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ANALYSIS OF OPEN-CHANNEL VELOCITY MEASUREMENTS COLLECTED WITH AN ACOUSTIC DOPPLER CURRENT PROFILER

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ABSTRACT

Acoustic Doppler Current Profilers (ADCP's) are easier to apply and more rapidly collect velocity data than traditional current-meter instruments. However, flow discharge estimates in natural rivers and canals based on ADCP measurements rely on extrapolations of the measured velocity profiles into the unmeasured zones of the flow. Furthermore, the accuracy and reliability of ADCP's have not been rigorously tested and formal protocols for discharge measurements with ADCP's have not been developed. Therefore, a comparison of the velocity profiles measured with an ADCP with theoretical velocity distributions is necessary. The analysis of two sets of approximate two-dimensional open-channel velocity distributions collected with a fixed ADCP at the Chicago Sanitary and Ship Canal (CSSC) at Romeoville, Illinois, is presented here. These measured velocity distributions are compared with the logarithmic- and power-law velocity distributions. The shear velocity and Nikuradse's equivalent sand roughness were estimated by fitting the data to the logarithmic law. The shear velocity and Nikuradse's equivalent sand roughness estimated from the first and second data sets are 0.23 m and 0.046 m/s, and 0.27 m and 0.020 m/s, respectively. Results indicate that both the logarithmic- and power-law fit the measured data well. The exponent of the power law was estimated to be very close to 1/6, which links the power law with Manning's equation. Furthermore, the values of Nikuradse's sand roughness of both data sets are equivalent to a Manning's $n \approx 0.030$, which seems consistent with the channel surface and bed conditions of the CSSC at Romeoville.

INTRODUCTION

Acoustic Doppler Current Profilers (ADCP's) are becoming more commonly utilized for flow measurements in natural streams and constructed channels. A detailed description of the operational principles of an ADCP can be found in Gordon (1989), RD Instruments (1989), Oberg and Muller (1994). ADCP's are particularly useful for flow conditions that cannot be adequately measured with conventional current meters. Oberg and Muller (1994) described some examples where ADCP's have been utilized in the collection of discharge data under difficult flow conditions. Two of the most relevant advantages of applying ADCP's relative to traditional current meters are that ADCP measurements can be made in much less time, and that they provide three-dimensional velocity information. At present, despite the experience with ADCP's for discharge measurements in streams and channels, the reliability and accuracy of ADCP measurements have not been rigorously tested in the field, and the U.S. Geological Survey (USGS) has not yet developed formal protocols to perform ADCP measurements. One of the primary issues concerning ADCP measurements that requires special attention is the extrapolation of the velocity distribution to zones of the flow field that cannot be measured with

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an ADCP. Velocities near solid boundaries and free surfaces cannot be measured with ADCP's because of interference in the acoustic signals resulting from boundary reflectance. As a result, for an angle of 20 degrees between the transducer beam and the vertical, the velocity measurements in the lower 6 percent of the distance from the ADCP to the reflecting surface are highly unreliable. Velocity within a distance of about 0.5 m from the transducers also cannot be measured with ADCP's because data processing is delayed for a short time after transmission of acoustic signals. Furthermore, since the transducers have to be submerged, velocities in the top 0.6 m of the flow depth are usually not measured. Two methods for extrapolation of the velocity profiles into the unmeasured zones are available in the ADCP data-processing software. In the first method, a constant velocity over the unmeasured zone equal to the last measured velocity is assumed, whereas in the second method, the velocity distribution is assumed to follow the power-law distribution with the restriction that the exponent has to be prescribed. This method must be considered from a theoretical perspective and tested with field data to develop more robust guidelines for selecting the appropriate extrapolation method, or alternative methods must be developed on the basis of fluid mechanics and hydraulics.

The vertical distribution of the streamwise velocity in a wide channel can be approximately determined from continuous ADCP velocity measurements at a fixed location in the center of the channel over an extended period. These measurements can then be compared with theoretical distributions to approximately determine which distribution can be considered reliable for the extrapolation of the velocity profile into the unmeasured zones. The results of analyzing two independent ADCP velocity measurements collected at the center of the Chicago Sanitary and Ship Canal (CSSC) at Romeoville, Illinois, are presented in this paper. This analysis constitutes a first step toward the more ambitious goal of developing more robust guidelines for extrapolation of velocity data into the unmeasured zones.

BACKGROUND

Nezu and Rodi (1985) found, based on accurate laser Doppler anemometer measurements of secondary currents in open-channel flows, that the flow is strongly dependent on the aspect ratio $\alpha \equiv b/h$ (where b is the channel width and h is the flow depth). Depending on this ratio, a channel can be classified as narrow or wide, as indicated below.

a) Narrow channel ($\alpha \le \alpha_c \approx 5$). Secondary currents due to sidewall effects result in a "dip" in the velocity distribution near the surface such that the maximum velocity is below the water surface.

b) Wide channel ($\alpha > \alpha_c$). The strength of the secondary currents due to sidewall effects is reduced in the central zone of the channel within a band of width equal to $b - \alpha_c h$. As a result, two-dimensional (2D) flow properties are present in this region in the long-term structures averaged over turbulence, as long as the widespan variation of the bed-shear stress is aperiodic.

The vertical distribution of streamwise velocity in turbulent open-channel flows is very complex. Three regions have been identified in the vertical flow field for steady uniform flow in smooth, wide, open channels: (a) the wall region [$y/h \le 0.15$ to 0.2, y is the distance above the boundary], referred to as the inner layer in boundary-layer theory, where the length and velocity scales are ν/u_*, and u_*, respectively, where ν is the kinematic viscosity of the fluid, u_* is the boundary shear velocity defined as $u_* = (\tau_b/\rho)^{1/2}$, τ_b is the boundary shear stress, and ρ is the fluid density; (b) the free-surface region [$0.6 \le y/h \le 1$], where the length and velocity scales are the flow depth h and the maximum velocity u_{max}; and (c) the intermediate region

0.15 to $0.2 < y/h < 0.6$, that is not strongly affected by either the wall properties or the free-surface properties and where turbulent energy production and dissipation are approximately equal.

Within the wall region in wide channels with a smooth bed, the velocity distribution in the viscous sublayer, i.e., $yu_*/\nu << B$ is described as

$$u^+ = y^+ \tag{1}$$

where $u^+ = u/u_*$, $y^+ = yu_*/\nu$ and $B \approx 26$ (Nezu and Rodi, 1986), whereas in the region $B < y^+ \leq 0.2u_*h/\nu$ the velocity distribution can be described by the logarithmic law

$$u^+ = \frac{1}{\kappa}\ln y^+ + A \tag{2}$$

where κ is the von Karman constant (equal to 0.41), and A is a constant.

In the case of rough channels, the length scale is represented by Nikuradse's equivalent sand roughness k_s, which accounts for the effect of the roughness elements. In general, k_s is a function of the shape, height, and width of the roughness elements, as well as their spatial distribution on the channel surface. Experimental observations suggest that the more uniform and evenly distributed the roughness elements on the channel bed are, the closer is k_s to the actual height of the protrusions (Schlichting, 1955, p. 423). Depending on the ratio of roughness and viscous length scales (often referred to as nondimensional roughness parameter or roughness Reynolds number), $k_s^+ = u_*k_s/\nu$, the turbulent flow regime in wide open channels can be classified as hydraulically smooth, transitionally rough, or fully rough. The flow regime is considered hydraulically smooth for $k_s^+ < 5$, fully rough for $k_s^+ > 70$, and transitionally rough for the range in between. In general, for the range between hydraulically smooth and completely rough flows, the logarithmic-law distribution is applicable whenever k_s is used as the length scaling factor; that is

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{y}{k_S}\right) + A_r \tag{3}$$

where $A_r = f(k_s^+)$. According to Nikuradse's measurements, for a turbulent flow in completely rough regime $A_r = 8.5$ (Schlichting, 1955, p. 420) and, thus, Equation 3 can be reduced to

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{30y}{k_s}\right) \tag{4}$$

Nezu and Nakagawa (1993, pp. 16-17) discuss that the logarithmic law is inherently valid only in the wall region and that deviations of the velocity distribution from this law should be accounted for by considering a wake function such as that proposed by Coles (1956). However, in practical applications it is still commonly assumed that the logarithmic law describes the velocity distribution over the entire depth of uniform, steady open-channel flows.

The power law is an alternative model to represent the vertical distribution of the streamwise velocity in open-channel flows. Chen (1991) presented a generalized power-law model for velocity distribution in open channels and analyzed the ranges of applicability of different powers. In general, the power-law model is expressed as

$$\frac{u}{u_*} = a\left(\frac{y}{y'}\right)^m \tag{5}$$

where y' is defined as the physical location in the boundary layer at which $u = 0$, and a and m are a coefficient and an exponent, respectively.

Based on theoretical considerations, Chen (1991) shows that for perfect agreement between the power law and the logarithmic law, the product of κ, m, a, and e, (where e is the base of natural logarithms) should be equal to 1. From this condition, upon substitution of the values of e and κ, the expression ma = 0.92 is obtained. This indicates that the exponent m is inversely proportional to the coefficient a. However, this is only a particular case that corresponds to a unique point in the domain of the logarithmic law. For fully rough flows, a relation between y' and k_s can be obtained from the logarithmic law as $y' = k_s / e^{\kappa A_r}$ or approximately $k_s/30$ (Chen, 1991). For this case, best-estimate values for a and m in the power law that for a certain range of u/u_* or (y/y') satisfy the logarithmic law within a given tolerance in a least-squares sense can be obtained based on nonlinear regression analysis. This part of Chen's analysis demonstrates that both parameters in the power law m and a vary with the global relative roughness for fully rough flows due to incomplete similarity.

Several methods are available to estimate u_* (see for example Nezu and Nakagawa, 1993, pp. 48-49). The simplest one, derived for steady uniform flow in wide channels, estimates u_* as $\sqrt{ghS_o}$, in which g is the gravitational acceleration, and S_o is the slope of the channel bed (for uniform flow the slope of the channel bed, the friction slope, and the water-surface slope are all equal). In the case of steady nonuniform flow, the energy slope S replaces S_o. Accurate assessment of the representative bed slope in the vicinity of the measured section is difficult; therefore, u_* must be estimated with other methods. These methods, however, are only applicable when accurate measurements of either velocity fluctuations or wall shear stress are available, such as in the case of carefuly performed laboratory experiments. An alternative method frequently applied to determine u_* is based on the best-fit of the measured mean velocity distribution to the logarithmic law.

FIELD MEASUREMENTS

The two data sets of fixed ADCP velocity measurements analyzed here were collected at the center of the CSSC at Romeoville, Illinois, by teams of USGS personnel led by the third author. The ADCP utilized for these measurements is a broadband type with a transmitting frequency of 1200 kHz and transducer beam angles of 20 degrees with a long-term bias of 0.2 cm/s. The measurements were made from a boat anchored to the channel bed. The CSSC at Romeoville is an excavated channel in limestone with vertical sides and essentially a fixed bed. It is approximately 49 m (162 ft) wide and the flow depth is typically between 6 and 8.5 m (20 and 28 ft). The aspect ratio of the flow for this range of flow depth is always greater than 5, thus the flow should be quasi-2D in a central band of width approximately equal to the flow depth.

An ADCP mounted on an anchored boat is not exactly fixed because of the unavoidable effects of pitching, rolling, heading, and translation. As a result, measurements collected under these conditions involve more spatial averaging than if collected with a completely fixed ADCP. However, within a 2D flow region, the effect of such spatial averaging is not important, because in this region the temporal mean velocity should be the same at each particular distance from the bed.

The first data set was collected on August 17, 1994. This set consists of 70 velocity profiles measured at time intervals of 4.75 s, while the average flow depth was 7.45 m. Each of these profiles consists of measurements at depth intervals of 0.25 m within 0.27 and 6.27 m from the channel bed. The second data set was collected on May 12, 1995. It consists of 25 velocity profiles measured at time intervals of 4.17 s, while the average flow depth was 8.23 m. These profiles consist of velocity measurements at depth intervals of 0.25 m, within 0.41 and 7.16 m from the channel bed.

DATA ANALYSIS AND DISCUSSION

In general, the time series of streamwise velocity measured at a given distance from the bed may reflect both random velocity fluctuations and nonstationary trends of the mean flow. Reliable estimates of velocity profiles can only be obtained by ensuring that the velocity time series are stationary and that time averaging is done in a representative time span. The stationarity of the velocity time series of the two data sets of fixed ADCP measurements collected in the CSSC was verified on the basis of the nonparametric run test (Bendat and Piersol, 1986, pp. 94-97). The effect of the averaging time span on the accuracy of the mean velocity estimates was assessed by comparing the deviations of the average of *l*-sequential velocity profiles with respect to the estimate of the mean velocity profile obtained from all the measured profiles, in terms of the full-data standard deviation. In the present analysis, it was found, based on the data set of August 1994, for which the coefficient of variation of the velocity measurements was between 0.1 to 0.2, that all the possible estimates of the mean velocity profile based on *10*-sequential profiles are within one standard deviation from the long-term mean velocity profile; whereas estimates based on *20*-sequential profiles are within half a standard deviation of the long-term mean velocity profile.

To compare the mean velocity profiles obtained from the two data sets collected in the CSSC with the theoretical velocity distributions obtained with the logarithmic and power laws, the values of u_* and k_s were determined first. Since in natural channels k_s reflects both surface roughness and form roughness of the channel bed (Rouse, 1965), its evaluation is complicated. The values of k_s and u_* for each data set were estimated by fitting the measured mean velocity profiles to the logarithmic law by nonlinear regression.

The values of k_s and u_* estimated from the data of August 1994 are 0.23 m and 0.046 m/s, respectively. The mean streamwise velocity over the measured vertical range was 0.68 m/s, and the Reynolds and Froude numbers were 5.6×10^6 and 0.08, respectively. In a similar fashion, the estimates of k_s and u_* for the data of May 1995 are 0.27 m and 0.020 m/s. The mean streamwise velocity over the measured vertical range was 0.29 m/s, whereas the corresponding Reynolds and Froude numbers were 2.6×10^6 and 0.03, respectively. The differences in mean velocity reflect the differences in energy slope and the corresponding shear velocity. The measured mean velocity profiles of each data set are compared to the logarithmic law in nondimensional form in Figures 1 and 2, and in dimensional form in Figures 3 and 4.

The values of k_s and u_* estimated from each data set were used to determine the values of the coefficient *a* and the exponent *m* in the power law by fitting the measured mean velocity profiles to the power law by nonlinear regression. The values of the *a* and *m* estimated for the data of August 1994 are 5.17 and 0.173, respectively; whereas the values estimated for the data of May 1995 are 4.88 and 0.182, respectively. The power-law velocity profiles for these estimates of *a* and *m* are also plotted in Figures 1-4. The mean velocity in wide open channels based on the power law with an exponent $m = 1/6$, is equivalent to Manning's equation for mean velocity in uniform flow (Chen, 1991); thus *n*, and k_s are related as

$$n = \frac{K_n}{\sqrt{g}} \frac{35}{162} \left(\frac{k_S}{30} \right)^{1/6} \qquad (6)$$

where K_n depends on the unit system and values of *n* used, 1 for metric and 1.486 for customary English units if *n* is read from Chow's tables (1959, pp. 110-113), or $\sqrt{g}$ in both systems if the *n* value is read from Yen's tables (1991 pp. 43-54, 1993). For the case of metric units with *n* read from the tables of Chow, *n* and k_s are related as $n = 0.0391\ k_s^{1/6}$.

Since fitting the mean velocity profiles of the two data sets to the power law resulted in exponents close to *1/6*, the Manning's *n* for the estimated values of k_s were estimated using the former relation. The corresponding *n* values are approximately 0.030, which seems consistent with the conditions of the channel surface and geometrical variations of the channel near the measurement location. Furthermore, the coefficient *a* in the power law for an exponent *m* held equal to *1/6* also was estimated through data fitting for comparison. The *a* value was 5.35 for both data sets. The velocity profiles corresponding to these *a* and *m* values are also presented in Figures 1-4.

CONCLUSIONS

A preliminary analysis of fixed ADCP measurements of velocity profiles in approximately 2D open-channel flow obtained in the CSSC at Romeoville, Illinois, was presented here. Based on this analysis the following conclusions can be drawn.

The measurements of velocity distribution in open channels obtained with an ADCP at locations where the flow is quasi-2D are in good agreement with theoretical fluid mechanics. Results indicate that both the logarithmic-law and the power-law velocity distributions (best fit and 1/6) fit well the measured mean velocity profiles of the two data sets, especially that from the data collected in August 1994. The coefficients of determination obtained from the nonlinear regression analysis for each theoretical distribution are practically equal (0.99 for the data of August 1994; 0.91 for the data of May 1995)

The deviations of the measured mean velocity profile obtained from the data set collected in May 1995, consisting of only 25 velocity profiles, with respect to the theoretical velocity profiles seem to result from the averaging time span. The results of the analysis performed on the August 1994 data set indicate that the deviations of estimates of the mean velocity based on *20*-sequential profiles are approximately within half a standard deviation from the long-term mean velocity. Based on these results and assuming that the coefficient of variation of the first data set is transferable to the second one, deviations of approximately ± 3.5 cm/s should be expected. The deviations observed in Figures 2 and 4 are consistent with this estimate.

The shear velocity estimated from the data set of August 1994, is approximately equal to twice that estimated from the data set of May 1995 (0.046 and 0.020 m/s, respectively). Because the corresponding water depths are of the same order of magnitude, the difference in shear velocity suggests that the flow was nonuniform during the measurements. The values of the

Nikuradse's equivalent sand roughness independently estimated from each data set are very similar (0.23 and 0.27 m, respectively).

The estimated exponents of the power law for the two sets of data are very close to *1/6*, which links the power law with Manning's equation for uniform flow in wide channels. Based on the relation between Manning's equation for wide channels and the power-law equation with $m = 1/6$, both estimates of k_s were equivalent to a Manning's $n \approx 0.030$. This value of n seems consistent with the channel conditions in the CSSC at Romeoville (the canal bed is fixed, but its elevation undulates in the vicinity of the measurement location contributing to form resistance).

These conclusions are based on the analysis of only two data sets and, thus, a more extensive study is necessary. Furthermore, the accuracy of the ADCP to measure velocities at locations closer to the side walls where the flow departs from 2D behavior has yet to be studied.

REFERENCES

Bendat, J. S., and Piersol, A. G., Random Data: Analysis and Measurement Procedures. John Wiley and Sons, Inc., New York, N.Y., 1986.

Coles, D., "The law of the wake in the turbulent boundary layer," Journal of Fluid Mechanics, Vol. 1, No. 2, 1956, pp. 191-226.

Chen, C.L., "Unified theory on power laws for flow resistance," Journal of Hydraulic Engineering, ASCE, Vol. 117, No. 3, March 1991, pp. 371-389

Chow, V.T., Open-channel hydraulics, McGraw-Hill Book Co., New York, N.Y., 1959.

Gordon, R.L., "Acoustic measurements of river discharge," Journal of Hydraulic Engineering, ASCE, Vol. 115 No. 7 July 1989, pp. 925-936.

Nezu, I., and Nakagawa, H., Turbulence in open-channel flows, Balkema Publishers, Rotterdam, Netherlands, 1993.

Nezu, I., and Rodi, W., "Experimental study on secondary currents in open channel flow," Proc., 21st Congress of IAHR, Melbourne, Australia, Vol. 2, 1985, 115-119.

Nezu, I., and Rodi, W., "Open-channel flow measurements with a Laser Doppler anemometer," Journal of Hydraulic Engineering, ASCE, Vol. 112 No. 5 May 1986, pp. 335-355.

Oberg, K.A., and Muller, D.S., "Recent applications of acoustic Doppler current profilers," Fundamentals and Advancements in Hydraulic Measurements and Experimentation, Hydraulics Division ASCE, August 1-5, 1994, pp. 341-350.

RD Instruments., "Acoustic Doppler current profilers, Principles of operation: A practical primer," RD Instruments, San Diego, 1989, 36 p.

Rouse, H., "Critical analysis of open-channel resistance," Journal of the Hydraulics Division, ASCE, Vol. 91, No. HY4, July 1965, pp. 1-25.

Schlichting, H., Boundary Layer Theory, 1st ed., McGraw-Hill Book Co., New York, N.Y., 1955.

Yen, B.C. "Hydraulic resistance in open channels,": Channel Flow Resistance: Centennial of Manning's Formula, Water Resources Publications, Littleton, Colo., 1991, pp. 1-135.

Yen, B.C. "Dimensionally homogeneous Manning's formula," Journal of Hydraulic Engineering, ASCE, Vol. 118, No. 9, September 1993, pp. 1326-1332

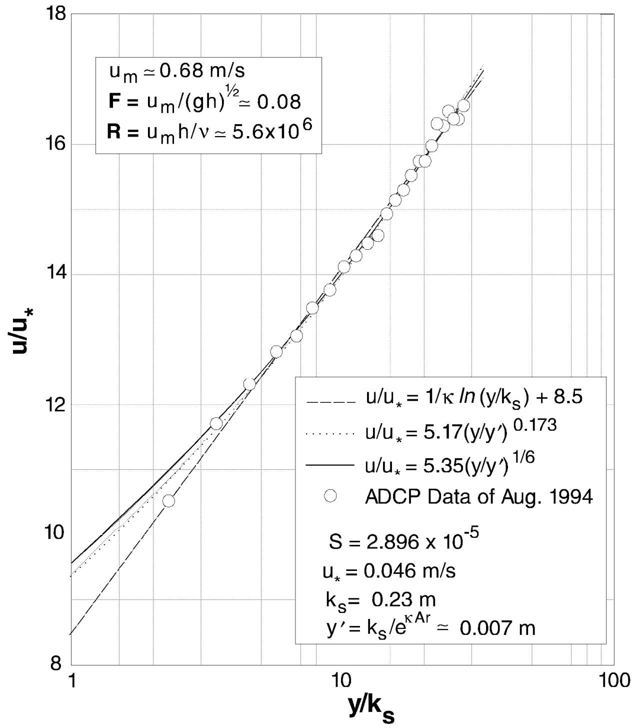

Figure 1. Nondimensional velocity profiles from fixed ADCP data collected in CSSC at Romeoville, Ill. on August 17, 1994.

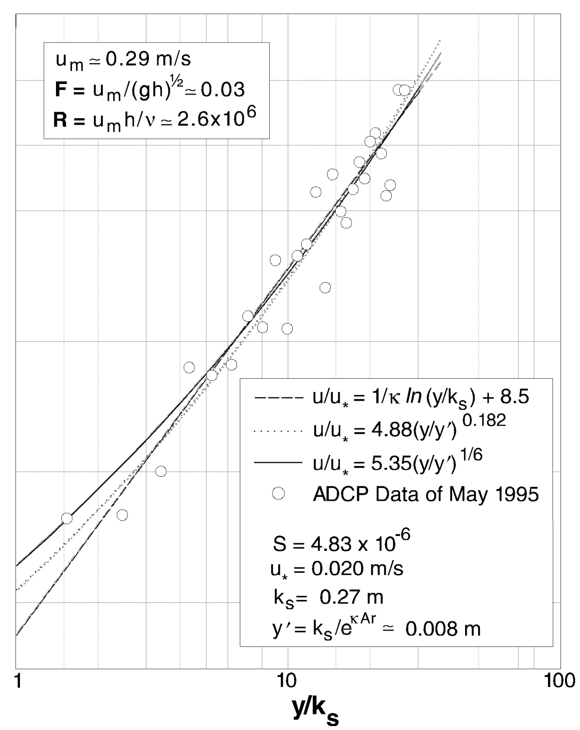

Figure 2. Nondimensional velocity profiles from fixed ADCP data collected in CSSC at Romeoville, Ill. on May 12, 1995.

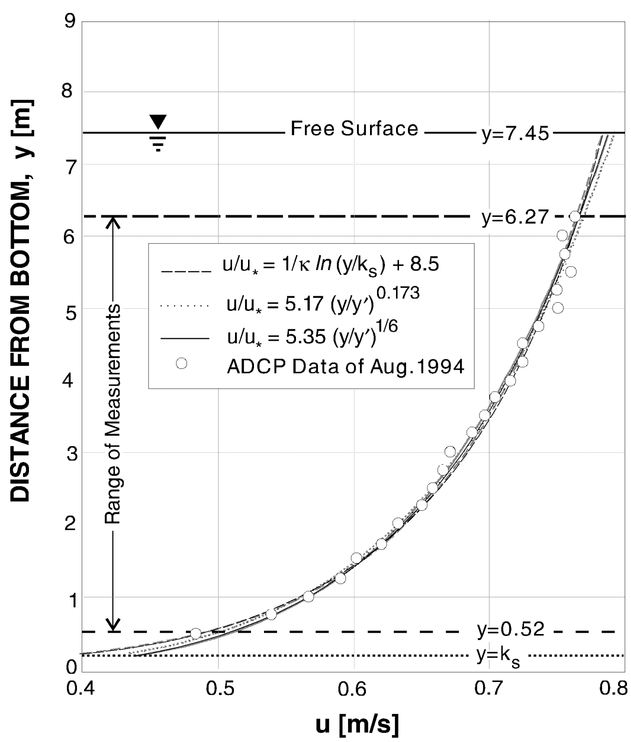

Figure 3. Velocity profiles from fixed ADCP data collected in CSSC at Romeoville, Ill. on August 17, 1994.

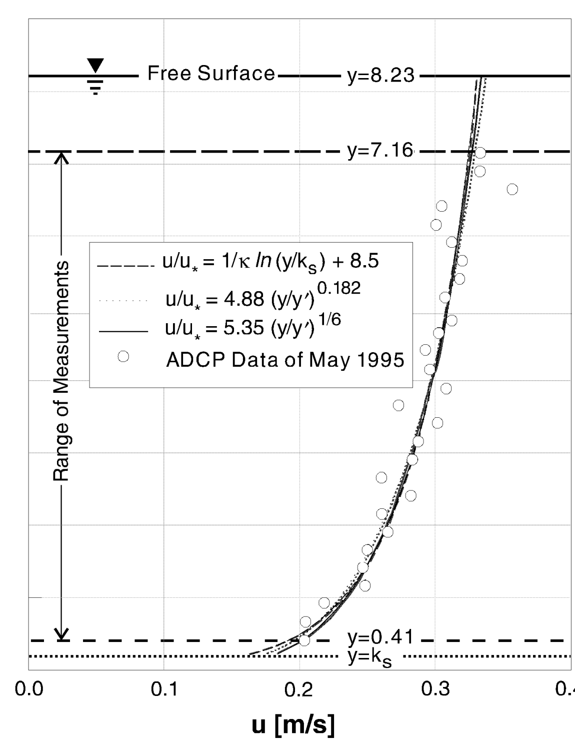

Figure 4. Velocity profiles from fixed ADCP data collected in CSSC at Romeoville, Ill. on May 12, 1995.