Turbulence characteristics in a 3-D open channel flow

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TURBULENCE CHARACTERISTICS IN A 3-D OPEN CHANNEL FLOW

ONG MUK CHEN

**SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY**

2005

Turbulence Characteristics In A 3-D Open Channel Flow

Ong Muk Chen

School of Civil & Environmental Engineering

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SUMMARY

In the past, most of the researches on open channel flow have focussed on 2-D flows. In a 2-D flow, the log law and velocity defect law (Coles, 1956) are well established to account for the mean velocity distribution. In addition, many semi-empirical models have been developed to describe the turbulence intensities distribution in a 2-D flow, for example: the exponential models from Nezu and Nakagawa (1993) for smooth bed and from Kironoto and Graf (1994) for rough bed. However, the flow behaviour in a 3-D uniform open channel flow is yet to be fully established.

It is the behaviour of velocity distribution and turbulent intensity structure in a 3-D flow that forms the focus and objective of the present study. An analytical approach is adopted to describe the characteristics of the velocity distribution and flow resistance in an open channel based on the characteristic local shear velocity in the Karman-Prandtl equation. Both the smooth and rough bed conditions are investigated. Simplified equations and turbulence models, for the smooth and rough bed conditions, are developed to describe the velocity profile from the bed to water surface and transversely from the centre line to the side wall region. The dip phenomenon in a 3-D uniform open channel flow is captured and described by the present velocity distribution model.

The local shear velocities are determined using log profile and covariance method (COV). The reliability and “ease of use” of these methods are evaluated. The effect of dip-phenomena on turbulence structure and several models on turbulence intensity structure are introduced. The writer has proposed and developed a new Reynolds stress distribution model. This model captures the Reynolds stress profiles well in both the 3-D smooth bed and rough bed uniform open channel flows. The location of the maximum velocity can be determined using this model.

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LIST OF SYMBOLS

Symbol	Description
b	Channel width
C_i	Integration constant of log law
C_r	Integration constant of log law (rough bed)
C_s	Integration constant of log law (smooth bed)
h	Flow depth
h_{max}	Vertical location where the velocity is the maximum
h_{maxR}	Vertical location where the velocity is the maximum (determined using Reynolds stress profile)
$h_{(z)}$	Effective depth for the computation of local bed shear velocity
k	Gradient of the division line for shear stress distribution $\frac{b}{h} \geq \alpha$
k_1	Gradient of the division line for shear stress distribution $\frac{b}{h} \leq \alpha$
k_s	Boundary roughness
l	Turbulent mixing length
Q	Flow Discharge
R	Hydraulic radius
S	Bed slope
S_f	Energy slope
u	Mean Velocity in the x direction
u'	Fluctuation component of u in the x direction
$\sqrt{u'^2}$	Horizontal turbulence intensity
u_{*h}	Shear velocity, $\sqrt{ghS}$
u_{*log}	Shear velocity obtained from log law
$u_{*log(z)}$	Local shear velocity for rough bed
$U_{mean(z)}$	Depth-averaged mean velocity
u_{*o}	Overall mean shear velocity, $\left(\frac{\tau_o}{\rho}\right)^{1/2}$

u_{*R}	Shear velocity, $\sqrt{gRS}$
u_{*T}	Local turbulent shear stress
$u_{*}(z)$	Local shear velocity, $\sqrt{gh_{(z)}S}$
$\overline{u_{*b}}$	Mean bed shear velocity
$\overline{u_{*w}}$	Mean wall shear velocity
v	Mean Velocity in the y direction
v'	Fluctuation component of v in the x direction
$\sqrt{v'^2}$	Vertical turbulence intensity
$-\overline{u'v'}$	Reynolds shear stress
y	Normal distance from the bed
y_o	Distance of the point of zero velocity from the bed
Y_o	Reference bed level for rough bed
z	Normal distance from sidewall
α	Critical aspect ratio
β	Dip correction factor for general case
β_r	Dip correction factor for rough bed
β_s	Dip correction factor for smooth bed
δ	Characteristic length expressing the extent of the wall effects similar to the viscous sub-layer thickness
κ	Von Karman constant
η	Effective eddy viscosity
μ	Dynamic viscosity
ρ	Fluid density
Π	Coles' wake strength parameter
Φ	Minimum relative distance
τ	Inner shear stress
$\overline{\tau_b}$	Mean bed shear stress
τ_o	Mean shear stress

LIST OF SYMBOLS

$\overline{\tau_w}$	Mean wall shear stress
$\tau_{(z)}$	Local bed shear stress
ν	Kinematic viscosity
ν_t	Eddy viscosity
%SF _b	Percentage of the shear force acting on the bed
%SF _w	Percentage of the shear force acting on the side wall

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

Sediment motion is closely related to the phenomenon of flow turbulence. Turbulence generates cascades of eddies in the vertical and lateral directions and entrains the sediment as suspension against the action of gravitational force. In the near-bed regime, bed shear stress and the near-bed turbulence structure play vital roles in the nature of sediment transport in open channel flows and estuaries. The bed shear stress controls erosion and deposition of sediments at the bed as well as its dispersal and diffusion in the water column.

Turbulent transport of momentum, heat and mass dominate many aspects of fluid flows. Due to the complexity of flow turbulence phenomenon, there is as yet no complete theory that could describe and explain fully each and every aspect of the turbulence phenomena. All the existing works are based on semi-empirical hypotheses which are used to establish the relationship between turbulence stresses and time-averaged velocities. (Chien and Wan, 1998)

The basic mechanism of turbulent flow has been investigated by many researchers, notably Prandtl (1925) and von Karman (1931, 1934). These authors proposed the mixing-length theory to describe the mean velocity distribution in a 2-D flow. Their theory was further developed and presented as the logarithmic law (log law). The log law, which can be derived analytically, involves only two constants: a universal constant that represents the characteristic of turbulence; and a second coefficient that characterises the boundary surface. These characteristics will be elaborated in later sections of the report.

In his classical experiments on circular pipes, Nikuradse (1930) confirmed the value of the universal constant of turbulence and determined empirically the constant for the surface characteristics for both smooth and rough circular pipes.

These results are well known and have been presented in details in most hydraulics or fluid mechanics textbooks (Chow 1959, Hinze 1959 and Raudkivi 1976).

In 1935, Taylor published his statistical theory of turbulence. By presenting turbulence as a statistical phenomenon, Taylor provided a physically sound framework for turbulence research. Other statistical development, such as the theoretical work of Kolmogorov (1942) had widely influenced research on turbulence properties after the Second World War. Since 1960's, modern measurement techniques such as the hydrogen bubble method, high speed photography, acoustic and laser Doppler anemometry have been widely used to investigate the characteristics of turbulence. The amount of raw data collected using these modern measurement techniques is huge. Nevertheless, with the advent of the high speed computer to process the data, the statistical approaches, such as covariance method, turbulent kinetic energy method etc, become feasible and have been readily adopted and carried out.

1.2 MOTIVATION OF THE STUDY

In the past, most of the researches on open channel flow focused on 2-D flow. The log-law and velocity defect law (Coles, 1956) were well established to account for the mean velocity distribution in a 2-D flow. With respect to turbulence structures, substantial semi-empirical models were developed to describe the turbulence intensities distribution in 2-D flow, for example: the exponential models from Nezu and Nakagawa (1993) for smooth bed and from Kironoto and Graf (1994) for rough bed.

The well-established knowledge in 2-D flow has aroused the writer's interest to look into the behaviour of a 3-D open channel flow. The dip-phenomenon, which is observed in a 3-D flow, cannot be accounted for in a 2-D flow model. The writer has planned to carry out extensive investigation on the characteristics of velocity distribution and turbulent intensity structure in this study.

1.3 OBJECTIVES OF THE STUDY

The primary aims of this study are to

- (1) use the fundamental principles of open channel flows and turbulence theory, and
- (2) use semi-empirical techniques

and apply to the problem of fully developed 3-D turbulent flow in an open channel.

The goal is to develop formulae to describe the characteristics of the velocity distribution and flow resistance in an open channel flow based on a characteristic local shear velocity in the Karman-Prandtl equation. Both smooth and rough bed conditions are investigated. Simplified equations, for smooth and rough bed conditions, are developed to describe the velocity profile from the bed to water surface and transversely from the centre line to the side wall region.

The study also aims to investigate several long-standing hydraulic phenomena such as the dip phenomenon, secondary flow and turbulence structure in a 3 dimensional flow:

- The dip phenomenon is investigated. Dimensional analysis and other analytical techniques are applied to obtain the equation that will determine the location of the maximum velocity.
- The local shear velocities are obtained using the log profile and covariance method (COV). The reliability and convenience of these methods will be evaluated in the present studies. The effect of dip-phenomena on turbulence structure is further investigated.

- Secondary flow turbulence behaviours are investigated in order to estimate the magnitude of the bed shear stress. The latter governs the transport capabilities of flow. Semi-empirical formulae are then established to describe the Reynolds shear stress.

1.4 ORGANISATION OF THE THESIS

The thesis comprises 6 chapters. The material in each chapter is related to that in the preceding chapters and forms the basis for the theoretical derivations and applications in a sequential manner.

Chapter 2 presents a general review of the literature, contribution to the experimental and theoretical knowledge of 3-D turbulent structures; velocity distribution and boundary shear stress in prismatic channels. The principle of logarithmic law is discussed. Yang's method (1996) of boundary shear stress distribution is investigated and used to estimate the near-boundary shear stress distribution in smooth rectangular open channel flows. The theoretical consideration on Reynolds shear stress profile, affected by the occurrence of dip-phenomenon (Yang et al, 2003) in smooth bed condition, is elaborated in this chapter.

Chapter 3 presents the experimental setup, experimental methods, equipment and procedure of the experiments on velocity measurement in rectangular open channels of various aspect ratios. Both smooth and rough bed conditions are investigated. The influence of the aspect ratio on the 3-D velocity distribution and flow resistance of the channel is studied.

Chapter 4 presents studies on velocity distribution of uniform open channel flow. The log-law is studied. The integration constants, C (for rough bed and smooth bed), which are elaborated in Chapter 2, are identified. Based on the present experimental data, critical aspect ratio that distinguishes the 2 dimensional from 3

dimensional flow regimes is established. The significance of the wake law is elaborated. The mechanism of the dip phenomenon in velocity distribution of open channel flow is investigated for both the smooth and rough bed condition.

Chapter 5 emphasizes the understanding of turbulence structure in an open channel flow. Semi-empirical equations are derived to describe distribution of Reynolds shear stress. The logarithmic profile method and covariance method are also evaluated in the present study.

Chapter 6 presents the conclusions of this study. Recommendations for future studies are included.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

Turbulent flows and their effects are encountered in nearly every case where fluid motion is involved. Therefore it is important to understand the physics of the phenomena. The basic mechanism of turbulent flow has been investigated by many researchers, especially Prandtl (1925) and von Karman (1931, 1934). They proposed the mixing length theory to describe the mean velocity distribution in 2-D flow. Schlichting (1979) devoted major effort to the problem of the stability of laminar boundary-layer flow.

Nevertheless, the flows in open channels and natural rivers are 3-dimensional in nature. They are usually too complicated to be represented as a 2-D flow. Certain factors such as the channel aspect ratio and non-uniform distribution of the boundary roughness along the wetted perimeter, distinguish a 3-D flow from 2-D flow. The laws of velocity distribution, boundary shear stress distribution and flow resistance are important parameters that are fundamental to the understanding and predictability of turbulent transport processes, such as sediment transport, pollutant transport, etc.

Since 1940's, the theoretical and experimental investigations of the mean flow properties and the turbulence structure of uniform open channel flow have been carried out. Nezu and Nakagawa (1993), Nezu and Rodi (1986), Cardoso et al (1989), Kironoto and Graf (1994), Song (1994), Yang et al (2003) and others have performed many relevant experiments and made many significant observations. The results can be applicable to many problems in practice, for example, the flows in man-made canals, the flows in rivers, etc.

2.2 VELOCITY PROFILE AND TURBULENT STRUCTURES

2.2.1 Mixing Length Theory and Log Law

The Reynolds equations can be derived from Navier-Stokes equations for turbulent flow by representing each velocity and pressure term with the corresponding mean value. However, due to the complexity of the Reynolds equation, determination of the mean flow properties of the turbulent flow becomes the one single important objective of researchers. There have been attempts at simplifying the equations by developing semi-empirical relationships between the Reynolds stresses and the mean velocity components. Substantial success and improvement in this direction has been attained. Boussinesq (1897) was among the first to use this approach.

In 1897, Boussinesq proposed that the shearing processes in laminar and turbulent flow may be represented as the sum of the stress due to the viscosity effect and an effective eddy stress due to turbulent transfer of momentum, i.e.

$$\tau = (\mu + \eta) \frac{du}{dy} = \mu \frac{du}{dy} - \rho \overline{u'v'} \quad (2-1)$$

where u = the mean velocity in the x -direction; y = distance from the wall; u' , v' = fluctuation components of u and v in the x and y direction, respectively; τ = inner shear stress; η = effective eddy viscosity; μ = dynamic viscosity and ρ = fluid density.

In the fully rough turbulent regime, the laminar part of the shear stress is insignificant compared to the turbulent part. Hence, Equation (2-1) can be rewritten as

$$\tau = \eta \frac{du}{dy} = -\rho \overline{u'v'} \quad (2-2)$$

In 1925, Prandtl proposed that momentum is conserved when a fluid particle moves from one region to another. A mixing length theory for the 2-D flow was proposed to describe the behaviour of turbulent flow. It yields

$$\tau = \rho l^2 \left(\frac{du}{dy} \right)^2 \quad (2-3)$$

Equating Equations (2-2) and (2-3) yields

$$\eta = \rho l^2 \left(\frac{du}{dy} \right) \quad (2-4)$$

The turbulent mixing length l is a measure of the eddy size. In the near bed region, the mixing length is proportional to the distance y from the wall, (i.e. $l = \kappa y$). Near the wall, τ is equal to the boundary shear stress, τ_o . Equation (2-3) becomes

$$\tau_o = \rho \kappa^2 y^2 \left(\frac{du}{dy} \right)^2 \quad (2-5)$$

By integrating Equation (2-5) with respect to y , the logarithmic form of law of wall, or log law is obtained:

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{y}{y_o} \right) \quad (2-6)$$

in which u_{*o} = overall mean shear velocity $= \left(\frac{\tau_o}{\rho} \right)^{1/2}$; κ = von Karman constant; y_o

denotes the distance of the point of zero velocity from the bed.

For flow near smooth walls, the fluid motions depend on the kinematic viscosity ν and u_{*o} . The parameter y_o may be considered proportional to the ratio of ν to u_{*o} . Hence,

$$y_o \propto \frac{\nu}{u_{*o}} \quad (2-7)$$

and

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*o} y}{\nu} \right) + C \quad (2-8)$$

the constant κ and C have been experimentally determined by Nikuradse (1930) for smooth pipes, where $\kappa = 0.4$ and $C = 5.5$, respectively. Thus, Equation (2-8) becomes

$$\frac{u}{u_{*o}} = 2.5 \ln \left(\frac{u_{*o} y}{\nu} \right) + 5.5 \quad (2-9)$$

However, the flow passes through the pore space of the rough wall and the fluid motions are affected by the size of the roughness elements, k_s . In this case, y_o may be considered to be proportional to k_s . Thus,

$$y_o \propto k_s \quad (2-10)$$

and

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{y}{k_s} \right) + C \quad (2-11)$$

According to Nikuradse's experimental data, the constant C was found to be 8.5 and the velocity distribution is given by:

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{y}{k_s} \right) + 8.5 \quad (2-12)$$

Equations (2-9) and (2-12) are widely accepted and used as the fundamental equations for normal applications for many practical problems and numerical modelling involving 2-D and 3-D flows. A more accurate value of von Karman constant, $\kappa=0.41$ was determined by Nezu and Rodi (1986). In this writer's study, the κ -value of 0.41 was used.

2.2.2 Velocity Defect Law

Recent studies have shown that open-channel flow consists of two regions: inner region, $y/h < 0.2$, and the outer region, $y/h > 0.2$. In the inner region, the log law is inherently valid. In the outer region, the velocity distribution can be described by Coles law (Coles, 1956)

$$\frac{\bar{u}}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*o} y}{\nu} \right) + 5.5 + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi y}{2h_{\max}} \quad \text{for smooth bed} \quad (2-13)$$

$$\frac{\bar{u}}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{y + Y_o}{k_s} \right) + 8.5 + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi (y + Y_o)}{2(h_{\max} + Y_o)} \quad \text{for rough bed} \quad (2-14)$$

in which, Π is Coles' wake strength parameter with an average value of 0.2 for open channel flow; Y_o is the reference bed level for rough bed; and $h_{\max}$ is the vertical location where the velocity is the maximum.

The wake law was first introduced by Coles (1956) who introduced the wake strength parameter of 0.55 in an air turbulent boundary. Nezu and Rodi (1986) obtained the wake strength-value in the range of 0 to 0.2; Kironoto and Graft (1994) observed that the value lies in the range of -0.08 to 0.15. Kirkgoz and Ardichoglu's (1997) experimental results show that the wake strength parameter is 0.1. Cardoso

et al (1989) claimed that the wake strength is not universal and is dependent on secondary currents, flow history and inactive turbulence components. The consensus is that the wake coefficient must be determined using the measured velocity profile because there is as yet no reliable formula to determine the coefficient from the flow conditions.

2.2.3 Dou's Theory (1981, 1987)

Dou (1981) proposed a stochastic theory for turbulent flow. Details of his derivation can be found in his book (1987). Only a brief summary of his complex derivation is given here.

In 2-D uniform flow, the shear stress variation can be expressed as:

$$\tau = \mu \frac{du}{dy} + (-\rho \overline{u'v'}) = \rho u_{*o}^2 \left(1 - \frac{y}{h}\right) \quad (2-15)$$

From stochastic theory, the turbulence shear formula obtained by Dou has the form of

$$\overline{u'v'} = -\frac{1}{2} U^2 T \frac{du}{dy} + \left(\frac{1}{4} m L^2 - \frac{1}{8} m^2 L^2 \right) \left(\frac{du}{dy} \right)^2 \quad (2-16)$$

$$m = \frac{y}{\delta}; \quad \frac{u^2}{u_{*o}^2} = \frac{y}{\delta + y}; \quad mL = \kappa y \sqrt{1 - \frac{y}{h}}; \quad U^2 T = \kappa u_{*o} y \left(1 - \frac{y}{h}\right) \quad (2-17)$$

where L , U , T , and m = characteristic parameters; y = distance from wall; h = flow depth; u_{*o} = shear velocity; δ = a characteristic length expressing the extent of the wall effects similar to the viscous sub-layer thickness; κ = von Karman constant.

By substituting Equations (2-17) and (2-16) into Equation (2-15), one obtains

$$\frac{du}{dy} = \frac{u_{*o}^2 (1 - \frac{y}{h})}{\frac{\kappa}{4} u_{*o} y (1 - \frac{y}{h}) + \nu} + \frac{\kappa^2 (2\delta y - y^2) (1 - \frac{y}{h})^3 u_{*o}^4}{8 [\frac{\kappa}{2} u_{*o} y (1 - \frac{y}{h}) + \nu]^3} \quad (2-18)$$

Taking $\frac{u_{*o} \delta}{\nu} = 11.6$ and $\kappa = 0.4$, and integrating Equation (2-18), it gives

$$\frac{u}{u_{*o}} = 2.5 \ln(1 + \frac{u_{*o} y}{5\nu}) + 7.05 \left(\frac{\frac{u_{*o} y}{5\nu}}{1 + \frac{u_{*o} y}{5\nu}} \right)^2 + 2.5 \left(\frac{\frac{u_{*o} y}{5\nu}}{1 + \frac{u_{*o} y}{5\nu}} \right) + C_1 \quad (2-19)$$

where C_1 is a constant of integration. In the case of smooth flow, the boundary condition is $u = 0$ at $y = 0$, therefore $C_1 = 0$.

For the region of $u_{*o} y/\nu \gg 1$, $(1 + u_{*o} y/5\nu) \approx u_{*o} y/5\nu$. Then, Equation (2-19) can be simplified into the log law formula,

$$\frac{u}{u_{*o}} = 2.5 \ln \frac{u_{*o} y}{\nu} + 5.52 \quad (2-20)$$

For the region of $u_{*o} y/\nu \ll 1$, $(1 + u_{*o} y/5\nu) \approx 1$, and $\ln(1 + u_{*o} y/5\nu) \approx u_{*o} y/5\nu$, Equation (2-19) becomes

$$\frac{u}{u_{*o}} = \frac{u_{*o} y}{\nu} \quad (2-21)$$

which is similar to the velocity distribution formula for the viscous sub-layer. Hence, Equation (2-19) is a general equation capable of describing the velocity distribution from the wall to the pipe centre or free surface.

Since the velocity distribution and equations of the characteristic parameters are known, the turbulence intensities distribution in smooth bed can be stated as below:

$$\frac{\sqrt{u'^2}}{u_{*o}} = \left\{ \frac{\frac{u_* y}{2\nu}}{11.6 + \frac{u_* y}{\nu}} + 0.36 \left(1 - \frac{y}{h}\right) \left[\frac{\frac{u_* y}{\nu}}{1 + \frac{u_* y}{\nu}} + \frac{0.464 \left(\frac{u_* y}{\nu}\right)^2 - 0.02 \left(\frac{u_* y}{\nu}\right)^3}{\left(1 + \frac{u_* y}{5\nu}\right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (2-22)$$

$$\frac{\sqrt{v'^2}}{u_{*o}} = \left\{ \frac{\frac{u_* y}{2\nu}}{11.6 + \frac{u_* y}{\nu}} + 0.04 \left(1 - \frac{y}{h}\right) \left[\frac{\frac{u_* y}{\nu}}{1 + \frac{u_* y}{\nu}} + \frac{0.464 \left(\frac{u_* y}{\nu}\right)^2 - 0.02 \left(\frac{u_* y}{\nu}\right)^3}{\left(1 + \frac{u_* y}{5\nu}\right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (2-23)$$

$$-\frac{\overline{u'v'}}{u_{*o}^2} = \left(1 - \frac{y}{h}\right) - \frac{\left(1 - \frac{y}{h}\right)}{1 + \left(1 - \frac{y}{h}\right) \frac{u_* y}{5\nu}} - \frac{\left[0.464 \left(\frac{u_* y}{\nu}\right)^2 - 0.02 \left(\frac{u_* y}{\nu}\right)^3\right] \left(1 - \frac{y}{h}\right)^3}{\left[1 + \left(1 - \frac{y}{h}\right) \frac{u_* y}{5\nu}\right]^3} \quad (2-24)$$

For rough bed,

$$\frac{\sqrt{u'^2}}{u_{*o}} = \left\{ \frac{\left(\frac{u_* k_s}{2\nu}\right) \left(\frac{y}{k_s}\right)}{11.6 + \left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)} + 0.36 \left(1 - \frac{y}{h}\right) \left[\frac{\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)}{1 + \left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)} + \frac{0.464 \left(\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)\right)^2 - 0.02 \left(\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)\right)^3}{\left(1 + \left(\frac{u_* k_s}{5\nu}\right) \left(\frac{y}{k_s}\right)\right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (2-25)$$

$$\frac{\sqrt{v'^2}}{u_{*o}} = \left\{ \frac{\left(\frac{u_* k_s}{2\nu}\right) \left(\frac{y}{k_s}\right)}{11.6 + \left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)} + 0.04 \left(1 - \frac{y}{h}\right) \left[\frac{\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)}{1 + \left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)} + \frac{0.464 \left(\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)\right)^2 - 0.02 \left(\left(\frac{u_* k_s}{\nu}\right) \left(\frac{y}{k_s}\right)\right)^3}{\left(1 + \left(\frac{u_* k_s}{5\nu}\right) \left(\frac{y}{k_s}\right)\right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (2-26)$$

$$-\frac{\overline{u'v'}}{u_{*o}^2} = \left(1 - \frac{y}{h}\right) - \frac{\left(1 - \frac{y}{h}\right)}{1 + \left(1 - \frac{y}{h}\right)\left(\frac{u_* k_s}{5\nu}\right)\left(\frac{y}{k_s}\right)} - \frac{\left[0.464\left(\left(\frac{u_* k_s}{\nu}\right)\left(\frac{y}{k_s}\right)\right)^2 - 0.02\left(\left(\frac{u_* k_s}{\nu}\right)\left(\frac{y}{k_s}\right)\right)^2\right]\left(1 - \frac{y}{h}\right)^3}{\left[1 + \left(1 - \frac{y}{h}\right)\left(\frac{u_* k_s}{5\nu}\right)\left(\frac{y}{k_s}\right)\right]^3} \quad (2-27)$$

Dou found that if $u_{*o} y/\nu \geq 100$, the height of the separation layer is at its maximum value and is equal to the thickness of the roughness, after which the height of the separation layer no longer increase as the Reynolds number increases, hence, $u_{*o} k_s/\nu$ should be equal to 100.

2.3 BOUNDARY SHEAR STRESS DISTRIBUTION IN SMOOTH CHANNEL

2.3.1 Introduction

In an open channel flow, the boundary shear stress and its distribution along the wetted perimeter is a significant factor in the computation of flow resistance, sidewall correction, sediment transport rate, channel erosion or deposition and designs of channel.

The mean overall shear stress of a channel can be obtained easily from the hydraulic radius and energy slope. The mean shear stress is uniformly distributed along the wetted perimeter. In real life, the shear stress distribution is not uniform over the bed and wetted perimeter.

Einstein (1942) was perhaps the first person to recommend a method to divide the flow cross sectional area into various segments. He divided the flow area into three parts, two corresponding to the side walls and one for channel bed through consideration of the isovel pattern. Researchers such as Haywood (1942), Adaichi (1962), Chien and Wan (1986), and Daido (1992) agreed with Einstein's

proposal. However, they had no general agreement on how the flow region should be divided.

Chien and Wan (1986) divided the flow area through consideration of isovel pattern based on Einstein's idea. The way of identifying the division line is to draw orthogonal lines to the velocity contours with the assumption that orthogonal lines to the isovels are surfaces of zero shear. However, the isovels should be known first before performing the dividing.

Following Einstein's method, Daido (1992) used the Prandtl-Karman equation to obtain an equation for the division line. The velocities in the partitioned areas corresponding to the bed and side wall, respectively, are assumed to be

$$\frac{u_1}{u_{*b}} = \frac{1}{\kappa} \ln \left(\frac{u_{*b} y}{\nu} \right) + C \quad (2-28)$$

$$\frac{u_2}{u_{*w}} = \frac{1}{\kappa} \ln \left(\frac{u_{*w} z}{\nu} \right) + C \quad (2-29)$$

where u_1 and u_2 = velocity at a certain distance from the bed and side wall, respectively; u_{*b} and u_{*w} are the shear velocities on the bed and side walls, respectively; y and z are normal distances from bed and side wall, respectively. Then by equating Equations (2-28) and (2-29), a non-linear equation is obtained for the division line, as shown in Figure 2.1.

However, based on Figure 2.1, it can be seen that the shear stress distribution near the corner is contradictory to the experimental findings of Knight et al (1984) (shown in Figure 2.2). Experimental measurements of the boundary shear stress in smooth and rough channel were conducted by Knight (1981). Many empirical relationships of the boundary shear stress, particularly on the mean bed and side wall shear stresses have been proposed. For a smooth rectangular channel, Knight et al (1984) gathered a compendium of 60 data points based on the

experiments performed by Cruiff (1965), Ghosh and Roy (1970), Kartha and Leutheusser (1970), Knight (1981), Myers (1982) and Noutsopoulos and Hadjipanose (1982). The data sets cover a wide range of Froude numbers, Reynolds numbers and aspect ratios. Based on the data sets, Knight et al (1984) proposed the following empirical formulae:

$$\frac{\bar{\tau}_b}{\rho g h S_f} = 1 - 0.01(\%SF_w) \quad (2-30)$$

$$\frac{\bar{\tau}_w}{\rho g h S_f} = 0.01(\%SF_w)\left(\frac{b}{2h}\right) \quad (2-31)$$

$$\%SF_b + \%SF_w = 1 \quad (2-32)$$

in which b = channel width, h = water depth, $\bar{\tau}_b$ and $\bar{\tau}_w$ = the mean shear stress on the bed and side wall respectively, S_f = energy slope and $\%SF_w$ is the percentage of the shear force acting on the side wall, which is determined using the following equation:

$$\%SF_w = \exp(-3.23 \log_{10} (b/h+3)+6.146) \quad (2.33)$$

Yang (1996) and Yang and Lim (1998) presented an analytical method for the computation of boundary shear stress distributions acting on the flow perimeter of prismatic open channels. The approach was based on the assumption that the surplus energy of any arbitrary unit volume of fluid in a 3 dimensional flow channel would be transported towards and dissipated at a unit area on the wetted perimeter. This approach lead to a concept which stated that the direction of energy transportation would define a minimum relative distance, Φ , between the source of energy in the flow field and the boundary. Based on this concept, the flow cross sectional area was partitioned into various parts corresponding to channel shape and roughness elements on the wetted perimeter. Figure 2.3 shows the definition sketch of the division line for a smooth rectangular channel. The final forms of the proposed formulae for shear stress distribution are depicted below:

$$\frac{\overline{\tau_b}}{\rho g R S_f} = \begin{cases} (1 - \frac{kh}{b})(\frac{2h}{b} + 1) & \frac{b}{h} \geq \alpha \\ k_1 b (\frac{2h}{4h} + 1) & \frac{b}{h} \leq \alpha \end{cases} \quad (2-34)$$

$$\frac{\overline{\tau_w}}{\rho g R S_f} = \begin{cases} \frac{k}{2} (\frac{2h}{b} + 1) & \frac{b}{h} \geq \alpha \\ (1 - \frac{k_1 b}{4h})(\frac{b}{2h} + 1) & \frac{b}{h} \leq \alpha \end{cases} \quad (2-35)$$

yielding

$$z = k y \quad \frac{b}{h} \geq \alpha \quad (2-36)$$

where $k = \frac{\overline{u_{*b}}}{\overline{u_{*w}}}$

and

$$y = k_1 z \quad \frac{b}{h} \leq \alpha \quad (2-37)$$

where $k_1 = \frac{\overline{u_{*w}}}{\overline{u_{*b}}}$

Here, α is the critical aspect ratio. k and k_1 represent the gradient of the division line for shear stress distribution. According to Yang (1996) and Yang and Lim (1998), the critical aspect ratio α for smooth boundary is 2. Figure 2.4 and Figure 2.5 show the comparisons between the experimental data with the computed results from Equation (2-36) and (2-37). The empirical formulae proposed by Knight et al (1984) are included for comparison. As is clearly shown in the comparisons, Knight's equation for shear stress distribution of side wall deviated considerably when $\frac{b}{h} > 15$, while Yang's method is generally satisfactory. The comparisons show that Yang's approach is reasonable.

Yang's method is adopted in this writer's study. The method is used to identify the division lines for shear stress distribution, which is an essential step to

lead into the studies as described in Chapter 4. Details of Yang's method for the division lines will be elaborated further in a later section.

Figure 2.1 Distribution of concave wall shear stresses in accordance with Daido's proposed division line (dashed line) (Daido, 1992)

Figure 2.2 Typical boundary shear stress distribution from Knight et al (1984)

(a)

Figure 2.3(a) and (b) Definition sketch of the division line for smooth rectangular channels (Yang and Lim, 1998)

(b)

$$\frac{b}{h} \leq \alpha$$

Figure 2.3(a) and (b) Definition sketch of the division line for smooth rectangular channels (Yang and Lim, 1998) (continued)

Figure 2.4 Comparison of computed (solid line) mean bed shear stress using Equation (2-34) and experimental data (compiled by Knight et al, 1984) (Yang, 1996)

Figure 2.5 Comparison of computed (solid line) mean bed shear stress using Equation (2-35) and experimental data (compiled by Knight et al, 1984) (Yang, 1996)

2.3.2 Derivation Of Slope Of Division Line For Shear Stress Distribution-Yang(1996) and Yang and Lim (1998)

With reference to the shear stress distribution theory by Yang (1996) and Yang and Lim (1998), derivation of slope of division line for shear stress distribution was discussed in detail in this section.

(i) For the case of $\frac{b}{h} \geq \alpha$ (shallow and wide type):

The bed boundary shear stress is expressed as follows:

$$\tau_{b(z)} = \rho g h S \quad z > \frac{h}{k} \quad (2-38)$$

$$\tau_{b(z)} = \rho g k z S \quad z \leq \frac{h}{k} \quad (2-39)$$

The mean bed and sidewall shear stresses are defined as follows:

$$\bar{\tau}_b = \frac{2}{b} \int_0^{b/2} \tau_{b(z)} dz \quad (2-40)$$

$$\bar{\tau}_w = \frac{1}{h} \int_0^h \tau_{w(y)} dy \quad (2-41)$$

Substituting Equations (2-38) and (2-39) into (2-40) yields

$$\bar{\tau}_b = \frac{2}{b} \left[\int_0^{h/k} \rho g k z S dz + \int_{h/k}^{b/2} \rho g h S dz \right] \quad (2-42)$$

or

$$\frac{\bar{\tau}_b}{\rho g h S} = 1 - \frac{h}{kb} \quad (2-43)$$

In the region $y > kz$, Reynolds equation can be written in the following form

$$\frac{\partial(uw - \tau_{xz} / \rho)}{\partial z} = gS \quad (2-44)$$

In the region $y < kz$, Reynolds equation can be written in the following form

$$\frac{\partial(uw - \tau_{xz} / \rho)}{\partial z} = 0 \quad (2-45)$$

Integration of Equation (2-44) and (2-45) with respect to z yields

$$\tau_{xz} = C_{3(y)} + \rho uw - \rho g S z \quad y > kz \quad (2-46)$$

$$\tau_{xz} = C_{4(y)} + \rho uw \quad y < kz \quad (2-47)$$

where $C_{3(y)}$ and $C_{4(y)}$ are integration constants. Applying the boundary condition, i.e., at $z = 0$, $-\overline{u'w'} = 0$, $u = 0$, $w = 0$, $\mu du/dz = \tau_{w(y)} =$ boundary shear stress. From Equation (2-46), one has

$$C_{3(y)} = \tau_{w(y)} \quad (2-48)$$

At the centre line where $z = b/2$, $w = 0$. and the shear stress τ_{xz} has to be zero, thus

$$C_{4(y)} = 0 \quad (2-49)$$

In the region of $y > kz$, the boundary shear stress can be determined using the upper boundary condition where $z = L$, and L is the normal distance from the sidewall to the division line shown in Figure. 2.3(a) and $L = y/k$. Substituting Equation (2-48) into (2-46), one obtains

$$\tau_{w(y)} = \rho g L S + (\tau_{xz} - \rho u w)_{z=L} \quad y > kz \quad (2-50)$$

The second term on the right hand side (RHS) of Equation (2-50) can be determined from Equation (2-47) and (2-49) as follows

$$C_{4(y)} = (\tau_{xz} - \rho u w)_{z=L} = 0 \quad (2-51)$$

Thus, the sidewall boundary shear stress distribution is obtained as follows

$$\tau_{w(y)} = \rho g S y / k \quad (2-52)$$

substituting Equation (2-52) into (2-54), one gets

$$\frac{\overline{\tau_w}}{\rho g h S} = \frac{1}{2k} \quad (2-53)$$

The slope of the division line, k ($= \overline{u_{*w}} / \overline{u_{*b}}$) can be derived using Equations (2-43) and (2-53) with the following form

$$k^2 = \left(\frac{\overline{u_{*w}}}{\overline{u_{*b}}} \right)^2 = \frac{\overline{\tau_w}}{\overline{\tau_b}} = \frac{1}{2k(1 - \frac{h}{kb})} \quad (2-54)$$

Thus, one has

$$2k^3 - 2k^2 \frac{h}{b} - 1 = 0 \quad (2-55)$$

(ii) For the case of $\frac{b}{h} \leq \alpha$:

The derivation is similar to the case of $\frac{b}{h} \geq \alpha$. Hence, the final Equations (2-34), (2-35) and (2-37) are used to derive the value of k_l . By equating Equation (2-34) and (2-35) for the case of $\frac{b}{h} \leq \alpha$, k_l can be deduced

$$\frac{\overline{\tau_w}}{\overline{\tau_b}} = k_l^2 = \frac{2(1 - \frac{k_l b}{4h})}{k_l} \quad (2-56)$$

$$k_l^3 + (b/2h)k_l - 2 = 0 \quad b/h \leq \alpha \quad (2-57)$$

The values of k and k_1 for various aspect ratios for smooth rectangular channels are tabulated in Table 2.1.

Table 2.1 Values of $1/k$ and $1/k_1$ for various aspect ratios of smooth rectangular channels (Yang and Lim, 1998)

b/h	1/k	1/k₁
0		1.26
0.1		1.25
0.267		1.225
0.4		1.207
0.5		1.195
0.667		1.172
1		1.128
2	1	1
4	1.128	
5	1.16	
6	1.17	
7	1.185	
10	1.207	
15	1.225	
∞	1.26	

2.4 REYNOLDS STRESS PROFILE AND MODIFIED VELOCITY DISTRIBUTION

Yang et al (2003) proposed that the Reynolds shear stress profiles can be approximately expressed as follows

$$-\frac{\overline{u'v'}}{u_*^2} = \left(1 - \frac{y}{h}\right) - \beta \frac{y}{h} \quad (2-58)$$

where β is a positive factor to be determined empirically. The secondary currents is accounted for in the additional term, $\beta \frac{y}{h}$, on the RHS of Equation (2-58). This term may subsequently cause the maximum velocity in a vertical profile occur at a distance below the water surface, as observed by Cardoso et al (1989). Turbulence closure as stated in Equation (2-59) is used to gain insight into the mechanism of velocity shift in the region near water surface. This shift of the maximum velocity is commonly known as the dip-phenomenon.

$$-\overline{u'v'} = \nu_t \frac{du}{dy} \quad (2-59)$$

where ν_t = eddy viscosity. Nezu and Nakagawa (1993) successfully conducted LDA measurements of eddy viscosity in open channels. Their experimental results show that the measured ν_t can be modelled by the following empirical Equation (Yalin, 1977)

$$v_t = \kappa u_* y \left(1 - \frac{y}{h} \right) \quad (2-60)$$

Substituting Equations (2-59) and (2-60) into (2-58), one obtains

$$\frac{du}{dy} = \frac{u_*}{\kappa y} - \left[\frac{\beta \frac{u_*}{\kappa h}}{\left(1 - \frac{y}{h} \right)} \right] \quad (2-61)$$

Integration of Equation (2-61) with respect to y and using the no-slip boundary condition i.e., $u = 0$, at $y = y_o$, yields

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{y}{y_o} \right) + \frac{\beta}{\kappa} \ln \left[\frac{\left(1 - \frac{y}{h} \right)}{\left(1 - \frac{y_o}{h} \right)} \right] \quad (2-62)$$

Except for very shallow water such as sheet flow, $y_o/h \ll 1$. Equation (2-62) can be further simplified as follows:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{y}{y_o} \right) + \frac{\beta}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (2-63)$$

in which κ = von Karman constant; $u_* = (gRS)^{0.5}$; $y_o = v/(cu_{*(z)})$ = y -distance at which the velocity is hypothetically equal to zero; and c = constant. If $\beta = 0$, Equation (2-63) is simplified to the classical log-law. The second term,

$\frac{\beta}{\kappa} \ln\left(1 - \frac{y}{h}\right)$, on RHS of Equation (2-63) plays an important role in the outer

region. It is negligible in the inner region since $\ln(1-y/h) \approx 0$.

In chapter 4, Equation (2-63) is further manipulated to account for the velocity distribution in outer region, and the dip-phenomenon. The parameters of β are identified for both the smooth bed and rough bed.

CHAPTER 3 EXPERIMENTAL SET-UP, MEASURING EQUIPMENTS AND DATA ANALYSIS

3.1 INTRODUCTION

All experiments for this study were performed in a straight glass-sided flume with a rectangular cross section. A 3-D Acoustic Doppler Velocimeter (ADV) was used to measure the velocity distribution and flow turbulence properties. The software, WinADV, developed by SonTek, was used to convert signals to useful data. For the rough bed condition, the channel was roughened using sand particles with a median diameter of 3.1mm. Several manometers were used to measure the water surface level.

Details of the flume system, experiment set-up, applications of measuring equipments and data treatment method are discussed in the following sections.

3.2 FLUME SYSTEM

The experiments were carried out using a glass-sided flume that was 14 m long, 600 mm wide and 600 mm deep (as shown in Figure 3.1). The water in the flume was re-circulated using a centrifugal pump. The speed of the pump's motor was controlled by a frequency inverter controller. An adjustable weir formed the downstream wall of the rectangular water tank. The weir provided the water level control.

Flow over the weir was re-circulated to the flume by the main pump. The flow entered the upstream end of the flume through a honeycomb flow straightener (depicted in Figure 3.1). An adjustable water surface skimmer was used to reduce surface wave formation. The honeycomb flow straightener effectively eliminated any rotational flow component induced in the return pipelines. Six manometers

and a hook gauge with 0.1mm resolution were attached vertically to the sidewall along the flume to measure the water surface elevation. The velocity measurement site was situated at 8m away from the entry of flow, where the flow was fully developed.

Figure 3.1 Schematic diagram of experimental flume

3.3 BOUNDARY ROUGHNESS

The channel bed of the flume was roughened using uniform sand with a median size of 3.1 mm. Figure 3.2 shows the particle size distribution of the sand used.

Figure 3.2 Sieve analysis of the sand used

The procedures of roughening the channel bed were as follows. First, a coat of paint was applied on the channel bed. Loose sand of the selected size was sprinkled uniformly over the bed until the entire painted surface was completely covered. The bed was left to dry for more than 48 hours. The roughened bed was checked and the exposed surface repainted/recoated as necessary to ensure that the whole surface was completely covered with sand.

3.4 MEASURING TOOLS - ACOUSTIC DOPPLER VELOCIMETER (ADV)

In the experiments, the velocity profiles were measured using an Acoustic Doppler Velocimeter (ADV) set at a sampling rate of 25Hz. Velocity measurement using ADV was not as straight forward as it appeared. In operating the ADV, certain considerations needed to be taken into account as are in the following sections:

(a) The principle behind the operation of the ADV is based on the Doppler effects. The Doppler effect states that if a sound source is moving relative to the receiver, the frequency of the sound received by the receiver is shifted from the transmitted frequency by the amount:

$$F_{doppler} = -F_{source} \frac{V}{C} \quad (3-1)$$

where $F_{doppler}$ = change in received frequency (Doppler shift), F_{source} = frequency of transmitted sound, V = velocity of source relative to receiver and C = speed of sound.

The velocity V represents the relative speed between the source and receiver (i.e. motion that changes the distance between the two). Motion perpendicular to the line connecting the source and receiver does not introduce a Doppler shift. If the distance between the two objects decreases, the frequency increases; conversely, if the distance increases the frequency decreases.

The parameters which control the quality of the signal/data, are the signal to noise ratio (SNR) and correlation coefficient (COR). A SNR value above 15 is normally considered good for a 25Hz sampling rate and the device is able to capture the fluctuation of the flow velocity. A SNR value of 5 is acceptable for mean velocity measurement. The COR is an indicator of the relative consistent behaviour of scatter in a sampling volume during the sampling period. According to the ADV

manufacturer (SonTek, 1997), the COR value recommended should be above 70. Wahl (2000b) mentioned that a COR value of less than 70 could sometimes provide good data especially when the SNR was high and the flow was relatively turbulent. In a turbulent flow, it would be reasonable to assume that particles in the sample volume would not maintain their relative position with each other. Therefore, this could cause the addition of the Doppler noise to the return signal. In this case, low signal correlations were encountered. It might not necessarily mean that the data was bad (Wahl, 2000b). According to Martin et al (2002), for turbulent flows, ADV measurement could be used to calculate average velocities and generate velocity profiles if the measured data were processed based on the correlation filter set to as low as 40%, and provided that after filtering 70% or more data had been retained for analysis.

(b) During the measurement, seeding particles were required to increase the SNR value. The SNR value without the seeding particles was found to be less than 5. The seeding particles which were used in the present study were kaolin powder ($3.4\mu\text{m} - 4.4\mu\text{m}$). The kaolin powder was mixed with water and then dispensed at the entrance of the flume.

(c) For the ADV used, the distance of sampling volume was 5 cm away from the transmitter probe. It was recommended that the distance of the probe to the boundary should be less than 25 cm. If it was more than 25 cm then the ADV would not be able to detect the boundary; and the position of the sampling volume could not be determined. In present experiments, it was found that the nearest distance from the sampling volume to the boundary was around 4.7 mm.

(d) The range of velocity could be determined before the measurement according to the expected magnitude of velocity. This range setting would improve the accuracy of measurement. For certain conditions, the ADV would automatically set the range (due to the noise) especially for measurement near the bed. The velocity data, position of measurement, SNR and COR which were recorded using the ADV could be extracted using an executable program, WinADV provided by the manufacturer.

There are three types of 3D-ADV based on the direction of measurement, i.e. up-looking, down-looking, and side-looking. Figure 3-3 shows these three types of probe. In this study, the down-looking 3D-ADV and side-looking 3D-ADV were used to measure the velocity profiles.

Figure 3.3. Three types of ADV probe.

3.6 REFERENCE BED LEVEL FOR ROUGHENED CHANNEL

For flow in a roughened channel, it is vital to determine a reference level. According to previous investigations of velocity profile measurement, determination of the reference level where the mean velocity is zero along the wall has caused considerable concern. It has been stated that the actual point where the velocity is zero is somewhere below the roughness elements. According to Kamphuis (1974) and Bayazit (1976), the reference bed level lies between the bottom and the top surface of the roughness elements. Kirkgoz (1989) suggested that the thickness of the reference shift, which represented the frictional viscous

sub-layer on a “rough” wall, decreased with increasing Reynolds number, but it was not affected by the roughness height. In 1962, Rotta used a value of $0.035k_s$ for the sand grain roughness, where k_s is the average height of the roughness elements, as shown in Figure 3.4. Dou (1987) obtained a theoretical value of $0.107k_s$ based on the analysis of flow separation between the particles on the boundary. Song (1994) applied a value of $0.25k_s$ from the top of the element as the reference bed level for his experiment. The findings of other researchers who investigated this phenomenon are tabulated in Table 3.1.

In this study, it was found that a value of $0.25k_s$ should be used to determine the reference bed level for experiments with roughened channel.

Table 3.1 Values of datum obtained by various investigators

Author	Type of roughness	Datum below the top of element
O’Loughlin & Macdonald (1964)	Sand roughness	$0.27k_s$
Blinco & Partheniades (1971)	Sand roughness	$0.27k_s$
Kamphuis (1974)	Sand roughness	$0.3k_s$
Bayazit (1976)	Hemispherical elements	$0.35k_s$
Hollingshead & Rajaratnam (1980)	Sand & hemispheres	$0.20k_s$

Figure 3.4 Definition sketch of reference bed level for rough channel

3.6 EXPERIMENTAL METHODS AND PROCEDURE

3.6.1 Setting Up Uniform Flow

For a certain discharge, the tailgate was gradually and carefully adjusted such that the flow depths, measured using manometers located along the upstream and downstream of the velocity measurement site were equal. The distance between the two manometers was 8m. If the flow depths were not equal or within the tolerance limit, then the discharge and tailgate were re-adjusted until the desired water depth and flow rate were obtained.

3.6.2 Velocity Measurement

A 3-D ADV was used to measure the point flow velocities. The velocity at any point at the test cross-section was recorded for duration of 60 seconds. If fluctuation is too large or unreasonable, more readings were taken to ensure that accurate results were obtained.

A total of 7 test runs were carried out for smooth bed conditions. Velocity profiles of 4 test runs were measured according to the scheme of the velocity measurement stations as shown in Figure 3.5. The velocity profiles of another 3 test runs were measured along the centre line of the flume.

For rough bed conditions, 8 test runs were also conducted. The velocity profiles of 3 test runs were measured according to the scheme of the velocity measurement stations as depicted in Figure 3.5. Only centre line velocity profiles were measured for the remaining 5 rough bed test runs.

Figure 3.5 Schematic sketch of the velocity measuring stations

3.6.3 Experimental Procedure

Before each run of the experiment, the following preparations were made:

1. The pump was started and the discharge was adjusted gradually until it reached the expected flow rate and depth. For a certain discharge, the tailgate was adjusted carefully to achieve the appropriate uniform flow condition in the channel. The experiment began when a uniform flow depth was established.
2. The flow depths were checked regularly to ensure that they remained constant throughout the experiments
3. The 3-D ADV were checked before and after each experiment.

A total of 7 tests were conducted in a smooth bed channel. The aspect ratios ranged from 1.95 to 4.62. Table 3.2 shows a summary of the relevant hydraulic parameters for the smooth bed channel runs.

Table 3.2 Summary of the experimental condition in smooth channel (b=60cm)

Run	Flow Depth h (cm)	Hydraulic Radius R (cm)	Aspect ratio b/h	Discharge Q (l/s)	Bed Slope S
S1	13.00	9.07	4.62	42.82	0.00065
S2	16.60	10.69	3.61	61.83	0.00065
S3	19.50	11.82	3.08	76.71	0.00065
S4	21.90	12.67	2.74	90.53	0.00065
S5	24.00	13.33	2.50	105.32	0.00065
S6	27.60	14.38	2.17	126.60	0.00065
S7	30.70	15.17	1.95	146.14	0.00065

A total of 8 experimental runs were also performed for rough bed channel. The roughness elements, in the form of sand with $k_s=3.1\text{mm}$, were attached firmly on the channel bed. The channel aspect ratios range from 2.21 to 4.48. Table 3.3 shows a summary of the relevant hydraulic parameters for the rough bed channel runs.

Table 3.3 Summary of the experimental condition in rough channel (b=60cm)

Run	Flow Depth h (cm)	Hydraulic Radius R (cm)	Aspect ratio b/h	Discharge Q (l/s)	Bed Slope S
R1	13.40	9.26	4.48	36.75	0.00075
R2	15.85	10.37	3.79	45.17	0.00075
R3	17.30	10.97	3.47	54.60	0.00075
R4	18.75	11.54	3.20	61.43	0.00075
R5	21.20	12.42	2.83	75.85	0.00075
R6	22.80	12.95	2.63	86.32	0.00075
R7	23.70	13.24	2.53	97.69	0.00075
R8	27.10	14.24	2.21	118.05	0.00075

CHAPTER 4 VELOCITY DISTRIBUTION IN UNIFORM OPEN CHANNEL FLOW

4.1 INTRODUCTION

Most laboratory experiments related to hydraulics and sediment transport are carried out in rectangular open channels. The laws which govern the flow motion in a rectangular open channel are very important both for practical applications and fundamental studies.

With reference to the literature review on classical knowledge of velocity distribution, it is clear that the logarithmic law (or log-law in short) plays an important role in determining the velocity distribution. To date, many researchers have attempted to extend the log law into a comprehensive and well-developed model to describe the velocity profiles.

According to Nezu and Nakagawa (1993), modern theory of turbulence indicates that the log-law is applicable only in the inner wall region ($\frac{y}{h} < 0.2$). The mixing-length in the outer region ($\frac{y}{h} > 0.2$) of an open channel flow is limited. In 1956, Coles derived an additional term, which acted as a supplement to the log law, to cater for the velocity deviation caused by wake (known as Coles law). However, it only worked when the aspect ratio of the flow, $\frac{b}{h}$, is considerably large. This modification could not be applied to the situation of dip phenomenon, as the latter normally occurs when the aspect ratio of the flow is relative small. It follows that the Coles law is insufficient to describe the whole velocity profile. Elaboration on the mechanism and modelling of dip phenomenon is necessary

In this chapter, the log laws for both the smooth bed and rough bed were further investigated and verified based on the present experimental data. Meanwhile, the significance of the Coles law was also investigated in light of the present experimental data. The critical aspect ratio, which distinguishes the two dimensional flow regions from that of the three dimensional flow for steady uniform flows with rough bed, was studied by examining the centreline velocity profile. Furthermore, simplified equations to describe the velocity profile from bed to surface and from centre location of the flow to sidewall were developed for both the smooth and rough bed. These equations were intended to cater for the dip phenomenon. Based on the developed velocity distribution equations, practical and simple semi empirical formulae were developed to locate the vertical location of the maximum streamwise velocity.

4.2 VELOCITY DISTRIBUTION IN A SMOOTH BED OPEN CHANNEL FLOW

With reference to Section 3.6.3, 7 tests were carried out for the smooth bed condition. In the present investigation, bed slopes were fixed at 0.00065. The Reynolds number varied between 2.85×10^5 and 9.74×10^5 , indicating that the investigated flows were turbulent. The hydraulic parameters of the present study are summarised in Table 4-1.

Table 4.1 Summary of the flow parameters for the smooth bed experiments

Run	Q (l/s)	S	h (cm)	R (cm)	$h_{\max}$ (cm)	b/h	U (cm/s)	Re (10^5)	u_{th} (cm/s)	u_{tr} (cm/s)	C_s	Π
S1	42.82	0.00065	13.00	9.07	10.50	4.62	54.90	2.85	2.88	2.40	5.20	0.10
S2	61.83	0.00065	16.60	10.69	13.10	3.61	62.08	4.12	3.25	2.61	5.62	0.09
S3	76.71	0.00065	19.50	11.82	15.00	3.08	65.56	5.11	3.53	2.75	5.10	0.13
S4	90.53	0.00065	21.90	12.66	15.55	2.74	68.90	6.04	3.74	2.84	5.50	0.08
S5	105.32	0.00065	24.00	13.33	16.50	2.50	73.14	7.02	3.91	2.92	5.70	0.10
S6	126.60	0.00065	27.60	14.38	18.30	2.17	76.45	8.44	4.20	3.03	5.75	0.11
S7	146.14	0.00065	30.70	15.17	20.10	1.95	79.34	9.74	4.42	3.11	5.80	0.09

Run	z/h	$u_{(z)}$ (cm/s)
S1	2.31	2.88
	1.50	2.88
	1.00	2.69
	0.50	1.90
S3	1.54	3.53
	1.50	3.53
	1.00	3.42
	0.50	2.42
S5	1.25	3.91
	1.00	3.85
	0.75	3.34
	0.50	2.72
S7	0.98	4.42
	0.75	3.84
	0.50	3.13
	0.25	2.21

Note: Q-Flow discharge; S- Bed Slope; h- Flow depth; R- Hydraulic Radius; $h_{\max}$ - Distance between the channel bed and the point where the streamwise velocity is maximum (at centreline profile; b/h- Aspect ratio; $Re = 4hU/\nu$, Reynolds number; $u_{*h} = \sqrt{ghS}$; $u_{*R} = \sqrt{gRS}$; C_s - Constant of integration of log law; Π – Coles wake factor; z – Distance from side wall; $u_{*(z)} = \sqrt{gh_{(z)}S}$; $h_{(z)}$ - Effective depth for the computation of local bed shear velocity. (Details can be referred to Section 2.3.2)

4.2.1 Logarithmic Law in A Smooth Bed Open Channel Flow

As mentioned in section 2.2.1, the velocity distribution in uniform flow for smooth bed can be expressed by the logarithmic law in the inner region where

$\frac{y}{h} < 0.2$, that is

$$\frac{u}{u_{*(z)}} = \frac{1}{K} \ln \left(\frac{u_{*(z)} y}{\nu} \right) + C_s \quad (4-1)$$

where $u_{*(z)} = \sqrt{g h_{(z)} S}$ and C_s = Integration constant

Based on the present experimental data, the validity of Equation (4-1) will be verified and the value of the constant C_s will be established.

Figure 4.1 shows the measured centreline velocity profiles of the 7 tests. The profiles are compared with Equation (4-1). The figure shows that the data points do not have a common slope. For smaller flow depth (larger aspect ratio), the gradient of the profile approaches the slope of Equation (4-1). In contrast, the slope of the profile deviates gradually from the slope of Equation (4-1) for smaller aspect ratios.

Figure 4.1 Centreline velocity distributions for smooth rectangular channels

The present experimental data were then re-plotted in the manner of $\frac{u}{u_{*o}}$ versus $\frac{u_{*(z)}y}{\nu}$, as shown in Figure 4.2. It was found that the data were well described by Equation (4-2).

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*(z)}y}{\nu} \right) + C_s \quad (4-2)$$

where $u_{*o} = \sqrt{gRS}$, $u_{*(z)} = \sqrt{g h_{(z)}S}$ and C_s = Integration constant

Tracy and Lester (1961) also observed this phenomenon. It is noted that Equation (4-1) could be further modified into Equation (4-2)

Figure 4.2 Centreline velocity distribution related to average shear velocity for smooth rectangular channels

The log law in the form of Equation (4.2) was then used to identify the actual value of C_s for each runs. The C_s values for each test runs are tabulated in Table 4.1. The comparisons of measured velocity and the logarithmic law are shown in Figure 4.3. The dividing line between the outer and inner region was established by deviation of the velocity profile away from log-law.

Figure 4.3 Comparisons of present measured velocity data and log law (smooth bed)

Figure 4.3 Comparisons of present measured velocity data and log law (smooth bed)
(continued)

Figure 4.3 Comparisons of the present measured velocity data and log law (smooth bed) (continued)

The values of C_s obtained from the present experimental data range from 5.1 to 5.8. They are in good agreement with values reported in the literature, i.e. $C_s = 5$ (Huffman and Bradshaw), $C_s = 5.29$ (Nezu and Rodi, 1986) and $C_s = 5.5$ (Kirkgoz, 1989).

4.2.2 Velocity Defect Law In A Smooth Bed Open Channel Flow

Figure 4.3 clearly shows that the log law cannot represent the velocity profile in the outer region. Therefore, the writer adopts the Coles law in the following form:

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*(z)} y}{\nu} \right) + C_s + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi y}{2h_{\max}} \quad (4-3)$$

where Π is the dimensionless wake factor.

The measured velocity profiles obtained in this study are presented as a function of $\frac{u}{u_{*o}}$ versus $\frac{u_{*(z)} y}{\nu}$ in Figure 4.4. The Coles law is also included in the plot. It is noted that the measured velocity agrees reasonably well with the Coles law in both the inner and outer regions for flows with large aspect ratio. It is also obvious from the plot that the Coles law is not able to describe the velocity distribution near the water surface for those flows with small aspect ratio, i.e. experiments S3, S4, S5, S6 and S7.

The distinct velocity deficits near the water surface as observed in experiments S3, S4, S5, S6 and S7 are known as dip phenomenon; and this topic is focused in the following section.

The values of Π obtained from the present experiment data ranges from 0.08 to 0.13 and they fall in the same range as the result of Nezu and Rodi (1986) and Kironoto and Graf (1994). The values of Π obtained are listed in Table 4.1.

Figure 4.4 Comparisons of present measured velocity and Coles law (smooth bed)

Figure 4.4 Comparisons of present measured velocity and Coles law (smooth bed)
(continued)

Figure 4.4 Comparisons of the present measured velocity and Coles law (smooth bed) (continued)

4.2.3 Dip Phenomenon In A Smooth Bed Open Channel Flow

The log-law and Coles law describe the velocity profile well when the aspect ratio of the flow is larger than the limiting aspect ratio. It is a well-known fact that when the aspect ratio of flow is less than the limiting aspect ratio, the flow is 3 dimensional in nature. The maximum velocity will be observed at some distance vertically below the free surface. This phenomenon is known as the “dip phenomenon”. The log law and Coles law could not be used to describe the region of dip phenomenon.

The writer attempts to discuss the dip phenomenon and develop a simplified equation to describe the velocity profile that would also include the dip phenomenon.

4.2.3.1 The Dip Phenomenon

The outer region is dominated by the flow depth and is featured by the dip-phenomenon. With reference to the statements made by Cardoso et al. (1989) and Nezu and Nakagawa (1993), a universal, simple and practical method should be discovered to describe the dip phenomena. In 2000, Sarma et al fitted the velocity distribution using a combination of the log-law and binary law for the outer region and inner region, respectively. Such investigation requires the prior knowledge of velocity distribution. Thus, good agreement between measured velocity profile and Sarma et al.'s binary law is not surprising because the coefficient for the binary law is highly dependent on the velocity profile.

One of the objectives of the present study is to develop a set of user-friendly equations to fill the deficiency of log law and Coles law and target the problem of the dip-phenomena. The set of equations should be able to describe the velocity profiles across the cross section of flows in both the smooth bed and rough bed. Smooth bed condition will be discussed first. Section 4.3.4 elaborates on the dip-phenomenon in rough bed condition.

4.2.3.2 Theoretical Consideration and Determination of the Dip-Correction Factor, β_s

Equation (2-63) can be re-written as follow by adding in the Coles law:

$$\frac{u}{u_{*o}} = \underbrace{\frac{1}{\kappa} \ln \left(\frac{u_{*o} y}{\nu} \right)}_{\text{Log law}} + C_s + \underbrace{\frac{2\Pi}{\kappa} \sin^2 \frac{\pi y}{2h_{\max}}}_{\text{Coles law}} + \underbrace{\frac{\beta_s}{\kappa} \ln \left(1 - \frac{y}{h} \right)}_{\text{Dip phenomenon term}} \quad (4-4)$$

The effect of Coles law on the velocity distribution is of lesser significance, as shown in Figure 4.4. As in all engineering approach, one would neglect the less significant term first. In order to simplify the problem and obtain the expression of

parameter β_s , the wake term of the Coles law can be taken out first. Equation (4-4) becomes

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*o} y}{\nu} \right) + C_s + \frac{\beta_s}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-5)$$

The location of the maximum velocity in a vertical profile can be derived analytically by differentiating Equation (4-5) and setting $\frac{du}{dy} = 0$, that is

$$\frac{h_{\max}}{h} = \frac{1}{1 + \beta_s} \quad (4-6)$$

where $h_{\max}$ is the distance of the maximum velocity point from the bed. Equation (4-6) shows that β_s is dependent only on the relative distance of the location of maximum velocity to the water depth, $h_{\max}/h$.

Figure 4.5 shows the measured β_s in the centreline velocity profile from the present experimental data plotted against aspect ratio, $\frac{b}{h}$. A simple empirical relationship

between β_s and $\frac{b}{h}$ is proposed with R^2 value of 0.95:

$$\beta_s = 1.5 \exp \left(-\frac{b}{2h} \right) \quad (4-7)$$

Figure 4.6 shows the relationship between β_s and $\frac{b}{h}$ based on the measured data from various researchers. It is seen that Equation (4-7) can describe the measured

data well. For a wide channel (large $\frac{b}{h}$), β_s is zero in the central portion, i.e. the dip-phenomenon disappears. The dip appears for smaller $\frac{b}{h}$ values.

Wang et al. (2001) obtained the following empirical equation based on measured data from the published literature,

$$\frac{h_{\max}}{h} = 0.44 + 0.212 \frac{z}{h} + 0.05 \sin\left(\frac{2\pi}{2.6} \frac{z}{h}\right) \quad (4-8)$$

His experiments have shown that $h_{\max}$ is related to the lateral position, $\frac{z}{h}$ of the measured velocity profiles in the channel.

Since the flow is uniform and under smooth bed condition, Equation (4-7) can be re-expressed as follow:

$$\beta_s = 1.5 \exp\left(-\frac{z}{h}\right) \quad (4-9)$$

Equation (4-9) describes the data obtained from experiments S1, S3, S5 and S7 well, as shown in Figure 4.7. The validity of equation was further verified using collected data from NHRI (1957) and Yang (1996), as depicted in Figure 4.8. Equation (4-8) developed by Wang et al (2001) is also included in Figure 4.8. Figure 4.8 shows that Equation (4-9) and Wang et al's (2001) equation yielded

similar values of β_s for $\frac{z}{h} < 2.5$. This figure also shows that the dip phenomenon

can be observed near the sidewall (small $\frac{z}{h}$) even if $\frac{b}{h}$ is large.

It can be concluded that the dip-correction factor β_s in Equation (4-4) can be evaluated using Equation (4-9) for smooth bed rectangular channels.

Figure 4.5 The measured β_s in the centreline velocity profile as obtained from the present experimental data plotted against aspect ratio, $\frac{b}{h}$

Figure 4.6 The relationship between β_s and $\frac{b}{h}$ based on measured data from various researchers.

Figure 4.7 The relationship between β_s and $\frac{z}{h}$, based on data from S1, S3, S5 and S7 of the present study.

Figure 4.8 The relationship between β_s and $\frac{z}{h}$, open symbols based on data were extracted from Yang (1996) and solid symbols from NHRI (1957).

4.2.3.3 Verification of the Cross-Sectional Velocity Profiles (Smooth Bed)

By examining Equation (4-4) and (4-9), an equation for describing the vertical velocity profiles from the centreline to sidewall is achieved.

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*(z)} y}{\nu} \right) + C_s + \mathcal{E} + \frac{1.5 \exp \left(-\frac{z}{h} \right)}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-10a)$$

where $u_{*(z)} = \sqrt{gh_{(z)} S}$; $\mathcal{E}$ - an error term; $h_{(z)}$ - the effective depth for the computation of local bed shear velocity. The value of $h_{(z)}$ can be computed using the division line method as described in Section 2.3.2.

The error term, $\mathcal{E}$, is assumed to be of a form similar to the wake term multiplied by a factor. In present study, the factor was found to be “1”. Equation (4-10a) is re-expressed as follow.

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*(z)} y}{\nu} \right) + C_s + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi y}{2h_{\max}} + \frac{1.5 \exp \left(-\frac{z}{h} \right)}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-10b)$$

The velocity measurements from the present study and Yang (1996) will be used to verify the validity of Equation (4-10b).

Figure 4.9 shows a comparison of the measured data points and the computed velocity profiles using Equation (4-10b). The comparison shows that the proposed equation is able to capture the whole velocity profiles well. The occurrence of the dip- phenomenon is depicted clearly.

The second set of data is from Yang (1996). The data was measured in a smooth rectangular channel. The parameter $\frac{u}{u_{*o}}$ is plotted against $\frac{u_{*(z)} y}{\nu}$ in Figure 4.10. It can be seen that the measured velocity data agrees reasonably well with that predicted using Equation (4-10b).

The above comparisons show that Equation (4-10b) is able to capture the velocity dip phenomenon and described adequately the velocity distribution in entire profile, including the inner and outer region. After introducing the term $u_{*(z)}$ in it, Equation (4-10b) is able to depict clearly the tendency of smaller shear velocity along the transverse direction towards the side wall. This is the major improvement of the present equation over the classical log law.

Figure 4.9 Comparisons of the present experiments and the computed velocity profiles using Equation (4-10b)

Figure 4.9 Comparisons of the present experiments and the computed velocity profiles using Equation (4-10b)

Figure 4.9 Comparisons of the present experiments and the computed velocity profiles using Equation (4-10b)

Figure 4.10 Comparisons of Yang (1996) data and the computed velocity profiles using Equation (4-10b)

4.3 VELOCITY DISTRIBUTION IN A ROUGH BED OPEN CHANNEL FLOW

The preceding section has satisfactorily described the velocity distribution in a smooth bed open channel flow. In this section, the velocity distribution model for a rough bed open channel flow will be introduced. With reference to Section 3.6.3, 8 tests were carried out for the rough bed condition. In the present investigation, the bed slopes were fixed to 0.00075. The Reynolds number varied between 2.45×10^5 and 7.87×10^5 indicating turbulent flow. The hydraulic parameters for the rough bed study are summarised in Table 4-2.

Table 4.2 Summary of the flow parameters for the rough bed experiments

Run	Q (l/s)	S	h (cm)	R (cm)	h_{max} (cm)	b/h	U (cm/s)	Re (10^5)	u_{log} (cm/s)	u_h (cm/s)	C_r	Π
R1	36.75	0.00075	13.40	9.26	13.40	4.48	45.71	2.45	3.12	3.14	7.94	0.15
R2	45.17	0.00075	15.85	10.37	15.85	3.79	47.50	3.01	3.24	3.41	8.18	0.20
R3	54.60	0.00075	17.30	10.97	17.30	3.47	52.60	3.64	3.53	3.57	8.06	0.19
R4	61.43	0.00075	18.75	11.54	16.00	3.20	54.60	4.10	3.73	3.71	8.12	0.17
R5	75.85	0.00075	21.20	12.42	17.20	2.83	59.63	5.06	4.06	3.95	8.22	0.10
R6	86.32	0.00075	22.80	12.95	17.50	2.63	63.10	5.75	4.19	4.10	8.17	0.15
R7	97.69	0.00075	23.70	13.24	18.50	2.53	68.70	6.51	4.39	4.18	8.40	0.06
R8	118.05	0.00075	27.10	14.24	18.70	2.21	72.60	7.87	4.63	4.47	8.25	0.12

	z/h	$u_{log(z)}$ (cm/s)
R1	2.23	3.12
	1.00	3.06
	0.75	3.03
	0.50	3.01
	0.25	2.93
R3	1.73	3.53
	1.00	3.50
	0.75	3.48
	0.50	3.46
	0.25	3.38
R7	1.27	4.39
	1.00	4.31
	0.75	4.22
	0.50	4.06
	0.25	4.02

Note: Q-Flow discharge; S- Bed Slope; h- Flow depth; R- Hydraulic Radius; $h_{\max}$ - Distance between the channel bed and the point where streamwise velocity is maximum (at centreline profile); b/h- Aspect ratio; $Re = 4hU/\nu$, Reynolds number; u_{*log} - Shear velocity obtained from log law; $u_{*h} = \sqrt{ghS}$; C_r - Constant of integration of log law; Π – Coles wake factor. $u_{*log(z)}$ - Local shear velocity obtained from log-law.

4.3.1 Two-Dimensionality of Flow In A Rough Bed Open Channel Flow

Past research has shown that in a smooth open channel flow a two-dimensional flow region exists near the centre if the aspect ratio, $\frac{b}{h} > 5$. The question now is whether the limiting aspect ratio value is also equal to 5 for flow with rough beds. In the present study, the writer measured the velocity profiles for flow with different aspect ratios ranging from 2.21 to 4.48. The measured centreline velocity profiles of the experiments are shown in Figure 4.11.

It can be seen from Figure 4.11 that the dip phenomenon starts to become obvious in the centreline velocity profile of R4. Thus, it is found that the limiting value of aspect ratio for distinguishing between a 2-D flow from a 3-D flow in this study is not equal to 5, but between 3.47 and 3.20. The value of 3.34 is taken as the limiting aspect ratio for this study.

Figure 4.11 Centreline velocity profiles of the rough bed experiments

4.3.2 Logarithmic Law In A Rough Bed Open Channel Flow

As mentioned in Section 2.2.1, the velocity distribution in a uniform flow with smooth bed can be expressed by the log law for the inner region, that is:

$$\frac{u}{u_{*log}} = \frac{1}{\kappa} \ln \left(\frac{y}{k_s} \right) + C_r, \quad \frac{y}{h} < 0.2 \quad (4-11)$$

where u_{*log} - local shear velocity and is identified from the velocity profile ; normally $C_r = 8.5$.

According to Section 3.6, the reference bed level should be integrated in Equation (4-11). In the present studies, a value of $0.25k_s$ was used as the reference bed level for experiments with roughened channel. This turns Equation (4-11) into

$$\frac{u}{u_{*log}} = \frac{1}{\kappa} \ln \left(\frac{y + 0.25k_s}{k_s} \right) + C_r \quad (4-12)$$

The logarithmic law, Equation (4.12) was then taken as the reference to the present experimental data in order to identify the actual values of u_{*log} and C_r for each test runs. The values of u_{*log} and C_r for each runs are tabulated in Table 4.2. The comparisons of the measured velocity and the logarithmic law are shown in Figure 4.12.

Figure 4.12 Comparisons of the measured centreline velocity and the log law (rough bed)

Figure 4.12 Comparisons of the measured centreline velocity and the log law (rough bed) (continued)

Figure 4.12 Comparisons of the measured centreline velocity and the log law (rough bed) (continued)

Figure 4.12 Comparisons of the measured centreline velocity and the log law (rough bed) (continued)

4.3.3 Velocity Defect Law In A Rough Bed Channel

Similar to the case of smooth bed, the log law cannot adequately describe the velocity profile in the outer region. Hence, Coles law is again used in the following form:

$$\frac{\bar{u}}{u_{*log}} = \frac{1}{\kappa} \ln \left(\frac{y + Y_o}{k_s} \right) + C_r + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi(y + Y_o)}{2(h_{max} + Y_o)} \quad (4-13)$$

Here, $Y_o = 0.25 k_s$. The details of Coles law has been described in Section 2.2.2.

The measured velocity profiles are shown as $\frac{u}{u_{*log}}$ versus $\frac{y + Y_o}{k_s}$ in Figure

4.13. Coles law is also plotted in the same figure. It is noted that the measured velocity profile agrees reasonably well with the Coles law in both the inner and

outer region for the flows with large aspect ratio. Again, Coles law cannot capture the velocity distribution near the water surface for those flows with small aspect ratio, especially experiments R5, R6, R7 and R8. Equation (4-13) should be improved to capture the dip phenomenon.

The values of Π are presented in Table 4.2. The values of Π obtained from the present experiment ranges from 0.05 to 0.20 and they fall in the same range as that of Song (1994).

Figure 4.13 Comparisons of the present measured velocity and Coles law (rough bed)

Figure 4.13 Comparison of the present measured velocity and Coles law (rough bed) (continued)

Figure 4.13 Comparison of the present measured velocity and Coles law (rough bed) (continued)

Figure 4.13 Comparison of the present measured velocity and Coles law (rough bed) (continued)

4.3.4 Dip Phenomenon In A Rough Bed Open Channel Flow

From the discussion in the preceding sections, it is clear that the log law and Coles law describe the velocity profile well when the aspect ratio of the flow is larger than the corresponding limiting aspect ratio. Similar to the problem encountered in smooth bed condition, the log law and Coles law are not able to describe the region of dip phenomenon for the case of rough bed. In the following sections, efforts are expended to introduce a term into the log law and Coles law in order to capture the full velocity profiles.

4.3.4.1 Theoretical Consideration and Determination of the Dip-Correction Factor, β_r

Equation (2-50) can be re-written as follow by adding in the Coles law:

$$\frac{u}{u_{* \log(z)}} = \underbrace{\frac{1}{\kappa} \ln \left(\frac{y + Y_o}{k_s} \right)}_{\text{Log law}} + C_r + \underbrace{\frac{2\Pi}{\kappa} \sin^2 \frac{\pi(y + Y_o)}{2(h_{\max} + Y_o)}}_{\text{Coles law}} + \underbrace{\frac{\beta_r}{\kappa} \ln \left(1 - \frac{y}{h} \right)}_{\text{Dip phenomenon term}} \quad (4-14)$$

The effect of Coles law on the velocity distribution is of lesser significance, as shown in Figure 4.13. In order to simplify the problem and obtain the expression of the parameter β_r , dip-correction factor, the wake term is taken out first. Equation (4-14) becomes

$$\frac{u}{u_{* \log(z)}} = \frac{1}{\kappa} \ln \left(\frac{y + Y_o}{k_s} \right) + C_r + \frac{\beta_r}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-15)$$

Firstly, by integrating u with respect to dy , the writer determines the depth-averaged mean velocity, $U_{mean(z)}$, as shown in Equation (4-16)

$$\frac{U_{mean(z)}}{u_{* \log(z)}} = \frac{1}{\kappa} \ln \left(\frac{h}{k_s} \right) + C_r - \frac{1}{\kappa} - \frac{\beta_r}{\kappa} \quad (4-16)$$

By re-arranging Equation (4-16), the dip-correction factor, β_r , can be determined as follow:

$$\beta_r = \ln \left(\frac{h}{k_s} \right) + \kappa C_r - 1 - \frac{\kappa U_{mean(z)}}{u_{* \log(z)}} \quad (4-17)$$

Similar to the case of smooth bed, by examining Equation (4-14) and (4-17), Equation (4-18) is obtained to describe the vertical velocity profiles from the centreline to sidewall for the case of rough bed.

$$\frac{u}{u_{*log(z)}} = \frac{1}{\kappa} \ln \left(\frac{y+Y_o}{k_s} \right) + C_r + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi(y+Y_o)}{2(h_{max}+Y_o)} + \frac{\left[\ln \left(\frac{h}{k_s} \right) + \kappa C_r - 1 - \frac{\kappa U_{mean(z)}}{u_{*log(z)}} \right]}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-18)$$

Verification of this proposed velocity distribution model is discussed in the next section.

4.3.4.2 Verification with Cross-Sectional Velocity Profiles (Rough Bed)

Velocity measurement from the present study and Yang (1996) were used to verify the applicability of Equation (4-18).

Figure 4.14 shows a comparison of the measured and the computed velocity profiles using Equation (4-18). The comparison shows that the agreement of proposed equation and the measured cross sectional velocity profiles is satisfactory.

Yang's (1996) experiments are used to verify Equation (4-18). Two sets of experiments, with flow depth of 16.7cm and 9.7cm were measured in a 500mm wide rough bed rectangular channel. The comparisons of Equation (4-18) and Yang's data are shown in Figures 4.15 (a) and (b). It can be seen that the measured velocity profile agrees reasonably well with that predicted using Equation (4-18).

The above comparisons show that Equation (4-18) is able to capture the velocity dip phenomenon well and gives good description of the velocity dip phenomenon, the velocity distribution in the entire profile including those in the inner and outer regions.

Figure 4.14 Comparisons of the measured and the computed velocity profiles using Equation (4-18)

Figure 4.14 Comparisons of the measured and the computed velocity profiles using Equation (4-18) (continued)

Figure 4.15(a) Comparisons of Equation (4-18) and Yang's data (1996) – ($h = 16.7$ cm)

Figure 4.15(b) Comparisons of Equation (4-18) and Yang's data (1996) – ($h = 9.7$ cm)

4.4 CONCLUSIONS

Full scale velocity distribution models, for the smooth and rough bed condition are developed with verifications satisfactorily. Based on the discussions in the preceding sections, it can be concluded that:

1. For the smooth bed condition, the classical log-law is valid in the entire inner region including the central and the corner portions if the local shear velocity is introduced, as in the form $\frac{u_{*(z)}y}{\nu}$.
2. A dip-modified log law model plus Coles law, which comprises Equation (4-10b) for smooth bed and Equation (4-18) for rough bed, has been derived.

The equations take into accounts the negative Reynolds shear stress near the free surface. This proposed model consists of a combination of two logarithmic distances, one from the bed and the other from the free surface, and a dip-correction factor β . If there is no dip in the velocity profile, i.e., $\beta = 0$, then the equation reverts to the classical log law and Coles law.

3. For a smooth bed, the dip-correction factor β_s is dependent only on the distance of the location of the maximum velocity from the bed. A simple equation has been proposed for β_s . For a rough bed, the corresponding dip-correction factor β_r is dependent on the depth-averaged mean velocity, $U_{mean(z)}$ and local shear stress $u^*_{log(z)}$.
4. The newly proposed models are able to describe very well the velocity distribution profiles transversely along the cross-section of the flow. It can simulate the dip phenomenon well.

CHAPTER 5 TURBULENCE DISTRIBUTION IN OPEN CHANNEL FLOW

5.1 INTRODUCTION

Due to the complexity of the physics involved, there is no single complete theory that is able to describe and explain fully the turbulence phenomena in an open channel flow. Most of the existing works are based on semi-empirical hypotheses to establish relationships between turbulence stresses caused in exchanges and the time-averaged velocities. A review of the literature shows that turbulence behaviours of two dimensional (2-D) open channel flows have been widely studied. Dou (1987), Nezu and Nakagawa (1993), and Kironoto and Graf (1993) have developed some turbulence models to cover the turbulence behaviours of a 2-D open channel flow. The comparisons of their models with measured data are in good agreement. However, the turbulence behaviours of a 3-D open channel flow are yet to be established by simpler and straightforward equations.

In this chapter, turbulence intensities in three dimensional (3-D) open channels were discussed. Both smooth and rough bed conditions were investigated. For the smooth bed condition, experiment sets S1, S3, S5 and S7 were measurements of velocity in the transverse direction. Similarly, data measurements of R1, R3 and R7 are similar measurements for the case of rough bed. Comparisons of the present measured data with the turbulence intensities models and Reynolds stress distribution models developed by Dou, Nezu and Nakagawa, and Kironoto and Graf were performed. Based on the dip-phenomenon discussed in earlier chapters, the writer introduced a modified Reynolds stress distribution model. The dip correction factors, β_s and β_r , have been determined for smooth bed and rough bed conditions, respectively.

In this chapter, the applicability and convenience of the present modified Reynolds shear stress model is verified. Determination of the location of maximum velocity using Reynolds shear stress profiles is discussed.

5.2 COVARIANCE METHOD (COV)

In turbulent flow, the value of local bed shear stress $\tau_{(z)}$ can be regarded as the near-bed Reynolds stress $\tau_{(z)} = -\rho \overline{u'v'}$ (Hearthershaw and Simpson, 1978). In the near bed logarithmic layer, the covariance component, $-\overline{u'v'}$ (Reynolds shear stress component) and $u_{*(z)}$, local shear velocity are related by (Tennekes and Lumley, 1972)

$$\frac{\overline{u'v'}}{u_{*(z)}^2} = 1 - \frac{1}{\left(\frac{\kappa u_{*(z)} y}{\nu} \right)} = 1 - \frac{1}{R} \quad (5-1)$$

$$\text{where } R = \left(\frac{\kappa u_{*(z)} y}{\nu} \right).$$

In a fully rough turbulent flow, the Reynolds number, R is large ($>>1$). Then, Equation (5-1) becomes

$$\frac{\overline{u'v'}}{u_{*(z)}^2} \approx 1 \quad (5-2)$$

The results obtained by Grass (1971) and McQuivey and Richardson (1969) for $\frac{\overline{u'v'}}{u_{*(z)}^2}$ are shown in Figure. 5.1. The shear stresses between flow layers are induced

by turbulence. The turbulent shear stresses $\rho \overline{u'v'}$ are linear with flow depth. The term $-\overline{u'v'}$ is zero near the surface and is at its maximum near the flow bed. The representative Reynolds shear stress can be identified by drawing a tangential line to the linear Reynolds shear stress distribution and obtain the intercept. The value of

the intercept is regarded as the corresponding Reynolds shear stress (turbulence shear stress) at the bottom boundary.

As compared to the log-profile method, the covariance (COV) method is not dependent on the vertical velocity profile spanwise. This method appears ideal because the covariance ($-\overline{u'v'}$) represents the unbiased prediction of the near-bed shear stress.

Figure 5.2 (a) and (b) shows the examples of determining the $-\overline{u'v'}$ in the smooth bed and rough bed conditions, respectively. The computed local turbulent shear velocities are summarised in Table 5.1(a) and (b). According to the comparisons of local shear velocities determined in the preceding chapter and local turbulent shear stress as shown in Table 5.1 (a) and (b), it was found that the difference of the values in every corresponding location and condition was within $\pm 10\%$. This further verified the applicability of COV method and served as a counter-check on the reliability of various methods on determining the local shear velocities.

Figure 5.1 Vertical Profile of $-\frac{\overline{u'v'}}{u_*^2}$ (after McQuivey, R.S., and Richardson, E.V. 1969)

Figure 5.2 (a) Example of determining turbulent shear stress in the smooth bed condition; (b) Example of determining turbulent shear stress in the rough bed condition.

Table 5.1 (a) Summary of local shear velocities in smooth bed experiments; (b) Summary of local shear velocities in rough bed experiments.

(a)

Run	z/h	$u^*_{(z)}$ (cm/s)	u^*_{τ} (cm/s)	$(u^*_{\tau} - u^*_{(z)})/u^*_{(z)}$ %
S1	2.31	2.88	2.98	3.5
	1.50	2.88	2.90	0.7
	1.00	2.69	2.66	-1.0
	0.50	1.90	2.07	8.9
S3	1.54	3.53	3.33	-5.5
	1.50	3.53	3.35	-5.0
	1.00	3.42	3.21	-6.3
	0.50	2.42	2.62	8.2
S5	1.25	3.91	4.06	3.8
	1.00	3.85	3.94	2.2
	0.75	3.34	3.63	8.8
	0.50	2.72	2.78	1.9
S7	0.98	4.42	4.36	-1.5
	0.75	3.84	4.04	5.2
	0.50	3.13	3.37	7.6
	0.25	2.21	2.49	10.2

(b)

Run	z/h	$u^*_{\log(z)}$ (cm/s)	u^*_{τ} (cm/s)	$(u^*_{\tau} - u^*_{\log(z)})/u^*_{\log(z)}$ %
R1	2.23	3.12	3.32	6.4
	1.00	3.06	3.09	1.0
	0.75	3.03	3.05	0.7
	0.50	3.01	2.98	-1.0
	0.25	2.93	2.86	-2.4
R3	1.73	3.53	3.76	6.5
	1.00	3.50	3.69	5.5
	0.75	3.48	3.46	-0.3
	0.50	3.46	3.31	-4.2
	0.25	3.38	3.13	-7.4
R7	1.27	4.39	4.60	4.9
	1.00	4.31	4.43	2.8
	0.75	4.22	4.34	2.7
	0.50	4.06	4.10	1.0
	0.25	4.02	3.98	-1.1

z = distance from sidewall; h = flow depth ; $u^*_{(z)}$ = local shear velocity for smooth bed;

$u^*_{\log(z)}$ = local shear velocity for rough bed; u^*_{τ} = local turbulent shear stress, $\sqrt{\overline{u'v'}}$.

5.3 TURBULENCE DISTRIBUTION IN A SMOOTH BED OPEN CHANNEL FLOW

In this section, the turbulence intensities distribution in a smooth bed open channel flow, including the horizontal turbulence intensities ($\sqrt{u'^2}$), vertical turbulence intensities ($\sqrt{v'^2}$) and Reynolds stress intensities ($-\overline{u'v'}$), are presented.

5.3.1 Horizontal Turbulence Intensities, $\sqrt{u'^2}$ in A Smooth Bed Open Channel Flow

The RMS-values of the horizontal velocity fluctuations measured in experiments S1, S3, S5 and S7 were used to investigate the behaviour of horizontal turbulence intensities, $\sqrt{u'^2}$.

According to Section 2.2.3, Dou (1987) has developed an equation to describe the distribution of $\sqrt{u'^2}$ in a 2-D flow, as depicted in equation (5-3).

$$\frac{\sqrt{u'^2}}{u_{*T}} = \left\{ \frac{\frac{u_* y}{2\nu}}{11.6 + \frac{u_* y}{\nu}} + 0.36 \left(1 - \frac{y}{h_{\max}} \right) \left[\frac{\frac{u_* y}{\nu}}{1 + \frac{u_* y}{\nu}} + \frac{0.464 \left(\frac{u_* y}{\nu} \right)^2 - 0.02 \left(\frac{u_* y}{\nu} \right)^3}{\left(1 + \frac{u_* y}{5\nu} \right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-3)$$

In 1993, Nezu and Nakagawa used the fiber-optic laser-Doppler anemometer data, together with hot-wire data and hot-film data to calibrate the exponential law. They found the following relationship for the 2-D smooth bed open channel flow:

$$\frac{\sqrt{u'^2}}{u_{*T}} = 2.3 \exp \left(-\frac{y}{h_{\max}} \right) \quad (5-4)$$

where $h_{\max}$ = vertical location of maximum velocity, $h_{\max}$ equals to flow depth for 2-D flow; y = vertical distance from bed.

These two models were compared with the writer's measurements, see Figures 5.3 (a), (b), (c) and (d).

Overall, $\sqrt{u'^2}$ decreases with an increase of y ; it attains a minimum value near the water surface. The comparisons show the applicability of Dou's equation and Nezu and Nakagawa's equation in describing the $\sqrt{u'^2}$ distribution transversely across the flow cross section. Nezu and Nakagawa's equation clearly show better agreement with the present measurements. Using $h_{\max}$ instead of flow depth in Equation (5-3) has made the equation more versatile and applicable to the 3-D cases as well. From the comparisons, it is clearly observed that Dou's equation is not able to describe the velocity distribution near the water surface when the dip phenomenon exists. This is mainly due to the effect of the term, $1 - \frac{y}{h_{\max}}$ in Equation (5-3). When the flow becomes closer to be a 3-D flow, dip phenomenon occurs. The term $h_{\max}$ becomes lower. The term $1 - \frac{y}{h_{\max}}$ becomes negative at the lower vertical location. As the value of $h_{\max}$ becomes lower, $1 - \frac{y}{h_{\max}}$ becomes more negative. Consequently, Equation (5-3) becomes invalid in addressing the $\sqrt{u'^2}$ distribution in a 3-D flow.

It can be concluded that Equation (5-4) from Nezu and Nakagawa is more appropriate and applicable in describing the distribution of $\sqrt{u'^2}$ in a 3-D flow.

Figure 5.3(a) The comparison of S1 with Equations (5-4) and (5-3)

Figure 5.3 (b) The comparison of S3 with Equations (5-4) and (5-3)

Figure 5.3 (c) The comparison of S5 with Equations (5-4) and (5-3)

Figure 5.3 (d) The comparison of S7 with Equations (5-4) and (5-3)

5.3.2 Vertical Turbulence Intensities, $\sqrt{v'^2}$ in A Smooth Bed Open Channel Flow

The RMS-values of the vertical velocity fluctuations measured in experiments S1, S3, S5 and S7 are used to study the behaviour of vertical turbulence intensities, $\sqrt{v'^2}$. Applicability of Dou's model and Nezu and Nakagawa's model is discussed.

Dou (1987) developed an equation to describe the distribution of $\sqrt{v'^2}$ in a 2-D smooth bed flow, as depicted in Equation (5-5).

$$\frac{\sqrt{v'^2}}{u_{*T}} = \left\{ \frac{\frac{u_* y}{2\nu}}{11.6 + \frac{u_* y}{\nu}} + 0.04 \left(1 - \frac{y}{h_{\max}} \right) \left[\frac{\frac{u_* y}{\nu}}{1 + \frac{u_* y}{\nu}} + \frac{0.464 \left(\frac{u_* y}{\nu} \right)^2 - 0.02 \left(\frac{u_* y}{\nu} \right)^3}{\left(1 + \frac{u_* y}{5\nu} \right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-5)$$

Nezu and Nakagawa (1993) found the following relationship for the smooth bed:

$$\frac{\sqrt{v'^2}}{u_{*T}} = 1.27 \exp \left(-\frac{y}{h_{\max}} \right) \quad (5-6)$$

The suitability of their model in capturing $\sqrt{v'^2}$ distribution in a 3-D flow is checked by comparing with current measurement, as shown in Figures 5.4 (a), (b), (c) and (d).

Basically, $\sqrt{v'^2}$ decreases with an increase of y ; it attains the minimum value near the water surface. The comparisons of Dou's equation and Nezu and Nakagawa's equation are shown in Figure 5.4 (a), (b), (c) and (d). Most of the measured data fall in between the predictions of Equation (5-5) and Equation (5-6)

in the outer region. In the inner region, Dou's equation predicts that the maximum turbulence intensity occurs at the location very near to the bed, which is different from the present measurement which depicts a higher location. It is also observed that Equation (5-6) tends to overestimate the magnitude of $\sqrt{v'^2}$ in the inner region. The deviation may be attributed to the difficulty in correctly orienting the hot-film anemometer, as pointed out by Krogstad et al. (1992). Physically, it might be due to the limitation of eddy development. The turbulence eddies may not develop in the vertical direction near the bed because of the proximity of the bed. When the location of eddy is further away from the bed, this limitation disappears gradually, and the eddy becomes larger and stronger, with the maximum intensities at a certain y above the bed. Further away, a cascade of smaller eddies is formed. Near the surface, the strength of eddy becomes minimum.

Figure 5.4 (a) The comparison of S1 with Equations (5-6) and (5-5)

Figure 5.4 (b) The comparison of S3 with Equations (5-6) and (5-5)

Figure 5.4 (c) The comparison of S5 with Equations (5-6) and (5-5)

Figure 5.4 (d) The comparison of S7 with Equations (5-6) and (5-5)

5.3.3 Reynolds Stress Distribution in A Smooth Bed Open Channel Flow

By combining the past research findings, the traditional Reynolds stress distribution can be expressed simply in Equation (5-7) as:

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h_{\max}} \quad (5-7)$$

The use of Equation (5-7) is highly dependent on $h_{\max}$, which needs to be determined first from the measured velocity profile.

Dou (1987) also proposed an analytical equation for describing Reynolds shear stress distribution in a 2-D flow. His equation is shown below. (Details can be found in Section 2.2.3)

$$\frac{\overline{u'v'}}{u_{*T}^2} = \left(1 - \frac{y}{h_{\max}}\right) - \frac{\left(1 - \frac{y}{h_{\max}}\right)}{1 + \left(1 - \frac{y}{h_{\max}}\right) \frac{u_* y}{5\nu}} - \frac{\left[0.464 \left(\frac{u_* y}{\nu}\right)^2 - 0.02 \left(\frac{u_* y}{\nu}\right)^2\right] \left(1 - \frac{y}{h_{\max}}\right)^3}{\left[1 + \left(1 - \frac{y}{h_{\max}}\right) \frac{u_* y}{5\nu}\right]^3} \quad (5-8)$$

In the preceding chapter, the dip-phenomenon was studied based on a modified Reynolds shear stress distribution. By combining Equation (2-58) and Equation (4-9), one could obtain an equation to capture Reynolds shear stress in a 3-D flow:

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h} - 1.5 \exp\left(-\frac{z}{h}\right) \left(\frac{y}{h}\right) \quad (5-9)$$

Equations (5-7), (5-8) and (5-9) are plotted against the present measurement as shown in Figures 5.5 (a), (b), (c) and (d).

Obviously, these three models have captured the Reynolds shear stress profiles well. This conclusion also extends to include the distribution transversely across the flow cross section. This also means that these three models are able to describe the effect of three dimensionality of the flow.

By examining, the versatility and simplicity of the models, Equation (5-9) appear to be more outstanding. Equations (5-7) and (5-8) are highly dependent on $h_{\max}$ and its accuracy crucial. The difficulty mounted as the complete velocity profile needed to be determined a priori. Hence, it is not user-friendly. Equation (5-8) may be too complicated for the application of normal engineering purpose. On the other hand, Equation (5-9) has the advantage of using the factor of $\frac{z}{h}$ with the effect of $h_{\max}$ accounted for. It avoids the inaccuracy incurred during the determination of $h_{\max}$.

As a result, Equation (5-9) is recommended for use to address the Reynolds shear stress distribution in a 3-D smooth bed open channel flow.

Figure 5.5 (a) The comparison of S1 with Equations (5-9), (5-8) and (5-7)

Figure 5.5 (b) The comparison of S3 with Equations (5-9), (5-8) and (5-7)

Figure 5.5 (c) The comparison of S5 with Equations (5-9), (5-8) and (5-7)

Figure 5.5 (d) The comparison of S7 with Equations (5-9), (5-8) and (5-7)

5.4 TURBULENCE DISTRIBUTION IN A ROUGH BED OPEN CHANNEL FLOW

Turbulence intensities distribution in a 3-D rough bed open channel flow including the horizontal turbulence intensities ($\sqrt{u'^2}$), vertical turbulence intensities ($\sqrt{v'^2}$) and Reynolds stress intensities ($-\overline{u'v'}$), are investigated. Explanations on various distribution models are suggested.

5.4.1 Horizontal Turbulence Intensities, $\sqrt{u'^2}$ in A Rough Bed Open Channel Flow

The RMS-values of the horizontal velocity fluctuations measured in R1, R3 and R7 are used to study the behaviour of horizontal turbulence intensities, $\sqrt{u'^2}$.

Similar to the case of a smooth bed, Dou (1987) developed an equation to describe the distribution of $\sqrt{u'^2}$ in a 2-D flow, as depicted in Equation (5-10a). (Detailed explanations have been presented in Section 2.2.3).

$$\frac{\sqrt{u'^2}}{u_{*T}} = \left\{ \frac{\left(\frac{u_* k_s}{2\nu} \right) \left(\frac{y}{k_s} \right)}{11.6 + \left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right)} + 0.36 \left(1 - \frac{y}{h_{\max}} \right) \left[\frac{\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right)}{1 + \left(\frac{u_* k_s}{5\nu} \right) \left(\frac{y}{k_s} \right)} + \frac{0.464 \left(\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right) \right)^2 - 0.02 \left(\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right) \right)^3}{\left(1 + \left(\frac{u_* k_s}{5\nu} \right) \left(\frac{y}{k_s} \right) \right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-10a)$$

$\frac{u_{*T(z)} k_s}{\nu}$ has a top capped value of 100 as explained in Section 2.2.3. Then Equation (5-10a) can be rewritten as:

$$\frac{\sqrt{u'^2}}{u_{*T}} = \left\{ \frac{50\left(\frac{y}{k_s}\right)}{11.6 + 100\left(\frac{y}{k_s}\right)} + 0.36\left(1 - \frac{y}{h_{\max}}\right) \left[\frac{100\left(\frac{y}{k_s}\right)}{1 + 20\left(\frac{y}{k_s}\right)} + \frac{4640\left(\frac{y}{k_s}\right)^2 - 20000\left(\frac{y}{k_s}\right)^3}{\left(1 + 20\left(\frac{y}{k_s}\right)\right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-10b)$$

Kironoto and Graf's (1994) conducted a series of experiments to study the turbulence characteristics in a uniform open channel flow with rough bed. In their study, a rough plate with a mean roughness height $k_s = 4.8\text{mm}$ and a gravel bed with $d_{50} = 23.0\text{mm}$ were used. A Pitot-tube was used to measure the velocity profiles. The turbulence characteristics were measured with a two-component hot film probe. Their experiments showed that for flows with rough beds, the turbulence intensity in the horizontal direction can be expressed as:

$$\frac{\sqrt{u'^2}}{u_{*T}} = 2.04 \exp\left(-0.97 \frac{y}{h_{\max}}\right) \quad (5-11)$$

In the present study, these two models in a 3-D rough bed open channel flow was compared with the present measurements. Figures 5.6(a), (b), (c) and (d) show the comparison of these two equations with the present measurements.

Generally, the observed distribution trend of $\sqrt{u'^2}$ in a rough bed is similar to the phenomenon observed in a smooth bed. The term $\sqrt{u'^2}$ decreases with an increase of y . The minimum value is found near the water surface. This trend is observed at every location in the transverse direction along the flow cross section. The comparisons show that Kironoto and Graf's equation is able to describe the trend of $\sqrt{u'^2}$ distribution transversely across the flow. From the comparisons, it is clearly seen that Dou's equation is not able to describe the distribution near to the water surface when the dip-phenomenon exists. Again, this is mainly due to the effect of the term, $1 - \frac{y}{h_{\max}}$ in Equations (5-10a) and (5-10b). When the flow

becomes 3-D, the dip phenomenon occurs. The term $h_{\max}$ becomes smaller and $1 - \frac{y}{h_{\max}}$ becomes negative when y is greater than $h_{\max}$. When the dip-phenomenon becomes more prominent nearer to the wall, the value of $h_{\max}$ becomes very low; it means that $1 - \frac{y}{h_{\max}}$ becomes more negative. This phenomenon causes Equations (5-10a) and (5-10b) to be invalid and not applicable for addressing the $\sqrt{u'^2}$ distribution in a 3-D flow.

It can be concluded that Equation (5-11) from Kironoto and Graf is better in describing the whole $\sqrt{u'^2}$ distribution in a 3-D rough bed open channel flow.

Figure 5.6 (a) The comparison of R1 with Equations (5-11) and (5-10a)/(5-10b)

Figure 5.6 (b) The comparison of R3 with Equations (5-11) and (5-10a)/(5-10b)

Figure 5.6 (c) The comparison of R7 with Equations (5-11) and (5-10b)

5.4.2 Vertical Turbulence Intensities, $\sqrt{v'^2}$ in A Rough Bed Open Channel Flow

The RMS-values of the vertical velocity fluctuations measured in R1, R3 and R7 are used to investigate the behaviour of vertical turbulence intensities, $\sqrt{v'^2}$. Dou's model and Kironoto and Graf's model are used to investigate the $\sqrt{v'^2}$ profiles with respect to $\frac{z}{h}$.

An analytical equation to describe the distribution of $\sqrt{v'^2}$ in a 2-D flow was developed by Dou in 1987. Equation (5-12a) shows the full form of the equation

$$\frac{\sqrt{v'^2}}{u_{*T}} = \left\{ \frac{\left(\frac{u_* k_s}{2\nu} \right) \left(\frac{y}{k_s} \right)}{11.6 + \left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right)} + 0.04 \left(1 - \frac{y}{h_{\max}} \right) \left[\frac{\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right)}{1 + \left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right)} + \frac{0.464 \left(\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right) \right)^2 - 0.02 \left(\left(\frac{u_* k_s}{\nu} \right) \left(\frac{y}{k_s} \right) \right)^3}{\left(1 + \left(\frac{u_* k_s}{5\nu} \right) \left(\frac{y}{k_s} \right) \right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-12a)$$

The term, $\frac{u_{*T(z)} k_s}{\nu}$ has a top capped value of 100 as explained in Section 2.2.3.

Equation (5-12a) can be rewritten as

$$\frac{\sqrt{v'^2}}{u_{*T}} = \left\{ \frac{50 \left(\frac{y}{k_s} \right)}{11.6 + 100 \left(\frac{y}{k_s} \right)} + 0.04 \left(1 - \frac{y}{h_{\max}} \right) \left[\frac{100 \left(\frac{y}{k_s} \right)}{1 + 20 \left(\frac{y}{k_s} \right)} + \frac{4640 \left(\frac{y}{k_s} \right)^2 - 20000 \left(\frac{y}{k_s} \right)^3}{\left(1 + 20 \left(\frac{y}{k_s} \right) \right)^3} \right]^2 \right\}^{\frac{1}{2}} \quad (5-12b)$$

Kironoto and Graf (1994) found the following relationship for the rough bed condition:

$$\frac{\sqrt{v'^2}}{u_{*T}} = 1.15 \exp\left(-0.76 \frac{y}{h_{\max}}\right) \quad (5-13)$$

The suitability of their model in capturing $\sqrt{v'^2}$ distribution in a 3-D flow is checked by comparing with the present measurements, as shown in Figures 5.7 (a), (b) and (c)

Similar to the case of the smooth bed, $\sqrt{v'^2}$ decreases when y increase; it attains a minimum value near the water surface. Both Equations (5-12a)/(5-12b) and (5-13) show satisfactory agreement with most of the measured data in the outer region. In the inner region, Dou's equation again does not tally with the experiment at the near bed region. Kironoto and Graf's equation (Equation (5-13)) tends to overestimate the magnitude of $\sqrt{v'^2}$ in the inner region. It may be due to the experimental error in adjusting the apparatus, as pointed out by Krogstad et al. (1992). It may also be due to the limitation of eddy development created by the flow and roughness element. The explanation of this phenomenon is similar to that found in Section 5.3.2 (the case of a smooth bed).

Figure 5.7 (a) The comparison of R1 with Equations (5-13) and (5-12a)/(5-12b)

Figure 5.7 (b) The comparison of R3 with Equations (5-13) and (5-12a)/(5-12b)

Figure 5.7 (c) The comparison of R7 with Equations (5-13) and (5-12b)

5.4.3 Reynolds Stress Distribution in A Rough Bed Open Channel Flow

The Reynolds stress distribution is normally expressed by Equation (5-14).

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h_{\max}} \quad (5-14)$$

The prediction of Equation (5-14) is highly dependent on $h_{\max}$, which needs to be determined first from the measured velocity profile.

Dou (1987) proposed an analytical equation for describing Reynolds shear stress distribution in a 2-D flow.

$$-\frac{\overline{u'v'}}{u_{*T}^2} = \left(1 - \frac{y}{h_{\max}}\right) - \frac{\left(1 - \frac{y}{h_{\max}}\right)}{1 + \left(1 - \frac{y}{h_{\max}}\right)\left(\frac{u_* k_s}{5\nu}\right)\left(\frac{y}{k_s}\right)} - \frac{\left[0.464\left(\left(\frac{u_* k_s}{\nu}\right)\left(\frac{y}{k_s}\right)\right)^2 - 0.02\left(\left(\frac{u_* k_s}{\nu}\right)\left(\frac{y}{k_s}\right)\right)\right]\left(1 - \frac{y}{h_{\max}}\right)^3}{\left[1 + \left(1 - \frac{y}{h_{\max}}\right)\left(\frac{u_* k_s}{5\nu}\right)\left(\frac{y}{k_s}\right)\right]^3} \quad (5-15a)$$

The term $\frac{u_{*T(z)} k_s}{\nu}$ has a top capped value of 100 as explained in Section 2.2.3.

Then, Equation (5-15a) can be rewritten as:

$$-\frac{\overline{u'v'}}{u_{*T}^2} = \left(1 - \frac{y}{h_{\max}}\right) - \frac{\left(1 - \frac{y}{h_{\max}}\right)}{1 + 20\left(1 - \frac{y}{h_{\max}}\right)\left(\frac{y}{k_s}\right)} - \frac{\left[46.4\left(\frac{y}{k_s}\right)^2 - 200\left(\frac{y}{k_s}\right)\right]\left(1 - \frac{y}{h_{\max}}\right)^3}{\left[1 + 20\left(1 - \frac{y}{h_{\max}}\right)\left(\frac{y}{k_s}\right)\right]^3} \quad (5-15b)$$

In the preceding chapter, the dip-phenomenon was studied based on a modified Reynolds shear stress distribution. Using Equation (2-58) and Equation (4-17), one can capture Reynolds shear stress in a 3-D rough bed flow as follow:

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h} - \left(\ln\left(\frac{h}{k_s}\right) + \kappa C_r - 1 - \frac{\kappa U_{mean(z)}}{u_{*log(z)}} \right) \frac{y}{h} \quad (5-16)$$

Equations (5-14), (5-15a)/(5-15b) and (5-16) are plotted against the present measurement as shown in Figure 5.8 (a), (b) and (c).

Obviously, these three models have captured the Reynolds shear stress profiles well. This means that these three models are able to describe the effect of three dimensionality of the flow.

Equations (5-14), (5-15a) and (5-15b) are highly dependent on the value of h_{max} . The accuracy of h_{max} becomes crucial. The difficult mounted as the complete velocity profile needed to be determined a priori. Furthermore, due to the lengthiness of Equations (5-15a) and (5-15b), it is not very convenient for engineering application. Determination of the log-law in the inner region and depth averaged velocity ($U_{mean(z)}$) are vital to the present model. As long as accurate log-law and $U_{mean(z)}$ are established the model normally predicted the Reynolds shear stress distribution well.

Figure 5.8 (a) The comparison of R1 with Equations (5-16), (5-15a)/(5-15b) and (5-14)

Figure 5.8 (b) The comparison of R3 with Equations (5-16), (5-15a)/(5-15b) and (5-14)

Figure 5.8 (c) The comparison of R7 with Equations (5-16), (5-15b) and (5-14)

5.5 DETERMINATION OF THE LOCATION OF MAXIMUM VELOCITY USING REYNOLDS STRESS PROFILE

The maximum velocity usually occurs at the water surface for a 2-D open channel flow. The value of $-\overline{u'v'}$ in the vicinity of water surface is zero. In the present experiments, the limiting aspect ratio for a rough bed with $k_s = 3.1\text{mm}$ is 3.34. The aspect ratio of R1, which is 4.48, is greater than the limiting aspect ratio. Therefore, the value of $-\overline{u'v'}$ is found to be zero as shown in Figure 5.8(a).

In a 3-D open channel flow, the value of $-\overline{u'v'}$ at the vertical location of maximum velocity is first assumed to be zero. Based on this assumption, the corresponding locations, h_{maxR} , is determined using the measured Reynolds stress profiles. The reliability of the method is then verified with the results obtained and compared with the velocity profiles presented in the previous chapter. The comparisons for the smooth bed and rough bed conditions are shown in Table 5.2 (a) and (b), respectively.

The writer finds that the differences between h_{max} and h_{maxR} for the smooth bed condition and rough bed condition are less than 9.8% and 6.4%, respectively. The comparisons appear satisfactory. The minute difference observed may be due to parallax error. Therefore, the writer regards h_{maxR} as h_{max} in a 3-D open channel flow.

Table 5.2 (a) Comparisons of locations of maximum velocity in smooth bed experiments; (b) Comparisons of locations of maximum velocity in rough bed experiments.

(a)

	z/h	$h_{\max}$ (cm)	$h_{\max R}$ (cm)	$(h_{\max R} - h_{\max})/h_{\max}$ %
S1	2.31	10.50	11.05	5.2
	1.50	10.50	9.49	-9.6
	1.00	8.30	8.45	1.8
	0.50	6.50	6.76	4.0
S3	1.54	15.00	15.41	2.7
	1.50	14.70	15.02	2.1
	1.00	13.30	13.26	-0.3
	0.50	10.30	11.31	9.8
S5	1.25	16.50	16.56	0.4
	1.00	15.00	15.60	4.0
	0.75	14.00	14.64	4.6
	0.50	12.50	12.96	3.7
S7	1.25	20.10	19.65	-2.2
	1.00	18.30	17.50	-4.4
	0.75	16.30	16.27	-0.2
	0.50	13.30	14.43	8.5

(b)

Run	z/h	$h_{\max}$ (cm)	$h_{\max R}$ (cm)	$(h_{\max R} - h_{\max})/h_{\max}$ %
R1	2.23	13.40	13.40	0.0
	1.00	13.40	13.40	0.0
	0.75	10.50	11.12	5.9
	0.50	10.20	10.85	6.4
	0.25	9.00	9.51	5.7
R3	1.73	17.30	16.44	-5.0
	1.00	14.10	14.36	1.8
	0.75	13.20	12.98	-1.7
	0.50	12.10	12.46	2.9
	0.25	10.20	10.48	2.8
R7	1.27	18.50	19.20	3.8
	1.00	16.80	17.54	4.4
	0.75	15.40	15.41	0.0
	0.50	13.50	13.51	0.1
	0.25	12.30	12.56	2.1

5.6 CONCLUSIONS

Turbulence intensities distribution models, for the smooth and rough bed condition are studied. Based on the discussions in the preceding sections, it can be concluded that:

For the smooth bed:

- (1) Equation (5-4) from Nezu and Nakagawa is more applicable in describing the whole $\sqrt{u'^2}$ distribution in a 3-D flow. Dou's equation is not able to simulate the whole distribution in a 3-D flow.
- (2) For $\sqrt{v'^2}$ distribution, both Nezu and Nakagawa's model and Dou's model could not simulate the distribution well in the inner region. This is mainly because the development of turbulent eddies has not been taken into account.
- (3) Equations (5-7), (5-8) and (5-9) capture the Reynolds stress profiles well in a 3-D flow. Equation (5-9) (present model) appears to be superior because the final form only relates to z/h , instead of $h_{\max}$.

For the Rough Bed:

- (4) Equation (5-11) from Kironoto and Graf is more suitable in describing the whole $\sqrt{u'^2}$ distribution in a 3-D flow. Dou's equation has not been able to simulate the whole distribution in 3-D flow.
- (5) For $\sqrt{v'^2}$ distribution in rough bed, both Kironoto and Graf's model and Dou's model could not simulate the distribution well in the inner region, mainly because the development of turbulent eddies has not been taken into account.

(6) Equations (5-14), and (5-15) are highly dependent on the value of $h_{\max}$. The accuracy of $h_{\max}$ becomes crucial. The determination of log-law in the inner region and depth averaged velocity ($U_{mean(z)}$) are vital to the present model (Equation (5-16)). As long as the accuracy of log-law and $U_{mean(z)}$ can be ascertained, the present model predicts the Reynolds shear stress distribution well.

According to the findings in the preceding section, the location of maximum velocity could be determined using Reynolds shear stress profile. The accuracy is shown to be satisfactory.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

The primary aims of this study were achieved. The fundamental principles of open channel flows and turbulence theory in a 3-D open channel flow were investigated and semi-empirical techniques were applied to fully developed 3-D turbulent flow in an open channel.

Two formulae were developed to describe the characteristics of the velocity distribution and flow resistance in an open channel flow. Both smooth and rough beds were investigated. These equations describe the velocity profile from the bed to water surface and transversely from the centre line to the side wall region. The dip phenomenon in a 3-D open channel flow was included in these equations, as shown below:

For smooth bed,

$$\frac{u}{u_{*o}} = \frac{1}{\kappa} \ln \left(\frac{u_{*(z)} y}{\nu} \right) + C_s + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi y}{2h_{\max}} + \frac{\beta_s}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-4)$$

For rough bed,

$$\frac{u}{u_{*\log(z)}} = \frac{1}{\kappa} \ln \left(\frac{y + Y_o}{k_s} \right) + C_r + \frac{2\Pi}{\kappa} \sin^2 \frac{\pi(y + Y_o)}{2(h_{\max} + Y_o)} + \frac{\beta_r}{\kappa} \ln \left(1 - \frac{y}{h} \right) \quad (4-14)$$

Turbulence structures in a 3-D open channel flow were investigated. The dip phenomenon and secondary flow were included in the modified Reynolds stress distribution, as follow:

For smooth bed,

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h} - 1.5 \exp \left(-\frac{z}{h} \right) \left(\frac{y}{h} \right) \quad (5-9)$$

For rough bed,

$$\frac{\overline{u'v'}}{u_{*T}^2} = 1 - \frac{y}{h} - \left(\ln \left(\frac{h}{k_s} \right) + \kappa C_r - 1 - \frac{\kappa U_{mean(z)}}{u_{*log(z)}} \right) \frac{y}{h} \quad (5-16)$$

6.1 VELOCITY DISTRIBUTION AND DIP PHENOMENON IN A 3-D UNIFORM OPEN CHANNEL FLOW

Velocity distribution and the dip phenomenon in a 3-D uniform open channel flow have been investigated in this study. Both the smooth and rough bed conditions have been included.

The dip-modified log law model for a smooth and rough bed respectively has been derived. The equations take into accounts the negative Reynolds shear stress near the free surface. This proposed model consists of a combination of two logarithmic distances, one from the bed and the other from the free surface, and a dip-correction factor β . If there is no dip in the velocity profile, i.e., $\beta = 0$, then the equation reverts to the classical log law and Coles law.

For a smooth bed, the dip-correction factor β_s is dependent only on the distance of the location of the maximum velocity from the bed. An equation for β_s has been proposed. For a rough bed, the corresponding dip-correction factor β_r is dependent on the depth-averaged mean velocity, $U_{mean(z)}$ and local shear stress $u_{*log(z)}$.

From Section 4.2.3.3 and Section 4.3.4.2, it can be seen that the newly proposed model is able to describe the velocity distribution profiles transversely across the flow. The model reproduces the dip phenomenon well in both the 3-D smooth bed and rough bed open channel flows.

This work forms a good basis for the future work which could include further improvement on the models and extending the models to include non-uniform flows.

6.2 TURBULENCE INTENSITIES DISTRIBUTION IN A 3-D UNIFORM OPEN CHANNEL FLOW

Turbulence intensities distribution models, for the smooth and rough bed condition have been investigated.

In the case of a smooth bed, Nezu and Nakagawa (1993)'s model is more appropriate in describing the $\sqrt{u'^2}$ distribution in a 3-D flow, while Dou's equation (1987) could not cover the full range of the distribution. Both Nezu and Nakagawa's model and Dou's model could not correctly simulate the $\sqrt{v'^2}$ distribution in the inner region correctly.

Nezu and Nakagawa's model, Dou's model and the present modified models capture the Reynolds stress profiles in a 3-D flow. The present modified model appears superior because it only relates to z/h and avoids the inaccuracy incurred in the determination of $h_{\max}$. The latter is an advantage of the present model over the other 2 models,

For a rough bed, Kironoto and Graf's model (1994) is more suitable in describing the whole $\sqrt{u'^2}$ distribution in a 3-D flow while Dou's equation is unable to cover the full range of the distribution. For $\sqrt{v'^2}$ distribution in a rough bed, both Kironoto and Graf's model and Dou's model could not simulate the distribution well in the inner region, primarily because the development of turbulent eddies has not been taken into account.

Kironoto and Graf's model, Dou's model and the present modified model capture the Reynolds stress profiles well in a 3-D (rough bed) flow. Kironoto and Graf's model and Dou's model are highly dependent on the value of $h_{\max}$. Determination of the log-law in the inner region and depth-averaged velocity ($U_{mean(z)}$) are vital to the present model. As long as the accuracy of the log-law and $U_{mean(z)}$ can be ascertained, the present model predicts the Reynolds shear stress distribution well.

The location of maximum velocity could be determined using Reynolds shear stress profile for both smooth bed and rough bed conditions with satisfactory accuracy.

The writer would like to recommend that future development work could include:

- Examination of the turbulence structures in non-uniform flows
- Modification of the present models for Reynolds stress distribution to capture the turbulence characteristics in a non-uniform open channel flows.

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APPENDIX A – SMOOTH BED EXPERIMENTS

(a) Centreline Velocity Distribution Data

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S1	42.82	0.00065	13.0	9.07	4.62
S2	61.83	0.00065	16.6	10.69	3.61
S3	76.71	0.00065	19.5	11.82	3.08
S4	90.53	0.00065	21.9	12.66	2.74

S1	
y (cm)	u (cm/s)
0.82	45.20
1.28	47.63
1.90	49.01
2.42	50.47
3.00	51.72
3.50	52.65
4.50	54.68
5.50	56.43
6.50	57.46
7.50	58.15
8.50	58.22
9.50	59.26
10.50	59.43

S2	
y (cm)	u (cm/s)
0.81	49.83
1.00	52.04
1.52	54.03
1.97	55.42
2.53	58.05
3.02	58.41
3.50	59.45
4.10	60.87
5.10	61.42
6.10	63.18
7.10	64.32
8.10	65.11
9.10	66.31
10.10	66.30
11.10	66.10
12.10	66.72
13.10	67.11
14.10	66.35

S3	
y (cm)	u (cm/s)
0.70	51.22
1.05	53.83
1.45	56.00
1.87	58.30
2.40	59.83
2.93	60.92
3.50	62.18
4.20	64.38
4.70	65.11
5.50	65.89
6.50	67.18
7.50	67.15
8.50	67.72
9.50	68.90
10.50	68.88
11.50	68.60
12.50	69.70
13.50	69.71
14.50	69.74
15.50	69.90
16.50	69.12
17.00	69.70

S4	
y (cm)	u (cm/s)
0.76	54.62
1.00	56.63
1.52	59.02
1.97	60.60
2.53	63.30
3.02	64.72
3.50	66.13
4.50	66.11
5.50	68.77
6.50	69.89
7.50	70.90
8.50	71.52
9.50	72.33
10.50	71.54
11.50	72.86
12.50	72.37
13.50	74.16
14.50	74.21
15.50	74.55
16.50	73.27
17.50	72.00
18.50	72.18
19.40	72.32

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S5	105.32	0.00065	24.0	13.33	2.50
S6	126.60	0.00065	27.6	14.38	2.17
S7	146.14	0.00065	30.7	15.17	1.95

S5	
y (cm)	u (cm/s)
0.93	59.15
1.20	60.50
1.64	62.03
2.10	64.51
2.49	65.33
3.00	66.92
3.50	68.71
4.50	69.68
5.70	71.12
6.50	73.11
7.50	73.91
8.50	75.75
9.60	74.93
10.50	75.77
11.50	76.43
12.50	76.45
13.50	76.84
14.50	76.05
15.50	77.85
16.50	78.67
17.50	77.24
18.50	76.11
19.50	77.40
20.50	76.61
21.50	74.59

S6	
y (cm)	u (cm/s)
0.60	58.42
1.03	62.20
1.51	64.91
2.05	66.34
2.45	68.74
3.01	69.53
3.50	71.10
4.10	71.95
5.10	74.36
6.10	75.64
7.10	76.93
8.10	77.36
9.10	77.72
10.10	78.71
11.10	78.29
12.10	79.52
13.10	80.70
14.10	80.03
15.10	81.61
16.10	80.91
17.10	81.52
18.10	80.64
19.10	79.94
20.10	81.46
21.10	81.46
22.10	78.97
23.10	80.37
24.10	77.03
25.10	76.34

S7	
y (cm)	u (cm/s)
0.80	62.12
1.05	64.91
1.46	67.32
2.00	68.51
2.52	71.10
3.10	72.32
3.79	74.87
4.40	75.84
5.53	77.63
6.60	78.80
7.30	78.41
8.30	80.42
9.30	81.22
10.30	81.26
11.30	80.62
12.30	82.83
13.30	82.37
14.30	82.98
15.30	83.77
16.30	82.48
17.30	83.41
18.30	83.12
19.30	84.21
20.30	84.36
21.30	83.43
22.30	83.12
23.30	82.04
24.30	82.52
25.30	80.95
26.30	81.31
27.30	80.10
28.30	79.32

(b) Cross-Sectional Velocity Distribution**(1) S1**

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S1	42.82	0.00065	13.0	9.07	4.62

S1 - z/h=2.31				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.82	45.20	5.63	2.81	7.30
1.28	47.63	5.59	2.90	7.60
1.90	49.01	6.12	2.91	7.35
2.42	50.47	5.56	2.84	6.85
3.00	51.72	5.65	2.79	6.31
3.50	52.65	4.66	2.69	6.74
4.50	54.68	3.92	2.71	4.64
5.50	56.43	3.89	2.25	3.50
6.50	57.46	3.89	2.16	4.02
7.50	58.15	4.06	2.08	3.59
8.50	58.22	2.94	2.10	1.59
9.50	59.26	3.32	1.83	1.75
10.50	59.43	2.28	1.80	-0.29

S1 - z/h=1.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.94	46.82	6.56	2.96	7.10
1.48	48.72	6.09	2.92	7.50
1.99	50.51	5.68	2.80	6.37
2.47	51.33	5.83	2.68	6.04
3.02	52.37	4.91	2.84	5.64
3.50	53.92	5.27	2.76	6.37
4.50	54.88	4.78	2.73	4.75
5.50	56.41	3.99	2.47	4.34
6.50	57.22	3.46	2.18	3.44
7.50	57.12	3.66	1.92	2.19
8.50	58.03	3.59	1.96	1.32
9.50	57.21	2.96	1.38	0.02
10.50	57.73	2.43	1.64	-0.35

S1 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.83	43.52	6.19	2.58	5.79
0.98	45.72	5.84	2.72	6.37
1.56	47.43	5.75	2.69	5.79
1.95	48.01	5.23	2.56	5.84
2.51	49.42	5.21	2.47	4.59
3.50	51.21	4.23	2.39	3.99
4.50	54.45	4.00	2.15	3.55
5.50	54.73	2.94	2.21	2.84
6.50	55.82	2.78	1.83	2.43
7.50	55.14	2.55	1.90	2.56
8.50	56.42	1.94	1.66	0.22
9.50	54.32	1.75	1.57	-0.11
10.50	54.81	1.56	1.24	-0.72

S1 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
1.03	42.84	4.41	1.86	2.86
1.52	43.42	3.68	2.01	3.15
2.47	45.11	2.92	2.05	3.13
2.48	46.32	3.39	1.68	3.33
3.02	48.17	3.11	1.64	2.69
3.50	49.71	3.37	1.42	1.82
4.50	50.52	2.79	1.44	2.12
5.50	51.32	2.39	1.14	0.43
6.50	52.51	2.25	1.13	-0.08
7.50	51.66	2.32	1.04	-0.82
8.50	50.63	1.80	0.85	-0.80
9.50	50.88	1.53	0.97	-1.08
10.50	48.83	1.56	0.83	-2.20

(2) S3

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S3	76.71	0.00065	19.5	11.82	3.08

S3 - z/h=1.54				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.70	51.22	7.23	3.38	9.60
1.05	53.83	6.86	3.43	8.49
1.45	56.00	6.40	3.45	9.27
1.87	58.30	6.50	3.39	9.47
2.40	59.83	7.02	3.25	8.29
2.93	60.92	6.36	2.81	8.88
3.50	62.18	6.32	3.26	7.80
4.20	64.38	6.44	3.04	7.54
4.70	65.11	5.46	2.94	7.67
5.50	65.89	5.33	2.55	6.47
6.50	67.18	5.13	2.59	5.82
7.50	67.15	5.14	2.85	5.69
8.50	67.72	5.03	2.65	3.48
9.50	68.90	4.83	2.57	4.00
10.50	68.88	5.03	2.41	2.94
11.50	68.60	4.10	2.45	2.61
12.50	69.70	4.42	2.37	2.29
13.50	69.71	3.60	1.98	-0.88
14.50	69.74	3.23	1.98	-0.29
15.50	69.90	2.50	1.92	-0.75
16.50	69.12	2.77	2.06	-1.76
17.00	69.70	2.33	1.88	-1.49

S3 - z/h=1.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	52.00	6.94	3.05	9.82
1.08	54.50	6.55	3.31	10.91
1.60	56.01	6.08	3.17	9.51
2.00	58.40	6.11	3.09	9.40
2.54	59.20	6.34	3.01	8.40
3.03	60.91	6.21	3.03	7.80
3.48	61.91	5.55	2.79	7.74
3.99	62.18	5.32	2.84	9.96
4.50	63.17	5.49	2.73	7.84
5.50	65.31	5.23	2.67	6.80
6.50	65.57	5.06	2.48	5.71
7.50	65.66	4.04	2.54	4.64
8.50	67.30	3.45	2.43	4.32

9.50	67.22	3.38	2.37	3.07
10.50	68.52	3.15	2.32	2.51
11.50	68.92	3.45	2.09	2.46
12.50	69.14	3.52	1.97	1.94
13.50	68.50	2.92	2.01	0.30
14.50	69.32	2.79	1.80	0.51
15.50	70.20	3.12	1.87	-0.29
16.50	68.37	2.46	1.80	-0.74
17.00	67.57	2.37	1.90	-1.90

S3 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	52.23	6.19	3.03	7.06
1.02	53.84	6.32	3.15	8.80
1.28	54.86	6.10	3.21	8.32
1.66	57.71	5.23	3.17	8.09
1.98	57.70	5.71	3.34	8.32
2.46	59.62	5.55	2.92	7.92
3.20	60.01	5.24	2.78	7.13
3.49	61.88	5.07	2.52	7.77
4.50	62.47	4.56	2.32	7.45
5.50	64.28	3.75	2.25	6.57
6.40	65.41	3.63	2.22	5.44
7.60	65.73	3.46	1.83	4.86
8.50	66.40	2.98	1.65	5.30
9.50	66.12	3.43	2.00	2.30
10.50	66.87	2.57	1.87	1.87
11.50	67.19	2.25	1.25	1.23
12.50	67.03	2.37	1.13	1.30
13.50	68.50	1.89	1.40	-1.18
14.50	66.86	1.80	1.54	-2.70
15.50	66.50	1.77	1.22	-3.48
16.50	65.91	2.21	1.06	-3.24
17.00	66.52	2.05	1.04	-3.65

S3 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.89	49.90	4.41	2.46	5.52
1.08	51.63	5.70	2.51	5.97
1.51	53.87	4.89	2.62	6.30
1.95	54.81	5.33	2.60	6.04
2.32	57.10	4.49	2.52	5.31
2.99	58.22	4.44	2.47	5.11
3.56	59.04	4.26	2.24	4.14
3.92	58.71	4.41	2.39	4.91
4.61	60.82	3.86	2.35	3.19
5.50	61.42	3.73	2.05	3.19
6.50	62.70	3.52	1.89	2.20
7.50	62.06	3.23	1.62	1.93
8.50	62.21	2.52	1.68	1.79
9.50	63.52	3.10	1.53	1.38
10.50	63.83	2.89	1.32	1.12
11.50	63.01	2.47	1.38	-0.12
12.50	62.44	2.52	1.37	-1.38
13.50	62.25	1.69	1.29	-1.79
14.50	62.70	1.71	1.31	-3.73
15.50	61.46	2.00	0.86	-2.83
16.50	59.30	1.77	0.69	-3.31
17.00	60.61	1.79	0.89	-3.45

(3) S5

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S5	105.32	0.00065	24.0	13.33	2.50

S5 - z/h=1.25				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.93	59.15	9.75	3.78	13.40
1.20	60.50	9.04	3.98	14.60
1.64	62.03	8.62	3.61	13.60
2.10	64.51	6.98	4.24	14.49
2.49	65.33	7.35	3.97	13.20
3.00	66.92	6.36	4.06	12.72
3.50	68.71	6.82	4.02	12.13
4.50	69.68	6.58	3.88	11.00
5.70	71.12	6.50	3.47	10.80

6.50	73.11	5.33	3.35	9.87
7.50	73.91	6.50	3.03	9.80
8.50	75.75	5.14	2.94	9.20
9.60	74.93	5.03	2.65	6.33
10.50	75.77	4.83	2.99	6.72
11.50	76.43	5.03	2.75	4.85
12.50	76.45	5.32	2.60	4.85
13.50	76.84	4.42	2.37	3.67
14.50	76.05	3.60	2.46	-0.55
15.50	77.85	3.23	2.26	1.31
16.50	78.67	3.40	2.26	-0.75
17.50	77.24	3.17	2.24	-1.53
18.50	76.11	2.19	2.14	-1.92
19.50	77.40	2.52	1.91	-1.80
20.50	76.61	2.44	1.89	-2.44
21.50	74.59	2.07	1.42	-2.44

S5 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.72	57.21	7.56	3.56	12.40
1.00	58.18	7.28	3.69	13.40
1.53	61.57	7.59	3.54	12.51
1.99	64.21	7.15	3.72	13.08
2.47	66.32	6.34	3.57	13.00
3.00	66.71	5.84	3.65	11.80
3.50	68.00	6.61	3.69	11.80
4.40	69.52	6.17	3.25	9.96
5.50	70.93	6.57	3.29	9.40
6.50	72.70	5.59	2.97	8.60
7.50	72.71	5.29	2.91	8.15
8.50	73.93	5.01	2.78	8.20
9.50	73.91	4.36	2.63	6.54
10.50	75.24	4.72	2.59	6.00
11.50	75.42	4.50	2.32	5.20
12.50	75.46	4.00	2.30	2.75
13.50	77.21	3.52	2.30	4.00
14.50	76.80	2.92	2.18	0.80
15.50	77.21	2.79	2.03	0.51
16.50	77.20	3.12	1.87	-0.29
17.50	75.39	2.94	2.09	-0.80
18.50	76.00	2.40	1.86	-1.80
19.50	74.31	2.07	1.57	-2.20
20.50	73.12	1.85	1.62	-3.40
21.50	73.90	2.00	1.43	-3.14

S5 - z/h=0.75				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.74	55.83	6.67	3.63	9.67
0.96	57.43	7.23	3.89	11.05
1.50	60.43	7.32	3.86	11.23
1.99	62.81	6.79	3.65	11.91
2.50	64.22	6.14	3.34	10.96
3.01	65.87	6.41	3.37	10.29
3.50	67.92	5.94	3.06	10.24
4.50	69.51	5.50	3.13	10.35
5.50	69.73	5.26	2.92	7.72
6.50	71.70	5.15	2.87	7.20
7.50	71.14	4.47	2.69	6.75
8.50	72.12	4.38	3.01	5.69
9.50	73.15	3.91	2.80	5.14
10.50	73.94	3.43	2.54	4.64
11.50	73.52	3.32	2.42	3.40
12.50	74.73	3.35	2.39	2.20
13.50	74.86	2.67	2.37	1.54
14.50	74.21	2.91	2.00	-0.20
15.50	73.51	3.20	1.86	-1.00
16.50	74.72	2.64	1.93	-1.29
17.50	74.13	2.21	1.67	-1.80
18.50	72.03	1.76	2.00	-2.67
19.50	72.11	1.70	1.55	-2.73
20.50	71.98	1.70	1.22	-3.84
21.50	68.50	1.62	1.33	-3.06

S5 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.82	54.73	4.41	2.24	6.36
1.15	57.18	5.33	2.52	6.27
1.64	59.20	4.89	2.55	6.30
2.04	62.10	4.88	2.66	6.04
2.49	61.79	4.66	2.52	5.94
3.00	64.18	4.66	2.43	5.40
3.50	65.31	4.26	2.47	4.80
4.50	67.12	4.11	2.28	4.91
5.50	67.92	3.86	2.14	3.91
6.50	69.09	3.16	2.05	4.20
7.50	69.31	3.16	2.03	3.12
8.50	69.73	2.86	1.93	2.35
9.50	69.12	2.52	1.67	1.79
10.50	71.30	2.03	1.65	2.07
11.50	72.11	1.75	1.63	1.12
12.50	72.70	2.03	1.64	0.73

13.50	71.13	1.66	1.33	-0.43
14.50	71.31	1.69	1.44	-1.09
15.50	71.75	1.28	1.05	-0.60
16.50	69.65	2.00	1.22	-1.37
17.50	70.67	1.55	1.00	-2.20
18.50	68.23	1.79	1.04	-2.70
19.50	66.22	1.44	1.17	-2.60
20.50	66.32	0.61	1.00	-2.40
21.50	65.39	0.44	0.71	-4.11

(4) S7

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
S7	146.14	0.00065	30.7	15.17	1.95

S7 - z/h=0.98				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.80	62.12	9.02	4.71	16.45
1.05	64.91	9.48	4.55	17.33
1.46	67.32	9.43	5.10	17.90
2.00	68.51	9.16	4.90	17.71
2.52	71.10	8.78	4.88	16.97
3.10	72.32	8.37	4.90	17.52
3.79	74.87	8.13	4.77	16.65
4.40	75.84	8.23	4.49	14.52
5.53	77.63	7.62	4.30	14.80
6.60	78.80	8.23	4.38	11.91
7.30	78.41	6.97	3.97	12.80
8.30	80.42	7.02	4.10	12.19
9.30	81.22	7.16	3.53	10.16
10.30	81.26	7.11	3.39	10.06
11.30	80.62	6.69	3.03	7.55
12.30	82.83	6.41	3.42	7.45
13.30	82.37	6.27	3.23	5.97
14.30	82.98	6.00	2.70	7.06
15.30	83.77	6.09	2.59	4.58
16.30	82.48	5.53	2.79	5.42
17.30	83.41	5.34	2.84	5.32
18.30	83.12	4.65	2.37	3.10
19.30	84.21	3.81	2.79	0.87
20.30	84.36	4.00	2.59	-0.97
21.30	83.43	2.93	2.62	-0.29
22.30	83.12	3.44	1.96	-2.44
23.30	82.04	3.02	2.40	-2.10

24.30	82.52	2.51	2.37	-3.29
25.30	80.95	2.74	2.20	-3.90
26.30	81.31	2.42	2.45	-4.00
27.30	80.10	1.95	2.37	-4.06
28.30	79.32	1.53	1.93	-4.70

S7 - z/h=0.75				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	62.81	8.34	3.70	12.80
1.00	65.89	7.93	3.94	13.42
1.52	68.52	8.57	4.24	13.58
2.04	69.72	7.15	4.04	13.08
2.49	70.71	7.49	3.86	14.80
3.04	74.51	6.41	4.04	12.52
3.79	73.74	6.61	3.90	12.80
4.67	76.02	6.52	3.72	12.62
5.69	77.21	6.22	3.65	11.52
6.30	79.01	5.59	3.53	13.72
7.30	77.60	5.29	3.45	9.73
8.30	78.82	5.01	3.30	8.20
9.30	79.45	5.36	3.03	8.53
10.30	80.35	4.72	3.01	5.62
11.30	80.62	4.77	2.87	5.23
12.30	80.57	4.17	2.72	4.35
13.30	81.62	4.36	2.45	4.01
14.30	80.61	3.87	2.68	1.66
15.20	81.62	3.63	2.60	3.20
16.30	82.83	4.80	2.37	1.26
17.30	82.41	3.98	2.31	-0.80
18.30	82.82	3.61	1.87	-0.93
19.30	81.64	3.09	2.42	-2.20
20.30	81.00	2.61	2.06	-3.40
21.30	79.62	2.61	1.97	-3.14
22.30	79.55	2.46	1.61	-3.88
23.30	79.81	2.61	1.47	-4.00
24.30	80.42	2.43	1.68	-4.26
25.30	79.43	2.58	1.64	-5.32
26.30	78.05	1.97	1.41	-5.61
27.30	79.59	2.42	1.47	-6.80
28.30	75.84	1.68	1.37	-6.91

S7 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.83	59.23	6.67	3.36	10.46
0.98	59.82	6.88	3.48	9.60
1.56	62.57	6.72	3.61	9.84
1.95	64.82	6.40	3.54	9.46
2.51	67.73	5.71	3.34	8.69
3.01	68.31	5.90	3.33	9.24
3.79	69.48	5.68	3.14	8.68
4.67	71.27	5.82	2.93	7.42
5.69	73.71	5.44	2.92	7.24
6.30	76.62	5.15	2.95	7.29
7.30	75.80	5.03	2.78	5.44
8.30	75.81	4.45	2.46	5.69
9.30	77.42	4.32	2.33	4.79
10.30	78.10	4.39	2.41	3.42
11.30	78.14	3.55	2.35	3.52
12.30	78.82	3.31	2.16	3.24
13.30	77.82	3.00	2.08	2.40
14.30	79.91	2.90	1.80	2.47
15.30	78.57	2.76	1.99	0.36
16.30	79.60	2.92	1.74	0.16
17.30	78.00	2.21	1.71	0.26
18.30	76.80	2.05	1.28	-2.15
19.30	77.12	2.08	1.62	-0.58
20.30	73.33	1.70	1.52	-1.45
21.30	75.21	1.86	1.43	-2.90
22.30	73.72	1.67	1.45	-4.90
23.30	73.74	1.64	1.30	-3.84
24.30	74.16	1.15	1.32	-4.22
25.30	72.12	1.11	1.24	-4.79
26.30	70.33	1.65	0.98	-4.90
27.30	70.72	1.15	0.70	-5.81
28.30	69.51	0.84	0.85	-5.24

S7 - z/h=0.25				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.87	56.82	4.64	2.29	5.62
1.01	58.21	5.16	2.43	4.71
1.47	60.83	4.75	2.43	5.08
2.00	62.63	4.55	2.45	5.58
2.51	65.03	4.38	2.35	5.52
2.96	65.32	4.42	2.32	4.91
3.79	67.51	4.06	2.24	5.20
4.67	70.89	3.88	2.14	3.22
5.69	70.09	3.41	1.97	3.91

APPENDIX A

6.30	70.32	3.78	1.87	5.15
7.30	71.67	3.24	1.82	3.12
8.30	72.73	2.86	1.68	3.23
9.30	73.48	2.51	1.64	1.61
10.30	74.12	2.32	1.56	2.07
11.30	73.71	1.87	1.29	1.12
12.30	74.10	2.03	1.48	0.73
13.30	74.32	1.81	1.48	1.05
14.30	73.74	1.57	1.27	0.50
15.30	71.81	1.62	1.27	-0.64
16.30	73.34	1.84	1.21	-1.61
17.30	72.02	1.55	1.00	-0.87
18.30	73.46	1.79	1.06	-1.22
19.30	71.55	1.44	0.94	-1.57
20.30	70.15	1.24	1.07	-2.41
21.30	70.37	1.10	0.41	-2.05
22.30	68.24	1.17	0.72	-3.26
23.30	70.10	0.75	0.79	-3.10
24.30	67.30	0.67	0.84	-2.73
25.30	66.74	1.15	1.24	-3.50
26.30	66.67	0.62	0.58	-4.18
27.30	64.58	1.20	0.82	-4.08
28.30	62.40	0.40	0.85	-3.41

APPENDIX B – ROUGH BED EXPERIMENTS

(a) Centreline Velocity Distribution Data

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
R1	36.75	0.00075	13.40	9.26	4.48
R2	45.17	0.00075	15.85	10.37	3.79
R3	54.60	0.00075	17.30	10.97	3.47
R4	61.43	0.00075	18.75	11.54	3.20
R5	75.85	0.00075	21.20	12.42	2.83
R6	86.32	0.00075	22.80	12.95	2.63
R7	97.69	0.00075	23.70	13.24	2.53
R8	118.05	0.00075	27.10	14.24	2.21

R1	
y (cm)	u (cm/s)
0.79	32.02
1.01	34.12
1.19	35.15
1.49	36.96
1.97	39.30
2.51	40.08
3.00	42.81
3.50	43.61
4.00	44.49
4.50	46.38
5.00	48.32
5.50	48.17
6.50	49.10
7.50	50.43
8.50	51.51
9.50	52.38
10.50	53.44

R2	
y (cm)	u (cm/s)
0.80	34.22
1.00	36.23
1.22	37.70
1.51	39.58
1.99	40.41
2.52	43.31
3.01	44.50
3.47	46.13
4.00	45.89
4.50	47.89
5.00	48.30
5.50	50.11
6.50	51.10
7.50	51.00
8.50	53.32
9.50	54.69
10.50	55.40
11.50	56.81
12.50	57.02
13.50	58.20

R3	
y (cm)	u (cm/s)
0.84	36.91
1.01	38.12
1.19	40.37
1.49	41.69
2.01	44.50
2.40	45.85
2.99	47.65
3.50	48.51
4.00	49.88
4.50	52.05
5.00	52.90
5.50	53.42
6.50	54.23
7.50	55.32
8.50	57.03
9.50	57.85
10.50	58.89
11.50	60.60
12.50	60.50
13.50	60.02
14.50	61.10

R4	
y (cm)	u (cm/s)
0.77	38.00
0.84	39.98
1.14	41.90
1.47	45.46
1.85	46.70
2.52	49.95
3.02	50.59
3.50	52.46
4.00	54.49
4.50	55.84
5.00	56.21
5.74	57.78
6.50	58.67
7.50	58.11
8.50	61.12
9.50	62.01
10.50	63.10
11.50	63.21
12.50	62.81
13.50	63.62
14.50	63.80
15.50	64.00
16.50	62.90

R5		R6		R7		R8	
y (cm)	u (cm/s)	y (cm)	u (cm/s)	y (cm)	u (cm/s)	y (cm)	u (cm/s)
0.73	42.74	0.78	44.61	0.81	47.10	0.97	51.66
0.90	44.23	0.86	44.98	1.02	50.01	1.55	56.52
1.15	47.61	0.98	46.12	1.21	51.48	1.98	59.58
1.28	48.00	1.01	46.71	1.50	54.80	2.55	63.38
1.51	49.10	1.17	48.02	2.01	56.62	3.10	65.79
1.70	50.22	1.37	49.51	2.51	58.07	3.57	66.72
1.93	52.20	1.60	51.60	3.01	60.71	4.23	66.93
2.16	51.83	1.59	50.73	3.50	63.50	5.06	69.54
2.42	54.19	1.85	52.70	4.00	65.05	5.99	72.25
2.59	54.01	1.92	53.08	4.50	65.12	6.96	74.14
2.91	55.48	2.06	53.28	5.00	66.93	7.70	75.15
3.19	57.22	2.17	54.53	5.50	68.75	8.70	77.93
3.50	56.61	2.36	55.00	6.50	68.34	9.70	78.50
3.70	57.68	2.51	56.04	7.50	69.92	10.70	78.44
4.00	58.79	2.71	56.77	8.50	69.71	11.70	80.81
4.20	59.30	3.02	57.38	9.50	72.85	12.70	80.92
4.50	60.13	3.11	58.72	10.50	73.33	13.70	83.10
5.00	61.21	3.31	59.59	11.50	73.68	14.70	82.02
5.50	62.72	3.49	59.44	13.50	76.80	15.70	81.39
6.50	64.03	3.82	60.76	15.50	76.75	16.70	83.78
7.50	64.40	4.00	61.46	17.50	77.00	17.70	82.78
8.50	66.04	4.50	62.62	19.50	76.24	18.70	84.53
9.50	66.72	5.00	64.51	21.20	74.52	19.70	82.21
10.50	67.75	5.50	64.62			20.70	81.43
11.50	68.40	6.00	65.97			21.70	79.42
13.50	68.32	6.50	67.22			22.70	81.00
14.50	68.29	7.00	67.60			23.70	78.87
15.50	68.34	7.50	68.90			24.70	78.02
16.50	68.70	8.50	69.61				
17.50	68.46	9.50	71.13				
18.50	67.52	10.50	71.92				
		12.00	72.82				
		13.00	73.41				
		14.00	74.13				
		15.00	74.28				
		15.50	74.63				
		16.50	74.14				
		17.50	74.70				
		18.50	74.31				
		19.00	73.80				
		20.00	73.84				

(b) Cross-Sectional Velocity Distribution**(1) R1**

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
R1	36.75	0.00075	13.40	9.26	4.48

R1 - z/h=2.24				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.79	32.02	5.97	2.90	9.47
1.01	34.12	6.43	3.00	10.40
1.19	35.15	6.57	3.14	9.94
1.49	36.96	6.20	3.17	9.73
1.97	39.30	6.30	3.01	10.82
2.51	40.08	5.87	3.03	9.00
3.00	42.81	5.57	3.03	8.48
3.50	43.61	5.61	3.00	8.44
4.00	44.49	5.07	3.01	7.80
4.50	46.38	5.14	3.03	8.10
5.00	48.32	4.78	2.91	7.70
5.50	48.17	4.81	2.97	6.76
6.50	49.10	4.11	2.72	5.52
7.50	50.43	4.11	2.70	5.52
8.50	51.51	4.11	2.67	4.25
9.50	52.38	3.55	2.56	3.06
10.50	53.44	3.08	2.28	3.05

R1 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.83	33.10	5.52	2.87	8.52
1.02	34.71	5.64	3.00	8.77
1.15	34.35	5.58	3.04	8.73
1.50	37.22	5.64	2.95	8.41
1.97	38.51	5.30	2.86	7.95
2.51	41.33	4.96	2.89	8.34
3.00	42.02	5.30	2.83	7.32
3.50	43.14	5.11	2.84	7.58
4.00	44.23	5.02	2.73	7.49
4.50	46.30	4.31	2.65	6.76
5.00	46.71	4.86	2.61	6.66
5.50	46.92	4.62	2.45	5.63

6.50	48.98	4.21	2.58	5.73
7.50	49.62	3.78	2.53	5.01
8.50	51.23	3.78	2.31	3.54
9.50	51.30	3.75	2.25	1.96
10.50	52.81	3.10	1.97	1.13

R1 - z/h=0.75				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.72	30.90	5.17	2.85	7.45
1.03	33.53	4.66	2.85	7.87
1.23	34.81	5.17	2.87	8.00
1.51	36.72	4.73	2.78	7.55
1.95	38.39	4.60	2.64	7.44
2.48	40.19	4.30	2.60	7.03
3.00	41.01	4.76	2.49	6.68
3.50	42.42	5.58	2.41	6.54
4.00	44.37	5.12	2.33	5.77
4.50	45.71	5.08	2.37	5.15
5.00	45.62	4.55	2.29	4.16
5.50	46.72	4.20	2.33	2.90
6.50	47.03	3.86	2.14	3.59
7.50	48.80	3.52	2.08	1.53
8.50	49.60	3.18	1.84	2.11
9.50	50.01	2.84	1.91	0.27
10.50	50.20	2.50	1.90	0.41

R1 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	31.31	5.26	2.66	8.13
1.03	33.12	5.29	2.83	7.68
1.17	34.02	5.52	2.84	7.97
1.47	35.89	5.07	2.94	7.85
1.98	38.51	4.83	2.78	7.34
2.48	39.03	4.68	2.71	7.29
3.00	39.89	4.68	2.62	6.45
3.50	42.31	4.56	2.42	6.28
4.00	43.12	4.62	2.45	5.50
4.50	44.60	4.35	2.25	5.31
5.00	45.69	4.52	2.48	5.00
5.50	46.18	4.14	2.18	4.53
6.50	46.40	3.48	1.99	3.63
7.50	48.71	3.42	1.99	3.43
8.50	48.92	2.61	1.95	2.15
9.50	49.11	2.64	1.99	0.67
10.50	48.92	1.98	1.68	0.67

R1 - z/h=0.25				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.83	31.57	5.07	2.59	7.56
1.02	32.94	4.95	2.71	6.49
1.23	33.50	5.22	2.83	7.03
1.48	35.16	5.07	2.76	6.25
2.01	37.20	5.43	2.81	6.73
2.52	38.35	4.83	2.59	5.63
3.00	39.39	4.68	2.64	4.92
3.50	40.28	3.98	2.67	5.60
4.00	42.01	4.16	2.33	4.35
4.50	42.53	4.49	2.40	4.46
5.00	42.00	4.13	2.36	3.94
5.50	43.67	3.02	2.25	3.24
6.50	44.87	2.84	1.87	2.48
7.50	44.81	2.35	1.93	1.33
8.50	45.08	2.05	1.88	1.14
9.50	44.93	2.29	1.85	0.37
10.50	44.74	1.96	1.86	-0.80

(2) R3

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
R3	54.60	0.00075	17.30	10.97	3.47

R3 - z/h=1.73				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.84	36.91	6.08	3.49	13.06
1.01	38.12	6.72	3.52	11.41
1.19	40.37	6.76	3.47	12.55
1.49	41.69	6.87	3.59	12.13
2.01	44.50	6.57	3.70	11.51
2.40	45.85	6.46	3.59	11.22
2.99	47.65	5.94	3.45	11.20
3.50	48.51	6.16	3.61	10.02
4.00	49.88	5.75	3.01	10.17
4.50	52.05	5.90	3.36	10.36
5.00	52.90	5.26	3.39	9.95
5.50	53.42	6.23	3.47	9.22
6.50	54.23	4.92	3.19	9.02

7.50	55.32	4.88	3.21	7.27
8.50	57.03	4.32	3.31	6.68
9.50	57.85	4.36	2.93	5.59
10.50	58.89	3.83	3.15	5.40
11.50	60.60	3.64	2.79	4.83
12.50	60.50	3.79	2.78	3.07
13.50	60.02	3.94	2.41	2.66
14.50	61.10	3.34	2.35	1.36

R3 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.80	36.79	6.64	3.72	11.74
1.00	38.51	6.93	3.54	11.74
1.30	39.82	6.56	3.48	12.02
1.49	41.68	6.45	3.61	12.40
1.86	43.61	6.42	3.46	11.18
2.50	46.71	5.90	3.47	12.40
2.98	46.40	5.30	3.32	9.67
3.50	48.25	5.24	3.26	9.79
4.00	49.14	4.76	3.21	9.11
4.50	49.65	5.16	3.14	8.35
5.00	51.82	4.79	3.09	8.83
5.50	52.33	4.72	3.07	8.92
6.50	53.54	4.68	3.07	6.76
7.50	54.16	3.95	2.90	6.09
8.50	55.78	3.95	2.81	5.09
9.50	57.41	4.31	3.00	5.25
10.50	57.66	3.13	2.72	3.26
11.50	58.12	2.58	2.58	3.36
12.50	58.21	3.32	2.43	0.24
13.50	58.26	2.62	2.41	1.29
14.50	57.63	3.10	2.60	-0.87

R3 - z/h=0.75				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	36.23	6.25	3.18	11.04
1.10	38.80	6.17	3.32	11.17
1.22	40.12	6.25	3.44	11.80
1.49	41.51	6.20	3.39	11.17
2.01	43.02	5.93	3.39	10.69
2.52	45.23	5.91	3.13	10.22
3.01	46.80	5.70	3.20	10.22
3.50	48.68	5.58	3.27	9.98
4.00	48.11	5.12	3.25	8.23
4.50	49.19	5.08	3.05	8.95
5.00	51.04	4.55	3.16	7.60

5.50	51.02	4.20	3.06	6.97
6.50	52.01	3.86	2.75	6.09
7.50	53.48	3.52	2.86	4.75
8.50	54.84	3.18	2.60	3.49
9.50	55.26	2.84	2.56	3.61
10.50	56.11	2.50	2.36	1.96
11.50	56.14	2.16	2.38	1.73
12.50	55.32	1.82	2.15	0.30
13.50	56.20	1.48	1.75	-0.41
14.50	54.71	1.14	2.07	-0.40

R3 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.80	35.84	5.56	3.01	9.14
1.02	37.71	5.87	3.07	9.65
1.23	38.85	6.30	3.09	10.70
1.49	40.99	5.87	3.11	9.05
2.01	42.82	5.53	3.18	9.81
2.49	45.07	5.59	3.12	8.82
3.01	45.71	5.46	3.11	8.55
3.50	47.56	5.19	2.95	8.55
4.00	49.29	5.29	2.98	7.11
4.50	49.53	4.96	2.92	6.77
5.00	49.22	4.52	2.93	7.78
5.50	51.26	4.62	2.65	5.92
6.50	51.58	4.52	2.63	5.50
7.50	51.85	3.98	2.60	4.60
8.50	53.21	4.01	2.42	2.11
9.50	54.23	3.27	2.25	2.34
10.50	55.30	3.44	2.34	1.40
11.50	55.82	2.90	2.13	1.04
12.50	55.64	2.83	2.17	0.01
13.50	55.21	1.92	1.97	-1.22
14.50	55.20	1.45	1.64	-1.40

R3 - z/h=0.25				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	35.89	5.16	2.76	7.77
0.95	36.72	6.27	2.63	8.40
1.00	38.48	5.55	2.83	8.58
1.51	40.21	5.82	2.79	8.11
2.02	43.80	5.61	2.69	7.35
2.52	43.72	5.37	2.67	7.16
2.98	45.21	5.31	2.58	6.60
3.50	46.90	5.28	2.48	6.17
4.00	48.08	4.59	2.54	5.93
4.50	48.77	3.92	2.33	5.88

5.00	49.32	4.19	2.44	5.60
5.50	49.34	4.19	2.40	4.95
6.50	50.46	3.80	2.16	3.41
7.50	51.06	3.50	2.02	3.31
8.50	52.72	3.14	1.86	2.93
9.50	53.70	2.78	1.91	1.73
10.50	53.91	3.02	1.71	-0.26
11.50	53.60	1.81	1.72	-0.79
12.50	51.65	1.54	1.50	-1.05
13.50	52.42	1.93	1.57	-1.75
14.50	53.51	1.69	1.65	-1.93

(3) R7

Run	Q (l/s)	S	h (cm)	R (cm)	b/h
R7	97.69	0.00075	23.70	13.24	2.53

R7 - z/h=1.27				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.81	47.10	8.01	4.22	19.15
1.02	50.01	8.14	4.36	18.08
1.21	51.48	8.19	4.32	19.08
1.50	54.80	8.32	4.35	17.78
2.01	56.62	8.06	4.41	16.87
2.51	58.07	7.37	4.28	17.77
3.01	60.71	7.51	4.17	17.30
3.50	63.50	7.51	4.38	16.80
4.00	65.05	7.74	3.01	16.37
4.50	65.12	8.10	3.99	14.10
5.00	66.93	7.68	4.26	13.17
5.50	68.75	7.01	3.79	14.50
6.50	68.34	6.32	3.87	14.84
7.50	69.92	5.54	3.49	11.53
8.50	69.71	5.20	3.23	9.99
9.50	72.85	4.92	3.21	9.99
10.50	73.33	4.37	2.86	7.17
11.50	73.68	4.29	2.88	5.77
13.50	76.80	3.90	2.87	6.51
15.50	76.75	3.79	2.94	2.57
17.50	77.00	3.94	2.81	2.05
19.50	76.24	4.38	2.67	-1.96
21.20	74.52	4.13	2.88	-2.62

R7 - z/h=1.00				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.80	46.30	8.70	3.98	16.91
1.00	48.72	8.17	4.05	17.64
1.30	51.90	8.58	4.12	17.74
1.49	55.09	8.13	4.07	18.01
1.86	54.52	7.92	4.17	16.39
2.50	57.10	8.09	4.05	17.05
2.98	58.32	7.64	3.88	17.19
3.50	61.18	7.88	3.98	13.42
4.00	61.87	7.82	3.86	12.13
4.50	62.54	7.45	3.88	12.94
5.00	64.35	7.26	3.73	10.81
5.50	65.47	6.88	3.61	13.25
6.50	65.72	6.53	3.50	9.43
7.50	67.70	5.83	3.45	10.27
8.50	69.32	5.51	3.12	9.33
9.50	70.13	4.78	3.09	7.84
10.50	70.49	4.41	3.04	8.09
11.50	71.72	4.84	3.17	5.53
13.50	74.10	3.69	2.71	5.25
15.50	74.72	3.67	2.67	0.24
17.50	73.52	3.44	2.70	-1.24
19.50	73.81	3.77	2.40	-1.51
21.20	72.54	3.99	2.50	-3.29

R7 - z/h=0.75				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm²/s²)
0.81	44.89	7.54	3.69	14.70
1.10	47.97	8.08	3.73	15.04
1.22	50.92	7.70	3.83	15.87
1.49	51.52	7.80	4.02	16.21
2.01	55.18	7.54	3.92	15.74
2.52	56.90	7.04	3.99	15.51
3.01	58.31	7.35	3.92	14.14
3.50	60.48	5.58	3.62	14.81
4.00	61.07	5.12	3.74	13.54
4.50	60.89	5.08	3.79	14.48
5.00	64.33	4.55	3.59	11.94
5.50	62.29	4.20	3.52	9.16
6.50	64.90	3.86	3.31	10.21
7.50	66.52	3.52	3.16	7.79
8.50	67.71	3.18	3.05	9.51
9.50	69.30	2.84	2.83	5.66
10.50	68.72	2.50	2.80	5.88
11.50	70.34	2.16	2.45	3.52
13.50	70.45	1.82	2.71	0.91

15.50	71.50	1.48	2.29	-0.17
17.50	70.51	1.14	2.17	-0.78
19.50	69.53	0.80	2.06	-3.20
21.20	66.49	0.46	2.20	-6.39

R7 - z/h=0.50				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.83	44.32	7.88	3.82	17.03
1.01	45.90	7.64	3.87	15.66
1.21	47.08	7.67	3.83	14.46
1.48	48.93	7.80	3.96	15.15
2.00	51.47	7.11	3.83	15.15
2.53	54.31	7.27	3.76	13.10
3.00	53.49	6.95	3.78	14.16
3.50	56.51	6.54	3.78	10.73
4.00	56.28	6.73	3.57	12.60
4.50	58.10	6.31	3.65	11.04
5.00	58.52	6.56	3.39	8.71
5.50	61.73	5.81	3.20	10.21
6.50	61.67	6.20	3.31	8.07
7.50	63.52	5.12	3.01	6.74
8.50	64.93	5.27	2.89	4.13
9.50	65.06	4.09	2.63	5.61
10.50	66.26	4.60	2.74	3.55
11.50	66.28	3.76	2.50	1.54
13.50	66.30	3.19	2.23	-0.04
15.50	66.12	3.20	2.25	-0.40
17.50	64.10	3.34	2.23	-3.75
19.50	63.75	3.36	2.29	-5.54
21.20	58.90	3.41	2.16	-7.56

R7 - z/h=0.25				
y (cm)	u (cm/s)	$\sqrt{u'^2}$ (cm/s)	$\sqrt{v'^2}$ (cm/s)	$-\overline{u'v'}$ (cm ² /s ²)
0.79	42.75	7.07	3.68	13.30
1.01	44.32	7.19	3.70	14.81
1.20	45.50	7.22	3.75	13.52
1.48	48.70	7.10	3.83	13.66
2.03	50.93	6.99	3.71	11.85
2.51	53.71	6.63	3.79	12.65
3.03	54.91	6.51	3.66	12.80
3.50	56.32	5.76	3.49	11.82
4.00	58.07	5.82	3.34	11.97
4.50	58.50	5.46	3.22	10.99
5.00	57.55	5.62	3.26	10.16
5.50	58.94	5.11	3.31	9.48
6.50	59.46	5.15	2.99	7.65
7.50	61.91	5.24	2.87	8.15
8.50	62.51	4.45	3.15	6.49
9.50	63.70	4.48	2.97	3.82

10.50	62.32	4.13	2.73	2.54
11.50	63.68	3.86	2.51	0.70
13.50	63.73	3.13	2.35	0.09
15.50	63.12	2.85	1.75	-1.57
17.50	61.73	2.08	1.84	-4.15
19.50	58.92	2.08	1.78	-6.56
21.20	57.32	2.37	1.46	-6.64