Regimes of Flow

When the average shear stress due to moving water on the river bed exceeds the critical shear stress, individual particles or grains making up the bed start moving and disturbs the plane bed. Since the particles are generally not exactly alike in size, shape or weight and also since a flow in a river has random turbulent fluctuations, all the bed particles do not start moving at the same time.

Gradually, a plane channel bed develops irregular or regular shapes of unevenness which are called *bed forms* which vary according to the flow conditions and are termed as 'Regimes of flow'.

Regimes of flow will considerably affect the velocity distribution, resistance relation and the transport of sediment in an alluvial river. It is defined as:

As sediment and flow characteristics are changed in an alluvial river, the nature of the bed surface and the water surface also changes accordingly. These bed and water surfaces are classified according to

Lower Flow Regime: (1) ripples; (2) dunes with ripples superposed; (3) dunes; and (4) washed-out dunes.
Transitional Flow Regime: The bed roughness ranges from dunes to plane bed or antidunes.
Upper Flow Regime: (1) plane bed; (2) antidunes with standing waves, (3) antidunes with breaking waves

Lower Flow Regime (generally associated with low velocity)
In the lower flow regime, resistance to flow is large and sediment transport is small. The bed form is either ripples or dunes or some combination of the two.

Transition
The bed configuration in the transition zone is erratic. It may range from that typical of the lower flow regime to that typical of the upper flow regime, depending mainly on antecedent conditions. Resistance to flow and sediment transport also have the same variability as the bed configuration in the transition.

Upper Flow Regime (generally associated with high velocity). In upper flow regime, resistance to flow is small and sediment transport is large. The usual forms are plane bed or antidunes. The water surface is in phase with bed surface except when antidune breaks and normally the fluid does not separate from the boundary.

1.



Typical ripple pattern

Ripples, Fr << 1

2.



Dunes with ripples superposed

Dunes with superposed ripples, Fr < 1

3.



Dunes Fr < 1

4.



Flat bed, Fr = 1

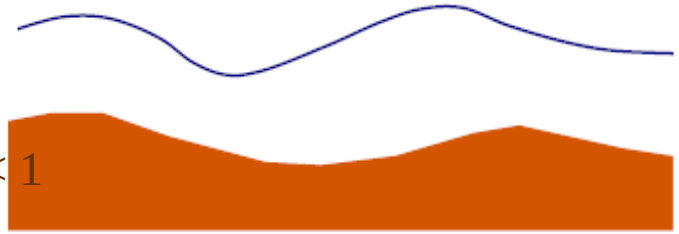
Washed out dunes

5.



Plane bed

6.



Antidune standing wave

Standing waves, Fr > 1

7.



Antidune breaking wave

Antidunes, Fr >> 1

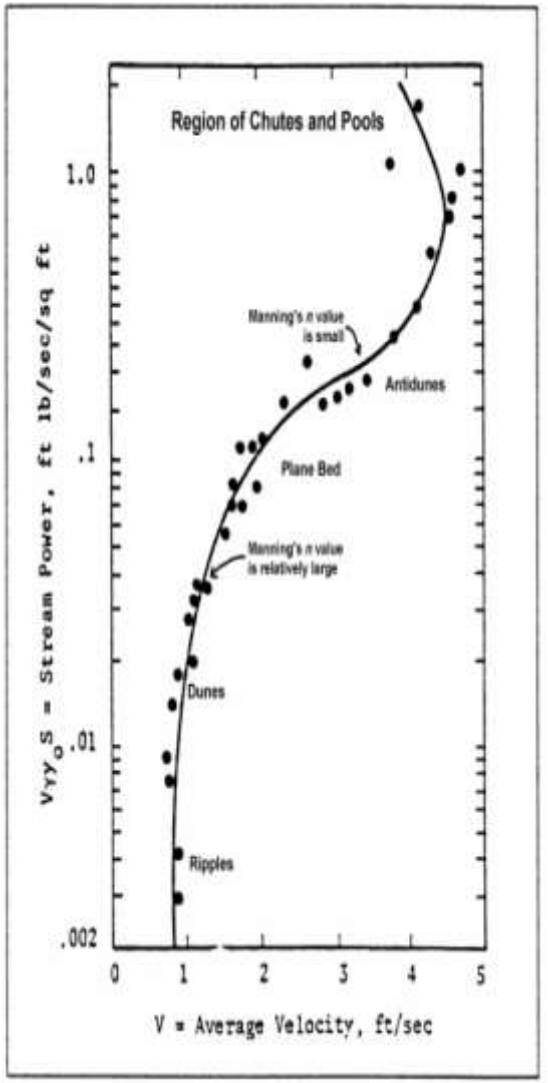
Bed Forms/Bed Configuration

The bed configurations that commonly form in sand-bed channels are plane bed without sediment movement, ripples, ripples on dunes, dunes, plane bed with sediment movement, and antidunes.

These bed configurations are listed in the order of occurrence with increasing values of stream power *(VρghS)* for bed materials having d_{50} less than 0.6 mm. For *bed materials coarser than 0.6 mm, dunes form instead of ripples* after beginning of motion at Small values of stream power.

A relation between stream power, velocity, and bed configuration is shown in figure.

The bed configurations and their associated flow phenomena are described in the order of their occurrence with increasing stream power.



Dunes in Brahmaputra/Jamuna



Ripples



Bed forms with increasing velocity

1. Plane bed with no motion of sediment particles
2. Ripples and dunes
3. Transition, and
4. Antidunes

1. Plane bed with no motion of sediment particles:

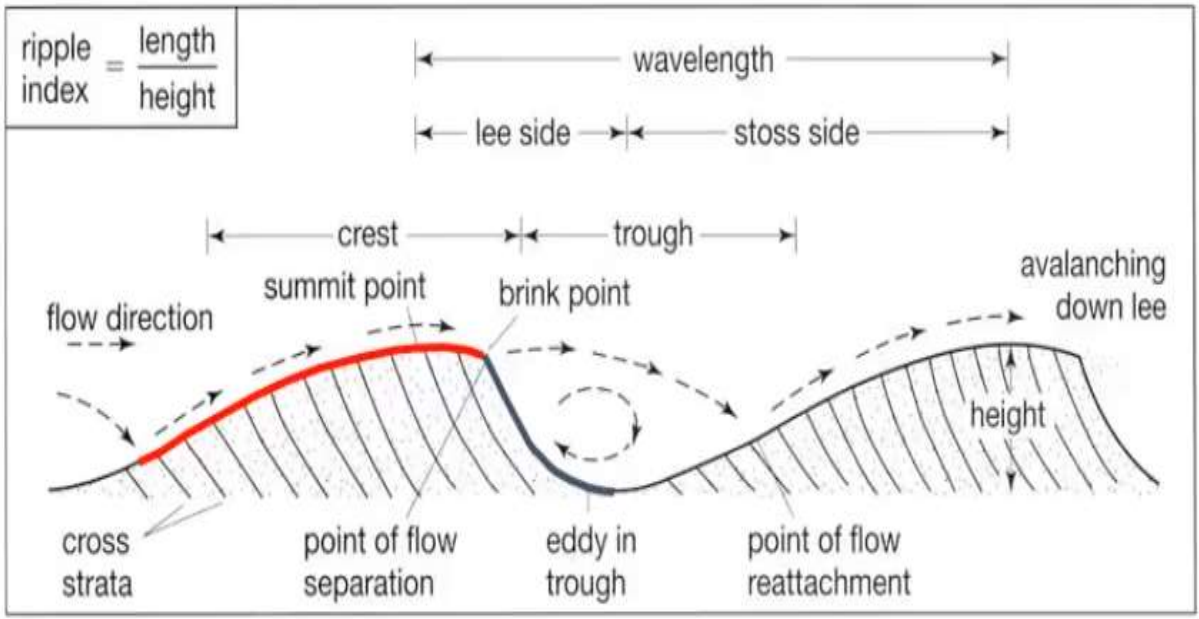
When the sediment and flow characteristics are such that the average shear stress on the bed is less than the critical shear stress, the sediment particle on the bed does not move. The water surface remains fairly smooth if the Froude number is low. Resistance offered to the flow is small and on account of the grain roughness only, and the Manning's equation can be used for prediction of the mean velocity of flow. Values of Manning's n range from 0.012 to 0.014 depending on the size of the bed material.

2. Ripples and Dunes

The sediment particles on the bed start moving when the average shear stress of the flow exceeds the critical shear stress. This results in small triangular undulations as the channel bed and is known as ripples. The

Ripples are the smallest bedform, typically a few cm tall and 10-20 cm wavelength



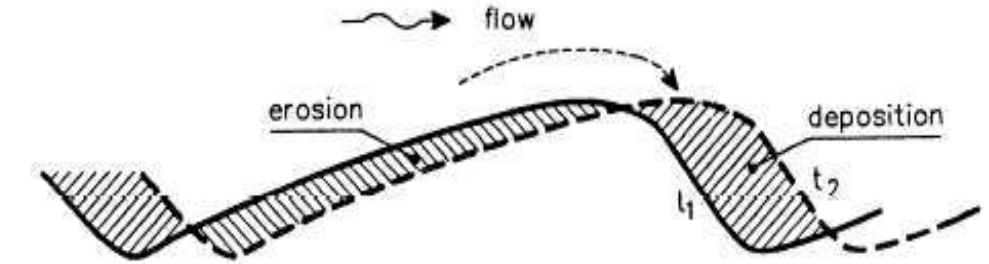


Erosion Deposition

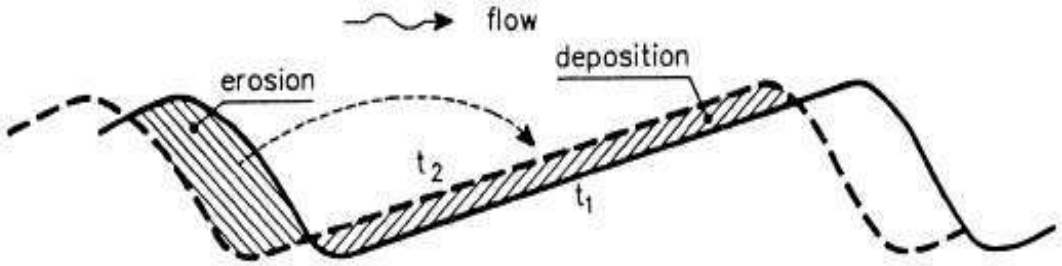
Ripples are formed at relatively weak flow intensity and are linked with fine materials, with d_{50} less than 0.7 mm. The size of ripples is mainly controlled by grain size. By observations the typical height and length of ripples are:

$$H \approx 100\, d_{50} \quad \text{and} \quad L \approx 1000\, d_{50}$$

At low flow intensity the ripples have a fairly regular form with an upstream slope 6° and downstream slope 32°. Ripple profiles are approximately triangular, with long gentle upstream slopes and short, steep downstream slopes.



DUNES IN LOWER REGIME



ANTI–DUNES IN UPPER REGIME

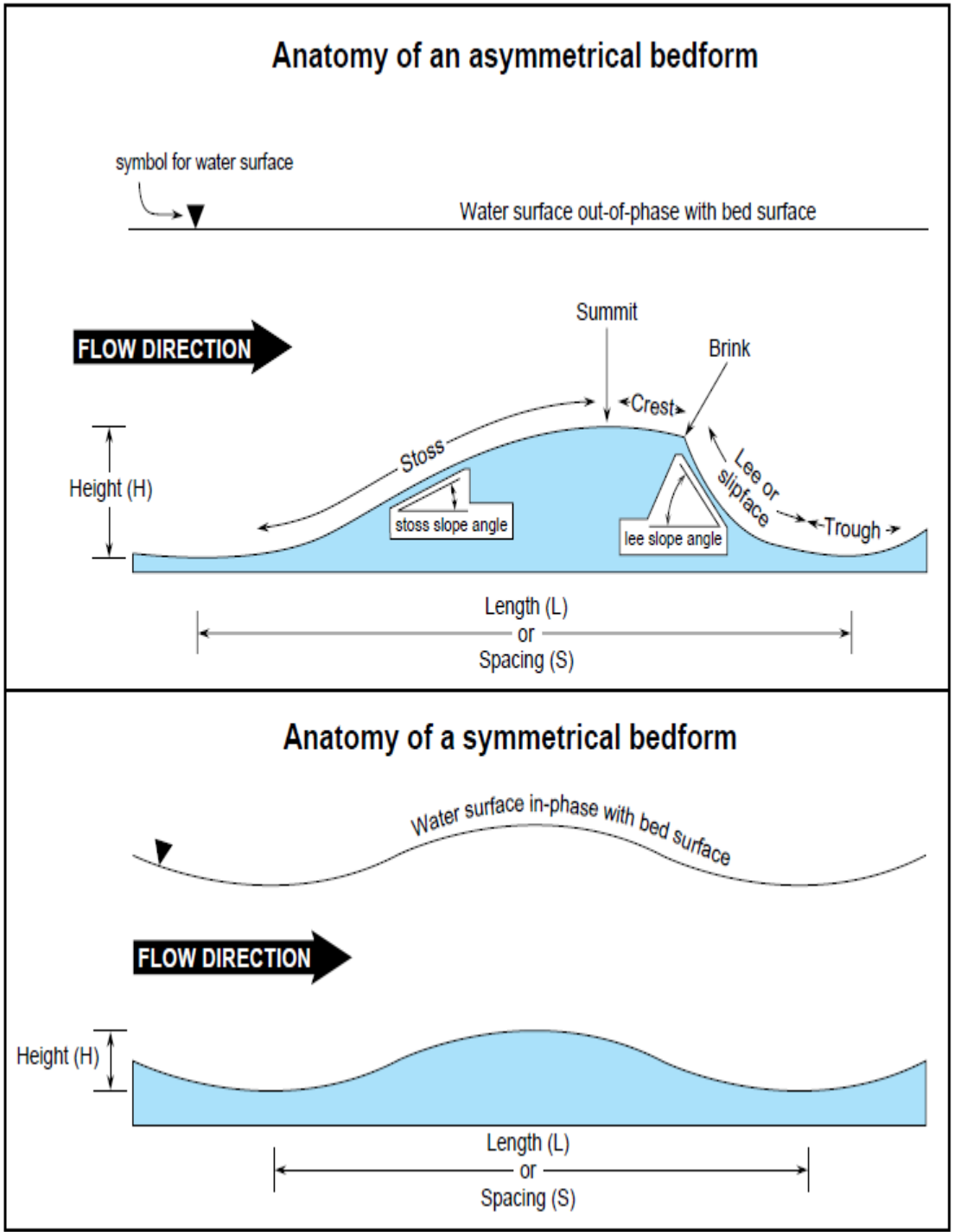
The distance between the successive crests of the ripples is usually less than 0.4m and the height from the crest to the trough is usually less than 0.04m. The sediment movement is confined in the region near the channel bed.
The ripples move in downstream direction at a slow speed.
Resistance to flow is large (with Manning's n ranging from 0.018 to 0.030) , and the bed-material discharge concentration is small, ranging from 10 to 200 ppm.

Dunes

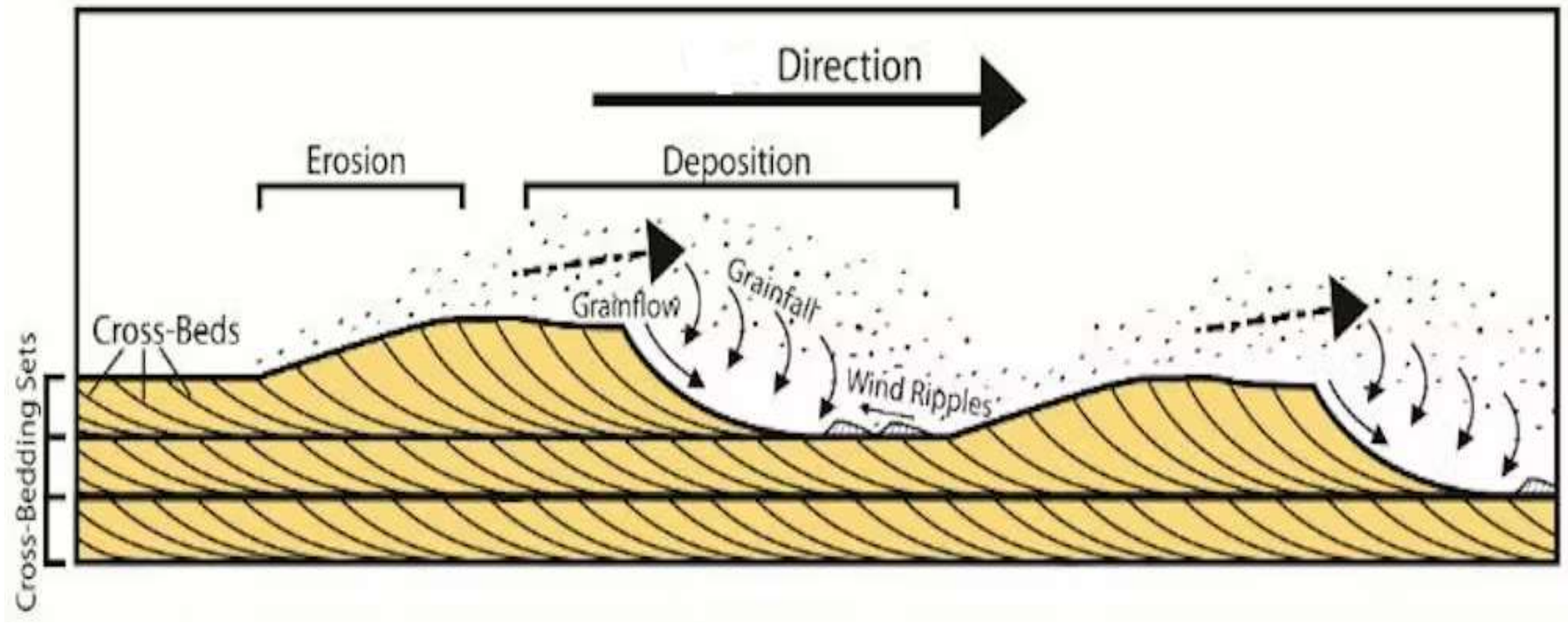
With increase in discharge, and consequently the average bed shear stress, the ripples grow in sizes which are then termed as dunes.

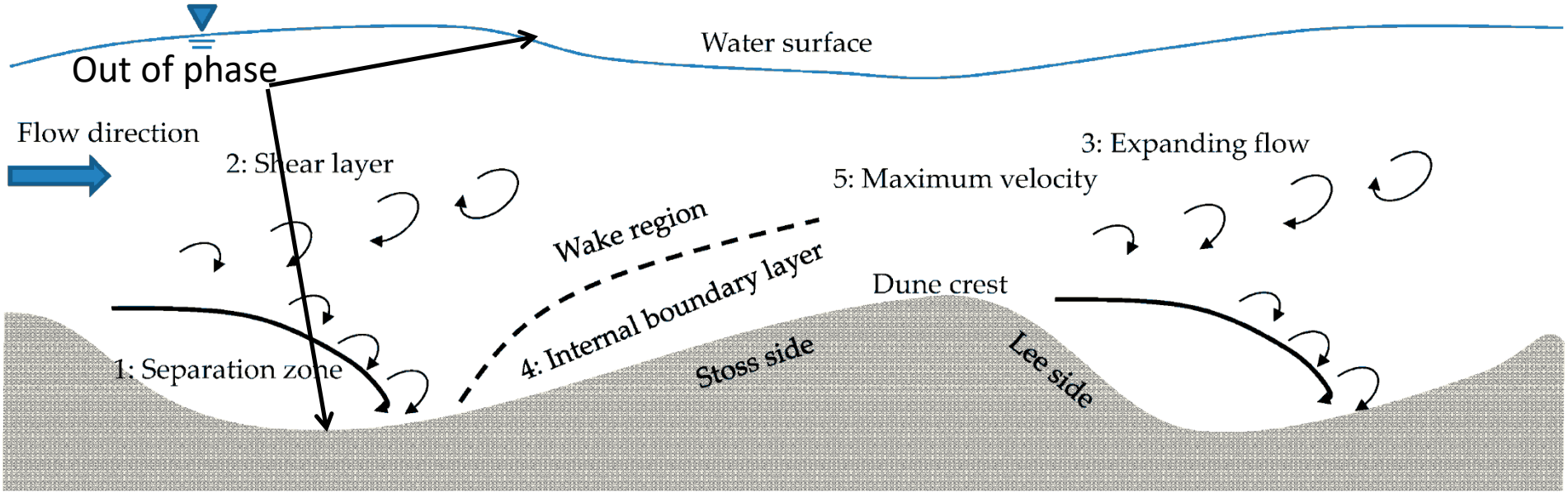
At smaller shear-stress values, the dunes have ripples superposed on their backs. These ripples disappear at larger shear values, particularly if the bed material is coarse sand.
Resistance to flow caused by dunes is large, but not as large as that caused by ripples formed of finer sand and at shallow depth. Manning's n ranges from 0.020 to 0.040.

Dunes are also triangular in shape but are larger than ripples. The triangular sections are not symmetric and the upstream face is inclined at about 10 to 20 degrees and downstream face at an angle of about 30 to 40 degrees with the horizontal.


Anatomy of an asymmetrical bedform
symbol for water surface
Water surface out-of-phase with bed surface
FLOW DIRECTION
Summit
Brink
Crest
Stoss
Lee or slipface
Trough
Height (H)
stoss slope angle
lee slope angle
Length (L)
or
Spacing (S)
Anatomy of a symmetrical bedform
Water surface in-phase with bed surface
FLOW DIRECTION
Height (H)
Length (L)
or
Spacing (S)

Section of a dune

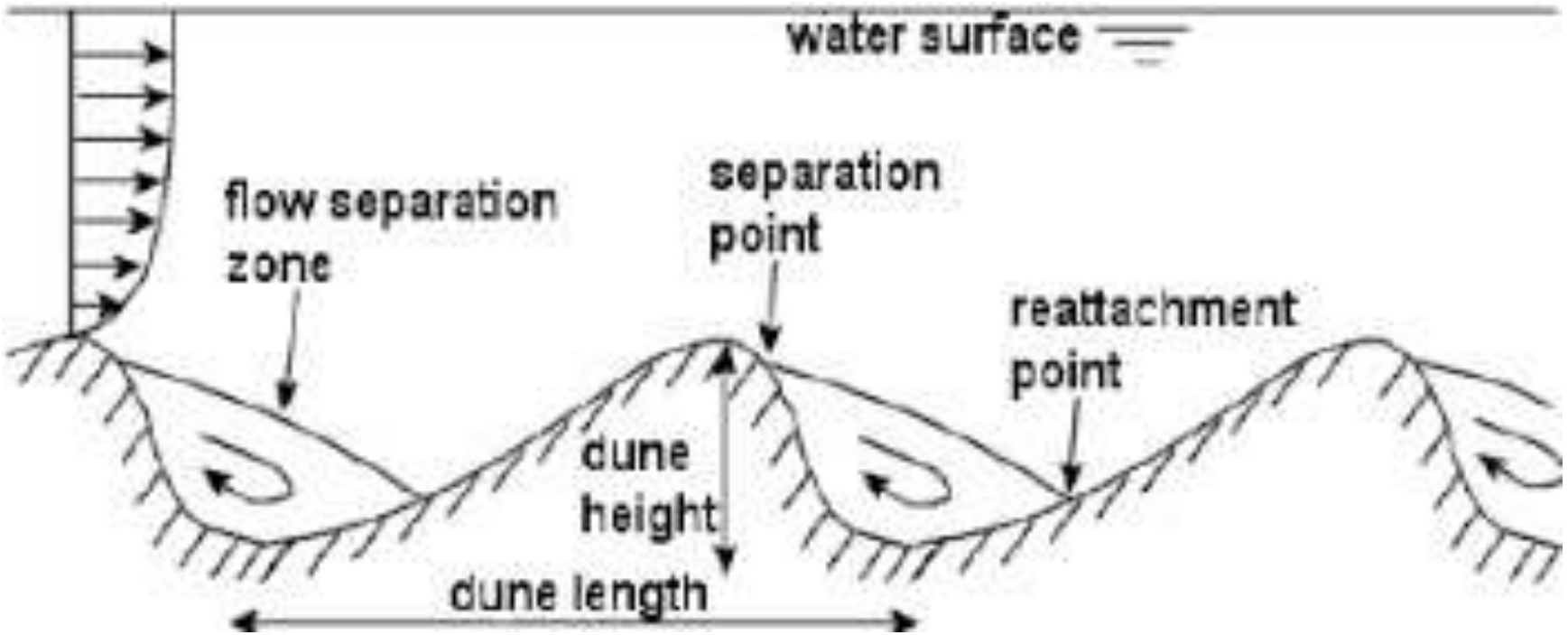




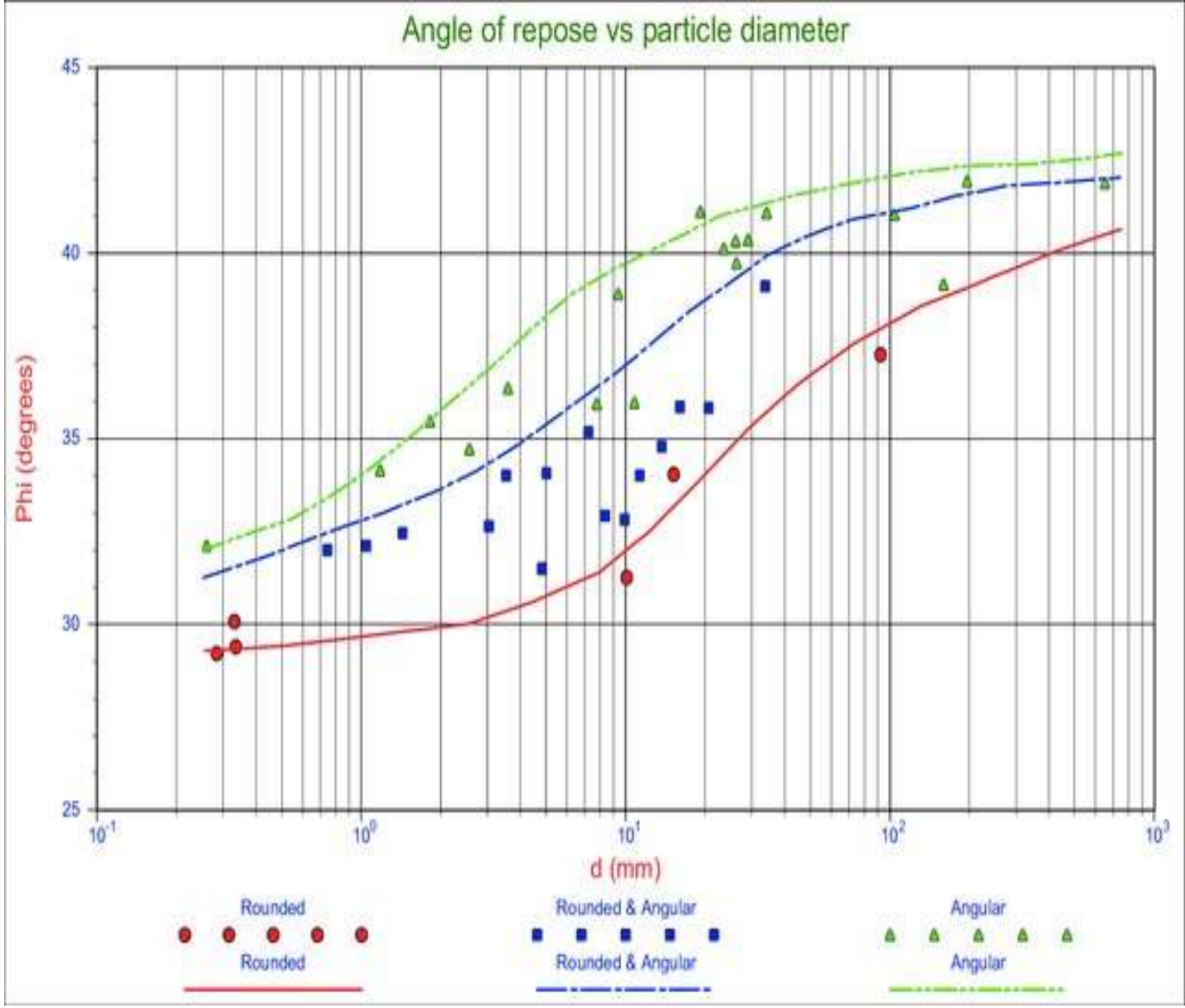
Impact of Eddies

These turbulent eddies are significant for several reasons:

- **Sediment Transport:** The strong ejections and localized upwellings caused by the eddies are highly effective at lifting and transporting sediment from the bed, moving it from high-shear regions to the separated-flow areas, which is fundamental to dune formation and migration.
- **Channel Roughness:** The presence and characteristics of these eddy systems significantly increase the hydraulic roughness of the river channel, which affects flow velocity, water levels, and flood management.



Soil Type	Dry	Moist	Wet
Top Soil; Loose	35 - 40		45
Loam; Loose	40 - 45		20 - 25
Peat; Loose	15	45	
Clay/Silt; Solid		40 - 50	
Clay/Silt; Firm		17-19	
Clay/Silt; Loose		20 - 25	
Puddle Clay			15-19
Silt		19	
Sandy Clay		15	
Sand; Compact		35 - 40	
Sand; Loose	30 - 35		25
Sandy Gravel; Compact		40 - 45	
Sandy Gravel; Loose		35 - 45	
Sandy Gravel; Natural		25 - 30	
Gravel; Medium Coarse	25 - 30		25 - 30
Shingle; Loose		40	
Shale; Hard		19 - 22	
Broken Rock	35		45



Angle of repose is related to the density, surface area and shapes of the particles, and the coefficient of friction of the material.

In large rivers, dunes may be quite long and also the height (vertical distance between the crest and troughs) may be great. For example, the dunes found in Lower Mississippi river have been found to be about 12 m height on an average and length of the order of few hundred meters.

These bed forms are not static, which means that they gradually move downstream with time, of course at a very slow and creeping velocity much less than the velocity of flow.

Dunes are formed with Froude number much less than unity – the flow condition is subcritical.

3. Transition

With further increase in discharge over the dune bed, the ripples and dunes are washed away, and only some very small undulations are left. In some cases, the bed may become nearly flat but the sediment particles remain in motion.
With slight increase in discharge, the bed and water surfaces attain a shape of sinusoidal wave form, which are called standing waves.

These waves form and disappear and their size doesn't increase much.
Thus, in transition regime, rapid changes in bed and water configuration occur with relatively small changes in flow conditions – from washed out dunes to flat or plane bed and then to symmetric sand waves.

The resistance to flow for flow over a plane bed results largely from grain roughness and Manning's n for plane-bed, sand channels ranges from 0.010 to 0.013.

The Froude number is relatively high but the flow conditions are sub-critical. This regime is extremely unstable.

4. Antidunes

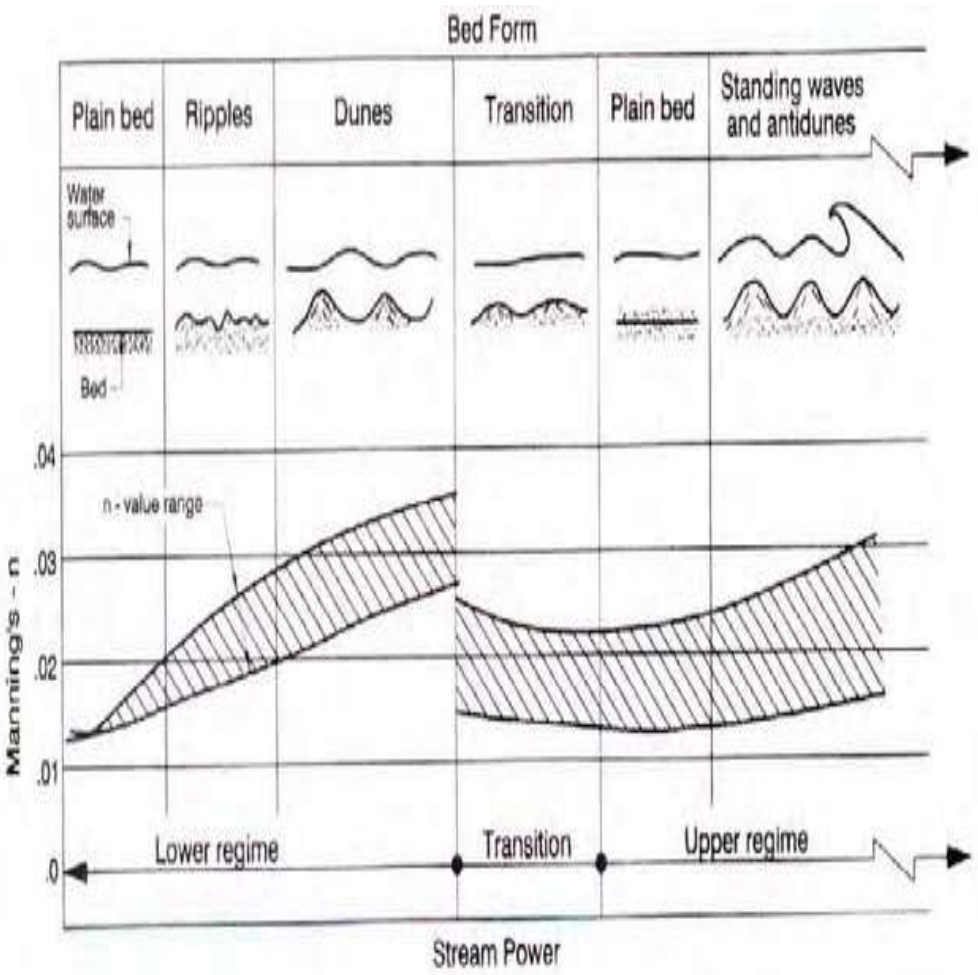
When the discharge is increased further and the Froude number increases to more than one, indicating super critical flow, the standing waves, which are symmetrical sand and water waves in the phase, move slowly upstream and break intermittently.

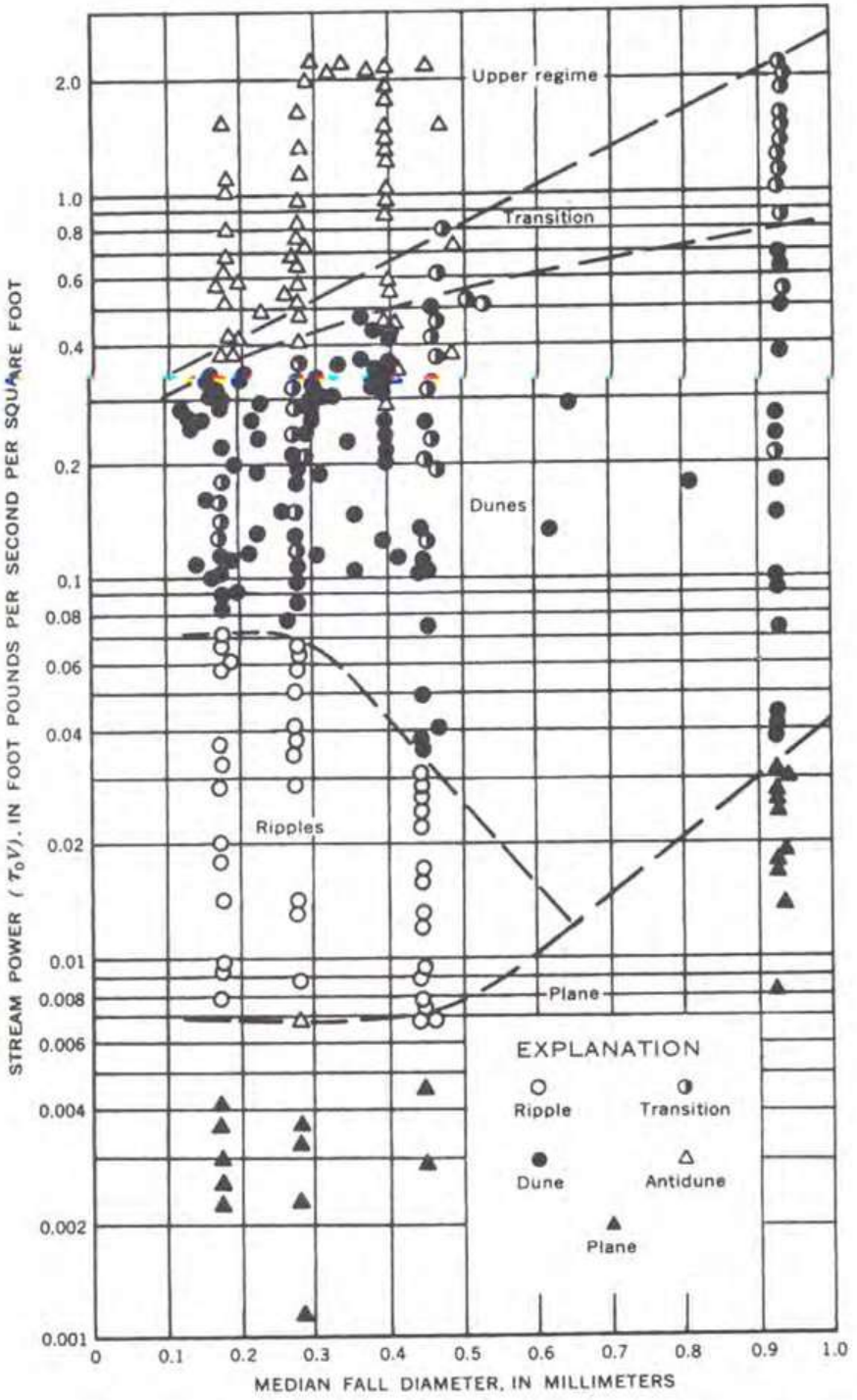
These are called antidunes because the movement of the direction of dunes is backwards compared to the direction of flow.

Since supercritical flow is rare in case of natural streams and channels, this type of bed forms do not occur generally in nature.

If the antidunes do not break, resistance to flow is about the same as for a plane bed. With breaking waves, Manning's n may range from 0.012 to 0.020.

The sediment discharge for antidunes is high and may vary from 5000 to 40,000 ppm.


Bed Form
Plain bed
Ripples
Dunes
Transition
Plain bed
Standing waves and antidunes
Water surface
Bed
n - value range
Manning's - n
.04
.03
.02
.01
.0
Lower regime
Transition
Upper regime
Stream Power


Upper regime
Transition
Dunes
Ripples
Plane
STREAM POWER ($\tau_0 V$), IN FOOT POUNDS PER SECOND PER SQUARE FOOT
2.0
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
MEDIAN FALL DIAMETER, IN MILLIMETERS
EXPLANATION
Ripple
Transition
Dune
Antidune
Plane

Variations of different variables with different regime of flow and form roughness.

Flow Regime	Forms of Bed	Sediment Load (ppm)	Manning's n	Froude Number
Lower Flow Regime	Plane	0	0.016	0.17
	Ripple	1 to 150	0.02 to 0.027	0.17 to 0.37
	Dunes	159 to 800	0.021 to 0.026	0.32 to 0.44
Upper Flow Regime	Plane	1000 to 3000	0.013 to 0.017	0.55 to 0.92
	Antidune	5000 to 42,000	0.014 to 0.022	1.0 to 1.3

Resistance to flow in alluvial rivers

Open channels with movable beds and boundaries are commonly encountered in water resources engineering.

In these cases, a resistance formula (Manning's and Chezy) can not be applied directly for the computation of velocity, slope, or depth, once a roughness coefficient has been determined. Although this concept is also used for natural channels but strictly speaking, for these kinds of channels, the resistance coefficient will change under different flow and sediment conditions.

Extensive studies have been made by different researchers for determination of roughness coefficients of alluvial beds. Their results differ from each other.

The resistance equation expresses relationship among the mean velocity of flow V, the hydraulic radius R, the water surface slope and characteristics of the channel boundary.

In case of alluvial channels, where the bed is composed of mobile material, like sand, so long as average bed shear stress on the boundary of the channel is less than the critical shear, τ_c the channel boundary can be considered rigid and any of the resistance equations valid for rigid boundary channels would yield results for alluvial channels too.

However, as soon as sediment movement starts, undulations appear on the bed, thereby increasing the boundary resistance. Besides, some energy is required to move the grains. Further, the sediment particles in suspension also affect the resistance of alluvial streams.

It is therefore, obvious that the problem of resistance in alluvial channels is very complex and the complexity further increases if one includes the effect of channel shape, non-uniformity of sediment size, discharge variation, and other factors on channel resistance.
The methods for computing resistance in alluvial channels can be:

The total resistance is separated into the resistance given by the grains of sand forming the channel bed and the resistance of the undulations in the bed.
The flow resistance is dominated by form drag whenever there are bed forms on the river bed. Thus, in this method, the total resistance is studied as a combination of grain resistance and form resistance.

Thus, the roughness of a moveable bed alluvial river consists of:

1. Roughness of the bed material called **grain roughness**
2. Roughness from the shape of the bed forms called **form roughness**

If Ks is the sum of the roughness corresponding to grain and form resistance, then: $K_s = K_{s1} + K_{s2}$
in which: K_{s1} = grain roughness and K_{s2} = form roughness

Van Rijn developed equations for Ks1 and Ks2 as:

$K_{s1} = 3\ d_{90}$ and

K_{s2} is related to the height of undulation (h) and the length of the dunes (L) as given by the formula

$K_{s2} = 1.1\ h\ (1\text{-}e^{-2gh/l})$

In determining the overall alluvial resistance it is important to distinguish between the roughness associated with the sediment grains (grain roughness) and the roughness associated with bed forms (form roughness).

Grain roughness:

This is the roughness associated with the sediment grains. The grain roughness related resistance results from the skin friction exerted by the flow on individual sediment particle.

In case of plane bed, the skin friction force acts on the entire length of the bed. While for a bed form it acts of the luff side only.

The usual measure is the d_{90} size of the bed sediments and the Colebrook-White effective roughness height is approximately 3 times d_{90} The grain roughness in gravel rivers is normally large as a result of the size of the bed material, while bed features are normally low.

The result is that the form roughness for gravel beds is normally smaller than the grain roughness and so the roughness is dominated by the grain roughness.

Form roughness:

It is the roughness associated with the flow as it passes over the bed forms.

This form of roughness results from the pressure difference over the bed form.

The flow is accelerated over the luff side while it is decelerated on the lee side of the bed form.

As a result the pressure on the luff side is smaller that that of the lee side resulting in force acting against the flow.

The shape of the bed forms vary in size and are dependent upon the nature of the sediment and the ambient flow conditions and hence the magnitude of the form roughness also varies.

Overall alluvial resistance comprises a combination of grain and form resistance with form resistance predominating in most practical situations.

Roughness based on Overall Flow Parameters

For regime channels (average cross-section does not change considerably with time – no substantial erosion or deposition), Lacey developed a silt factor which is related to Manning's n as:

$$f = 1.76 \sqrt{d_{50}} \quad \text{and}$$

$$n = 0.022 f^{0.2}$$

Deposition/Settling/Fall/Terminal Velocity of Particles

Sphericity

Ratio of the surface area of a particle P and the surface area of a sphere of the same volume as P.

Thus,

Sphericity = As/Ap

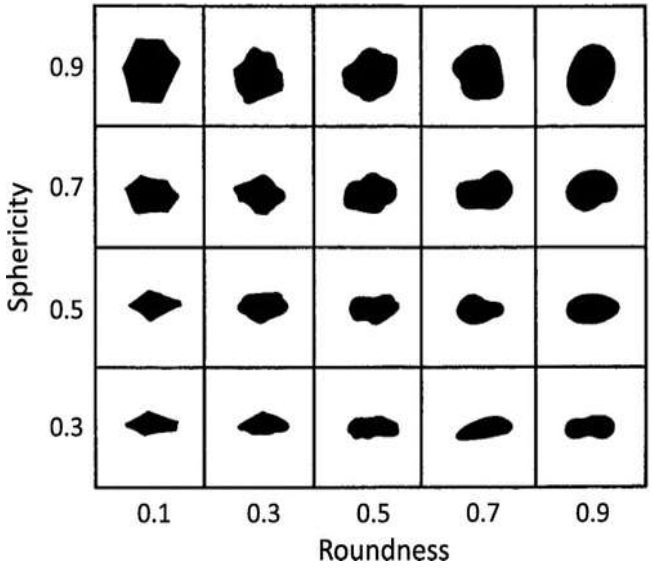
where, Ap is the surface area of a test particle P, and As is the surface area of a sphere S with the same volume as P.

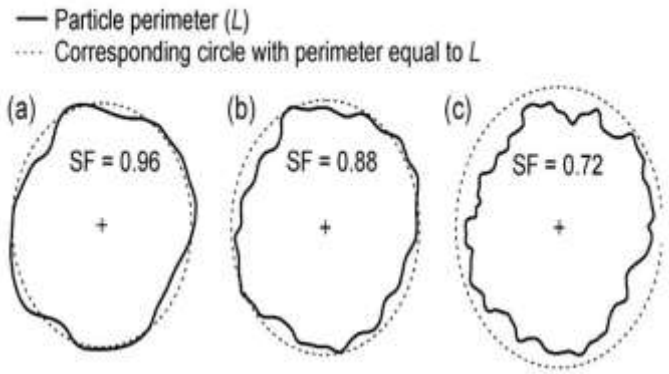
Shape Factor

Shape factor of a particle is defined by the ratio of the axes as:

Shape factor = $c / \sqrt{ab}$

where a is the major axis of the particle, b is the intermediate and c is the minor axes.





size class	diameter range (mm)	microns
gravel	2.00 +	
v. coarse sand	1.0 - 2.0	
coarse sand	0.5 - 1.0	
medium sand	0.25 - 0.5	250 - 500
fine sand	0.125 - 0.25	125 - 250
v. fine sand	0.0625 - 0.125	63 - 125
coarse silt	0.031 - 0.0625	31 - 63
silt	0.0039 - 0.031	3.9 - 31
clay	< 0.0039	

Type	D (mm)	Notes
Clay	< 0.002	Usually cohesive
Silt	0.002 ~ 0.0625	Cohesive ~ non-cohesive
Sand	0.0625 ~ 2	Non-cohesive
Gravel	2 ~ 64	“
Cobbles	64 ~ 256	“
Boulders	> 256	“

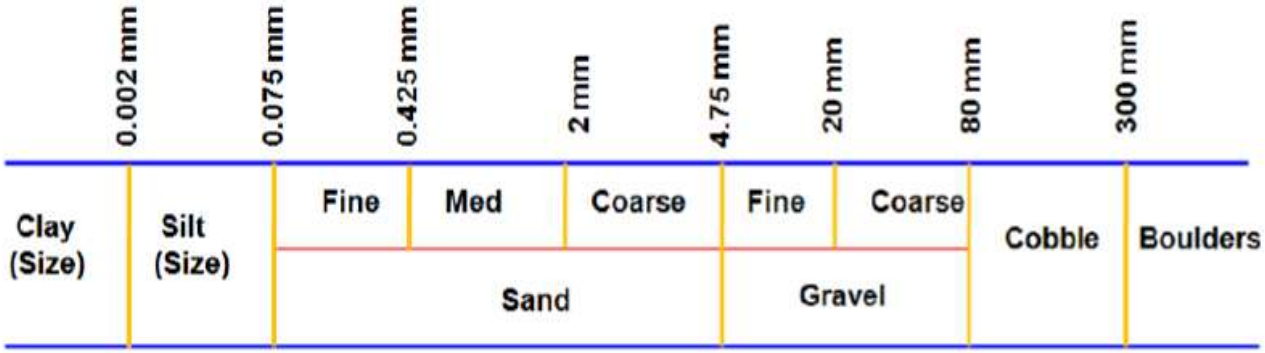


Fig. 2: Indian Standard Soil Classification scale

Deposition/Settling/Fall/Terminal Velocity of Particles

Fall velocity in still water is influenced by two sets of forces:
1. submerged weight of particle
2. viscous fluid resistance and inertia effects

Small and big particles behave differently. For small particles, viscous resistance dominates; inertia is negligible. But for large particles that fall quickly, inertial forces dominate.

Speed at which particle settles depends on:

Particle properties: d, ρ_s, shape

Fluid properties: ρ_f, μ, Re

Conditions under which of these effects dominates can be discerned using a particle Reynolds number (N_{Re}):

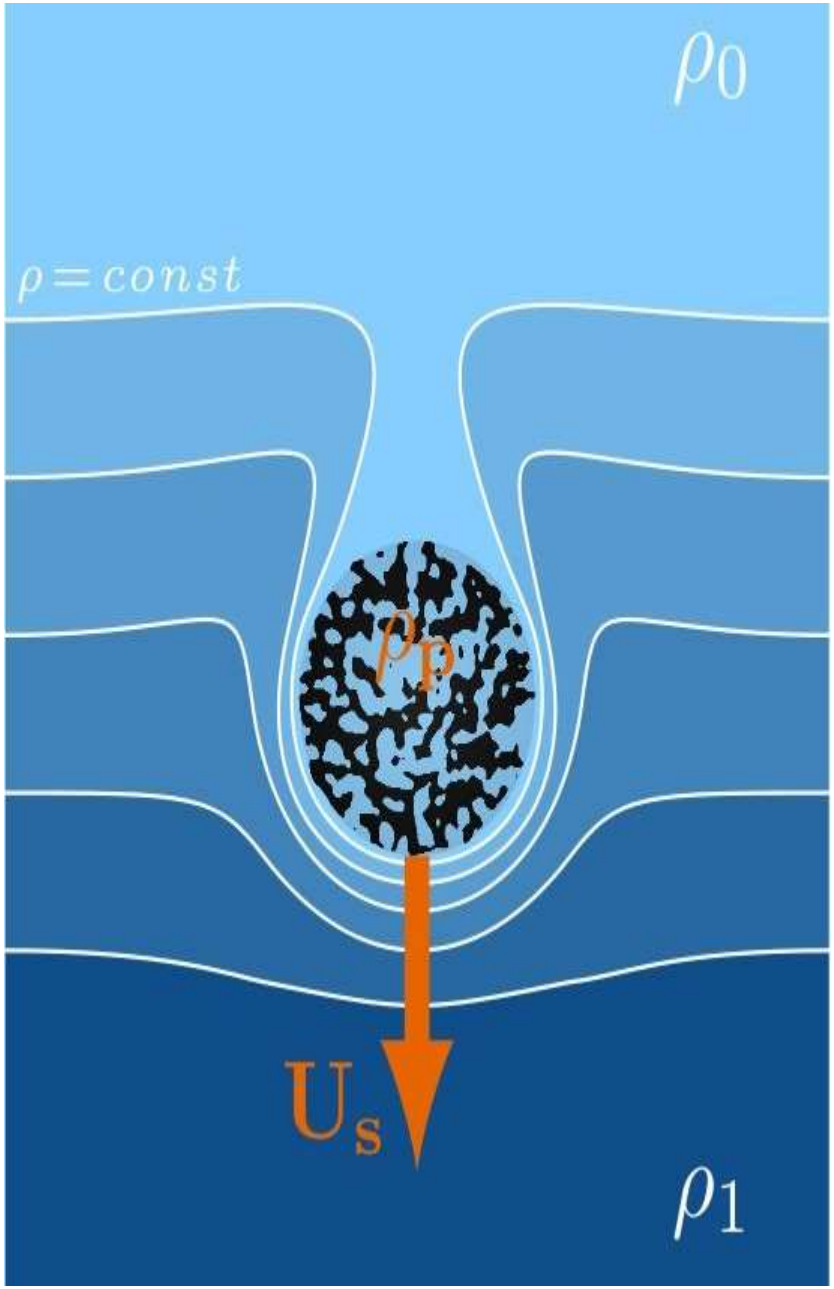
$$N_{Re} = \omega\, d / v$$

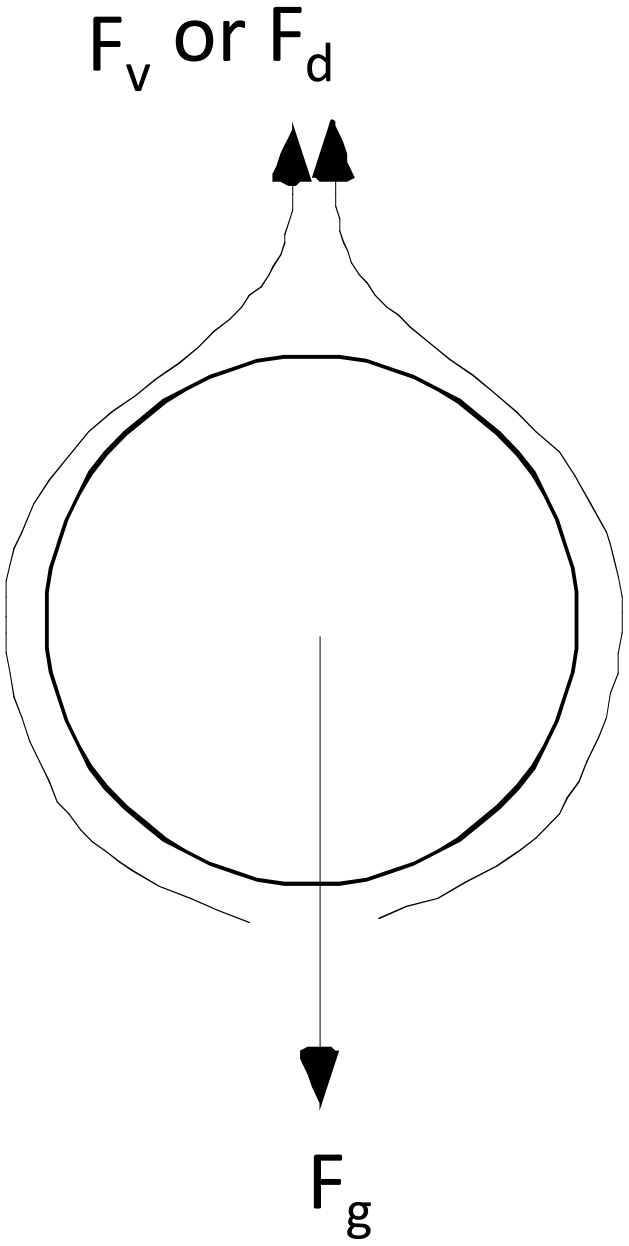
where ω is the fall velocity, d is the particle diameter, and v is the kinematic viscosity of water.

Based on experiments, inertia is negligible where:

$N_{Re} < 1$: *the boundary layer around the particle is laminar*, and the fall is smooth (silt and clay).

For $N_{Re} > 1000$, *the viscous force is negligible, the boundary layer around the particle is turbulent* (sand and larger particles).


ρ_0
$\rho = const$
ρ_p
U_s
ρ_1


F_v or F_d
F_g

Deposition/Settling/Fall Velocity of Particles

A. Forces due to weight of particle and viscous resistance

Stokes (1851) considered the problem of the balance between the downward force due to the suubmerged weight of a particle and a viscous resistance force.

Submerged weight of a spherical particle:

$$Fg = (\pi/6)d^3(\rho s - \rho)\, g$$

Viscous resistance = f (surface area, dynamic viscosity, and fall velocity)

$$Fv = 6\pi r\, \mu\, \omega = 3\pi d\, \mu\, \omega$$ (considering a sphere with radius r)

where μ = dynamic viscosity and ω = fall velocity.

Assuming no acceleration of a falling particle (i.e., constant terminal velocity, ω) then Fg = Fv

$$(\pi/6)\, d^3\, (\rho s - \rho)\, g = 3\, \pi\, d\, \mu\, \omega$$

Rearranging in terms of the fall velocity yields:

$$\omega = (1/18)\, d^2\, (\rho s - \rho)\, g / \mu \quad \ldots\ldots\ldots\ldots (1)$$

Hence the <u>fall velocity of small particles (i.e. with no inertial effects) is proportional to the square of the diameter</u>.

Hence the fall velocity of small particles (i.e. with no inertial effects) is proportional to the square of the diameter.

Note also that the settling velocity depends upon the viscosity of the fluid (inversely related) — colder temperatures can make particles settle slower, thereby allowing smaller upward velocity fluctuations to keep them suspended above the stream bed for longer duration.

Limits of Stokes Settling Equation

1. Assumes smooth, small, spherical particles - rough particles settle more slowly - sphericity/shape factor
2. Flocculation - joining of small particles (especially clays) as a result of chemical and/or biological processes - bigger diameter increases settling rate
3. **Assumes laminar settling (ignores turbulence)**
4. Settling velocity for larger particles determined by considering inertial force.

Deposition/Settling/Fall Velocity of Particles

B. Forces due to weight of particle and inertial resistance

Particles larger than about 0.2 mm (i.e., sand and larger particles) encounter resistance from the "impact" force given by the momentum per unit time of the cylindrical column of water whose cross-section area is the projected area of the falling grain.

The impact force is given by:

$$Fd = C_D A_c \rho \left(\frac{\omega^2}{2} \right) \qquad A_c = \left(\frac{\pi}{4} \right) d^2$$

Where Fd is the force due to inertia, C_D is the drag coefficient and Ac is the projected area.

The force balance between the submerged weight of this falling particle and the impact force is given by equating Fd = Fg and the terminal settling/falling velocity:

$$(\pi/6)d^3(\rho s - \rho)\, g = C_D\, (\pi/4)d^2\, \rho\, \omega^2 / 2$$

Rearranging terms yields:

$$\omega = \sqrt{\frac{4g}{3C_D} \left(\frac{\rho_s - \rho}{\rho} \right) d} \qquad C_D = \frac{24}{N_{\mathrm{Re}}} + \frac{3}{\sqrt{N_{\mathrm{Re}}}} + 0.34$$

C_D (drag coefficient) depend on whether the flow regime around the particle is laminar or turbulent or function of N_{Re}

Deposition/Settling Velocity of Particles

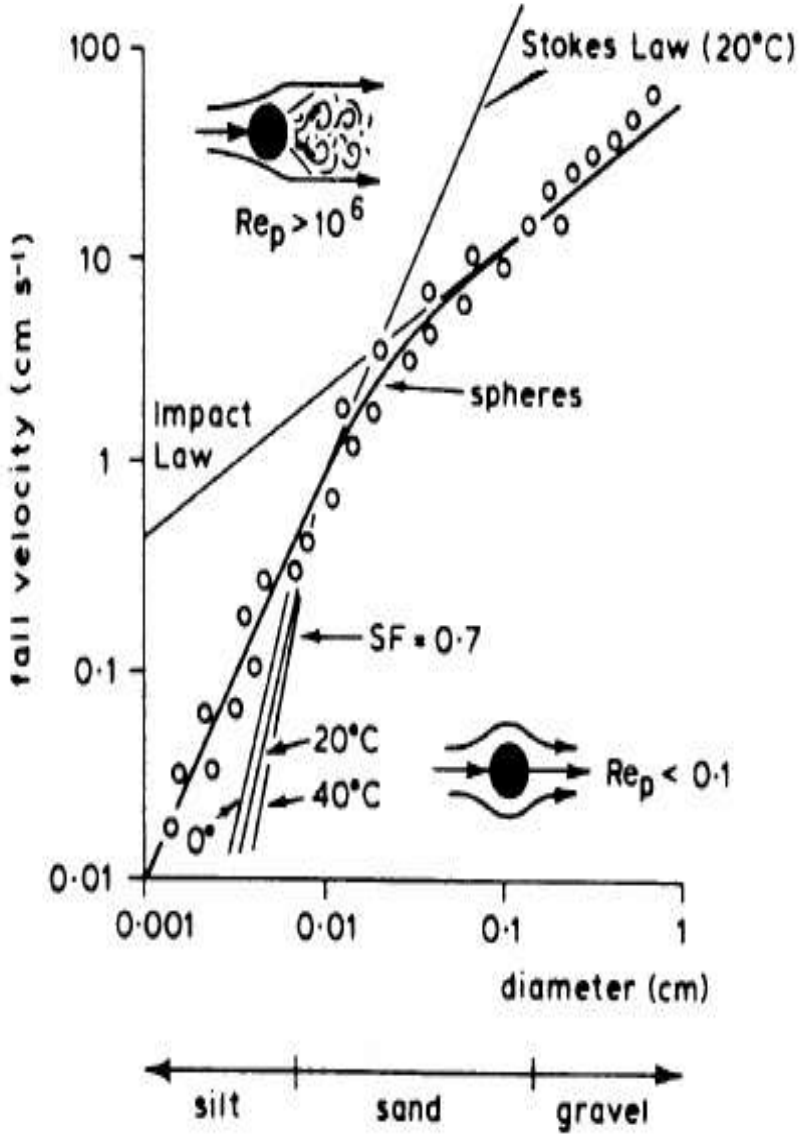
Hence, large grains fall at a rate proportional to the square root of their size, which leads to a strong size dependence to the fall velocity of large particles in stream flow.

$$N_{\mathrm{Re}} = \frac{\omega d \rho}{\mu} = \frac{\omega d}{\nu}$$

For non-spherical particles, formula for Reynold number and settling velocity calculation are modified using the shape factor (ϕ) [1]:

$$\mathrm{Re} = \phi \frac{\rho_f u_t D_p}{\mu_f} \qquad (3.7.9)$$

$$u_t = \sqrt{\frac{4}{3} \frac{(\rho_p - \rho_f)}{\rho_f} \frac{g D_p}{\phi C_D}} \qquad (3.7.10)$$



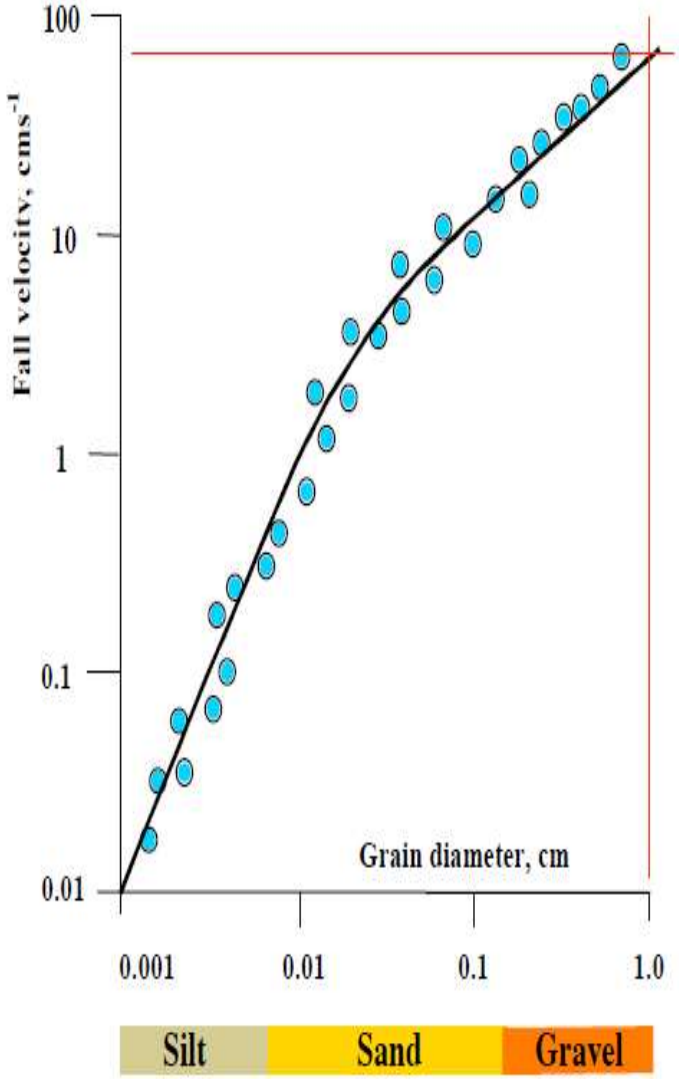


Figure 4.2: Fall velocity in relation to diameter of a spherical grain of quartz

$$C_D = \frac{24}{N_{\mathrm{Re}}} + \frac{3}{\sqrt{N_{\mathrm{Re}}}} + 0.34$$

- $N_{Re} < 1$: laminar flow; $C_D = 24/N_{Re}$

$$\omega = \frac{g}{18\mu}\left(\rho_s - \rho\right)d^2$$

Stokes equation

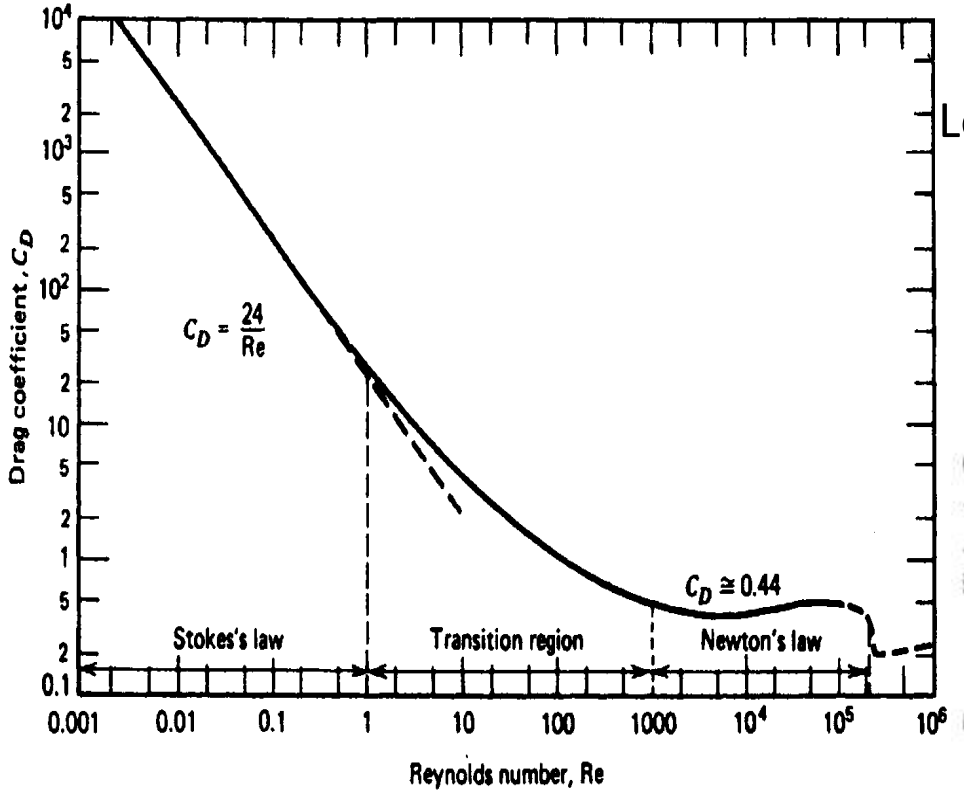
- $1 < N_{Re} < 10^3$: transition flow;

$$C_D = \frac{24}{N_{\mathrm{Re}}} + \frac{3}{\sqrt{N_{\mathrm{Re}}}} + 0.34$$

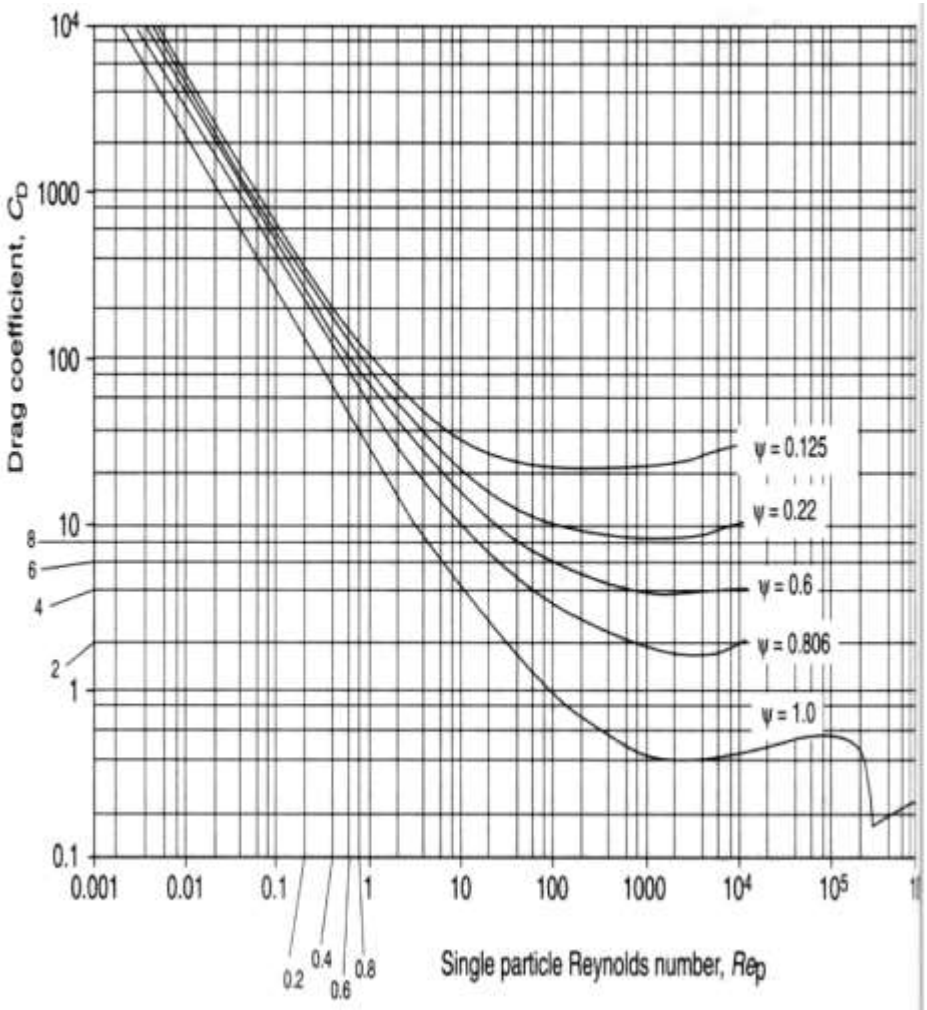
- $N_{Re} > 10^3$: turbulent flow; $C_D = 0.44$

$$\omega = \sqrt{\frac{4g}{3C_D}\left(\frac{\rho_s - \rho}{\rho}\right)d} \quad ; \quad \omega = \sqrt{\frac{4g}{3C_D}\left(S_s - 1\right)d}$$

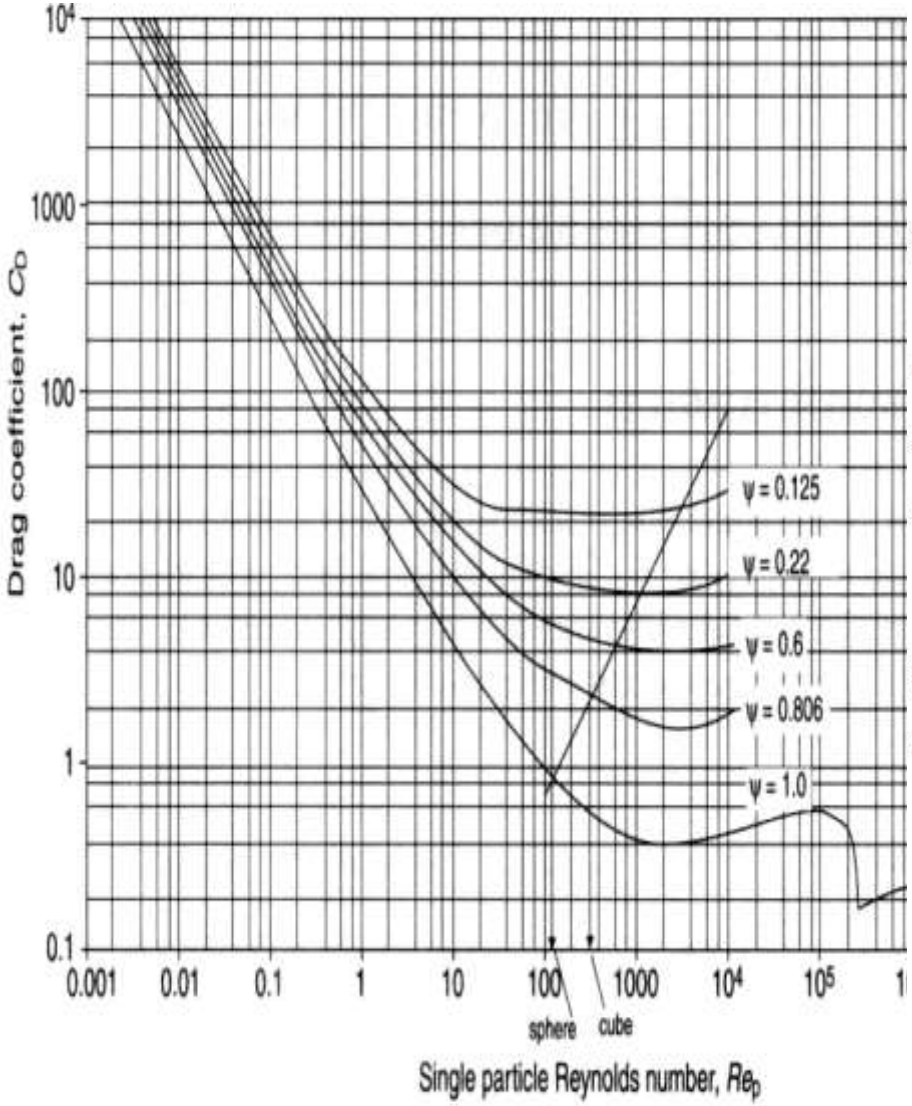
Deposition/Settling Velocity of Particles



Low sphericity increases the resistance and hence the C_D



Drag coefficient C_D versus Reynolds number Re_P for particles of sphericity ranging from 0.125 to 1.0



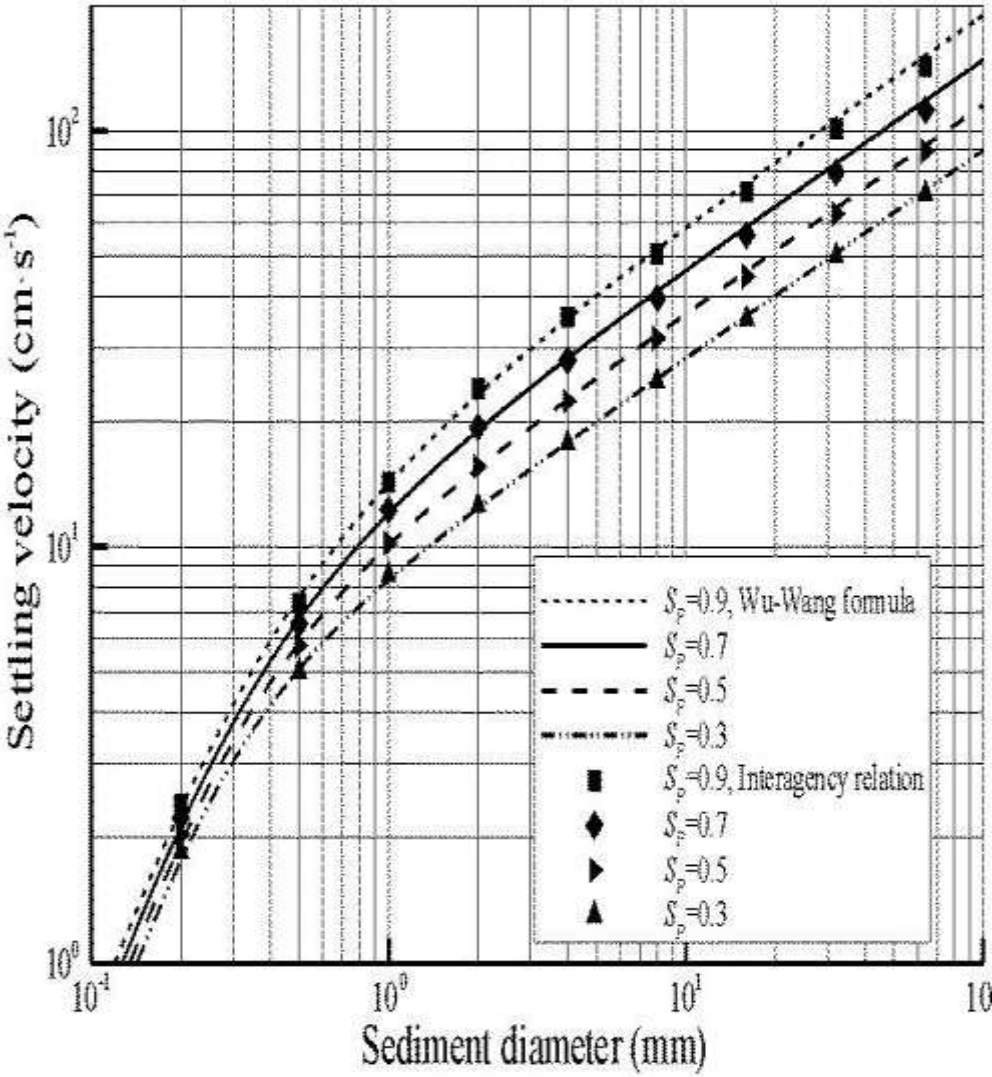
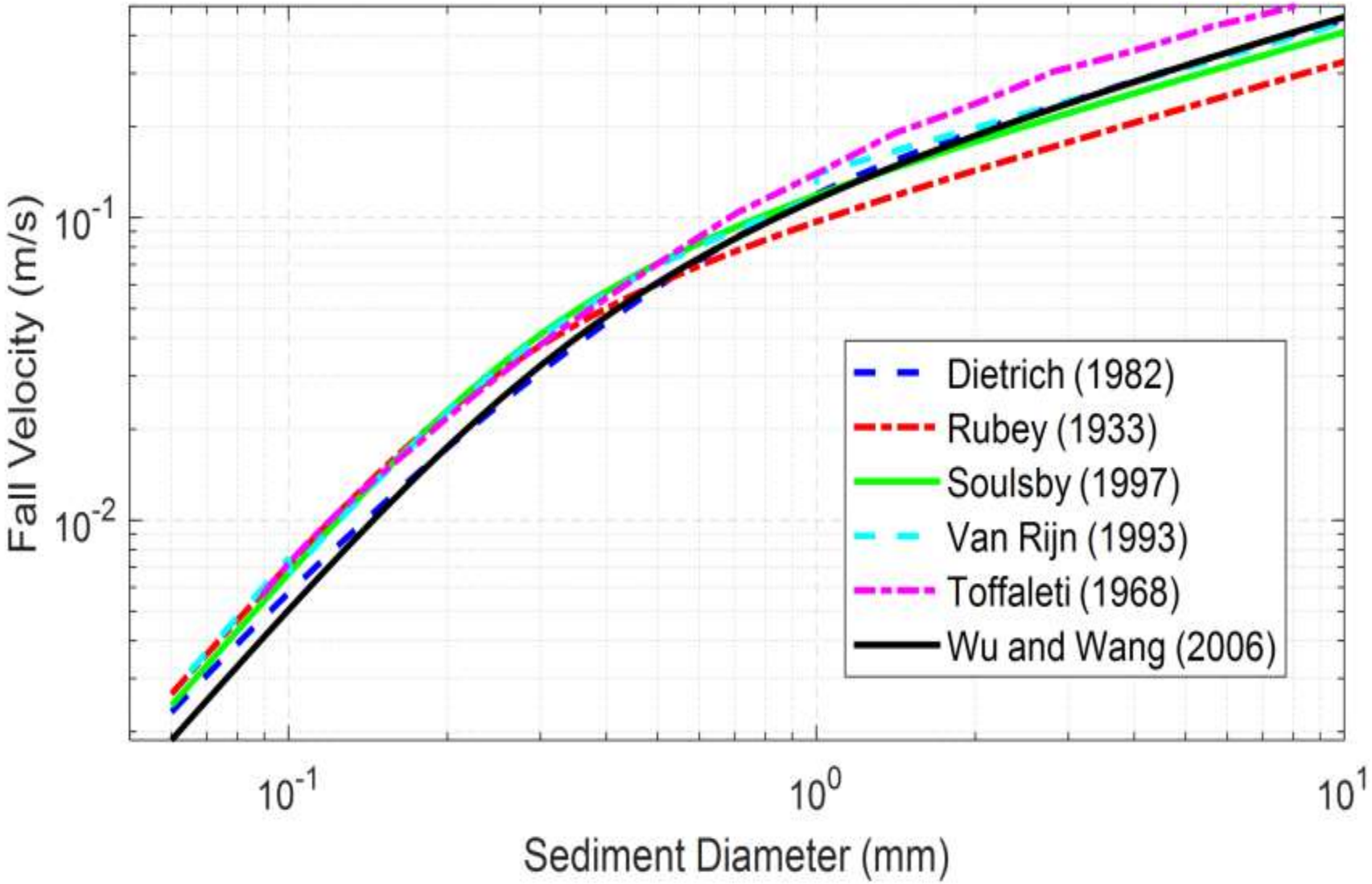


Figure 2W5.1 Drag coefficient C_D versus Reynolds number Re_p.

Sediment particle fall velocity by formulas (assuming a water temperature is 13ºC, shape factor of 0.7, specific gravity of 2.65



Settling Velocities of different sizes of sediment particles

How long to settle through 10 m of water column

	Size (D)	ω (Stokes)	Time(S)
Very coarse sand	1 mm	64 cm/s	16 sec
Fine to very fine sand	0.1 mm	0.64 cm/s	26 min
Silt	0.01 mm	0.0064 cm/s	43 hrs
Clay	0.001 mm	0.000064 cm/s	180 days

Problem 3.7.1: A sand particle has an average diameter of 1 mm and a shape factor of 0.90 and a specific gravity of 2.1, determine the terminal velocity of the particle settling in water at 20 °C (kinematic viscosity of water=1.003×10^{-6} m^2/s and specific gravity=1). Drag coefficient can be computed using the following equation:

$$C_D=\frac{24}{Re}+\frac{3}{\sqrt{Re}}+0.34$$

$$\omega=\sqrt{\frac{4g}{3C_D}\left(\frac{\rho_s-\rho}{\rho}\right)d}$$

Solution: Kinematic viscosity$(\nu)=\mu_f/\rho_f=1.003\times10^{-6}$

$$\mu_f=1.003\times10^{-6}\times10^3=1.003\times10^{-3}\ kg/ms$$

Settling velocity using stokes law is:

$$u_t=\frac{g(\rho_p-\rho_f)D_P^2}{18\mu_f}=\frac{9.81\times\left((2.1\text{-}1)\times1000\right)\times\left(1\times10^{-3}\right)^2}{18\times1.003\times10^{-3}}=0.597\ m/sec$$

$$Re=\phi\frac{\rho_f u_t D_P}{\mu_f}=0.90\frac{10^3\times0.597\times\left(1\times10^{-3}\right)}{1.003\times10^{-3}}=536.32$$

Since Re>1, therefore, Newton's law should be used for finding terminal velocity in transition zone. For initial assumption of settling velocity, stoke's law is used. This initially assumed velocity is used to determine the Reynold number which is further used to find settling velocity. This iterative procedure is repeated till initial assumed velocity is approximately equal to settling velocity calculated from Newton's equation.

Initial drag coefficient is calculated as:

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34 = 0.5142$$

$$u_t = \sqrt{\frac{4}{3}\frac{(\rho_p - \rho_f)}{\rho_f}\frac{gD_p}{\phi C_D}} = 0.1763 \text{ m/s}$$

Now, iterative procedure is continued:

u_t (previous calculated)	Re	C_D	u_t	Difference
0.5977	536.3272	0.5143	0.1763	0.4214
0.1763	158.2037	0.7302	0.1480	0.0283
0.1480	132.7684	0.7811	0.1431	0.0049
0.1431	128.3690	0.7917	0.1421	0.0010
0.1421	127.5052	0.7939	0.1419	0.0002
0.1419	127.3315	0.7943	0.1419	0.0000

Final settling velocity=0.1419 m/s.