CHAPTER 140

THE EFFECT OF WIND ON CURRENTS AND DIFFUSION IN COASTAL SEA AREAS

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ABSTRACT

The calculation of turbulent flow using Navier's equations assumes the introduction of a turbulent viscosity coefficient the value of which is normally constant, conforming with Boussinesq's hypothesis.

It was shown that setting aside this hypothesis, a velocity profile quite different to that resulting from the classic theory is obtained in the case of flow induced by wind. This result appears to be confirmed by the tests carried out in the Mediterranean. The advantage of this method is that it gives the vertical turbulent diffusion which is of particular interest to pollution studies.

During the studies and experiments carried out in the Mediterranean sea on pollution, we had envisaged estimating the diffusion of a rhodamine stain by aerial photography.

The difficulties of interpreting coloured stains leaving indications of high speed-gradients near the surface, which will be discussed later, led us to reconsider the method of calculating currents due to wind.

The classic EKMAN theory is based on the simplified BOUSSINESQ theory. This theory can now be set aside owing to recent work on turbulent flow, in particular that by Messrs. Biesel, Huffenus and Gauthier at SOGREAH.

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Two supplementary equations have to be treated which require numerical treatment with a computer. The results obtained from this program, called the EOLE program, are confirmed by our measurements in the Mediterranean and by certain work at present being carried out in French universities and offer new information.

It is well known that the transposition of the Navier equation :

$$\frac{\partial v}{\partial t} + V.\nabla V = -\frac{1}{p}\,\text{grad } P + \nu \Delta V$$

to turbulent flow, by substituting $V = \overline{V} + v$, involves terms accounting for internal tension called Reynolds forces :

$$\frac{\partial \overline{V}}{\partial t} + \overline{V}.\nabla\overline{V} = -\frac{1}{p}\,\text{grad } P + \text{div } (\nu \text{ grad } \overline{V} - \overline{v_i v_j})$$

BOUSSINESQ's theory compares these forces to viscous forces which leads to the kinematic viscosity of water being replaced by a much higher turbulent viscosity : the eddy viscosity μ which has a totally empirical value. In each case, the applications require physical measurements.

$$\frac{\partial \overline{V}}{\partial t} + \overline{V}.\nabla\overline{V} = -\frac{1}{p}\,\text{grad } P + \text{div } (\mu \text{ grad } \overline{V})$$

$\mu \gg \nu$

The problem is therefore to define a more precise approach to the phenomenon of turbulence. In the wake of extensive research work, SOGREAH developed programs based on a first order schematic representation of turbulence. Although semi-empirical, the representation is largely justified by the better conformity of results calculated from these measurements.

This method of calculation consists of representing the viscosity by a function of two parameters :

- the turbulent energy dissipated locally,
- a length defining the scale of turbulence.

which are included in the Navier equation, the first establishing the turbulent energy balance, the second defining the scale of turbulence.

In the case of flow induced by the wind the equations become :

$$\frac{\partial V}{\partial t} = - gi + \nu \frac{\partial}{\partial z} \left[(1 + k_1 R_T) \frac{\partial V}{\partial z} \right]$$

$$\frac{\partial E}{\partial t} = k_1 \nu R_T \frac{\partial^2 V}{\partial z^2} - \nu (k_3 + k_4 R_T) \frac{E}{l^2} + \nu \frac{\partial}{\partial z} \left[(\frac{5}{3} + k_2 R_T) \frac{\partial E}{\partial z} \right]$$

$$l = k_5 z / \sqrt{1 + k_6 R_T}$$

$$R_T = l \sqrt{E/\nu}$$

where :

V = local flow velocity

i = slope of the sea surface

z = depth

v = kinematic viscosity

E = turbulent energy

l = eddy scale

k_1 to k_6 = numerical coefficients

R_T = Reynold's Number.

The boundary conditions express the shearing forces due to the action of the wind on the surface of the sea and the rugosity of the wall on the sea bed.

The program itself determine a variable distribution of calculation points in Z, which is indispensable for taking into account boundary layers. First of all, it solves the last two equations then calculates the velocity profile with the aid of the first equation.

The first EOLE program, deliberately simplified, was written to verify the validity of the calculation method. It assumes that the wind direction, the speed of water and the line with the steepest slope to the surface of the water are all in the same vertical plane. It calculates the speed of water as a function of the depth assuming an established permanent regime. It will be immediately pointed out that its extension to three dimensions, the consideration of Coriolis' forces and the putting into operation of the model are at present in progress.

In its initial form, the EOLE program is applied to two boundary cases :

- the first case is where the wind is parallel to a rectilinear coastline. The surface of the sea is then horizontal and there is a general flow in the direction of the wind.

- In the second case the wind is assumed perpendicular to the shore. Simple considerations of continuity show that the flow of the surface bounded by the coast should be compensated by a deep inversed current. In permanent regime, the total discharge along the vertical is zero. The free surface of the sea presents an inclination.

In spite of its initial simplified nature, the EOLE program throws new light on the present knowledge of the subject.

In all cases, the speed profile is very different to that obtained by the classic theories. A rapid decrease of the speed in the upper boundary layer is always observed. In addition, the speed at lower levels decreases almost lineraly.

Graph 1 shows the parabolic speed profile, calculated assuming constant eddy viscosity, and that obtained with the EOLE program when the wind is perpendicular to the coast. It will be noted that the return current is a maximum at a short distance from the bed.

Graph 2 shows the same comparison but with the wind parallel to the coast.

The eddy viscosity is not as uniform as is shown in Graph 3. It also varies in a notable manner as a function of the general flow conditions.

This questions EKMAN's theory of depth friction and all the conclusions from it, particularly in the field of overall transport. It is found that the EKMAN depth is always of the order of the real depth in shallow water.

In spite of the enormous difficulty of measuring the current at low speeds, the measurements made in the Mediterranean confirm the shape of the speed profile Graph 4. It should be pointed out that measurements were only made at the surface and down to 10 metres. The depth of the test area was around 50 metres.

The results are of particular interest to the study of transport and diffusion with respect to the problems of pollution. The average transport will be very different depending on the thickness of the polluted layer. In addition, the measurement of velocity with the aid of a very thin float is only significant of the upper boundary layer and not of the transport of the mass.

The eddy viscosity is a measure of the rate of exchange between the various flowing layers ; it strictely defines the vertical coefficient of eddy diffusion. Its high variation with depth will give very different effects on dilution depending on the thickness of the polluted layer. Obtaining the vertical diffusion by calculation could reduce experimental work in the sea.

At the begining of this review, I mentioned the difficulties of interpreting diffusion from a rhodamine cloud, followed by aerial photograph. The images of the rhodamine cloud show a sharp front whereas the rear is diffuse and descends progressively. With due consideration being given to the results given above, this phenomenon is easily explained.

The cloud is highly sheared by the variations in velocity at the surface. In the fastest surface layer the turbulent diffusion is zero which explains why the front of the cloud is always well defined. On the other hand, diffusion of the rear of the rhodamine cloud increase depth since turbulent diffusion increases with depth.

This does not work for longitudinal and vertical diffusion for which transport and velocity profile considerations have to be made. This is only possible using highly sophisticated mathematical models. SOGREAH is, at present in the process of finishing such a model.

Sea pollution studies assume a more and more refined knowledge of circulation in coastal waters where flow due to wind is often preponderant. We wanted to show that the application of the most advanced theories to the calculation of turbulent flow has thrown new light on the subject. In particular results from the EKMAN theory are considerably complemented by directly obtaining the vertical diffusion value.

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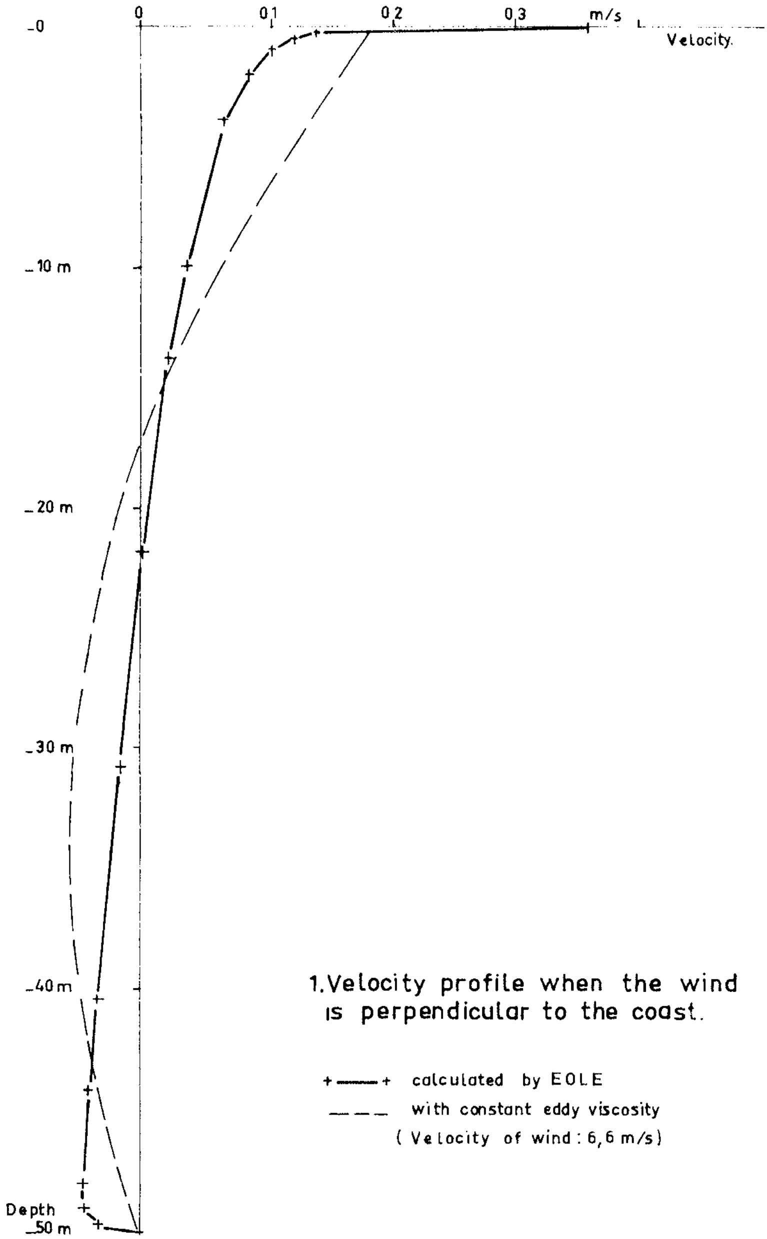
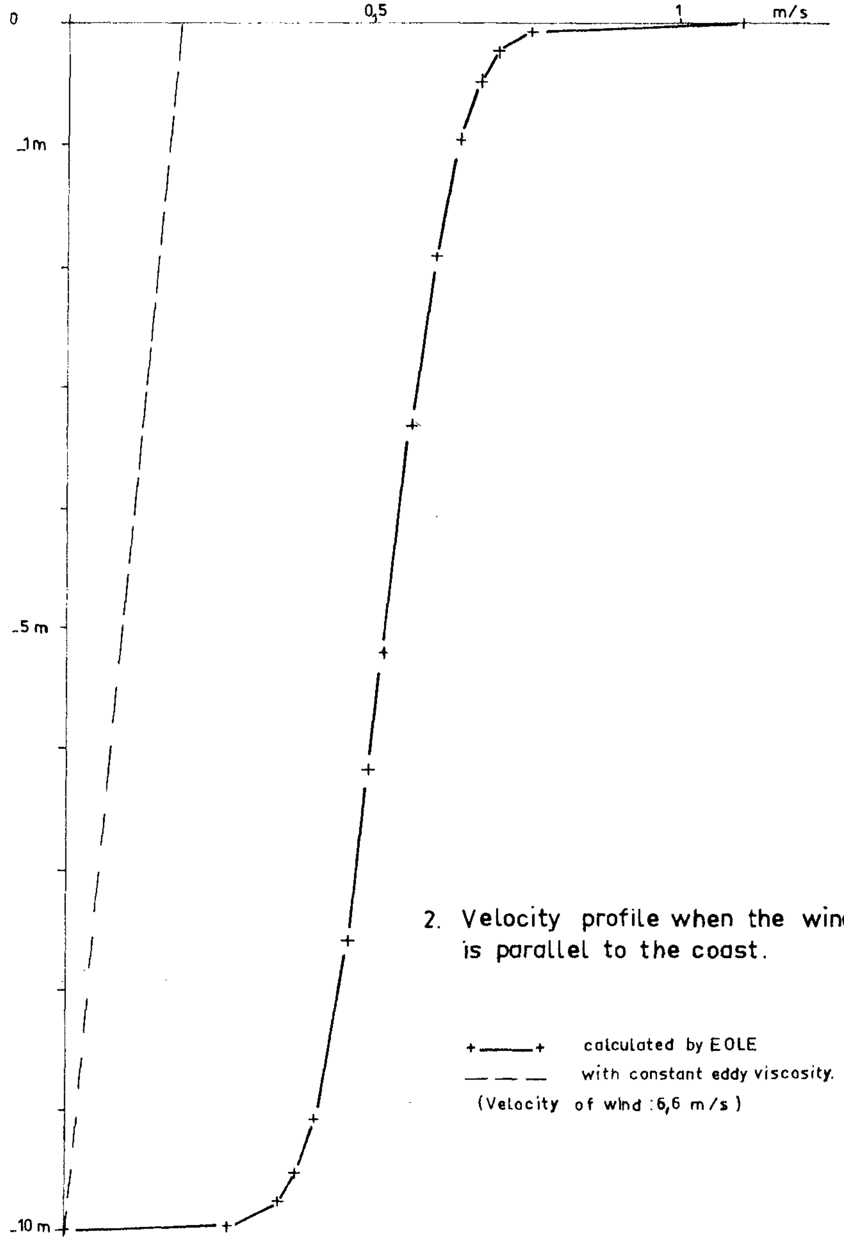
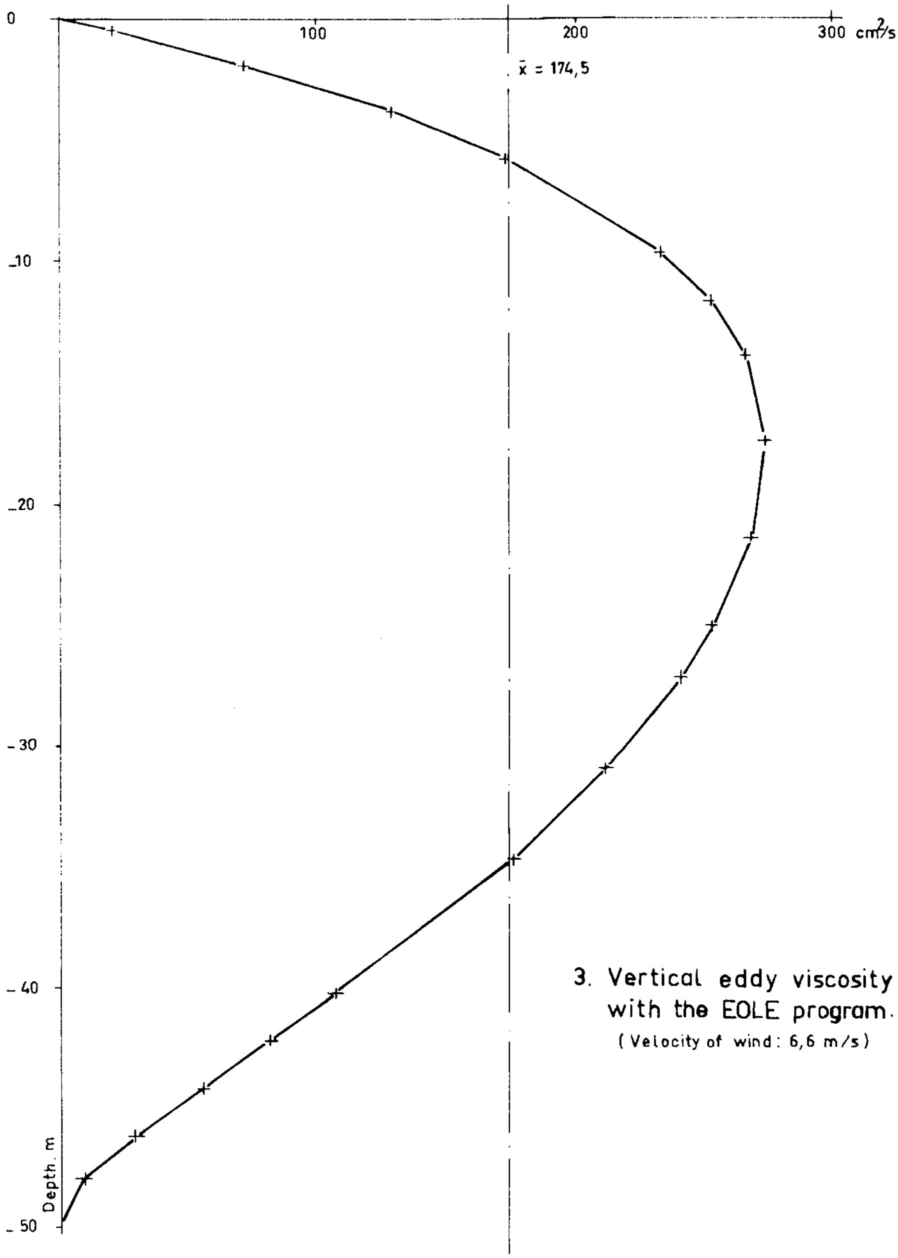


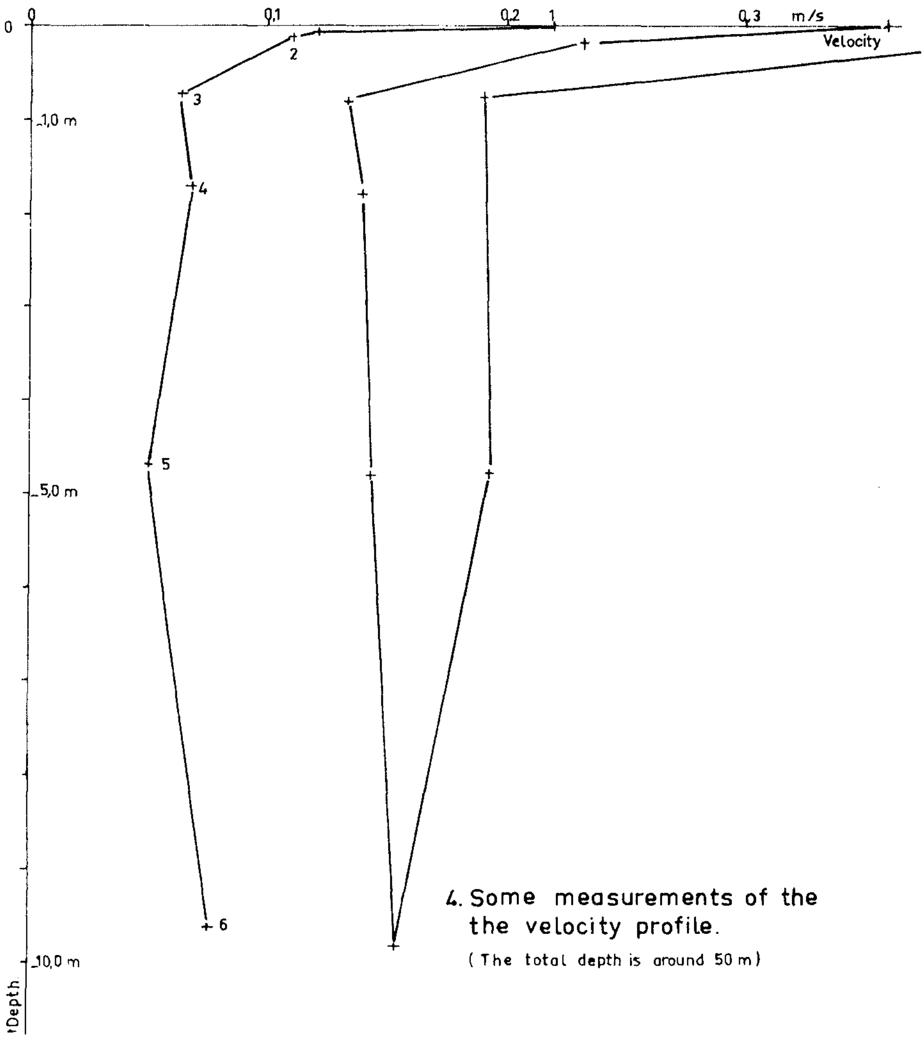
1. Velocity profile when the wind is perpendicular to the coast.



2. Velocity profile when the wind is parallel to the coast.



3. Vertical eddy viscosity with the EOLE program.
(Velocity of wind: 6,6 m/s)



4. Some measurements of the the velocity profile.
(The total depth is around 50 m)