafter became sufficiently developed to form a barrier beach and the channel through which the river crossed this beach became the new orifice, probably after the occurrence of a nearby hurricane during June, 1936. Sketches based on a series of excellent aerial mosaics by Jack Ammann, Photogrammetric Engineers, Inc., permit the reconstruction of the subsequent history. By December, 1938, (Figure5-B) a new bar had formed blocking the channel at a distance of about 4.5 diameters in front of the original bar. A period of relative stability followed, and the site of this new bar soon became the point of channel bifurcation, while wave refraction, particularly active during a hurricane which passed over the area in August, 1942, molded the entire complex into even more of a triangle, as shown by photography in September, 1944 (Figure 5-C). Hurricanes crossing inland in this immediate region during August, 1945, and October, 1949, created barrier beaches bordering this deposit, so by late October, 1949, (Figure 5-D) there is again only one channel bisecting the cuspate delta. It should be noted that bays have formed behind the barrier beaches. On larger deltas, such embayments might be termed "delta-flank depressions", as in the case of Barataria Bay on the west flank of the present Mississippi delta, but their history shows that they are obviously the result of a combination of natural levee and barrier beach formation. Thus, the formation of a delta such as that of the new Brazos is obviously the result of a balance of forces between bar formation with resulting channel bifurcation versus wave action concentrated by wave refraction because of unusual bottom conditions.

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At the present time, our research has not been pursued far enough to adequately develop a method for predicting the depth of channel over the bars deposited according to the above theory. However, there are several promising approaches, and by the next Coastal Institute, it is hoped that this problem will have been solved.

For almost a century the importance of the effect of the earth's rotation on stream flow has been a debatable question. This apparent deflecting force, appropriately named the "Coriolis force" after the French mathematician Coriolis, has been believed by some to be responsible for anomalous stream-meandering, a phenomenon considered to occur in accordance with "Baer's Law". The favored opinion has been that while the effect existed, it was so slight that other environmental factors always masked it. This opinion still prevails, as we have found by polling some of the world leaders in hydraulics and geomorphology, as well as by reviewing current literature in the fields of hydraulics and limnology. However, detailed oceanographic studies of estuaries of the United States during the past four years have indicated again and again that Coriolis force is strong enough to cause seaward flowing water to be deflected to the right-hand side of the estuary as it flows downstream. While aware of this world-wide effect as early as 1949, it was only during the summer of 1952 that an example has been located by the authors from the Southern Hemisphere. Figure 6 shows the cross-sectional profile of isohalines across the Hawkesbury River just north of Sydney, Australia, at two stages of the tide on July 14-15, 1952. These data have been kindly furnished by Dr. D. J. Rochford of the Australian Marine Biological Laboratory, and are believed to be the first to clearly illustrate the manner in which outflowing fresh water is shunted to the left-hand side of an estuary in the Southern Hemisphere. The opposite effect is known to occur in the Northern Hemisphere, as in the case of the James River where Pritchard (1952a) finds the fresh-water to move seaward along the right-hand bank. The theory of such asymmetry has already been given in detail by Pritchard (1952b); the importance of this phenomenon in harbor flushing has been discussed by Elliott, Tressler, and Myers (1953).

Coriolis force is also important at the mouths of at least major rivers such as the Mississippi. For example, Figure 7 shows that at the time of the first complete hydrographic survey (1859-1871) of the eight major outlets in the lower Mississippi delta, seven of the passes or bayous had their right-hand banks extending further seaward than did the left-hand banks; while the eighth pass (Northwest Pass) was questionable for it had only an unusual cluster of islands beyond the tip of the right-hand shore, which bank did not extend as far as the left-hand bank. Studies by the U. S. Corps of Engineers (1919) have also shown that this anomalous depositional pattern appears in isopach studies of sediment volumes deposited off the passes; for example, an area on the left-hand tip of Southwest Pass received but 72% of the volume of sediment deposited between 1867 and 1905 in an area of comparable size and location off the right-hand tip of the

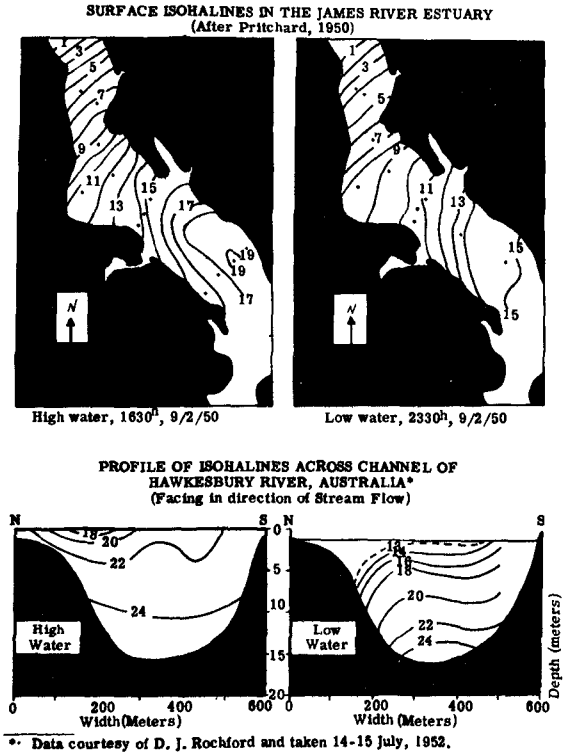

Fig. 6. Asymmetric distribution of salinity in estuaries of the northern and southern hemispheres caused by Coriolis force.

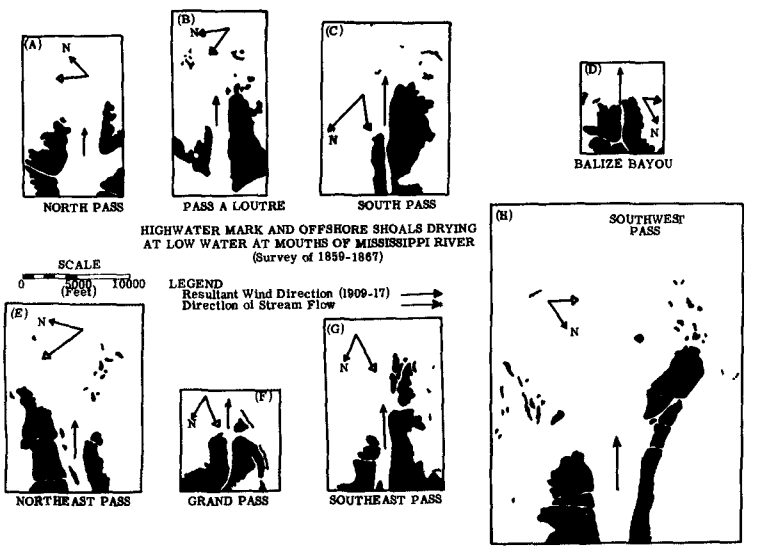

Fig. 7. Asymmetric formation of river banks at important mouths of the Mississippi River, the major causative factor probably having been Coriolis force.

pass. Such anomalies have been ascribed by the Corps of Engineers to a littoral current flowing from east to west created by the prevailing wind. Inasmuch as the resultant wind in this area is from 115° at a speed of about 3.2 statute miles per hour, it is obviously incapable of creating the littoral current reported. In the forthcoming geological paper on deltas, it will be demonstrated that the right-bank extensions are the result of two manifestation of Coriolis force, namely, a cross-channel slope and a deflection of the outflow as it leaves the distributary mouths.

This marked deflection of rivers to the right upon entering a basin was reported by Fehlman (1948) for Swiss lakes but he did not ascribe the effect to any particular cause. Study of this effect at the mouths of the Mississippi River indicates that the phenomenon is caused by Coriolis force and that it is widespread geographically, occurring at the mouths of such rivers as the Po, Danube, Volga, and Nile. Off the Mississippi and during periods of low winds, the turning appears to be at a more rapid rate than that calculated by using the arc of an inertial circle based on issuing velocity; on the other hand, the turning is at a slower rate than would be expected if the flow were a combination of littoral currents and jet flow. The turning is powerful enough, however, for a relatively fixed boundary to form between river and oceanic water five to ten miles off the eastern half of the Mississippi delta during flood stage. The main discharge of the distributaries presumably remains inside this boundary, the flow along this boundary being directed first to the southeast and then veering slowly to the west off the southern portion of the delta, so that this source contributes an important, if not major, portion of the water making up the east-west current present. However, aerial photographs taken by the U. S. Corps of engineers of the outflow from South to Southwest Passes, today's main navigational channels, show that both discharges take the shape of parabolic jets similar to the one shown in Figure 2. Both jets turn to the right, although their turning is obviously more limited in extent--that is, by a smaller angle than that observed off the passes to the north and northeast where the trajectory of the flow approaches an 180° arc. As soon as enough water has been banked against the coast to permit downslope gravitational force to balance Coriolis force and density patterns created by the flow of fresh water over saline water, the flow from South and Southwest Passes tends, at best, to only parallel the main shoreline (90° or a little more); frequently, the turning is not that great. Strong winds during "Northers", of course, deflect this surface flow and may temporarily direct it towards the south or southeast.

To conclude, it has been proposed that on the basis of modified jet theory it is possible to explain rationally and quantitatively much that occurs at the mouths of rivers emptying into the sea. These explanations are based on physical principles which have been checked in the laboratory and supported by field observations made throughout the world. Because the approach is quantitative, it may permit objective forecasting of future conditions at natural and artificial outlets that are of interest to the hydraulic engineer.

ACKNOWLEDGMENTS

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