BOUNDARY SHEAR STRESS MEASUREMENTS BELOW FREE-SURFACE STANDING WAVES : APPLICATION TO BED FORM PROCESSES

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ABSTRACT

Waters flowing in natural streams and rivers have the ability to scour and to deposit materials, hence to change the bed topography. It is recognised that undular flows have great potential for sediment dispersion. In the present study, a fixed-bed model was used to investigate the spatial variations of boundary shear stress under standing waves (i.e. undular flow). The results (Fig. 5) highlight the three-dimensionality of the boundary shear stress distributions. Maximum boundary shear stress are observed under the wave crests and minimum shear stress under the wave troughs. The experimental findings suggest the formation of three-dimensional standing waves bed forms below undular flows. Overall the study emphasises the existence of large boundary shear stress variations below free-surface undulations.

Keywords : boundary shear stress, undular flow, standing wave, sediment transport, bed form, bed form formation.

INTRODUCTION

Waters flowing in natural streams and rivers have the ability to scour channel beds, to carry sediments and to deposit materials, hence changing the bed topography. This phenomenon is of great economical importance but yet not well understood, in particular the transport of sediment with standing wave flows. It is recognised that undular flows have great potential for sediment dispersion : e.g., HOUK (1934) observed standing wave heights (from crest to trough) in excess of 4.5 m in Denver and he noted : "the jump [...] presented [a] repulsive appearance [..] because of the presence of about 10 per cent. of black silt in the flow".

TISON (1949), SIMONS et al. (1961) and KENNEDY (1963) investigated experimentally the formation of standing wave bed forms associated with free-surface undulations, in mobile-bed laboratory flumes. Recent publications (e.g. GRANT 1997, TINKLER 1997) attempted to relate the appearance of standing waves with the flow properties. But experimental observations demonstrate that free-surface undulations may occur in numerous circumstances for which the flow is NOT critical (i.e. $Fr \neq 1$) and that the standing waves may take place for $0.3 \le Fr \le 3$ (CHANSON 1995,1996).

In the specific energy/flow depth diagram, a very-small change of energy (e.g. caused by a bottom or sidewall irregularity) can induce a very-large change of flow depth. The 'unstable' nature of the flow is favourable to the development of large free-surface undulations or standing waves (e.g. IMAI and NAKAGAWA 1992, CHANSON and MONTES 1995, MONTES and CHANSON 1998). In the present study, a fixed-bed model was used to investigate the spatial variations of boundary shear stress under standing waves (i.e. undular jump). The results are then applied to gain a better understanding of the formation of standing wave bed forms.

EXPERIMENTAL INVESTIGATION

EXPERIMENTAL APPARATUS

A 20-m long fixed-bed channel (0.25-m wide, rectangular) was used to investigate the boundary shear stress in undular jump flows. The water discharge is measured with a V-notch weir. The longitudinal flow depths are measured using a rail mounted pointer gauge. Pressure, velocity and bed shear stress distributions are recorded with a Prandtl-Pitot tube (3.3-mm external diameter). The translation of the gauge and Pitot tube, in the direction normal to the channel bottom, is controlled by a fine adjustment travelling mechanism (error less than 0.1 mm).

For each experiment (Table 1), the start of the standing waves was located at least 10-metres downstream of the channel intake. The upstream supercritical flow was uniform equilibrium (i.e. normal flow conditions). Pressure and velocity measurements were recorded at characteristic positions : upstream of the jump (U/S), at the start of the shock wave (SW), at the 1st wave crest (1C), 1st wave trough (1B), 2nd wave crest (2C)

CALIBRATION OF THE PITOT TUBE

The boundary shear stress distributions were measured with the Prandtl-Pitot tube used as a Preston tube for four flow conditions (Table 1). The Pitot tube was calibrated in-situ in uniform equilibrium flows. The calibration curve was best fitted by :

$$t_0 = 3.43 V_b^{1.65} \qquad (1)$$

where t_0 is the boundary shear stress and V_b is the velocity measured by the Pitot tube lying on the boundary. Equation (1) is similar to the calibration curves obtained by PRESTON (1954) and PATEL (1965), and MACINTOSH (1990) who used the same experimental channel.

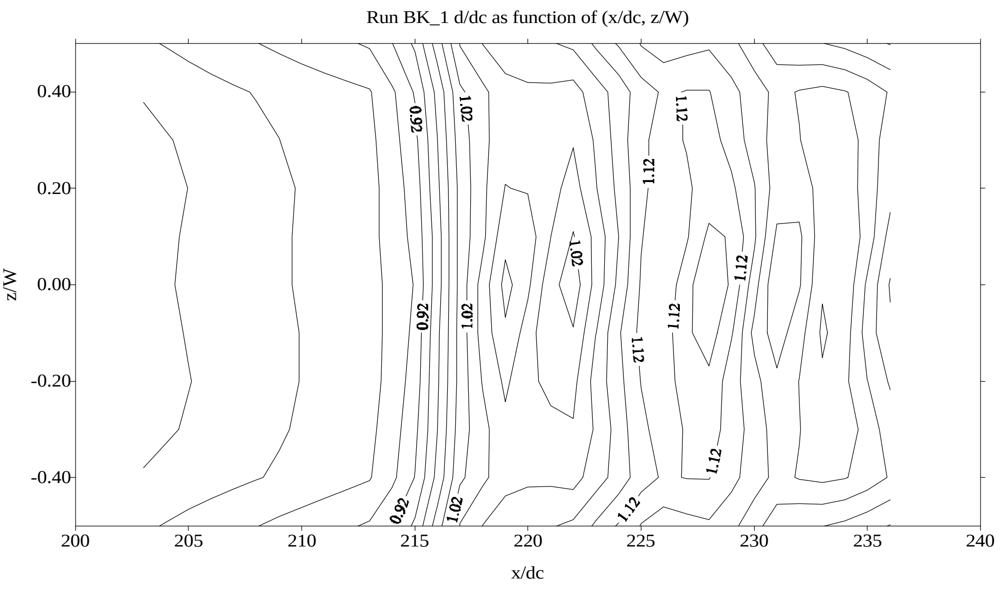


Figure 1 - Dimensionless free-surface profile $\{x/d_c, z/W, d/d_c\}$ (Run BK_1)

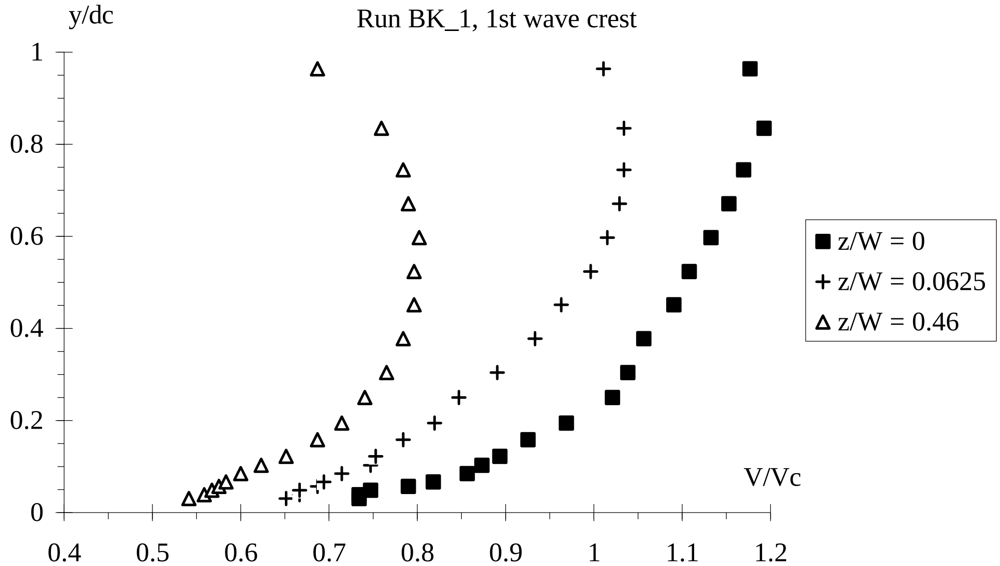
EXPERIMENTAL RESULTS

A typical free-surface contour is presented in Figure 1. The data illustrate the undular nature of the flow, and the three-dimensional free-surface profile. Maximum wave amplitude are recorded on the channel centreline (CHANSON and MONTES 1995, CHANSON 1995).

Figure 2 shows velocity distributions at crest and trough. Basically the fluid is decelerated at each wave crest and accelerated at the wave trough (e.g. MONTES and CHANSON 1998). The effect is more pronounced next to the sidewall and next to the bed.

Bed-shear stress measurements are presented in Figures 3, 4 and 5. Figure 3 shows cross-wise distributions of boundary shear stress where Z is the cross-wise coordinate {Z = 0 on centreline, Z/W = 0.5 at corner, Z/W > 0 upward coordinate along the wall}, τ_o is the boundary shear stress, ρ is the water density, d_c and V_c are respectively the critical depth and velocity, x is the longitudinal distance from the channel intake.

The data show consistently significant variations of the velocity and pressure distributions along the undular flow, associated with large fluctuations of boundary shear stress in the longitudinal direction x and cross-wise direction Z (Fig. 3). The bed shear is minimum at wave crests and maximum at wave troughs.



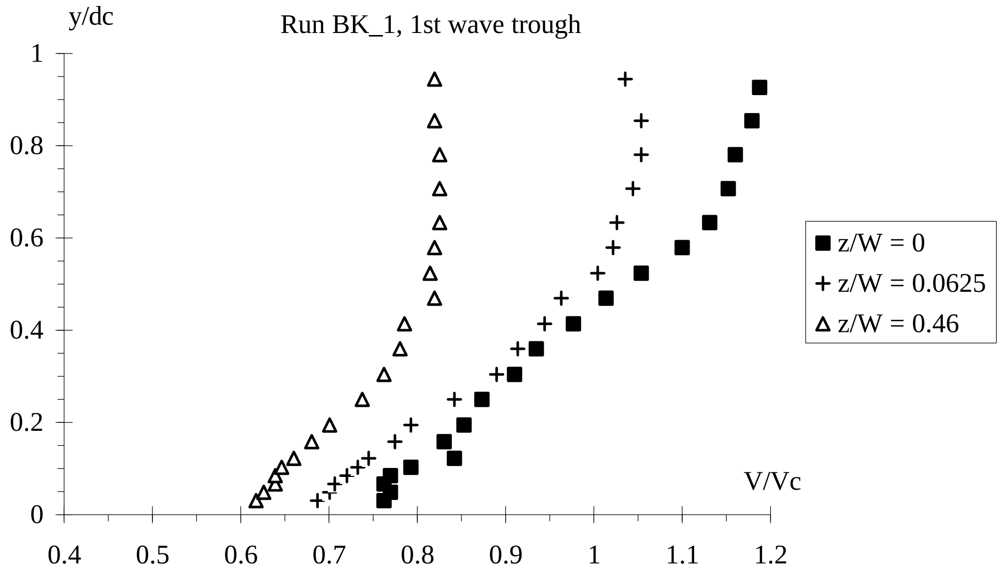


Figure 2 - Dimensionless velocity distributions V/V_c (Run BK_1)

DISCUSSION : BED SHEAR STRESS DISTRIBUTION UNDER STANDING WAVES

Below free-surface standing waves, large fluctuations of boundary shear stress are observed in the cross-wise and longitudinal directions (Fig. 3 and 4). A contour map (Fig. 5) provides an overall picture of the bed and sidewall boundary shear stress distributions. The location of the wave crests and troughs is indicated, as well as the corner.

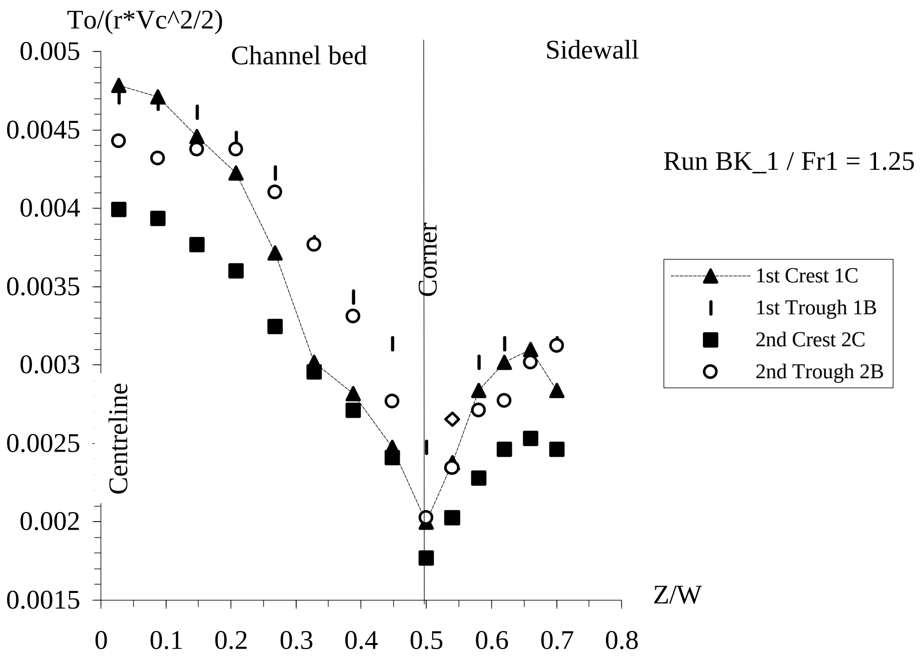


Figure 3 - Dimensionless bed-shear distributions $\tau_o/(0.5*\rho*V_c^2)$ (Run BK_1)

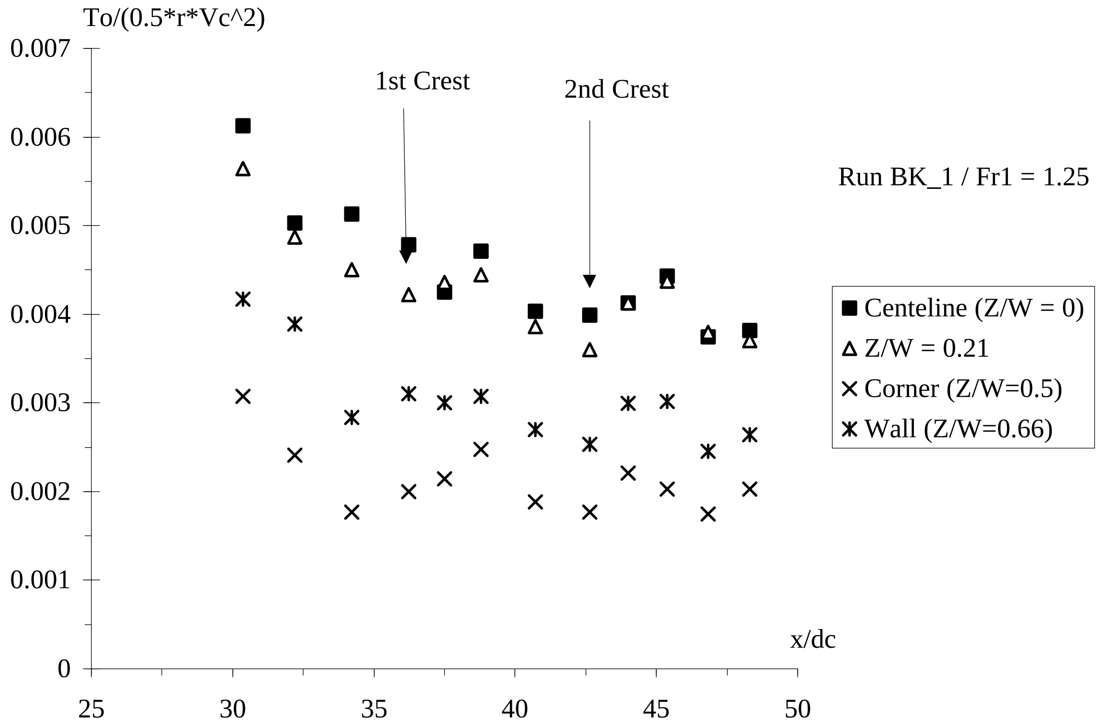


Figure 4 - Bed shear stress distributions :
longitudinal bed shear stress profile (Run BK_1)

During all the experiments, it was consistently observed that the bed shear is minimum below the wave crests and maximum underneath the wave troughs (i.e. in phase with the free-surface undulations). The findings are in agreement with the data of IMAI and NAKAGAWA (1992).

The results have direct implications to mobile-bed channels. Considering a flat movable-bed stream, an undular flow might take place during a flood event or in an estuary during a period of the tide. Below the free-surface standing waves, the movable bed becomes subjected to an non-uniform boundary shear stress distribution (Fig. 5). Erosion may take place underneath the wave troughs while accretion may occur below the wave crests. This process leads to the formation of standing waves bed forms, in phase with the free-surface standing waves.

The bed forms will have a three-dimensional shape. The boundary shear stress is consistently smaller at the sidewall than on the channel centreline, and it is minimum in the corner (Z/W = 0.5) (Fig. 5). Sediment motion will be more intense near the channel centreline than next to the banks. The three-dimensional distributions of boundary shear stress imply the formation of three-dimensional standing forms. This result is consistent with KENNEDY's (1963) observations : he noted the chaotic nature of the bed form life cycle "with a period of one to several minutes" and its "three-dimensional features".

Further undular flows may be characterised by flow separation (CHANSON and MONTES 1995, MONTES and CHANSON 1998). With the existence of recirculation region(s) and three-dimensional boundary shear stress distributions, the channel friction SHOULD not be modelled with Darcy and Strickler-Manning equations as some researchers suggested (GRANT 1997, TINKLER 1997). A complete flow modelling is required (e.g. MONTES and CHANSON 1998).

SUMMARY AND CONCLUSION

Boundary shear stress distributions were measured below undular flows in a fixed-bed channel. The results (Fig. 3, 4 and 5) highlight the three-dimensionality of the shear stress profiles. Below free-surface standing waves, maximum boundary shear stress are observed under the wave crests and minimum shear stress under the wave troughs. The bed shear stress is lower along the wall than on the centreline, and minimum in the channel corner.

The experimental findings ascertain the existence of standing waves bed forms below undular flows and they highlight the three-dimensional nature of the bed form formation.

Overall the study emphasises the existence of large boundary shear stress variations below free-surface undulations. Flow resistance in standing wave flows cannot be modelled with simplistic model (e.g. Darcy, Manning) but a detailed flow modelling is necessary.

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Reference	Run No.	q_w m^2/s	Bed slope degrees	d_1 m	Fr_1	UJ Type	d_c/W	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Smooth-wall	experim.							W = 0.25 m.
CHANSON (1993)	HMTJ1	0.020	0.254	0.0292	1.27	B	0.137	
	HMTJ2	0.020	0.487	0.0240	1.70	C	0.137	
	HMTJ5	0.020	0.754	0.0210	2.10	D	0.138	
	HMTJ6	0.020	0.993	0.0191	2.40	E	0.137	
	HMTJ3	0.040	0.248	0.0468	1.25	B	0.217	
	HMTJ7	0.040	0.353	0.0420	1.48	C	0.218	
	HMTJ4	0.040	0.477	0.0384	1.70	D	0.219	
CHANSON (1995)	TT2_2	0.060	0.283	0.0656	1.14	A-B	0.286	
	TT2_4	0.060	0.328	0.0618	1.25	B	0.286	
	TT2_1	0.060	0.401	0.0587	1.35	C	0.286	
	TT2_3	0.060	0.435	0.0558	1.45		0.286	
	WZ3_1	0.100	0.382	0.0840	1.31	D	0.403	
Present study	BK_1	0.040	0.210	0.047	1.25	B	0.219	W = 0.25 m.
	BK_2	0.040	0.304	0.042	1.48	C	0.219	
	AW_1	0.100	0.430	0.0771	1.48	C	0.403	
	AW_2	0.100	0.319	0.0861	1.252	B	0.403	
Rough-sidewall	experim.							W = 0.248 m.
CHANSON (1995)	WZ3_2	0.100	0.386	0.0860	1.27	D (?)	0.406	

Table 1 - Experimental flow conditions : pressure, velocity and bed shear stress measurements at undular hydraulic jumps

Notes :
UJ typetype of undular hydraulic jump as defined by CHANSON and MONTES (1995)

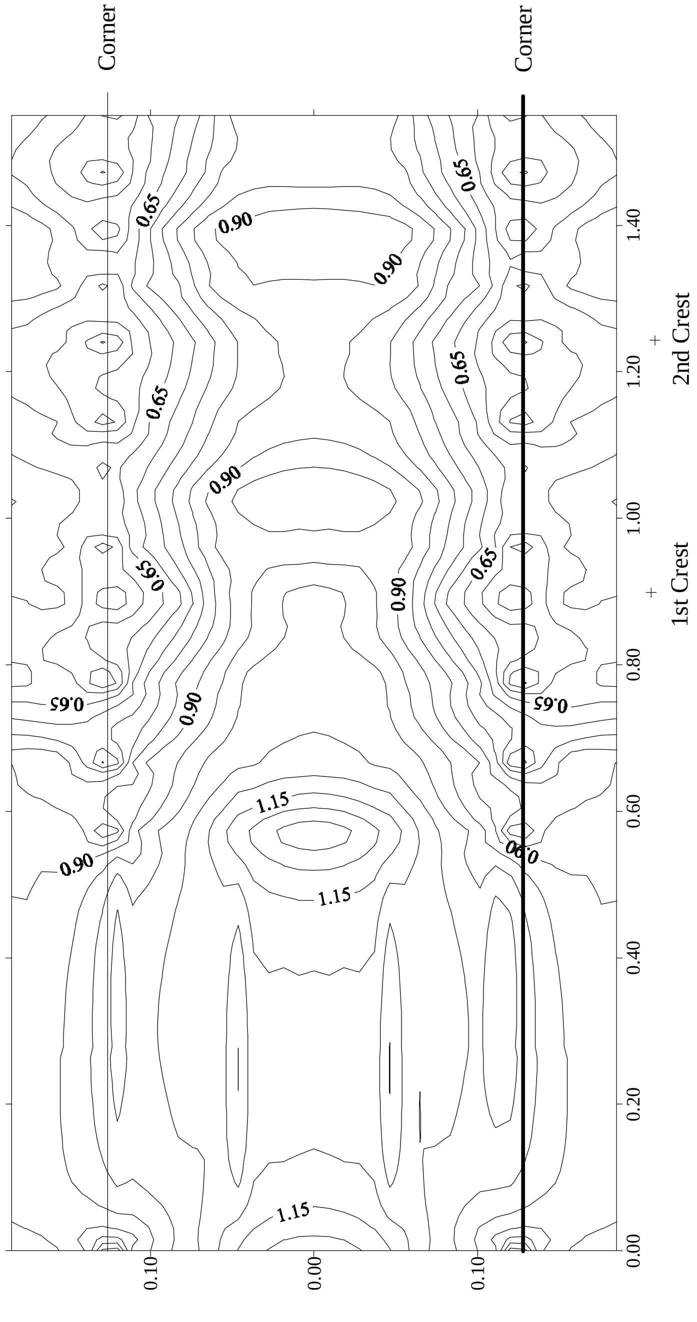

Figure 5 - Bed shear stress contour map {x (m), Z (m), τo (Pa)} (Run BK_1)