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U.S. Army Corps of Engineers  
Washington, DC 20314-1000 | EM 1110-2-1601  
1 July 1991/  
30 June 1994 |
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<td>Engineering and Design</td>
<td>HYDRAULIC DESIGN OF FLOOD CONTROL CHANNELS</td>
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<td>Approved for public release; distribution is unlimited.</td>
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# Chapter 2

## Open Channel Hydraulic Theory

<table>
<thead>
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<tbody>
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</table>
Open Channel Hydraulic Theory

• Physical Hydraulic Elements
• Hydraulic Design Aspects
• Flow Through Bridges
• Transitions
• Flow in Curved Channels
• Special Considerations
• Stable Channels
Physical Hydraulic Elements

- Channel slope
- Cross-sectional area
- Wetted perimeter
- “Most efficient section”
- Boundary surface roughness
Invert Slope

• Controlled by surrounding topography
• Can be altered to achieve desired project goals, but...
  - Cut/fill can be expensive
  - Effect on hydraulics and costs
  - Need to examine out of reach influences
Channel Cross-Section

- Balance capacity with costs
- Typically:
  - Trapezoidal for rural areas
  - Rectangular for urban reaches
  - V-bottom for minimizing effects of sediment
Roughness

- Absolute roughness
  - Theoretical interest only
- Effective roughness
  - Dimension of length
  - “Effective roughness height”
- Composite roughness
  - Most common approach
Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- **Hydraulic Design Aspects**
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels
Hydraulic Design Elements

- Assumptions
- Friction Losses
- Friction Coefficients
- Flow Classification
Assumptions

• Familiar with concepts of:
  - Uniform flow
  - Gradually varied flow
  - Conservation of Energy
  - Conservation of Momentum
  - Conversion of friction loss terms

• Have or have access to Chow (1959)
Hydraulic Design Elements

• Assumptions
• Friction Losses
• Friction Coefficients
• Flow Classification
Friction Losses

- Three main equations/concepts
  - Chezy
  - Manning
  - Darcy-Weisbach

- Included
  - Losses due to friction
  - Uniform turbulence and eddy losses

- Not Included
  - Local turbulence and eddy losses
Types of Fluid Flow

• Laminar Flow - flow persists as unidirectional movement
  - Molecules flow parallel
  - Movement up and down by diffusion
• Turbulent Flow - highly distorted flow
  - Large scale flow perpendicular to direction of flow
  - Transfer of movement up and down by macroscale processes
• Turbulence = irregular and random component of fluid motion
• Eddies = highly turbulent water masses
Laminar vs Turbulent Flow

- **Laminar flow** - velocity constant at a point over time
- **Turbulence**
  - Most flows = turbulent
  - Slow settling velocity - upward motion of water particles
  - Increases effectiveness of fluid in eroding and entraining particles from the bed; but less efficient transport agent
  - Velocity measured at a point over time - tends towards an average value; but varies from instant to instant
Friction Losses
Type of Energy Losses

In consideration of the energy losses in fluid flow, they are generally broken down into 2 types:

- Major losses
- Minor losses
Major head losses are a form of energy considered to take place continuously along the path of flow.

These losses are generally called "Friction Head Losses".
Friction Losses

Minor Head Losses

Minor head losses are those losses generally created by increased turbulence and resistance to flow at points in the stream where the direction of flow is changed or where other obstruction take place.

The most commonly encountered forms of minor head losses are as follows:

- **Hf** head losses due to a sudden or gradual enlargement of the cross section of flow.
- **Hc** head losses due to a sudden or gradual contraction of the cross section of flow.
- **Hg** head losses due to obstruction in the path of flow (gates, valves, metering devices, and so on)
- **Hb** head losses occurring at bends and changes in direction of the flow path.
Friction Losses

Total Head Losses

The total head loss in a stream of flowing fluid is equal to the sum of all the head losses along its path.

Total Head Losses = Major Head Losses + Minor Head Losses

\[ H_i = h_f + h_e + h_c + h_g + h_b \]
Hydraulic Design Elements

• Assumptions
• Friction Losses
• Friction Coefficients
• Flow Classification
Recap

• If depth & velocity remain constant over a length of channel which has a constant cross-section and slope, then the flow is uniform and water surface will be parallel to streambed. The depth is called the normal depth.

• If depth and/or velocity change over distance then it is varied flow, which can be divided into gradually varied or rapidly varied
Steady Flow

- Law of continuity
  - \( Q = V_1A_1 = V_2A_2 = \ldots \)
  - \( Q \) = discharge, \( V \) = Average velocity, \( A \) = cross sectional area
  - Must have continuous, steady-varied flow

- Flow may also be:
  - Unsteady-varied
  - Unsteady-uniform
  - Steady-uniform
Uniform flow

- Gravity (force causing motion)
- Friction (force opposing motion)
- For uniform flow the gravity force will equal the friction force and the energy line, the water surface and the streambed will be parallel (have the same slope)
Antoine Chezy, in 1775

A French civil engineer developed the Chézy equation, which relates the uniform flow velocity to channel roughness, hydraulic radius, and bed slope.

\[ v = C \sqrt{RS} \]

- \( v \) = average velocity of flow
- \( R \) = hydraulic radius
- \( S \) = slope of the channel
- \( C \) = coefficient depending upon the various characteristics of the channel and their comparison with those of another similar channel.
Chezy’s Equation

• The gravitation force is approximately proportional to the velocity squared

• \( V = \sqrt{(\rho g/\alpha)RS} \)
  - \( V \) is the mean velocity (ft/s)
  - \( \alpha \) is a coefficient mainly dependent on channel roughness
Chezy’s “C”

• The term $\sqrt{\frac{\rho g}{\alpha}}$ was later replaced with a single coefficient $C$
• $C$ has units of $(\text{ft}^{1/2}/\text{s})$
• And varies from:
  - 30 (small rough channels)
  - 90 (large smooth ones)
TABLE XI. VALUES OF $C$ FOR USE IN THE CHEZY FORMULA

$V = C \sqrt{rs}$

(Art. 286, p. 315.)

<table>
<thead>
<tr>
<th>Slope</th>
<th>$r$</th>
<th>.020</th>
<th>.025</th>
<th>.030</th>
<th>.035</th>
<th>.040</th>
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<td>58</td>
</tr>
</tbody>
</table>

Note.—For $r = 3.28$ feet, $n$ constant, $C$ is constant for all values of slope. For slopes greater than 0.01, or fall of 52.8 feet per mile, $C$ remains nearly constant.

From "River Discharge," by Hoyt and Grover.
Chezy

\[ S_f = \frac{V^2}{C^2 R} \]

Where:

- \( S_f \) = EGL slope
- \( V \) = velocity
- \( C \) = Chezy coefficient
- \( R \) = Hydraulic radius
Chezy

Hydraulically smooth channels

\[ C = 32.6 \log_{10} \left( \frac{5.2R_n}{C} \right) \]

Where:

\( C = \) Chezy coefficient

\( R_n = \) Reynolds number
Reynolds Number

\[ \text{Re} = \frac{VL}{\nu} \]

or

Internal Forces

Viscous Forces

Where:

- \( \text{Re} \) = Reynolds number
- \( L \) = characteristic length
- \( \nu \) = kinematic viscosity
- \( V \) = velocity
Chezy

Hydraulically rough channels

\[ C = 32.6 \log_{10} \left( \frac{12.2R}{k} \right) \]

Where:

\( C = \) Chezy coefficient
\( k = \) effective roughness
\( R = \) hydraulic radius
Hydraulically Rough or Smooth?

- Hydraulically rough
  - $k_s > k_c$
- Hydraulically smooth
  - $k_s < k_c$
Hydraulically Rough or Smooth?

\[ k_c = \left( \frac{5C}{\sqrt{g}} \right) \left( \frac{v}{V} \right) \]

Where:
- \( k_c \) = Equivalent roughness
- \( C \) = Chezy C
- \( v \) = kinematic viscosity
- \( g \) = gravity
- \( V \) = Velocity
Darcy-Weibach Formula

Henry Darcy, 1857

Showed that $f$ is not dimensionless but dependent upon numerous parameters:
- the roughness of conduit wall
- the velocity of flow
- the viscosity and density of fluid
- the diameter of pipe
Julius Weisbach, developed a formula for pipe flow, based to some extent on the Chezy formula.

\[ h_f = f \times \frac{l}{d} \times \frac{v^2}{2g} \]

- \( f \) = friction factor
- \( d \) = pipe diameter
- \( l \) = pipe length
- \( h_f \) = head losses over pipe length
- \( v \) = velocity
Analysis of Major Energy Losses

Darcy-Weibach Formula

Values for $f$ for water flowing in straight smooth pipe are shown in table.

<table>
<thead>
<tr>
<th>Diameter, mm</th>
<th>0.10</th>
<th>0.25</th>
<th>0.50</th>
<th>1.00</th>
<th>1.50</th>
<th>3.00</th>
<th>5.00</th>
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<td>0.032</td>
<td>0.029</td>
<td>0.027</td>
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<td>0.024</td>
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<td>0.023</td>
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<tr>
<td>200</td>
<td>0.030</td>
<td>0.027</td>
<td>0.025</td>
<td>0.023</td>
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<td>0.022</td>
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<tr>
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<td>0.028</td>
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<td>0.022</td>
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<td>450</td>
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<td>0.021</td>
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<td>0.019</td>
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<tr>
<td>900</td>
<td>0.020</td>
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<td>0.017</td>
<td>0.016</td>
<td>0.016</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Darcy - Weisbach $f$

Where:

$$S_f = \frac{fV^2}{8Rg}$$

$S_f = \text{EGL slope}$

$V = \text{velocity}$

$f = \text{Darcy-Weisbach coefficient}$

$R = \text{Hydraulic radius}$
L.F. Moody developed the diagram which expresses the relationships between
- Reynolds number
- \( f \) for various ranges of values of \( k/d \)

Moody diagram
- all curves are concave upward and tend to flatten out as value of \( R_e \) increase.

\[
R_e = 400 \frac{d}{k} \log(3.7 \frac{d}{k})
\]
Moody Diagram

pipe friction chart
applicable to circular pipes running full

\( f = \frac{h}{\frac{L}{d}} \frac{u^2}{2g} \)

\( \frac{u d}{v} \)

\( Re = \frac{u d}{v} \)

\( Re \) = Reynolds Number

\( f \) = Friction Factor

\( h \) = Friction head loss

\( L \) = Length of pipe

\( d \) = Diameter of pipe

\( u \) = Velocity of fluid

\( v \) = Kinematic viscosity

\( g \) = Acceleration due to gravity

\( n \) = Surface roughness

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Open-Channel Flow Formulas

Manning Formula

Robert Manning, in 1885

Developed Manning formula used for open channel flow conditions.

\[ v = \frac{1}{n} \cdot R^{2/3} \cdot S^{1/2} \]

- \( v \) = velocity of flow, m/s
- \( R \) = hydraulic radius, m
- \( S \) = slope of the energy gradient
- \( n \) = a roughness coefficient
Manning’s Equation

- \( V = \frac{1}{n} R^{2/3} S^{1/2} \)
- \( Q = \frac{1}{n} AR^{2/3} S^{1/2} \)
  - \( Q \) is discharge (ft3/s)
  - \( n \) is a coefficient known as “Manning’s n”
  - SI units (imperial are multiplied by 1.486)
- \( n = s d^{1/6} \)
  - \( d \) is the median diameter in (mm) \( d_{50} \), for which 50% of streambed particles are smaller
- \( n = \frac{0.1129 R^{1/6}}{(1.16+2 \log(R/d_{84}))} \)
  - \( d_{84} \) is the diameter (m) for which 84% of streambed particles are smaller
Manning

\[ S_f = \frac{V^2 n^2}{2.21 R^{4/3}} \]

Where:
- \( V \) = velocity
- \( S_f \) = EGL slope
- \( n \) = Manning’s \( n \)
- \( R \) = Hydraulic radius
**Manning's $n$ Examples**

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Manning $n$ (ft$^{1/6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very smooth surfaces such as glass, plastic, or brass</td>
<td>0.010</td>
</tr>
<tr>
<td>Very smooth concrete and planed timber</td>
<td>0.011</td>
</tr>
<tr>
<td>Smooth concrete</td>
<td>0.012</td>
</tr>
<tr>
<td>Ordinary concrete lining</td>
<td>0.013</td>
</tr>
<tr>
<td>Good wood</td>
<td>0.014</td>
</tr>
<tr>
<td>Vitrified clay</td>
<td>0.015</td>
</tr>
<tr>
<td>Shot concrete, untroweled, and earth channels in best condition</td>
<td>0.017</td>
</tr>
<tr>
<td>Straight unlined earth canals in good condition</td>
<td>0.020</td>
</tr>
<tr>
<td>Rivers and earth canals in fair condition; some growth</td>
<td>0.025</td>
</tr>
<tr>
<td>Winding natural streams and canals in poor condition; considerable moss growth</td>
<td>0.035</td>
</tr>
<tr>
<td>Mountain streams with rocky beds and rivers with variable sections and some vegetation along banks</td>
<td>0.041–0.050</td>
</tr>
</tbody>
</table>

**Manning's n Examples**

<table>
<thead>
<tr>
<th>Bed Form</th>
<th>Manning n (ft$^{1/6}$)</th>
</tr>
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<tbody>
<tr>
<td><strong>Lower regime</strong></td>
<td></td>
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<tr>
<td>Ripples</td>
<td>0.017–0.028</td>
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<tr>
<td>Dunes</td>
<td>0.018–0.035</td>
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<tr>
<td><strong>Washed-out dunes or transition</strong></td>
<td>0.014–0.024</td>
</tr>
<tr>
<td><strong>Upper regime</strong></td>
<td></td>
</tr>
<tr>
<td>Plane bed</td>
<td>0.011–0.015</td>
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<tr>
<td>Standing waves</td>
<td>0.012–0.016</td>
</tr>
<tr>
<td>Antidunes</td>
<td>0.012–0.020</td>
</tr>
</tbody>
</table>

Coefficient Relation

\[ \frac{C}{1.486} = \frac{R^{1/6}}{n} = \frac{10.8}{f^{1/2}} \]
Plate 3 - $k$ to $C$ and $f$
Hydraulically Rough Channels

OPEN CHANNELS
C = n - R - k RELATION
0.008 < n < 0.04

BASIC EQUATIONS

\[ C = \frac{32.8 \log_{10} 12.2R/K}{n^{1/6}} \]

\[ n = \frac{23.85 + 21.95 \log_{10} R/K}{R^{1/6}} \]

WHERE:
- C = CHEZY COEFFICIENT
- n = MANNING'S RESISTANCE COEFFICIENT
- R = HYDRAULIC RADIUS, FT
- k = EQUIVALENT ROUGHNESS HEIGHT, FT

Plate 5
Hydraulically Rough Channels

OPEN CHANNELS
C-n-R-k RELATION
0.03 < n < 0.15

BASIC EQUATIONS
\[ C = 32.6 \log_{10} \left( \frac{22.2 R}{k} \right) \]
\[ n = \frac{R^{1/6}}{23.85 + 21.05 \log_{10} R/k} \]

WHERE:
C = CHEZY COEFFICIENT
n = MANNING'S RESISTANCE COEFFICIENT
R = HYDRAULIC RADIUS, FT
k = EQUIVALENT ROUGHNESS HEIGHT, FT
Rules of Thumb

• Most channels are hydraulically rough
• $k$ values for natural rivers:
  - 0.1 to 3.0 (ft)
• Typically larger than spherical diameters of bed materials - why??
Rules ofThumb

- If field data is available
  - Determine $k$ from:

\[
C = 32.6 \log_{10} \left( \frac{12.2R}{k} \right)
\]

\[
S_f = \frac{V^2}{C^2R}
\]
Rules of Thumb

• If field data is available
  - Determine k from Equation 2-6

• Value of k can be assumed for flow levels at or lower than observed condition

• Appendix C outlines method for determining an effective roughness
Why use $k$?

- Can be assumed to be spherical diameter of average bed material
  - What if losses other than friction?
- Consider relations:

\[
\frac{C}{1.486} = \frac{R^{1/6}}{n}
\]

\[
C = 32.6 \log_{10} \left( \frac{12.2R}{k} \right)
\]

$k$ does not vary with $R$

$n$ varies with $R^{1/6}$
However...

- $k$ must be evaluated for each subsection
- Use subsections:
  - Differing bed materials
  - Bed forms present
  - Expansions and contractions
  - Form roughness significant
Why do we need to know all this stuff?

• Environmental flows
  - Depth of flow
  - Min particle size to prevent erosion

• The depth of flow is obviously important in calculating possible flood depths....

• But its not that simple, we actually use this for back water calculations.
Hydraulic Design Elements

• Assumptions
• Friction Losses
• Friction Coefficients
• Flow Classification
Flow Classification

- Tranquil and rapid flow
- Pulsating rapid flow
- Varied Flow
Tranquil vs. Rapid Flow

- Distinction centered around specific energy and critical depth

\[ H_e = d + \alpha \frac{V^2}{2g} \]

\[ d_c = \left( \frac{q^2}{g} \right)^{1/3} \]
Depth vs. Specific Energy

NOTE:  
q = 100 CFS/FT
H_e = d + 0.5v^2/2g
k = EQUIVALENT ROUGHNESS HEIGHT, FT
n = MANNING'S n
S_o = INVERT SLOPE
d = DEPTH
d_c = CRITICAL DEPTHS
Depth vs. Specific Energy

Tranquil Flow $d > 1.1d_c$ or $Fr < 0.86$

Rapid Flow $d < 0.9d_c$ or $Fr > 1.13$

NOTE: $q = 100$ CFS/FT

$H_e = d + \alpha V^2/2g$

$k =$ EQUIVALENT ROUGHNESS HEIGHT, FT

$n =$ MANNING’S $n$

$S_o =$ INVERT SLOPE

$d =$ DEPTH

$d_c =$ CRITICAL DEPTHS
Depth vs. Specific Energy

If in instability region:

Evaluate both high and low resistance values

Adjust slope (or k) to design in proper zone

NOTE:  

\( q = 100 \text{ CFS/FT} \)

\( H_e = \frac{d + av^2}{2g} \)

\( k = \text{EQUIVALENT ROUGHNESS HEIGHT, FT} \)

\( n = \text{MANNING'S } n \)

\( S_o = \text{INVERT SLOPE} \)

\( d = \text{DEPTH} \)

\( d_c = \text{CRITICAL DEPTHS} \)
Pulsating Rapid Flow

- Occurs at Froude numbers much greater than 1
- Formation of slugs
- Typically on steep slopes with shallow depths
- What is effect?
Pulsating Rapid Flow

• Need to determine roughness
• Concept of limiting Froude number
• Rather difficult to quantify
Roughness

\[
\frac{0.0463 R^{1/6}}{n} = 4.04 - \log_{10} \left( \frac{F}{F_s} \right)^{2/3}
\]

EQ. 2-10

Where:

\begin{align*}
R &= \text{Hydraulic radius} \\
n &= \text{Manning’s } n \\
F &= \text{Froude number of flow} \\
F_s &= \text{Limiting Froude number}
\end{align*}
Limiting Froude Number

\[ F_s = \frac{\xi}{\sqrt{g} \ \zeta^{3/2} \ (1 + Z\zeta)} \]

EQ. 2-11

Where:

\( F_s \) = Limiting Froude number
\( g \) = Gravity
\( \xi \) = Flow function
\( \zeta \) = depth/width ratio
\( Z \) = Channel side slope
Limiting Froude Number

\[ \xi = \frac{Q}{b^{5/2}} \]
\[ \zeta = \frac{d}{b} \]

Where:
- \( \xi \) = flow function
- \( \zeta \) = depth/width ratio
- \( d \) = flow depth
- \( b \) = bottom width
Pulsating Rapid Flow

Q = 1000
b = 10
Y = 3

z = 2
Fs = 2.12
??

z = 0
Fs = 3.4
??

Plate 7
Varied Flow Profiles

- Prismatic Channels
  - Unvarying cross sections
  - Constant invert slope
  - Straight alignment
- How to determine profile
  - Direct integration
  - Direct step
  - Standard step
Direct Step Method

\[ \Delta x = \frac{E_2 - E_1}{S_o - S_f} \]

- Calculation steps
  - Determine starting depth
  - Assume second depth and compute parameters associated with that depth
  - Solve for step length
Direct Step Method

- **Compute**
  - Upstream direction
    - Subcritical flow
  - Downstream direction
    - Supercritical flow
- Utilize small changes of $y$ so that:

$$S_f = \frac{n^2 V^2}{2.22 R^{4/3}}$$

$$S_f = \frac{fV^2}{8gR}$$
Standard Step Method

\[ WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \]

\[ h_e = L S_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \]

- Calculation steps
  - Assume \( WS_2 \) at upstream location
  - Compute associated velocity head
  - Solve for \( S_f \)
  - Solve for \( WS_2 \)
  - Compare with assumed \( WS_2 \)
  - Iterate as needed
## Comparison

**Comparison between direct step and standard step methods.**

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<th>No.</th>
<th>Characteristic</th>
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<th>Standard step method</th>
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<td>Difficult (months)</td>
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<td>any (prismatic or nonprismatic)</td>
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<td>length of channel</td>
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<td>4</td>
<td>Dependent variable</td>
<td>length of channel</td>
<td>flow depth</td>
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<td>by iteration (trial and error)</td>
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<td>spread sheet (or programming)</td>
<td>HEC-RAS (or programing)</td>
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<td>10</td>
<td>Reliability</td>
<td>Answer always possible</td>
<td>Answer sometimes not possible (depends on the type of cross-sectional data)</td>
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Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- Hydraulic Design Aspects
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels
Flow Through Bridges

- Energy losses
- Turbulence
- Water surface elevations
Abutment Losses

• Rapid flow
  - Stay out of channel!

• Tranquil flow
  - Flow depth between abutments is $>y_c$
  - Preliminary layout
    • 1.0 for expansion loss
    • 0.5 for contraction loss

• Bradley (1978) - Design charts
Pier Losses

• Three conditions (Chow 1959)
  - Class A
  - Class B
  - Class C
Pier Losses

- Three conditions:
  - Class A
  - Class B
  - Class C

Plate 10

Energy

Momentum

CLASS A

CLASS B

CLASS C

ELEVATION

\[ d_1 > d_c \]

\[ d_2 > d_{c2} \]

\[ d_2 = d_{c2} \]

\[ d_3 > d_c \]

\[ d_3 < d_c \]

\[ d_1 < d_c \]

\[ d_2 < d_{c2} \]

\[ d_3 < d_c \]
Pier Losses

EQUATIONS FOR LIMITING \( \lambda \)

\( \lambda_3 = \) ENERGY METHOD (YARNELL) (CHOW 1969)

\[
\alpha_1 = -\frac{3\lambda_3^2}{2\lambda_3^2 + 1}
\]

\( \lambda_3 = \) MOMENTUM METHOD (KOCH 1926)

\[
\alpha_1 = 1 - \frac{3\lambda_3}{(1 - \lambda_3^2)}
\]

\( \lambda_1 = \) MOMENTUM METHOD (KOCH 1926)

\[
\alpha_1 = 1 - \left[ \frac{3\lambda_1}{\lambda_1^2 + 2} \right]^{1/2}
\]

Note: \( \lambda_1 = \frac{d_1}{d_2} \)

\( \lambda_3 = \frac{d_2}{d_3} \)

\( d_1 = \) UPSTREAM WATER DEPTH

\( d_3 = \) DOWNSTREAM WATER DEPTH

\( d_c = \) CRITICAL DEPTH WITHIN THE UNOBSOURED CHANNEL SECTION

\( \alpha = \) HORIZONTAL CONTRACTION RATIO

\( \alpha = (1 \times \) PIER WIDTHS + CHANNEL WIDTH

\( d = \) DEPTH WITHOUT BRIDGE PIERS

DEFINITION SKETCH

Plate 11
Energy Method

\[ E_1 = E_2 + h l_{1-2} \]

\[ E_2 = E_3 = h l_{2-3} \]

Where:

- \( E_1 \) = Energy at Section 1
- \( E_2 \) = Energy at Section 2
- \( E_3 \) = Energy at Section 3
- \( h l_{1-2} \) = Losses between sections 1 and 2
- \( h l_{2-3} \) = Losses between sections 2 and 3
**Momentum Method**

\[
M = \beta \left( \frac{\gamma Q V}{g} \right)
\]

Where:

- \(M\) = momentum per unit time (lbs)
- \(\beta\) = momentum correction factor (1.0)
- \(Q\) = discharge (cfs)
- \(V\) = average channel velocity (fps)
Momentum Method

\[ m_1 - m_p + \frac{\gamma Q^2}{gA_1^2} (A_1 - A_p) = m_2 + \frac{\gamma Q^2}{gA_2^2} \]

\[ = m_3 - m_p + \frac{\gamma Q^2}{gA_3^2} \]

Where:
- \( m_1 \) = hydrostatic force in section 1
- \( m_p \) = hydrostatic force on pier ends
- \( m_2 \) = hydrostatic force in section 2
- \( m_3 \) = hydrostatic force in section 3
Pier Losses

---

**d. FORCE CURVES FOR CHANNEL SECTIONS I, II, AND III**

\[
\begin{align*}
I &= m_1 - m_2 + \frac{v^2}{gA_1} (A_1 - A_p) \\
II &= m_2 + \frac{v^2}{gA_2} \\
III &= m_3 - m_4 + \frac{v^2}{gA_3}
\end{align*}
\]

\[\frac{v^2}{gA} = \text{MOMENTUM FORCE} \]

\[m = \sqrt{gA} \]

---

**c. FORCE EQUATIONS FOR CHANNEL SECTIONS I, II, AND III**

**b. FLOW PROFILES**

**TRAPEZOIDAL SECTION**

**MOMENTUM METHOD**

**EXAMPLE CURVES**

**d. CHANNEL SECTION II**

\[Q = 140,000 \text{ CFS} \]
### Analysis Tools

**Plate 14**

**Plate 15**

#### GIVEN:
- Rectangular channel section
- Round nose piers
- Channel discharge ($Q$) = 40,000 cfs
- Channel width ($W_x$) = 200 ft
- Total pier width ($W_p$) = 20 ft
- Depth without bridge piers ($d_1$) = 14.3 ft

#### COMPUTE:
1. Horizontal contraction ratio ($\alpha$)
   \[ \alpha = \frac{W_p}{W_x} = \frac{20}{200} = 0.10 \]
2. Discharge ($q$) per ft of channel width
   \[ q = \frac{Q}{W_x} = \frac{40,000}{200} = 200 \text{ cfs} \]
3. Critical depth ($d_2$) in unobstructed channel
   From Chart 510-8, $d_2 = 10.6$ ft for $q = 200$ cfs.
4. $\lambda = \frac{d_2}{d_1} = \frac{10.6}{14.3} = 0.732$
5. Flow classification
   - On Plate 41, intersection of $\alpha = 0.10$ and $\lambda = 0.732$ is in zone marked Class A or B.
6. Upstream depth ($d_1$)
   a. Class A flow - Energy Method
      \[ d_1 = d_2 + H_3 \] (Plate 14)
      \[ H_3 = Xd_c \]
      - $X = 0.127$ for $\alpha = 0.10$
      - $H_3 = 0.127 \times 13.8 = 1.77$ ft
   b. Class B flow - Momentum Method
      \[ d_1 = \lambda d_2 \] (Plate 16)
      \[ \lambda = 1.435 \] for $\alpha = 0.10$
      \[ d_1 = 1.435 \times 10.8 = 15.50 \text{ ft} \]
   c. Class C flow - Energy Method
      \[ d_1 = \lambda d_2 \] (Plate 17)
      \[ \lambda = 1.460 \] for $\alpha = 0.10$
      \[ d_1 = 1.460 \times 10.8 = 15.77 \text{ ft} \]
Analysis Tools

Plate 16

Plate 17

RECTANGULAR SECTION
MOMENTUM METHOD
CLASS B FLOW

RECTANGULAR SECTION
ENERGY METHOD
CLASS B FLOW
Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- Hydraulic Design Aspects
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels

Start 22 SEP
What Is A Transition?

- Structure that joins two geometrically dissimilar cross-sections
- Contraction or expansion of flow
- Minimizes flow disturbance
- Affects the water surface elevation through energy loss
Transitions

Contraction & Expansion

Plan View

Contraction

\[ b_1 > b_2 \]

Expansion

\[ b_1 < b_2 \]
Application of Transition Structures

- Approach to bridge and culvert crossings
- A placeholder between existing and future improvements
- To create a choke in the channel
Analysis of Transition Structures
Principles of Open Channel Hydraulics

Three Governing Principles
- Conservation of Mass
- Conservation of Momentum
- Conservation of Energy

\[ E_1 = E_2 + Losses \]
Energy Equation (Bernoulli’s)

\[ \frac{v_1^2}{2g} + y_1 + z_1 + \frac{p_1}{\gamma} = \frac{v_2^2}{2g} + y_2 + z_2 + \frac{p_2}{\gamma} + h_{L,1-2} \]

- velocity head
- elevation head
- pressure head
- Energy loss between sections 1 and 2
Open Channel Energy Equation

\[
\frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_{L,1-2}
\]
Open Channel Energy Equation

\[ \frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_{L,1-2} \]
Open Channel Energy Equation

\[ \frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_{L,1-2} \]
Open Channel Energy Equation

\[ \frac{v_1^2}{2g} + y_1 + z_1 = \frac{v_2^2}{2g} + y_2 + z_2 + h_{L1-2} \]
Open Channel Energy Equation

- Head Losses

\[ h_{L1-2} = \text{Major Losses} + \text{Minor Losses} \]

- Friction between fluid and its flow boundary
- Change in velocity or change in flow
Open Channel Energy Equation

- Losses due to Transitions are considered Minor Losses

\[ h_{L1-2} = \text{Major Losses} + \text{Minor Losses} \]

Change in velocity or change in flow
Open Channel Energy Equation

• General Equation for Minor Losses

\[ h_{Lm} = \frac{K_m V^2}{2g} \]
Transition Types

• For connecting trapezoidal and rectangular sections
  - Cylindrical quadrant
  - Warped
  - Wedge
• Rectangular sections
  - Straight-line
• Abrupt/square
Types of Transitions

- Warped
- Straight Line
- Cylindrical Quadrant
- Wedge (longer or shorter than warped?)
- Abrupt (square)
Abrupt Transition
Channel Transitions

• **Subcritical Flow**
  - Each type can be used in either direction
  - *Cylindrical quadrant used for:*
    - Expansions from rectangular to trapezoidal
    - Contractions from trapezoidal to rectangular
  - *Straight-line transition or quadrant for rectangular channels*
Channel Transitions

• Supercritical Flow
  - Cylindrical quadrant
    • Subcritical in trap section to supercritical in rectangular
  - Straight-line for contractions in rectangular sections
  - Special shape for expansions in rectangular channel
Transition Design

• Subcritical Flow
  - Rectangular to trapezoidal
    • Wedge Type
    • Plate 20
### TABLE OF GEOMETRIC VALUES

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\( ^\circ \) DEGREES

---

**DEFINITION SKETCH**

**NOTE:**

- BC = EF
- EG = DH
- \( \angle CED = 5^\circ \)
Transition Design

- Subcritical Flow
  - Rectangular to trapezoidal
    - Plate 20
  - $6^\circ$ maximum change in flow line
  - Water surface profiles determined by step computations
  - $< 20$ percent change in velocity between steps
  - Adjust to make water surface as straight as practicable
Transition Design

• Supercritical Flow
  - Between trapezoidal and rectangular
    • Typically incorporate wedge or straight-line transition
    • Need to minimize/contain standing waves
    • Rule of thumb:
# Recommended Convergence and Divergence Rates

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<th>Mean channel velocity (fps)</th>
<th>Wall flare (horizontal to longitudinal)</th>
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Transition Design

• Supercritical Flow
  - Rectangular contractions:
Plate 21

a. SCHEMATIC PROFILE

b. PLAN
Transition Design

• Supercritical Flow
  - Rectangular contractions:

\[
\tan \theta = \frac{\tan \beta_1 \left( \sqrt{1 + 8F_1^2 \sin^2 \beta_1} - 3 \right)}{2 \tan^2 \beta_1 + \sqrt{1 + 8F_1^2 \sin^2 \beta_1} - 1}
\]

\[
\frac{y_2}{y_1} = \frac{1}{2} \left( \sqrt{1 + 8F_1^2 \sin^2 \beta_1} - 1 \right)
\]

\[
F_2^2 = \frac{y_1}{y_2} \left[ F_1^2 - \frac{1}{2} \frac{y_1}{y_2} \left( \frac{y_2}{y_1} - 1 \right) \left( \frac{y_2}{y_1} + 1 \right)^2 \right]
\]
Transition Design

• Supercritical Flow
  - Rectangular contractions:

\[
L = \frac{b_1 - b_3}{2 \tan \theta}
\]

EQ 2-25

However, disturbances are minimized when \( L = L_1 + L_2 \) so:

\[
L_1 = \frac{b_1}{2 \tan \beta_1}
\]

EQ 2-26

\[
L_2 = \frac{b_3}{2 \tan (\beta_2 - \theta)}
\]

EQ 2-27
Transition Design

• Supercritical Flow
  - Rectangular contractions:
  - Correct design requires choosing a value of $\Theta$ so that $L = L_1 + L_2$
  - Either solve equations simultaneously or use Plate 22
  - Plate 23 is a “go-by”
**GIVEN**

<table>
<thead>
<tr>
<th>( F_1 )</th>
<th>( y_1 )</th>
<th>( y_2 )</th>
<th>( \beta_1 )</th>
<th>( \tan \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1.20</td>
<td>5.00</td>
<td>19.2</td>
<td>0.0924</td>
</tr>
<tr>
<td>2.0</td>
<td>1.12</td>
<td>5.00</td>
<td>18.3</td>
<td>0.0949</td>
</tr>
<tr>
<td>1.3</td>
<td>1.07</td>
<td>5.35</td>
<td>17.6</td>
<td>0.0927</td>
</tr>
<tr>
<td>1.2</td>
<td>1.06</td>
<td>5.30</td>
<td>17.5</td>
<td>0.0929</td>
</tr>
</tbody>
</table>

**REQUIRED**

<table>
<thead>
<tr>
<th>CONVERGENCE ANGLE ( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>191</td>
</tr>
<tr>
<td>287</td>
</tr>
<tr>
<td>441</td>
</tr>
<tr>
<td>478</td>
</tr>
</tbody>
</table>

**PROCEDURE**

Assume values of \( \theta \) and by repetitive use of Plate 22 solve Equations 2-25, 2-26, and 2-27 until \( L = L_1 + L_2 \). If \( L_1 \) is greater than \( L_2 \), continue computation using value of \( \theta \) with \( F_1 \) in same manner as was done with \( F_2 \). To compute Col 11 through 18, each subscript in Plate 22 is assumed to be increased by one unit.

**COMPUTATION**

<table>
<thead>
<tr>
<th>( L_1, \text{ FT} = (b_1 - b_1)^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tan \theta )</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>0.348</td>
</tr>
<tr>
<td>0.331</td>
</tr>
<tr>
<td>0.319</td>
</tr>
<tr>
<td>0.315</td>
</tr>
</tbody>
</table>

**Plate 22**

**Plate 23**

113
\[ L = \frac{b_1 - b_3}{2 \tan \theta} \]

\[ L_1 = \frac{b_1}{2 \tan \beta_1} \]

\[ L_2 = \frac{b_3}{2 \tan (\beta_2 - \theta)} \]
Transition Design

• Supercritical Flow
  - Rectangular expansions
    • Model studies have shown that changes in flow direction are much more gradual in expansions than in contractions
    • Theory and empirical data show that a curved transition helps regulate wave propagation
    • Model testing has indicated that downstream depths can be significantly greater than what theory predicts
Transition Design

• Supercritical Flow
  - Rectangular expansions
Transition Design

• Supercritical Flow
  - Rectangular expansions

\[
\frac{Z}{b_1} = \frac{1}{2} \left( \frac{X}{b_1 F_1} \right)^{3/2} + \frac{1}{2}
\]

Where:
- \(Z\) = Transverse distance from channel centerline
- \(b_1\) = approach channel width
- \(X\) = longitudinal distance from beginning of expansion
- \(F_1\) = approach Froude number
Plate 24

1. GENERALIZED DESIGN CURVES

REPRODUCED FROM REF. 86, NOLES.
(HOOFT, AND HSU 1951)

HALF PLAN
(NO SCALED)

POINTS

<table>
<thead>
<tr>
<th>PC</th>
<th>0</th>
<th>b f</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRC</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2} \frac{b}{f}</td>
<td>\frac{b}{f}</td>
</tr>
<tr>
<td>PT</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2}</td>
<td>\frac{b}{2}</td>
</tr>
<tr>
<td>PC TO PRC</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2} \frac{b}{f}</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2}</td>
</tr>
<tr>
<td>PRC TO PT</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2}</td>
<td>\frac{b}{2} \left( \frac{b}{f} \right)^{1/2}</td>
</tr>
</tbody>
</table>

WHERE

\[ q = \frac{x}{y} \left( \frac{b}{f} \right) \left( \frac{b}{f} \right)^{1/2} \]

AND

\[ q = \frac{x}{y} \left( \frac{b}{f} \right) \left( \frac{b}{f} \right)^{1/2} \]
Transition Design

• Supercritical Flow
  - Non-rectangular transitions:
    • No real design guidance, typically need to model
Transition Design

- Supercritical to Subcritical Flow
  - Typically expansions from rectangular to trapezoidal
  - Wedge type transition
  - Can be rapid or gradual
  - Jump needs to be contained within transition
  - Scenario??
HEART BUTTE DAM
SPILLWAY AND OUTLET WORKS
STILLING BASIN DETAILS
Transition Losses

• Subcritical flow
  - Design should minimize energy losses and costs

• Supercritical Flow
  - Can be substantial and drive the design
Transition Loss Equations

**Contraction:**

\[ h = K_c \frac{V_2^2 - V_1^2}{2g} \]

**Expansion:**

\[ h = K_e \frac{V_1^2 - V_2^2}{2g} \]
## Transition Loss Coefficients

<table>
<thead>
<tr>
<th>SHAPE</th>
<th>$K_c$ (Contraction)</th>
<th>$K_e$ (Expansion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrupt (Square)</td>
<td>0.30</td>
<td>0.80</td>
</tr>
<tr>
<td>Straight Line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10°</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>15°</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>20°</td>
<td>0.10</td>
<td>0.40</td>
</tr>
<tr>
<td>30°</td>
<td>0.10</td>
<td>0.70</td>
</tr>
<tr>
<td>Warped Design</td>
<td>0.10</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Design Considerations

• Define purpose of structure
• Define project constraints
  - Right-of-Way
  - Site conditions
  - Economic feasibility
  - Location of transition structure
• Design will be case by case
General Guidelines for Design

1. Define design parameters
   • Design discharge, Q (cfs)
   • Geometry of existing and proposed channel section
2. Determine location of transition structure
3. Length of transition structure
4. Determine transition head loss, $H_t$
5. Determine existing WSE at beginning and end of preliminary location of transition
6. Based on initial water surface elevation calculation (output), refine design of transition
Key Points to Remember

• Transitions in Subcritical Flow are analyzed using the Energy Equation
• Transition losses are energy losses associated with a change in velocity
• If possible, avoid design of transitions in supercritical and unstable range of flows
• Design of transitions is case by case and comes with experience
References

9. Orange County Flood Control District Design Manual, O.C.F.C. D., Orange County, California

*Note:* Graphics and text depicting the Energy Equation were obtained from another slide presentation on the web. Author was not named.
Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- Hydraulic Design Aspects
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels

Start 6 OCT 08
Flow in Curved Channels

- Superelevation
- Limiting curvature
- Bend losses
- Shear stress
Flow in Curved Channels

- Superelevation
- Secondary currents
- Shift in maximum velocity
Flow in Curved Channels

• Superelevation

\[ \Delta y = C \frac{V^2 W}{gr} \]

EQ. 2-31

Where:

- \( y \) = rise in water surface
- \( C \) = coefficient
- \( V \) = average velocity
- \( W \) = channel width
- \( g \) = gravity
- \( r \) = radius of curvature

Table 2-4

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Cross Section</th>
<th>Type of Curve</th>
<th>Value of C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tranquil</td>
<td>Rectangular</td>
<td>Simple Circular</td>
<td>0.5</td>
</tr>
<tr>
<td>Tranquil</td>
<td>Trapezoidal</td>
<td>Simple Circular</td>
<td>0.5</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Simple Circular</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Trapezoidal</td>
<td>Simple Circular</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Spiral Transitions</td>
<td>0.5</td>
</tr>
<tr>
<td>Rapid</td>
<td>Trapezoidal</td>
<td>Spiral Transitions</td>
<td>1.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>Rectangular</td>
<td>Spiral Banked</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Flow in Curved Channels

- **Superelevation**
  - Subcritical
    - Increase wall height along outside of curve to account for rise in water surface elevation
    - Can have waves on inside of channel bend
Flow in Curved Channels

• Superelevation
  - Supercritical
    • Effect propagated downstream requiring increased wall height
  • Mitigation
    - Spiral transition curves
    - Spiral banked curves
    - Limiting curvature
Flow in Curved Channels

- Spiral transition curves
  - Induce curvature and superelevation at a gradual rate
  - Gradually increases from infinity to a maximum value at plan view center point

$$L_s = 1.82 \frac{VW}{\sqrt{gy}}$$  \text{EQ. 2-32}
Flow in Curved Channels

• Spiral banked curves
  - Used in rectangular channels
  - Rotate channel bottom about centerline
  - Maximum banking twice $\nabla y$ from EQ 2-31
    • Inside bend depressed by $\nabla y$
    • Outside bend elevated by $\nabla y$
  - Permits wall heights to be equal on both sides of channel
Flow in Curved Channels

- Limiting curvature
  - Subcritical flow
    - \( R_c > 3 \) times channel width
  - Supercritical flow
    - Use Equation 2.34
Flow in Curved Channels

\[ r_{\text{min}} \geq \frac{4V^2W}{gy} \]  

EQ. 2-34

Where:

- \( r_{\text{min}} \) = minimum radius of curvature
- \( V \) = average velocity
- \( W \) = channel width at design water surface
- \( y \) = flow depth
Flow in Curved Channels

• Bend losses
  - Scobey (1933) recommended increasing $n$ by 0.001 for each 20° of curvature per 100 feet of channel
  - Maximum increase of 0.003
  - Minor losses in HEC-RAS, assumed to be negligible
  - Effective roughness due to secondary currents
  - Recent experiments indicate that losses can be significant for values of $r_c/W < \sim 4$
Curved Channels and Shear Stress
Shear Stress Distribution
Upstream Bend
Baseline Test

Flow Direction

8 cfs
12 cfs
16 cfs

- $R_c$ = Centerline Radius of Curvature
- $B$ = Channel bottom width
- $K_b = \tau_b / \tau_o$
- $\tau_b$ = Maximum bend shear stress
- $\tau_o$ = Average approach shear stress
Data Information

• Ippen, A. T., et. al. (1962) ; 16 data points
• USBR (1964) ; 1 data point
• Yen, B.C. (1965) ; 5 data points
• CSU / USBR (2002) ; 8 data points

• Characteristics (for all sets)
  - Trapezoidal channels
  - Preston Tube utilized for shear measurements
  - Rigid boundary
<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Slope</td>
<td>1 to 2</td>
</tr>
<tr>
<td>Bottom Width</td>
<td>1 to 10.2 ft</td>
</tr>
<tr>
<td>Top Width</td>
<td>1.67 to 16.27 ft</td>
</tr>
<tr>
<td>Centerline Radius of Curvature</td>
<td>5 to 65 ft</td>
</tr>
<tr>
<td>Centerline Radius of Curvature / Top Width</td>
<td>1.22 to 6.73</td>
</tr>
<tr>
<td>Centerline Radius of Curvature / Bottom Width</td>
<td>2.5 to 10.83</td>
</tr>
</tbody>
</table>
Maximum Shear in Channel Bends

- Ippen (1962)
- USBR (1964)
- Yen (1965)
- CSU (2002)
- Upper Envelope

Best Fit on All Data
\[ K_b = 3.16 \left( \frac{r_c}{b} \right)^{-0.43} \]
\[ R^2 = 0.59 \]

Upper Envelope Curve
\[ K_b = 4.89 \left( \frac{r_c}{b} \right)^{-0.53} \]

Original HEC-15 Curve
\[ K_b = 2.86 \left( \frac{r_c}{b} \right)^{-0.41} \]
EM-1601 Method

Maximum Shear in Channel Bends

- Best Fit on All Data
  \[ K_b = 2.63 \left( \frac{r_c}{w} \right) - 0.47 \]
  \[ R^2 = 0.80 \]

- Upper Envelope Equation
  \[ K_b = 3.53 \left( \frac{r_c}{w} \right)^{0.50} \]

- Original EM-1601 Equation
  \[ K_b = 2.65 \left( \frac{r_c}{w} \right)^{-0.50} \]

- Data Points:
  - Ippen (1962)
  - USBR (1964)
  - Yen (1965)
  - CSU (2002)
Comparison of Methods

Shear Stress Correction Factor for Channel Bends

\[ K_b = \frac{\tau_b}{\tau_o} \] (HEC-15 Envelope)

\[ K_b = \frac{\tau_b}{\tau_o} \] (CSU/USBR Upper Envelope Equation)

Linear Fit to Data

Line of Equal Fit

65% Maximum Variability

\[ y = 1.44x \]
Reality
3-D problem

INNER BANK REGION  MID-CHANNEL REGION  OUTER BANK REGION

Superelevated water surface

Outward shoaling flow across point bar

Path lines of secondary flow

Development of meandering channel with riffles at inflection points and pools at bend apices where bank erosion is concentrated
Boundary shear stress has been determined to be a fundamental part of channel migration (Brown, 1988).
• **Boundary Shear Stress in a stream bend** can be expressed as

\[ \tau_b = \tau_{\text{viscous}} + \tau_{\text{turbulent}} \]

\[ \tau_{\text{viscous}} = \text{viscous boundary shear stress in a stream bend} \]

\[ \tau_{\text{turbulent}} = \text{turbulent boundary shear stress in a stream bend} \]
Theory - Overview

- And in further detail as

\[ \tau_b = \tau_o + \tau_{lat} + \tau_g + \tau_{xz} + \tau_{yx} + \tau_{zy} \]

- \( \tau_b \) = total boundary shear stress in a stream bend
- \( \tau_o \) = average longitudinal viscous shear stress
- \( \tau_{lat} \) = average lateral viscous shear stress
- \( \tau_g \) = average additional viscous shear stress due to channel geometry
- \( \tau_{xz} \) = average vertical turbulent shear stress component in longitudinal direction
- \( \tau_{yx} \) = average lateral turbulent shear stress component in longitudinal direction
- \( \tau_{zy} \) = average vertical turbulent shear stress component in lateral direction
The theory illustration shows the breakdown of the tangential stress, $\tau_b$, into Viscous and Turbulent components:

$$\tau_b = \tau_o + \tau_{lat} + \tau_g + \tau_{zx} + \tau_{yx} + \tau_{zy}$$
The diagram illustrates various forces and angles associated with the flow direction, centerline, top of bank, cross section, and toe of bank. The notation includes symbols such as $\tau_{lat}$, $\tau_{zy}$, $\tau_{xz}$, $\tau_{yx}$, $\tau_0$, and $\theta$. The theory presented explains the mechanics of flow and the forces acting on the bank under different conditions.
Theory - Viscous Shear Stress

\[ \tau_o = \gamma RS_f \]

Where:
- \( \tau_o \) = average longitudinal viscous shear stress
- \( \gamma \) = unit weight of water
- \( R \) = hydraulic radius
- \( S_f \) = friction slope
 Theory - Viscous Shear Stress 

\[ \partial \tau_{lat} = \rho \bar{V}_z \partial V_y - \frac{\rho \bar{V}_x^2 \partial z}{r} + \gamma S_y \partial z \]

Where:  
\( \tau_{lat} \) = average lateral viscous shear stress  
\( \gamma \) = unit weight of water  
\( r \) = centerline radius of curvature  
\( \rho \) = density of water  
\( S_y \) = lateral water surface slope  
\( V_x \) = average velocity in the x-direction  
\( V_y \) = average velocity in the y-direction
Theory - Viscous Shear Stress

\[ \tau_g = \tau_s - \tau_o \]

Where:  
\( \tau_g \) = average additional viscous shear stress due to channel geometry  
\( \tau_o \) = average longitudinal viscous shear stress  
\( \tau_s \) = average longitudinal boundary shear stress due to super elevation
Theory - Illustration
Theory - Illustration

\[ \tau_{yx} + \Delta \tau_{yx} \]

\[ \tau_{xx} + \Delta \tau_{xx} \]

\[ \tau_{zx} + \Delta \tau_{zx} \]
Theory – Turbulent Shear Stresses

\[
\begin{bmatrix}
\tau_{xx} & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \tau_{yy} & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \tau_{zz}
\end{bmatrix}_{\text{app}} =
\begin{bmatrix}
-\rho(u')^2 & -\rho(u'v') & -\rho(u'w') \\
-\rho(v'u') & -\rho(v')^2 & -\rho(v'w') \\
-\rho(w'u') & -\rho(w'v') & -\rho(w')^2
\end{bmatrix}
\]

- normal to the x-plane applied in the x-direction
- normal to the x-plane applied in the y-direction
- normal to the x-plane applied in the z-direction
- normal to the y-plane applied in the x-direction
- normal to the y-plane applied in the y-direction
- normal to the y-plane applied in the z-direction
- normal to the z-plane applied in the x-direction
- normal to the z-plane applied in the y-direction
- normal to the z-plane applied in the z-direction
Theory - Turbulent Shear Stresses

\[
\begin{bmatrix}
\tau_{xx} & \tau_{yx} & \tau_{zx} \\
\tau_{yx} & \tau_{yy} & \tau_{zy} \\
\tau_{zx} & \tau_{zy} & \tau_{zz}
\end{bmatrix}_{\text{app}} =
\begin{bmatrix}
-\rho(u')^2 & -\rho(v'u') & -\rho(w'u') \\
-\rho(v'u') & -\rho(v')^2 & -\rho(w'v') \\
-\rho(w'u') & -\rho(w'v') & -\rho(w')^2
\end{bmatrix}
\]

- normal to the x-plane applied in the x-direction
- normal to the y-plane applied in the x-direction
- normal to the z-plane applied in the x-direction
- normal to the y-plane applied in the y-direction
- normal to the z-plane applied in the y-direction
- normal to the z-plane applied in the z-direction
Theory – Turbulent Shear Stresses

\[
\begin{bmatrix}
\tau_{yx} \\
\tau_{zx} & \tau_{zy}
\end{bmatrix}
\begin{bmatrix}
-\rho(\bar{v'u'}) \\
-\rho(\bar{w'u'}) & -\rho(\bar{w'v'})
\end{bmatrix}
\]
Theory - Illustration

- Top of Bank
- Cross Section
- Flow Direction
- Centerline
- Toe of Bank
- $\tau_{zy}$
- $\tau_{lat}$
- $\tau_{t}$
- $\theta$
- $\tau_{b}$
Illustration

Type 1 Bend (U/S) Piezometer Depths

Concrete Cap

Top of Plywood Cross Section and Fill Dirt

20 cfs WSE

8 cfs WSE

1' 5'
# Example Data

Model discharge was 20 cfs.

\( \tau_o \) was calculated to be 0.0225 psf

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezometer</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>( \tau_p ) (lb/ft(^2))</td>
<td>0.022</td>
<td>0.029</td>
<td>0.038</td>
<td>0.028</td>
<td>0.026</td>
<td>0.024</td>
<td>0.028</td>
<td>0.033</td>
</tr>
<tr>
<td>( \tau_g ) (lb/ft(^2))</td>
<td>0.000</td>
<td>0.006</td>
<td>0.015</td>
<td>0.005</td>
<td>0.003</td>
<td>0.001</td>
<td>0.005</td>
<td>0.011</td>
</tr>
<tr>
<td>% of ( \tau_o )</td>
<td>0%</td>
<td>28%</td>
<td>68%</td>
<td>23%</td>
<td>14%</td>
<td>5%</td>
<td>23%</td>
<td>49%</td>
</tr>
<tr>
<td>( \tau_{lat} ) (lb/ft(^2))</td>
<td>0.000</td>
<td>0.003</td>
<td>0.007</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
<td>0.005</td>
</tr>
<tr>
<td>% of ( \tau_o )</td>
<td>0%</td>
<td>13%</td>
<td>31%</td>
<td>13%</td>
<td>10%</td>
<td>4%</td>
<td>9%</td>
<td>22%</td>
</tr>
</tbody>
</table>

* These values were estimated.
In this particular example, $\tau_b$, would have a magnitude of 0.038 psf with an angle $\theta$ of 82.4 degrees, which is a total of 68% larger than $\tau_o$. 

Illustration of Example
Summary of Theory

• Total boundary shear stress in a stream bend can be theoretically calculated, however:
  - All terms except, $\tau_o$, require a detailed set of data
  - The dataset would require:
    • Direct shear measurements
    • Water surface elevations throughout and across the bend
    • Turbulent three-dimensional velocities
    • Detailed channel geometry
  - All of which are not generally available
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Shear Stress Distribution
Upstream Bend
Baseline Test

8 cfs

12 cfs

16 cfs

Flow Direction

0.005 psf
0.009 psf
0.013 psf
0.017 psf
0.021 psf
0.025 psf
0.029 psf
0.033 psf
HEC-15 Method

Maximum Shear in Channel Bends

- Original HEC-15 Curve: $K_b = 2.86 \left( \frac{r_c}{b} \right)^{-0.41}$
- Upper Envelope Curve: $K_b = 4.89 \left( \frac{r_c}{b} \right)^{-0.53}$

Best Fit on All Data: $K_b = 3.16 \left( \frac{r_c}{b} \right)^{-0.43}$

$R^2 = 0.59$
Maximum Shear in Channel Bends (HEC-15)

Old Upper Envelope Curve (Black Dash Line)
\[ K_b = 4.89 (r_c/b)^{-0.53} \]
\[ R^2 = 0.64 \]

New Upper Envelope Curve (Pink)
\[ K_b = 3.8687 (r_c/b)^{-0.2775} \]
\[ R^2 = 1 \]

Old Best Fit on All Data (Black Solid Line)
\[ K_b = 3.16 (r_c/b)^{0.43} \]
\[ R^2 = 0.59 \]

New Best Fit on All Data (Green)
\[ K_b = 2.842 (r_c/b)^{-0.321} \]
\[ R^2 = 0.4352 \]
Maximum Shear in Channel Bends

- Best Fit on All Data
  \[ K_b = 2.63\left(\frac{r_c}{w}\right)^{-0.47} \]
  \[ R^2 = 0.80 \]

- Upper Envelope Equation
  \[ K_b = 3.53\left(\frac{r_c}{w}\right)^{-0.50} \]

Maximum Shear in Channel Bends (EM1601)

- **Old Upper Envelope Equation (Black Dash Line):**
  $$\frac{K_b}{\tau_0} = 3.53 (\frac{r_c}{w})^{0.50}$$
  $R^2 = 0.8004$

- **New Best Fit on All Data (Green):**
  $$y = 2.5099 (\frac{r_c}{w})^{0.3667}$$
  $R^2 = 0.6249$

- **New Upper Envelope Curve (Pink):**
  $$\frac{K_b}{\tau_0} = 3.3928 (\frac{r_c}{w})^{0.3208}$$
  $R^2 = 1$

- **Old Best Fit (Black Solid Line):**
  $$\frac{K_b}{\tau_0} = 2.6281 (\frac{r_c}{w})^{-0.4691}$$
  $R^2 = 0.8004$

**Centerline Radius of Curvature, $r_c$ / Top Width, $w$**
1.5 < $K_b$ < 3.25

1.05 < $K_b$ < 2.0

$K_b = 3.53\left(\frac{r_c}{w}\right)^{-0.50}$

$R^2 = 0.8004$

$y = 2.5099\left(\frac{r_c}{w}\right)^{-0.3667}$

$R^2 = 0.6249$
Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- Hydraulic Design Aspects
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels
Special Considerations

- Freeboard
  - Distance from WSE to top of channel wall or containment
  - Provides factor of safety against
    - Changes in hydrology
    - Urbanization
    - Sedimentation
    - Variations in channel/overbank roughness
Special Considerations

• Freeboard
  - Identify local areas where WSE may be indeterminate
    • Bridge piers
    • Hydraulic jumps
    • Transitions
    • Drop structures
Freeboard

• Amount
  - Concrete lined channels
    • Rectangular sections – 2 ft
    • Trapezoidal sections – 2.5 ft
  - Riprap channels
    • 2.5 ft
  - Earthen channels
    • 3 ft

• Consequence of damage!
Special Considerations

• Sediment Transport
  - EM-1601 provides limited information and is generally out of date
  - However..
    • Plate 27
Plate 27

Basic Data Sources

Field Data

<table>
<thead>
<tr>
<th>River</th>
<th>Location</th>
<th>Investigator</th>
<th>Date of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Loop</td>
<td>Dunning, Nebraska</td>
<td>Gilbert</td>
<td>1914</td>
</tr>
<tr>
<td>Niobrara &amp;</td>
<td>Cody, Nebraska</td>
<td>Barton and Lin</td>
<td>1955</td>
</tr>
<tr>
<td>Elkhorn</td>
<td>Waterlo, Nebraska</td>
<td>Simons, et al.</td>
<td>1964</td>
</tr>
<tr>
<td>Lower Colorado</td>
<td>Northern Mississippi</td>
<td>Brooks</td>
<td>1969</td>
</tr>
<tr>
<td>Pigeon Roost Cr.</td>
<td>St. Louis, Mo.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pigeon</td>
<td>Mississippi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cedar</td>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Blue</td>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Loop</td>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Loop</td>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rio Grande</td>
<td>New Mexico</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rio Puerco</td>
<td>New Mexico</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Sources of published flume and field data are given in Colby (1966). Some field data have not been published. Curves are for water temperature of 60°F and no suspended fine sediment load and are extrapolated from a plot in the reference.

2 Total load measured for these two streams; suspended load measured and bed load computed for other field data.
Plate 27

- Estimate relative effects of channel characteristics on bed-load movement
- Estimate equilibrium sediment discharge
- Estimate scour and/or deposition
- Estimate size of a detention basin
Open Channel Hydraulic Theory

- Physical Hydraulic Elements
- Hydraulic Design Aspects
- Flow Through Bridges
- Transitions
- Flow in Curved Channels
- Special Considerations
- Stable Channels
Stable Channels

- Lanes balance
From Rosgen (1996), from Lane, Proceedings, 1955.
Published with the permission of American Society of Civil Engineers.

Fig. 1.13 – Factors affecting channel degradation and aggradation: Concept of “Stream Balance.”
Stable Channels

- Lanes balance
- Scour of channel bed and banks are typically main concerns
- Revetments designed through analysis of tractive force:
  - Limiting shear stress
  - Limiting velocity
## Limiting Velocity

### Table 2-5

**Suggested Maximum Permissible Mean Channel Velocities**

<table>
<thead>
<tr>
<th>Channel Material</th>
<th>Mean Channel Velocity, fps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine Sand</td>
<td>2.0</td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>4.0</td>
</tr>
<tr>
<td>Fine Gravel(^1)</td>
<td>6.0</td>
</tr>
<tr>
<td>Earth</td>
<td></td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>2.0</td>
</tr>
<tr>
<td>Silt Clay</td>
<td>3.5</td>
</tr>
<tr>
<td>Clay</td>
<td>6.0</td>
</tr>
<tr>
<td>Grass-lined Earth</td>
<td></td>
</tr>
<tr>
<td>(slopes less than 5(^%))</td>
<td></td>
</tr>
<tr>
<td>Bermuda Grass</td>
<td></td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>6.0</td>
</tr>
<tr>
<td>Silt Clay</td>
<td>8.0</td>
</tr>
<tr>
<td>Kentucky Blue Grass</td>
<td></td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>5.0</td>
</tr>
<tr>
<td>Silt Clay</td>
<td>7.0</td>
</tr>
<tr>
<td>Poor Rock (usually sedimentary)</td>
<td>10.0</td>
</tr>
<tr>
<td>Soft Sandstone</td>
<td>8.0</td>
</tr>
<tr>
<td>Soft Shale</td>
<td>3.5</td>
</tr>
<tr>
<td>Good Rock (usually igneous or hard metamorphic)</td>
<td>20.0</td>
</tr>
</tbody>
</table>
Limiting Velocity

U.S. STANDARD SIEVE OPENING IN INCHES
6 4 3 2 1 1 1/2 1 3/8 1/2 3 4 6 8 10 14 16 20 30 40 70 100 140 200
U.S. STANDARD SIEVE NUMBERS
HYDROMETER

PERMISSIBLE VELOCITY, F/S

GRAIN SIZE MILLIMETERS

0 0.1 0.05 0.01 0.005 0.001

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 10

COBBLES

GRAY

SAND

SILT OR CLAY

"SELF ARMORING"
RIPRAP SIZES
SCOUR AND DEPOSITION
BED-LOAD SIZES
SCOUR ONLY
WASH-LOAD SIZES

UNSTABLE ZONE

STABLE ZONE

PARA. 2-7c (TABLE)

Plate 28
| CECW-EH-D | Department of the Army  
| Engineer Manual 1110-2-1601 | U.S. Army Corps of Engineers  
| | Washington, DC 20314-1000 | EM 1110-2-1601  
| | | 1 July 1991/30 June 1994 |

**Chapter 3**

**Riprap Protection**