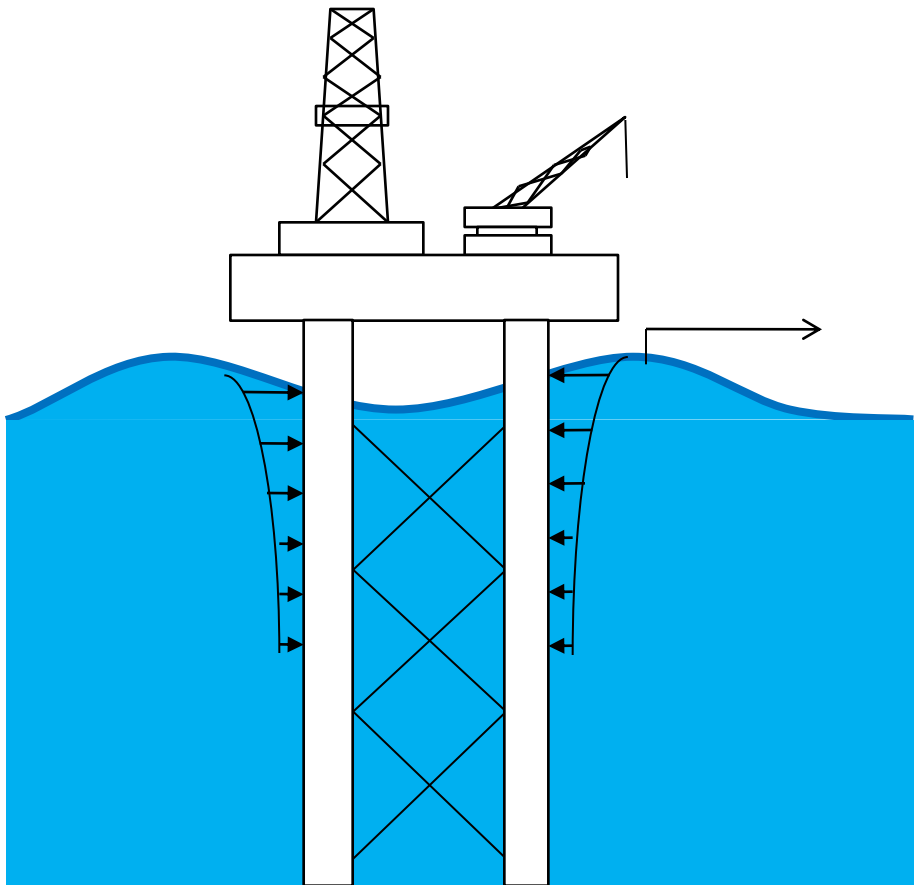
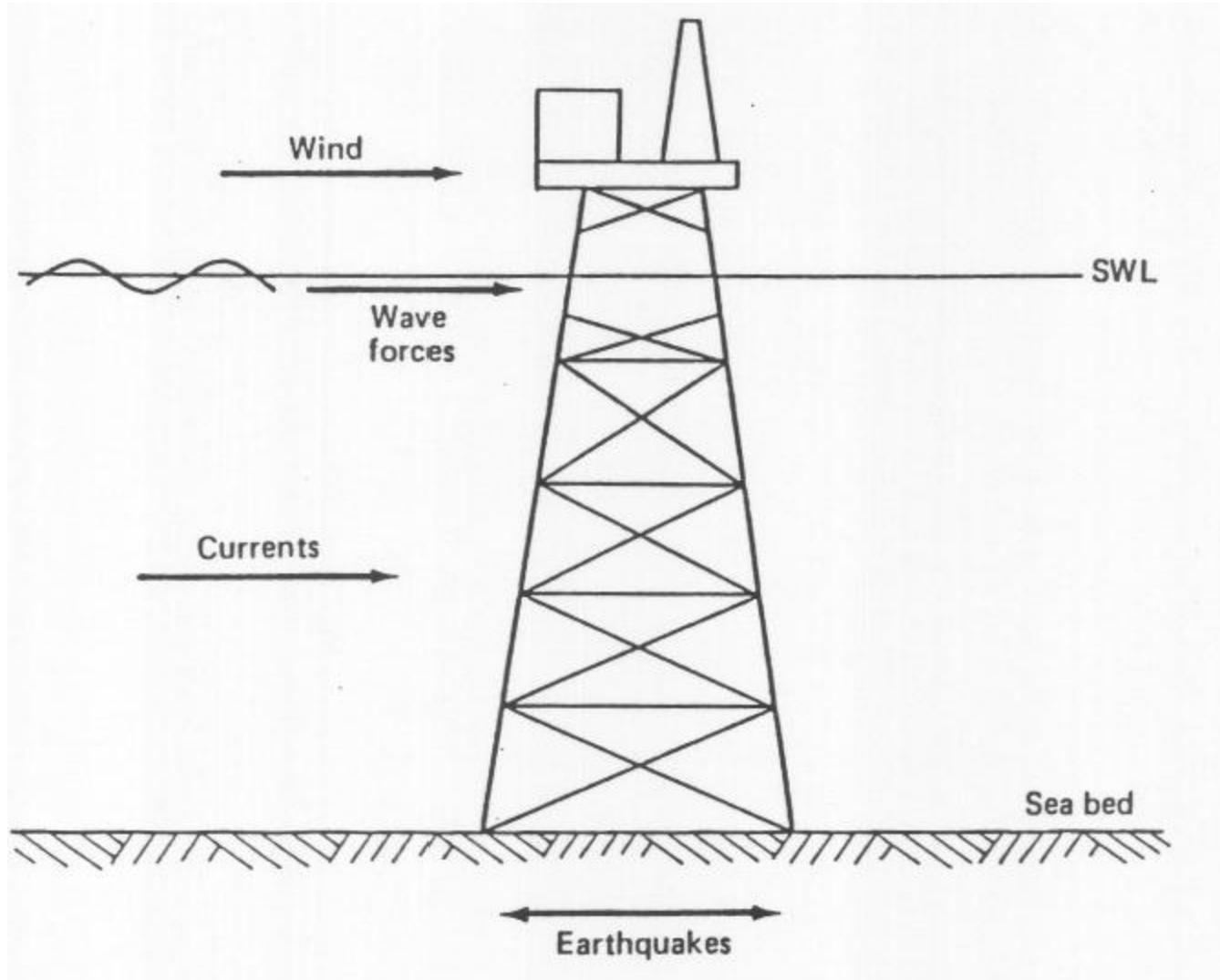


Wave, current, and wind forces



An offshore structure is designed to withstand the 100-year storm (wave/current/wind). A **mono-chromatic wave of height H_{max}** is assumed.



OFFSHORE PLATFORMS are comprised of many cylindrical or prismatic components (structural elements, floatation parts, risers, tendons, mooring lines, etc)

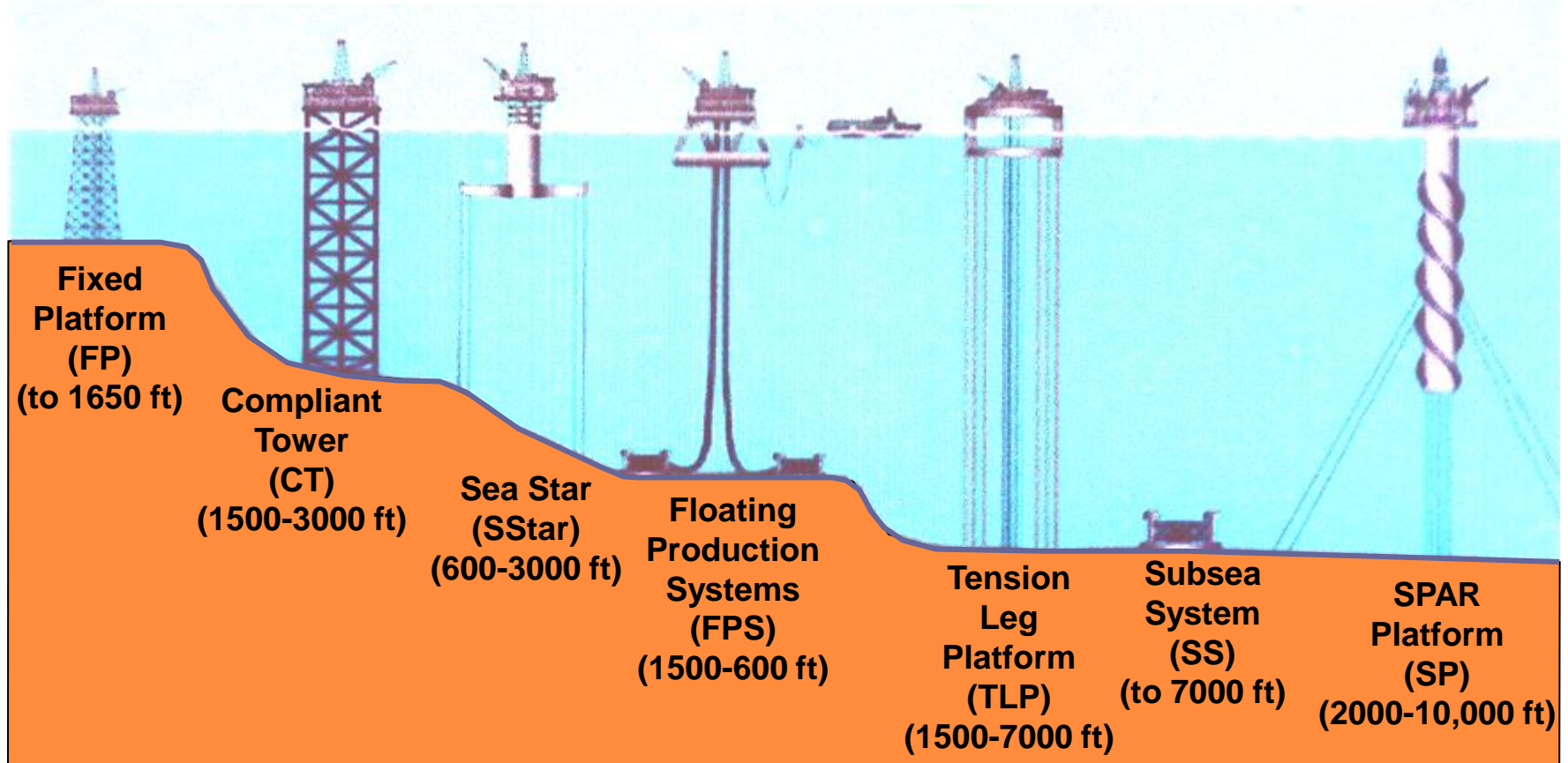
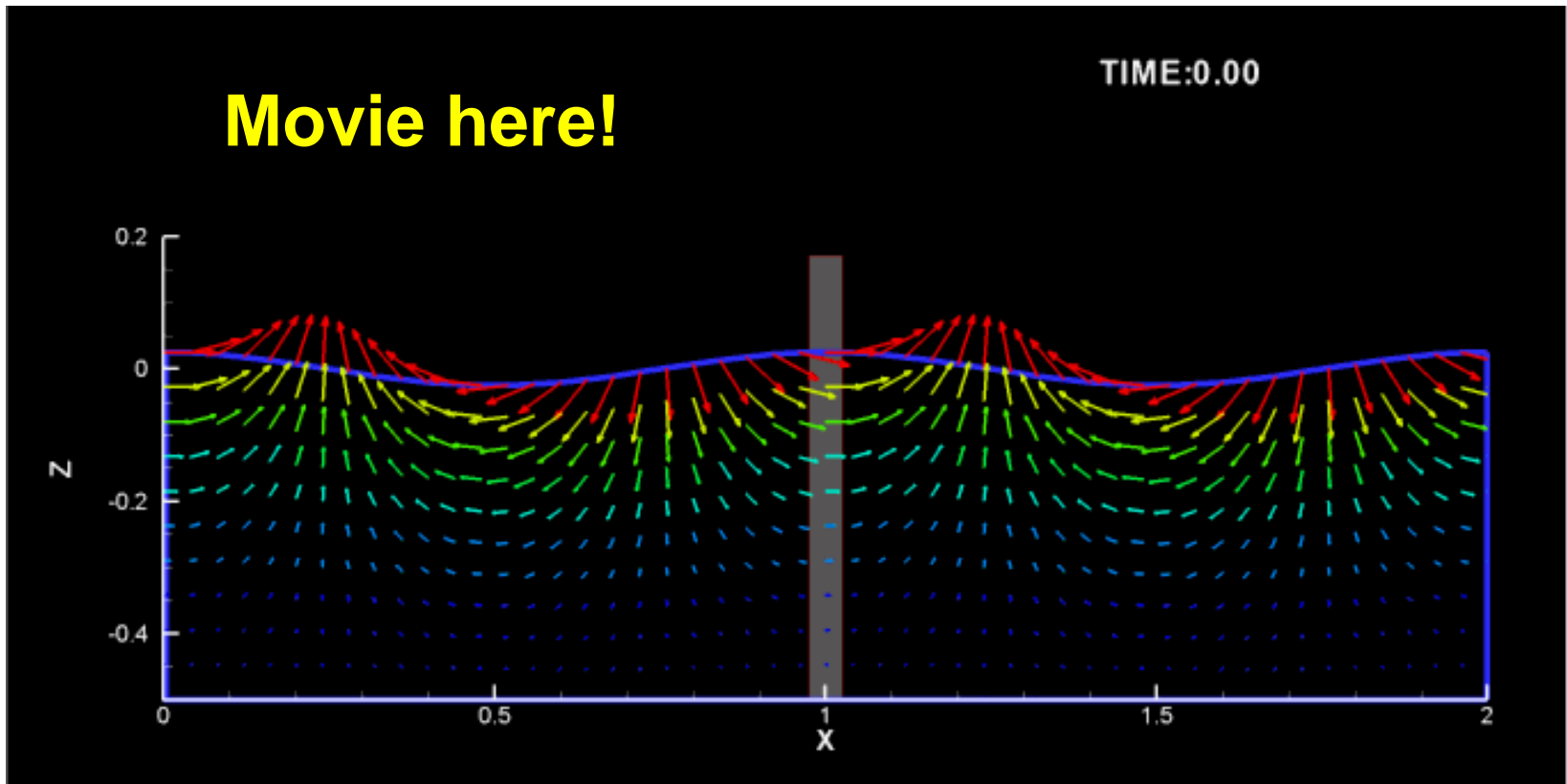
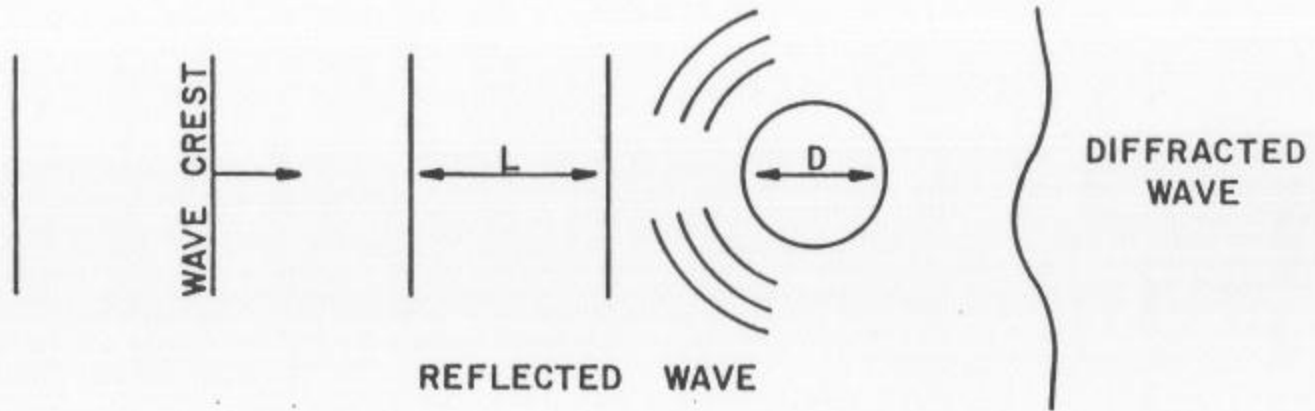


Figure from BOEMRE, U.S. Department of the Interior

What inflow velocity would a pile be subjected to?

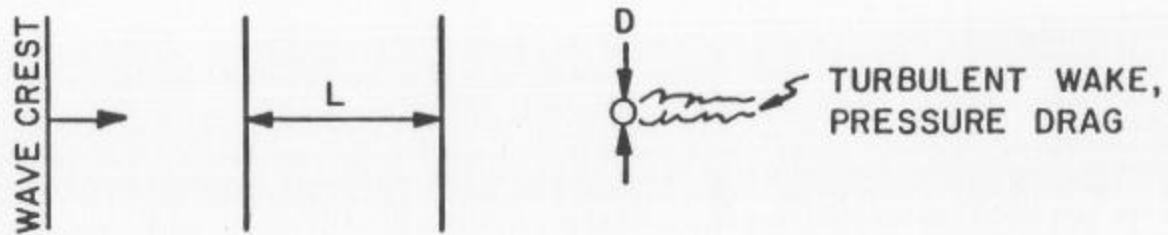


WAVE FORCE LIMITING CASE



WAVES MODIFIED BY OBJECT, $D > \frac{L}{5}$

WAVE FORCE LIMITING CASE

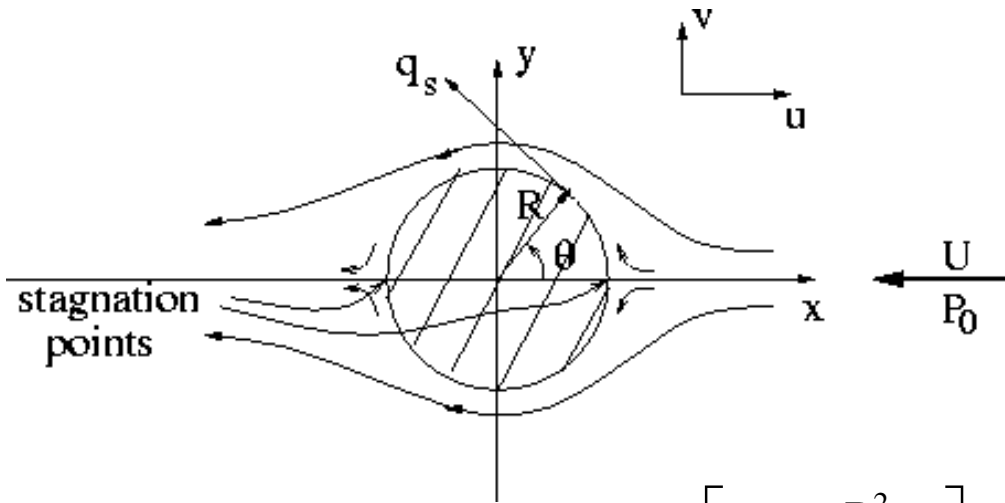


WAVE DOES NOT "FEEL" OBJECT, $D < \frac{L}{6}$

Steps to take:

- Study steady flow around 2-D cylinder (circle) subject to steady inflow
- Study unsteady flow around 2-D cylinder (circle) subject to accelerating inflow
- Apply the study and the formulas developed in the previous steps, on “slices” of the 3-D cylinder, subject to wave and current, and integrate along its length to determine total forces and moments

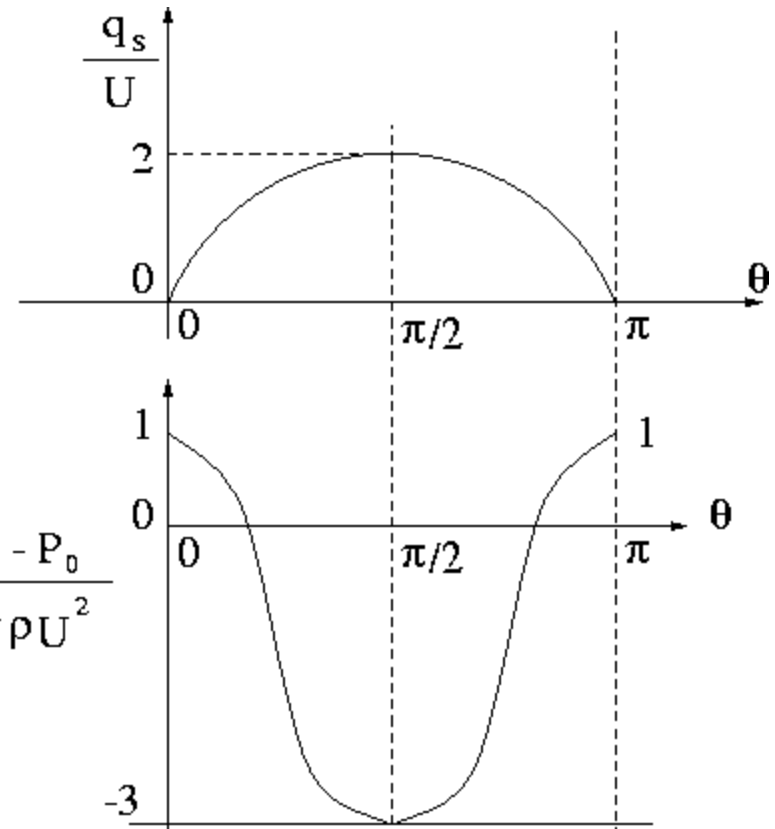
Inviscid Flow Around a Circle



Velocity potential:
$$\Phi = -Ux \left[1 + \frac{R^2}{x^2 + y^2} \right]$$

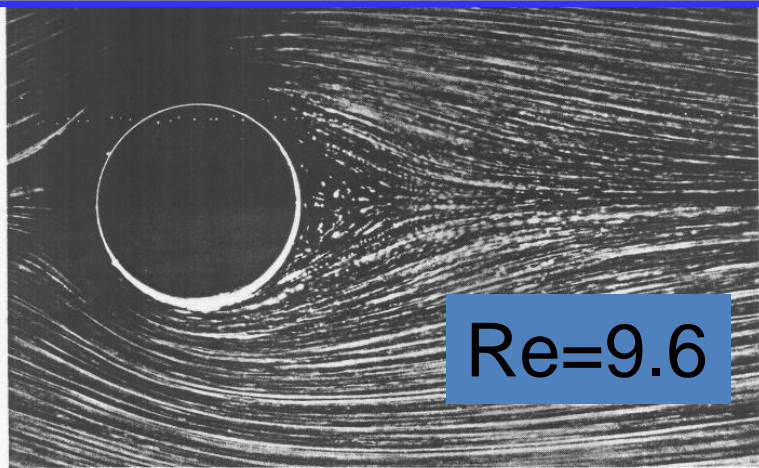
Surface velocity
$$q_s = \sqrt{u^2 + v^2} = 2U \sin \theta$$

Surface pressure coefficient
$$C_p = \frac{P_s - P_0}{\frac{1}{2} \rho U^2} = 1 - \left(\frac{q_s}{U} \right)^2 \quad C_p = \frac{P_s - P_0}{\frac{1}{2} \rho U^2}$$

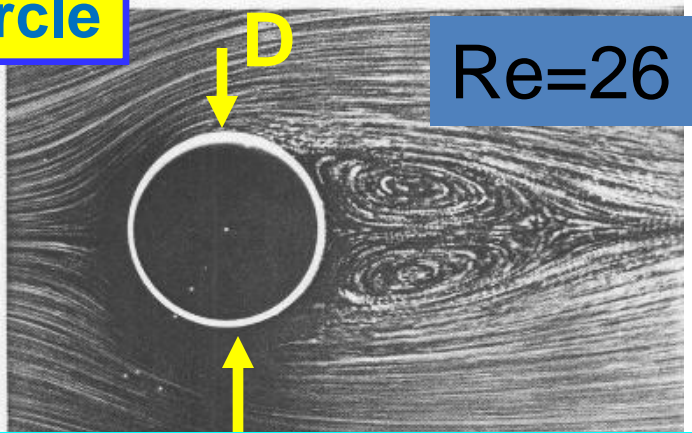


D'Alembert "paradox": The force on a body subject to inviscid steady flow is equal to zero!

Effect of viscosity on flow around circle

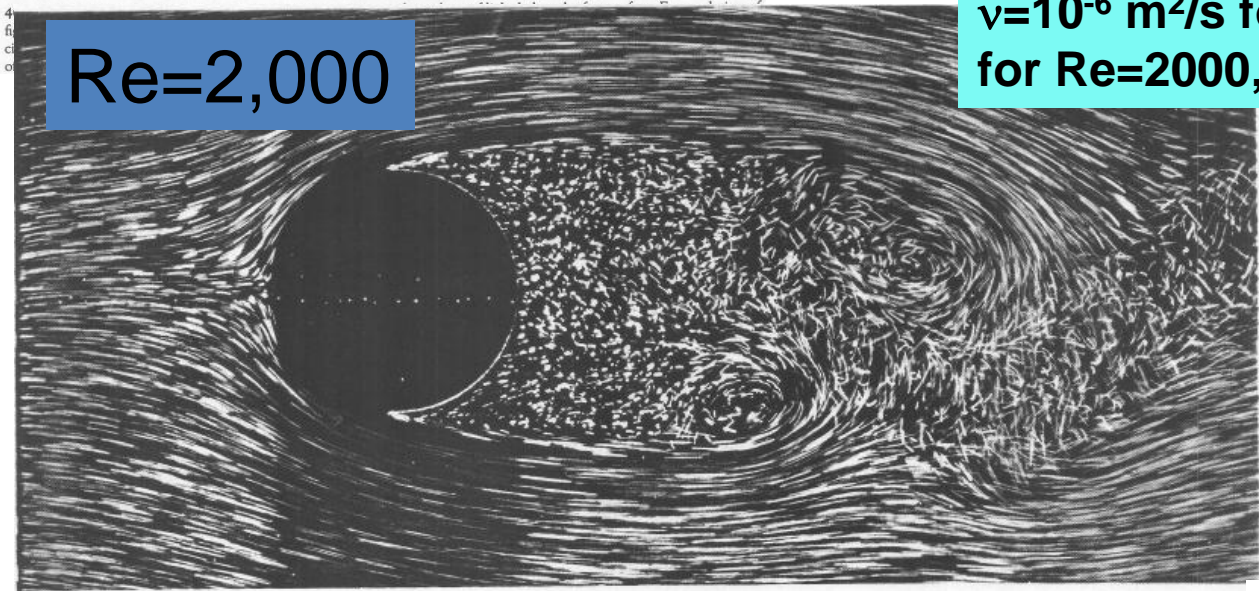


Re=9.6



Re=26

$\nu = \mu / \rho =$ kinematic viscosity
 $\nu = 10^{-6} \text{ m}^2/\text{s}$ for H_2O at 20°C . If $D = 20 \text{ cm}$
 for $\text{Re} = 2000$, U should be 0.01 m/s



Re=2,000

Reynolds Number

$$\text{Re} = \frac{UD}{\nu}$$

47. Circular cylinder at $R=2000$. At this Reynolds number one may properly speak of a boundary layer. It is laminar over the front, separates, and breaks up into a turbulent wake. The separation points, moving forward as

the Reynolds number is increased, have now attained their upstream limit, ahead of maximum thickness. Visualization is by air bubbles in water. ONERA photograph, Werlé & Gallon 1972

Photos from Album of Fluid Motion of M. Vandyke

Physical properties of air and water circle

Table A.3 MECHANICAL PROPERTIES OF AIR AT STANDARD ATMOSPHERIC PRESSURE

Temperature	Density	Specific Weight	Dynamic Viscosity	Kinematic Viscosity
	kg/m ³	N/m ³	N · s/m ²	m ² /s
-20°C	1.40	13.70	1.61 × 10 ⁻⁵	1.16 × 10 ⁻⁵
-10°C	1.34	13.20	1.67 × 10 ⁻⁵	1.24 × 10 ⁻⁵
0°C	1.29	12.70	1.72 × 10 ⁻⁵	1.33 × 10 ⁻⁵
10°C	1.25	12.20	1.76 × 10 ⁻⁵	1.41 × 10 ⁻⁵
20°C	1.20	11.80	1.81 × 10 ⁻⁵	1.51 × 10 ⁻⁵
30°C	1.17	11.40	1.86 × 10 ⁻⁵	1.60 × 10 ⁻⁵
40°C	1.13	11.10	1.91 × 10 ⁻⁵	1.69 × 10 ⁻⁵
50°C	1.09	10.70	1.95 × 10 ⁻⁵	1.79 × 10 ⁻⁵
60°C	1.06	10.40	2.00 × 10 ⁻⁵	1.89 × 10 ⁻⁵
70°C	1.03	10.10	2.04 × 10 ⁻⁵	1.99 × 10 ⁻⁵
80°C	1.00	9.81	2.09 × 10 ⁻⁵	2.09 × 10 ⁻⁵
90°C	0.97	9.54	2.13 × 10 ⁻⁵	2.19 × 10 ⁻⁵
100°C	0.95	9.28	2.17 × 10 ⁻⁵	2.29 × 10 ⁻⁵
120°C	0.90	8.82	2.26 × 10 ⁻⁵	2.51 × 10 ⁻⁵
140°C	0.85	8.38	2.34 × 10 ⁻⁵	2.74 × 10 ⁻⁵
160°C	0.81	7.99	2.42 × 10 ⁻⁵	2.97 × 10 ⁻⁵
180°C	0.78	7.65	2.50 × 10 ⁻⁵	3.20 × 10 ⁻⁵
200°C	0.75	7.32	2.57 × 10 ⁻⁵	3.44 × 10 ⁻⁵
	slugs/ft ³	lbf/ft ³	lbf-s/ft ²	ft ² /s
0°F	0.00269	0.0866	3.39 × 10 ⁻⁷	1.26 × 10 ⁻⁴
20°F	0.00257	0.0828	3.51 × 10 ⁻⁷	1.37 × 10 ⁻⁴
40°F	0.00247	0.0794	3.63 × 10 ⁻⁷	1.47 × 10 ⁻⁴
60°F	0.00237	0.0764	3.74 × 10 ⁻⁷	1.58 × 10 ⁻⁴
80°F	0.00228	0.0735	3.85 × 10 ⁻⁷	1.69 × 10 ⁻⁴
100°F	0.00220	0.0709	3.96 × 10 ⁻⁷	1.80 × 10 ⁻⁴
120°F	0.00213	0.0685	4.07 × 10 ⁻⁷	1.91 × 10 ⁻⁴
150°F	0.00202	0.0651	4.23 × 10 ⁻⁷	2.09 × 10 ⁻⁴
200°F	0.00187	0.0601	4.48 × 10 ⁻⁷	2.40 × 10 ⁻⁴
300°F	0.00162	0.0522	4.96 × 10 ⁻⁷	3.05 × 10 ⁻⁴
400°F	0.00143	0.0462	5.40 × 10 ⁻⁷	3.77 × 10 ⁻⁴

SOURCE: Reprinted with permission from R. E. Bolz and G. L. Tuve, *Handbook of Tables for Applied Engineering Science*, CRC Press, Inc., Cleveland, 1973. Copyright © 1973 by The Chemical Rubber Co., CRC Press, Inc.

Table A.5 APPROXIMATE PHYSICAL PROPERTIES OF WATER* AT ATMOSPHERIC PRESSURE

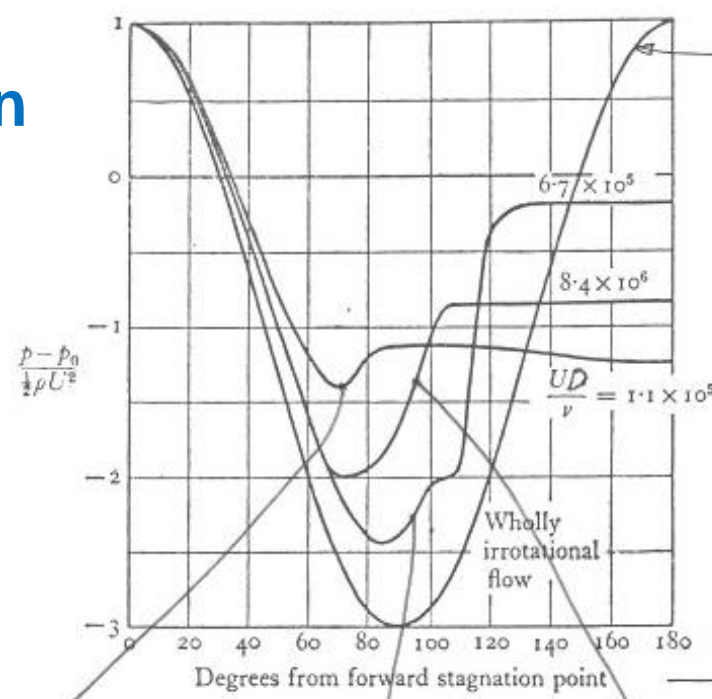
Temperature	Density	Specific Weight	Dynamic Viscosity	Kinematic Viscosity	Vapor Pressure
	kg/m ³	N/m ³	N · s/m ²	m ² /s	N/m ² abs
0°C	1000	9810	1.79 × 10 ⁻³	1.79 × 10 ⁻⁶	611
5°C	1000	9810	1.51 × 10 ⁻³	1.51 × 10 ⁻⁶	872
10°C	1000	9810	1.31 × 10 ⁻³	1.31 × 10 ⁻⁶	1,230
15°C	999	9800	1.14 × 10 ⁻³	1.14 × 10 ⁻⁶	1,700
20°C	998	9790	1.00 × 10 ⁻³	1.00 × 10 ⁻⁶	2,340
25°C	997	9781	8.91 × 10 ⁻⁴	8.94 × 10 ⁻⁷	3,170
30°C	996	9771	7.97 × 10 ⁻⁴	8.00 × 10 ⁻⁷	4,250
35°C	994	9751	7.20 × 10 ⁻⁴	7.24 × 10 ⁻⁷	5,630
40°C	992	9732	6.53 × 10 ⁻⁴	6.58 × 10 ⁻⁷	7,380
50°C	988	9693	5.47 × 10 ⁻⁴	5.53 × 10 ⁻⁷	12,300
60°C	983	9643	4.66 × 10 ⁻⁴	4.74 × 10 ⁻⁷	20,000
70°C	978	9594	4.04 × 10 ⁻⁴	4.13 × 10 ⁻⁷	31,200
80°C	972	9535	3.54 × 10 ⁻⁴	3.64 × 10 ⁻⁷	47,400
90°C	965	9467	3.15 × 10 ⁻⁴	3.26 × 10 ⁻⁷	70,100
100°C	958	9398	2.82 × 10 ⁻⁴	2.94 × 10 ⁻⁷	101,300
	slugs/ft ³	lbf/ft ³	lbf-s/ft ²	ft ² /s	psia
40°F	1.94	62.43	3.23 × 10 ⁻⁵	1.66 × 10 ⁻⁵	0.122
50°F	1.94	62.40	2.73 × 10 ⁻⁵	1.41 × 10 ⁻⁵	0.178
60°F	1.94	62.37	2.36 × 10 ⁻⁵	1.22 × 10 ⁻⁵	0.256
70°F	1.94	62.30	2.05 × 10 ⁻⁵	1.06 × 10 ⁻⁵	0.363
80°F	1.93	62.22	1.80 × 10 ⁻⁵	0.930 × 10 ⁻⁵	0.506
100°F	1.93	62.00	1.42 × 10 ⁻⁵	0.739 × 10 ⁻⁵	0.949
120°F	1.92	61.72	1.17 × 10 ⁻⁵	0.609 × 10 ⁻⁵	1.69
140°F	1.91	61.38	0.981 × 10 ⁻⁵	0.514 × 10 ⁻⁵	2.89
160°F	1.90	61.00	0.838 × 10 ⁻⁵	0.442 × 10 ⁻⁵	4.74
180°F	1.88	60.58	0.726 × 10 ⁻⁵	0.385 × 10 ⁻⁵	7.51
200°F	1.87	60.12	0.637 × 10 ⁻⁵	0.341 × 10 ⁻⁵	11.53
212°F	1.86	59.83	0.593 × 10 ⁻⁵	0.319 × 10 ⁻⁵	14.70

* Notes: (1) Bulk modulus E_v of water is approximately 2.2 GPa (3.2×10^5 psi); (2) water-air surface tension is approximately 7.3×10^{-2} N/m (5×10^{-3} lbf/ft) from 10°C to 50°C.

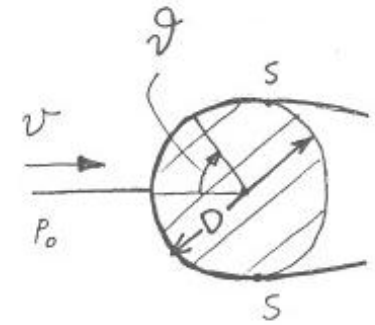
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From Engineering Fluid Mechanics of Crowe et al, 2009

Effect of Re on the pressure distribution on surface of circle



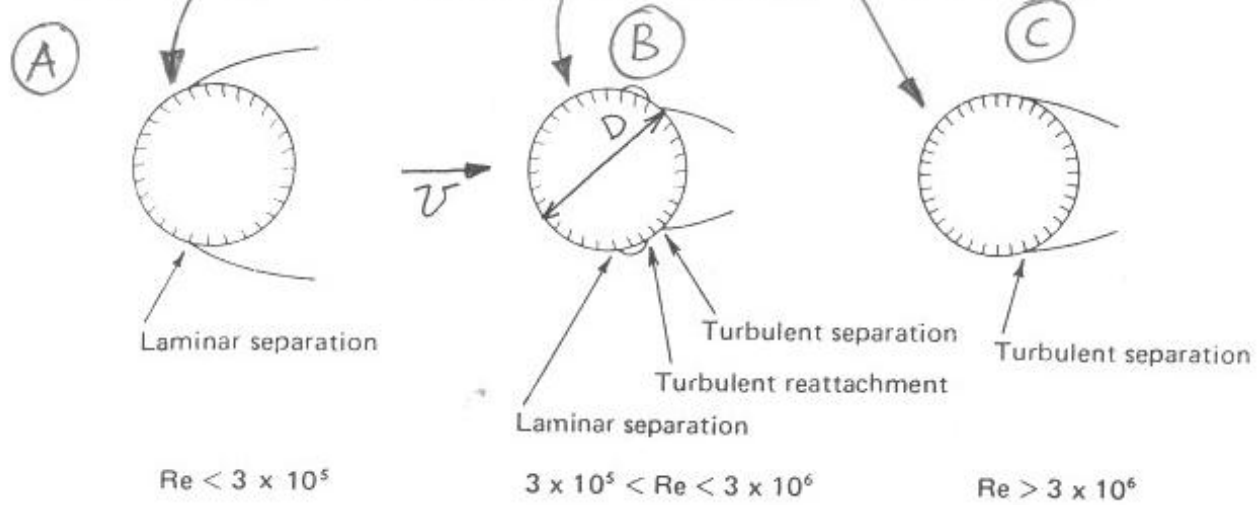
Inviscid Flow



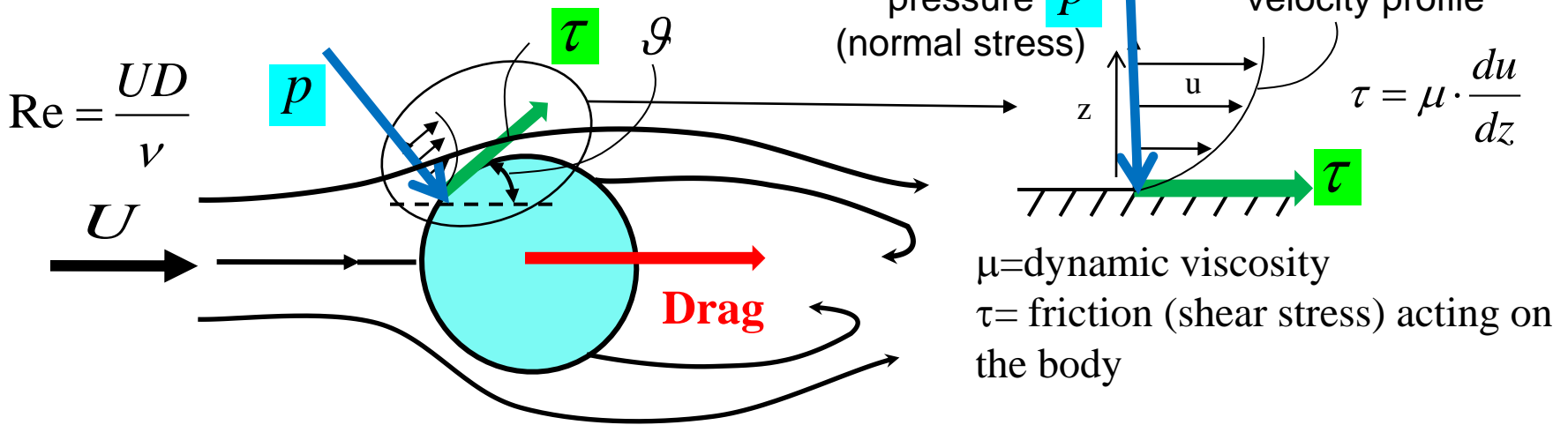
$$Re = \frac{UD}{\nu}$$

$\nu = \frac{\mu}{\rho}$ (Kinematic viscosity)

Figure 5.11.5. The measured pressure distribution at the surface of a circular cylinder in a stream of speed U at different Reynolds numbers; p_0 = pressure at infinity.



Drag and Drag coefficient



Total Drag = Friction Drag + Pressure Drag

Friction Drag = $\int \tau ds \cos \theta \neq 0$

Pressure (or form) Drag = $\int p ds \sin \theta \neq 0$

Drag Coefficient (in 2-D):

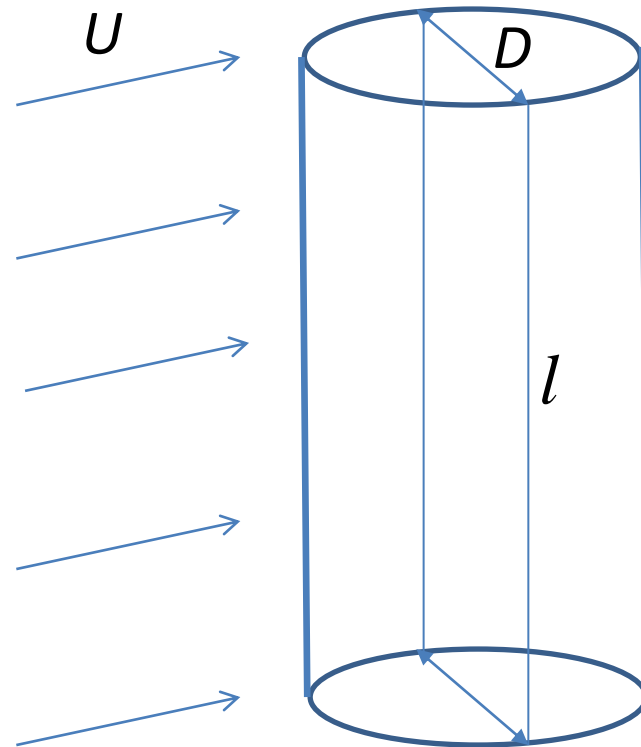
$$C_D = \frac{\text{Drag force per unit width}}{\frac{1}{2} \rho U^2 D}$$

(in 3-D):

$$C_D = \frac{\text{Drag force}}{\frac{1}{2} \rho U^2 A_{proj}}$$

A_{proj} is the **projected area** of the body on a plane normal to the direction of inflow

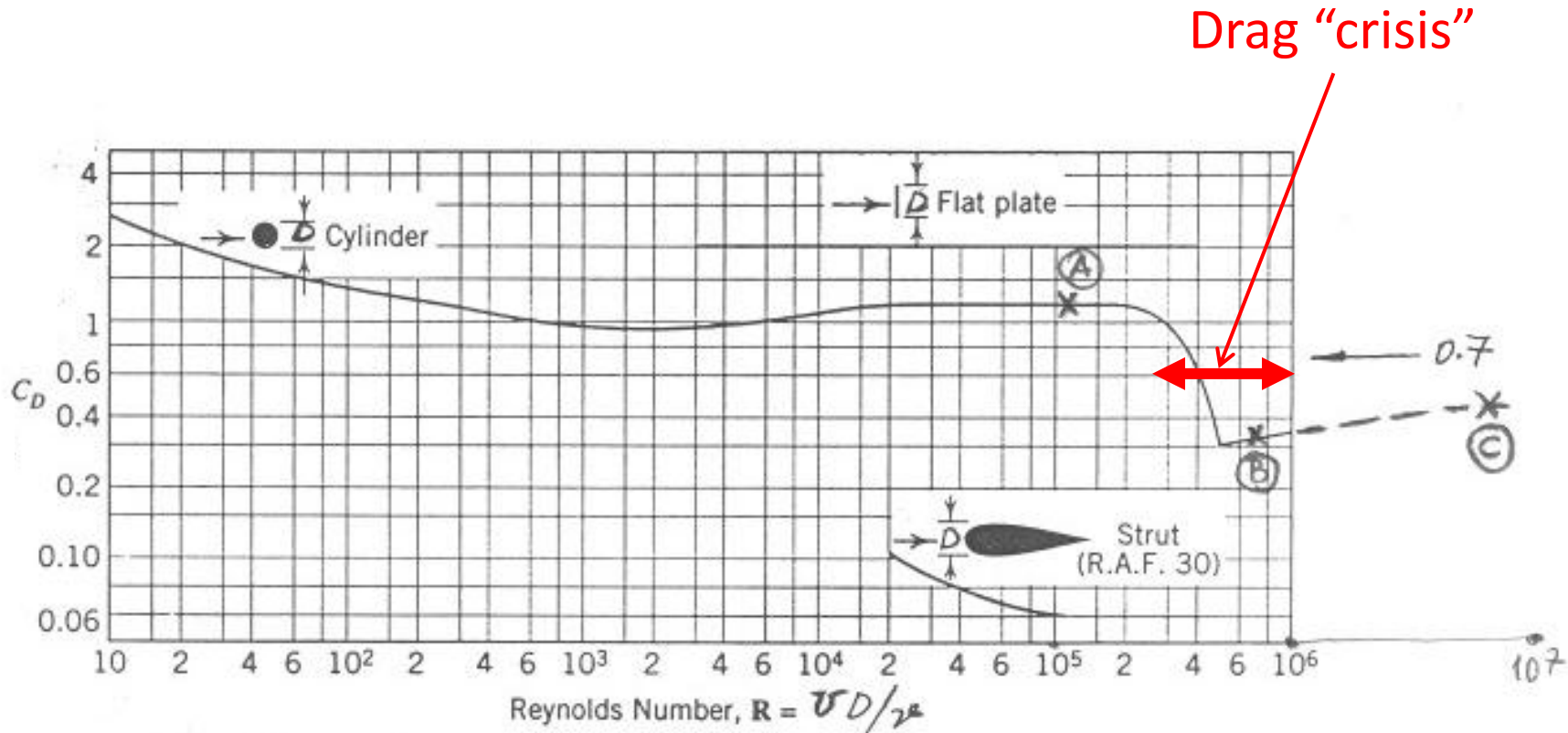
Drag force on a cylinder subject to uniform current U



$$A_{proj} = Dl$$

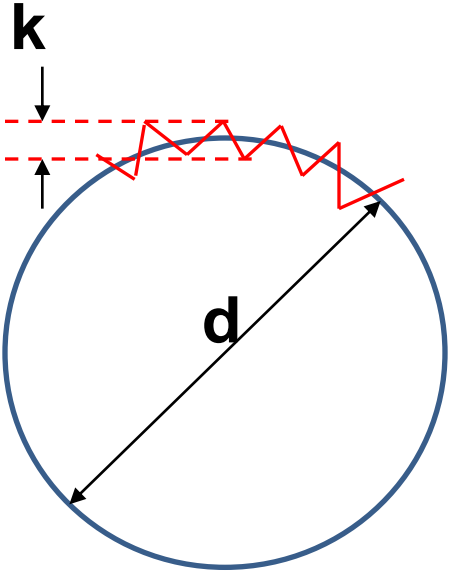
$$C_D = \frac{\text{Drag force}}{\frac{1}{2} \rho U^2 A_{proj}} = \frac{\text{Drag force}}{\frac{1}{2} \rho U^2 Dl} = \frac{\text{Drag force per unit width}}{\frac{1}{2} \rho U^2 D}$$

Effect of Re on Drag coefficient on Cylinder

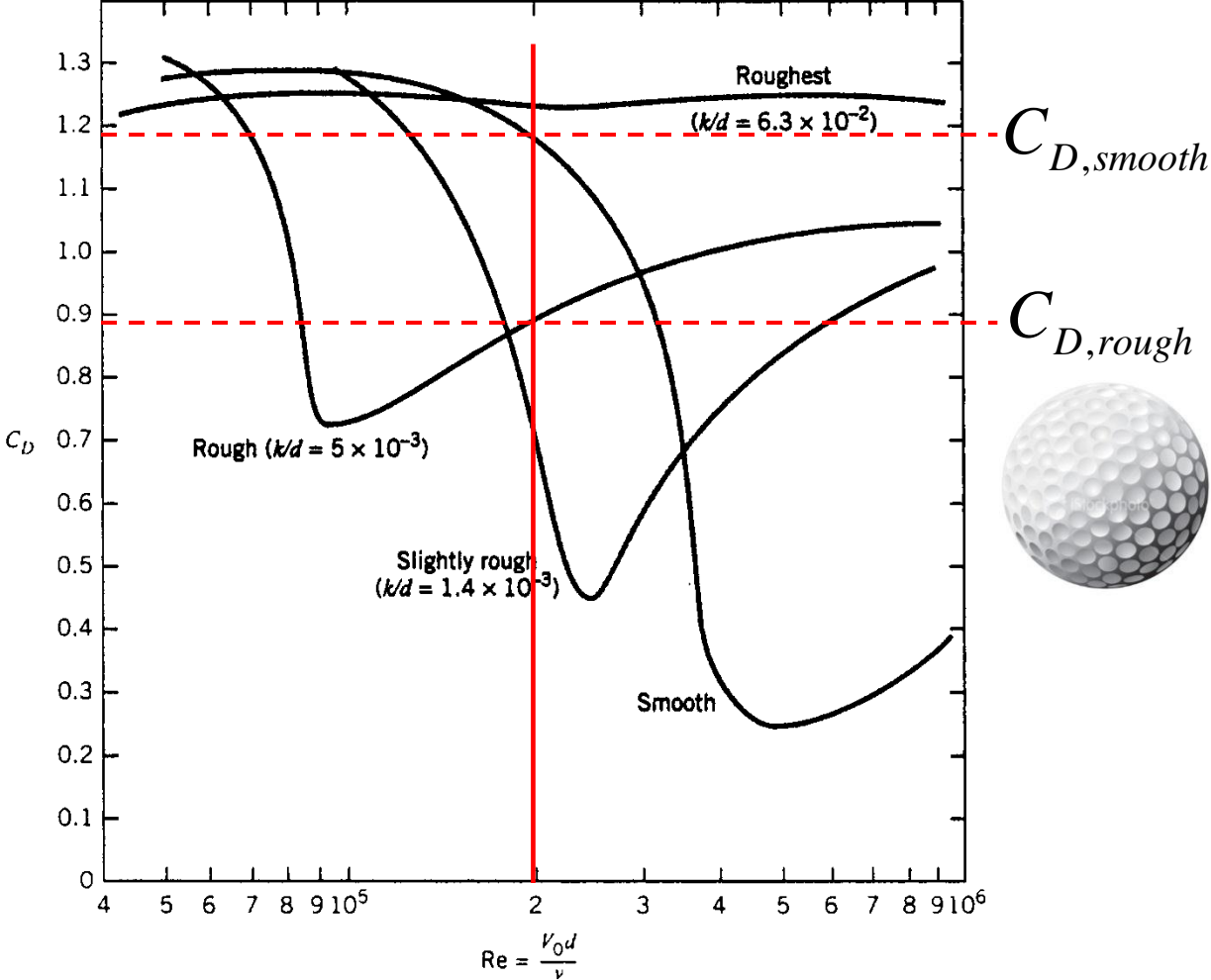


$$C_D = \frac{\text{Drag force per unit width}}{\frac{1}{2} \rho U^2 D}$$

Effect of roughness on Drag coefficient on Cylinder



$k/d =$ relative roughness

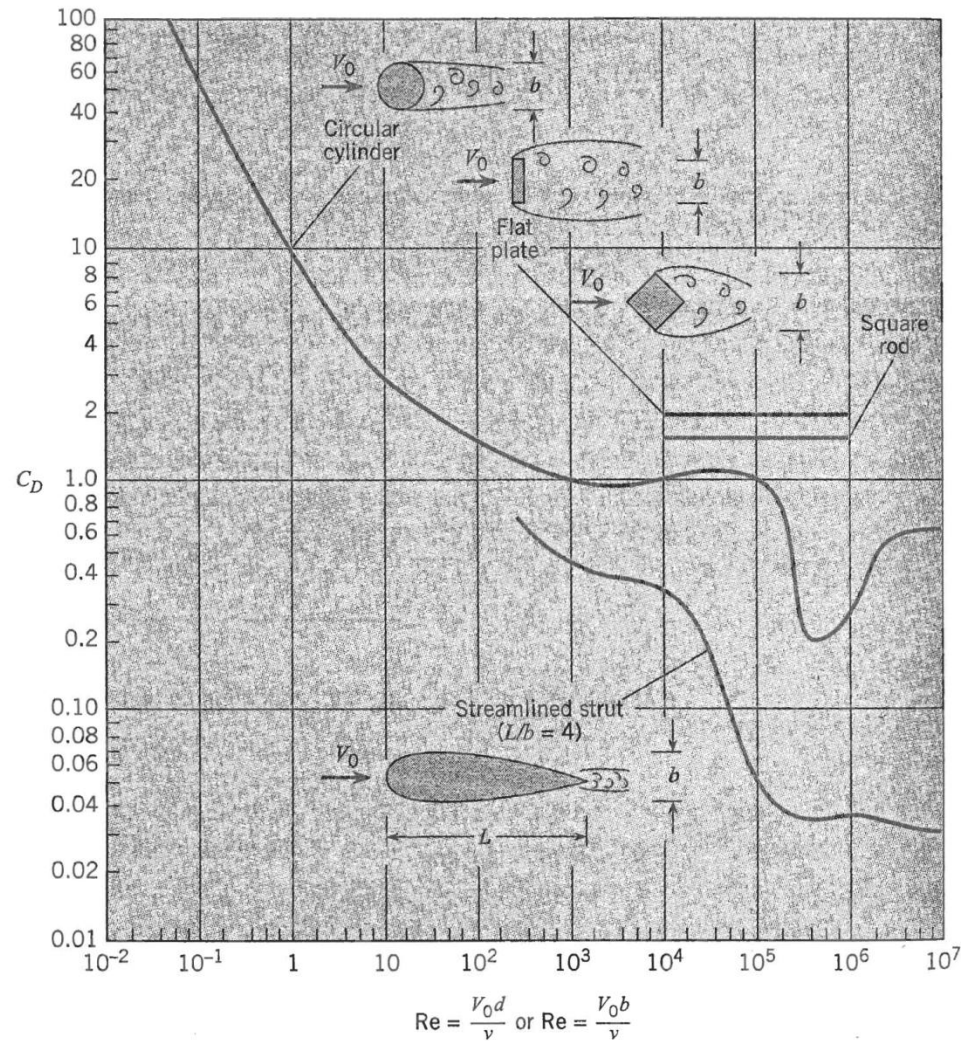


From Engineering Fluid Mechanics of Crowe et al, 2009

Drag coefficients for some other 2-D shapes

FIGURE 11.5

Coefficient of drag versus Reynolds number for two-dimensional bodies. [Data sources: Bullivant (5), Defoe (9), Goett and Bullivant (12), Jacobs (15), Jones (17), and Lindsey (21)]



From Engineering Fluid Mechanics of Crowe et al, 2009