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# MEASUREMENT OF MOMENTUM TRANSFER CAUSED BY A GROYNE IN A COMPOUND CHANNEL

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**ABSTRACT:** The present study investigates flow in an asymmetrical compound channel with a thin obstacle set on the floodplain, perpendicular to the main flow direction. Six flow configurations were investigated. Two flows were carried out under uniform flow conditions and four flows were carried out with a thin obstacle of variable length ($d$). Depending on the investigated relative depths ($Hr$) and aspect ratios $d/B_{fp}$ (where $B_{fp}$ = floodplain width), depth-averaged velocity and distribution of water depth across the channel were first examined. Streamwise profile of discharge distribution and mass exchanges were then deduced. Using a one dimensional momentum equation in each subsection, momentum balances were finally worked out. In addition to the classical turbulent exchange located at the vertical interface between the main channel and the floodplain, a significant momentum flux related to mass exchanges between subsections was observed when flow occurred near the groyne. In the floodplain, analysis emphasizes that the momentum transfer due to mass exchanges is (1) several orders of magnitude larger than momentum transfer due to turbulent exchange and (2) have the same magnitude order as friction on solid walls, whatever the groyne length and the relative depth are. In the main channel, solid wall friction is equivalent or larger than momentum transfers.

*Keywords*: compound channel, rapidly varied flow, momentum transfer, mass exchange

## 1 - INTRODUCTION

During a flood event, the river main channel (*MC*) may overflow in the contiguous floodplains (*FP*). The flow in the main channel, fast and deep, interacts with the flow in the floodplain, which is slow and shallow. In such a configuration, the river is generally modeled as a two-stage channel and such a flow is called ‘compound channel flow’. Under uniform flow conditions, in addition to the classical friction on solid walls and secondary currents, the spanwise velocity distribution generates a mixing layer on each side of the vertical interface between the main channel and the floodplain The latter is characterized by momentum transfers due to turbulent exchange between each channel and is a source of an additional shear; consequently, the river conveyance is reduced (Knight & Demetriou, 1983). As soon as the river cross-section gradually and continuously varies (meander, diverging/converging or skewed floodplain), depending on the geometry variations, each channel either yields or receives momentum due to mass exchanges from its contiguous channel(s) (Bousmar, 2002; Proust 2005). According to Proust *et al.* (2009), when considering a channel with a skewed floodplain (semi-angle smaller than 5.1 degrees):

- momentum exchanges due to turbulence are larger than momentum transfers due to mass exchanges in the converging floodplain,
- the contrary is observed in the diverging floodplain.

Finally, when a flow occurs in the vicinity of a thin embankment, the river cross-section rapidly and discontinuously varies (railway, embankment, groyne; see Peltier *et al.*, 2008). In such a configuration, the obstacle contracts the flow and promotes two flow separations. Indeed, recirculating zones develop upstream and in the lee of the obstacle. Moreover, upstream the groyne, due to the sudden contraction of the flow, mass exchanges and momentum transfers are forced from the floodplain to the main channel; the floodplain acts there like a converging floodplain. Downstream of the obstacle, the contrary is observed and the flow slightly goes to 'equilibrium'; the floodplain acts like a diverging floodplain. A parallel can be made with a flow developing in a compound channel with a Venturi shape, as the converging part of the flow is separated from the diverging part by a throat. Notice that the presence of a recirculating zone strongly disturbs the discharge distribution across the channel and momentum transfers due to mass exchanges are much stronger than those observed in gradually varied flows (Proust, 2005). These 'compound channel' flows are quite common in the field, but a few studies deal with this topic.

The present study investigates flow in a compound channel with a groyne set on the floodplain. Experiments are first presented. Then, depending on (i) the length of the obstacle and (ii) a small and a large relative depth (0.2 and 0.4) for which the interfacial momentum flux are different, a description of the longitudinal and transverse evolution of depth averaged velocity, water depth and discharge distribution across the channel is done. Finally, using a one dimensional momentum equation, momentum balances are worked out; each term: momentum transfers due to mass exchanges (measured), solid wall friction (modeled) and interfacial turbulent flux (modeled) are compared to the bed slope. Their predominance are examined, depending on the experimental parameters.

## 2 - METHODS

### *2.1 - Experimental set-up*

Experiments were conducted in an experimental flume located at the 'Laboratoire de Mécanique des Fluides et d'Accoustique' (*LMFA*) in Lyon, France. This flume is straight and asymmetrical, and the main channel cross-section is rectangular. The floodplain and the main channel are PVC made and their surface state is smooth: roughness ($\varepsilon$ in m) is within [$1.5 \times 10^{-6} - 0.5 \times 10^{-5}$]. Geometrical parameters are reported in Figure 1.

Without adapted boundary conditions, the length of the flume (Tab. 1) does not enable uniform flow conditions to be obtained. Thus, separated inlets and outlets were set in the flume (Fig. 1). Consequently, flow boundary conditions can be independently adjusted in each subsection. The separated inlets accelerate the flow development along each channel, by deleting the excess in floodplain discharge obtained when a single inlet is used (Bousmar *et al.*, 2005). The separated outlets enable a better adjustment of downstream boundary conditions by reducing the mass transfer between the subsections at the end of the flume (Proust, 2005).

**Table 1. Characteristics of the flume.**

| $L$ [m] | $B$ [m] | $B/B_{fp}$ [-] | $h_{bf}$ [m] | $So$ [-] | $Hr = h_{fp} / h_{mc}$ |
|---|---|---|---|---|---|
| 8 | 1.2 | 1.5 | 0.0515 | 0.0018 | |

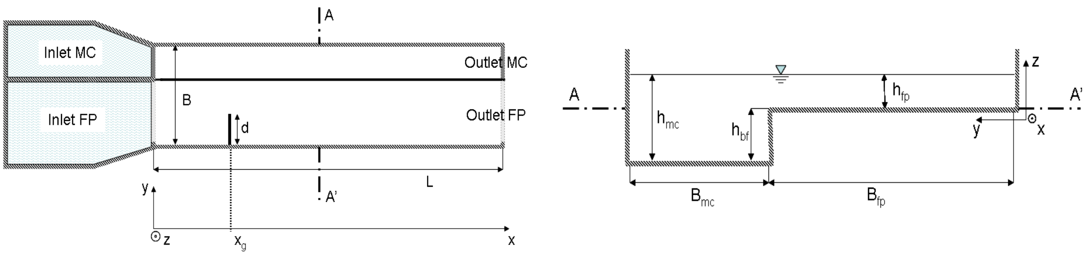



**Figure 1. Cross-sectional and plan views of the flume.**

The first two experiments were performed under uniform flow conditions (*i.e.* without groyne), with respectively a small relative depths ($Hr = 0.2$) and a large one ($Hr = 0.4$). Then, using the same upstream and downstream boundary conditions as the reference flow, four non-uniform flows with a groyne set on the floodplain perpendicular to the main flow direction were carried out. Experiments main characteristics are summed up in Table 2.

**Table 2. Experimental parameters of reference flows and flows with a groyne**

| Reference flow | | | | | | Flows with a groyne of length $d$ | | |
|---|---|---|---|---|---|---|---|---|
| $Q_{total}$ [l/s] | $Q_{mc}$ [l/s] | $Q_{fp}$ [l/s] | $Hr$ | $n_{mc}$ [$m^{-1/3}$.s] | $n_{fp}$ [$m^{-1/3}$.s] | $d$ [m] | $d/B_{fp}$ | $\Delta Hr$ |
| 17.3 | 14.9 | 2.4 | 0.21 | 0.00909 | 0.00957 | 0.3 | 0.375 | 0.12 – 0.23 |
| | | | | | | 0.5 | 0.625 | 0.11 – 0.3 |
| 36.2 | 22.2 | 14 | 0.42 | 0.00906 | 0.00889 | 0.2 | 0.25 | 0.32 – 0.49 |
| | | | | | | 0.3 | 0.375 | 0.29 – 0.51 |

$\Delta Hr$ represents the relative depth variation of flows with a groyne in the floodplain. This variation has to be compared with the uniform flow value.

Using a LSPIV technique (Muste *et al.*, 2008) and a HD Video-Camera, surface velocity profiles were first measured. Then, using an automatic displacement device, measurements of water depths and mean velocities were carried out. Depth was surveyed using an ultrasonic probe. Most of the mean velocities were measured using a micro-propeller and a vane to obtain the flow direction; as soon as water depth was too shallow to use the micro-propeller ($h <$ 0.014 cm), a Pitot tube was used. Finally, recirculation patterns and dimensions were estimated using micro-propeller measurements and LSPIV images (see, Fig. 2). Notice that, a throat appears in the flow out of the recirculation downstream the groyne, since obstacles are thin and promote a flow contraction. Moreover, as flows are stationary, recirculation is a zone of zero discharge. Its boundary can be considered in 'first approach' as a wall. Consequently, the width of the floodplain varies with the transverse length of the recirculation and, using this assumption, the discharge distribution in the floodplain can be worked out (Eq. 1):

$$Q_{FP}(x) = \int_{Ly}^{Bfp} U(x,y).h(x,y).dy \tag{1}$$

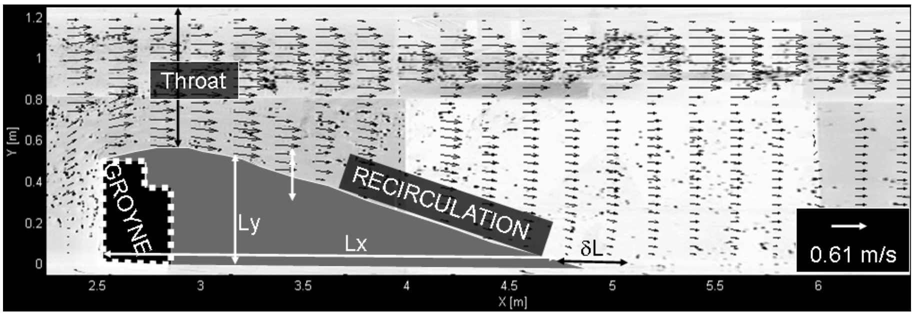



**Figure 2. $H_r$ = 0.2 and $d/B_{fp}$ = 0.625: Surface velocity field obtained using LSPIV technique. Image is ortho-rectified and is displayed as a film negative.**

### *2.2 - Momentum equation*

Momentum transfers in experiments were estimated using a one dimensional momentum equation (Eq. 2). Thus, assuming that the Boussinesq coefficient in a subsection ($\beta_i$) is equal to unity, the momentum equation, in a subsection, is similar to the one proposed by Proust *et al.* (2009):

$$\rho \frac{dA_i U_i^2}{dx} + \rho g A_i \frac{dh_i}{dx} = \rho g A_i So - \rho g A_i Sf_i - \rho g A_i St_i + \rho q_i U_{int} \tag{2}$$

'$U$' means depth averaged velocity on a subsection, '$h$' means mean depth on the subsection, 'A' means subsection wetted area, subscript '$i$' means either floodplain or main channel, subscript '$int$' means 'interface' and 'q' is a lateral discharge.

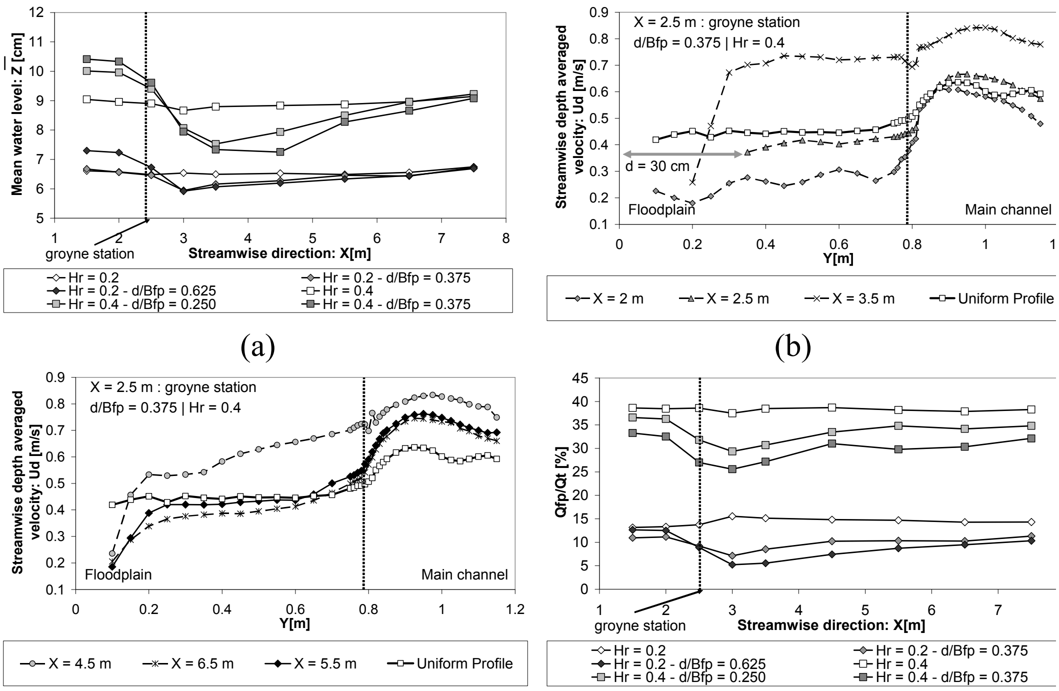
Equation 2 models the main phenomena found in a compound channel: wall friction ($Sf$), mixing layer at the interface (Subscript $St$) and momentum transfers due to mass exchanges through the interface ($\rho q U_{int}$). Both equations in a subsection are linked together by the continuity equation. In this paper, the turbulence at the interface is modeled using a mixing length model (Eq. 3; see Bousmar, 2002; Proust 2005) and is written as following:

$$\text{MC: } St_i \equiv St_{mc} = \frac{\psi\left(U_{mc} - U_{fp}\right)^2 h_{int}}{gA_{mc}} \text{ \& FP: } St_i \equiv St_{fp} = \frac{-\psi\left(U_{mc} - U_{fp}\right)^2 h_{int}}{gA_{fp}} \tag{3}$$

'$\psi$' is a mixing length determined under uniform conditions; its value, calibrated in the LMFA flume (Proust, 2005), equals 0.02. Finally, in absence of bed shear stress measurements, friction term is modeled using Manning's formula (see Manning's friction coefficient values in Table 2).

## 3 - EXPERIMENTAL RESULTS

### *3.1 - Flow description*




(a) (b)

(c) (d)

**Figure 3. (a) Longitudinal water surface profiles for the six flow cases (b-c) Streamwise evolution of depth-averaged velocities (b) in the converging part of the flow, (c) in the diverging part of the flow. (d) Longitudinal distribution of floodplain discharge (normalized by the total discharge).**

The longitudinal free surface profiles measured for the six experiments are plotted in Figure 3a. As expected, compared to uniform water depths, non-uniform flow depth remains equivalent or increases upstream the groyne section and decreases in the downstream part including stations within [2.5 m < $x$ < 3 to 3.5 m]. The upper limit $x$ = 3 to 3.5 m corresponds to the 'throat' generated by the flow contraction. Thus considering the part within the interval [0 m < $x$ < 3 to 3.5 m], the free surface level is decreasing and an acceleration in depth averaged velocity is observed (Fig. 3b). This behaviour is similar to the one observed in a flume with a converging floodplain. The recirculation acts like a wall and strongly reduces the width of the floodplain (Fig. 2). Consequently the water depth decreases and the depth averaged velocity increases. As soon as the 'throat' is passed, the free surface level increases and velocities progressively decrease (Fig. 3c). At the end of the flume, the water levels reach the level of their corresponding uniform flow while velocities still go slowly to uniform distribution (Fig. 3c). Notice that the spanwise free surface were measured too;

except in the groyne cross-section, in which the absolute level differences can reach 7 mm (*Hr* = 0.4 & *d/Bfp* = 0.375), evel differences are smaller than 1 mm between the main channel and the floodplain.

At a given relative depth, the free surface slope increases with the growth of $d/B_{fp}$ upstream the groyne, while they remain similar from the obstacle cross-section to the throat. Downstream the throat free surface slightly decreases at *Hr* = 0.2 and there is no relevant differences between groyne lengths. On the other hand, at *Hr* = 0.4, flows seems to be forced to reach the downstream boundary and this effect grows with the groyne length.

Finally, considering a groyne length, an increase in relative depth increases the effects of the groyne (Fig. 3a). Absolute differences in free surface slope increases with the relative depth. The same remarks apply to depth averaged velocity distributions.

### *3.2 - Discharge distribution*

Using the water depth and the depth-averaged velocities existing out of the recirculation (Fig. 2), discharge distributions in the floodplain (Fig. 3d) and in the main channel are worked out. Regarding Figure 3a and 3d, the decrease in discharge in the floodplain coincides with the decrease in free surface slope. The flow contraction in the floodplain creates mass transfers from the floodplain toward the main channel. Then, as soon as the throat is reached, a diverging effect appears and discharge (/mass) is redistributed between the main channel and the floodplain. At *Hr* = 0.2, this effect appears after $x$ = 3 m, and after station $x$ = 3.5 m at *Hr* = 0.4. Afterward, the discharge distribution progressively seems to go to the uniform distribution, but cannot exactly reach them at the end of the flume. Considering the groyne length and the relative depth, tendencies are clear:

- at a fixed relative depth (*Hr*), the more the ratio $d/B_{fp}$ increases, the more significant the mass exchanges are.
- at a given ratio $d/B_{fp}$, the higher the relative depth (*Hr*) is, the bigger mass exchanges are.
- the more the relative depth (*Hr*) and the ratio $d/B_{fp}$ increase, the more significant the mass exchanges are.

## 4- DISCUSSION: MOMENTUM ANALYSIS

Impacts of mass exchanges on momentum balance are finally examined. Momentum transfers due to mass exchanges are worked out using the last term of the one dimensional momentum equation (Eq. 2), while the momentum exchanges due to turbulence are modeled using the mixing length model (Eq. 3). Frictions are modeled using Manning's formula. In Figure 4, values are normalized by the bed slope 'So', which is the main contributor to the motion of the flow. This normalization enables the quantification of additional contributions of each phenomenon; the bed friction is always opposed to the motion while both momentum transfers either resist or contribute to the motion depending on the position in the flow. Regarding momentum transfers due to turbulence (Fig. 4, white bars), the latter are generally 20 % equal to the bed slope and they are several orders smaller than the other stresses; this, in each experiment, whatever the channel or the position (converging or diverging part) in the flume. Consequently, momentum transfers due to turbulence at the interface can be neglected in momentum balances.

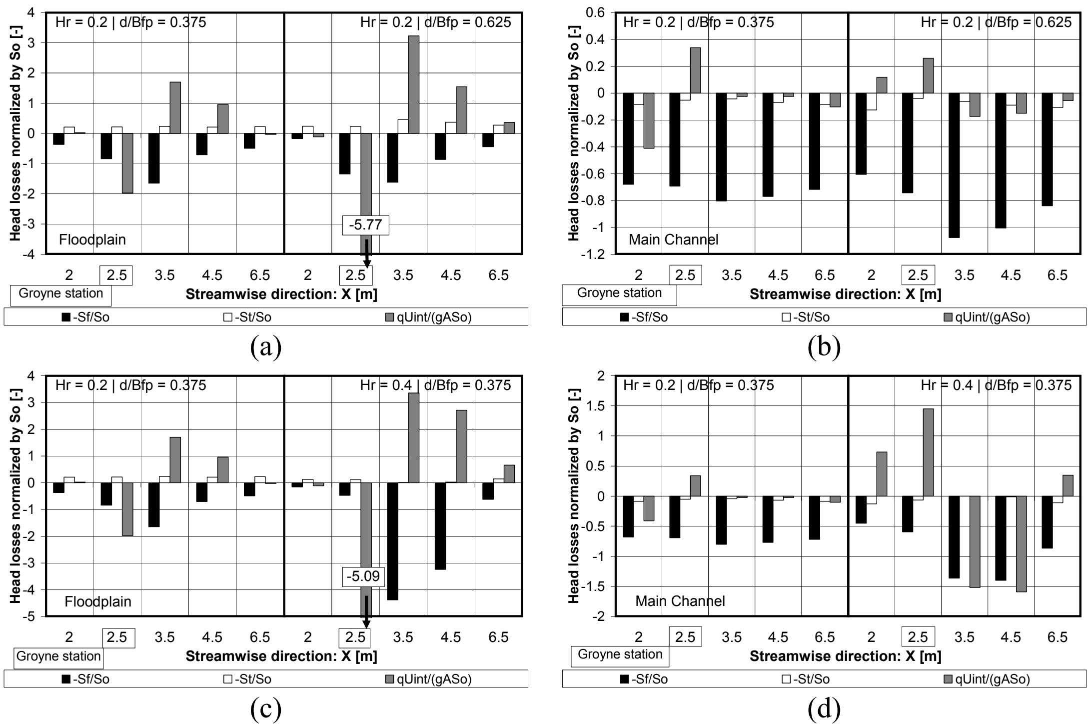



**Figure 4. Friction slope (Sf), Head loss due to turbulent shear stress at the interface (*St*) and momentum transfer due to mass exchanges (*qUint/(gASo)*) normalized by the bed slope *So*. (a-b) Comparisons at fixed $H_r$ = 0.2 and variable $d/B_{fp}$ [0.375, 0.625] (c-d) Comparisons at fixed $d/B_{fp}$ = 0.375 and variable $H_r$ [0.2, 0.4] (c)**

In the floodplain, in the converging part of the flume ($x$ < 3 to 3.5 m), momentum transfers are negative. The mass decrease generates a decrease in momentum due to mass exchanges (Fig. 4, gray bars). (1) At a fixed relative depth (*Hr*): *qUint/(gASo)* increases with the length of the groyne. (2) At a fixed $d/B_{fp}$: the higher the relative depth is and the higher the momentum transfers due to mass exchanges (*qUint/(gASo)*) are. Mass and momentum, as expected, are correlated. These momentum transfers can be four or five time higher than the bed slope and consequently cannot be neglected. Once the throat is passed (downstream $x$ = 3.5 m), as the mass comes back into the floodplain, the momentum transfers are positive. Their magnitude is still large, but smaller than one observed in the previous part of the flume. Notice that in the recirculation cross-section, the friction slope magnitude is similar to the momentum one and consequently bigger than the bed slope. The mass decrease in the floodplain creates an increase in the main channel. Momentum magnitudes are however smaller than the floodplain ones and are smaller (Fig. 4b) or equivalent (Fig. 4d) to the friction slope magnitude in the main channel. Notice that they are of the same order as the bed slope.

## CONCLUSION

To conclude, experiments were carried out in a two stage channel with an obstacle partially blocking off the floodplain. Consequently, strong mass exchanges were generated between the main channel and the floodplain. In such a configuration, flow acts like in a Venturi flume. In the floodplain, upstream of the obstacle, the flow is contracted and a recirculation develops in the lee of the groyne cross-section; mass is exchanged towards the main channel and momentum transfers due to mass exchanges are negative. As soon as the 'throat' in the flow is passed, downstream the obstacle, transfer direction is opposed; mass goes back into the main channel and momentum transfers become positive. The longer the groyne is, the higher the relative depth is and the larger the mass exchanges and the momentum transfer magnitudes are. In the main channel, the momentum transfer signs are opposite and the momentum transfer magnitudes (due to mass exchanges) are smaller than the floodplain ones. Considering the turbulence at the interface, in the main channel like in the floodplain, the latter can be neglected in front of the momentum transfers due to mass. Finally, the modelled friction slope magnitude is equivalent to the magnitude of the momentum transfers due to mass in the floodplain and is larger than the one in the main channel. For future research, turbulence and bed shear stress measurements will be carried out to assess the validity of their modelling.

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