CHAPTER 124

ORIGIN OF SUBMARINE DUNES

by

M.S. Yalin [1]

ABSTRACT

The turbulent bursting process is outlined and attention is drawn to the fact that the "coherence distance" of the regenerating macroturbulent eddies is of a magnitude that is much the same as the length of dunes. Consequently it is postulated that the length of dunes is merely the "imprint" of the coherence distance on the deformable surface of a movable bed and the origin of dunes is explained accordingly. It is shown that the frequently observed similarity between tidal and unidirectional dunes is due to the similarity of the tidal transport and the transport corresponding to an intermittent unidirectional flow. The explanations presented herein are expected to be valid for dunes caused by both unidirectional flows and tidal currents.

INTRODUCTION

Measurements carried out in the field indicate that the large scale bed features (dunes, megadunes) produced by tidal currents approximate rather closely to the dunes produced by the equivalent unidirectional flows. Thus in Ref [1] H. Ozasa states that "the dimensions of submarine sand waves (dunes) formed by tidal currents in the Bisan Strait at the Seto inland sea in Japan are approximately equal to the values calculated by Yalin's formula". Similarly, in Ref [2] Per Bruun points out that the dunes on the bottom of the Cook Inlet in Alaska are much the same as those on the bottom of the Mississippi river (where the flow conditions are comparable with those of the Cook Inlet). The data obtained from some parts of the British coast also appear to indicate the resemblance between the two types of dunes (W.A. Price, Hydraulics Research Station, Wallingford - private communication).

The approximate equality of unidirectional and tidal dunes can be explained by the similarity of the mechanisms of their production. Indeed if a tidal current is present then the cyclic velocity and shear stress diagrams (corresponding to a location) can no longer be symmetrical. It will be assumed in the following that the positive part of the τ_o diagram is higher than its negative part (Fig 1) and that

---

[1] Professor of Hydraulics, Queen's University, Kingston, Canada.

$$| (\tau_o)^{+}_{max} | > (\tau_o)_{cr} \quad \text{while} \quad | (\tau_o)^{-}_{max} | < (\tau_o)_{cr} \ . \qquad (1)$$

In this case the transport will be present, and dunes will form, only during the time interval θ^+ when the tidal flow is virtually a unidirectional flow. One can say that if (1) is valid, then the dunes are formed by the tidal flow in the same manner as if they were formed by an intermittent unidirectional flow. It should be remembered that the duration $(\mathcal{T})$ of the development of large size dunes is of the order of several months. Thus $\mathcal{T}$ is much larger than the tidal period T which justifies the expression "intermittent unidirectional flow". Clearly in some cases $| (\tau_o)^{-}_{max} |$ can also be larger than $(\tau_o)_{cr}$. This, however, can hardly invalidate the above description in principle, as the presence of the less effective opposite transport during θ^- will merely reduce the efficiency of the "build up" during θ^+ . The reduction of "efficiency" will, of course, lead to the extension of the development duration $\mathcal{T}$, but this has no bearing on the argument.

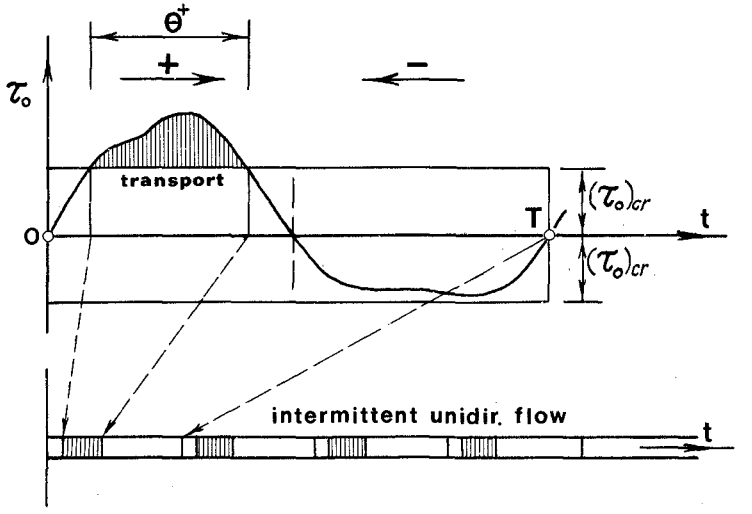

FIG. 1

No dunes have been observed in laminar flows, and the prevailing view is that they are due to turbulence. The author is of the same view. The present paper is his attempt to explain the occurrence of dunes in the light of the new information gained in the field of turbulence research.

Much has changed with regard to the understanding of turbulent flows in the past few years. Recent research (Refs [3] to [8]) has revealed that "turbulence is not as chaotic and random as has been assumed previously", (J. Laufer, Ref [3]). It has been found that turbulence contains in its structure "a certain order" which manifests in the form of an "observable chain of events", even if the elements forming this "chain" exhibit some substantial stochastic deviations from their (definable) average values. The total chain of the events mentioned is referred to as the "bursting process". In the following, first outline information on the bursting process is given, then, using this information, an attempt is made to explain the origin of dunes (i.e., of the sand waves which have the size proportional to the external dimensions of flow). This explanation appears to be clearer than previous ones (Ref [9]).

The descriptions and considerations that follow refer to unidirectional flows. However, as it can be inferred from the earlier part of this Introduction, they should be applicable also to tidal flows (during the time intervals θ^+) .

BURSTING PROCESS

1. Consider a developed macroturbulent eddy E transported in the direction of the flow (Fig 2.1). The current formed by the (adverse) velocities of its lower part is referred to as the "sweep". The arrival of a sweep at a location of the flow boundary (bed) slows down the flow contacting the bed at that location. The reduction of the flow velocities leads to a local conversion of turbulent flow contacting the bed into a retarded viscous flow. Since the eddy E is usually three-dimensional (e.g., spheroidal rather than cylindrical) the sweep and consequently the retarded local viscous flow layer, shortly the "low-speed streak", are also three-dimensional (i.e., they have a limited width).

2. The passage of the eddy E further downstream causes appropriate conditions for the "separation" (or the "lift-up") of the low-speed streak (Fig 2.2), and consequently for the formation of a "recirculation cell" C . The separated low-speed streak ("ejected fluid") and the recirculation cell C constitute together the "lifting module" which moves away from the bed and which is transported downstream (by the time average flow).

3. The removal of the lifting module causes the replacement fluid to move instead ("cleansing sweep"). Thus the motion of the lifting module inevitably generates a flow field as shown schematically in Fig 2.3. Note that the recirculation cell C and the cleansing sweep adjacent to its downstream side form a "new" eddy E' which progressively grows in its size when the elevation of the lifting module increases. One can say that the progress of the lift-up is equivalent to the growth of a "newly born" macroturbulent eddy (E') .

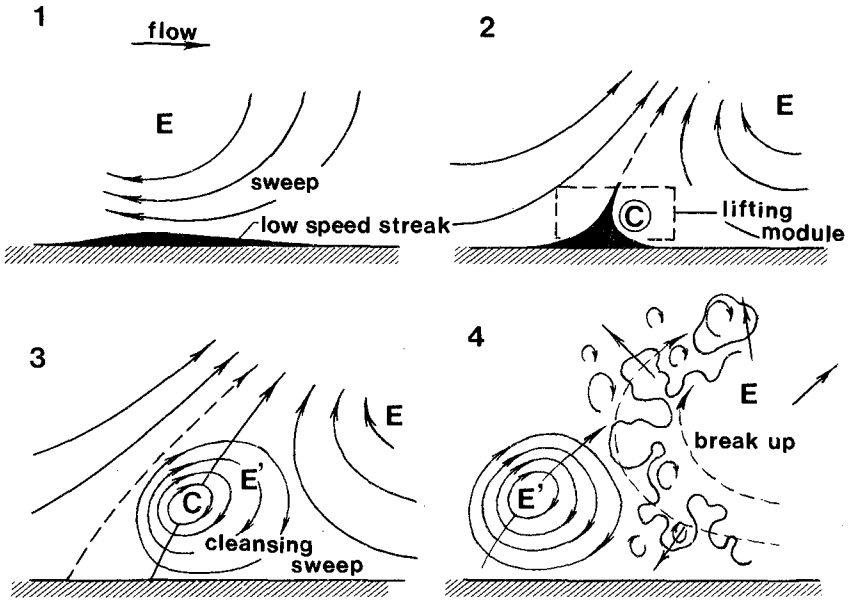
1
flow
E
sweep
low speed streak
2
E
C
lifting
module
3
E
E'
C
cleansing
sweep
4
E
break up
E'

FIG. 2

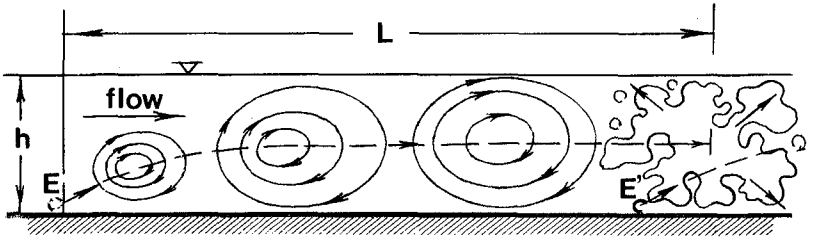
L
flow
h
E
E'

FIG. 3

4. The lifting module E' moves downstream immediately behind the "parent" module E . Since much of the energy of the parent module E was spent for the birth of E' , the module E is in a "weak" state, and therefore the adverse velocity fields of E' and E (Fig 2.4) are likely to destroy the module E by disintegrating it into a multitude of smaller eddies ("break-up phase"). The scattered multitude of smaller eddies manifests itself in the form of high frequency fluctuations (microturbulence) superimposed on the low frequency ones (macroturbulence).

Although the study of the quasi-cyclic events is still only at its beginning, the researchers in the field seem to be in agreement that the bursting process is regenerative, i.e., that the "birth" of one module is associated with the "death" of another, and thus that the path of a module (E) should end at the location where the path of the next module (E') begins (Fig 3). Let L be the average value (expectation) of the possible path lengths L_i . It is clear that the length L , which can be called the average "coherence length", is yet another linear characteristic determining the internal structure of a turbulent flow (in addition to the eddy sizes ℓ). Since a macroturbulent eddy carried by the flow downstream can maintain its identity or coherence only along a distance L_i comparable with L , a "signal" transmitted by an eddy, on average, cannot travel farther than L . One can say that the length L signifies the average extent of the longest disturbances that can occur in the longitudinal direction (x) of a turbulent flow. How big are the coherence lengths L_i of macroturbulent eddies? The measurements of M.A. Badri Narayanan and his co-workers (Ref [5]), carried out for a boundary-layer flow, indicate that the distances L_i are "of the order of several boundary-layer thicknesses δ ". Indeed, as can be seen from their plot (Fig 9 (middle) in Ref [5]), the majority of the experimental points are scattered within the interval

$$\approx 4\ \delta < L_i < \approx 7\ \delta \qquad (2)$$

which includes the value $L_i = 2\ \pi\ \delta$. In the case of a two-dimensional flow in an open channel, h must figurate instead of δ and one would expect that the average coherence distance should be close to $2\ \pi\ h$ which is a "standard" for the orientative prediction of the length of dunes. A more detailed prediction of the dune length Λ can be carried out with the aid of Fig 7.28 in Ref [9] which is the graph of the function

$$\Lambda = \phi(X,Z) \cdot h \qquad (3)$$

where $\phi(X,Z) \approx 2\ \pi$ if $X > \approx 40$ and/or $Z > \approx 10^4$.

If (as is often postulated) the large scale formations on the flow bed (dunes) are caused by the large scale longitudinal disturbances that occur in the velocity field (u) of a turbulent flow, then the effective spectral density function $S(\omega)$ of the stochastic process $u = f(x)$ (which reflects the fluctuations along the flow direction x at a given instant) must be regarded as defined over a "narrow band" which includes the lowest spacial frequencies $\omega = 1/L_i$ only (Fig 4). The frequency $1/L$ is in the midst of the "band", corresponding autocorrelation function being

$$R_x = e^{-\alpha x} \cdot \cos\left(2\pi \frac{x}{L}\right) \qquad (4)$$

As is clear from the (trigonometric) nature of this function, shown schematically in Fig 4, any disturbance of the field u at a section $x = 0$, say, must be accompanied by similar kinds of disturbances (along x) with the intervals L. For example, if the disturbance in the field u at $x = 0$ (e.g., due to an imperfection or discontinuity on the bed surface) is as to produce an "accretion" (+), then the tendency for an accretion will also be present at the sections $x = L, 2L$ .... etc. (though with a lesser intensity, due to the "damping factor" $e^{-\alpha x}$); at the sections $x = L/2$, $3L/2$ .... etc., the tendency for an "erosion" (-) will be present. The sequence of alternate accretions and erosions will inevitably deform the flat initial bed surface into a wavy one, the wave length Λ being the same as L.

When concluding this paper it should be mentioned that the average coherence length L of macroturbulent eddies is, in fact, proportional to their maximum size ℓ_{max}. Since in the case of a unidirectional flow the size of the largest eddies is the same as the thickness of the flow (δ or h) the proportionalities such as $L \sim \delta$ or $L \sim h$ (introduced above) are justifiable. In general, however, $L \sim \ell_{max}$, and $\Lambda \approx L$ should be regarded as given by

$$\Lambda \approx 2\pi \cdot \ell_{max} \qquad (5)$$

(if $X > \approx 40$ and/or $Z > \approx 10^4$)

In some cases of a tidal flow the time average value of ℓ_{max} (during θ^+) may be less than the average flow depth h, and therefore it would be more prudent to consider the length Λ of the tidal dunes as a quantity which "cannot exceed $2\pi h$" (if $X > \approx 40$ and/or $Z > \approx 10^4$) rather than as that which is "equal to $2\pi h$".

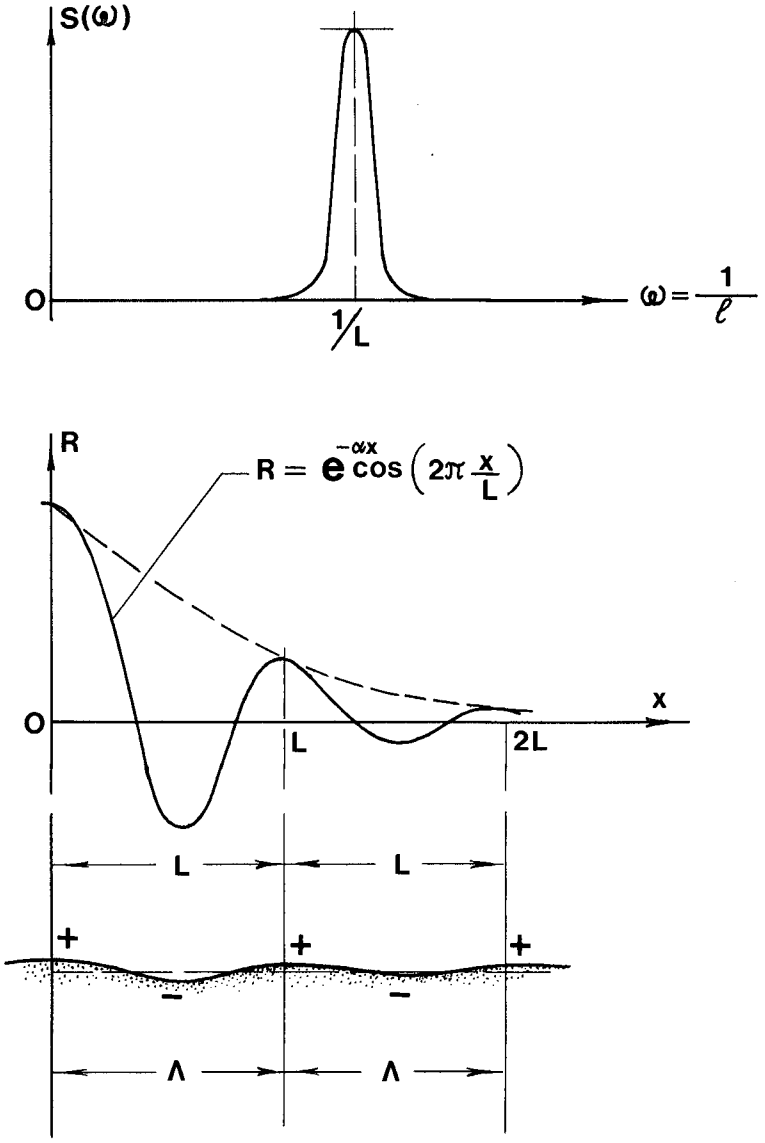

FIG. 4

REFERENCES

1. H. Ozasa: Field investigation of large submarine sand waves. Coastal Engineering in Japan, Vol. 17, 1974.

2. Per Bruun: Port Engineering. Gulf Publishing Co., Houston, Texas, 1973.

3. J. Laufer: New trends in experimental turbulence research. No. 8076, Annual Review of Fluid Mechanics, Annual Reviews Inc., Palo Alto, California, Vol. 7, 1975.

4. G.R. Offen, S.J. Kline: A proposed model of the bursting process in turbulent boundary layers. J. Fluid Mech., Vol. 70, Part 2, 1975.

5. K. Rao, R. Narasimna, M.A. Badri Narayanan: The "bursting" phenomenon in a turbulent boundary layer. J. Fluid Mech., Vol. 48, 1971.

6. G.R. Offen, S.J. Kline: Combined dye-streak and hydrogen-bubble visual observations of a turbulent boundary layer. J. Fluid Mech., Vol. 62, 1974.

7. H.T. Kim, S.J. Kline, W.C. Reynolds: The production of turbulence near a smooth wall in a turbulent boundary layer. J. Fluid Mech., Vol. 50, 1971.

8. S.G. Nychas, H.C. Hershey, R.S. Brodkey: A visual study of turbulent shear flow. J. Fluid Mech., Vol. 61, 1973.

9. M.S. Yalin: Mechanics of Sediment Transport, Pergamon Press, Oxford, 1972.

LIST OF SYMBOLS

t	time
x	direction parallel to the flow
y	direction perpendicular to flow
ρ	fluid density
ν	kinematic viscosity
h	flow depth
δ	boundary layer thickness
u	local flow velocity
τ	local shear stress
τ_o	shear stress acting on the bed
$(\tau_o)_{cr}$	critical value of τ_o (corresponding to the beginning of sediment transport)
$v_* \equiv \sqrt{\tau_o/\rho}$	shear velocity
D	representative grain size (usually D_{50}) of bed material
$X = v_* D/\nu$	grain size Reynolds number
$Z = h/D$	relative flow depth
Λ	dune length
$\mathcal{T}$	duration of the dune development
T	tidal period
θ	part of the tidal period where $\tau_o > (\tau_o)_{cr}$
L_i	"coherence distance" of an eddy (i)
L	average value (expectation) of the distances L_i