SCRIPT

CHAPTER 10 IS DEDICATED TO CONDUIT FLOW.

IF CONDUIT WALLS COMPLETELY DEFINE FLOW TUBE, THEN CONDUIT (CLOSED-CONDUIT) FLOW.

CONDUIT WILL HAVE "PRESSURE" ON ALL WALLS

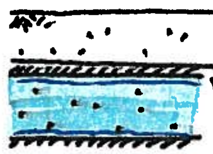
BOARD

FLOW IN CONDUITS

- CONDUIT IS A PIPE, TUBE, DUCT COMPLETELY FILLED WITH FLOWING FLUID

- THE WALLS OF THE CONDUIT ARE THE BOUNDARIES THAT LIMIT FLOW

CONDUIT

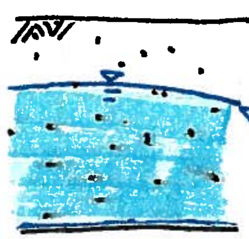


SCRIPT

IF CONDUIT HAS "FREE" SURFACE, THEN CALLED OPEN (CONDUIT) CHANNEL FLOW (CHAPTER 15)

BOARD

NOT-CONDUIT (BY THIS CHAPTER)



SCRIPT

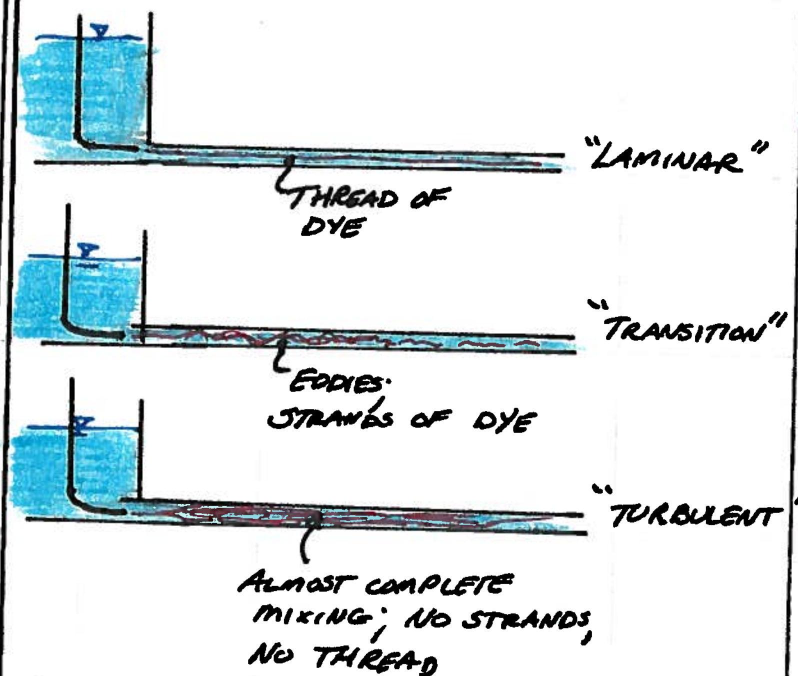
FLOWS ARE CLASSIFIED AS LAMINAR OR TURBULENT —

THE REGIME IMPACTS HOW FRICTION IS MANIFEST

– THE CLASSIFICATION IS VITAL FOR SELECTING CORRECT HEAD LOSS EQUATION

BOARD

OSBORNE REYNOLDS EXPERIMENT



SCRIPT

REYNOLDS EXPERIMENT INJECTED THIN THREADS OF DYE

FOUND THAT AT LOW VELOCITY THREAD PRESERVED $(V = \frac{Q}{A})$

AT HIGH VELOCITY, ALL DYE WOULD MIX AT ONCE

AT SOME INTERMEDIATE VELOCITY DYE THREAD WOULD BREAK INTO STRANDS

BOARD

REYNOLDS DISCOVERED THAT ONSET OF TURBULENCE WAS PREDICTABLE BASED ON A π-GROUP

$$\frac{\rho V D}{\mu}$$

NOW CALLED REYNOLD'S NUMBER. USUALLY SYMBOLIZED AS $Re_{\underline{\underline{D}}}$

THE SUBSCRIPT CHANGES DEPENDING ON THE "CHARACTERISTIC" LENGTH

I "SAY" REYNOLDS NUMBER BASED ON DIAMETER: ANOTHER Re_d IS REYNOLDS NUMBER BASED ON GRAIN SIZE.

SCRIPT

THE CHANGE OCCURS IN A PIPE-EQUIVALENT SYSTEM AT ABOUD $Re_D \approx 2000$

BOARD

$Re_D < 2000$ LAMINAR

$2000 \leq Re_D \leq 3000$ TRANSITION

$3000 \leq Re_D$ TURBULENT

SCRIPT

BRIEF DISCUSSION ON FULLY DEVELOP FLOW

Pg 361–362 TEXT.

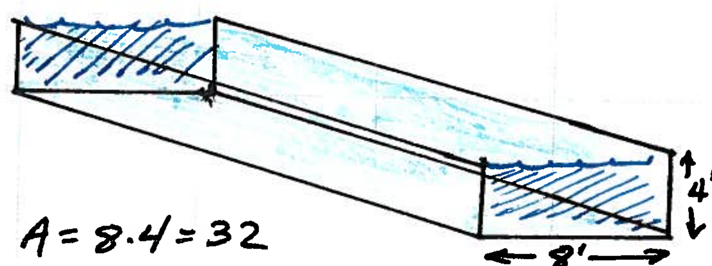
BOARD

FULLY DEVELOPED FLOW WHEN $\frac{dv}{dy} \approx$ CONSTANT SHAPE.

TAKES ABOUT 50 DIAMETERS (CHARACTERISTIC LENGTHS)

SCRIPT

BOARD



$A = 8 \cdot 4 = 32$

$P_w = 8+4+4 = 16$

$R_H = A/P = 32/16 = 2$

$D_H = 2(R_H) = 4 ft$

EXPECT ABOUT 200 FT FOR FULLY DEVELOPED FLOW

(OPEN CHANNELS ARE SIMILAR WILL EXAMINE MORE CH15)

SCRIPT

PIPES ARE OFTEN BURIED.

IN ADDITION TO FLUID MECHANICS ALSO HAVE TO DEAL WITH EXTERNAL LOADS

"FLUID MECHANICS" PART DEALS WITH FLOW INSIDE PIPE (I.E. = I.D. is D)

BOARD

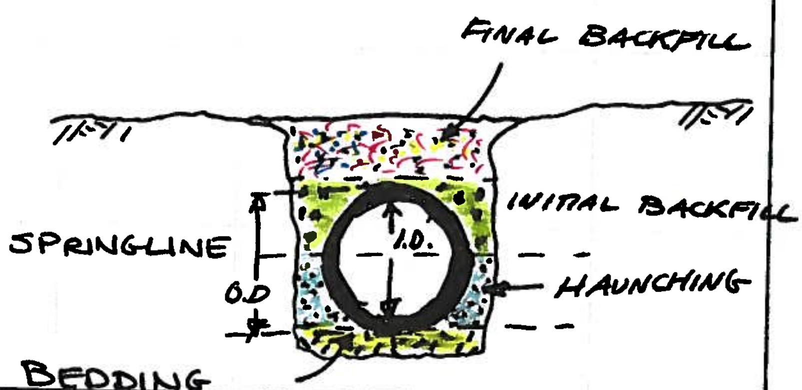
PIPE SIZES

- COMMERCIAL SIZES pg 363.

DEPENDS ON MATERIALS

PRESSURE RATING

ABILITY TO CARRY OVERBURDEN (OUTSIDE) LOADS

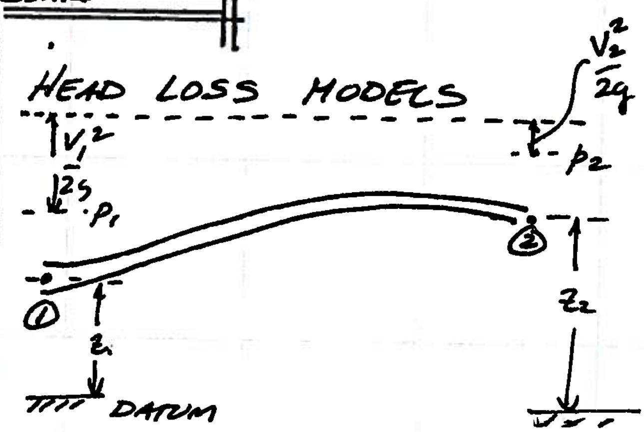


SCRIPT

HEAD LOSS MODELS ARE USED TO QUANTIFY AND ESTIMATE ENERGY LOSSES IN PIPELINE SYSTEMS

BOARD

HEAD LOSS MODELS



IF NO LOSS

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} \quad \text{(BERNOULLI)}$$

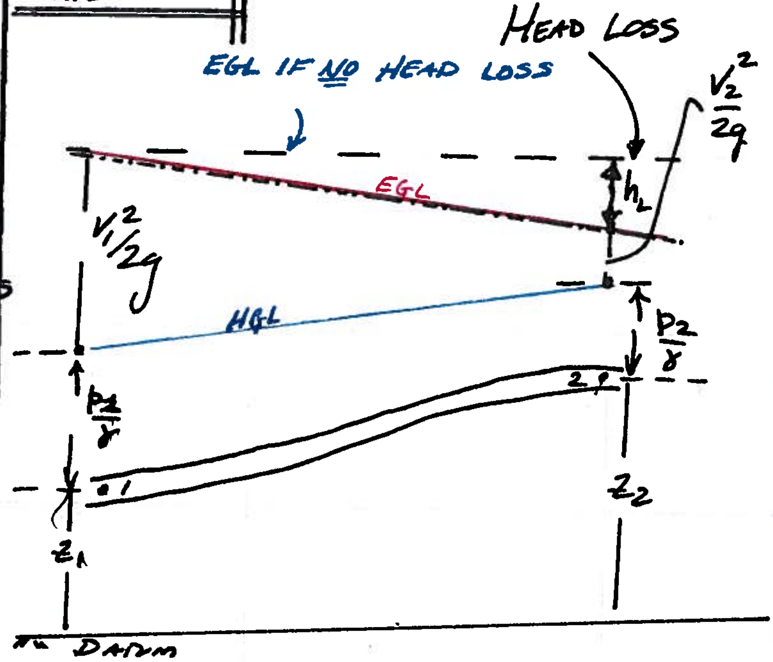
SCRIPT

THREE MODELS IN COMMON USE ARE

ANY FLUID { DARCY-WEISBACH } LIQUIDS
CHEZY-MANNING

WATER ONLY { HAZEN-WILLIAMS

BOARD



$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}+z_1 = \frac{p_2}{\gamma}+\frac{V_2^2}{2g}+z_2+h_L$$

SCRIPT

EMPIRICAL; MADE TO "LOOK" LIKE D-W.

SOMETIMES EQUIVALENT PIPE LENGTH CONCEPT USED FOR CALCULATIONS

BOARD

h_L IS TOTAL HEAD LOSS

- PIPE FRICTION (PIPE LOSS) } DARCY-WEISBACH AS PRESENTED
- JUNCTION FRICTION
- BENDS/TRANSITIONS
- INLETS/OUTLETS

SCRIPT

P 364-378
DOES NICE JOB —
HEREIN IS A
SKETCHY DERIVATION

BOARD

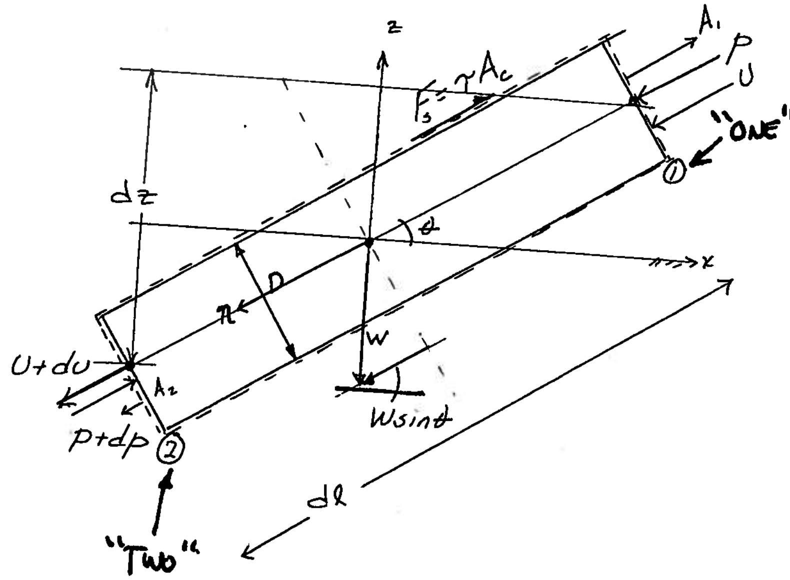
D·W DERIVATION

Flow in Closed Conduits (Pipes & Ducts)

Fundamental Equation from Momentum Analysis

SKETCH →

FLOW IS SHOWN AS ① → ②



SCRIPT

Continunity

$$0 = \frac{d}{dt}\int_{CV} \rho \, d\forall + \int_{CS} \rho \vec{V} \cdot d\vec{A} = -\rho U A_1 + \rho(U+dU)A_2$$

For constant cross section, $A_1 = A_2$

$$\therefore \rho U A = \rho(U+dU)A$$

APPLY CONTINUNITY —
RELATES VELOCITY
CHANGE(S) TO
CROSS SECTIONAL AREA
ESSENTIALLY A FORM OF
$Q = VA$

SCRIPT | BOARD

NEXT APPLY MOMENTUM

Momentum

$$\Sigma F_\eta = \frac{d}{dt}\int_{cv} \rho \vec{v}\, d\forall + \int_{c.s.} \rho \vec{v}(\vec{v}\cdot d\vec{A})$$

$$= -\rho u^2 A + \rho(u+du)(u+du)A$$

From continuity $= \rho u A$

$$= -\rho u^2 A + \rho(u+du)uA = \rho u \underbrace{du}_{=\frac{1}{2}du^2} A$$

$-\rho u^2 A + \rho u A(u+du) = \Sigma F$

$-\rho u^2 A + \rho u^2 A + \rho u du A = \Sigma F$

$\rho u du A = \Sigma F$

–WILL NOT NEGLECT FRICTION THIS ANALYSIS

$$\therefore \Sigma F_\eta = \rho \frac{A}{2} du^2$$

Analyze the forces

SHEAR STRESS — CONTACT AREA

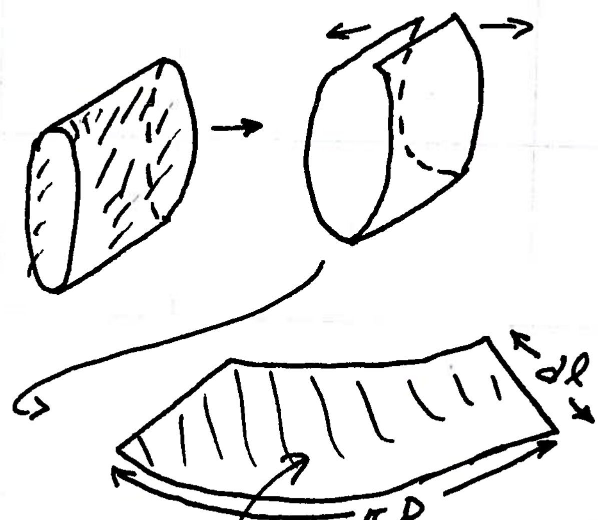
$$\underbrace{pA - (p+dp)A}_{=-dpA} + \rho g A \underbrace{dl \sin\theta}_{=-dz} - \tau \underbrace{A_c}_{=\pi D dl} = \rho \frac{A}{2} du^2$$

SCRIPT

$$\therefore -dpA - \rho g A dz - \tau \pi D dl = \rho \frac{A}{2} du^2$$

$$A = \frac{\pi D^2}{4}$$

"UNWRAP" THE PIPE TO FIND THE CONTACT AREA WHERE SHEAR STRESS APPLIES



AREA WHERE SHEAR IS APPLIED

SCRIPT

RELATE PRESSURE & ELEVATION GRADIENT TO SHEAR TERM

BOARD

Divide by $\rho g A$ & substitute $A = \frac{\pi D^2}{4}$

$$-\frac{dp}{\rho g} - dz - \frac{4\tau\, dl}{\rho g D} = \frac{du^2}{2g}$$

Rearrange

$$-\frac{dp}{\gamma} - \frac{du^2}{2g} - dz = \frac{4\tau\, dl}{\gamma D} \quad : \underline{\underline{(1)}}$$

Solve for τ

SOLVE FOR HOW SHEAR WILL LOOK →

$$\tau = \frac{\gamma D}{4}\left[-\frac{dp}{\gamma dl} - \frac{du^2}{2g dl} - \frac{dz}{dl}\right]$$

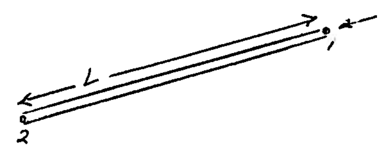
If $\frac{du^2}{dl} = 0$ (As in text) then

$$\tau = \frac{\gamma D}{4}\left[-\frac{dp}{\gamma dl} - \frac{dz}{dl}\right] = -\frac{r}{2}\underbrace{\left[\frac{d}{dl}(p+\gamma z)\right]}_{\text{GRADIENT OF STATIC HEAD ALONG FLOWLINE}} \quad : \underline{\underline{(2)}}$$

SCRIPT

WE WILL EXAMINE (1) AND (2) CLOSELY

SCRIPT	BOARD
RELATE SHEAR STRESS TO ENERGY GRADIENT	Return to ① and write $$\frac{dp}{\gamma} + dz + \frac{du^2}{2g} = \frac{4\tau\, dl}{\gamma D}$$ Divide by dl $$\underbrace{\frac{d}{dl}\left(\frac{p}{\gamma} + z + \frac{u^2}{2g}\right)}_{\text{head loss per unit length along the flowline}} = \frac{4\tau}{\gamma D}$$



SCRIPT	BOARD
INCORPORATE FINITE LENGTH	$$\int_1^2 d\left(\frac{p}{\gamma} + z + \frac{u^2}{2g}\right) = \int_1^2 \frac{4\tau}{\gamma D}\, dl$$ $$\frac{p_2}{\gamma} + z_2 + \frac{u_2^2}{2g} - \frac{p_1}{\gamma} + z_1 - \frac{u_1^2}{2g} = \frac{4\tau L}{\gamma D} = h_{f\,1\to 2}$$

EXPRESSED AS HEAD LOSS

SCRIPT

EXAMINE LOSS TERM

τ IS THE "CRITICAL" UNKNOWN

LAMINAR FLOW SOLUTION IS FINDABLE FROM FIRST PRINCIPLES

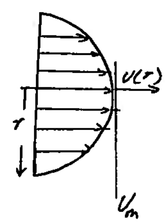
SCRIPT

BOARD

Loss Term

$$\frac{4\tau L}{\gamma D}$$

In laminar flow the velocity profile is parabolic.



$\bar{V} = V_m/2$

$$\therefore \frac{4\mu \frac{du}{dr} / L}{\rho g \; D}$$

$$= \frac{4\mu \frac{2U_m}{D} L}{\rho g D} = \frac{\mu\, 8U_m L}{\rho g \; D^2} = \underbrace{\frac{\mu}{\rho U_m D}}_{\text{"} \frac{1}{Re_d} \text{"}} \frac{L}{D} \frac{8U_m^2}{g}$$

$$\therefore \frac{4\tau L}{\gamma D} = \frac{1}{Re_d} \cdot \frac{L}{D} \cdot \frac{8 \cdot 4\bar{U}^2}{g} = \frac{64}{Re_d} \cdot \frac{L}{D} \cdot \frac{\bar{U}^2}{2g}$$

HEAD LOSS IN LAMINAR FLOW IS A FUNCTION OF REYNOLDS NUMBER (AND VELOCITY HEAD) ONLY.

$$f = \frac{64}{Re_d}$$ ← ONLY APPLIES IN LAMINAR REGIME

SCRIPT

pg 365 Textbook

-NOTE I AM SIMPLY RELATING MATHEMATICAL STRUCTURE

$$\frac{64}{Re_d} = f$$

ONLY IN LAMINAR!

SCRIPT

BOARD

So the loss term in laminar flow is

$$\frac{4\tau L}{\gamma D} = \underbrace{\frac{64}{Re_d}}_{\text{Called the friction factor}} \frac{L}{D}\frac{\bar{U}^2}{2g}$$

$$h_f = f\frac{L}{D}\frac{\bar{U}^2}{2g}$$

This form of loss term is called the Darcy-Weisbach friction loss formula

The momentum derived ~~Bernoulli's~~ Pipe Flow equation is

$$\frac{p_1}{\gamma} + z_1 + \frac{U_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{U_2^2}{2g} + f\frac{L}{D}\frac{\bar{U}^2}{2g}$$

LOOKS LIKE

BERNOULLI + EXTRA TERM

ENERGY EQUATION

NOT BY ACCIDENT; IN CLOSED CONDUIT FLOW MOMENTUM TRANSFER AND ENERGY LOSS ARE INTIMATELY RELATED

SCRIPT

BOARD

Return to ②

$\frac{dv^2}{d\ell} = 0$ when pipe section is constant.

$\therefore \tau = -\frac{r}{2}\left[\frac{d}{d\ell}(p + \gamma z)\right]$

From definition of shear stress (laminar)

$$\tau = -\mu \frac{dv}{dr} = -\frac{r}{2}\left[\frac{d}{d\ell}(p + \gamma z)\right]$$

$$\frac{dv}{dr} = \frac{r}{2\mu}\left[\frac{d}{d\ell}(p + \gamma z)\right]$$

$$\int_{v}^{0} dv = \int_{r}^{R} \frac{1}{2\mu}\frac{d}{d\ell}(p + \gamma z)\; r\,dr$$

$$-v = \frac{R^2 - r^2}{2} \cdot \frac{1}{2\mu}\frac{d}{d\ell}(p + \gamma z)$$

$$\underbrace{v(r) = \frac{R^2 - r^2}{4\mu}\left[-\frac{d}{d\ell}(p + \gamma z)\right]}_{\text{Parabolic profile}}$$

SCRIPT

SCRIPT

SERVER HAS A COUPLE OF ORIGINAL PAPERS EXAMINING PIPE FLOW ISSUES;

THESE ARE SOME OF COLEBROOK'S PAPERS

BOARD

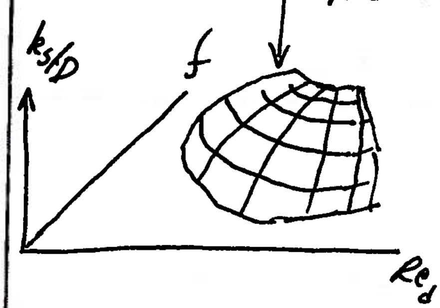
TURBULENT FLOW USES OBSERVED CORRELATIONS TO POSTULATE A MODEL FOR FRICTION FACTOR.

AFTER MANY EXPERIMENTS f WAS FOUND TO CORRELATE WITH REYNOLD'S NUMBER, AND A MATERIAL PROPERTY CALLED ROUGHNESS HEIGHT.

THESE CORRELATIONS NOW APPEAR AS EITHER

SCRIPT

THIS SURFACE IS PUSHED INTO f, Re PLANE



k_s/D "ELEVATIONS" ARE SHOWN AS CONTOUR LINES ON FLAT CHART.

BOARD

REGRESSION EQUATIONS OR PLOTTED ON THE MOODY-STANTON CHART.

THE MOODY CHART IS ACTUALLY A 2D PLOT OF THREE CORRELATED VARIABLES;

$$Re_d, \ f, \ \frac{k_s}{D}$$

REYNOLDS' NUMBER

FRICTION FACTOR

RELATIVE ROUGHNESS

SCRIPT

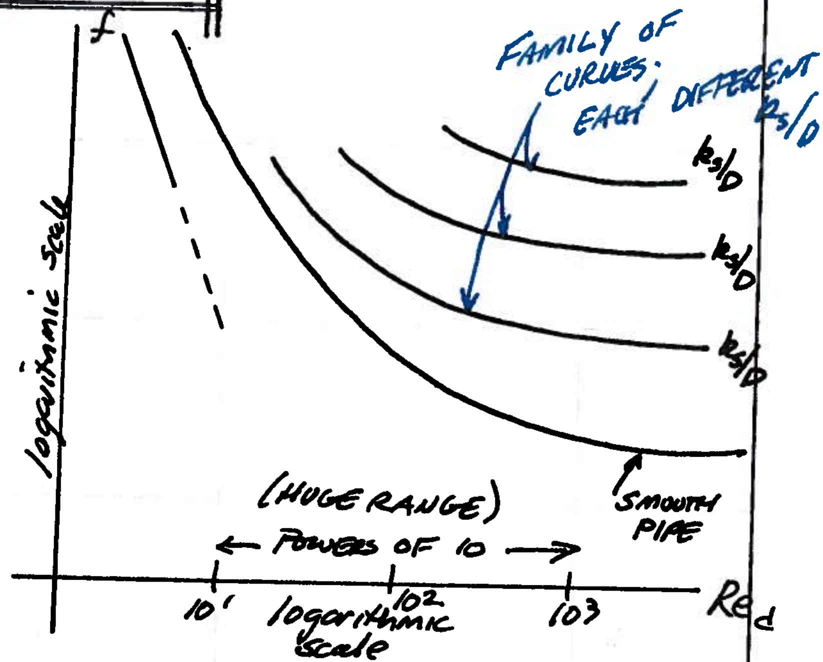
MOODY CHART

USED IN 3 TYPICAL WAYS

① FIND h_L
GIVEN
Q, D, material

② FIND Q
GIVEN
h_L (OR Δp), D, material

BOARD



SCRIPT

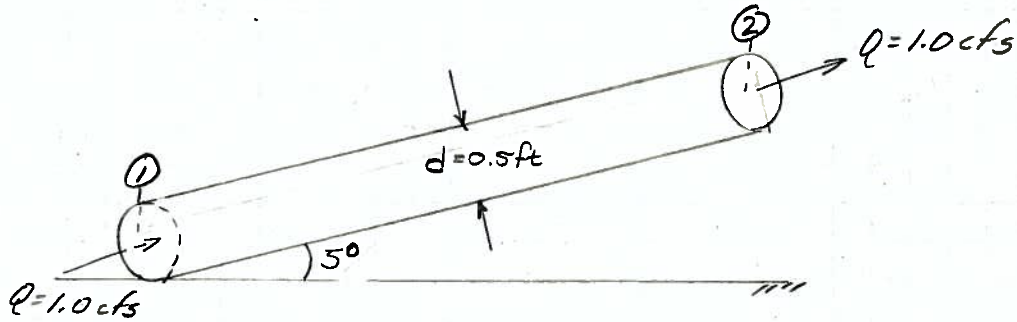
③ FIND D,
GIVEN
h_L, Q, material

BOARD

NEXT SEVERAL EXAMPLES ILLUSTRATE MOODY CHART USE.

EXAMPLE 1

OIL WITH S.G. = 0.9 $\nu = 0.00003\ ft^2/s$ FLOWS AT 1.0 cfs THROUGH A SIX INCH CAST IRON PIPE 2000 ft LONG. SLOPE IS +5° IN DIRECTION OF FLOW. FIND HEAD LOSS AND PRESSURE DROP.



CONTINUITY

$$\frac{d}{dt}\int_{CV} \rho\, d\forall + \int_{CS} \rho \mathbf{V} \cdot d\mathbf{A} = 0$$

$$= -\rho V_1 A_1 + \rho V_2 A_2 \qquad \begin{matrix} A_1 = A_2 \\ \rho = \text{CONST.} \end{matrix} \Rightarrow V_1 = V_2$$

ENERGY

$$\frac{P_1}{\gamma} + \alpha_1 \frac{V_1^2}{2g} + z_1 + \cancel{h_P}^{\,0} = \frac{P_2}{\gamma} + \alpha_2 \frac{V_2^2}{2g} + z_2 + \cancel{h_T}^{\,0} + h_f$$

$$\alpha_1 = \alpha_2$$

(NOTE: $\Delta z = z_2 - z_1$, $\Delta p = p_2 - p_1$)

$$\Rightarrow \frac{p_1 - p_2}{\gamma} + z_1 - z_2 = h_f$$

$$\boxed{\frac{-\Delta P}{\gamma} - \Delta z = h_f}$$ ← BERNOULLI'S EQN

$$\boxed{h_f = f \frac{L}{D} \frac{V^2}{2g}}$$ ← DARCY WEISBACH

COMBINE:

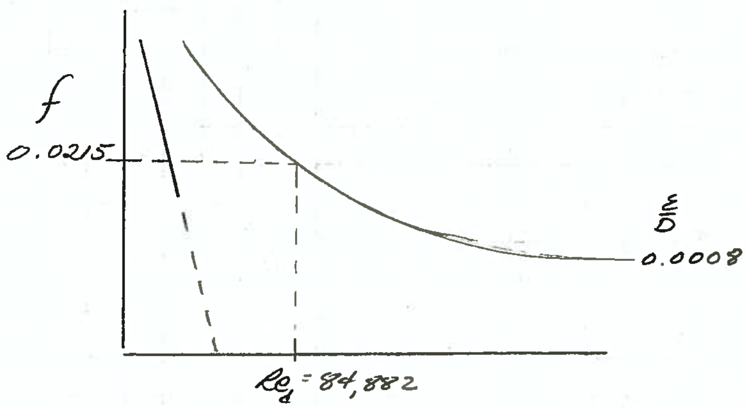
$$\frac{\Delta P}{\gamma} + \Delta z = -f \frac{L}{D} \frac{V^2}{2g}$$

EXAMPLE 1 (CONT.)

$$Re_d = \frac{Vd}{\nu} = \frac{4\,(1\,ft^3/s)(0.5\,ft)}{\pi\,(0.5\,ft)^2(0.00003\,ft^2/s)} = 84{,}882.6$$

$Re_d > 2000 \;\therefore$ NON-LAMINAR

$$\frac{\varepsilon}{D} = 0.0008$$



$$h_f = (0.0215)\frac{(2000\,ft)}{(0.5\,ft)}\left(\frac{4\,(1\,ft^3/s)}{\pi\,(0.5\,ft)^2}\right)^2\left(\frac{1}{2(32.2\,ft/s^2)}\right) = 34.64\,ft$$

$$\Delta z = -2000\,ft\,\sin 5^\circ = -174.3\,ft$$

S.G. oil

$$\Delta p = (h_f - \Delta z)\,\gamma = (34.64\,ft + 174.3\,ft)(62.4\,\tfrac{lbf}{ft^3})(0.9)$$

$$= 11.74 \cdot 10^3\,lbf/ft^3 = 81.4\,psi$$

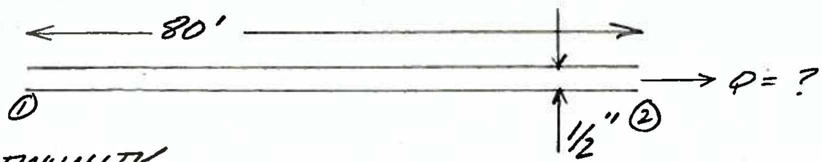
$\underline{\underline{h_f = 34.64\,ft}}$ ← HEAD LOSS FROM 1 TO 2

$\underline{\underline{\Delta p = 81.4\,psi}}$ ← PRESSURE DROP FROM 1 TO 2

NOTE: IN THIS EXAMPLE $P_1 > P_2$, $z_1 < z_2$

EXAMPLE 2

WATER AT 20°C FLOWS THROUGH AN 80 ft, 1/2 inch WROUGHT IRON PIPE. HEAD LOSS IS 40 ft. FIND FLOW RATE



CONTINUITY

$$0 = \frac{d}{dt}\int_{CV} \rho \, d\forall + \int_{CS} \rho V \cdot dA$$

$$0 = -\rho V_1 A_1 + \rho V_2 A_2 \qquad A_1 = A_2, \quad \rho = \text{CONST}$$

$$\Rightarrow V_1 = V_2$$

ENERGY

$$\frac{P_1}{\gamma} + \frac{\alpha_1 V_1^2}{2g} + z_1 + \cancel{h_P}^{\,0} = \frac{P_2}{\gamma} + \frac{\alpha_2 V_2^2}{2g} + z_2 + \cancel{h_T}^{\,0} + h_F$$

$$z_1 = z_2$$
$$V_1 = V_2, \quad \alpha_1 = \alpha_2$$

$$\frac{P_1 - P_2}{\gamma} = h_f = 40 \text{ ft}$$

$$h_f = f \frac{L}{D}\frac{V^2}{2g} = f \frac{L}{D}\left(\frac{Q}{A}\right)^2 \frac{1}{2g}$$
$$= f \frac{8L}{\pi^2 D^5}\frac{Q^2}{g}$$

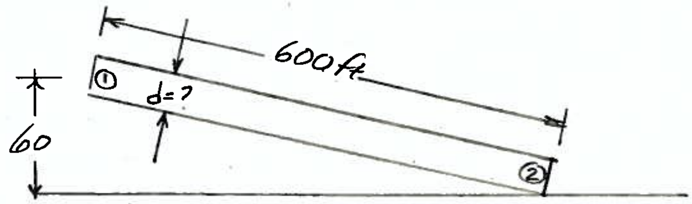
$$\frac{\varepsilon}{D} = 0.0036$$

Q (cfs) GUESS	Re_d	f	$h_{f(GUESS)}$ $h_{f(OBS)} = 40'$
0.001	$2.83 \cdot 10^3$	0.036	0.57
0.005	$1.41 \cdot 10^4$	0.032	12.7
0.008	$2.264 \cdot 10^4$	0.031	31.6
0.009	$2.252 \cdot 10^4$	0.030	37.9

$Q \simeq 0.009$ cfs ← FLOW RATE THROUGH PIPE

EXAMPLE 3

WHAT SIZE OF STEEL PIPE IS REQUIRED TO DELIVER WATER @ 20°C AT 3 cfs? THE PIPE WILL BE 600 ft LONG. ELEVATION CHANGE IS −60 ft, PRESSURE DROP IS 6 ft.



CONTINUNITY

$$0 = \frac{d}{dt}\int \rho \, d\forall + \int_{c.s.} \rho V \cdot dA$$

$$= -\rho V_1 A_1 + \rho V_2 A_2 \qquad A_1 = A_2$$

$$\Rightarrow V_1 = V_2 \qquad \rho = \text{CONST}$$

ENERGY

$$\frac{P_1}{\gamma} + \cancel{\frac{\alpha_1 V_1^2}{2g}} + z_1 + \cancel{h_p}^{\,0} = \frac{P_2}{\gamma} + \cancel{\frac{\alpha_2 V_2^2}{2g}} + z_2 + \cancel{h_t}^{\,0} + h_f$$

$$V_1 = V_2 ; \ \alpha_1 = \alpha_2$$

$$\frac{P_1}{\gamma} - \frac{P_2}{\gamma} + z_1 - z_2 = h_f$$

$$-\frac{\Delta P}{\gamma} - \Delta z = h_f$$

$$66' = h_f = f \frac{L}{D}\frac{V^2}{2g} = f \frac{8L}{\pi^2 D^5}\frac{Q^2}{g}$$

D_{guess}	Re_d	$\frac{\varepsilon}{d}$	f	$\frac{h_f}{f}$	h_f
0.25′	$1.41 \cdot 10^6$	0.0006	0.018	$1.39 \cdot 10^5$	2500′
0.5′	$7.06 \cdot 10^5$	0.0003	0.016	$4.35 \cdot 10^3$	69.6′
0.51′	$6.92 \cdot 10^5$	0.00029	0.016	$3.94 \cdot 10^3$	63.0′

D BETWEEN 0.5′ − 0.51′. CHOOSE 6-7″ I.D. PIPE ← DIA.

NOTE: CHOOSE STANDARD PIPE SIZES LARGER THAN CALC. SIZE

Page 204

MODIFIED PROCEDURE FOR EXAMPLE 3

1. CHOOSE f
2. SOLVE FOR D (DARCY-WEISBACH)
3. COMPUTE Re_d, $\frac{\varepsilon}{d}$
4. NEW f
5. REPEAT UNTIL f STOPS CHANGING

$i=1$; $f=0.02$

$$h_f = f\frac{8L}{\pi^2 D^5}\frac{Q^2}{g}$$

$$66 = \frac{(0.02)(600)(16)(9)}{D^5\pi^2(64.4)}$$

$$\left(\frac{h_f}{f\,8LQ^2}\pi^2 g\right)^{-\frac{1}{5}} = D$$

$D = 0.528$

$\frac{\varepsilon}{D} = 0.00028$

$Re_d = 6.69\cdot10^5$ } MOODY CHART, NEW $f=0.016$

$i=2$; $f=0.016$

$$66 = \frac{(0.016)(600)(16)(9)}{D^5\pi^2(64.4)}$$

$D = 0.505$

$\frac{\varepsilon}{d} = 0.0003$

$Re_d = 6.99\cdot10^5$ } MOODY CHART, NEW $f=0.016$

STOP

CANNOT RESOLVE ANY FURTHER

SELECT PIPE I.D. = $\underline{\underline{0.505'}}$ ← PIPE DIA.

SCRIPT

BOARD

ALTERNATIVE TO MOODY CHART, USED IN COMPUTER PROGRAMS IS TO REPLACE THE CHART WITH REGRESSION EQUATIONS

EXAMPLES ARE

① COMPUTE Re_d

LAMINAR ($Re_d < 2000$)

$$f = \frac{64}{Re_d}$$

TRANSITION ($Re_d > 2000$)

COLEBROOK-WHITE.

IMPLICIT ($\sqrt{f}$ APPEARS BOTH SIDES!!)

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\frac{k_s}{D}}{3.7} + \frac{2.51}{Re_d\sqrt{f}}\right)$$

SCRIPT

BOARD

HYDRAULICALLY ROUGH

HORIZONTAL PART OF $\frac{k_s}{D}$ CURVES

$$\frac{1}{\sqrt{f}} = 2\log\left(3.7\cdot\frac{D}{k_s}\right) \quad (Re_d > 2000)$$

HYDRAULICALLY SMOOTH

HIGH CURVATURE PART OF $\frac{k_s}{D}$ CURVES

$$\frac{1}{\sqrt{f}} = 2\log\left(\frac{Re_d\sqrt{f}}{2.51}\right) \quad (Re_d > 2000)$$

SWAMEE-JAIN (DISCHARGE)

COVERED Pg 359-379

OTHERS ARE IN SUPPLEMENTAL READING

—NEXT LECTURE:

FITTING LOSSES