

Watershed Sciences 6900

FLUVIAL HYDRAULICS & ECOHYDRAULICS

WEEK Four – Lecture 6

VELOCITY DISTRIBUTION

Joe Wheaton



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& ECOHYDRAULICS



FOR TODAY, YOU SHOULD HAVE READ...

[Assignments >](#)

Reading for Tuesday, February 1st

posted Jan 29, 2011 10:37 AM by Joseph Wheaton

What you should Read

Lecture on Tuesday will cover Chapter 5, on 'Velocity Distributions'. You should read the entire chapter. §5.1 is a review of previous material, so I will skip that in lecture and assume you are competent with regard to vertical force profiles in uniform flows. You should focus the rest of your reading on the topics we are covering in lecture (below), but please do vote in the poll for what topic you'd like to cover that are not planned.



What we Will Cover in Lecture

In lecture, we will focus on:

- Velocity Profile in Laminar Flows (§5.2)
- Velocity Profile in Turbulent Flows (§5.3) covering:
 - Most of §5.3.1 (The Prandtl-vn Karman Velocity Profile)
 - Brief mention of §5.3.2 (The Velocity-Defect Law)
 - Power Law Profiles (§5.3.3)
- Observed Velocity (vertical) Distributions (§5.4.2)

PLEASE [vote on our poll](#) on the forum by Monday afternoon to determine what additional topics we might cover in the last 10 minutes of lecture.

[Corresponding Lecture Topic](#)



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LET'S GET ON WITH IT...

Tuesday Reading - Velocity Profiles

[POST/REPLY](#) Search this topic...

Please choose the topic(s) you want more help on in lecture:

Poll runs till Tue Feb 01, 2011 6:19 pm
You may select 1 option

55.1 - Vertical Force Profile in Uniform Flows	<input type="radio"/>	0	No votes
55.3.4 - Hyperbolic-Tangent Profile	<input type="radio"/>	0	No votes
55.3.5 - Other Theoretical Profiles	<input type="radio"/>	0	No votes
55.4.1 - Velocity Distribution in Ideal Parabolic Channel	<input type="radio"/>	0	No votes
55.4.3 - Statistical Characterizations of Velocity Distribution	<input type="radio"/>	1	25%
I rather you spend the whole time on the topics you are already covering	<input type="radio"/>	3	75%
Total votes : 4			
<input type="button" value="Submit vote"/>			



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TODAY'S PLAN

VELOCITY DISTRIBUTIONS

- I. Velocity Profile in Laminar Flows
- II. Velocity Profile in Turbulent Flows
 - I. Prandtl von Karman Velocity Profile
 - II. Velocity Defect Law
 - III. Power Law Profiles
- III. Observed Velocity Distributions



From Chanson (2004)

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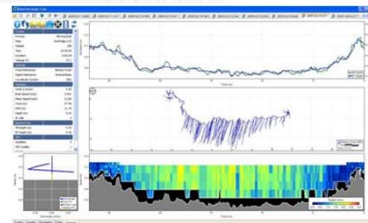
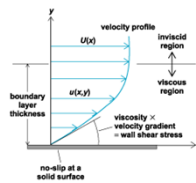
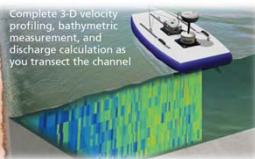
VELOCITY DISTRIBUTIONS

Previous chapters have discussed the velocity of individual fluid elements (point velocities), denoted as u_x , u_y , u_z , and the average velocity through a stream cross section, denoted as U . The main objective of the present chapter is to explore the connection between point velocities and cross-section average velocity by developing physically sound quantitative descriptions of the distribution of velocity in cross sections.

However, there has been little research on the distribution of velocities in entire cross section, so most of the discussion here will be devoted to velocity profiles:

Most of discussion limited to vertical velocity profiles...

The **velocity profile** is the relation between downstream-directed velocity $u(y)$ and normal distance above the bottom, y .¹

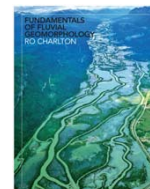
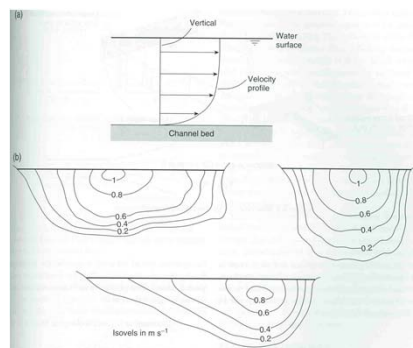


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WHY DO WE CARE?

- Basis for formulating expressions of flow resistance

$$F_D = F_R$$



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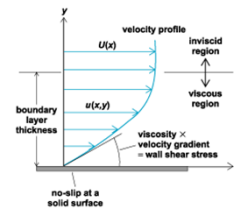
WHAT IS A VELOCITY PROFILE?

- A mathematical function for velocity as a function of depth (or height above bed): $u(y) = ?$

$$U_w = \frac{1}{Y_w} \cdot \int_0^{Y_w} u(y) \cdot dy$$

$$U = \frac{1}{A} \cdot \int_0^A U_w(w) \cdot dA(w)$$

Is this a velocity profile?



- U_w - Local average 'vertical' velocity
- U - Average cross section velocity
- Y_w - Local Depth
- A - Cross Sectional Area
- w - Water surface width

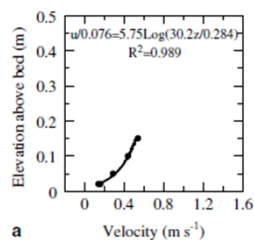


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HOW DO I MEASURE A VELOCITY PROFILE?

- You take a bunch of points...
- Say every few centimeters?



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BOUNDARY SHEAR STRESS DISTRIBUTION...

Depth-Slope Product: Boundary
Shear Stress:

$$\tau_0 = \gamma \cdot Y_w \cdot \sin \theta_s$$

Linear shear stress relationship for both
laminar & turbulent flow:

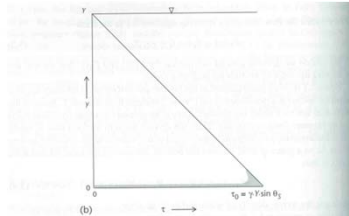


Figure 5.2 (a) The linear relation between shear stress, τ , and distance above the bottom, y , given by equation 5.6. This relation applies to both laminar and turbulent flow states. (b) Shear stress distribution in a turbulent flow. The shaded area schematically represents the parabolic total shear stress that is due to molecular viscosity. Total shear stress is the sum of that due to molecular viscosity and that due to eddy viscosity.



TODAY'S PLAN

VELOCITY DISTRIBUTIONS



- I. Velocity Profile in Laminar Flows
- II. Velocity Profile in Turbulent Flows
 - I. Prandtl von Karman Velocity Profile
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 - III. Power Law Profiles
- III. Observed Velocity Distributions



LAMINAR FLOW - PROFILE

$$u(y) = \frac{\gamma}{\mu} \cdot \left(Y_w \cdot y - \frac{y^2}{2} \right) \cdot \sin \theta_s$$

To visualize this distribution, we can first use equation 5.11 to calculate the velocity at the surface, $u(Y_w)$:

$$u(Y_w) = \frac{\gamma}{\mu} \cdot \left(\frac{Y_w^2}{2} \right) \cdot \sin \theta_s. \quad (5.12)$$

Then we can plot the dimensionless relative velocity $u(y)/u(Y_w)$ versus relative distance above the bottom, y/Y_w , in figure 5.3, where from equation 5.11 and 5.12,

$$\frac{u(y)}{u(Y_w)} = 2 \cdot \frac{y}{Y_w} - \left(\frac{y}{Y_w} \right)^2. \quad (5.13)$$

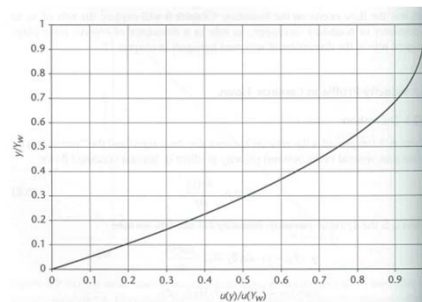


Figure 5.3 Relative velocity $u(y)/u(Y_w)$ as a function of relative distance above the bottom y/Y_w , for laminar open-channel flows (equation 5.13).



WHAT'S HE TELLING US?

- Average vertical velocity

5.2.2 Average "Vertical" Velocity

The average local "vertical" velocity of a wide laminar flow, U_w , is given by substituting equation 5.11 into 5.2 and integrating; evaluating that expression leads to

$$U_w = \left(\frac{\gamma}{3 \cdot \mu} \right) \cdot Y_w^2 \cdot \sin \theta_s. \quad (5.14)$$

Recall from section 3.4.2 that laminar flow only occurs when the Reynolds number, Re , is less than 500, where

$$Re = \frac{U_w \cdot Y_w}{\nu}. \quad (5.15)$$

If we substitute 5.14 into 5.15 and recall that $\nu = \mu/\rho$ and $\gamma = \rho \cdot g$, we arrive at

$$Re = \frac{g \cdot Y_w^3 \cdot \sin \theta_s}{3 \cdot \nu^2}. \quad (5.16)$$

and if $Re = 500$, the limiting value for laminar flow, we have

$$Y_w = \left(\frac{1500 \cdot \nu^2}{g \cdot \sin \theta_s} \right)^{1/3}. \quad (5.17)$$

We can use equation 5.17 to find the maximum depth for which a flow will be laminar at a specified slope; this relation is shown in figure 5.4. Note that even for surfaces with very low slopes (e.g., parking lots), this depth is in the centimeter range; for hillslopes, for which typically $\sin \theta_s > 0.01$, the maximum depth is in the millimeter range.

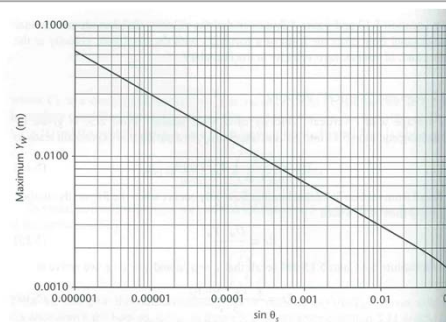


Figure 5.4 Maximum depth at which laminar flow occurs as a function of slope (equation 5.17). Kinematic viscosity is assuming a water temperature of 10°C.



TODAY'S PLAN



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From Chanson (2004)

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SO IN TURBULENT FLOWS....

- It's most commonly treated with the 'Law of the Wall' (i.e. Prandtl von Karman)
- For practical purposes... it is very difficult to measure the viscous sublayer in natural streams

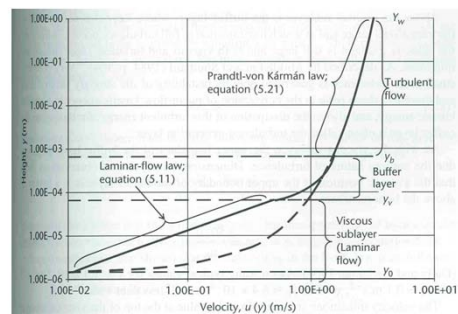
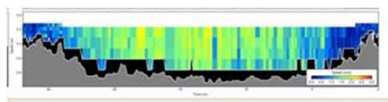


Figure 5.6 Velocity structure in a turbulent boundary-layer flow. The heavy line is the actual velocity profile. The P-v-K profile applies from the top of the buffer layer y_b to the surface; the laminar profile applies from the bottom to y_v . See text for detailed explanation.



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WHAT DOES IT MEAN?

- In log-log space, a straight line means?
- The profile is logarithmic...

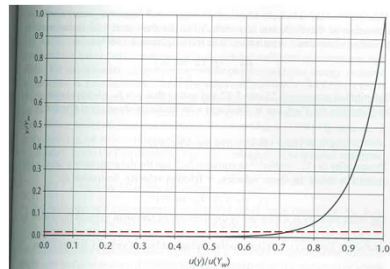


Figure 5.5 Relative velocity $u(y)/u(Y_w)$ as a function of relative distance above the bottom, y/Y_w , as given by the Prandtl-von Kármán universal velocity distribution (equation 5.21) for a turbulent open-channel flow with a depth $Y_w = 1\text{ m}$ and a slope $\sin \theta = 0.001$.

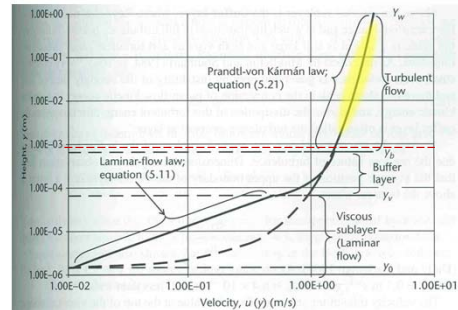


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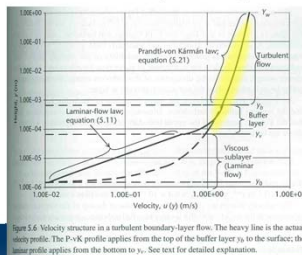


DERIVATION OF Prandtl-von Kármán (P-vK)

- Starting with equations 3.40a & 5.6 (in sections you will have read but we did not cover...)
- Bunch of math magic...

$$u(y) = \left(\frac{1}{\kappa}\right) \cdot (g \cdot Y_w \cdot \sin \theta_s)^{\frac{1}{2}} \cdot \ln \left(\frac{y}{y_0}\right)$$

- Where you know everything... except κ



- In practice $\kappa = 0.4$
- Can range from 0.2 to 0.4



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SHEAR VELOCITY (FRICTION VELOCITY)

$$u(y) = \left(\frac{1}{\kappa}\right) \cdot (g \cdot Y_w \cdot \sin \theta_s)^{\frac{1}{2}} \cdot \ln \left(\frac{y}{y_0}\right)$$

5.3.1.3 Shear Velocity (Friction Velocity)

The quantity $(g \cdot Y_w \cdot \sin \theta_s)^{1/2}$ in equation 5.21 has the dimensions of a velocity. This quantity is called the **shear velocity**, or **friction velocity**, designated u_* :

$$u_* \equiv (g \cdot Y_w \cdot \sin \theta_s)^{1/2} \quad (5.24)$$

The shear velocity is a measure of the intensity of turbulent velocity fluctuations. To see this, recall from equation 3.32 that the shear stress at a height y above the bed in a turbulent flow, $\tau(y)$, is related to the average turbulent velocity fluctuations as

$$\tau(y) = -\rho \cdot \bar{u}_x'(y) \cdot \bar{u}_y'(y) \quad (5.25)$$

where $\bar{u}_x'(y)$ and $\bar{u}_y'(y)$ are the average fluctuations in the x - and y -directions, respectively. We also saw from equation 3.31 that the magnitudes of these fluctuations are proportional, so we can write

$$\tau(y) = -k_{yx} \cdot \rho \cdot [\bar{u}_x'(y)]^2 \quad (5.26)$$

where k_{yx} is the proportionality constant. Now, noting equation 5.7, we see that

$$u_* = \left(\frac{\tau_0}{\rho}\right)^{1/2} \quad (5.27a)$$

and

$$\tau_0 = \rho \cdot u_*^2 \quad (5.27b)$$

Comparing equation 5.27 with 5.26, we see that in turbulent flows u_* and τ_0 are alternate ways of expressing both the intensity of turbulence and the boundary shear stress. Shear velocity u_* expresses these physical quantities in kinematic (velocity) terms, whereas τ_0 expresses them in dynamic (force) terms. Also note that u_* can be thought of as a characteristic near-bed velocity in a turbulent flow.

$$u(y) = \left(\frac{1}{\kappa}\right) \cdot u_* \cdot \ln \left(\frac{y}{y_0}\right)$$



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RELATIVE VELOCITY PROFILE (DIMENSIONLESS)

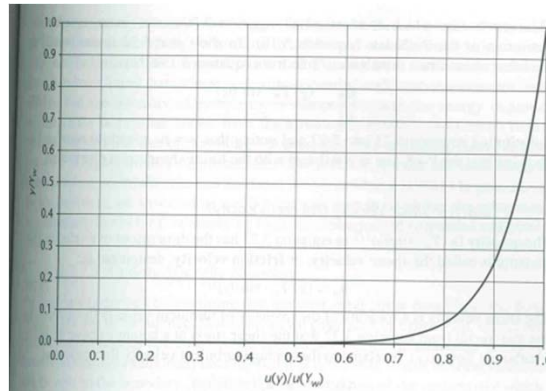


Figure 5.5 Relative velocity $u(y)/u(Y_w)$ as a function of relative distance above the bottom, y/Y_w , as given by the Prandtl-von Kármán universal velocity distribution (equation 5.21) for a turbulent open-channel flow with a depth $Y_w = 1\text{ m}$ and a slope $\sin \theta = 0.001$.



ROUGHNESS REYNOLDS NUMBER

Recall:

$$Re \equiv \left(\frac{\rho \cdot Y \cdot U}{\mu} \right) = \left(\frac{Y \cdot U}{\nu} \right)$$

Let thickness of the sublayer y_r be the characteristic length... Then, the boundary Reynolds number (or roughness Re) is:

$$Re_b \equiv \left(\frac{y_r \cdot u_*}{\nu} \right)$$

Experiments have shown that Re_b :

- Smooth: $Re_b > 5$
- Transitional: $5 > Re_b > 70$
- Rough: $Re_b > 70$

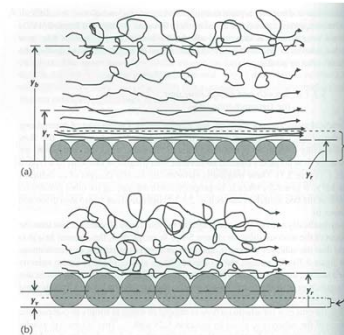


Figure 5.7 Schematic diagram of hydraulically (a) smooth and (b) rough turbulent flow. Arrows represent flow paths. In smooth flow, the viscous sublayer thickness y_r exceeds the height of the roughness elements y_r , and the viscous sublayer is present at the bed. In rough flow, the roughness height exceeds the viscous sublayer height, and no sublayer is present.

WHAT IT ALL BOILS DOWN TO...

5.3.1.8 The P-vK Law: Summary

To summarize the discussions of sections 5.3.1.2–5.3.1.7, we use equations 5.24 and 5.32 to write the P-vK law in the forms that we will usually apply it:

Smooth flows, $Re_b \leq 5$:

$$u(y) = 2.50 \cdot u_* \cdot \ln \left(\frac{9 \cdot u_* \cdot y}{\nu} \right); \quad (5.34a)$$

Rough flows, $Re_b > 5$:

$$u(y) = 2.50 \cdot u_* \cdot \ln \left(\frac{30 \cdot y}{y_r} \right). \quad (5.34b)$$

Note that these are mathematically equivalent to Smooth flows, $Re_b \leq 5$:

$$\frac{u(y)}{u_*} = 2.50 \cdot \ln \left(\frac{u_* \cdot y}{\nu} \right) + 5.49 = 5.76 \cdot \log \left(\frac{u_* \cdot y}{\nu} \right) + 5.49; \quad (5.34c)$$

Rough flows, $Re_b > 5$:

$$\frac{u(y)}{u_*} = 2.50 \cdot \ln \left(\frac{y}{y_r} \right) + 8.50 = 5.76 \cdot \log \left(\frac{y}{y_r} \right) + 8.50; \quad (5.34d)$$

and the P-vK law may be written in any of these forms.



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AVERAGE VERTICAL VELOCITY (TURBULENT FLOW)

- Starting with a definition of the average vertical velocity, derived by integration P-vK law over its range of validity (i.e. above the top of the buffer zone:

$$U_w = \frac{1}{Y_w - y_b} \cdot \int_{y_b}^{Y_w} 2.50 \cdot u_* \cdot \ln \left(\frac{y}{y_0} \right) \cdot dy$$

Using the facts that

$$\ln \left(\frac{y}{y_0} \right) = \ln(y) - \ln(y_0)$$

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and

$$\int \ln(y) \cdot dy = y \cdot \ln(y) - y,$$

we can evaluate equation 5.35 as

$$U_w = \left(\frac{2.50 \cdot u_*}{Y_w - y_b} \right) \left[Y_w \cdot \ln \left(\frac{Y_w}{y_0} \right) - Y_w - y_b \cdot \ln \left(\frac{y_b}{y_0} \right) + y_b \right]. \quad (5.36)$$

However, we have seen that y_b is generally very small relative to the depth Y_w (figure 5.6), and if this is true, then $y_b \approx 0$ and equation 5.36a can be simplified to

$$U_w = 2.50 \cdot u_* \cdot \left[\ln \left(\frac{Y_w}{y_0} \right) - 1 \right]. \quad (5.36b)$$

This expression for the local mean "vertical" velocity in a turbulent flow can be used to solve a practical problem—the measurement of discharge through a stream cross section. Recall that discharge Q is

$$Q = U \cdot Y \cdot W, \quad (5.37)$$

where U is average cross-section velocity, Y is average cross-section depth, and W is water-surface width. The velocity-area method of discharge measurement (described in section 2.5.3.1) involves dividing the cross section into I subsection and determining Q as

$$Q = \sum_{i=1}^I U_i \cdot Y_i \cdot W_i, \quad (5.38)$$

where U_i and Y_i are the local velocities and depths U_w and Y_w , respectively, at successive points $i = 1, 2, \dots, I$, and W_i is the width of subsection i . Measurement of depth and width for each subsection is straightforward, but since velocity varies vertically, there is the problem of how to determine an average without measuring velocity at a large number of heights at each subsection.

This problem is solved by noting that the actual velocity $u(y)$ must equal the average value U_w at some height $y = y_U$. Taking $y_U = k_U \cdot Y_w$, the P-vK law gives

$$U_w = 2.50 \cdot u_* \cdot \ln \left(\frac{k_U \cdot Y_w}{y_0} \right), \quad (5.39)$$

and equating this to equation 5.36b gives

$$2.50 \cdot u_* \cdot \ln \left(\frac{k_U \cdot Y_w}{y_0} \right) = 2.50 \cdot u_* \cdot \left[\ln \left(\frac{Y_w}{y_0} \right) - 1 \right]. \quad (5.40)$$

The value of k_U can be found from equation 5.40 as

$$k_U = \frac{1}{e} = 0.368, \dots \quad (5.41)$$

where $e = 2.718 \dots$ is the base of natural logarithms.

Thus, we see that, according to the P-vK law, the velocity measured at a depth $0.368 \cdot Y_w$ above the bottom equals the average value for the profile. This finding



PRACTICAL UTILITY OF P-VK LAW

- $0.368 \approx 0.4$
- The six-tenths rule...
- If velocity profile follows P-vK (i.e. logarithmic) then I can just take one measurement!

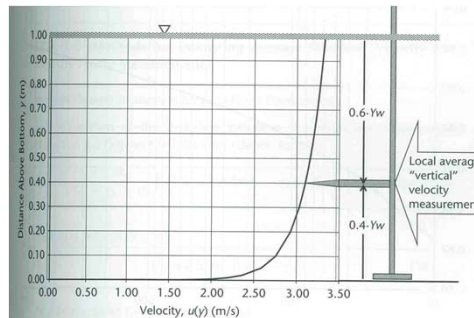


Figure 5.10 P-vK velocity profile for a turbulent flow with $Y_w = 1$ m, showing velocity measurement by current meter at six-tenths of the depth measured from the surface. According to the P-vK law, the actual velocity $u(y)$ equals the average velocity U_w at $y/Y_w = 0.368$ This is the basis for the "six-tenths-depth rule" for measuring local average "vertical" velocity.

the basis for the **six-tenths-depth rule** used by the U.S. Geological Survey and others for discharge measurement:

If the P-vK law applies, the average velocity U_w at a point in a cross section is found by measuring the velocity six-tenths of the total depth downward from the surface, or four-tenths (≈ 0.368) of the depth above the bottom (figure 5.10).

TODAY'S PLAN

VELOCITY DISTRIBUTIONS

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THE VELOCITY-DEFECT LAW

- P-vK states τ is constant through flow boundary (wall); this is known as the **law of the wall**
- Far from the bed the velocity gradient ($\frac{du}{dy}$) does not depend on viscosity (μ) or bed roughness, but only on distance from bed
- In this region, the velocity profile is the difference between velocity at the surface ($u(Y_w)$) and the velocity at an arbitrary level ($u(y)$) and is only a function of $\frac{y}{Y_w}$

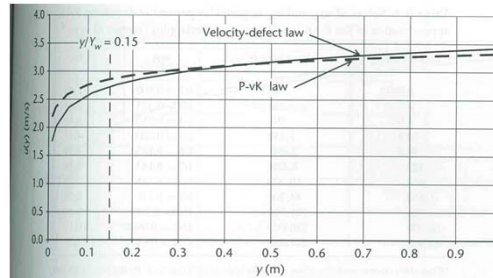


Figure 5.12 Comparison of velocity profiles given by the P-vK law (dashed line, equation 5.34) and the velocity-defect law (solid line, equation 5.44). The average velocities over the two profiles are identical. The difference between the velocities given by the two profiles differs by less than 4% for $y/Y_w > 0.15$.

$$\frac{u(Y_w) - u(y)}{u_*} = f_{VD} \left(\frac{y}{Y_w} \right)$$



VELOCITY-DEFECT REARRANGED & APPLIED

- The function $f_{VD} \left(\frac{y}{Y_w} \right)$ is determined by experiment...

$$\frac{u(Y_w) - u(y)}{u_*} = f_{VD} \left(\frac{y}{Y_w} \right)$$

- Daily & Harleman (1966), for $\frac{y}{Y_w} > 0.15$:

$$\frac{u(Y_w) - u(y)}{u_*} = -3.74 \cdot \ln \left(\frac{y}{Y_w} \right)$$

- But:

In the region near the boundary is not compelling. Furthermore, we saw that velocities given by the velocity-defect law do not differ greatly from the P-vK law (figure 5.12). Therefore, we can conclude that there is usually no need to invoke the velocity-defect law in preference to the P-vK law.



TODAY'S PLAN



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From Chanson (2004)

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POWER-LAWS AS AN ALTERNATIVE...

- What is a power law?
 - A polynomial relationship that exhibits scale invariance and of the form:

$$f(x) = ax^k$$

- Can't do it for $u(y)$, but can do it for $u\left(\frac{y}{y_0}\right)$.

$$u(y) = k_{PL} \cdot u_* \cdot \left(\frac{y}{y_0}\right)^{m_{PL}}$$

- When integrated over depth...

$$U_w = u_* \cdot \left(\frac{\kappa_{PL}}{m_{PL} + 1}\right) \cdot \left(\frac{Y_w}{y_0}\right)^{m_{PL}}$$

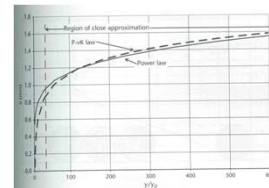


Figure 5.13 Velocity profiles for a flow with $Y_w = 1$ m, $\sin \theta = 0.001$, and $y_0 = 50$ mm as given by the Prandtl law (dashed) and the power law (solid). The power law profile is computed in equation 5.43 with $m_{PL} = 1.76$, $\kappa_{PL} = 5.39$, and $u_* = 1.97 \times 10^{-3}$ m and gives a good approximation only in the range: $36.4 < y/y_0 < 5,490$ (table 5.1).



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VELOCITY DISTRIBUTIONS

- I. Velocity Profile in Laminar Flows
- II. Velocity Profile in Turbulent Flows
 - I. Prandtl von Karman Velocity Profile
 - II. Velocity Defect Law
 - III. Power Law Profiles

III. Observed Velocity Distributions

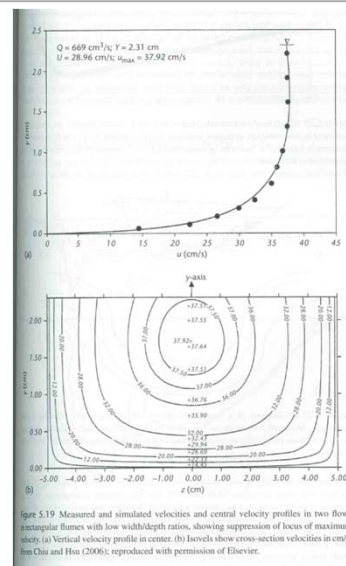


From Chanson (2004)

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A BORING RECTANGULAR FLUME...



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SOMETHING MORE INTERESTING...

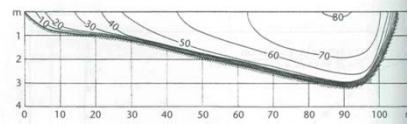


Figure 5.20 Isovels (cm/s) in a meander bend of the River Klarälven, Sweden, showing typical pattern of highest velocities in deepest portion of the cross section leading to helicoidal flow as shown in figure 5.21a. Note vertical exaggeration. From Sundborg (1956); reproduced with permission of Blackwell.

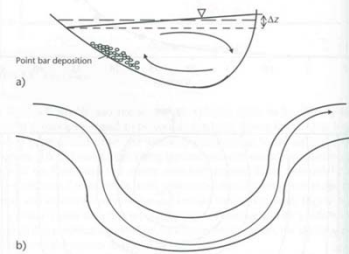


Figure 5.21 (a) Diagram of a meander bend (vertically exaggerated), showing typical asymmetry, helicoidal flow, point-bar deposition on inside of bend, and super-elevation Δz . (b) Diagrammatic plan view of successive meander bends showing trace of thread of maximum velocity.



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HOW GOOD IS Pv-K?

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Error propagation for velocity and shear stress prediction using 2D models for environmental management

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KEYWORDS

Shear stress;

2D models;

River restoration;

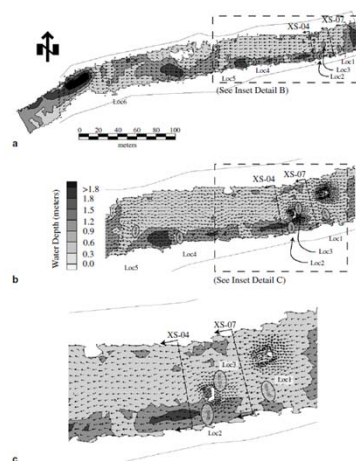
Hydraulics

Summary Resource managers, scientists, government regulators, and stakeholders are considering sophisticated numerical models for managing complex environmental problems. In this study, observations from a river-rehabilitation experiment involving gravel augmentation and spawning habitat enhancement were used to assess sources and magnitudes of error in depth, velocity, and shear velocity predictions made at the 1-m scale with a commercial two-dimensional depth-averaged model. Error in 2D model depth prediction averaged 21%. This error was attributable to topographic survey resolution, which at 1 ft per 1 ft², was inadequate to resolve small humps and depressions influencing point measurements. Error in 2D model velocity prediction averaged 29%. More than half of this error was attributable to depth prediction error. Despite depth-velocity error, 26% of tested 2D model predictions of shear velocity were within the 95% confidence limit of the best field-based estimation method. Ninety percent of the error in shear velocity prediction was explained by velocity prediction error. Multiple field-based estimates of shear velocity differed by up to 160%, so the lower error for the 2D model's predictions suggests such models are at least as accurate as field measurement. 2D models enable detailed, spatially distributed estimates compared to the small number measurable in a field campaign of comparable cost. They also can be used for design evaluation. Although such numerical models are limited to channel types adhering to model assumptions and yield predictions only accurate to ~20–30%, they can provide a useful tool for river-rehabilitation design and assessment, including spatially diverse habitat heterogeneity as well as for pre- and post-project appraisal.
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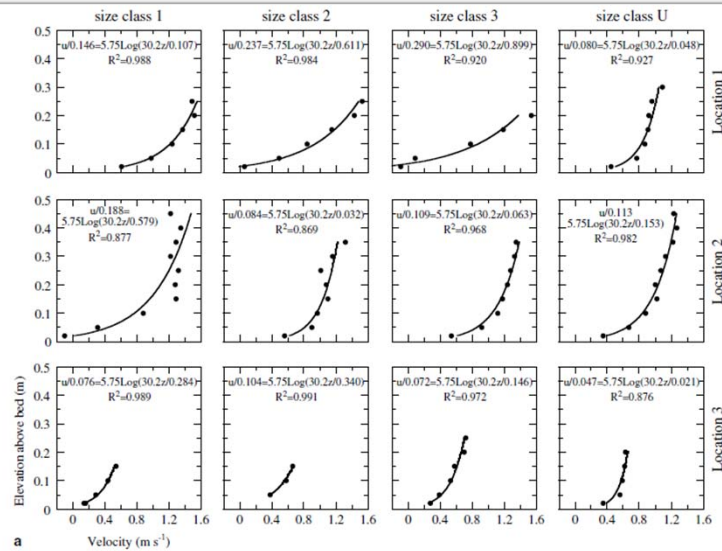
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doi:10.1016/j.jhydrol.2005.12.003



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SOME EMPIRICAL DATA...



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- III. Observed Velocity Distributions



READING/LAB

- I'll post this tonight... (Chapter 6 – Uniform Flow & Flow Resistance)
- This week's lab... more time to work through Chapter 6
- Next week, get back to something more fun in lab... flume experiment

