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The Setup and Validation of a Numerical Model for Wall Shear in Trapezoidal Open Channels

K. ANSARI, N.A.MEMON, A.A. MEMON

Department of Civil Engineering, Mehran University of Engineering and Technology, Jamshoro.

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Abstract: The validation of a numerical model is done using Computational Fluid Dynamics (CFD) commercial software ANSYS CFX. Six trapezoidal channels which were used by Tominaga et al. (1989) in their experimental studies are modelled. Special emphasis is done on the distribution of shear stress and secondary currents. The channels have the sidewall inclinations of 30^o, 46^o and 58^o to the vertical. The bottom width of the trapezoidal channels is kept constant for each slant angle and only the depth is varied to get different aspect ratios. The roughness on the boundaries is also varied. The results are compared with the published results found in the literature. The results are quiet encouraging and the model may therefore be used with confidence for other similar studies.

Keywords: Validation, Open Channels, CFD Modelling, Boundary Shear Stress, Secondary Currents.

1. INTRODUCTION

The validation of a numerical model is very important for the confirmation of the results thus produced. The boundary shear stress is one of the most important parameters in open channel flow but at the same time also one of the most difficult to analyze from a purely theoretical point of view (Knight, 1981). The pattern and the number of secondary flow cells as well as the channel cross-sectional shape influence the lateral distribution of the boundary shear stress (Mohammadi and Knight, 2004).

Turbulent structures and the boundary shear stress in steady and uniform flows have been studied by many researchers such as (Tracy 1965, Knight Patel 1985 and Yang 2002). Some empirical equations for the boundary shear on the bed and walls have been proposed by many such as (Knight, 1981, Zheng, Jin 1998, Guo and Julien 2005). A lot of work has also been done on the distribution of shear in smooth rectangular ducts such as Rhodes and Knight (1994), (Jin *et al.,* 2004). (Mohammadi and Knight 2004) also worked on the distribution of shear stress in a V-shaped channel whereas (Knight and Sterling 2000) have worked on the boundary shear in partially full pipes. Unfortunately, little work has been done on the distribution of boundary shear in trapezoidal channel sections thus far, except for some contributions by (Flintham and Carling 1988), (Tominaga *et al.,* 1989 and Yuen 1989). This despite the fact that trapezoidal channels are the most commonly used manmade irrigation and drainage channels. Also almost negligible work has been done using the numerical models. The aim of the present study is to validate a CFD numerical model so that these models may further be used in future studies with confidence.

This study is conducted on a set of simulations of six trapezoidal channels, replicating the ones used by (Tominaga *et al.,* 1989) in their experimental work. The experimental conditions and the channel dimensions of the (Tominaga *et al.,* 1989) channels are given in the **Ошибка! Источник ссылки не найден.**. The channels have sidewall inclinations of 30^o, 46^o and 58^o to the vertical. The bottom width of the trapezoidal channels is constant for each slant angle and only the depth is varied to get different aspect ratios. The aspect ratios varied from 2.13 to 5.95.

2. Numerical modelling

The commercially available CFD software ANSYS-CFX version 11 (2008) was used.

2.1 Boundary conditions and coordinate system

A consistent frame of reference for the coordinate axes is taken with the x-axis corresponding to the stream-wise direction, the y-axis to the cross stream direction and the z-axis to the vertical direction. The three components of velocity u, v, and w are aligned with the axes x-, y- and z-axes respectively. The origin is placed at the left most part of the channels and coincides with the base of the channel and the water is taken to be flowing in the positive x-direction. Both the walls (bed and side) were taken as non-slip smooth walls. The free surface was modelled using a symmetry boundary condition. All the simulations were solved as single phase, steady state problems with water used as the fluid. Periodic boundary conditions were used on the up- and downstream faces of the single cell thick section, hence a momentum source in the stream-wise equal to ρgS, where ρ is the density of water (997 kg/m^3), g is the acceleration due to gravity (9.81 m/s)

++Corresponding author: K. ANSARI

a consequence of using periodic boundary conditions a cycle was created which drives the flow of water until it reaches a steady state condition.

3. MATERIAL AND METHODS

CFD Model Setup

The experimental conditions and the channel dimensions of the (Tominaga *et al.*, 1989) channels are given in the **(Ошибка! Источник ссылки не найден.)**. The channels have sidewall inclinations of 30^o, 46^o and 58^o to the vertical. The bottom width of the trapezoidal channels is constant for each slant angle and only the depth is varied to get different aspect ratios. The aspect ratios varied from 2.13 to 5.95.

Table 1 Experimental conditions for trapezoidal channels (Tominaga *et al.*, 1989).

Channel	Flow depth h (cm)	Bottom width b (cm)	Surface width T (cm)	Aspect ratio b/h	Sidewall Angle Θ (degrees)	Energy gradient S (x10^{-3})
T12	06.36	24.80	32.20	3.90	30	0.670
T13	11.00	24.80	37.50	2.25	30	0.389
T01	03.36	20.00	27.00	5.95	46	1.381
T02	05.01	20.00	30.40	3.99	46	1.000
T03	09.05	20.00	38.90	2.21	46	0.594
T23	07.12	15.20	39.80	2.13	58	0.594

The flow characteristics as given by (Tominaga *et al.*, 1989) are given in **(Ошибка! Источник ссылки не найден.).** The discharge, mean velocity, maximum velocity, Reynolds number, and Froude number for each flow condition are given. All the channels operate under turbulent flow conditions as the Reynolds number, Re, vary from 35,900 to 87,600. The flow in each channel was also found to be sub-critical as the Froude number, Fr, varied between 0.32 and 0.61.

Table 2 Flow characteristics for trapezoidal channels (Tominaga *et al.*, 1989).

Channel	Discharge Q (l/s)	Mean velocity U_m (cm/s)	Max. velocity U_{max} (cm/s)	Reynolds number Re (x10^4)	Froude number Fr
T12	06.33	34.90	45.16	5.74	0.47
T13	10.55	30.09	39.36	6.48	0.32
T01	02.72	35.21	42.72	3.59	0.61
T02	04.59	36.92	44.36	5.59	0.53
T03	09.95	37.33	45.36	8.76	0.40
T23	06.22	32.98	38.01	5.34	0.47

using a source term commensurate with channel energy gradient, by keeping the bed and the sidewalls smooth during the simulations and the mass flow rate was compared with that in the experimental data. It was however found that the CFD results were showing a flow rate larger than the one observed during the experiments. Consequently, a uniform roughness height k_s was initially introduced on the bed and sidewalls and the mass flow rate was hence adjusted to match the experimental discharge. **(Ошибка! Источник ссылки не найден.)** shows the final roughness height that achieved the same flow rate and the comparative flow rates for experimental and CFD simulations. The difference in the experimental and observed discharges is less than 0.37% for all the cases.

Channel	Roughness height k_s (mm)	Discharge Experimental Q (lit/s)	Discharge (CFD) Q (lit/s)	Difference [a] (%)
T12	0.08	06.33	06.33	0.00
T13	0.37	10.55	10.55	0.00
T01	0.20	02.72	02.71	0.37
T02	0.15	04.59	04.59	0.00
T03	0.13	09.95	09.94	0.10
T23	0.17	06.22	06.22	0.00

Table 3 Roughness height k_s introduced for each channel and the comparison of discharge, [a]difference in discharge of experimental and CFD results in percentage.

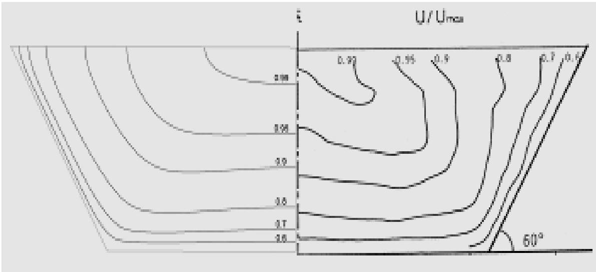
The difference between roughness height of bed and walls plays an important part on the shear stress distribution on the wetted perimeter (Flintham and Carling, 1988). It is measured through k_{sb}/k_{sw} ratio which is a dimensionless roughness parameter expressed in terms of Nikuradse's equivalent sand roughness height. The results with both types of simulations i.e. with uniform roughness on the bed and sidewalls and different roughness on the bed and sidewalls are compared with the results given by (Tominaga *et al.*, 1989) for validation of the CFD model.

4. RESULTS

The validation of the CFD model is done by comparing the CFD predictions first with the results given by (Tominaga *et al.*, (1989) and then with some other results found in the literature and is discussed below.

a. Isovel pattern analysis

First of all, isovel patterns for the three cases T13, T03 and T23 are plotted and the graphs are compared with those given by (Tominaga *et al.*, 1989). **(**



normalized by U_{max}.

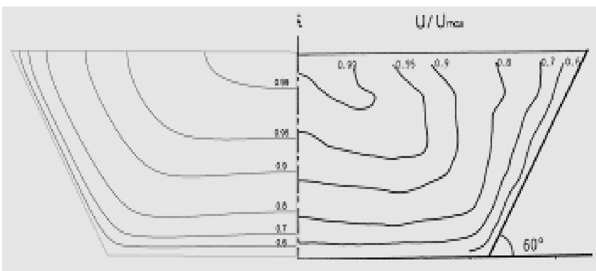


Fig. 1 Comparison of the isovel patterns between CFD predictions (left) and (Tominaga *et al.*, 1989) (right) for T13.

The comparisons of the graphs show good agreement between the CFD predictions and the experimental results. However, a shift of the velocity is seen near the free surface especially as the sidewalls are opened and the velocity dip as observed in the experimental results is not seen. This is most probably due to the free surface boundary condition, a symmetry plane here, which does not account for free surface effects on turbulence.

b. Secondary currents analysis

The secondary current vectors for the three cases T13, T03 and T23 were plotted with the help of CFD-Post and the graphs were compared with those given by (Tominaga *et al.*, 1989) as shown in **(**

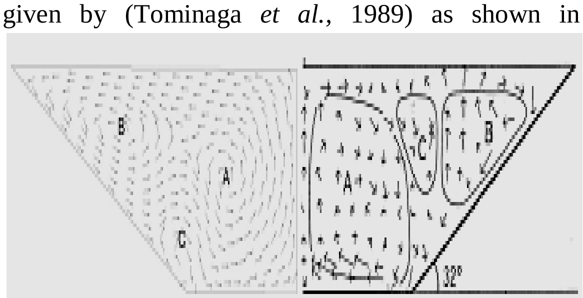


Fig. 2). The vectors have been normalized to show the direction only and not the magnitudes just to see the longitudinal vortices developed due to these secondary currents.

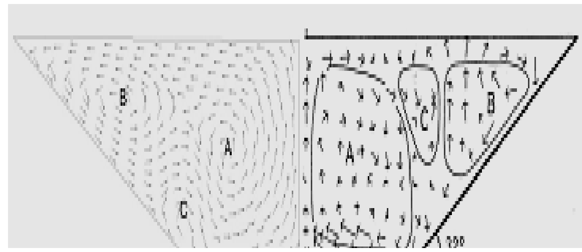


Fig. 2 Comparison of the secondary current vectors between CFD predictions (left) and Tominaga *et al.* (1989) (right) for T23.

It was observed that the three vortices of secondary currents as seen by Tominaga et al. for trapezoidal channels were also visible but a shift towards the corner is seen in the case of Vortex C. This vortex as described by (Tominaga *et al.*, 1989) corresponds to the free surface vortex and the shift is most probably due to the same reason of capping of the free surface with the symmetry boundary condition.

c. Distribution of boundary shear

The distribution of the boundary shear on the bed and sidewalls is plotted next. The results are compared with the experimental ones given by (Tominaga *et al.*, 1989) and shown in **(**

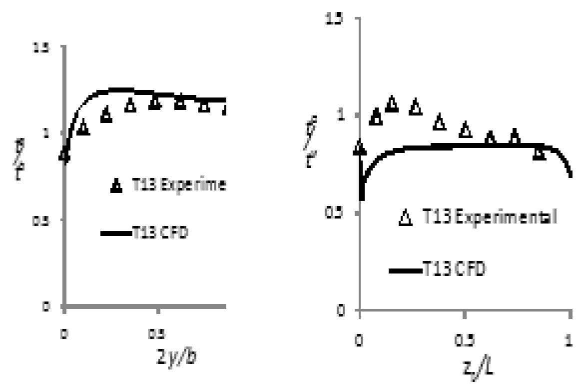


Fig. 3). The shear on the bed is plotted for the half width of the channel section due to symmetry along the centre line of the channel, whereas, on the sidewalls it is plotted along the whole length. The distance along the bed and sidewall has been non- dimensionalized by dividing with half width of the channel and length of the sidewall respectively. Zero is the corner of the bed and sidewall and one for bed is the centre of the channel, whereas for sidewall it is the free surface.

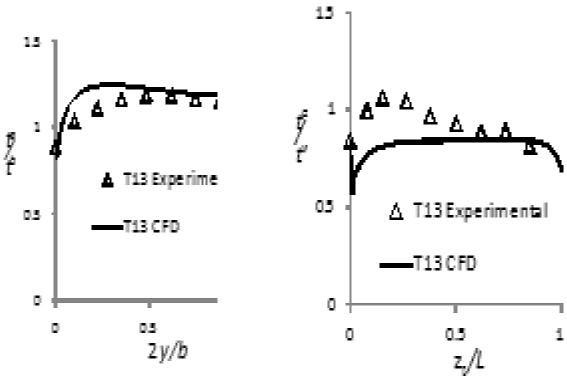


Fig. 3 Comparisons of local non-dimensionalized wall shear on bed (τ_b/τ_o) and sidewalls (τ_w/τ_o) between CFD predictions and (Tominaga *et al.*, 1989).

For the bed shear stress it was observed that the distribution is seen a bit flattened especially at the centre of the channel as compared to experimental observed values and might be due to the difference of circulation pattern of secondary currents which the CFD simulations have not been able to fully reproduce. The difference in the distribution of sidewall shear stress is more noticeable. The variations of shear stress seen in the experiments especially at the corner joining the bed and sidewall and near the free surface are not found in the CFD simulations. Weaker or ill-positioned secondary cells are the obvious culprits here. At the free surface, the use of a symmetry plane is clearly not sufficient it would appear.

5. CONCLUSIONS

The comparisons of the CFD results with the experimental results of (Tominaga *et al.,* 1989) show good agreement and hence show that the CFD model is working well. Hence it may be concluded that CFD models may be used for the analysis of the shear force distribution on the wetted periphery of the open channels.

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