Applicabilité des Equations de Distribution de Vitesses dans les Ecoulements en Canal Ouvert à fond rugueux

Applicability of Velocity Distribution Equations in Rough-Bed Open-Channel Flow

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On cherche ici à valider l'utilisation de profils de vitesses en canal ouvert à fond rugueux, formules logarithmiques ou fondées sur un principe d'entropie maximale. Pour atteindre cet objectif, 24 expériences de laboratoire, avec plus de 1200 points de mesures, ont été réalisées. Le nombre de Reynolds varie de 3.4 10^4 a 1.7 10^5, et le rapport entre largeur (B) et profondeur (H) de 4.2 a 12.0. Les équations ne représentent pas bien la distribution de vitesse près du lit rugueux, ni près de la surface libre lorsque la vitesse maximale ne se trouve pas atteinte en surface (dip effect). Parmi les équations logarithmiques, la formulation de Coles se montre la meilleure en toutes régions d'écoulement. L'équation de l'entropie de Chiu présente de bons résultats, quoique s'écartant des résultats expérimentaux près du lit. Si le paramètre M est calculé par l'expression proposée ici, l'équation de Chiu devient meilleure en toutes circonstances. Les données expérimentales ont permis de formuler des expressions empiriques associant la rugosité au coefficient de résistance de Darcy-Weisbach et au nombre de Froude. Des investigations permettent de conclure ce qui suit. (1) En écoulement rugueux, la décroissance de la vitesse au voisinage de la surface de l'eau (dip effect) est toujours observée quand le rapport d'aspect B/H est inférieur à 5 ; il est observé seulement près du mur latéral quand 10 < B/H < 5 ; il n'est pas observé quand B/H > 10. (2) Pour les trois équations logarithmiques étudiées, l'équation de Coles est la meilleur (erreur 6.8 %) et la distribution de vitesse est suffisament précise, sauf près du lit rugueux. (3) Si l'équation basée sur le principe d'entropie maximale de Chiu est utilisée avec le paramètre M calculé par l'expression traditionnelle, il y a des divergences considérables près du lit (erreur 9.9 %). Néanmoins, si on utilise la nouvelle expression proposée ici pour calculer M, l'équation de l'entropie présente une performance plus précise (erreur 4.0 %). (4) Les expériences menées dans le cadre de cette recherche ont montré que l'équation de Chiu et Tung, pour évaluer la localisation de la vitesse maximale, a produit des résultats relativement précis : la position relative calculée (h/H = 0.17) est proche de la position mesurée (h/H = 0.21).

I ■ INTRODUCTION

The distribution of flow velocity is one of the basic properties of an open channel flow. It is directly related to other flow properties, such as the shear stress distribution, secondary flow, as well as sediment and contaminant transport. Because of the practical importance of the problem, a number of analytical [Sill, 1982 ; Willis, 1985] and experimental [Rajaratnam and Muralidhar, 1969 ; Kirkgoz, 1989 ; Ferro and Baiamonte, 1994 ; Araujo and Chaudhry, 1996 ; Kirkgoz and Ardiclioglu, 1997] investigations have sought to determine velocities distributions on both smooth and rough surfaces open channel flow. In nature, the solid boundary of open-channel flows is usually rough.

The pioneering works of von Karman [1930] and Prandtl [1932] originally gave expressions depicting the velocity distributions in circular pipes and over flat plates. In those studies, a linear velocity distribution was found to prevail in the laminar sub-layer close to the solid boundary in which the viscous forces were dominant whereas, away from the boundary where the turbulent effect prevails, the velocity distributions were observed to obey such laws as the velocity defect law or the law of the wall. Coles [1956] extended the law of the wall by introducing a purely empirical correction function, which can be used to predict velocities in the fully turbulent part of inner region as well as in outer region.

The velocity distribution has also been investigated using probabilistic approaches. Chiu and Chiou [1986] have developed a two dimensional mathematical model of flow in open channels which does not require velocity data. They asserted that the model has answered some of the major questions that existed in open channel hydraulics. Using the probabilistic formulation, the mean velocity can be expressed as a linear function of the maximum velocity through a dimensionless entropy parameter M. The M value is a fundamental measure of information about the characteristics of the channel section and it can be derived from the pairs of maximum and mean velocities measured at channel section [Chiu, 1988 ; 1989 ; 1991].

II ■ REVIEW OF VELOCITY DISTRIBUTION EQUATIONS

● II.1 Logarithmic distribution equations

The grading, shape, and spacing of the surface's roughness elements affect the velocity distribution in rough-surface open-channel flow. In case of rough bed and turbulent flow the vertical Reynolds-averaged velocity profile is often assumed to be logarithmic. For uniform and steady nonuniform open channel flows, the velocity distribution in the inner region, assumed to be limited to z/H < 0.20, can be expressed by the log law.

$$\frac{u}{u_*} = \frac{1}{k}\ln\left(\frac{z}{k_s}\right) + B_c \quad (1)$$

in which u is the velocity in the longitudinal direction ; k =0.40 is the von Karman's constant ; u_* is the friction velocity ; z is the distance from the bed ; k_s is the equivalent sand roughness ; B_c is a constant of integration, being $B_c = 8.5 \pm 15\ \%$ [Song and Graf, 1996]. Coles [1956] proposed a wake function to describe the velocity distribution in the outer part of the flow so that the complete profile becomes :

$$\frac{u}{u_*} = \frac{1}{k}\ln\left(\frac{z}{k_s}\right) + B_c + \frac{2\Pi}{k}\sin^2\left(\frac{\pi z}{2z_{max}}\right) \quad (2)$$

in which the constants k and B_c can be determined by using the data measured in the region $z < 0.15\ z_{max}$ (z_{max} is the position of maximum velocity u_{max}). The wake coefficient Π is calibrated with the data in the outer flow. In open channel flows Π cannot be directly calculated if u_{max} is unknown. Nezu and Rodi [1986], Kirkgoz [1989] and Kironoto and Graf [1994] obtained values of Π from experiments. Cardoso and Graf [1989] considered the wake coefficient not a universal parameter but dependent on secondary currents, flow history and inactive turbulence components. According to Kirkgoz [1989] in the fully turbulent part of the inner region (that is, for u_*z/u between 100 and 400), Eq. (3) is applicable for rough-surface flows.

$$\frac{u}{u_*} = 2.4\ \ln\frac{u_* z}{\upsilon} - 0.8 \quad (3)$$

Eq. (3) differs from that of the smooth wall. The values of u/u_* are much lower for rough than for smooth surfaces : the limit point where the law of the wall distribution becomes applicable moves to a higher value, about $u_*z = 100$, in comparison to the smooth wall case.

● II.2 Entropy equation for velocity distribution

By probabilistic formulation and entropy maximization, Chiu [1989] derived a two-dimensional velocity distribution in the form

$$u = \frac{u_{max}}{M}\ln\left[1 + \left(e^M - 1\right)\frac{x - x_0}{x_{max} - x_0}\right] \quad (4)$$

In Eq. (4), $(x - x_0)/(x_{max} - x_0)$ represents the cumulative probability distribution function, in which x(y,z) is the curvilinear coordinate associated with the isovels ; $x_{max} = x$ at the point where u_{max} occurs ; $x_0 = x$ at the channel bed where u = 0 ; and M is the entropy parameter [Chiu, 1988]. On the vertical z-axis, where the maximum velocity u_{max} occurs, x may be expressed as a function of z [Chiu and Said, 1995].

$$x = \frac{z}{H - h}\exp\left(1 - \frac{z}{H - h}\right) \quad (5)$$

The entropy parameter M is a function of the ratio between the mean and maximum velocities u_{max}.

$$\frac{\bar{u}}{u_{max}} = \phi = \frac{e^M}{e^M - 1} - \frac{1}{M} \quad (6)$$

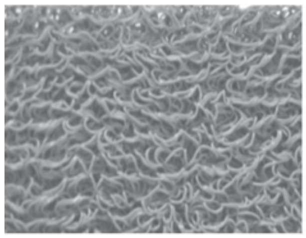
Moramarco et al. [2004] adjusted Eq. (4) to vertical profiles, generating Eq. (7), which can be applied to any vertical, given u_{max} of that specific vertical.

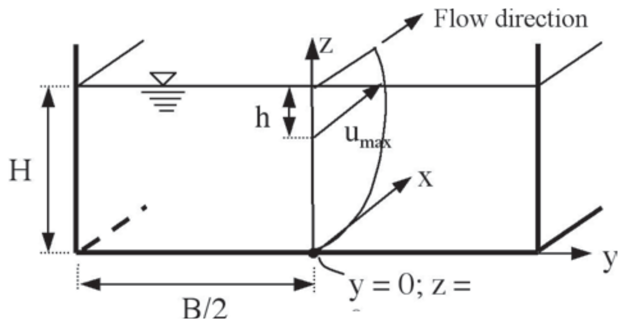
$$u_i = \frac{u_{max_i}}{M_i}\ln\left[1 + \left(e^{M_i} - 1\right)\frac{z}{H_i - h_i}\exp\left(1 - \frac{z}{H_i - h_i}\right)\right] \qquad i = 1,2,....,N_v \quad (7)$$

In Eq. (7), u_i and H_i are velocity and water depth along the ith vertical, respectively ; N_v is the number of verticals sampled in the cross-sectional flow area ; and M_i, h_i, and u_{max}, are parameters.

III ■ EXPERIMENTS

Experiments were performed in a glass-walled laboratory flume at the Hydraulics Laboratory of Erciyes University, which is 9.0m long, 0.6m wide, and 0.6m deep. All flow velocities were measured using a propeller velocity meter mounted on a tripod, which can move freely in three dimensions. Point velocity measurements were repeated three times ; each taking a period of 10 seconds, and the mean value of these three readings was taken as the point velocity. With the purpose of creating a rough surface in the open channel of the test rig, a plastic doormat, having a thickness of 10 mm, was laid firmly on and stoutly glued to the glass at the bottom of the channel. Fig. 1(a) show the rough bed material used in the experiments. The measurements were taken for 24 different uniform flows produced, and the pertinent data are summarized in Table 1. All the generated uniform flows were sub-critical and turbulent with Froude numbers ranging from 0.14 to 0.76, Reynolds numbers from $3.4\ 10^4$ to $1.7\ 10^5$ and the aspect ratios from 4.2 to 12.0. The section at which the velocity distributions were measured was consistently kept as the one 6.0 m downstream from the entrance where developed flow occurs. Point velocity measurements were taken at various points on seven verticals (y = 0, 5, 10, 15, 20, 25, 27 cm, see Fig. 1 b). Due to the symmetry, the velocity measurements were taken only on one side of the cross-section. For every vertical, measurements were taken from 7.5mm over the flume bed with 10 mm increments up to the water surface. Free surface velocity was estimated, then, by regression of the upper two measurements.





(a) **(b)**

Fig. 1 : (a) Plastic doormat for rough bed and (b) definition sketch showing notation for velocity distribution used in experiments

IV ■ RESULTS AND DISCUSSIONS

● IV.1 Maximum velocity dip

The most important feature related to secondary currents in narrow open channel is that the maximum velocity does not appear at the free surface. Nezu and Rodi [1985] defined the flow velocity dip dv as the ratio between the maximum experimental velocity u_{max} and surface velocity u_s and found that the velocity dip phenomenon appears in the range B/H < 5.0. In Fig. 2 the flow velocity dip dv is plotted versus the aspect ratio and the distance to the center of the flume. As shown in Fig. 2, for B/H > 10.0 the sidewall effect disappears for all verticals and the open channel flow can be classified as wide for rough-surface flow. When the aspect ratio 10.0 ≤ B/H ≤ 5.0, mean value of dv < 1.05 for 2y/B < 0.83. But near the sidewall (2y/B ≥ 0.83), mean dv increased to 1.11. For B/H < 5.0 dip effect was observed for all verticals and mean dv was calculated as 1.08.

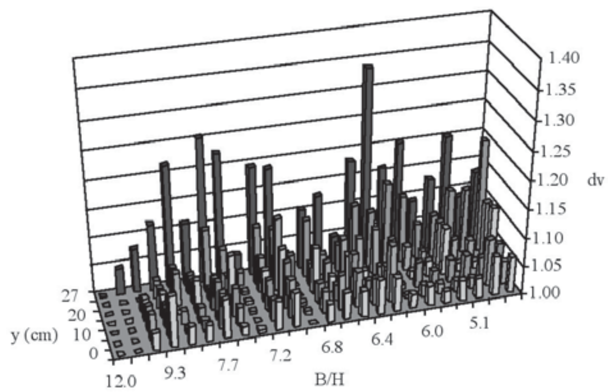


Fig. 2 : Velocity dip against aspect ratio and measured verticals (dv = u_{max}/u_s)

● IV.2 Logarithmic equations

In order to evaluate shear velocity (u_*), traditional law of the wall distribution (Eq. 3) was used. The values of u_* that gave the best fit to log law for inner region were taken. Using logarithmic distribution Eq. (3), shear velocities were calculated for all experiments. For the experiments, the inner region boundaries ranged 100-600 ≤ u_*z/υ ≤ 200-1100. The experimental values of both the lower and upper limits of the inner region (u_*z/υ) increased with increasing Reynolds number.

Using the calculated shear velocity for all verticals and Eq. (1), Nikuradse's original uniform sand roughness k_s (mm) was calculated and is given in Table 1 column (9). Eqs. (1) and (3) were also used for velocity distribution with calculated u_* and k_s.

The relative error between measured (u_{meas}) and calculated (u_{cal}) velocity was defined as $\varepsilon = |u_{meas} - u_{cal}|/u_{meas}$, which was used to assess performance of Eqs. (1), (2) and (3). Mean relative error was calculated, and is given in Table 1 for these equations in columns (11), (12) and (13) respectively. As shown in Table 1, for all flow conditions mean relative error and standard deviation were found respectively as 7.4 % and 1.6 % for Eq. (1). When Coles's equation (Eq. 2 with Π = 0.1) was used, velocity distribution showed good agreement with measured data for all flow conditions and for all regions. Eq. (2) showed the best performance among logarithmic equations, with least mean relative error (6.8 %) using Eq. (3), velocity distributions were calculated for all flow conditions. Mean relative errors were calculated as 10.7 % and standard deviation15.1 %, which is a worse performance than Eqs. (1) and (2).

Because of the superiority of Eq. (2) concerning the rough-surface experiments, it will be used hereafter to represent logarithmic equations in the plots of Fig. (3). In Fig. 3 (a)-(b) measured and calculated (Eq. 2) velocity distributions are given for two different rough-surface flow conditions. In Fig. 3 (a) R3 (B/H = 12.0), showed good agreement for all verticals, with relative mean error of 2.9 %. No dip effect was observed for the investigated verticals (dv < 1.05). In Fig. 3 (b), referred to experiment R20 (B/H = 6.0), Eq. (2) based distribution also gives good results for z/H ≥ 0.2, but diverges near the free surface, because of the dip effect observed for z/H ≥ 0.7, leading to mean relative error of 8.3 %.

When calculated k_s is dimensionless with real roughness height (k) which equall k = 10mm and plotted against Froude number, as shown in Fig. 4, a consistent relation is found (Eq. 8) with determination coefficient of R^2 = 0.89.

$$\frac{k_s}{k} = -0.183\mathrm{Ln}(\mathrm{Fr}) + 0.053 \tag{8}$$

Darcy-Weisbach resistance coefficient $f = 8\left(\frac{u_*}{\bar{u}}\right)^2$ showed to be a polynomial function with dimensionless rougness

Table 1. Variables of the velocity profiles measurements and errors of the calculated equations

Test	Q (L/s)	H (cm)	$\overline{u}$ (m/s)	u_{max} (m/s)	B/H	Re	Fr	k_s(mm)	h(cm)	ε_1	ε_2	ε_3	$\varepsilon_{7\&6}$	$\varepsilon_{7\&10}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
R1	6.92	6.04	0.191	0.247	9.93	3.37E+04	0.25	3.80	1.29	0.053	0.049	0.060	0.104	0.035
R2	7.61	9.40	0.135	0.180	6.38	3.39E+04	0.14	4.80	2.65	0.082	0.077	0.810	0.127	0.039
R3	10.04	5.00	0.335	0.426	12.01	5.04E+04	0.48	2.20	0.00	0.032	0.029	0.034	0.053	0.037
R4	10.92	8.79	0.207	0.272	6.83	4.94E+04	0.22	3.20	2.04	0.093	0.082	0.093	0.130	0.037
R5	11.44	9.04	0.211	0.273	6.64	5.14E+04	0.22	3.00	1.29	0.064	0.052	0.069	0.106	0.052
R6	12.54	11.81	0.177	0.231	5.08	5.26E+04	0.16	3.60	2.06	0.102	0.089	0.107	0.140	0.050
R7	12.63	6.48	0.325	0.404	9.26	6.07E+04	0.41	2.30	1.73	0.059	0.053	0.059	0.083	0.028
R8	13.24	5.28	0.418	0.531	11.36	6.59E+04	0.58	2.00	0.00	0.053	0.051	0.067	0.079	0.032
R9	13.79	10.17	0.226	0.285	5.90	6.02E+04	0.23	3.00	2.42	0.088	0.080	0.089	0.123	0.036
R10	17.90	7.33	0.407	0.513	8.19	8.41E+04	0.48	1.90	1.58	0.068	0.066	0.070	0.092	0.032
R11	18.07	7.78	0.387	0.488	7.71	8.39E+04	0.44	2.20	2.03	0.070	0.063	0.072	0.087	0.038
R12	18.28	8.04	0.379	0.472	7.46	8.43E+04	0.43	2.00	2.29	0.086	0.079	0.086	0.108	0.027
R13	19.63	7.13	0.459	0.570	8.42	9.28E+04	0.55	1.80	1.38	0.063	0.058	0.065	0.082	0.038
R14	21.00	13.11	0.267	0.373	4.58	8.55E+04	0.24	2.80	2.36	0.090	0.079	0.091	0.114	0.056
R15	21.80	14.14	0.257	0.328	4.24	8.67E+04	0.22	2.80	3.39	0.090	0.100	0.100	0.119	0.049
R16	25.94	8.33	0.519	0.648	7.20	1.19E+05	0.57	1.60	1.58	0.064	0.060	0.066	0.092	0.043
R17	31.00	8.32	0.621	0.802	7.21	1.42E+05	0.69	1.20	1.57	0.070	0.063	0.070	0.111	0.050
R18	31.63	8.11	0.650	0.829	7.40	1.46E+05	0.73	1.10	1.36	0.078	0.069	0.079	0.098	0.038
R19	32.45	9.56	0.566	0.727	6.28	1.44E+05	0.58	1.30	1.81	0.081	0.075	0.081	0.012	0.047
R20	32.63	9.96	0.546	0.695	6.02	1.43E+05	0.55	1.20	2.21	0.087	0.083	0.087	0.113	0.041
R21	34.77	8.41	0.689	0.860	7.13	1.59E+05	0.76	1.20	1.66	0.080	0.069	0.077	0.095	0.037
R22	35.53	9.18	0.645	0.802	6.54	1.59E+05	0.68	1.20	2.43	0.069	0.062	0.069	0.101	0.042
R23	37.16	11.14	0.556	0.709	5.39	1.58E+05	0.53	1.30	1.39	0.075	0.071	0.075	0.098	0.043
R24	37.66	9.98	0.629	0.802	6.01	1.65E+05	0.64	1.20	2.23	0.089	0.079	0.089	0.115	0.034
							Mean			0.074	0.068	0.107	0.099	0.040
							Stand dev			0.016	0.015	0.151	0.027	0.008
							Cv			0.214	0.225	1.409	0.268	0.189

Notes : Q = flow rate ; H = water depth ; $\overline{u}$ = cross section-averaged velocity determined by integration of the point velocities ; u_{max} = maximum velocity, B/H = flow aspect ratio, Re = Reynolds number ; Fr = Froude number = $\overline{u}/\sqrt{gH}$; k_s = uniform sand roughness ; h = distance from the surface to where u_{max} occurs, ε = relative error Stand dev = standard deviation ; Cv = coefficient of variation.

(k_s/k) calculated, for the 24 rough surface flow conditions, as given in Fig. 5. Relation between f and (k_s/k), (Eq. 9) presented a determination coefficient of $R^2 = 0.66$. Eqs. 8and 9 give very useful relations to calculate friction factors.

$$f = 5.1\left(\frac{k_s}{k}\right)^2 - 1.67\left(\frac{k_s}{k}\right) + 0.182 \qquad (9)$$

IV.3 Entropy-based equation

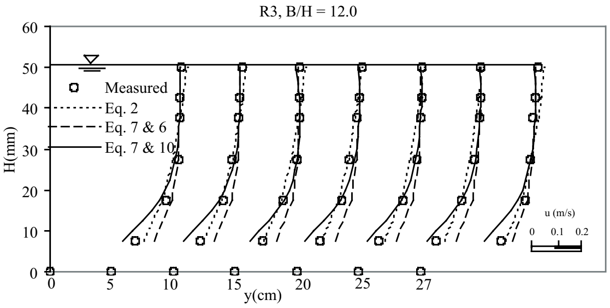
IV.3.1 Entropy equation with parameter M computed by Eq. (6)

Fig. 6 shows the relationship between the maximum velocity (u_{max}) and the cross-sectional mean velocity ($\overline{u}$) obtained experimentally in rough-surface open channel set of measurements. As shown in Fig. 6, u_{max} and $\overline{u}$ present a linear relationship in which (l/f) is the slope of the line. This means M is admitted constant for each channel section and invariant with either the discharge or the flow depth, according to the conclusion of Chiu and Said [1995]. The M value for the rough surface experimental flume was calculated by Eq. (6) as 4.5. As shown, for instance, in Figs. 3 (a)-(b), deviations between measured and calculated (Eqs. 7 and 6) velocity profiles occur both near the bed and above z_{max} = H-h, wherever velocity dip occurs. Consequently Eqs. (7 and 6) did not correctly depict the measured distributions for all the vertical lines covered in the experiments. Mean and standard deviation of relative error were 9.9 % and 2.7 %, respectively, as given Table 1.

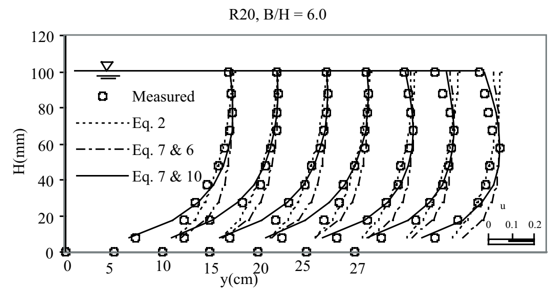
IV.3.2 Entropy equations with parameter M computed by Eq. (10)

Due to constraints in applicability of parameter M calculated by Eq. (7) in rough-surface flows, a new equation to compute for M is suggested.

$$M = \frac{u_{max}}{\overline{u}} \qquad (10)$$



(a) Experiment R3



(b) Experiment R20

Fig. 3. Measured and calculated velocity distributions for several experiments

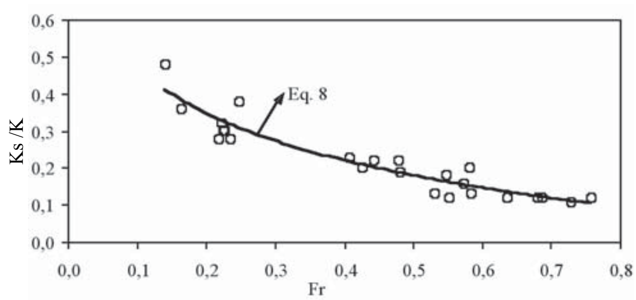


Fig. 4 Relation between dimensonless roughness (k_s/k) and Froude number (Fr) for the experiments of Table 1

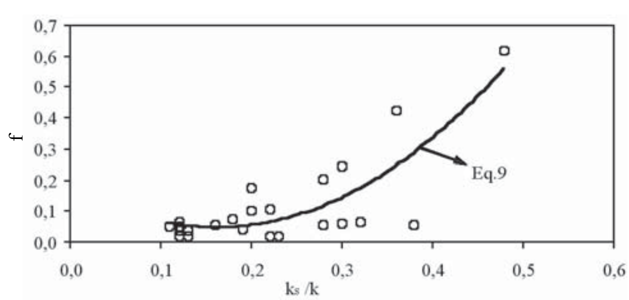


Fig. 5 Friction factor (f) as a function of dimensonless roughness (k_s/k) for the experiments of Table 1

The value of parameter M (Eq. 10) was found to be 1.3 for the 24 experiments of this research, which yielded a better match of the calculated velocity distributions with the measured ones along the cross section for all experiments. Figs. 3 (a)-(b) and Table 1 show the results obtained by Eq. (7) if M is computed by Eq. (10). Mean and standard

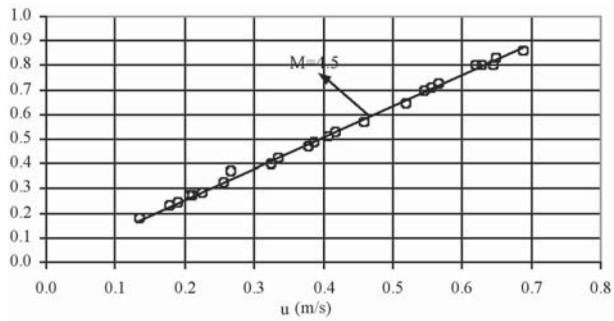


Fig. 6 Relation between u_{max} and based on rough-surface open channel flow experimental data

deviation of relative error between measured and calculated velocities (Eqs. 7 and 10) were respe tively 4.0 % and 0.8 %. These errors are also smaller than those of all logarithmic distributions.

Figures 7 present all experimental values of longitudinal velocities against computed by Eq. (7), with M computed by Eq. (10). When Eq. (7) is used with Eq. (10), no relevant trend was observed, except for a slight trend of underestimation for velocity between 0.2 and 0.6 m/s. Also in this aspect, entropy-based Eqs. (7 and 10) showed the best result of the investigated formulations for rough-surface flow.

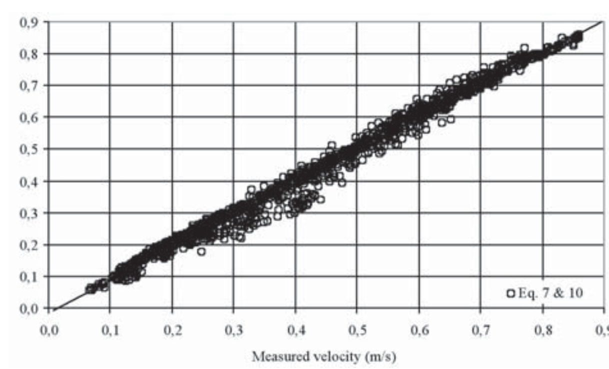


Fig. 7. Comparison between experimental and computed velocity distribution by entropy-based Eqs. (7) and (10)

IV.3.3 Location of maximum velocity

Chiu and Tung [2002] introduced that the magnitude and location of maximum velocity in a channel section contain valuable information. The location of maximum velocity as well as that of mean velocity is a function of parameter M. Chiu and Tung [2002], using large number of sets of laboratory and field data collected under various flow and channel conditions including both steady and unsteady flows, described an empirical relation between h/H and the function G(M) as :

$$\frac{h}{H} = -0.2 \ln \frac{G(M)}{58.3} \tag{11}$$

where G(M) is described as a function of both M and ϕ, as in the following

$$G(M) = \frac{e^M - 1}{M \cdot \phi} \tag{12}$$

Eq. (11) can, therefore, be used to determine h from M, which reduced the number of parameters in velocity distribution equation to only one (u_{max}). For the 24 rough surface experiments of Table 1, h values were calculated and given column (10). Fig. 8 shows the h/H values plotted against u_{max}, which indicates that h/H is quite stable and invariant with either u_{max} or discharge. The maximum velocity u_{max} occurs at a vertical distance h below the water surface for all flow conditions whenever $B/H < 10$. h/H ratio changed between 0.12 – 0.28 and occurred even near the mid section of the channel ($y = 0$). The average value of h/H was obtained to be 0.21 and standard deviation was found to be 0.04.

When G(M) is calculated by Eq. (12) using $M = 4.5$ (Eq. 6) and $\phi = 0.79$, its magnitude is found to be 25.04. The average value of h/H is computed as 0.17 using Eq. 11, with relative error of 19 %. A possible reason for the fairly high magnitude of the error could be the missing of the true magnitude and location of the maximum point velocity, once the measurements were taken at 10 mm intervals.

If there is no record of discharge, Chiu and Tung [2002] suggested that, in order to determine reasonable mean values for M and ϕ in Eq. (11), the relationship between $\bar{u}/u_{max}$ and h/H be analyzed for a number of set of velocity samples on the z axis, and the M value be obtained from Eq. (11). The results, using this procedure, should hold a good reliability level.

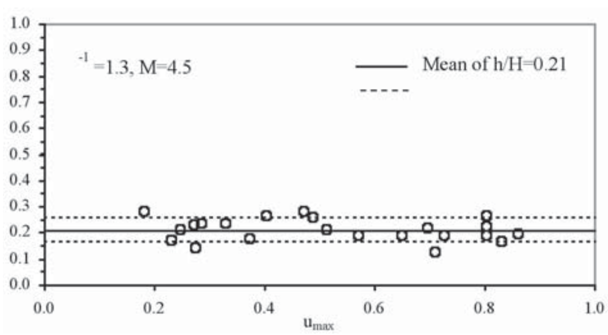


Fig. 8 Relation between h/H and u_{max} for the rough-surface open-channel flow experiments

V ■ CONCLUSIONS

On the basis of the experimental results and computational analysis, the following conclusions may be drawn for rough-surface open-channel flow with rectangular cross section. In rough-surface flows, maximum velocity dip effect occurred depending on aspect ratio (B/H). For $B/H < 5$ dip effect was observed along the whole cross section ; for $10.0 \leq B/H \leq 5.0$ it was observed only near the side wall ; whereas for $B/H > 10$ maximum velocities always occurred near the free surface.

For the three investigated logarithmic distributions, Coles Eq. (2) showed the best agreement with measured velocities, with mean error of 6.8 %. Applicability of Chiu`s entropy-based Eq. (7) was also assessed for rough-surface flows. If M parameter is computed by Chiu's Eq. (6), calculated velocities scatter from experimental data near the bed, which led to average error of 9.9 %. If, otherwise, entropy-based Eq. (7) is used with M parameter computed by here-proposed Eq. (10), velocity profiles near the bed are in good agreement with the experiments, yielding average error of 4.0 %.

Based on the experiments of this research, empirical relations between dimensionless roughness (k_s/k) both Froude number (Fr) and Darcy-Weisbach resistance coefficient (f) were found. Finally, the experiments showed that Chiu and Tung's equation (11), used to assess position of maximum velocity, applies. Calculated value ($h/H = 0.17$) was found in reasonable consonance with experimental result ($h/H = 0.21$).

VI ■ ACKNOWLEDGMENT

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