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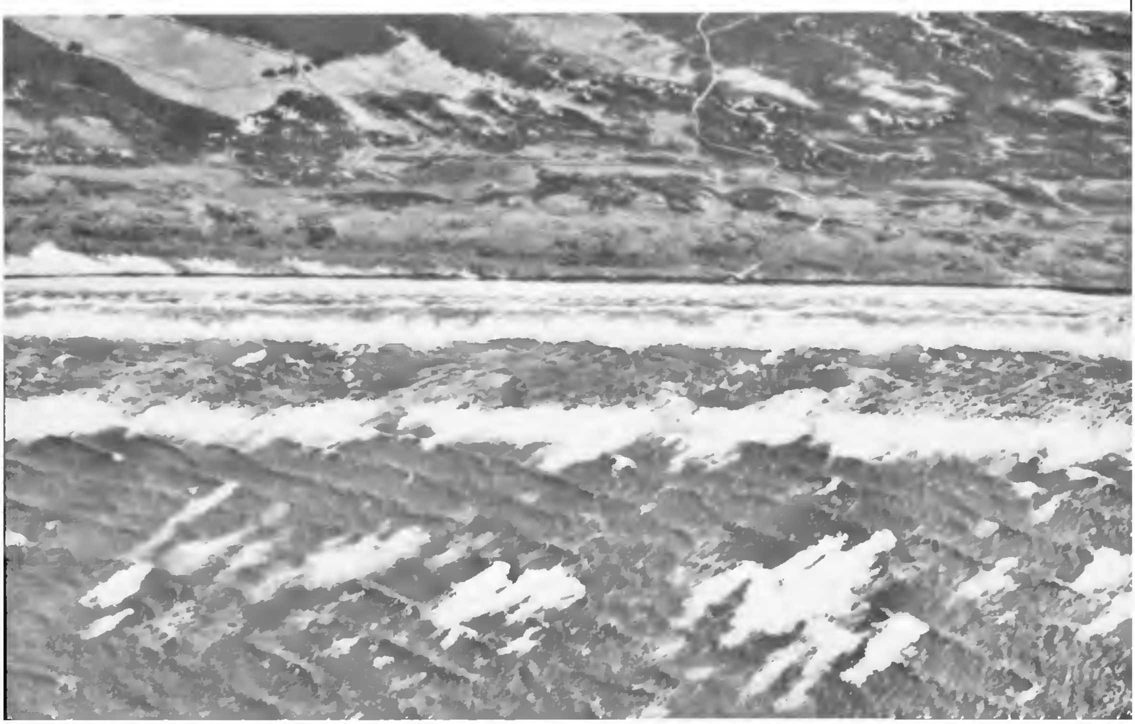
PART II

COASTAL SEDIMENT PROBLEMS

Danish West Coast



CHAPTER 38

FEASIBILITY OF COASTAL MORPHOLOGICAL MODELS

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ABSTRACT

The paper deals with the initial ideas and concepts for development of a morphological model for a Delta coast, having particularly the Nile Delta in mind. The paper concentrates on the offshore zone, in which sediment is assumed primarily to be transported in suspension and during periods of sufficient agitation by the combined action of waves and ocean currents. In the Nile Delta great offshore changes take place due to the deprivation of the shelf area of Nile sediments by the closure of the Aswan High Dam, and serious nearshore long-range changes are expected to result from the changes to the offshore morphology. The modelling aids in establishing the mechanisms of the Delta shore, but the primary goal of the model is reliable prediction of future coastal changes. Fundamentally, the modelling is based on verification of the model - by trial and error - against known states of the model domain.

Part A of the paper deals with the general concepts, while especially the entrainment of sediments is treated in Part B of the paper, yielding practical formulas for determining the treshold values for sediment entrainment by unidirectional flow and by wave action.

PART A - THE GENERAL CONCEPTS

1. Introduction

The paper is the prelude to the work of developing a workable mathematical model for the prediction of future morphological changes to the Nile Delta continental shelf area, and although the subject is treated in a general manner, the Nile Delta area shown in sketch map fig. 1 is constantly being kept in mind and being referred to.

The motivations of a Nile Delta model have been discussed briefly by the author in (1). A model seems to provide the only rational manner for systematic recording and analysis of the large number of space and time data collected for the Nile Delta, and for predicting future changes if such predictions are to be not mere guess-work. No research worker on coastal processes underestimates the complexities of the actual processes in nature and the limitations of laboratory experiments, and it is realized that no exact modelling shall ever be possible.

A few words on terminology are called for. Geomorphology deals with the 'sleeping', i.e. static surface of the Earth, and the generally used term 'dynamic geomorphology' applying to changes to the surface forms is really a misphrasing. Geomorphology is a descriptive discipline dealing only with space and materials, while 'dynamic geomorphology' dealing also with time and changes and the physical processes causing the changes is quantitative and interdisciplinary. Scheidegger (2) uses the term 'geodynamics' in connection with endogenetic surface features due to processes occurring inside the solid Earth and reserves the term 'geomorphology' for exogenetic surface features due to processes occurring outside the solid Earth. However, as mentioned for instance by Strakhov (3), the endogenetic features are of sufficient magnitudes to influence strongly the exogenetic processes and their effects upon the surface morphology and evolution. Consolidation settlement of clayey sediments are for instance on the border between endogenetic and exogenetic features, and even within historical time intervals tectonic changes including seismic effects can affect the coastal morphology and thus the past geomorphological states used for verification of models of evolution and prediction. While the Nile Delta model will be designed primarily for prediction of geomorphological changes within the next 50 years or less, the model will none the less be tested against evidence of past changes, in historical and recent geological time. It must be an essential condition for a model that it is stable over past time intervals, during which the physical processes were not significantly affected by sea level variations or endogenetic processes.

The contemplated model is most easily perceived by imagining the continental shelf area - in the case of the Nile Delta some 250x50 km^2 - during a storm. The prior storm has left the sea bottom in a state involving sorting of sediments according to water depths, but with the sorting being influenced by the ocean current pattern, and over the sea bottom area the in-situ density of the sediments varies with sediment characteristics. This varying sea bottom with its geographical shape formed through thousands of years of delta build-up is now agitated by the combined action of waves and currents. The intensity of agitation varies not alone with depth, but also with geographical location in the Eastern Mediterranean. Driven by the ocean currents, clouds with varying concentrations of fine suspended sediments move continuously across the shelf area and into areas, in which the entrainment and transport capacity does not correspond to the actual concentrations of suspended materials, and deposition or elevation of materials takes place. The resulting accretion and erosion over the shelf area determines the new morphology of the sea bottom after the storm, and the process repeats itself with each storm, every time creating a new sea bottom topography. The modelling aims primarily at reproducing the described processes and extending them into the future. The emphasis is upon the long-range mechanisms and changes, rather than on the detailed short-range changes.

2. The model

A morphological state of the domain to be modelled must be defined to include not alone the surface topography, but also the sediment characteristics that influence the subsequent morphological states.

As a first approximation the definition may be limited to include the sediment characteristics influencing the subsequent states within a specified time interval, but this limitation has to be used with caution, for instance for finegrained sediments consolidating gradually or for non-cohesive sediments being slowly compacted under wave action. The important sediment characteristics are composition and density, grain shape, and inner structure of the sediment deposits to the depth at which appreciable interactions between water motions and sediments cease.

A set of subsequent morphological states determined at specified time intervals constitute in themselves an 'inactive' model and may be presented graphically as for instance by the so-called T-X diagrams. In case the changes between subsequent states can be related to the forces acting during the respective time intervals by a common 'law' applying to all space and time intervals, the 'inactive' model becomes an active model representing the total time interval of the set of determined morphological states. Provided a reasonably accurate statistical record can be established of forces acting prior to the time interval of the determined states, the model may be operated back in time and may be checked against features known from maps of the past or from historical and geological records. Once properly verified, the model may be applied to prediction of future morphological changes, using the expected forces as inputs.

Thus, the sediments of the sea bottom constitute the medium of the model, the hydrodynamic forces are the inputs of the model, and the morphological changes are the outputs. The response factor of the model is the above mentioned 'law' representing the relationship between forces and changes. The changes are initially expressed by quantities of sediments shifted by the forces and are transformed into morphological changes by volumetric considerations. The model must be verified against two or more known past morphological states.

The model is discrete in space and time. The force inputs are statistical quantities, and the verification of the model against known states determined at considerable time intervals implies that resulting changes over the time interval will be related to resulting forces. Predicted future states based on expected values of force inputs will represent cumulative changes and will be expressed in terms of probabilities of occurrence.

The response factor is deterministic, relating the model outputs to statistically described inputs. The true response factor, or 'law', is a general sediment transport formula and cannot be determined exactly, due to the complexities of the processes involved, which in themselves contain elements of probability, in turbulence, grain interactions and sediment structure. The verification of the model against known states aims at determining suitable approximations to the true 'law' and is based upon the fact, that the 'law' is a unique physical relationship (with statistical values for probability elements) between the sediment characteristics and the forces acting directly upon the sediments and is invariant in space and time.

3. The model domain and its boundaries

The model domain must be delineated so that the boundary conditions are determinable. The 'law' itself is invariant with respect to the boundary conditions, but the forces - and hence the sediment movements within the model domain - may depend upon conditions outside the domain, and it would then become necessary to know the 'feed-back' functions. In case the true 'law' were known, it would suffice to determine the forces and the 'feed-backs' across the boundaries in order to operate a model with known sediment characteristics and use it for morphological predictions. In the present case, the 'law' itself must be determined from differences between known morphological states, assuming the force fields for the corresponding time interval to be known and also the characteristics of the sediment involved in the transition from one state to another. Sediment budget calculations, including sediment fluxes across boundaries and also sediment discharges through estuaries and outlets, are then absolutely necessary for an overall control of the adequacy of the determined approximation to the true 'law' and for safe-guarding the stability of the model.

The nearshore and offshore zones are here defined respectively as the zones within which and beyond which wave breaking significantly affects the sediment transport. The empirical, two dimensional relationship between wave energy and sediment transport capacity, or a modified form of it, must for the time being suffice as the 'law' for the nearshore zone, but sediment fluxes across the internal boundary between the near-shore and offshore zones cannot be ignored, and the condition of geo-morphological continuity across the common boundary gives rise to inter-actions ('feed-backs') between the two zones. In the model the two zones are treated as separate subdivisions, with a common active boundary. The 'law' for the offshore zone will, by a procedure of trial and error, be determined from verification against two (or more) known morphological states. The present detailed knowledge of the mechanisms of sediment entrainment and sediment transport will guide the trial and error procedure.

Determination of boundary conditions, including 'feed-backs' across the boundaries dominates the modelling treatment of any shore area and rather limits the extent to which the subject matter can be treated in a general manner. In the case of the Nile Delta the boundary conditions can be dealt with without introducing unreasonable simplifying assumptions. The model domain will cover the continental shelf from Abuquir to Port Said (see sketch map fig. 1). The western boundary at Abuquir is in relation to Nile sediment quantities practically neutral in respect of sediment fluxes, as the shore formations to the west are indurated with calcareous materials. Along the offshore boundary at the shelf edge Corioli effects and shallow water refraction tend to turn the west to east ocean currents shoreward. At Port Said the nearshore zone is bounded by the breakwater protecting the entrance to the Suez Canal and to a certain extent also by the entrance channel to the canal. The offshore conditions east of Port Said do not materially affect the sediment transport processes inside the model domain, and the eastern offshore boundary conditions (sediment fluxes) can, therefore, be determined from the processes inside the model

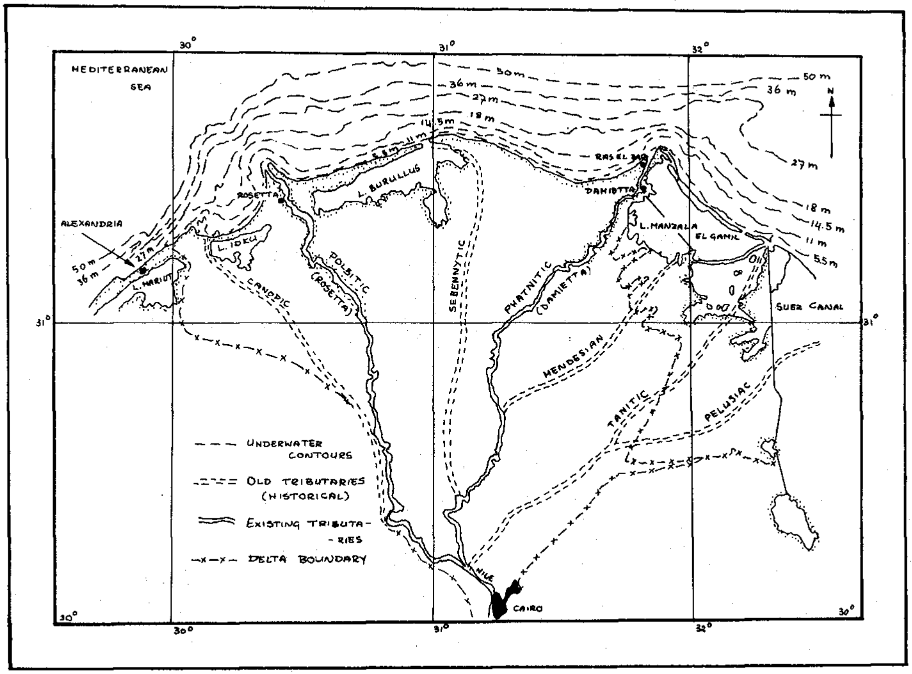

FIG. 1. - NILE DELTA.

domain. Quantitatively, the morphological changes in the offshore zone by far exceeded the nearshore sediment movements during the time interval between the verification states of the Nile Delta model, and the offshore sediment movements are expected still to be dominant. The offshore processes will, therefore, significantly affect the processes in the nearshore domain, whereas the nearshore processes cannot significantly affect the processes in the offshore zone except maybe close to the common boundary. Hence, the sediment fluxes across the internal boundary between the two zones can with reasonable accuracy be determined solely from the offshore processes and thereafter be introduced as known quantities in the nearshore model. Aeolian sediment fluxes across the shore boundary are rather insignificant for the offshore zone, but an estimated quantity may be introduced in the sediment budget. The Nile sediment discharges prior to the closing of the Aswan High Dam in 1964 are reasonably well known, and by far the greater quantities were deposited on the offshore shelf and reworked. Sediment discharges from lake outlets are insignificant except locally, but can be judged from flow studies in the outlets.

The offshore model domain of the Nile Delta can thus be treated independently of the nearshore zone and overall sediment budget calculations can be made. And with neutral west and east boundaries of the nearshore zone and known sediment fluxes across the seaward boundary, the nearshore zone can be dealt with, in respect of budget calculations, without necessarily knowing a priori the significant aeolian fluxes across the shore boundary.

4. Verification of the model

4.1 The offshore domain

The offshore model involves vast quantities of shifting sediments and continuously varying sea bottom morphology, both due to the vast pre-1964 yearly sediment deposits and the subsequent post-1964 inequilibrium of the offshore areas. The Nile Delta project shall not be able to carry out repeated detailed and exact surveys of the sea bottom configurations on the continental shelf, and in large parts of the shelf the changes over few years are likely to be of some magnitude or smaller than the accuracy of the surveys, but may none the less involve large quantities of sediments due to the vast area of the shelf. The model is, therefore, to be verified against the cumulative changes of some 50 years, this being the period between the last accurate hydrographic survey in 1920-1924 and the present survey being carried out by the project. The hydrodynamic forces will be hindcast for the verification interval.

The response factor of the model, the 'law', essentially involves quantities of sediments entrained and the vectorial transport distance of the entrained sediments, both corresponding to prevailing specified hydrodynamic conditions. Morphological changes in terms of erosion or accretion - possibly accompanied by changes to sediment characteristics - would at any one location of the model domain be determined as the resulting, or cumulative, difference between the sediments entrained at that particular location and the sediments originating from other locations of entrainment, being deposited at the location considered. Entrainment and deposition are not necessarily mutually exclusive. The entrainment mechanisms are different from transport mechanisms, but both are functions of grain size, and coarser grains entrained elsewhere could under some circumstances possibly settle down, while finer sediments are being entrained at the same location.

In case the true 'law' for the model were known, the quantities of sediments entrained and deposited at each location of the model domain could be determined uniquely, and assuming known hydrodynamic conditions throughout the verification period and known or calculable sediment fluxes across the external boundaries of the model domain, successive applications of the 'law' would automatically transform one known state of the model domain into another known state. When the true 'law' is not known, but has to be replaced with an adequate approximation to be determined from two known morphological states, the question arises whether the two known states alone yield a unique, although approximate, solution, or whether different expressions for the 'law' could yield the same cumulative changes in space over the verification interval. As the physical relationship for sediment transport, and both relationships are invariant in space and time, only one unique 'law' can satisfy the cumulative changes throughout the space domain, and an approximation to the 'law' can only satisfy the cumulative changes throughout the space domain with corresponding approximation. If a sufficiently accurate approximation to the law can at all be found, it can be considered as a unique solution, and theoretically two known states suffice for the determination of the 'law'. The proposed procedure for verification of the model is feasible in theory. The practical difficulties arise partly from the trial and error procedures needed and partly from the inaccuracies ('noise') in the model and the stability of the model with time.

4.2 The nearshore domain

When the generally accepted empirical formula for alongshore transport in the nearshore zone is applied as the 'law', the verification of the nearshore model against known states consists of determining the coefficients entering into the two-dimensional formula. The coefficients depend on sediment characteristics and would vary along the shore. The rather important, but not well known aeolian sediment fluxes across the shore boundary would enter into the verification procedures. The model is sensitive to geographical changes caused by the shifting sediments, and during the successive applications of the 'law', adjustments must be made for changing wave refraction and shore alignment. The empirical two-dimensional formula used as the 'law' yields no information about the geographical changes caused by the calculated quantities of erosion and accretion in the nearshore zone. This subject matter needs further general research developments. The governing factor for determination of the actual geographical changes is the dynamical equilibrium profile, but the variable phase shift between hydrodynamic forces and corresponding profile changes caused by the limited onshore-offshore transport capacity of the wave depends upon the sequence of events causing the changes, and the actual sequence of events (determined from hindcastings) would have to be considered when verifying the model against known cumulative changes over the period of verification. The resulting geographical changes would also depend upon the nearshore and downshore boundary conditions. In the case of the Nile Delta the Rosetta estuary cone must have been a source area since 1964.

It would be characteristic for a true three-dimensional model, that it should be able to reproduce oscillatory changes caused primarily by variations to the input forces, and it should also be able to reproduce a sawtoothed coastline when operated with unidirectional, oblique waves as input. Both conditions are fulfilled in nature, the latter even on rocky coasts (i.e. SW-coast of India, Eastern part of Turkey's Black Sea coast). On soft sediment coasts the reproduction of sawtoothed coastlines involves the relationship between maximum alongshore transport capacity and the capacity of the sea to shape equilibrium profiles, which again depends upon the capacity of the sea to change the offshore zone. The offshore changes, involving shifting of large quantities of sediments under less active forces than those affecting the narrow nearshore zone, take place at a slower rate than that applying to nearshore changes. Consequently, erosion of the nearshore zone will initially leave a bench in the profile, while places of accretion in the nearshore zone will act as drains towards the offshore zone, because offshore 'supports' for the nearshore accretions can only be built up very slowly.

Letting the nearshore model operate with a unidirectional wave input on a preliminary straight and infinitely long coast should result in (1) beginning bench erosion at some place of the coast, (2) increasing amount of sediment transport downshore and correspondingly decreased bench erosion, (3) saturation and deposition of sediments and offshore draining of sediment, and (4) renewed bench erosion. The offshore draining of sediments, due to lack of offshore 'support', would presumably take place in the same manner as rip currents, and in a model with unidirectional and uniform wave action the offshore sediment drainage and rip currents would be likely to coincide. The bench erosion would decrease with widening bench as the shore direction would assymptotically approach the wave crest direction, and at the same time the offshore 'support' for accretion would gradually increase, permitting a shore advance. For this imaginary uniform operation of the nearshore model, any point of beginning bench operation could initially be taken as a nodal point with zero alongshore transport, and any downshore point of sediment drain could be taken as the downshore boundary of the model. The results of the model operation would then be the transformation of a straight shore into a sawtoothed shore. The average position of the sawtoothed shore would be parallel to the original shore, but shifted inland a distance corresponding to the quantities of sediments drained to the offshore, and the original shoreline will divide the side of the 'sawtooth' parallel to the wave crests into two unequal sections, with the shorter one closest to the point of the tooth. However, in soft shore sediments the short side of the 'sawtooths', perpendicular to the wave crests, is unstable, and the whole sawtooth pattern would continuously move upshore, involving an overall downshore sediment transport fed at the upshore boundary. In the Nile Delta the sawtoothed coast can, somewhat imperfectly, be observed for instance, at Baltim Sea Resort during periods of dominating north-westerly storms, and the Rosetta estuary cone is an upshore source area.

It is to be noted that bar formations are natural parts of the nearshore zone, and that the sawtoothed pattern is more pronounced on steeper shores with coarser sediments than on flatter shores with finer sediments, along which rip currents are also not very marked. It is logical to believe, that on flatter shores with finer sediments alongshore moving water masses and their sediments gradually return to the offshore zone and not as bursts of saturated flows. It is also to be noted that interactions between after-storm landwards shifts of storm bar formations and alongshore sediment transport in the nearshore zone may create temporary spit formations and land build-up that would interfere with the more regular shore changes patterns described above.

In case the nearshore model were operated in the above described imaginary uniform manner in conjunction with the offshore model, the tendency by the sea to create equilibrium profiles would cause corresponding offshore erosion off the eroded bench sections and alongshore offshore sediment transport (by ocean currents and/or the alongshore component of wave mass transport) until halted by the sediment drains from the nearshore, but the offshore processes would initially take place at a much slower rate than the nearshore changes. However, ultimately the nearshore bench erosion would decrease assymptotically, but the upshore shift of the sawtooth pattern of the shoreline would continue at a rate, that would be much greater than the corresponding shifts in the pattern of the offshore zone. Therefore, the nearshore and offshore models will, due to the different hydrodynamic processes, always remain out of phase, even in the imaginary uniform model, and both as regards rates of changes in plan as rates of changes in profile. These phase shifts will cause considerable difficulties for determining the boundary conditions along the active boundary between the nearshore and offshore zones, unless the rates of changes are so widely different that the two zones may be treated practically independently, adjusting the model only at long time intervals.

The above described behaviours of a three-dimensional nearshore model and its relations to the offshore model are fundamental for three-dimensional modelling of the nearshore zone. However, within the limits of this paper the 'law' for a three-dimensional nearshore model cannot be discussed further.

5. Details of the offshore model

5.1 The domain

The model is discrete in space and time. The space intervals are chosen as large as possible governed by the condition that with adequate approximation a subdivision may be considered uniform in respect to morphology and hydrodynamic forces. The time intervals are chosen as minimum one year so as to eliminate seasonal changes to the sea bottom configuration, particularly 'summer' and 'winter' beaches. For a two-dimensional nearshore model the space divisions become stretches of uniform shore in respect of sediments and wave direction. The offshore space divisions may be increased in size with increasing water depths and decreasing rates of change.

With large offshore space subdivisions the resulting sediment flow for the whole subdivisions is calculated and thereafter referred to one single point representing the subdivisions. The contour lines and gradient lines of the sea bottom may conveniently be used as division lines for the space divisions. Changes in profiles for each time interval would be represented by quantities of erosion or accretion referred to single points along the profile and representing the width of sea bottom between adjacent profiles. The point 'loads' must be converted into a continuous line distribution along the profile either by linear sections or by drawing a smoothed-out equilibrium profile through the points. For each time interval adjustments can subsequently be made to the contour lines by linear or smoothing-out procedures. After successive applications for a number of time intervals, profile and contour changes may be large enough to warrant corrections to wave refraction patterns.

Although some idea of changes to sediment characteristics may be gained from successive time interval operations of the model, core drillings in the sea bottom give the best indication of possible layerings and changes to sediment characteristics during the model verification period.

5.2 The sediments on the Nile Delta shelf

The source of the Nile Delta sediments is primarily the rocks of Ethiopia and Eritrea, the red soil weathering products of the Tertiary outpourings particularly yielding montmorillonitic clays, but some contribution could come from the upper Nile valley and the deserts. International atlases show the general sediment types on the continental shelf area of the Nile Delta. The sediments are fine sands, silts and clays, deposited by the Nile branches and reworked by the sea. The nearshore zone and estuary cone consist of fine sands and some silts, while silts and soft clays (muds) dominate the offshore zone. Beyond the breaker zone, in 5-6 m water depth, the medium grain sizes are generally less than 0,15 mm. Judging from processes of deposition and from experience with silts elsewhere, there is reason to believe that the sediment structure in the offshore zone is very loose with close to maximum water content and that clayey sediments are soft and muddy. Biogenic materials may be present, but hardly dominating except on the outer part of the shelf. Terrestrial organic materials are likely only to be found in places where ancient lagoonal deposits or one-time emergent sea bottom may be eroded. It is to be expected that silt and clay deposits tend to be cohesive in their natural state.

5.3 The water motions on the Nile Delta shelf

So far little is known about the actual currents near the sea bottom of the Nile Delta continental shelf. The ocean surface currents are not expected to exceed 0,5-1 knot (0,25-0,50 m/sec), except maybe under special wind conditions; prior to 1964 the velocities would also have been greater near the Nile branch estuaries during the flood seasons. The maximum tidal currents - according to atlas information (4) moving in a NW-SE direction over the shelf - can only be in the order of 0,2 m/sec in 10 m water depth, 0,1 m/sec in 40 m depth and about 0,08 m/sec in 80 m depth. The maximum particle velocity near sea bottom for a 5 m wave with 10 sec period would be about 2,2 m/sec in 10 m water depth, 1,3 m/sec in 20 m depth, 0,60 m/sec in 40 m depth and about 0,13 m/sec in 80 m depth, and the corresponding figures for say a 3 m wave with 8 sec period would be respectively 1,2 m/sec; 0,8 m/sec; 0,07 m/sec and 0,02 m/sec. Long period seiches (1-2 min or more) with appreciable nearshore amplitudes (0,5 m) are said to occur, but rarely as compared to the frequency of occurrence of regular storms, and standing waves could no doubt also be generated in the Eastern Mediterranean basin by particular meteorological surface pressure distributions, but standing waves would probably be infrequent and imperfect due to the relatively rapid moving cyclonic pressure distributions characteristic for the Eastern Mediterranean.

Consequently, the combined wave and ocean current action is dominating, with wave action playing the major role up to 20-40 m depths and ocean currents becoming increasingly important at larger depths, provided the ocean bottom currents are of the same magnitude and with approximately the same directions as the surface currents, a condition which may not necessarily be fulfilled on the Nile Delta shelf. The tidal motions alone, decreasing strongly with water depth, are not likely to play any major role for sediment entrainment and transport. The ocean currents on the shelf are presumably generated partly by the circulation off the shelf and partly by wind and pressure over the shelf area. Density currents generated on the shelf itself are not likely to be of importance.

PART B - THE DETAILED PROCESSES

1. Sediment entrainment

1.1 General remarks

The scarcity of definite quantitative knowledge about entrainment and transport distances of in-situ sediments by combined oscillatory and unidirectional fluid motions is evident from scanning the literature. For verification of the model against known states and with known total sediment budgets it suffices to know the relative values of entrainment and transport over the model domain. Initially and until more definite knowledge is made available by the Nile Delta project itself or from outside research, the project must be guided by the available relevant literature. Presently it is a matter of examining the fundamental factors involved in determining the response factor, or 'law', of the model, i.e. the factors governing entrainment of the sediments and transport of the entrained sediments.

The existence of the delta built-up by Nile sediments testifies to the fact, that large quantities of sediments from the two Nile branches did settle on the shelf itself, and approximate budget calculations show that the major part of the Nile sediments stayed on the shelf off the delta. The distribution pattern of the sediments on the shelf and the present shelf area topography further indicate that the major part of the Rosetta branch sediments remained west of Burullus while the major part of the Damietta branch sediments settle down primarily off the shore between the Damietta estuary and Port Said and Lake Bardawil area. However, at both river branches sizeable quantities of Nile sediments were deposited west of the respective estuaries. It may further be remarked that even ocean currents with relatively small velocities acting continuously over the shelf area would have a very great sediment transport capacity, so that in case this transport took place continuously, all the Nile sediments would have been transported away from the Nile Delta shelf area and not deposited in the above described pattern.

Therefore, it stands to reason that the current velocities most of the time were below the minimum entrainment values, and that the currents during deposition also were below the values needed to keep the entrainment sediments in constant suspension. From the present knowledge of the shelf sediment characteristic it may also be surmized that no large scale migratory sediment movements take place along the offshore sea bottom areas, whereas bed transport may well take place in the estuary cone areas with somewhat coarser sediments.

1.2 Entrainment of sediments by unidirectional flow

Considering the limited accuracy of modelling procedures and the present state of basic knowledge of sediment transport processes, it is useless to delve into great detail of the transport mechanisms in order to determine the relative sediment transport over the model domain. Comparison of Hjulstrøm's diagrams (reproduced in (2) and (5)) with the results of Boneville, Pernecker, Vollmers and Dou Go-zen (6) yields a fair presentation of sediment entrainment relationships. All the diagrams are in log-log representation and visual similarities conceal great differences in actual values. Hjulstrøm's emirically determined diagrams refer to average flow velocities in rivers and streams and to sediments of uniform texture. There are significant differences between the actual values of the original paper of 1935 (2) and the later paper of 1939 (5). Dou Go-zen's diagrams is based on theoretical considerations involving the submerged weight of the grains, the water depth and the adhesion between the thin water films surrounding the single grains. In the quoted reference it is not stated clearly whether the mean velocity refers to mean over cross section of flow or mean of near-bottom currents. Bonneville's diagram introduces the non-dimensional parameters

$$D* = \left(\frac{\rho' \cdot g}{\nu^2}\right)^{1/3} \cdot D \quad \text{and} \quad R* = \frac{u* \cdot D}{\nu} \text{, with } \rho' = \frac{\rho_s - \rho}{\rho} \text{ ,}$$

ρ_s and ρ specific mass of respectively grains and fluid, ν= kinematic viscosity, D = grain diameter, u_*= shear velocity representing equally well tangential stress $\tau = \rho \cdot u_*$. Bonneville also introduces mean flow velocity v by writing the Strickler formula as $v = 21 \cdot (\frac{h}{D})^{1/6} \cdot \sqrt{h \cdot I}$ and $u_* = 0{,}15 \cdot (\frac{D}{h})^{1/6} \cdot v$. The coefficient 0,15 is $\sqrt{g}/21$, and g would thus be 9,81 m/sec^2 and the subsequent diagram is in meter units. $21 \cdot (\frac{h}{D})^{1/6}$ would be Chezy's coefficient of dimension $m^{\frac{1}{2}}.sec^{-1}$.

Bonneville's diagrams represent $v = 22 \cdot h^{1/6} \cdot D^{1/12}$ (h and D in m) for 0,01 cm$<D\leq$0,1 cm and $v = 55 \cdot h^{1/6} \cdot D^{13/30}$ for D>0,1 cm, in non-dimensionless formulation respectively $D^* = 2{,}5 \cdot R^{*\,4/5}$ for $R^* < 12$ and $D^* = 3{,}8 \cdot R^{*\,5/8}$ for $R^* > 12$. The diagrams are valid only for $R^* > 1$. With $\rho' = 1{,}65$; g=981 cm.sec^{-1}; $\nu = 0{,}01$ cm^2.sec; $D^* = 253 \cdot D$ (D in cm) and $R^* = 1$ corresponds to $D^* = 2{,}5$ or D=0,01 cm. This is below D-values for minimum entrainment velocities in Hjulstrøm's and Dou Go-zen's diagram, and $v \simeq D^{1/12}$ certainly cannot remain valid for very fine sediments. Hjulstrøm's diagram (5) has minimum value of v for D$\sim$0,4-0,5 mm, whereas the 1935 diagram and Dou Go-zen's diagrams have minimum value for D=0,2 mm. Introducing the constant factors in Dou Go-zen's formula yields

$$v^2 = 11200\ D + \frac{3{,}4}{D}\ (1 + 0{,}0082 \cdot h),\ v \text{ in cm.sec}^{-1},\ h \text{ and } D \text{ in cm.}$$

For h=0 minimum value of v occurs for $D^2 = 3{,}4/11200$, D=0,0175 cm and is v=20 cm.sec^{-1} and not about 14 m.sec^{-1} as shown in the diagram. The strong dependence of v on h for fine materials is not easily explainable physically and is much more pronounced than for Hjulstrøm's or Dou Go-zen's diagrams.

Many formulas introduce critical drag in the form $\tau_{cr} = \text{const} \cdot g \cdot (\rho_s - \rho) \cdot D$, with $\rho_s - \rho$ being mass per unit volumen. Leliavsky (7) plotted different tests results and arrived at the simple expression $\tau_{cr} = \text{const} \cdot D$, which is identical to the above formula if the tests were made on materials with same ρ_s. It is obvious from Leliavsky's diagram that application is doubtful for d<1,0 mm. Introducing $\tau_{cr} = \rho \cdot u_*^2$, $R^* = \frac{u_* \cdot D}{\nu}$ and $D^* = (\frac{\rho' \cdot g}{\nu^2})^{1/3} \cdot D$ in the critical drag formula yields $R^{*2} = \text{const} \cdot D^{*3}$, where the constant is the same as in the drag formula. The constant may be determined from Leliavsky's diagram with $\tau_{cr} = 500$ grams per sq.m for D=3 mm, or 0,5 kg.m^{-2} = const.1650 kg.m^{-3} 0,003 m, or const=0,1, and $D^* = 2{,}15 \cdot R^{*\,2/3}$ as against $D^* = 3{,}8 \cdot R^{*\,5/8}$ by Bonneville.

Hjulstrøm's and Dou Go-zen's diagrams depict entrainment under flow conditions varying from flow over a smooth surface of fine materials bordering on clays via flow over coarser materials able to form ripples to flow over a rough bottom with ration between drag force and gravitational force determining initial entrainment. A minimum value of the curve v versus D is recognized by both authors. For D<0,004 cm (refer (6), p.38) the surface 'breaks' suddenly and the sediments go into suspension, but for increasing value of v with decreasing grain size. With u_* proportional to v and only slightly dependent on D (refer (6), p.39), v^2 would approximately be proportional to the tangential shear stress, and in case the shear strength of the sediments increases approximately proportionally to D^{-1}, ε_K in Dou Go-zen's formula would be nearly constant with dimension force/length. For fine sand and silt fractions the'cohesion' between the grains is probably not cohesion in exactly the same sense as used for clay minerals (D<0,0002 cm), but the shearing behaviour of loosely deposited fine sands and silts does approach that of 'quick' clays (8). The undrained shear strength would, however, vary strongly with the porosity, and for same grain size the porosity can vary very much according to conditions of deposition and consolidation. If, however, bottom materials with D<0,004 cm go directly into suspension when broken loose by the flow, such a bottom would have been formed by slow settlement of the same materials during small flow velocities and would in so case be near the loosest state of deposit. Its shear strength then conceivably vary approximately linearly with D^{-1}, so that $\rho . v^2 \simeq const/D$, where the constant would in some intricate manner represent the forces binding together the particles of any size D and involving the water films around the grains, but not in the manner expressed in the last part of Dou Go-zen's formula.

Hjulstrøm's and Dou Go-zen's diagrams represent clearly a superposition of an approximately linear relationship in D expressing drag force $\rho \cdot v^2$ on coarse materials and an approximately hyperbolic relationship expressing shear stress $\rho \cdot u_*^2$ on a fine material bottom surface, and through the superposition the diagrams are made applicable to the whole range of materials above clay size. Mixed materials as found in nature will no doubt present special problems, as such soils according to the grain size distribution and consolidation may vary in character from being sandy to being clayey. The project will study these problems in the laboratory on actual Delta materials with in-situ composition and properties.

The above quoted entrainment formulas are based on flume tests or flows in rivers and streams and corresponding mean velocities across the flow section and boundary layer conditions and are not necessarily directly applicable to velocities of unidirectional flow measured in-situ near the sea bottom. Especially the strong dependence on depth h may be questionable for the open shelf area beyond the breaker zone and up to 100 m depth and more. In view of the many uncertainties involved as shown in the above deliberations, Hjulstrøm's diagram may serve as well as any other formula as basis for initial model verification. Within the ranges of grain size found on the Delta shelf the diagram may for practical (computerized) use be expressed by the algebraic formula $v^k = a_1 \cdot D^m + a_2 \cdot D^{-n}$, (k,m and n positive), in which m/k and n/k represent the extreme slopes in the log-log representation of the combined curve. k,m,n, a_1 and a_2 are determined from the following values read from Hjulstrøm's diagram:

Slope m/k : D=1 cm, v=100 cm.sec^{-1}, D=0,01 cm, v=4 cm/sec
Slope n/k : D=0,0002 cm, v=150 cm.sec^{-1}, D=1 cm, v=0,8 cm/sec
Min. velocity 12 cm.sec^{-1} (for 0,02 cm<D<0,03 cm).

The resulting dimensional equation is

$$\underline{v^{1,56} = 1320 \cdot D^{1,09} + 0,71 \cdot D^{-0,96}}$$

For coarse materials the equation reduces to $v^2 = 10{,}000 \cdot D^{1,40}$, and for fine materials to $v^2 = 0,65\ D^{-1,23}$. These powers to D are somewhat different from those in Dou Go-zen's formula, but there is really no reason to expect any simple algebraic expression with rounded exponents when the complexities of the entrainment processes are borne in mind.

If Hjulstrøm's diagram is substantially correct, dimensional analysis of the above formula would show that $v^2 \approx g \cdot D$ for coarse materials and $v^2 \approx c/\rho \cdot D$ (c=cohesion) for fine materials are too simplified relationships, although dimensionally correct. This is no wonder, as Hjulstrøm's curve really represents physical entrainment processes varying continuously in character from fine to the coarse materials, involving over half the range varying cohesive type forces obeying non-mechanical physical laws and also smooth bottom boundary flow, and over the other half of the range rough, ripple forming bottom conditions with correspondingly varying turbulence and drag forces on single sediment grains.

When the formula $v^{1,56} = 1320 \cdot D^{1,09} + 0,71 \cdot D^{-0,96}$ (v in cm.sec^{-1}, D in cm) is not non-dimensional, it is to be interpreted that materials of a certain diameter D will be entrained at a correspondingly defined velocity v given by the formula, whichever the entrainment mechanism may be.

1.3 Entrainment of sediments by wave motion

Plotting the laboratory results of different investigations in a D*/R* diagram, Bonneville and Pernecker (refer (6)) conclude that relations D*=f(R*) for unidirectional flows are also applicable for initiation of sediment transport by wave motion if

$$R^* = 2,2 \cdot \frac{D}{\nu} \left| \frac{\nu \cdot H^2}{T^3 \cdot \sin^2 h \frac{2\pi d}{L}} \right|^{1/4}$$

where H,T,L are the wave characteristics and d is water depth. Introducing maximum particle velocity near the sea bottom (first order)
$U = \dfrac{\pi \cdot H}{T \cdot \sinh \frac{2\pi d}{L}}$ and $D^* = \left(\dfrac{\rho' \cdot g}{\nu^2}\right)^{1/3} D$ into formula $D^* = 2,5\ R^{*4/5}$ yields

$$R^* = 2,2 \cdot \frac{D}{\nu} \cdot \left| \frac{\nu \cdot U^2}{\pi^2 \cdot T} \right|^{1/4} \quad \text{and} \quad U^2 = D \cdot T \cdot \frac{(\rho' \cdot g)^{5/3}}{\nu^{1/3}} \cdot \frac{\pi^2}{2,5^5 \cdot 2,2^4}$$

or with $\nu=0{,}01\ cm^2.sec^{-1}$, $g=981\ cm.sec^{-2}$, $\rho'=1{,}65$ $\underline{U^2/T = 4470 \cdot D}$ (U in $cm.sec^{-1}$, T in sec, D in cm).

U/T is an acceleration and in case the maximum acceleration near the sea bottom, with phase angle $\pi/2$ with U, is denoted by U', the relation between U and U' is $U' = \frac{2\pi}{T} \cdot U$, yielding from above equation $|U \cdot U'| = 28000 \cdot D$, indicating that U and U' might play equal roles for the entrainment of coarse sediments. The relationship $D^*=2{,}5\ R^{*4/5}$ is probably not valid for $D^*<5$, or $D<0{,}02$ cm, and certainly not down to $D=100\mu$ as shown in the nomograph. Grains of diameter D will be entrained at any water depth if $U^2/T \geq 4470 \cdot D$, where U is maximum orbital velocity. Reverting to H,T,L and d,

$U^2/T = \frac{H^2}{T^3} \cdot \frac{\pi^2}{\sinh^2 \frac{2\pi d}{L}}$, L being a function of T and d. In a(d,T) diagram the lines $U^2/\pi^2 H^2 \cdot T$ = const. can be drawn, showing equal entrainment capacity in terms of d and T (fig.2), but of course varying with H^2.

With $U = \frac{\pi \cdot H}{T \cdot \sinh \frac{2\pi d}{L}}$, lines for $\frac{U}{\pi \cdot H}$ = const. are shown in fig. 3 in terms of T and d. The diagrams figs. 2 and 3 can be superimposed on each other, yielding (H,D) lines shown in fig. 3 (for maximum and minimum values of D only).

It is seen from the superimposed H-lines in fig. 3, that sediment entrainment takes place at nearly constant orbital velocity over the (T,d) range, depending practically only upon H. From figs. 2 and 3 can also be calculated that entrainment of sediments with D=0,02 cm takes place at the following values of U

H cm	100	200	300	400	500	600
U $cm.sec^{-1}$	29	30	32	33	32	32

or av. $U \sim 32\ cm.sec^{-1}$, and entrainment for D=1 cm at the following values of U

H cm	100	200	300	400	500	600
U $cm.sec^{-1}$			190	210	225	205

or av. $U \sim 210$ cm/sec. Introducing these values in the equation $(k.U)^{1,56} = 1320 \cdot D^{1,09} + 0{,}71 \cdot D^{-0,96}$, in which k is a constant, yields k=0,38 for D=0,02 cm and k=0,48 for D=1 cm. Tentatively a factor <u>k=0,40</u> is proposed for the Nile Delta model. As the velocity is governing, it is reasonable to assume initially for the verification of the model that the <u>same</u> formula applies both for sediment entrainment by unidirectional flow and by wave motion, provided v in unidirectional flow is replaced with <u>0,40·U</u> in wave motion. Here again the dimensional aspects are ignored, attributing the lack of non-dimensionality to the complexities of the true mechanisms, involving boundary layer turbulence influenced by D and also cohesional forces for finer sediments.

1.4 Entrainment of sediments by combined wave and current action

If the entrainment criterium for the formula $D^*=2{,}5 \cdot R^{*4/5}$ is initial movement of sediments, the reduction factor k found for the orbital velocity originates presumably from lesser turbulence in the boundary layer of oscillating motion than for unidirectional flow. The combined wave and

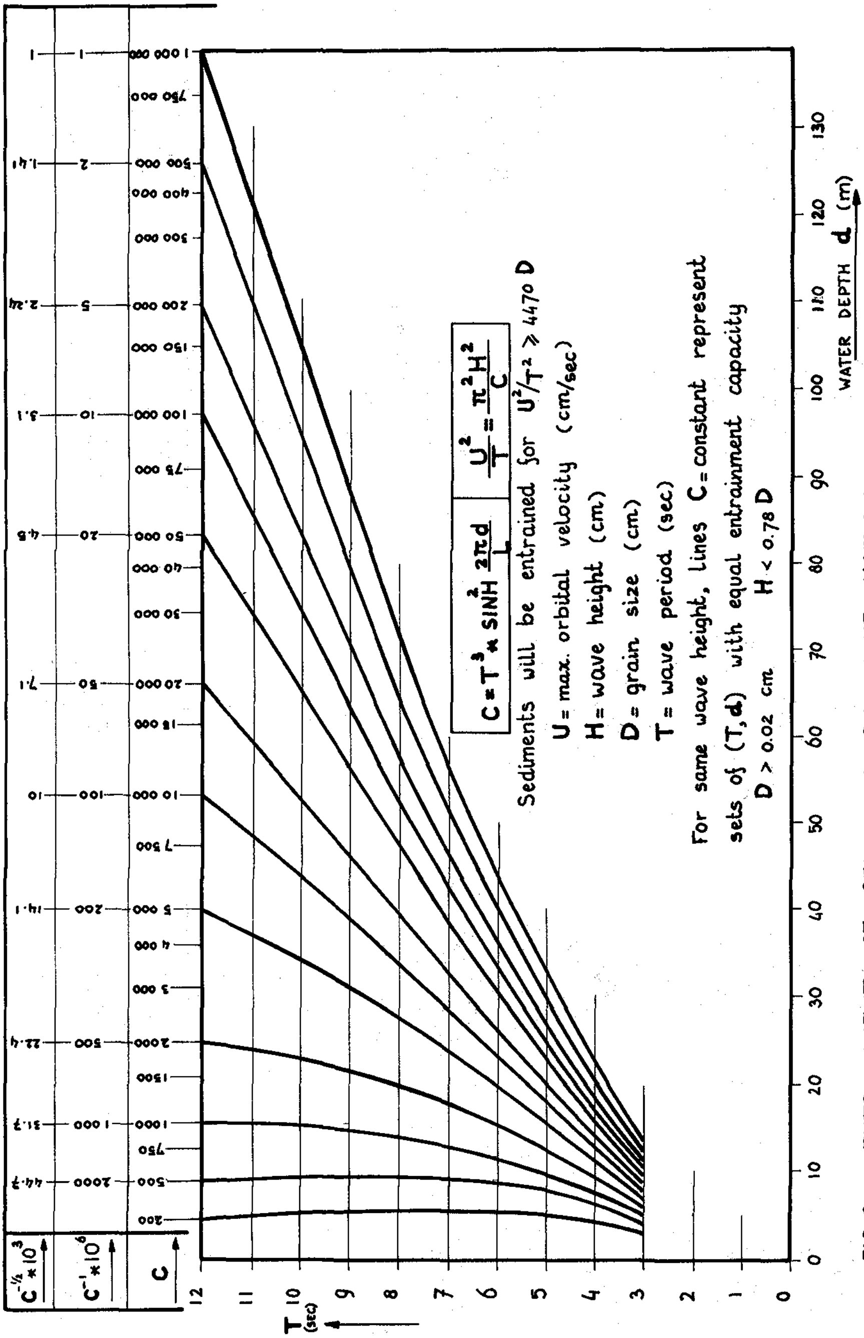

FIG. 2. - ENTRAINMENT OF SEDIMENTS BY WAVE MOTION.

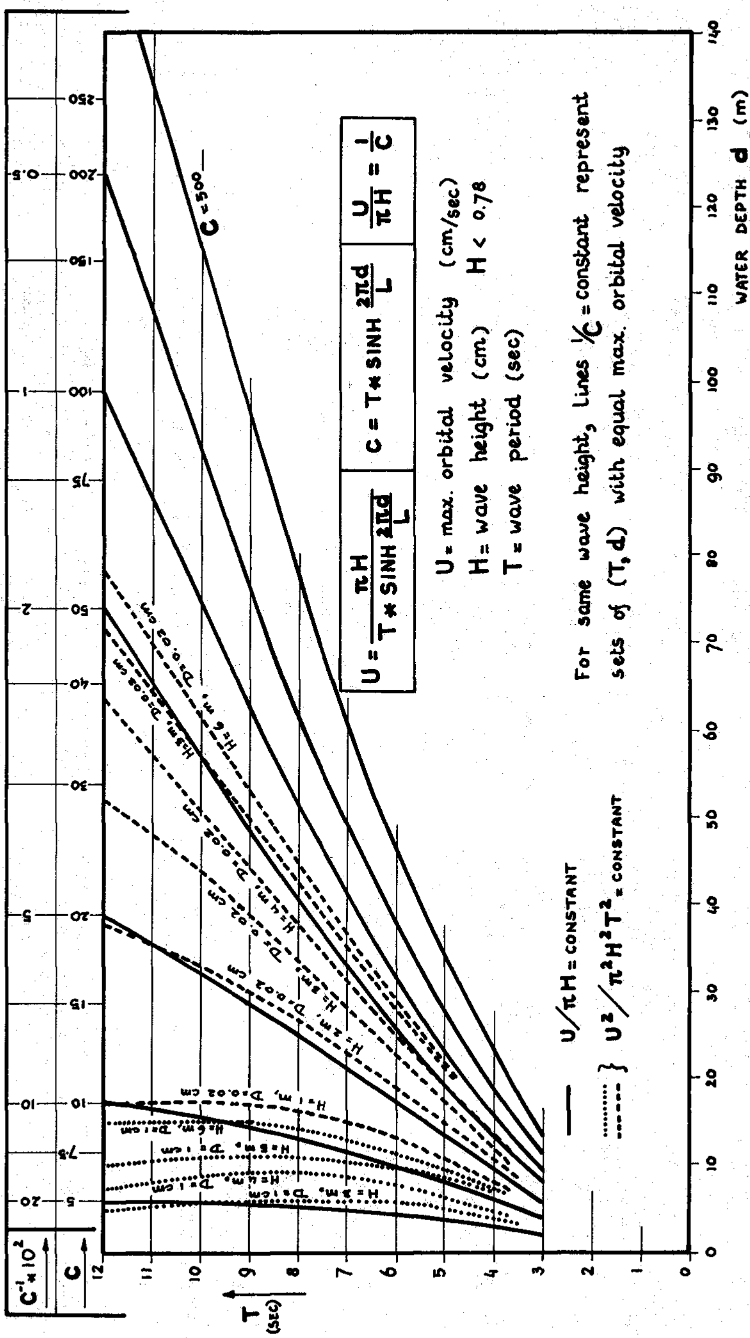

FIG. 3. - DIAGRAMS FOR $U/\pi H$ = CONSTANT AND $U^2/\pi^2 H^2 T$ = CONSTANT.

current motion is likely to increase the turbulence, depending upon relative magnitudes and directions. However, for the relative effects of different combined wave and current motions, such increased turbulence may be of lesser importance.

The question arises, however, whether current velocities and reduced orbital velocities (numerical values) shall be added vectorially, or numerically, independently of directions. There is for the author an intuitional motivation for the latter, maybe coupled with a weighting function reflecting dominance of one or the other motion. Knowledge on this problem is very scarce, and the project shall have to study this matter further.

2. Quantities of sediments entrained and transported

2.1 Sediments in suspension

The difficulties to be overcome in order to determine the quantities of sediment entrained during wave motion can be judged for instance from (9), in which Einstein takes recourse to a strictly empirical approach in order to deal with fine sediments in suspension, and from the more theoretical approaches of (10) and (11). Field measurements and laboratory tests show a considerable upwards diffusion of fine sediments during wave motion, and assuming turbulent flow and equilibrium between settlements due to gravity and upwards movements due to diffusion towards lower concentrations as for uniform flow, the concentrations at specified levels above the sea bottom can be expressed in terms of fall velocity of suspended particles, shear velocity of flow and von Karman's constant, provided the concentration at a reference level near the sea bottom can be determined by measurements.

Jensen and Sørensen (12) found by field measurements in the open sea, that the transport by ocean currents of fine materials brought into suspension by wave action could be calculated from the concentrations for unidirectional flow, when the concentration near the bed is determined solely from wave conditions and the concentrations at higher levels solely from the ocean current flow profile with shear velocity u_*=0,05 times average velocity over depth. These authors also believe that there is an (unproven) proportionality between the concentration near the bed and the third power (U^3) of maximum orbital velocity near the sea bottom. From observations of agitated seas it appears that the equilibrium distribution of suspended materials is reached quickly once the initial entrainment velocities are reached, and that the sediments settle relatively fast after cessation of wave action. In the quoted reference (12) with silt of 0,08 mm median diam. 90% of the actual materials in the sea have settling velocities less than 7.10^{-3} m/sec, and the materials are practically all within 7 m from the sea bottom, requiring thus max. 20 min. for settling on the bottom if no currents are present. The period of effective entrainment can thus be determined from B/1.2-1.4 above, while relative quantities of entrainment could possibly be determined from U^3 and the equilibrium concentrations, and the transport directions and distances are determined by the actual ocean currents. The wave mass transport is of secondary order, but may play a role in shallower water with largest concentrations of suspended materials. The influence of the elliptic tidal flows along the Delta coast is presumably negligible.

In the case of the transport of suspended materials in the sea, an average current velocity over the depth can most likely be applied, thus facilitating the numerical integration of the sediment concentrations over the profile.

The work and suggestions cited from reference (12) will be studied closer by the project, probably in collaboration with the Suez Canal Authority, faced with a similar problem at the entrance of the Suez Canal. The results will have to be generalized to be applicable to all conditions in the shelf area.

2.2 Bed load sediments

In the Nile Delta shelf area considerable quantities of sediment are being eroded from the estuary cones, and a considerable part of the eroded sediments is most likely being transported as bed load, mainly by ocean currents after agitation by wave action. In order to verify a model comprising all sediment movements not affected by wave breaking, it will most probably be necessary to take the estuary cone materials into consideration. The proposals by Sternberg (13), modified to consider the combined wave and current motions, may perhaps be applicable for this part of the transport; being based on a logarithmic velocity profile in the boundary layer, the method is akin to and can be compared with the classical bed load calculations (refer for instance (6), p.41). This problem is, however, outside the scope of this paper, but it is worth to note, that after Bagnold (14) the bed load transport (flux per unit area per time unit) for unidirectional flow is proportional to u_*^3, and in Sternberg method u_* is calculated as $u_*=5{,}47.10^{-2}.U_{100}$, where U_{100} is mean velocity measured 100 cm above the sea bed. In (12) u_* is taken as 0,05 times the average ocean current velocity over the depth of the flow profile. According to Bagnold and Sternberg the average mass per unit area of bed load sediments moved by combined wave and current action would be proportional to U^2.

3. Geomorphological changes

To specific hydrodynamic conditions correspond specific 'saturation' profiles of suspended sediments, and in case a profile is undernourished, it will soon pick up additional materials from the sea bottom, while sediment will be deposited in profiles overnourished due to greater influxes than discharges from a specific area. This is a three-dimensional model akin to the two-dimensional model for nearshore changes, in which erosions or accretions are determined from the variations in wave power and transport capacity.

In practical application the model will have to operate with fields of varying wave and current intensities and corresponding concentrations and rates of movement of suspended sediments. In principle the model will be Eulerian, dealing with discrete differential variations with time, in each point representing a subdivision of the model area. Theoretically, the deposition of erosion per unit time in each unit area of the model is determined (i) from the variation in entrainment capacity as determined from the force fields, water depths and sediment characteristics and (ii) from the variation in concentration along the ocean current flow lines through the unit area. In practice, the calculations will be made for large discrete space and time intervals, but this presents no principal problems. The wave motion contributes only to the sediment entrainment, while only the ocean currents contribute to the shifting of the sediments. If the entrainment force field can be considered constant over a time unit and over distance v along the flow line, where v is the ocean current flow velocity, a surface z=f(x,y) can represent the momentaneous total sediment concentrations above the model area, and a new surface z=g(x,y) created by shifting all the ordinates z a distance v=h(x,y) along the flow lines would represent the sediment distribution over the model area one time unit later. If the agitating motion suddenly stopped and the suspended sediments settled rapidly, the difference between z=f(x,y) and z=g(x,y) would represent the morphological changes (in volumen) over the model area during the time unit considered. The entrainment force field need, however, not be constant for any length of time, and neither the ocean current velocity field, and the sediment concentration variations and the morphological changes must be calculated by taking the force and velocity variations with time into consideration.

CONCLUDING REMARKS

This paper outlines the initial thoughts on how to establish and operate a geomorphological model covering the Nile Delta continental shelf area. Years of trial and error and further development work may lie ahead and only the future can show whether the task is possible in the sense, that fairly reliable predictions of future coastal changes can be made by operating the model. Theoretical and practical studies by the project or elsewhere may well change the concepts or introduce new ideas and approaches, but a start has to be made and it is believed that the chances for success are greatly improved, if during all project studies the ultimate goal of creating a model for prediction is kept in mind.

The many deterministic and statistic inaccuracies involved in the model framework are only too obvious for the coastal engineer, but it is fundamental for the proposed modelling, that satisfactory verification against known states of the model area is the decisive element governing the stability and usefulness of the model. In dealing with nature's processes the author advocates the principle of determining first the approximate framework through some assessible upper and lower limit values of the unknown factors and thereafter gradually increasing the accuracy by narrowing the margin between the upper and lower limit values. Once the stage is reached, where a model can reproduce the resemblance of a known state from another known state, the processes of refinement can be tackled rationally.

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REFERENCES

(1) NIELSEN, EV. (1973) - Coastal Erosion in the Nile Delta. Nature and Resources, Unesco.

(2) SCHEIDEGGER, A.E. (1970) - Theoretical Geomorphology.

(3) STRAKHOV, N.M. (1967) - Principles of Lithogenesis.

(4) Oceanographic Atlas of the North Atlantic Ocean (1968) - Section 1, Tides and Currents; U.S. Naval Oceanographic Office.

(5) KUENEN, Ph.H. (1960) - Marine Geology.

(6) PIANC (1969) - Section II, Subject 4.

(7) LELIAVSKY, S. (1959) - An introduction to Fluvial Hydraulics (p.45).

(8) Norwegian Geotechnical Institute (1961) - Publication No. 45.

(9) EINSTEIN, H.A. (1972) - Sediment Transport by Wave Action; 13th Coastal Engineering Conference 1972,(p. 933).

(10) KENNEDY, J.F. & LOCHER, F.A. (1972) - Sediment Suspension by Water Waves. Waves and Beaches (ed. R.E.Meyer), (p.249).

(11) TELEKI, P.G. (1972) - Wave Boundary Layers and their Relation to Sediment Transport. Shelf Sediment Transport (ed. Swift et al.), (p.21).

(12) JENSEN, J.K. & SØRENSEN, T. (1972) - Measurement of Sediment Suspension in Combination of Waves and Currents. 13th Coastal Engineering Conference 1972 (p.1097).

(13) STERNBERG, R.W. (1972) - Predicting Initial Motion and Bed Load Transport of Sediment Particles in the Shallow Marine Environment. Shelf Sediment Transport (ed. Swift et al.) (p.61).

(14) BAGNOLD, R.A. (1963) - Beaches and Nearshore Processes. The Sea (ed. M.N.Hill), vol. III, (p.507).

(15) PROJECT EGY/70/581 (1973) - Technical Report No.1 (to be published shortly), Academy for Scientific Report and Technology, Egypt, United Nations Development Programme (UNDP) and United Nations Educational, Scientific and Cultural Organization (UNESCO).