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Study of Turbulent Friction in a Gradually Varied Flow

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Abstract: Most of the studies relating to the gradually varied flows were based on the analysis of the average magnitude and the evolution of the associated free surface curve. The phenomena of erosion or of friction on the bottom being globalised or being deduced from models defined for uniform permanent flows. In the research presented here, we study the flow above a threshold by privileging an approach based on the analysis of turbulence and the turbulent boundary layer, in a flow where the phenomena related to the acceleration and deceleration cannot be neglected. Our objective is to obtain a formulation allowing to define the evolution of the share stress in the various points of the surface of the threshold.

Key words: Gradually varied flows, erosion, share stress, dune

INTRODUCTION

Erosion phenomena in gradually varied flows are actually misunderstood for the following reasons:

- They are free surface flows meanwhile, these last are still often attacked on the 'hydraulic' aspect based on the evolution of mean quantities.
- They are flows where there exist strong variations in the mean velocity meanwhile, the models which lead to the definition of turbulent friction are elaborated principally for the permanent and uniform flows. The acceleration and deceleration phenomena of the flow are not taken into consideration.

In the preceding studies realized in the laboratory, we have shown that turbulence in the boundary layer generated by wave on the sea bed was different according to the phases of the peak and the hollow of the wave (Tcheukam-Toko *et al*., 1997). Most recently, our results had put in evidence that the wave modulated the turbulence scales (Murzyn and Bélorgey, 2002a, b) and that the acceleration or deceleration of the mean flow was an important phenomenon to take into consideration. In fact, we have shown that:

- The acceleration phases reduced the turbulence scale sizes.
- The deceleration phases increased the turbulence scale sizes.

These turbulence phenomena in the acceleration and deceleration zone are also found in the gradually varied flows, as much as it concerns the flow above a threshold in a channel and the flow of a tide current above an underwater dune.

The results that we present here are based on a dimensional flow above a threshold as much as concerns the mean field and the turbulent field. We will base our attention on the different natures in the turbulence between the acceleration zone and the deceleration zone. And we will look forward to showing this difference at the share stress modelling level at the bottom.

EXPERIMENTAL DEVICE

The tests were realized in the wave channel with the circulation of the Coastal and Continental Morphodynamic Laboratory-Fluid Mechanic Group (M2C. GMF-UMR CNRS 6143) of the University of Caen, France.

This channel (orange channel) 18 m long (length of vein 12 m) for a cross section of 0.5 m in width and 0.6 m in height permits the realisation of more current wave flows. The walls are glass in order to permit the measurement of the velocity and turbulence field by anemometer laser. The bottom is made up of PVC sheet-plates in such a way that models can be fixed to it.

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The research we present in these papers only take into consideration the action of current.

The flow realised in the vein, thanks to the circulation circuit, is an uniform free surface flow and variable flow rate. It is generated by a helix pump VENERONI-POMPES type E30-A1. The disruptions generated by this on the flows and those of the return circuit are eliminated thanks to a diffuser at the inlet of the pump equipped with radial fan blades to eliminate whirlpool created by the helix, followed up with a honeycomb placed at the entrance of the test vein.

The model of the dune occupies all the width of the channel (0.5 m). Its profile is realised in a PVC sheet-plate of 5 mm thick fixed on 4 suitable profile supports. Its form is axis symmetric and the peak is well rounded to reduce the undulations of the flow at this point. Its position in the channel with respect to the honeycomb is shown on Fig. 1. Its dimensions have been chosen according to the characteristics proposed by Ashely (1990), who for the similar geometrical forms established a difference between ripples and dunes Table 1.

The experimental device has been defined in a way that shows the influence of the variation of the flow velocity (acceleration and deceleration) on the nature of the turbulence and consequently on the friction at the bottom. On this account, the flow haven been laminated by the honeycomb, this last, is not confined in the study zone as in a classic channel. In this zone, at the centre of the vein the effects of vertical walls are negligible and the classic boundary layer, whose origin is situated at the inlet of the honeycomb develops at the bottom.

Considering these conditions, the flow parameters are given by:

- The mean velocity at the centre of the vein: U_0.
- The height of water: h.

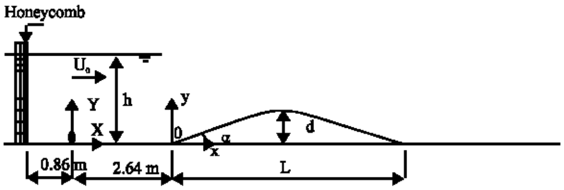

Fig. 1: Experiment configuration

Table 1: General characteristics of dunes with respect to ripples

Form	Slope	Long (m)	Height (m)	Effect
Ripples	Steep	Low: 0.01-0.5	Low: 0.001-0.1 m	Modified the bed's rough
Dune	Low	Long: 1-1000	Tall: 0.1-10 m	Free surface profile is affected

The mean velocity at the centre of the vein along the channel does not change much in the measure zone, which in this zone, confers properties of infinite width to the channel.

This particularity allows us to define the flow's Reynolds number by the relation:

$$\mathrm{Re} = \frac{U_0.h}{\upsilon} \tag{1}$$

where,

υ : The kinematics viscosity of the fluid.

Two flow conditions have been studied (for the velocity less than the critical value, which would lead to the establishment of a hydraulic leap at the inlet of the dune).

- $U_0 = 0.20\ \mathrm{m\ s^{-1}}\ h = 0.248\ \mathrm{m}$.
- $U_0 = 0.25\ \mathrm{m\ s^{-1}}\ h = 0.248\ \mathrm{m}$.

The velocity and the turbulent fields have been analysed with the aid of a velocimeter laser DANTEC with two components in the retro-diffusion mode. Thanks to the particles added to the flow, the acquisition ratio varied between 30 and 100 Hz, which assured us of a good turbulence spectral characterisation (Nezu and Nakagva, 1993). The optic sounding line of a focal of 500 mm was fixed on a displacement table (vertical and horizontal) permitting the automation of measurements with a displacement precision of 0.1 mm.

For each type of the flow, a set of 50 velocity profiles has been realised: at the outlet, above and at the inlet of the dune. These profiles correspond to the measurement of the velocity field, at the centre of the vein, where the influence of the vertical walls is negligible. For each of them:

- The vertical displacement step near the bottom ($y<20$ mm) was 1 and 10 mm ($y>20$ mm).
- The first point of the measurement was situated at 1 mm from the bottom.

And at each point of measurement we have determined:

- The horizontal and vertical components of the mean velocity (temporal mean).

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{2}$$

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{3}$$

where,

n : The number of instantaneous measurements at each point.

- The turbulence intensities associated to the horizontal and vertical fluctuations of the velocity.

$$u_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(u_i - \bar{u}\right)^2} \qquad (4)$$

$$v_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(v_i - \bar{v}\right)^2} \qquad (5)$$

- The Reynolds stress

$$-\rho\overline{u'v'} = -\rho\frac{1}{n}\sum_{i=1}^{n}\left(u_i - \bar{u}\right)\left(v_i - \bar{v}\right) \qquad (6)$$

ANALYSES OF THE EXPERIMENTAL RESULTS

We have analysed the influence of the form of the bottom on the different flow parameters:

- The mean velocities.
- The boundary layer at the bottom.
- The nature of the turbulence.

The flow being gradually varied (non uniform), we had 3 flow regions:

- Uniform flow on the outlet and inlet faces of the dune.
- Accelerated flow on the outlet face of the dune.
- Decelerated flow on the inlet face of the dune.

To show our results, we have chosen the abscissa axis origin at the start of the dune. The peak of this one is then situated at x/L = 0.5.

The mean velocities: About the mean velocities in each profile and for the flow conditions which are ours, the influence of the dune:

- Starts at a weak distance at the outlet of the dune (x/L = -1 or x = -L).
- Prolongs on a more important distance at the inlet (x/L = 3 or x = 3L).

This result permits the evaluation of the free surface deformation zone on both sides of the dune.

The dune (Fig. 2) the evolution of the horizontal component of the velocity is conformed to that of a flow above a threshold showing an undulation at the inlet and a circulation after the peak. We notice however, a more remarkable influence of the free surface in the case of flow number 2. In fact, the velocities being more important, the friction at the interface of air-water is more significant.

The vertical component is more sensible to the presence of the dune (Fig. 3a) and the influence of the free surface deformation is more outstanding (Fig. 3b).

The boundary layer: Considering the classical definition of the thickness of the boundary layer δ ($U_\delta = 0.99\ U_0$), our results show (Table 2 and Fig. 4):

- A relatively classical increasing evolution of δ at the outlet of the dune.
- A very strong decreasing of δ in the acceleration flow zone (outlet of the dune).
- An undulation of the boundary layer at the inlet near the peak.

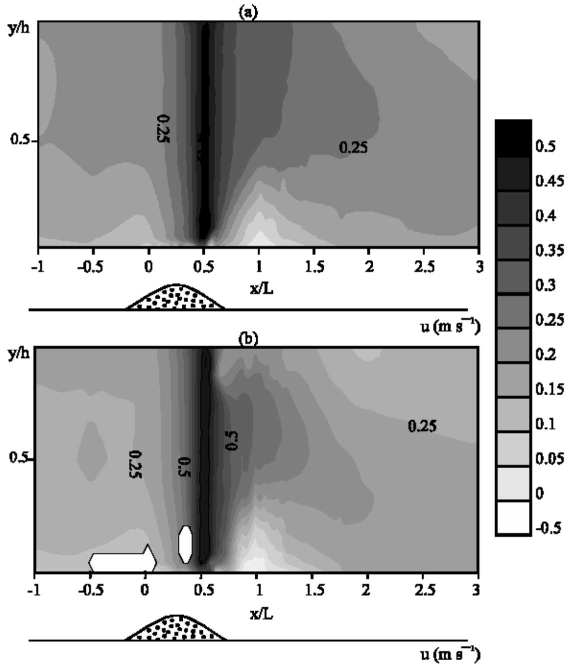

Fig. 2: Changes in the horizontal component of the mean velocity. a: $U_0 = 0.20$ m s^{-1}, b: $U_0 = 0.25$ m s^{-1}

Table 2: Evolution of the thickness δ of the boundary layer

x/L	δ (m)
-2	0.0897
-1	0.0874
-0.5	0.0985
0	0.1181
0.5	<0.003

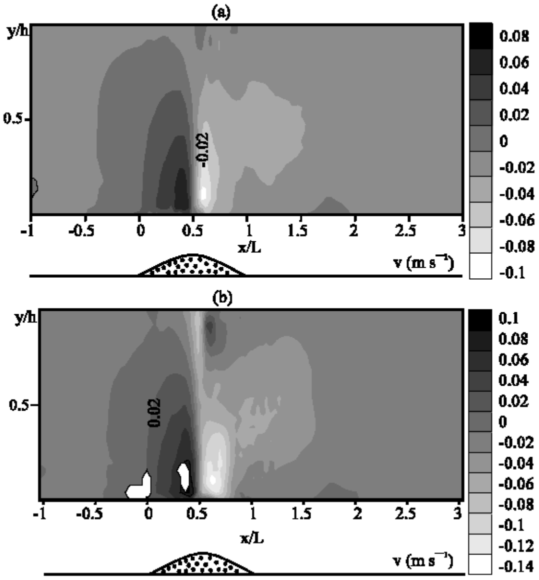

Fig. 3: Evaluation of the vertical component of the mean velocity. a: $U_0 = 0.20$ m s^{-1}, b: $U_0 = 0.25$ m s^{-1}

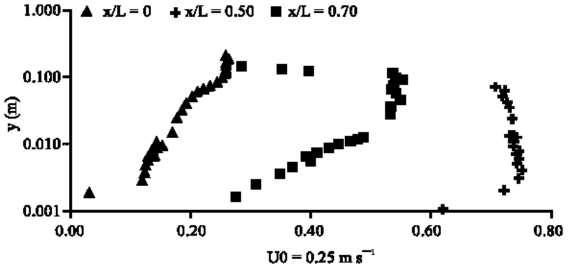

Fig. 4: Profiles of the horizontal components of the mean velocities

- A tight to the wall and a return to a thickness δ, relatively normal to the near inlet of the dune (δ = 0.10 m).

The turbulent field: We have started the analyses of the turbulent field by the measurement of the turbulence ratio of horizontal and vertical components of the velocity, the determination of the turbulent kinetic energy and the analyses of the correlation coefficient R_{uv}.

$$R_{uv} = \frac{-1/n\sum_{i=1}^{n}\left(u_i-\bar{u}\right)\left(v_i-\bar{v}\right)}{\sqrt{1/n\sum_{i=1}^{n}\left(u_i-\bar{u}\right)^2}\sqrt{1/n\sum_{i=1}^{n}\left(v_i-\bar{v}\right)^2}} \qquad (7)$$

Our results show the following elements:

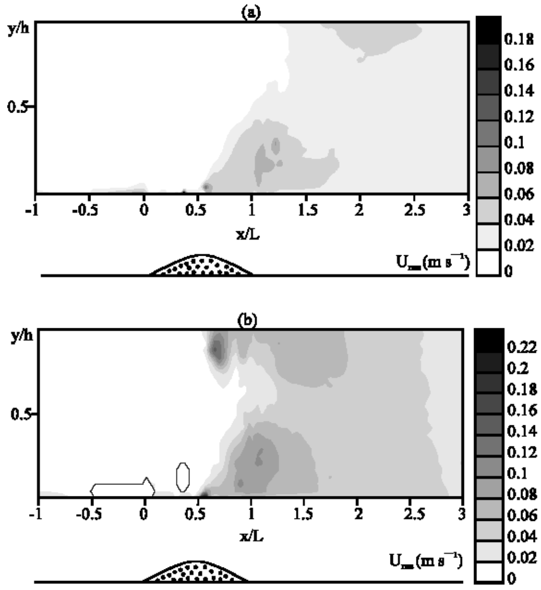

Fig. 5: Variation of the standard deviation of horizontal component of velocity. a: $U_0 = 0.20$ m s^{-1}, b: $U_0 = 0.25$ m s^{-1}

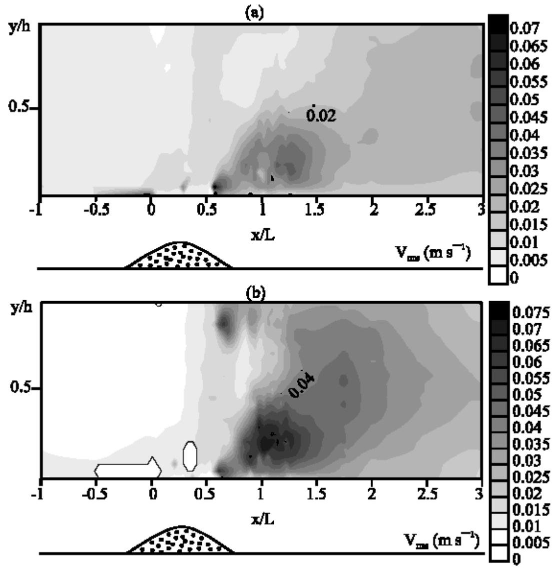

Fig. 6: Variation of the standard deviation of vertical component of velocity. a: $U_0 = 0.20$ m s^{-1}, b: $U_0 = 0.25$ m s^{-1}

- Very strong turbulence ratio associated to the undulation zone at the inlet of the peak (Fig. 5 and 6). The presence of this undulation implies a shear layer (the interface between the mean flow and the return flow) where the production of turbulence, associated to the strong gradient of the velocity at this interface, is dominated by the instabilities of Kelvin-Helmholtz (Muller and Gyr, 1982, 1986).

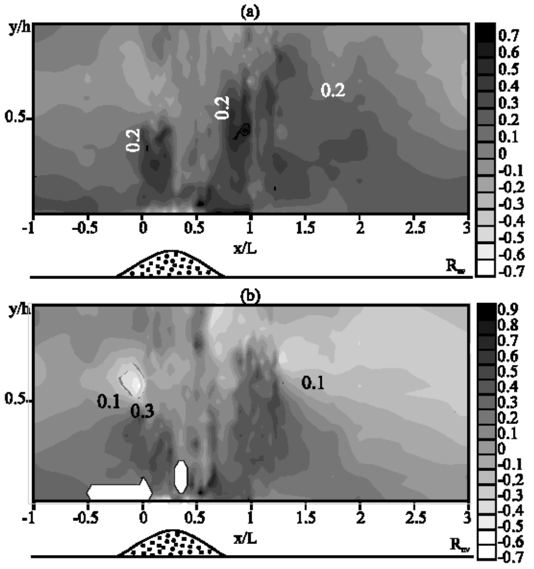

Fig. 7: Variation of correlation coefficient Ruv. a: $U_0 = 0.20$ m s^{-1}, b: $U_0 = 0.25$ m s^{-1}

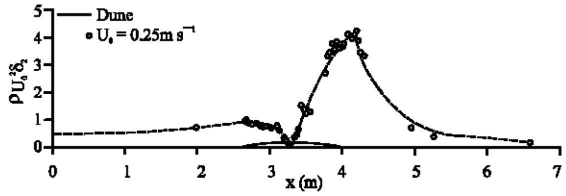

Fig. 8: Evolution of the quantity $\rho U_0^2\delta_2$

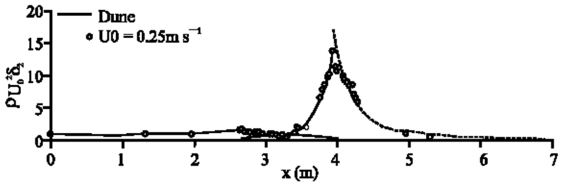

Fig. 9: Evolution of the quantity $\rho U_0^2\delta_1$

- A region of strong turbulence ratio at the free surface, immediately after the peak. This phenomenon which depends on the flow velocity is stronger for the turbulence ratio linked to the vertical component of the velocity.
- Particular characteristics in the development of the correlation coefficient R_{uv} (Fig. 7).

The share stress: The study of the boundary layer in a gradually varied flow permits us to express the share stress in the form:

$$\tau_p = -\left[\frac{d(\rho U_0^2\delta_2)}{dx} + \rho U_0 \frac{dU_0}{dx}\delta_1\right] \qquad (8)$$

The determination of this quantity necessitates the analysis as a function of the dimensional abscissa X, of the evolution of U_0 and the integral quantities associated to the boundary layer: δ_2 (quantity linked to the displacement thickness Fig. 8) and δ_1 (quantity linked to the quantity of movement variation thickness Fig. 9), as well as their derivatives.

DISCUSSION

In intensity, our results are collectively (as a whole) in agreement with those of Vendity and Bennett (2000) who found, for a flow above a dune, $R_{uv}<0.5$ for $0<y/h<0.5$ (except at the inlet of the peak, for flow n° 3). On the other hand, a more detailed analysis shows that this coefficient has important peaks (for x/L = 0.2; 0.65; 1.3) at the immediate inlet of the slope rupture (x/L=0; 0.5; 1).

The evolutions of the integrals quantities show that in the zones where the flow is accelerated or decelerated, the variation of these quantities (quantities linked to δ_1 and δ_2) are very important which is what authorises us to think that the share stress on the bottom is in these zones, principally sensible to the variation of the movement quantity. On the other side, a more precise characterisation of this share stress as well as it modelling necessitates finer measurements of the velocity field and the turbulent field very close to the wall.

CONCLUSION

Our first results show that in gradually varied flows, the nature of the turbulence and the integral quantities associated to the boundary layer strongly depend on the acceleration or deceleration nature of the flow.

In our study, we did not analyse the evolution of quantities associated to the share stress on the bottom in the case of flow above the threshold, but our studies are to be followed up to arrive at a modelling of this quantity as a function of the intensity of this acceleration (or deceleration).

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