CHAPTER 253

EBB TIDAL DELTA EVOLUTION OF COASTAL INLETS

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ABSTRACT

Previous investigations have established the dependence of ebb delta volumes on wave energy and tidal energy at sandy inlets. In this study, this dependence was examined with respect to the rate of delta growth and the final equilibrium delta volume starting with the opening of a new inlet when no delta is present. A diagnostic model was developed for examining the influence of the ratio of wave energy to tidal energy on delta growth. Model sensitivity tests showed that increasing the suspended sediment concentration in the littoral zone caused the delta to approach equilibrium faster, but did not affect the equilibrium volume. Increasing the wave height increased the time of approach to equilibrium but decreased the volume. Finally, increasing the sand size increased the growth rate as well as the equilibrium volume. The model was applied to five Florida inlets. It was shown that the delta may never attain a true equilibrium volume, and the actual volume may fluctuate about a "quasi"-equilibrium volume consistent a wave energy to tidal energy ratio representative of the long-term wave and tidal conditions at the entrance.

INTRODUCTION

At the seafloor in the immediate vicinity of a coastal inlet the interrupted littoral sediment tends to accumulate and raise the floor, leading to the formation of an ebb delta. The ebb tidal delta grows due to the supply of littoral sediment and ultimately reaches an equilibrium volume when the condition of no net deposition is attained. At new inlets, or ones which have been closed for a period of time, the rate at which the seafloor is modified by deltaic formation depends on the prevailing physical

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conditions, availability of littoral sediment, and geologic setting. Previous investigations have established the dependence of the delta volume on wave energy and tidal energy at sandy inlets. In this study, this dependence was examined with respect to the rate of delta growth and final equilibrium delta volume starting with the opening of a new inlet when no delta is present. The aim of this study was therefore to examine the inter-dependence between significant physical parameters governing sediment transport and the rate of delta formation at coastal inlets.

PROCEDURE

To examine the influence of the effects of current and waves on the growth rate of ebb deltas, a diagnostic approach is developed. The growth process of the delta will have an initial condition of a new inlet with no delta present (Figure I.A). The opening of an inlet the ebb delta volume increases as the inlet tidal current deposits material derived from the littoral system and ultimately reaches an equilibrium volume when the condition of no net deposition is attained. Delta accumulation height will be simulated by modeling tidal currents and superimposed waves to determine the combined shear stress, τ_b (Pa). The seafloor will continue to rise on the condition that the combined shear stress is smaller than the critical shear stress, τ_{cr} (Pa), for deposition (Figure I.B). The model must then determine the delta volume when the seafloor reaches an equilibrium elevation (Figure I.C) due to a balance of shear stresses (ie. $\tau_b = \tau_{cr}$), and the estimate the time for the equilibrium to occur.

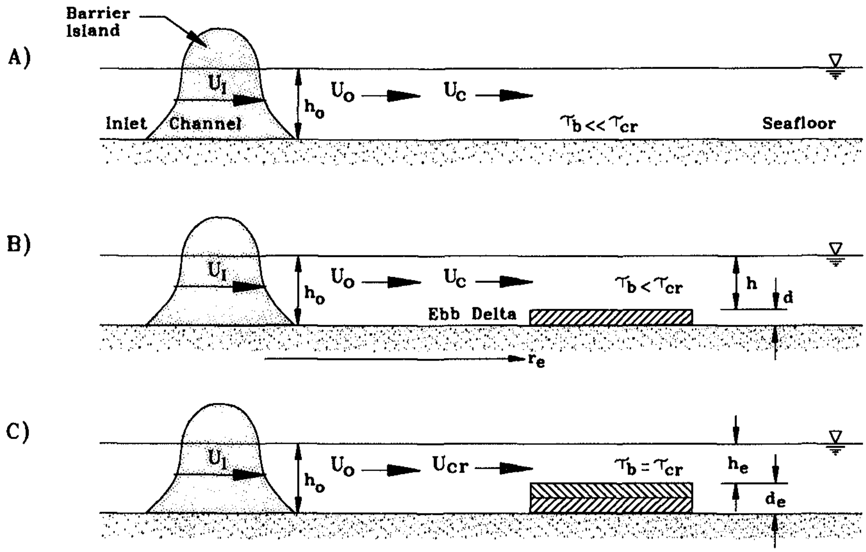

Figure I. Idealized ebb delta growth: A) initial condition; B) growth period; and, C) equilibrium condition

DIAGNOSTIC EXAMINATION OF SEAFLOOR EVOLUTION

The net decrease of suspended sediment mass per unit delta bed area, m, with respect to time, t (s), is related to sediment settling flux by

$$\frac{dm}{dt} = F_s \tag{1}$$

Substituting $F_s = -pW_sC_s$, where W_s = particle settling velocity (m/s), C_s = depth-averaged suspended sediment concentration (kg/m^3), and p = probability of deposition which is given as $p = (1 - \tau_b/\tau_{cr})$ (Krone, 1962) which can range between 1 (total deposition) and 0 (no deposition). The settling velocity can be expressed as $W_s = [(4gd_{50}/3C_D)(\rho_s\text{-}\rho_w/\rho_w)]^{1/2}$, where ρ_s = particle density (kg/m^3), ρ_w = seawater density (kg/m^3), d_{50} = median particle size (mm), g = acceleration due to gravity (m/s^2), and C_D = drag coefficient (Schiller and Naumann, 1933). The value of C_D outside the Stokes range (Reynolds number < 1) decreases rapidly then levels off and becomes nearly constant (e.g., 0.43 for spheres) in the fully turbulent flow regime considered.

Equation 1 can thus be expressed as

$$\frac{dm}{dt} = -H_f\left(1 - \frac{\tau_b}{\tau_{cr}}\right)W_sC_s \tag{2}$$

where H_f [x] = heavyside function such that H_f [x > 0] = x, and H_f [x ≤ 0] = 0. Next, $\rho_d = A_Dm/V$, where ρ_d = dry bed density, A_D = ebb delta deposition area (m^2), m = mass (kg), and V = delta volume (m^3). Furthermore, $dV = dhA_D = d(d)A_D$, where dh = change in water depth and $d(d)$ = change in ebb delta height. Substituting these relations into Equation 1 results in an expression for the change of ebb delta height over time:

$$\frac{d(d)}{dt} = -H_f\left(1 - \frac{\tau_b}{\tau_{cr}}\right)\frac{W_sC_s}{\rho_d} \tag{3}$$

Given W_s, C_s, and ρ_d, Equation 3 can be solved provided τ_b and τ_{cr} are determined. Komar and Miller (1974) found that data for sediment threshold under oscillatory flows closely agreed with Shields' (1936) relationship for incipient grain motion under unidirectional flows. Thus, $\tau_{cr} = 0.058(\rho_s - \rho_w)gd_{50}$, can be used to determine the critical shear stress for waves and currents. Grant and Madsen (1978) prescribed the following relationship for shear stress due to both current and waves, $\tau_b = 0.5\,\rho_w f_{cw} U_t^2$, where f_{cw} is the wave-current friction factor, and the combined wave-current velocity near the bottom, $U_t = (U_{wb}^{\ 2} + U_{cb}^{\ 2} + 2U_{cb}\,U_{wb}\cos\phi)^{1/2}$. The quantity, U_{cb}, is the near-bed current velocity over the bottom, U_{wb} = near-bed orbital velocity due to waves (m/s), and ϕ = angle between the current and wave direction. During flood flow, when $\phi = 0$, the waves are able to penetrate over the shoal and into the inlet channel thereby causing more bottom scour at the delta during flood flow than ebb. Therefore, $\phi = 0$ will be assumed for this study.

For calculating the bottom stress, τ_b, the friction factor due to the combined current and waves is given by $f_{cw} = (|U_{cb}|\, f_c + |U_{wb}|\, f_w)/(|U_{cb}| + |U_{wb}|)$, where f_c = friction factor due to current, and f_w = friction factor due to waves. The near-bed orbital velocity due to waves can be obtained from linear wave theory, $U_{wb} = [H\pi \cosh(kh)/T \sinh(kh)]$ (Dean and Dalrymple, 1984), where k = wave number equal to $2\pi/L$ (1/m), L = wave length (m), T = wave period (s), and h = water depth at the delta (m). As a wave train propagates from offshore into shallower water, the wave height changes as the depth changes. According to linear wave theory, the shoaled wave height (m), $H = [H_o(C_o/2C)^{1/2}(b_o/b_s)^{1/2}]$, where b_o = distance between two adjacent deep water wave rays (m), b_s = distance between two adjacent nearshore wave rays (m), C_o = deep water wave celerity (m/s) equal to $gT/2\pi$, C = shallow water wave velocity (m/s) equal to $(gh)^{1/2}$, and H_o = deep water wave height (m). The model assumes the contours are to remain straight and parallel. Thus, the refraction coefficient, $(b_o/b_s)^{1/2} = 1$.

The initial step to determine the near-bed current velocity over the delta, U_{cb}, is to obtain the maximum velocity (m/s) through the inlet for a spring tide is given by $U_{max} = (0.86\pi P/ T_t A_c)$, where P = spring tidal prism (m^3), T_t = tidal period (s), and A_c = throat cross-sectional area of the inlet (m^2) (O'Brien, 1969). The average inlet velocity at the mouth of the inlet channel over one-half tidal cycle (m/s), $U_I = (2U_{max}/\pi)$. As the flow exits the inlet channel it is considered to spread out from the inlet mouth. To obtain a characteristic velocity (m/s), U_o, at the shoreward end of the deposition area, this velocity is assumed to occur along an arc, one-half the distance (m), r_e (Figure I.B), from the entrance mouth to the outer edge of the tidal prism based ebb delta area (m^2), A_P, where $r_e = (2A_P/\pi)^{1/2}$ is obtained from continuity. Thus, $U_o = (2U_I w/\pi r_e)$, where w = width of the entrance (m).

As the seafloor rises, the water depth decreases with respect to the initial water depth (m), h_o, whereby to maintain the continuity of flow, the current velocity over the delta (m/s), U_c, must increase. The current velocity, U_c, decreases with distance from the entrance as the flow spreads out over the delta from its inner to outer limit. For this study, U_c will be defined as its value at the inner limit of the delta. It should also be noted that the velocity profile of U_c is vertically uniform, it is therefore necessary to apply a correction factor to obtain the near-bed velocity (m/s), U_{cb}.

From the logarithmic velocity profile (Mehta, 1978), the ratio of the near-bed velocity to the depth averaged current velocity, $U_{cb}/U_c = ln(z_b/z_o)/ln(h/z_o)-1$, in which z_o = theoretical origin of the logarithmic profile (m), and z_b = distance above profile origin (m) and is set here equal to 0.05 m. The virtual origin of the profile is obtained from the Manning-Strickler formula, $z_o = 10^7 n^6$.

Mehta and Özsoy (1978) noted that a representative Manning's n value of 0.028 can be used for sandy inlets with a typical initial water depth of 4.0 m. Thus, the current velocity obtained by continuity is multiplied by a correction factor of 0.40, $U_{cb} = 0.40U_o(h_o/h)$. Note that when the equilibrium delta volume is attained, $U_c = U_{cr}$, hence $U_{cb} = U_{cr} = 0.40U_o(h_o/h_e)$, where h_e = equilibrium water depth (m).

Inserting equations above into Equation 3 results in the governing equation for ebb delta height variation with time, and is expressed as

$$\frac{d(d)}{dt} = -\frac{W_s C_s}{\rho_d}\left\{1-\frac{\rho_w f_{cw}}{2\tau_{cr}}\left[\frac{(H\sigma)^2\cosh^2 kh}{4\sinh^2 kh}+0.16\left(\frac{U_o h_o}{h}\right)^2+\frac{H\sigma\cosh kh}{2.5\sinh kh}\frac{U_o h_o}{h}\right]\right\} \quad (4)$$

In the finite difference form, the left hand side of Equation 4 becomes $\Delta d/\Delta t$, and was solved using the fourth order Runge-Kutta iteration method for the incremental change in delta accumulation, Δd, for $\Delta t = T_t$ (tidal period). The incremental change in delta accumulation, Δd, can then be multiplied by the depositional area, A_D, to obtain the incremental ebb delta volume, ΔV. The cumulative volume change is then plotted to illustrate the effects of waves and currents on ebb delta growth rate and estimate the duration to achieve an equilibrium volume.

MODEL PARAMETERS

Ebb delta area, A_D. It is necessary to identify the ebb delta depositional area, A_D, over which deposition occurs. This was achieved by empirically correlating the tidal prism based ebb delta area, A_P, with A_D using measurements of 21 ebb delta areas of Florida's lower Gulf Coast inlets (Davis and Gibeaut, 1990). The equation of the regression line relating the tidal prism based delta surface area and the delta depositional area, $A_D = 2.34A_P^{0.81}$, corresponds to the coefficient of regression of $r^2 = 0.65$ which shows an acceptable relationship. The surface area, $A_P = P/2a_{os}$, is characterized by spring tidal prism, P and spring sea tidal amplitude (m), a_{os}.

Suspended sediment concentration, C_s. Downing (1984) presented a time-series of sediment concentrations at three locations across the surf zone at Twin Harbor Beach, Washington. The investigator found two distinct types of vertical concentration profiles. The first occurred between resuspension events ranged from 0.0002 to 0.0004 kg/m^3, when the sediment concentration had vertical uniformity. While during resuspension events a concentration gradient, 0.0015 to 0.0100 kg/m^3, occurred within 0.10 m above the bed in a total column water depth of 0.25 m. These concentration ranges will be assumed to apply for this study.

Sediment grain size diameter, d_{50}. Mehta and Özsoy (1978) noted that for sandy inlets the median grain size at most inlets range between 0.2 and 0.4 mm. This range will be considered in the present study.

Deep water wave height and period, H_o. The deep water wave height has a significant effect on the growth rate of the ebb delta and its equilibrium volume. By adjusting the wave height, the model generated delta volume-time curve can be made to pass through the appropriate smallest and largest measured delta volumes at a given inlet. A characteristic wave period of 8 seconds will be used for all model runs.

Friction factors, f_w, f_c. The friction factor due to current, $f_c = 8gn^2/h^{1/3}$, where Manning's n and h = water depth (Mehta, 1978). Mehta and Özsoy (1978) noted that a typical mean Manning's n value of 0.028 can be used for sandy inlets. The initial water depth used to model the evolution of the ebb deltas averaged 4 m (Dombrowski, 1994), resulted in a characteristic friction factor due to current of 0.039. It should be noted that Mehta (1978) determined friction factors for three inlets on the Gulf Coast of Florida ranging between 0.021 to 0.050.

The friction factor due to waves, f_w, was obtained from the wave friction factor diagram developed by Jonsson (1965) which plots the friction factor against the wave Reynolds number. Given, h = 4 m, H_o = 0.4 m, and wave period of 8 seconds, $R_e = 1.7 \times 10^4$, corresponds to the fully turbulent flow range (Figure 6 in Jonsson, 1965). Given the typical variation of R_e in the present study, a representative value of $f_w = 0.005$ in the fully turbulent flow range was chosen.

Tidal inlet characteristics. The tidal inlet characteristics used in the analysis are derived from the database found in Dombrowski (1994). The characteristics include: inlet throat width, throat depth, tidal prism, and spring tidal range.

EFFECTS OF IMPORTANT PARAMETERS ON DELTA GROWTH

The effects of important parameters on the rate of delta formation at coastal inlets is examined. The three selected parameters are 1) suspended sediment concentration, C_s; 2) median sediment grain size, d_{50}; and 3) deep water wave height, H_o. The influence of varying these parameters on the volume growth curves are shown in plots of ebb delta volume versus time, beginning with a new inlet with no delta. The range of values of these three parameters are found in Dombrowski (1994).

Suspended sediment concentration, C_s. In the Equation 4 for the change rate of ebb delta height, $d(d)/dt$, is proportional to the suspended sediment concentration, C_s. Figure II plots the ebb delta volume, $V = A_D(h_o\text{-}h)$, versus time (years) for three suspended sediment concentrations. A characteristic that is evident from the growth curves is that the equilibrium ebb delta volumes are the equal (1.4×10^6 m^3) for the three concentrations. However, it is evident that as C_s increases the rate of deposition becomes more rapid.

Sediment grain size diameter, d_{50}. Two physical parameters are dependent on the median grain size diameter, d_{50}, the settling velocity, W_s, and the critical shear stress

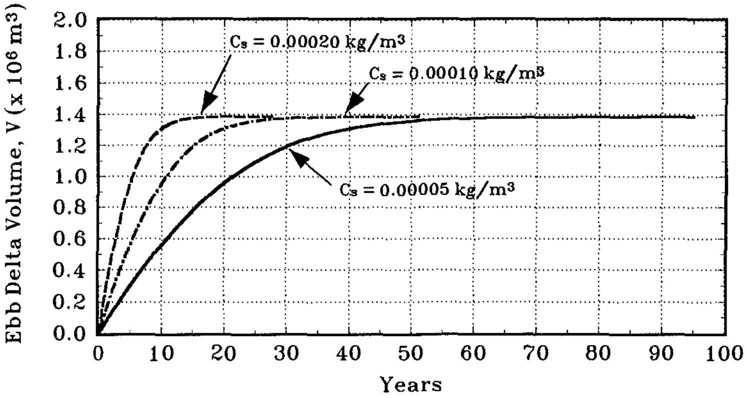

Figure II. An illustration of the influence of suspended sediment concentrations on calculated delta growth rate.

for sediment transport, τ_{cr}. The ebb delta volume versus time plot for varying sediment diameters (Figure III) is characterized by three different growth rates and equilibrium volumes. The increase in the sediment diameter increases the rate of deposition, due to the dependence of particle fall velocity on sediment size. An increase in the sediment size also increases the critical shear stress, allowing the sediment bed to remain more stable as compared to a bed composed of smaller grain size under the same flow conditions. This effect results in an increase in the equilibrium volume for increasing grain diameters.

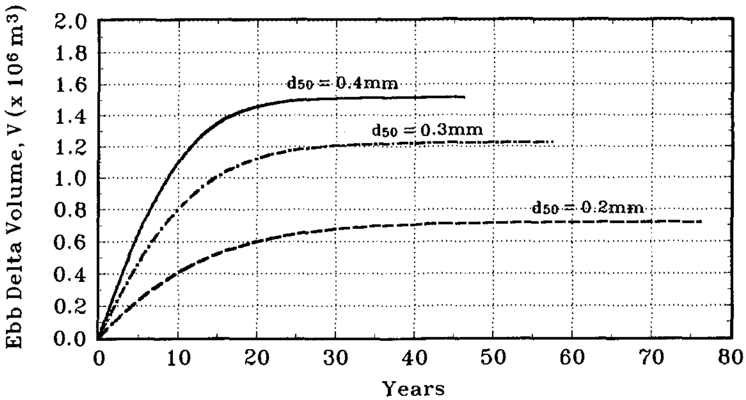

Figure III. An illustration of the influence of sediment grain size diameters on calculated delta growth rate.

Deep water wave height, H_o. As the waves approach the shoreline, its height increases as the water depth decreases. This increase in wave height in turn increases the near-bed orbital velocity, U_{wb}, hence reduces the rate of deposition. Figure IV plots the ebb delta volume versus time illustrating delta growth due to current alone, 0.0 m wave height, and two additional deep water waves heights of 0.4 and 0.8 m. During sea conditions when the deep water wave height is equal to 0.0 m, the rate of deposition is observed to be relatively rapid compared to the other two wave conditions. Note the drastic decrease in the equilibrium volume with increasing H_o.

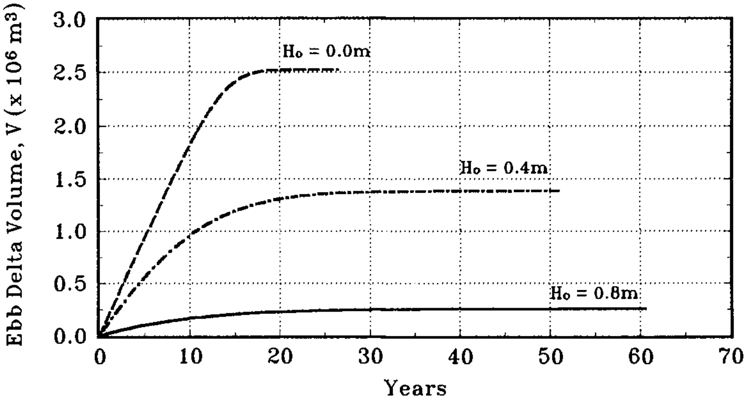

Figure IV. An illustration of the influence of deep water waves on calculated delta growth rate.

Model sensitivity tests showed that increasing the suspended sediment concentration in the littoral zone caused the delta to approach equilibrium at a greater rate, but did not affect the equilibrium volume. Increasing the wave height increased the time the delta approached equilibrium but decreased the equilibrium volume. Finally, increasing the sand size increased the growth rate as well as the equilibrium volume.

TIME-EVOLUTION OF DELTA VOLUMES

The time-evolution of sand volumes of five selected deltas along the east coast of Florida including those at 1) Jupiter Inlet; 2) South Lake Worth Inlet; 3) Boca Raton Inlet; 4) Bakers Haulover Inlet; and 5) Sebastian Inlet were analyzed. These inlets were chosen because 1) the date when each inlet was opened was available, and 2) four or more data points were available per inlet to represent the time-variation of ebb delta volumes. A plot of the measured delta volumes versus date of survey with the corresponding volume ranges for Jupiter Inlet obtained from the model is presented. The theoretical volume curves were derived from the model using the specific characteristics of the respective inlet. These data including 1) spring tidal prism, P; 2) inlet throat width, w; 3) inlet depth, h_o; and 4) spring tidal range, $2a_{os}$

are summarized in Dombrowski (1994). By adjusting the deep water wave height, H_0, and the suspended sediment concentration, C_s, the delta volume-time curves were made to pass through the appropriate smallest and largest measured delta volumes.

Wave energy to tidal energy ratio, α. The inlet stability parameter, α, was introduced by O'Brien (1971) and was later expanded by Mehta and Hou (1974) to provide an indicator of the stability of inlets. An inlet in equilibrium is due to a balance between the wave energy which tends to close an inlet and the tidal energy which maintains the opening. For the present study, the (non-dimensional) stability coefficient, α, defined as the ratio of longshore wave energy to the tidal energy is used to provide an indication of the relative effect of waves and tidal current in governing the rate of growth of the ebb delta. In a reduced form for a representative deep water wave height H_o, the relationship can be expressed as:

$$\alpha = \frac{H_o^2 T w T_t}{64 \pi a_{os} P} \tag{5}$$

where T = wave period (s), T_t = tidal period, a_{os} = spring tidal range, and P = spring tidal prism).

As the deep water wave height is increased at a given inlet, α increases and reflects a tendency to drive material toward the inlet and the nearshore area, thus limiting the delta volume. Conversely, if the deep water wave was set to zero, the corresponding α would equal zero indicating a current-determined delta. This condition results in a larger ebb delta volume as compared to a higher α-value for the same inlet when waves are present.

Jupiter Inlet. Nine delta volumes were available for Jupiter Inlet since this entrance was re-opened for navigation in 1947 (Figure V). The near linear delta growth rate from 1947 to 1967 is characteristic of the high initial growth of the delta following the opening of the inlet. This high growth rate is consistent with the occurrence of a deep sea floor at the time of the entrance opening when the incipient influence of wave action is low. The non-zero delta volumes range between 0.23 x10^6 m^3 and 0.77 x10^6 m^3, for the years 1981 and 1993, respectively. This variability may, in part, be due to the method used in estimating the volumes which could be on the order of 15% for Jupiter Inlet. We infer that this variability is primarily influenced by wave action and its seasonal as well as year-to-year variation.

The model was used to simulate the growth curves matching the volume range. The α-value of 0.17 resulting from a H_0 = 0.54 m yielded a volume of 0.77 x10^6 m^3 in 1993. The higher α-value of 0.27 was calculated for a H_0 = 0.68 m to modify the growth curve to achieve a volume of 0.23 x10^6 m^3 in 1981. It is therefore surmised that the relative wide range in the delta volumes between the two curves is the result of waves relative to current. Larger delta volumes correspond to lower values of α and vice versa. The maximum range of α being 0.17 to 0.27 for this inlet.

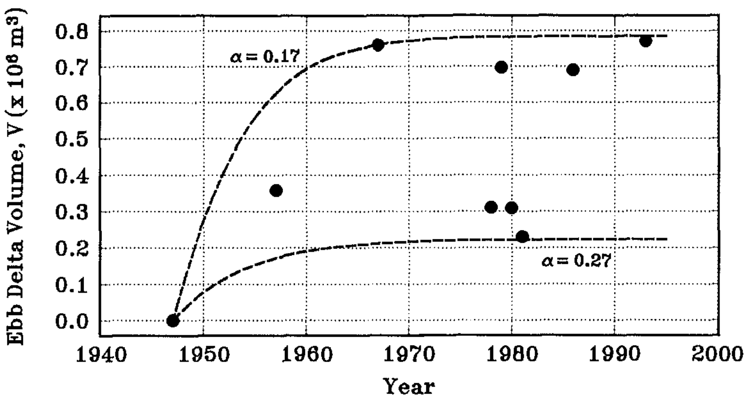

Figure V. Ebb delta volume versus year with model-calculated volume ranges for Jupiter Inlet.

INFLUENCE OF α ON DELTA GROWTH

A comparison of the ebb delta volume ranges and the corresponding wave to tidal energy ratio, α, for each of the five inlets is illustrated in Figure VI.

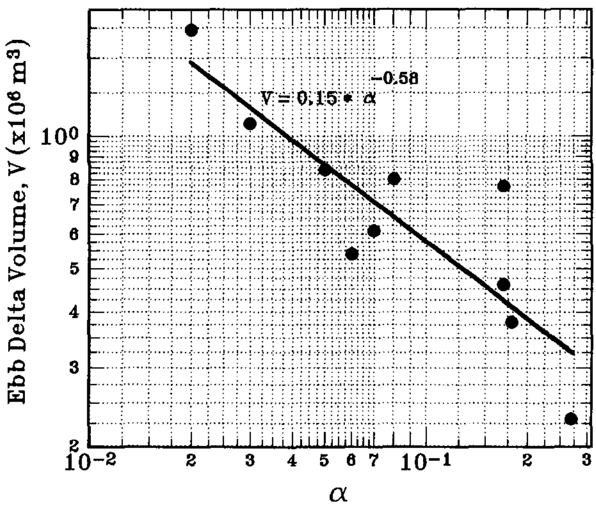

Figure VI. Ebb delta volume against wave to tidal energy ratio, α

As α increases, the ebb delta volume has a tendency to decrease, and vise versa. Although there is data scatter and a r^2-value of 0.58, which is low, the regression line does show that there in an inverse relationship between the delta volume to α.

The equation of the regression line relating α and V is

$$V = 0.15\alpha^{-0.58} \tag{6}$$

Note that V (delta volume) in this case may not represent the actual equilibrium value, but may be close to it, given the manner in which the curve fitting was conducted.

DELTA VOLUME VERSUS MAXIMUM WAVE HEIGHT

Devine (1996) related historical ebb delta volumes with episodic extreme sea conditions. The calculated delta volumes for three inlets were plotted against the corresponding maximum WIS (Hubertz *et al.*, 1993) wave height of the preceding year which showed an inverse relationship between the volumes and wave heights. For one inlet, there was no district relationship presumably because the ebb delta has not reached a equilibrium condition.

For this study, 13 surveys performed between 1974 and 1995 of Sebastian Inlet ebb delta were estimated and plotted versus the maximum WIS (Hubertz *et al.*, 1993 and Brooks, unpublished) wave height of the preceding year (Figure VII). A "best-fit" line through the data shows an inverse relationship of wave conditions on the ebb delta volumes. The average ebb delta volume for this time period, based on the available data, is 1.48 x10^6 m^3. The inlet has not undergone any major modification since before 1974, therefore the only one parameter controlling the delta volume is the changing sea conditions. The fluctuation of data about the average may be indicative of the ebb delta being in a "quasi"-equilibrium condition due to: 1) the variation of sea conditions; and, 2) the sink not available to accumulate more sand.

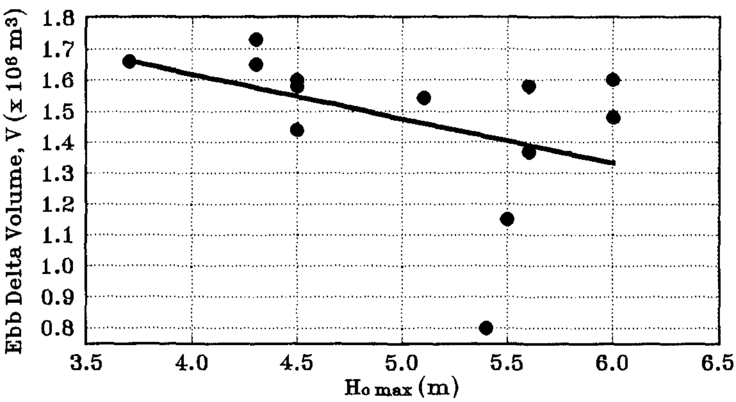

Figure VII. Ebb delta volume versus maximum WIS wave height for Sebastian Inlet.

CONCLUSIONS

Effects of Significant Physical Parameters on Delta Growth. Three parameters, namely the suspended sediment concentration, sediment grain size, and the deep water wave height, were varied in the diagnostic model developed for delta growth to determined their effects on the rate of delta formation at coastal inlets. It was found that an increase in the suspended sediment concentration increases the rate of approach to equilibrium, but does not result in a change in the equilibrium volume. On the other hand, a change in the sediment grain size and the deep water wave height effect both the rate of growth and the equilibrium volume. Thus, an increase in the sediment diameter increases the rate of growth due to the dependence of the particle fall velocity on sediment size, and increases the critical shear stress resulting in an increase in the equilibrium volume. An increase in the deep water wave height increases the near-bed orbital velocity at the site of the delta, hence decreases the rate of growth. The equilibrium delta volume likewise decreases.

Effects of α on Equilibrium Delta Volumes. It was shown through the application of the model to five Florida inlets that there is a dependence between the ebb delta volume and the wave to tidal energy ratio, α. The growth of the delta is determined by the rate at which the sand, supplied by the littoral system, is deposited by the ebb tidal flow. As wave action increases, thus increasing α-value, the delta growth rate decreases as wave and current induced bottom shear stresses scours sand deposited on the delta.

The dependence of delta volume on α partly explains the observed fluctuations in the delta volume at many inlets, since α tends to vary seasonally as well as annually. This relationship was further illustrated by plotting the ebb delta volume of Sebastian Inlet versus the maximum wave height of the preceding year. Another cause of variation of the delta volume at a given inlet is that even under constant sea conditions, the equilibrium volume often occurs after several decades following the opening of an inlet. Thus the delta volumes measured during the early years of evolution will be lower than the equilibrium volume. It was shown that the delta may never attain a true equilibrium volume, and the actual volume may fluctuate about a "quasi"-equilibrium condition. This would be consistent with a value of the wave energy to tidal energy ratio representative of the long-term wave and tidal conditions at the entrance.

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