



İTÜ



Sediment Transportation

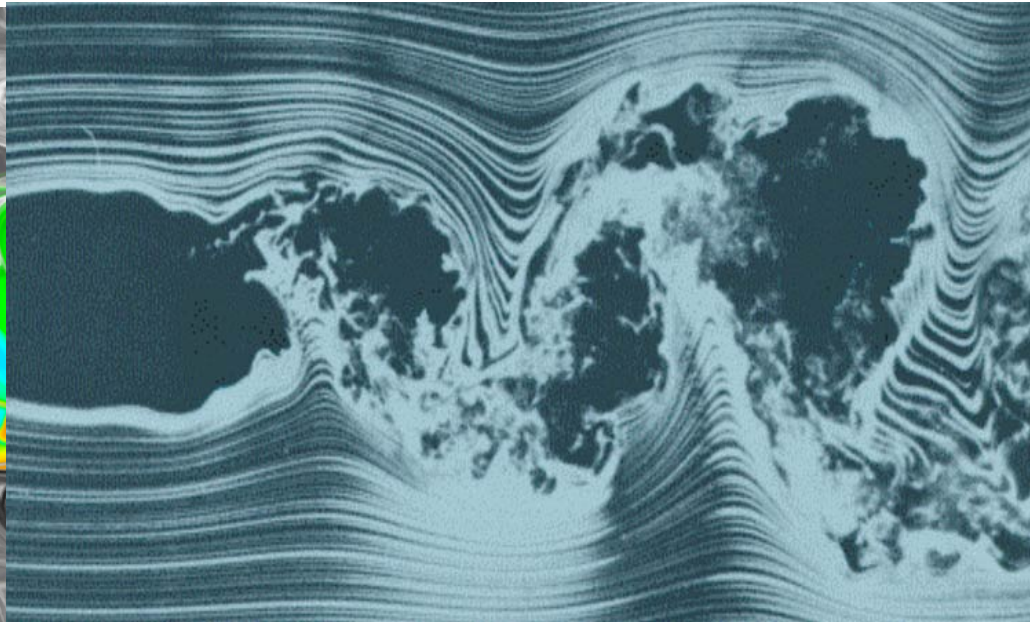
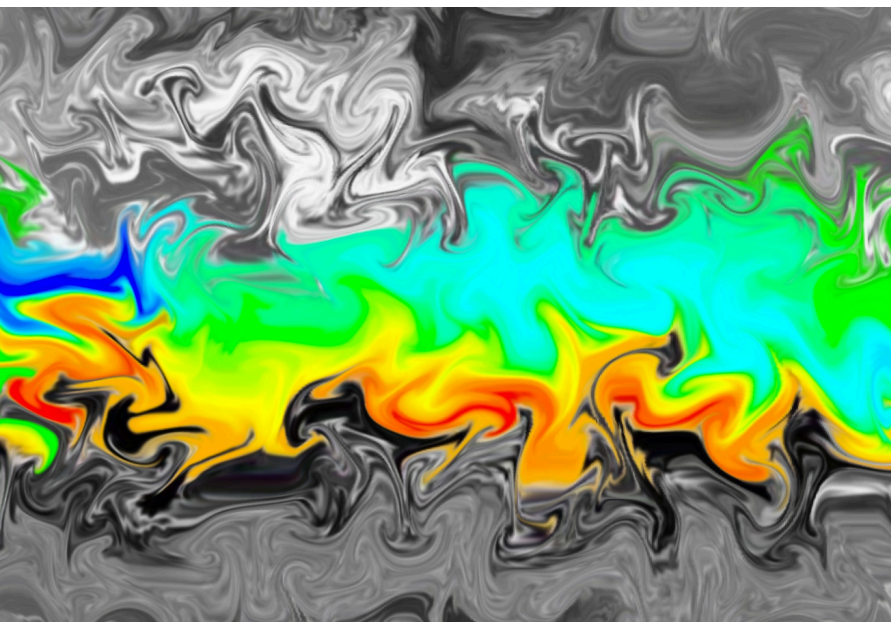
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Professor,

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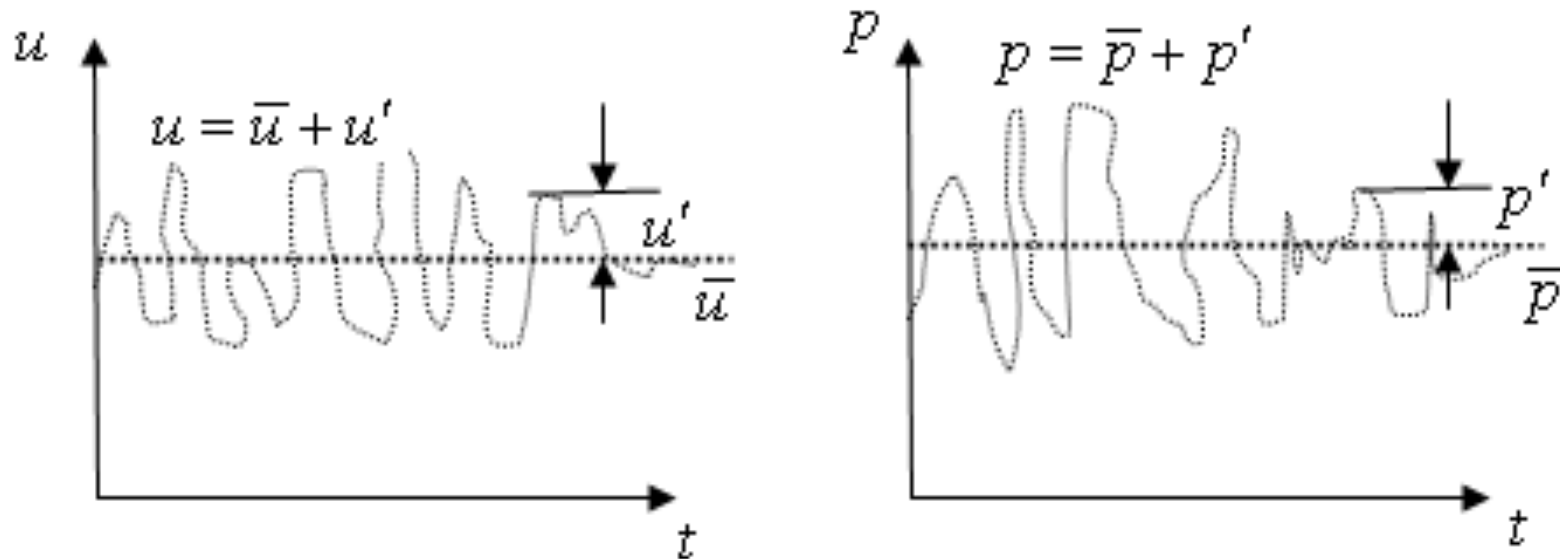
TURBULENCE

- The *turbulence* is strongly related to *sediment motion* Because turbulence induces the *interchange of eddies in the vertical direction*



TURBULENCE

Velocity and pressure fluctuations induced by turbulence near to bed river.



Mean and fluctuating turbulent velocity and pressure

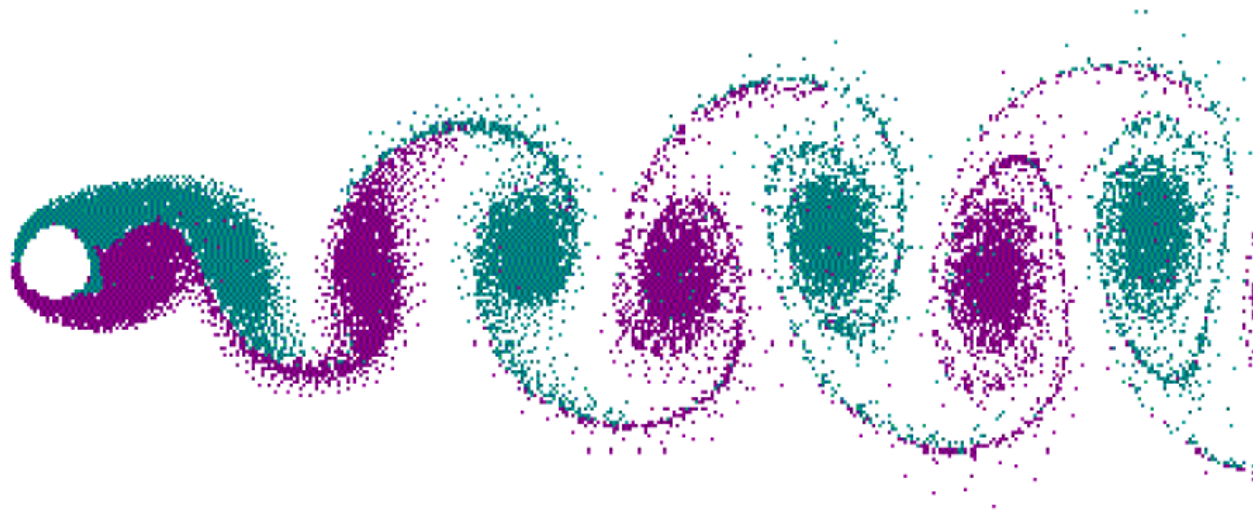
Velocity and pressure fluctuations are strongly related to incipient motion and bed motion

TURBULENCE

Turbulence in a sediment-laden flow affects the settling of the sediment particles in three ways

1.

Flow fluctuations causes the external forces on sediment particles to vary continuously



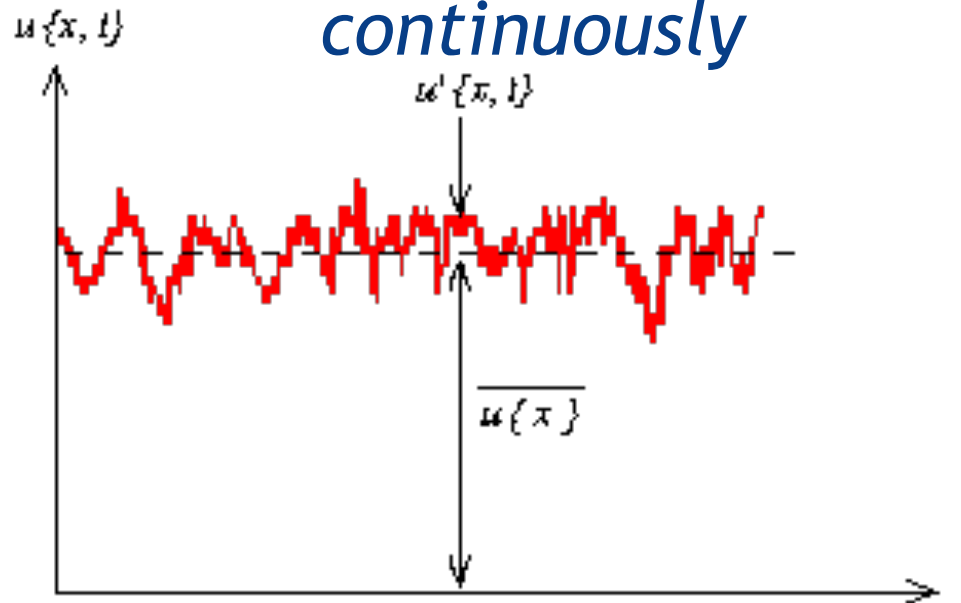
Because the eddies rotate, the particles rotate as they settle

They do not maintain a stable settling orientation. Actually, a sediment rotate as it settles even in

TURBULENCE

2.

The magnitude and the direction of flow vary continuously

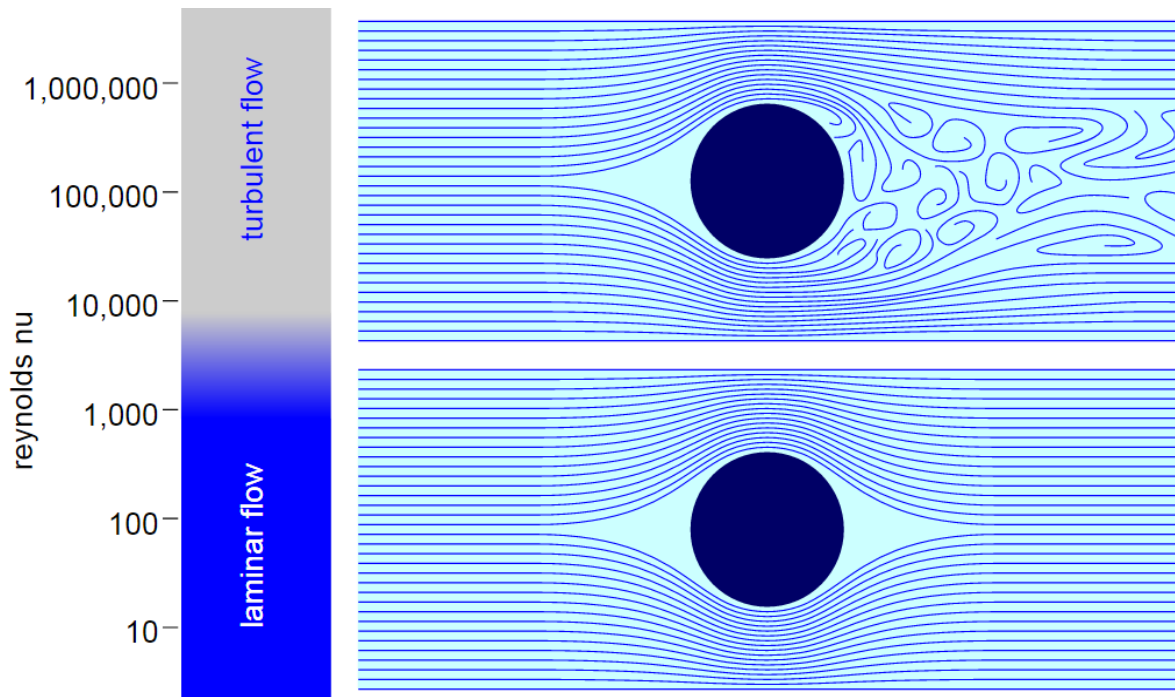


For this reason, a particle is sometimes accelerated and sometimes decelerated by the flow

So besides the usual drag force on a particle, an additional force due to acceleration or deceleration is present

TURBULENCE

The surface pressure distribution is effected by turbulence



As a result, the **drag on particle** can be either less or more than that for steady



Sediment (Alluvium): The formation of disintegrated particles caused by mechanical weathering

Sediment Transportation

The process of *erosion, transportation*
and accumulation of sediments



In all water-supply and power projects, the sediment should be removed from sediment-laden water







Properties of Sediment

For individual particles

- * Size*
- * Shape*
- * Fall velocity*
- * Mineral composition*
- * Surface texture*
- * Orientation*

Bulk Properties

- * particle size distribution*
- * specific weight*
- * porosity*
- * angle of repose*



granules



very coarse
sand



coarse
sand



medium
sand



silt & clay



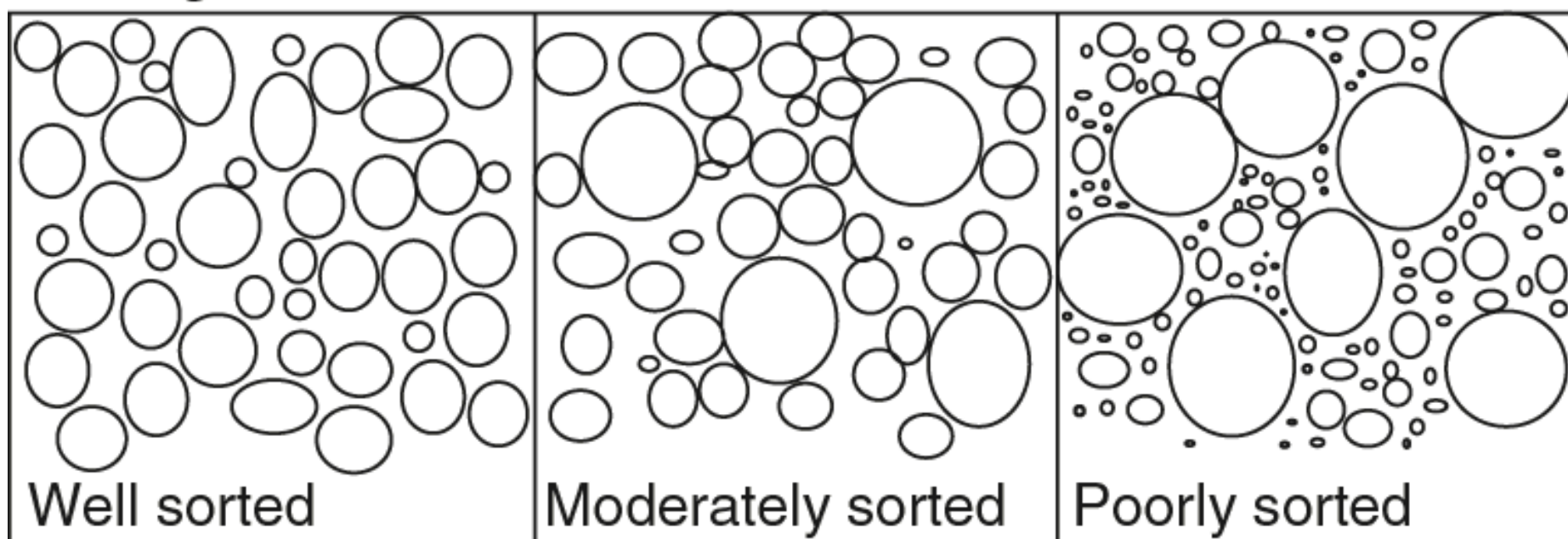
very
fine sand



fine sand

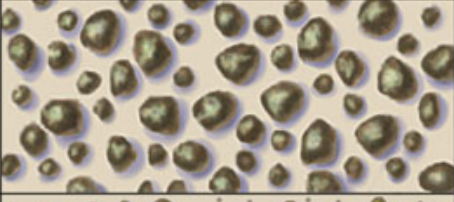
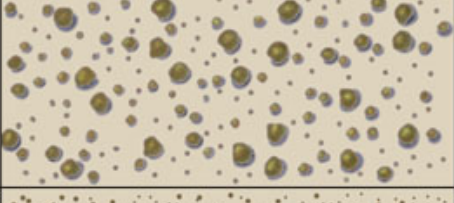
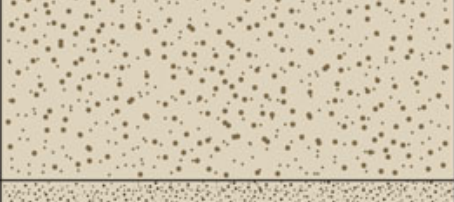


Sorting:



SEDIMENT COMES IN ALL SIZES

256 mm and up	BOULDERS	GRAVEL
64-256 mm	COBBLES	
2-64 mm	PEBBLES	
0.0625-2 mm	SAND	
0.002-0.0625 mm	SILT	
0.002 mm and smaller	CLAY	

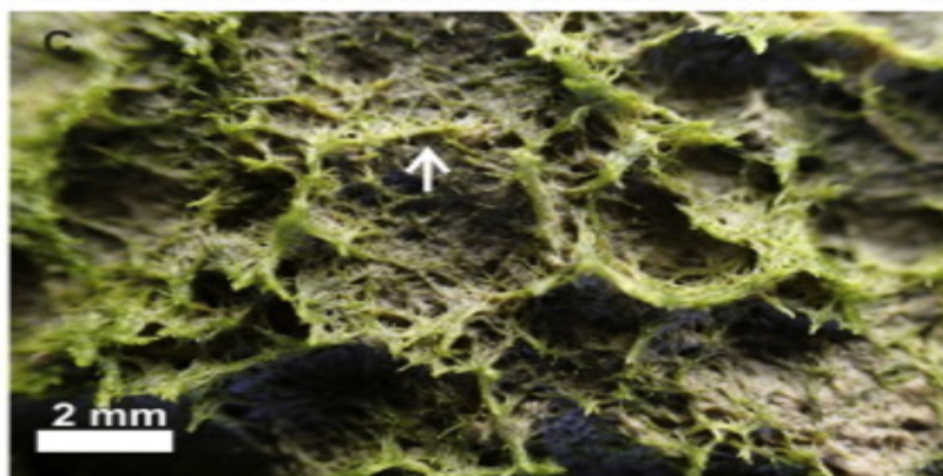
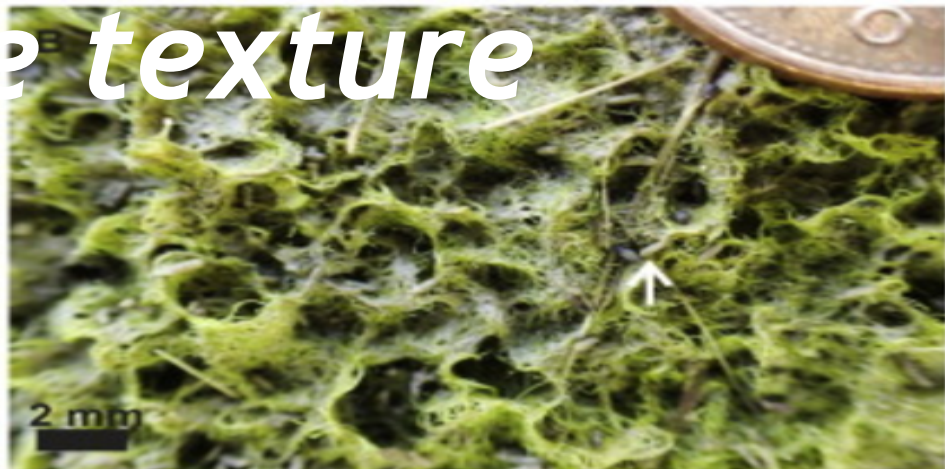
A. Grain size		
"Gravel" > 2mm	Pebbles 4–64 mm	
	Granules 2–4 mm	
	Coarse sand 0.5–2 mm	
	Medium sand 0.25–0.5 mm	
	Fine sand 0.06–0.25 mm	
	Silt 0.004–0.06 mm	
	Clay < 0.004 mm	

B. Rounding		
		
Angular	Sub-rounded	Well-rounded

C. Sorting	
	Poorly sorted
	Well-sorted

D. Grains and matrix	
	Grain Matrix

Surface texture



Minerals



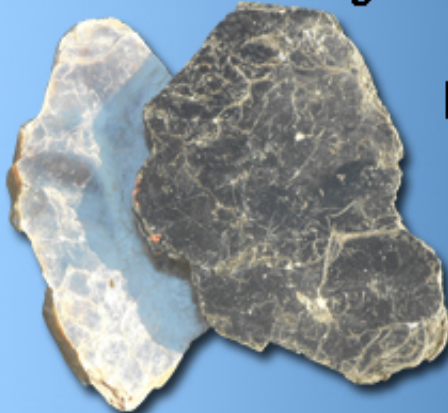
Quartz

Feldspars



Orthoclase and Plagioclase

Micas



Muscovite and Biotite

Rocks

Igneous



Granite

Sedimentary



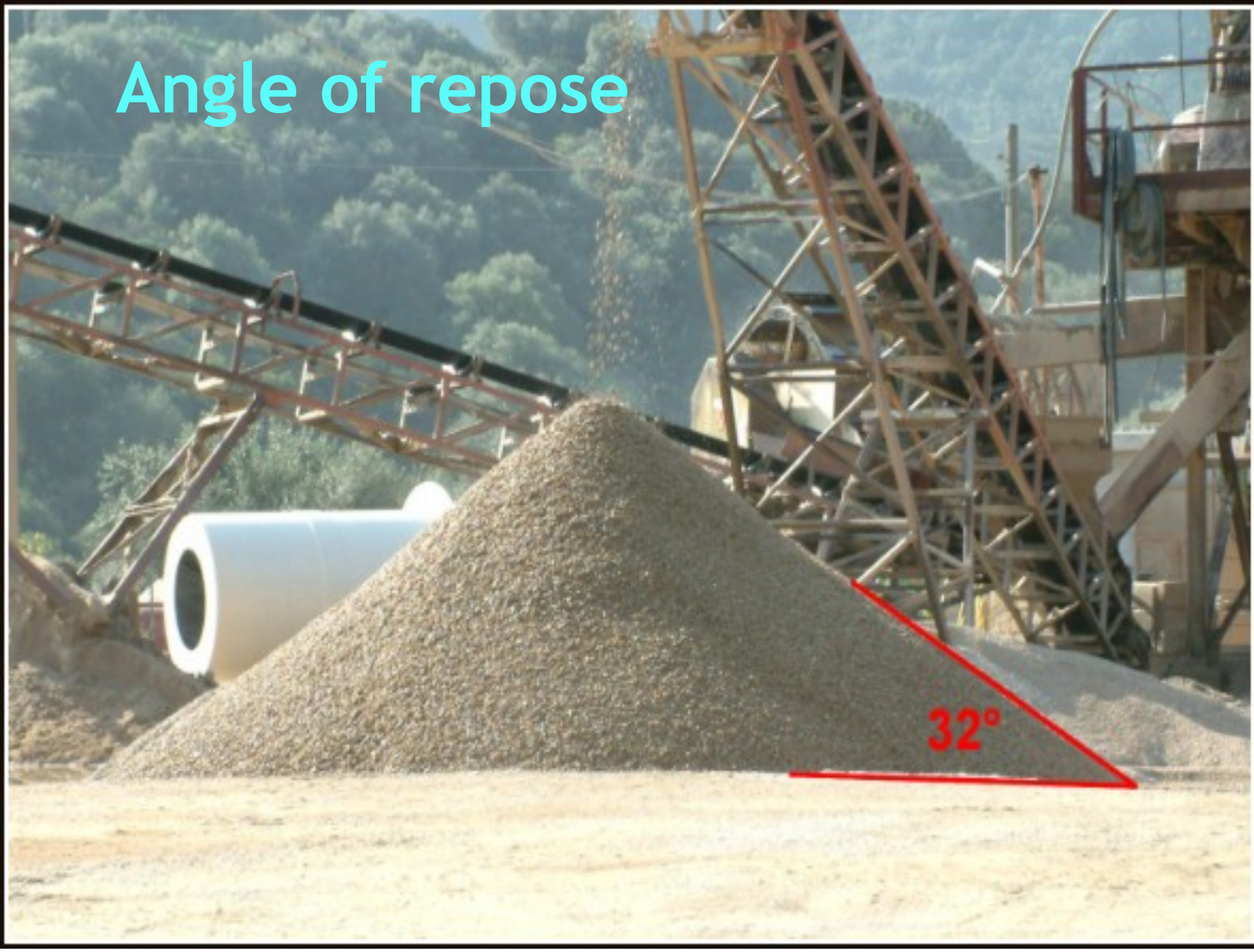
Sandstone

Metamorphic



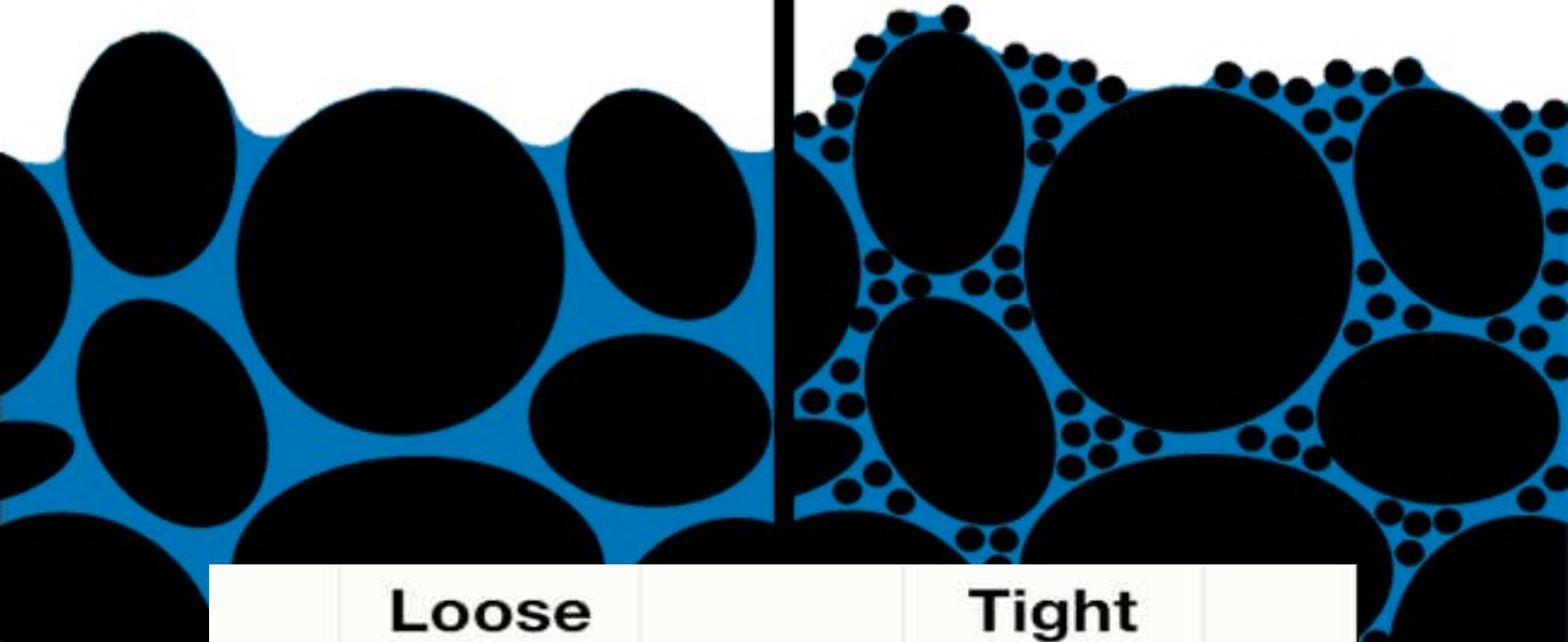
Gneiss

Angle of repose



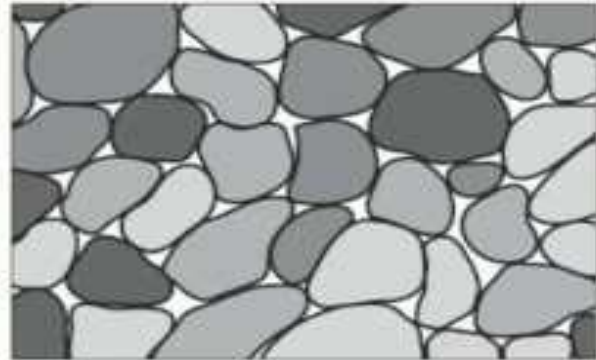
Greater porosity

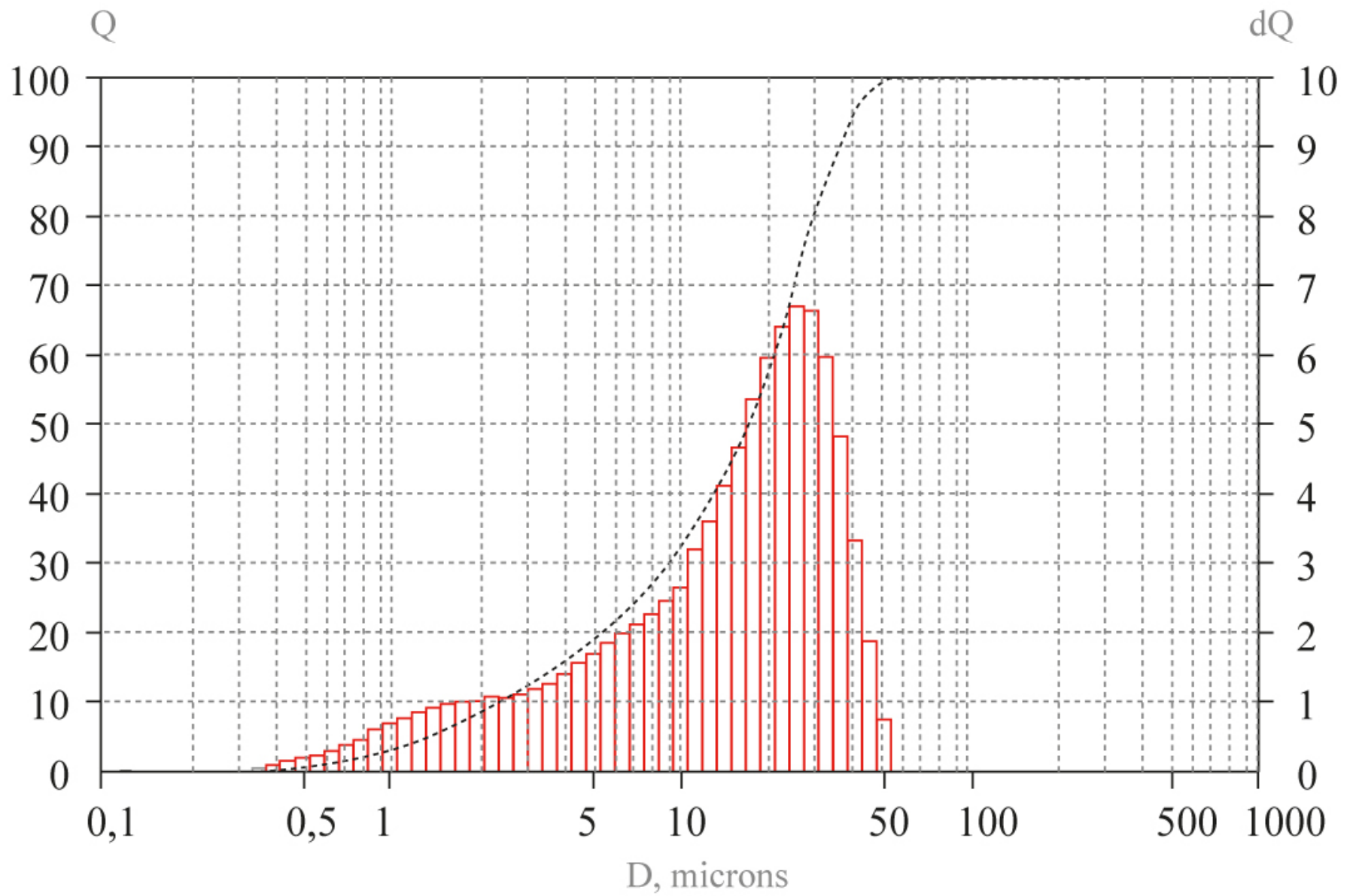
Less porosity



Loose

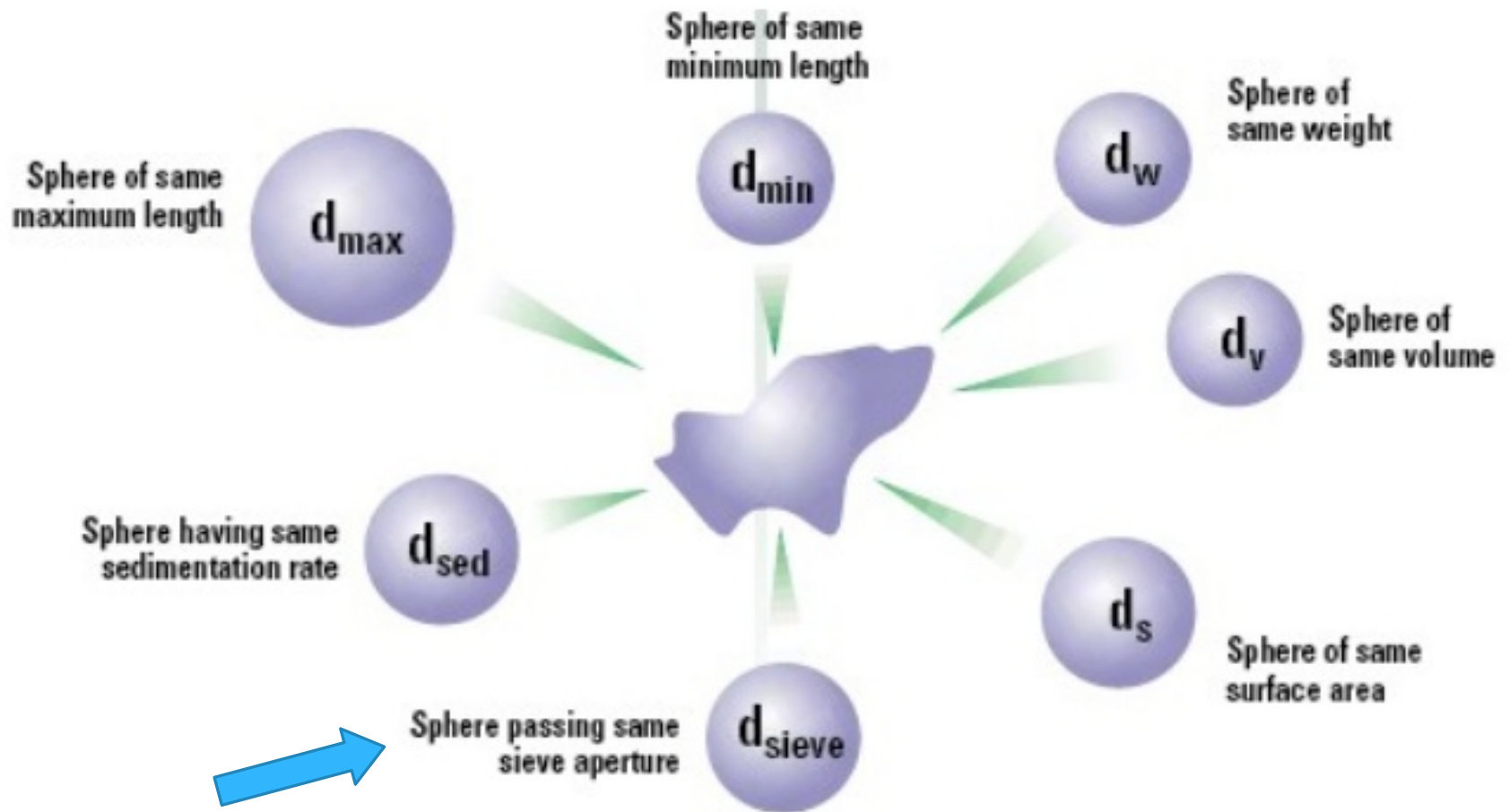
Tight





Particle size distribution

Different Equivalent Spheres



❖ Sieve size → Characteristic size of sediment

❖ Shape of particle effects

❖ *Bed resistance*

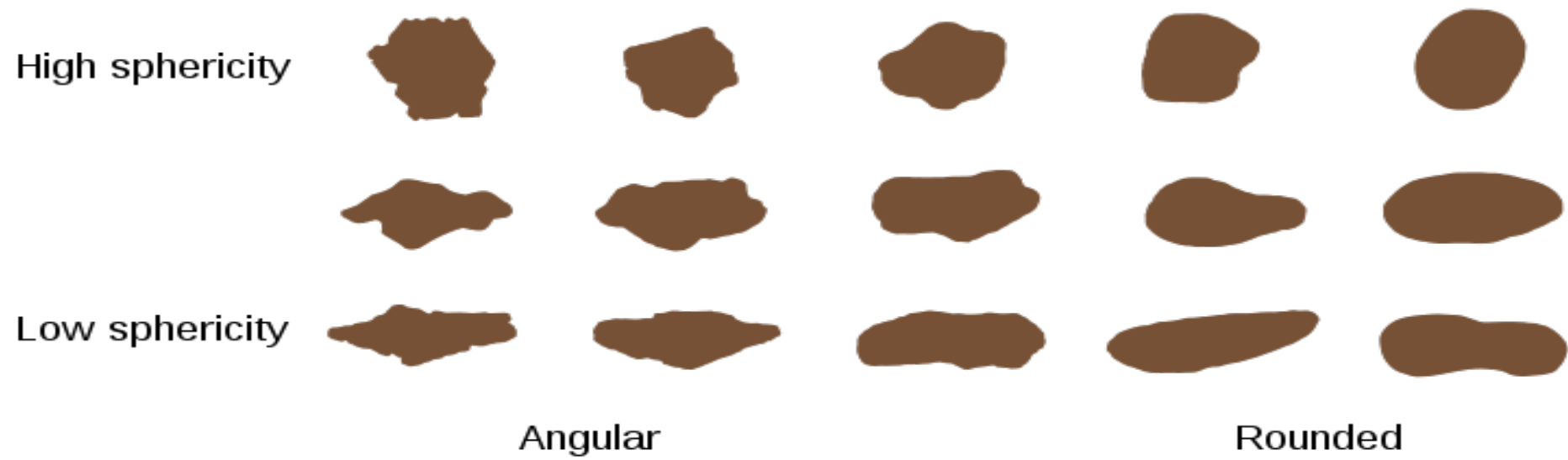
❖ *The mean velocity close to*





very angular *angular* *sub-angular* *sub-rounded* *rounded* *very rounded*
For the shape expression:

- **Sphericity**
- **Roundness**
- **Shape Factor**
(more common)



Properties of Sediment

$$S f = \frac{c}{(a b)^{1/2}}$$

***a, b, c** : major intermediate minor axes of a particle*

- *For natural sand $\rightarrow 0.7$*



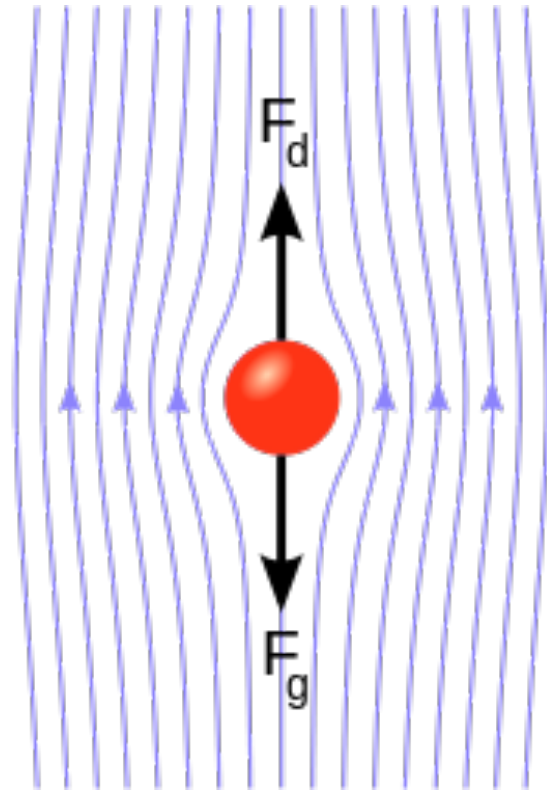
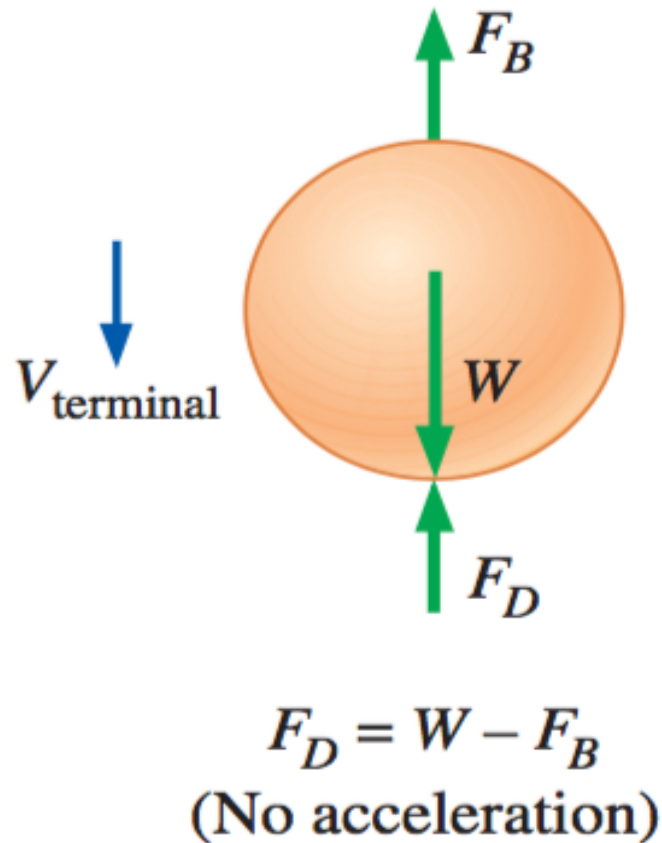
Terminal velocity of Sediment particles

Terminal velocity:

Velocity of descending sediment grain in still water

*The terminal velocity of a sediment particle, defined as the rate at which the particle settles through a fluid and is *important* in terms of sediment transport*

Terminal velocity



As a consequence, the sphere then falls with a constant velocity which is termed as terminal velocity.



Force due to Gravity

Terminal velocity

Terminal velocity

There are *many factors* that *affect terminal velocity* of sediment particles

- characteristics of the settling particle,
- properties of the fluid in which the particle is falling



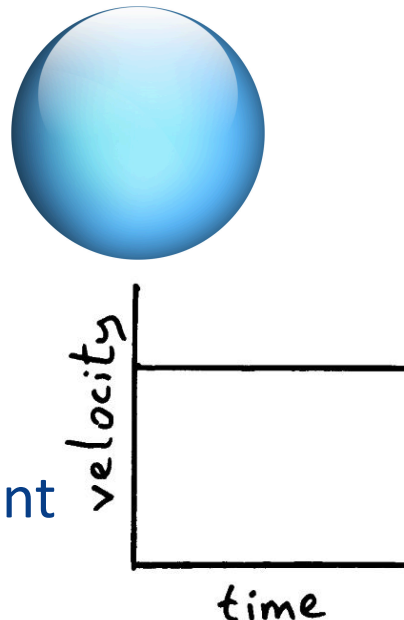
- force of gravity



There are assumptions to be considered in analyzing the mechanics of a settling particle in a fluid, and

These are:

- i. Quiescent water
- ii. Large extent
- iii. A single sphere
- iv. Falling with a constant



Let's analyze a *single spherical particle* by considering the above mentioned assumptions

The force of Gravity, G , acting on a spherical body with diameter D is written as follow

$$G = \frac{(\gamma_s - \gamma) \pi D^3}{6}$$

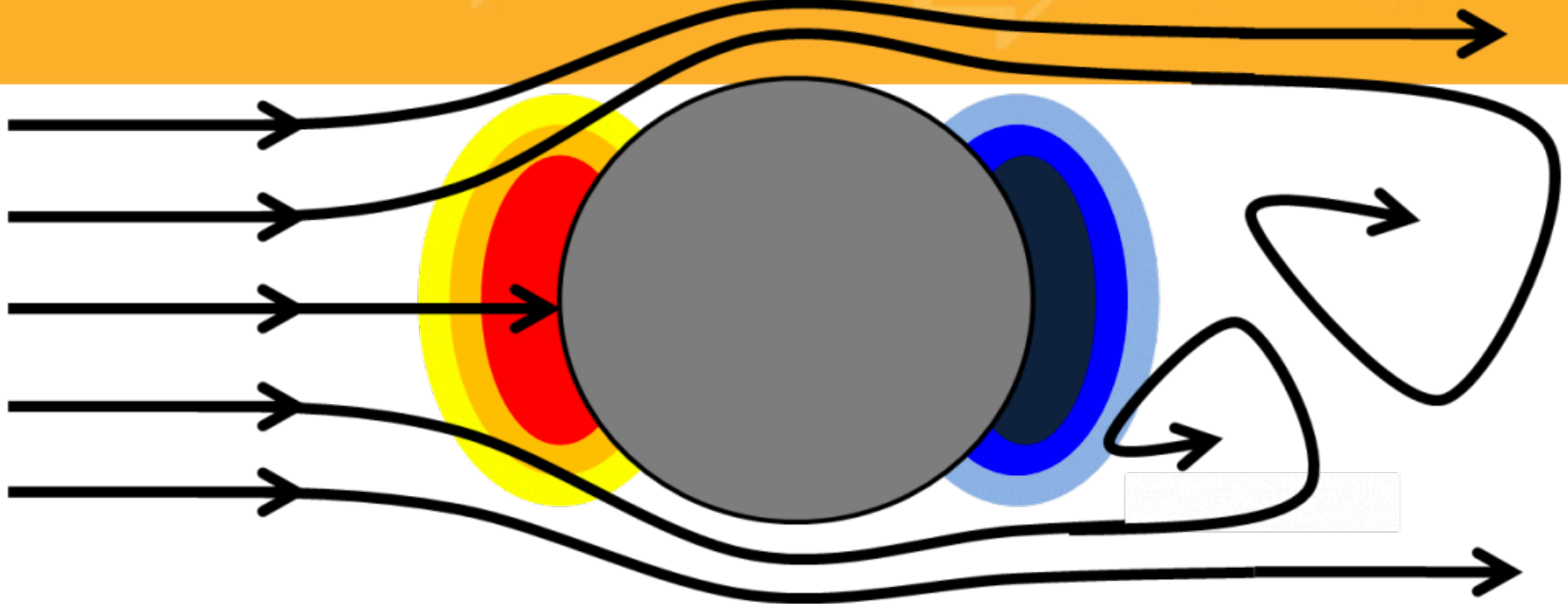
The Drag force, F_D , which is the resistance to motion, is expressed as follows.

$$F_D = C_D \frac{\pi D^2}{4} \rho \frac{w^2}{2}$$

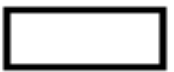
w : Terminal velocity

C_D : drag coefficient, which is function of Reynolds number

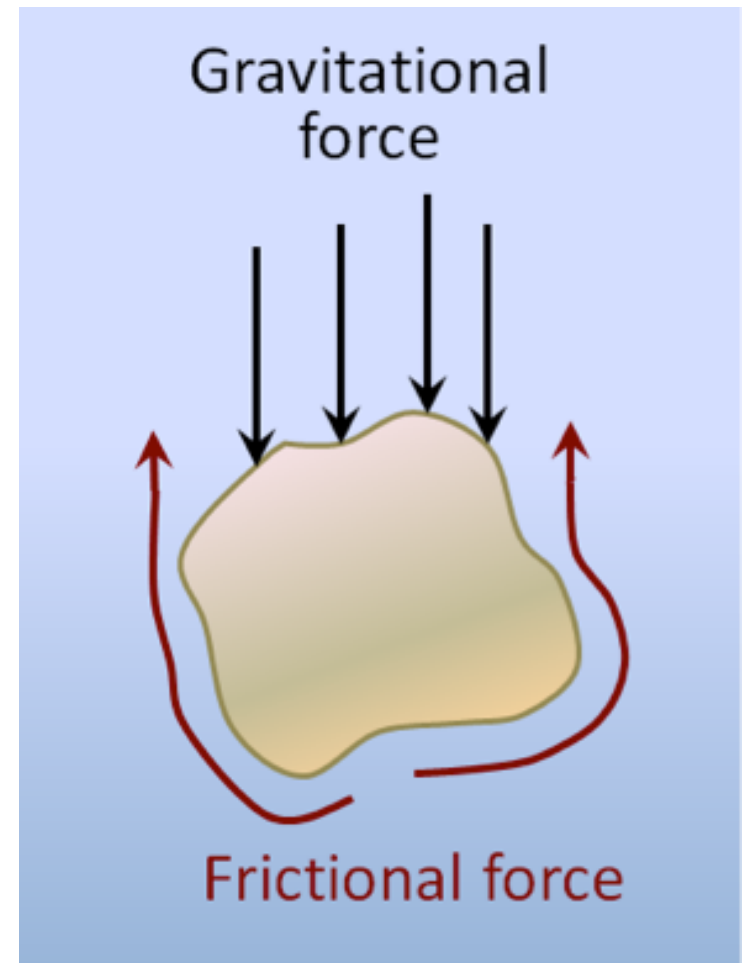
D R A G



Drag Coefficient

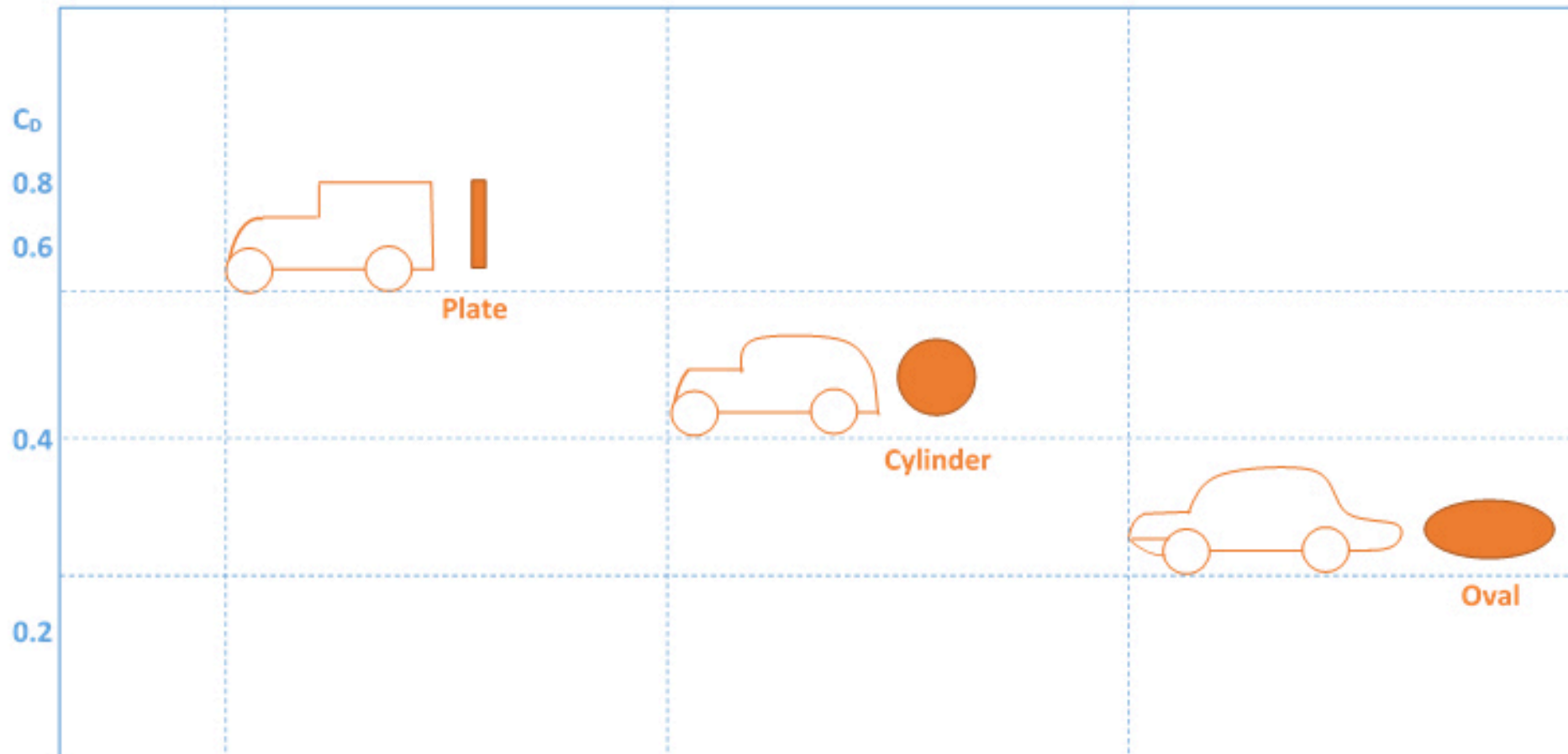
Shape		Drag Coefficient
Sphere	→ 	0.47
Half-sphere	→ 	0.42
Cone	→ 	0.50
Cube	→ 	1.05
Angled Cube	→ 	0.80
Long Cylinder	→ 	0.82
Short Cylinder	→ 	1.15
Streamlined Body	→ 	0.04
Streamlined Half-body	→ 	0.09

Measured Drag Coefficients



Drag Coefficient

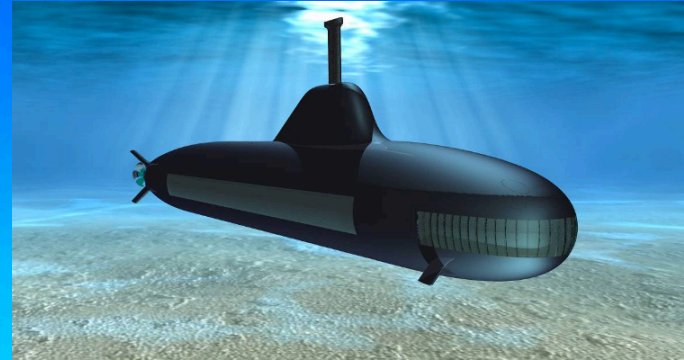
Time history of cars' aerodynamic drag in comparison to change in geometry of streamlined bodies (blunt to streamline)



Dolphins

*Drag Coefficient is
0.0035 !!!*

That is why we mimic th →

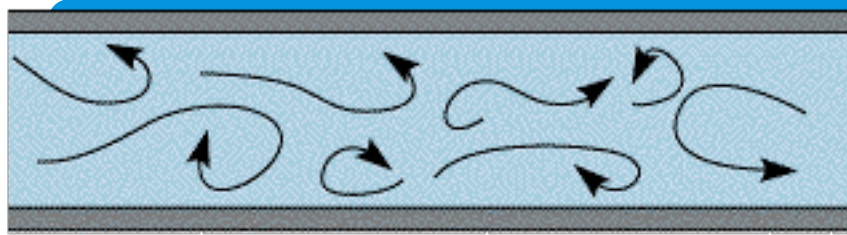


The *expression for determining terminal velocity, w* , is obtained as:

$$w = \sqrt{\frac{4}{3} \frac{g}{C_D} \frac{(\gamma_s - \gamma)}{\gamma} D}$$

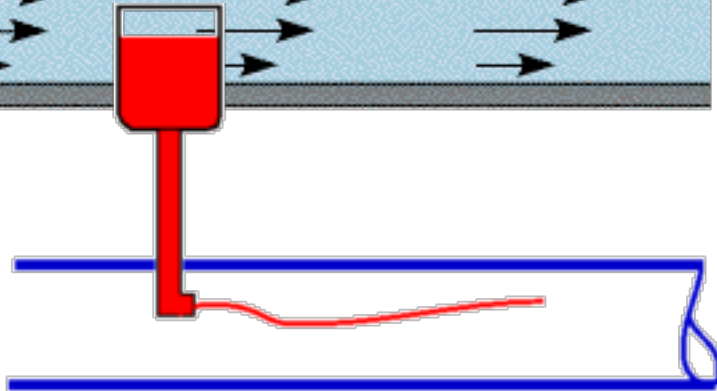
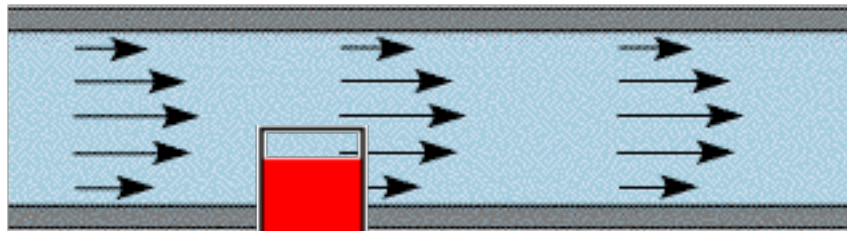
This expression is general for both *laminar* and *turbulen*
flow conditions

Turbulent

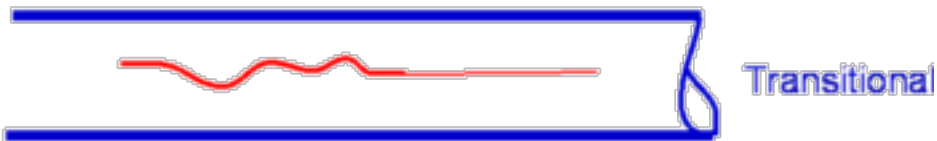


Laminar vs Turbulent

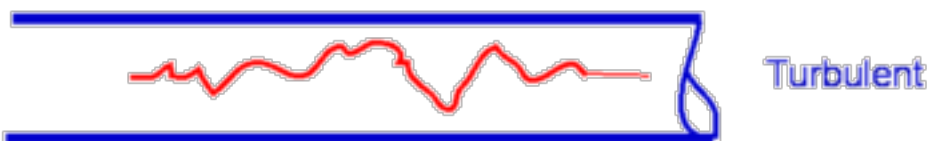
Laminar



Laminar

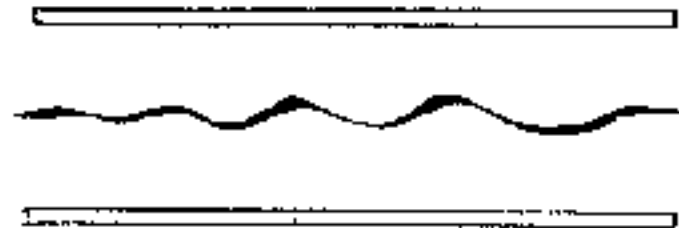
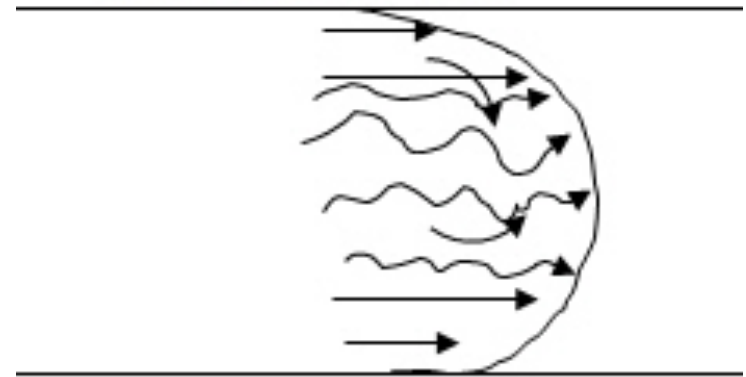


Transitional



Turbulent

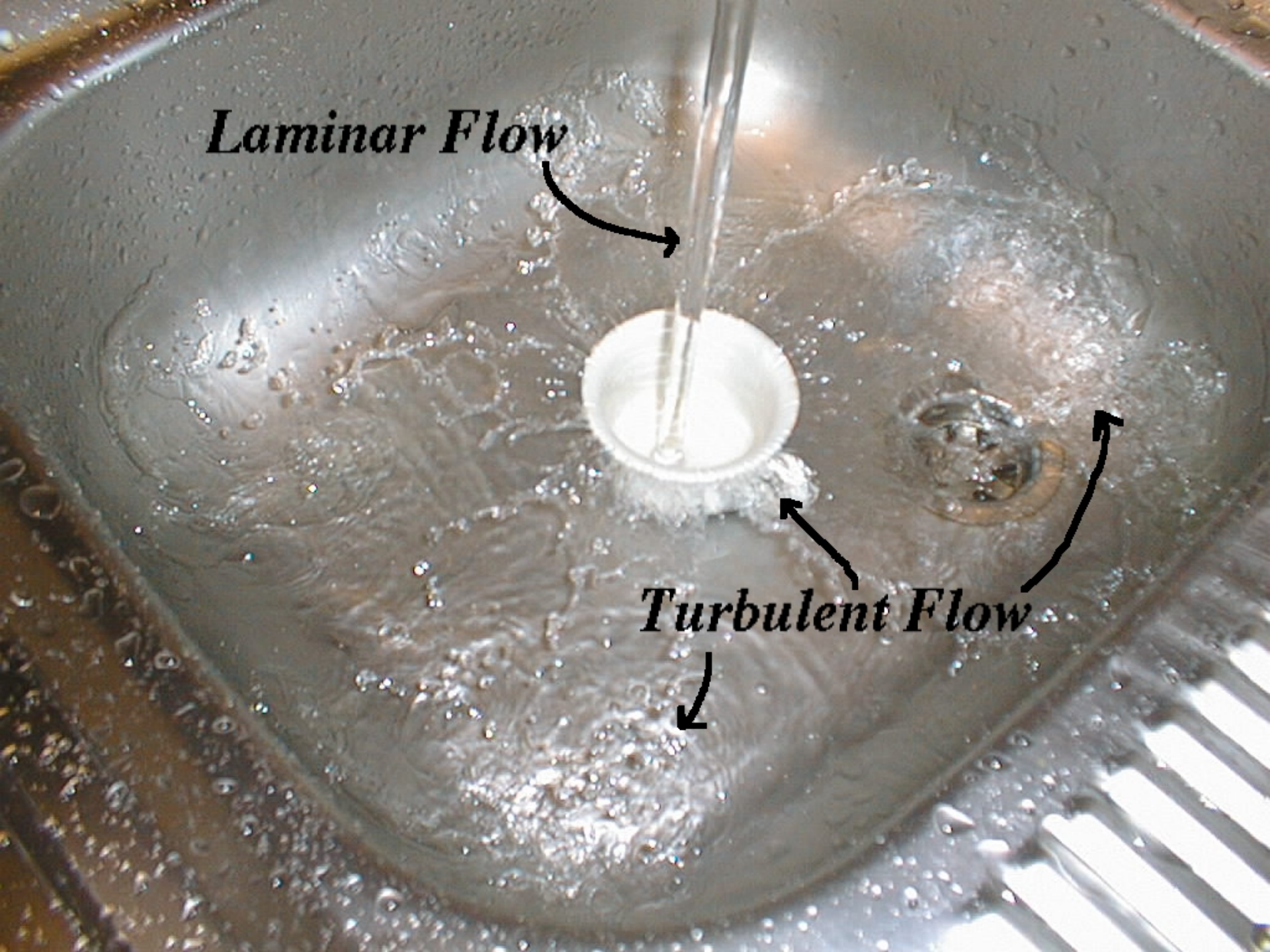
Transition Flow



Transitional

Laminar Flow

Turbulent Flow





Mechanics of Spheres Settling in Quiescent Water

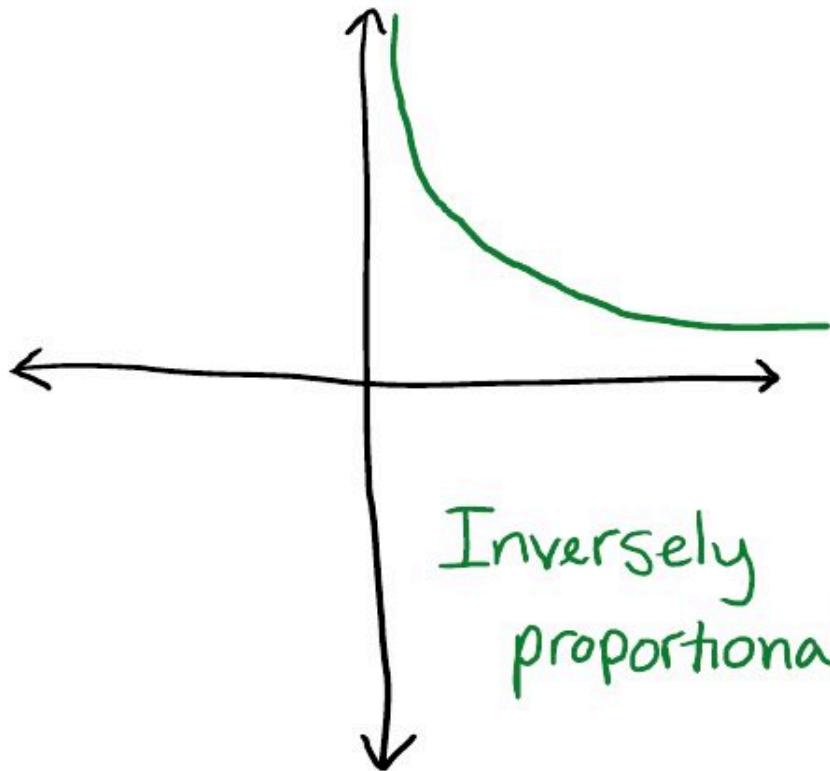
*Determination of **terminal velocity** if the surrounding condition is laminar flow:*

*Drag coefficient is inversely proportional to the **Reynolds number**, which is the ratio of inertia force to viscous force.*

Drag coefficient

The *drag coefficient* can be described for *laminar* flow

as follow:

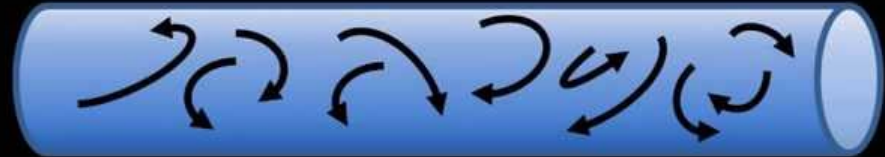


$$\frac{24}{Re} = \frac{24}{\frac{w D}{\eta}}$$

Laminar flow



Turbulent flow



Osborne Reynolds
(1842-1917)

Reynolds Number – Single best predictor
of the type of flow.

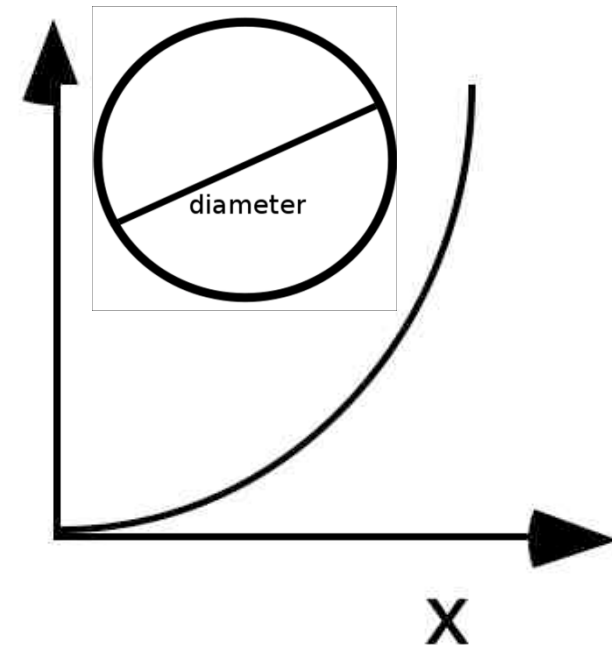
$$Re = \frac{\text{Inertia force}}{\text{Viscous force}}$$

Promotes turbulent flow →

$$\text{Reynolds Number} = \frac{\text{Inertial Force}}{\text{Viscous Force}}$$

As can be seen, **terminal velocity** is proportional to square of sphere diameter for **laminar** flow condition.

$$w = \frac{1}{18} \frac{(\gamma_s - \gamma)}{\gamma} \frac{g D^2}{\nu}$$



Mechanics of Spheres Settling in Quiescent Water

For transition flow ($0.1 \leq R_e \leq 2.1$), the value of C_D is computed from

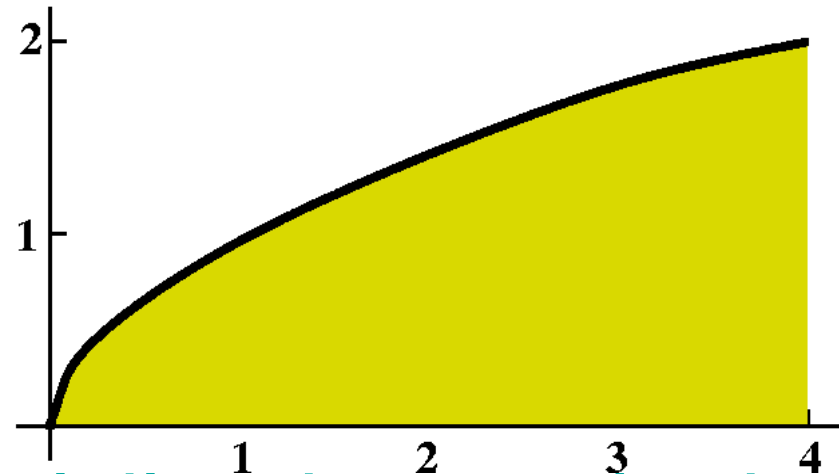
$$C_D = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34$$

The *drag coefficient* can be considered as a constant,
 $C_D = 0.45$ when the *Reynolds number* is greater than

1000

Determination of terminal velocity if surrounding condition is turbulent flow

$$w = 1.72 \sqrt{\frac{(\gamma_s - \gamma)}{\gamma} g D}$$



In this condition, *terminal velocity is linearly proportional with square root of the diameter of the sphere*



Types of Sediment Transportation

Solution: *soluble materials like clay-brownish color in river flow*

Suspension: *due to river turbulence*

Saltation: *the particles having grater sizes than required for suspension movement-motion takes place in contact with the bed*

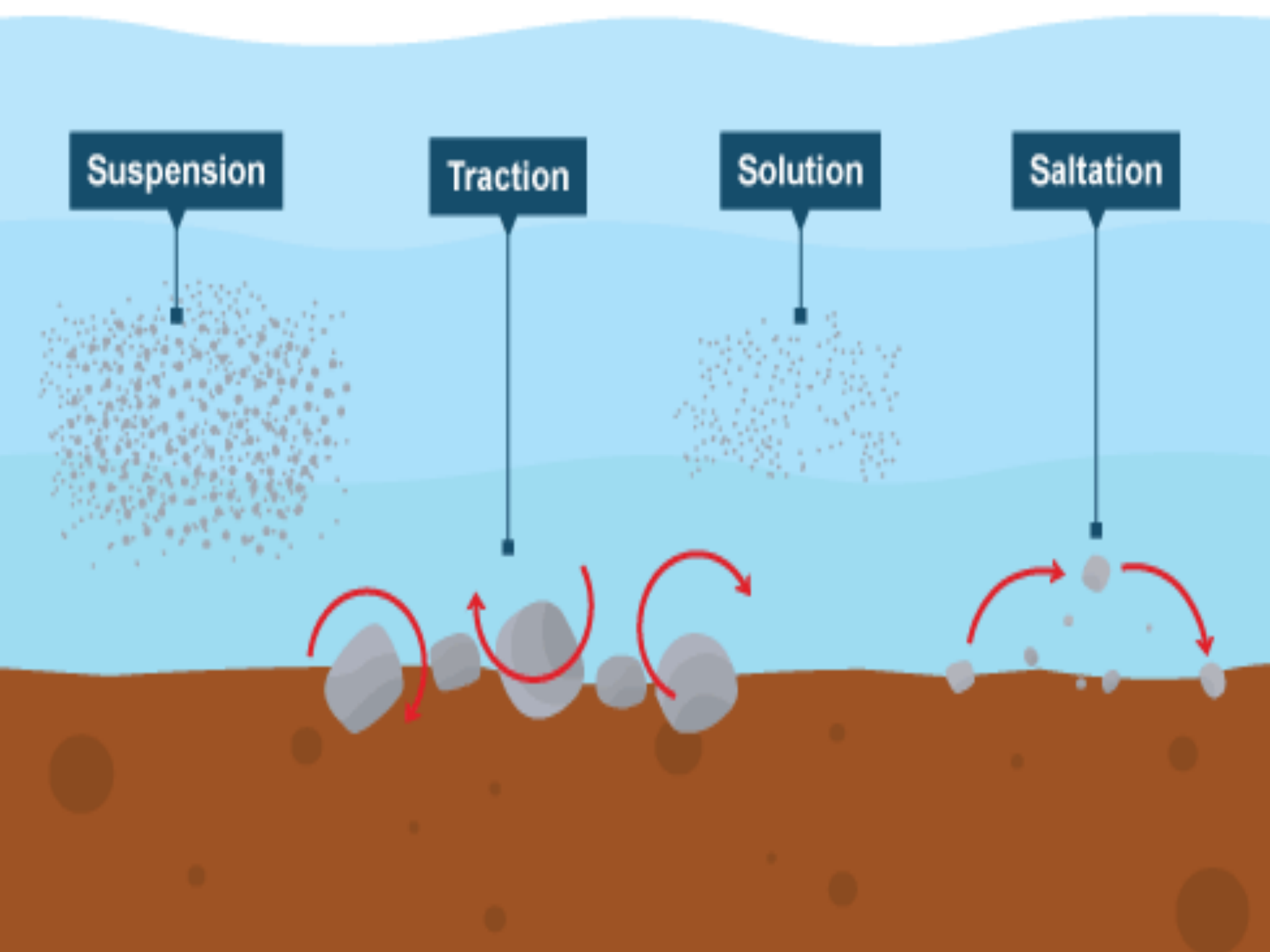
Rolling and Traction: *dragging of larger particles in contact with the bed*

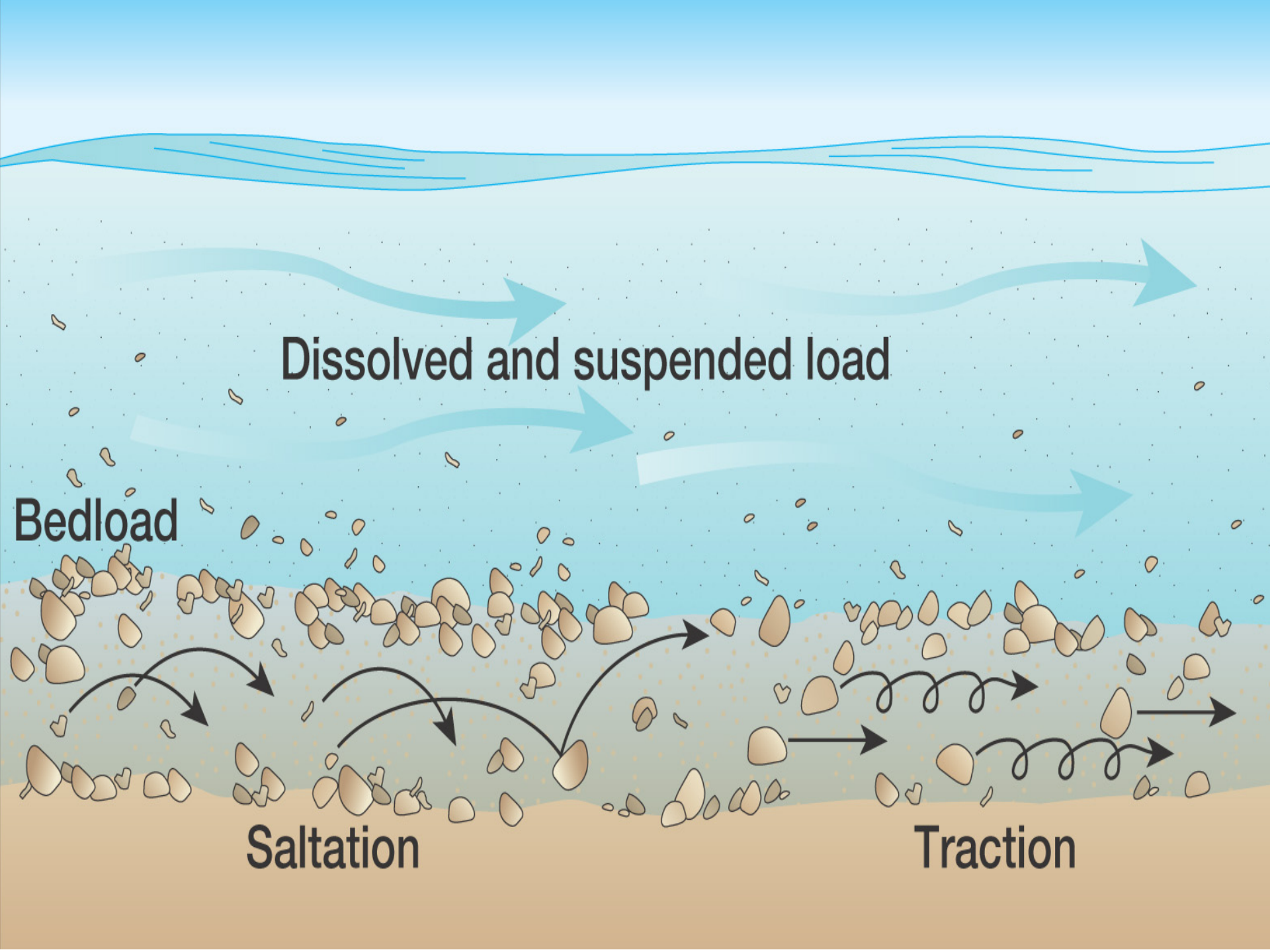
Suspension

Traction

Solution

Saltation





Dissolved and suspended load

Bedload

Saltation

Traction

Types of Sediment Transportation

Transportation of particles are based on

- *Sediment type*
- *Size*

Sediment particles are transported

by ➤ solution,

- *suspension*
- *traction (rolling) and sliding*
- *saltation*

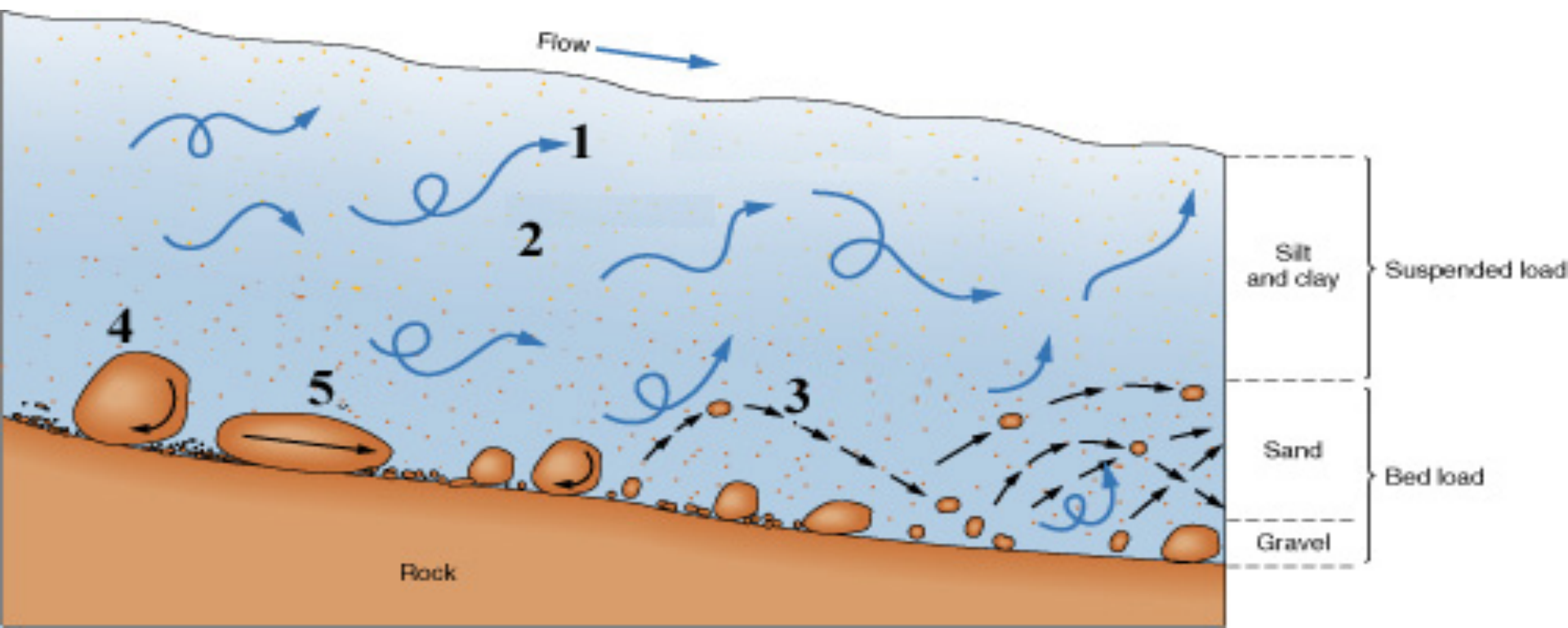
SUSPENSION: Fine, light material is carried along by the river

SOLUTION: Minerals are dissolved in the water. This is a chemical change

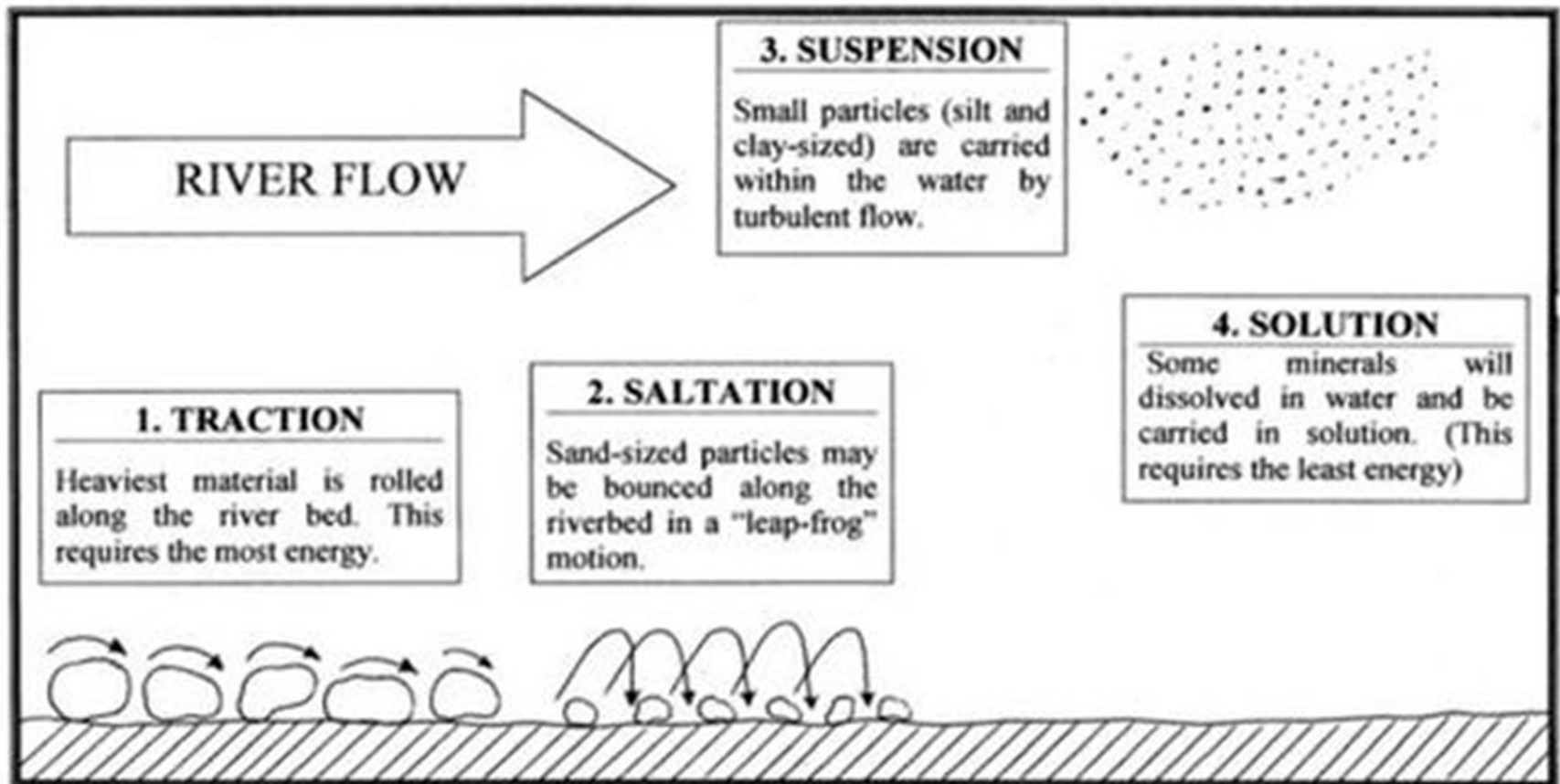
TRACTION: large boulders and rocks are rolled along the river bed

SALTATION: small pebbles and stones are bounced along the river bed

River bed



River Processes: Transportation







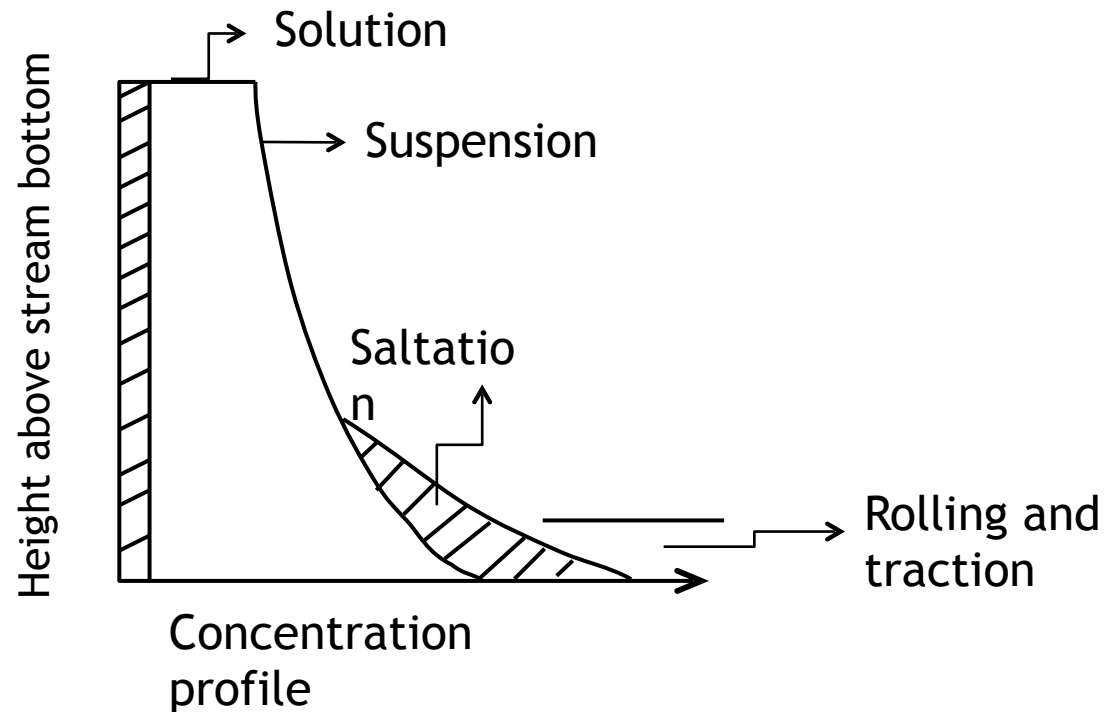
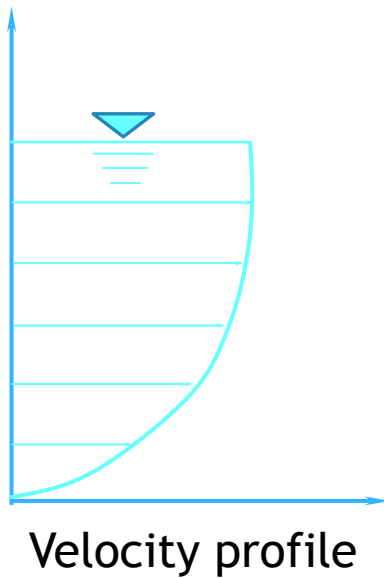








Types of Sediment Transportation



Sediment concentration profile (Mitchell, 1976)



Types of Sediment Transportation

Suspended Load: *Total material transported by solution and suspension*

Bed Load: *Total material transported by saltation, rolling and traction*

Very hard to define a layer for the bed transportation

Wash Load: *suspended load composed of fine materials entering from side tributaries or overland flow*

Dissolved load
(in solution)

Stream flow

Suspended
load

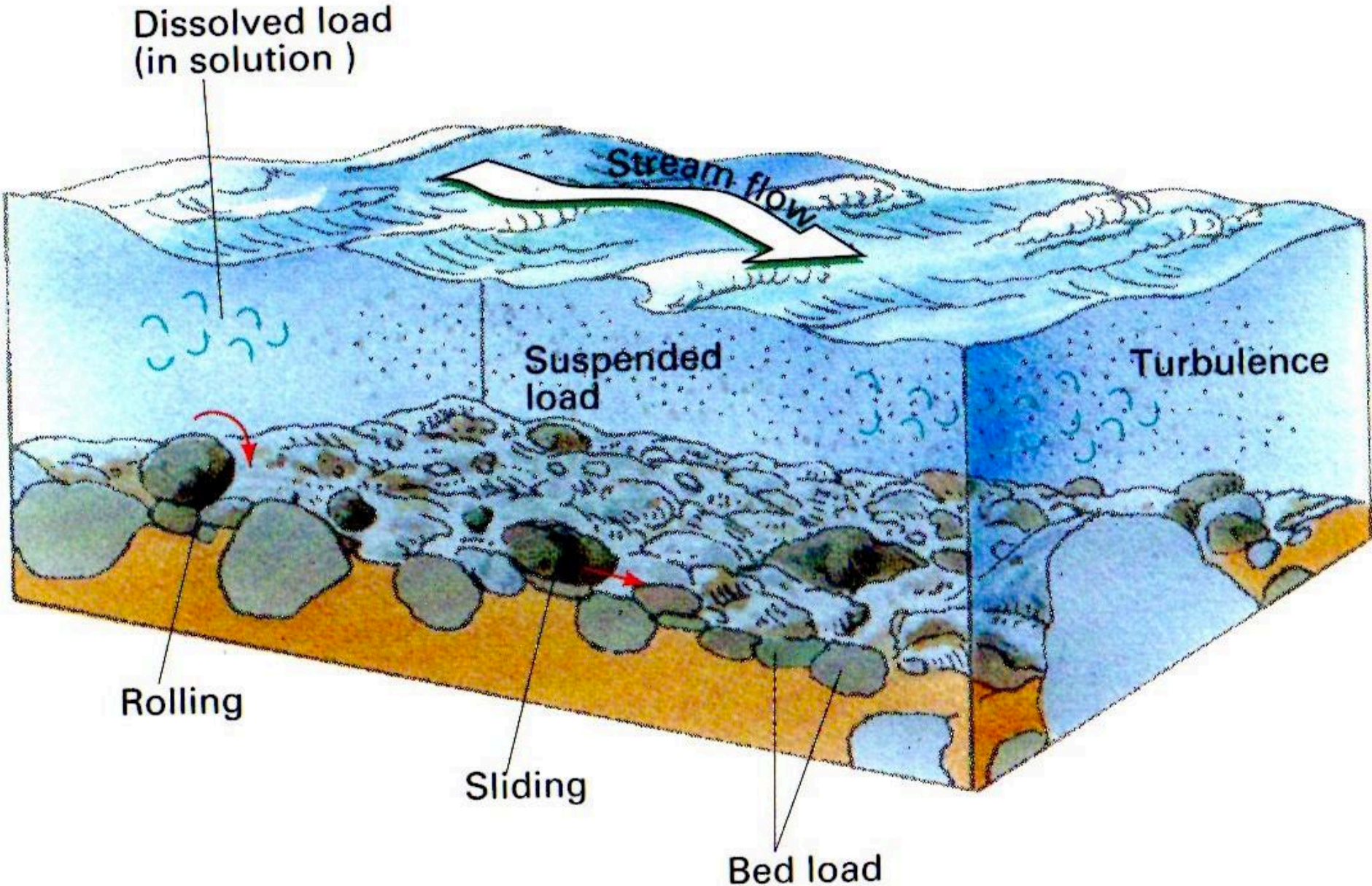
Turbulence

Rolling

Sliding

Bed load

The sediment can be maintained in suspension against the action of gravitational force



Types of Sediment Transportation

Dynamic Equilibrium: *the amounts of sediment entering and leaving a certain length of river reach are equal to each other.*

$$S_I - S_o = 0$$

Aggradation: *a rise in bed level*

Degradation: *a fall in bed level*

Local scour: *degradation around any hydraulic structure due to flow acceleration (e.g., bridge piers)*



Initiation of Particle Motion

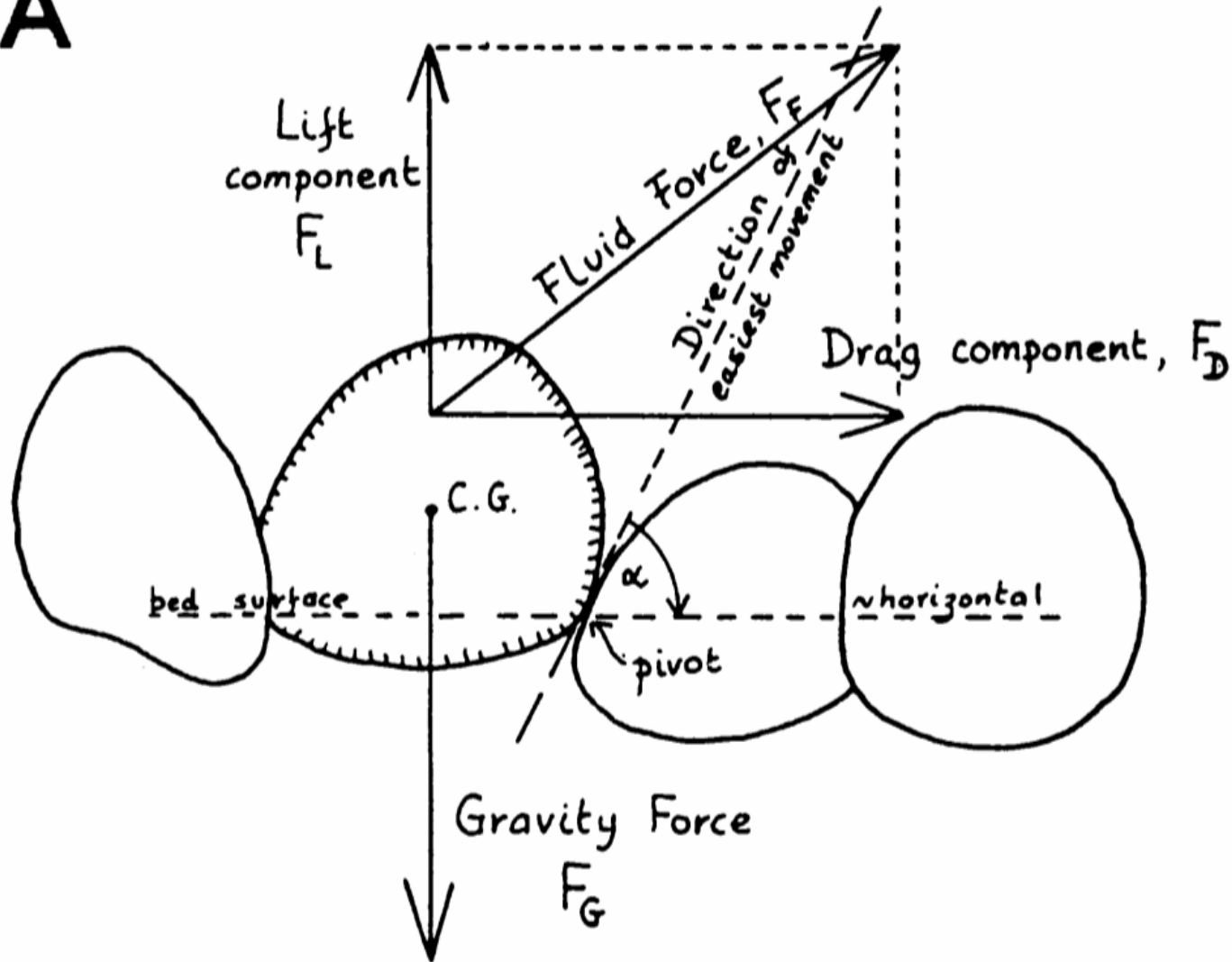
Discharge ↑ → the effects of *disturbing forces*
(*hydrodynamic lift and drag forces*) ↑
After a critical condition; equilibrium of particles ↓
→ *random motion occurs on the bed*

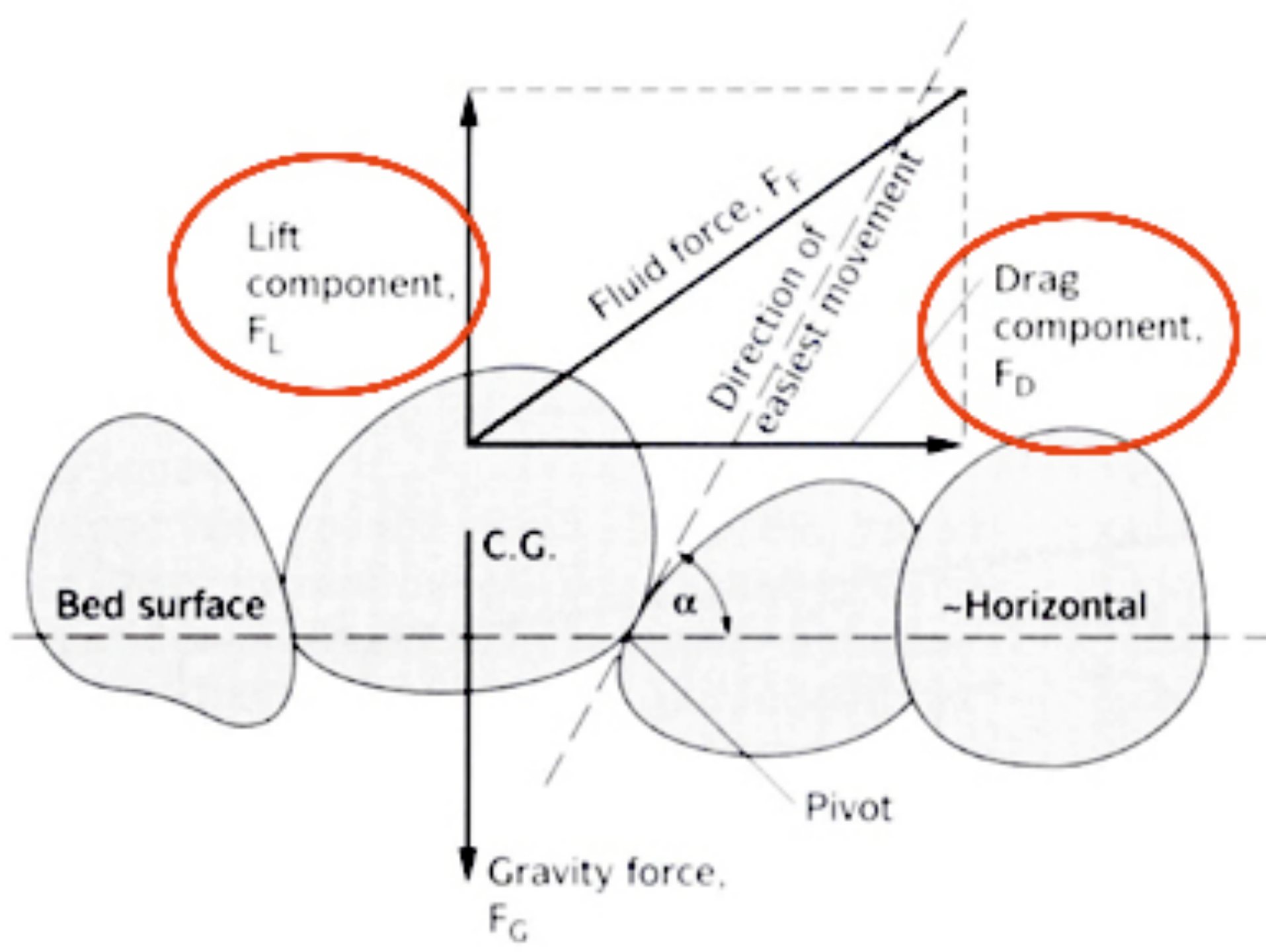
This is named as

“incipient motion” or “threshold of motion”

Forces Acting on a Grain

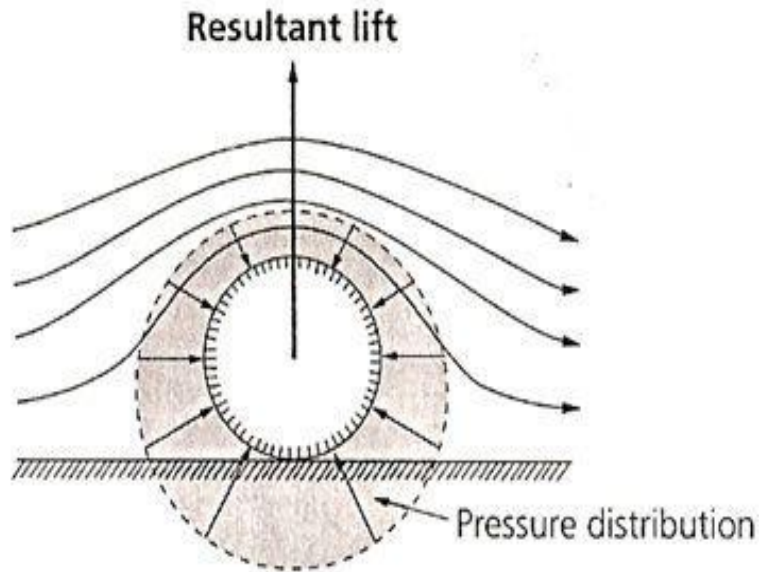
A





FORCES ON PARTICLE ON BED

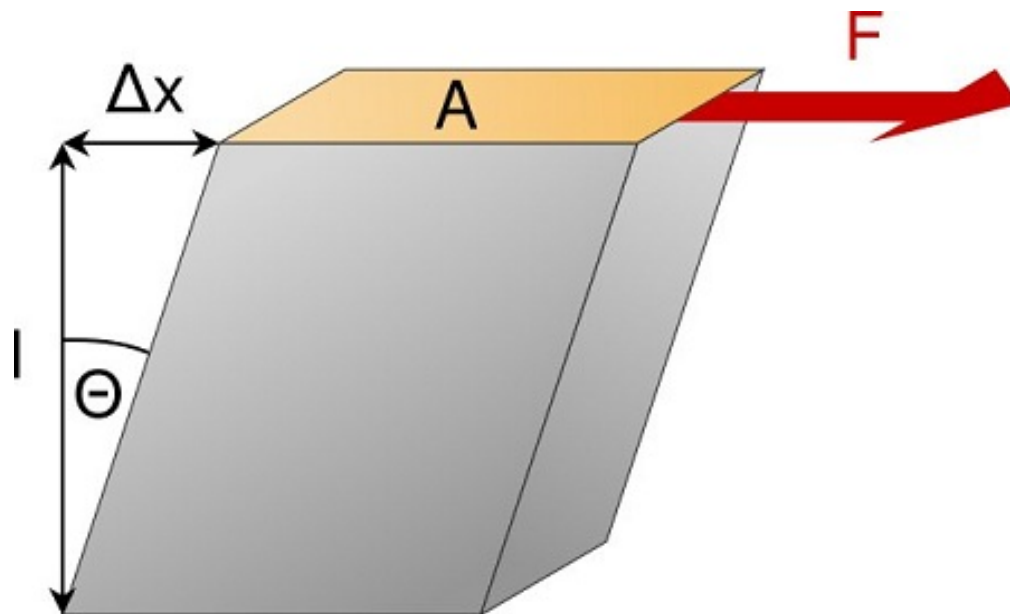
(a)



Cylinder on horizontal bed
below inviscid fluid.

No viscosity: no drag force.

Stream lines converge and then
diverge over cylinder in symmetrical
fashion: pressure distribution results
in net upward force: lift force.



***Shear
Stress***



Initiation of Particle Motion

From lab experiments:

Functional relation between the physical parameters affecting the stability of the sediment grains on flatbed:

$$f(\tau_0, h, D, \nu, \Delta, g, S_0) = 0$$

Physical Parameters

- τ_o : bed shear stress
- H : average water depth
- D : Diameter of spherical particle
- $\Delta = (\gamma_s - \gamma) / \gamma$
- γ : specific weight of water
- γ_s : specific weight of sediment
- S_o : channel bottom slope

Initiation of Particle Motion

The dimensionless terms are obtained through

Buckingham's π -theorem

(Streeter and Wylie, 1985)

$$f\left(\frac{\tau_0}{(\gamma_s - \gamma) \cdot D}, \frac{u_* D}{\vartheta}, \frac{h}{D}\right) = 0$$

Where

- γ is the specific weight of water
- u is the shear velocity
- $\Delta = 1.65$ (The river bed is mostly composed of quartz sand)



Initiation of Particle Motion

➤ *Shields (1936)* analyzed incipient motion of uniform sediments and plotted the results in terms of dimensionless critical shear stress and velocity

$$\frac{\tau_{0c}}{(\gamma_s - \gamma) \cdot D} = f\left(\frac{u_{*c} D}{\nu}\right)$$

➤ The relation between a particle Froude and a particle Reynolds numbers is as known as Shields diagram.

Dimensionless parameters

➤ Reynolds Number

$$R = \frac{\rho V l}{\mu}$$

➤ Froude Number

$$F = \frac{V}{\sqrt{gl}}$$

➤ Weber Number

$$W = \frac{V^2 l \rho}{\sigma}$$

➤ Mach Number

$$M = \frac{V}{c}$$

➤ Pressure Coefficient

$$C_p = \frac{-2\Delta p}{\rho V^2} \quad C_d = \frac{2\text{Drag}}{\rho V^2 A}$$

➤ (the dependent variable that we measure experimentally)

Initiation of Particle Motion

The shields diagram is frequently used in order to determine incipient motion depending on bed shear

The points on the ^{stress} curve represent critical condition which correspond to sediment motion

The points above the curve correspond motion and below the curve correspond no motion

Initiation of Particle Motion

Shields concluded that critical condition is related with *two dimensionless parameters*

- i. Dimensionless shear stress (Shields
These are:
parameter)*
- ii. Grain Reynolds numbers*

Initiation of Particle Motion

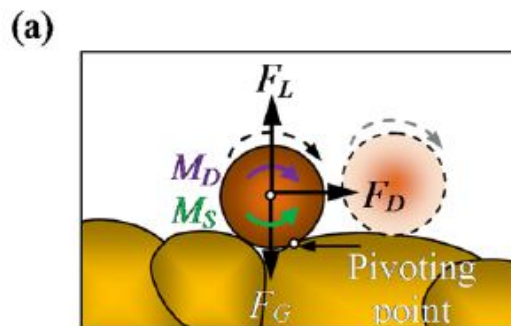
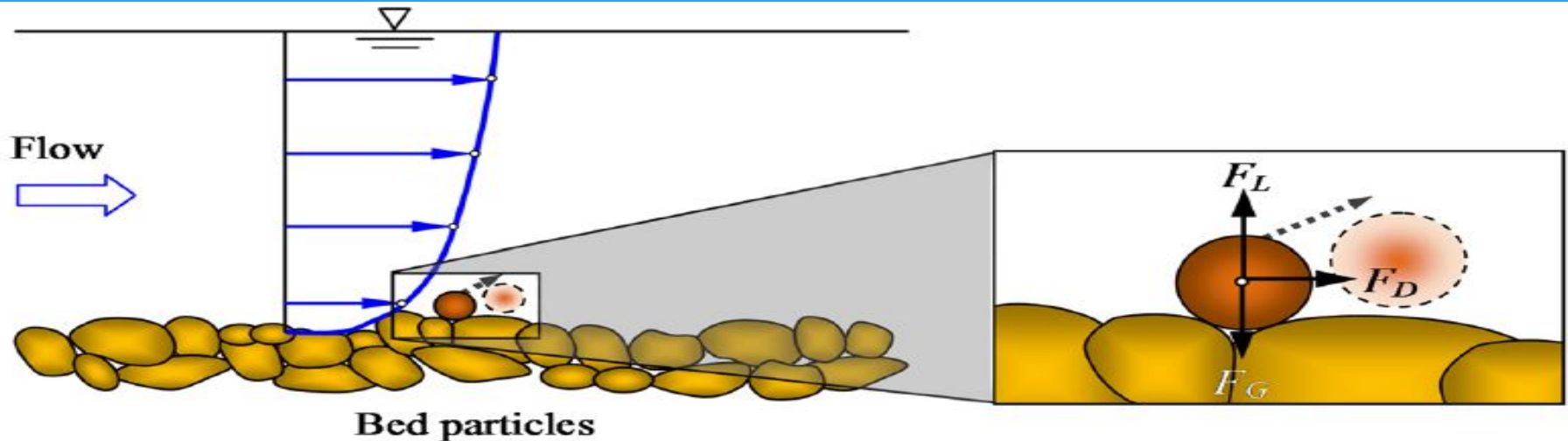
Shields parameter is ratio of drag force to resistance force

This parameter can be computed

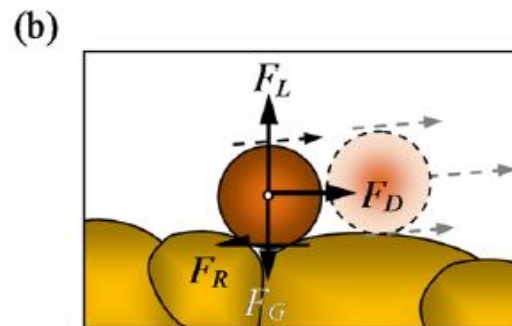
$$\phi = \frac{\tau_0}{(\gamma_s - \gamma) \cdot D}$$

The relationship between *Shields parameter* and *Shear Reynolds number* are obtained *experimentally*

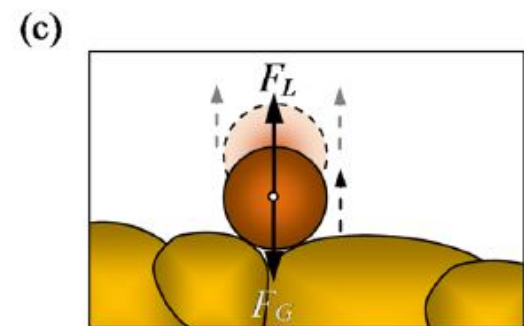
The Particle Entrainment Criteria in Modes



Rolling mode
($M_D \geq M_S$)



Sliding mode
($F_D \geq F_R$)



Lifting mode
($F_L \geq F_G$)

Bizimana and Altunkaynak (2019). A novel approach for the prediction of the incipient motion of sediments under smooth, transitional and rough flow conditions using Geno-Fuzzy Inference System model. Journal of Hydrology , 577 :123952

Entrainment Thresholds of Particle

Rolling Threshold

The following expressions have been used for these forces

$$W = \frac{\pi D^3}{6} \gamma_s \quad \text{Weight of Particle}$$

$$F_U = \frac{\pi D^3}{6} \gamma_f \quad \text{Buoyancy Force}$$

$$F_G = \frac{\pi D^3}{6} (\gamma_s - \gamma_f) \quad \text{Submerged Weight of Particle}$$

$$F_D = \frac{1}{2} C_D \rho A u_b^2 \quad \text{Drag Force}$$

$$F_L = \frac{1}{2} C_L \rho A u_b^2 \quad \text{Lift Force}$$

The Rolling Threshold

- * $u_b^2 > B_R^2$

- * B_R is the rolling threshold, which can be expressed as

- *
$$B_R = \sqrt{\frac{L_W}{C_D L_D + C_L L_L} \frac{\pi D^3}{3 A} \frac{(\gamma_s - \gamma)}{\rho}}$$

Lifting Threshold

$$*u_b^2 > B_L^2$$

B_L is the lifting threshold, which can be expressed as

$$*B_L = \sqrt{\frac{\pi D^3}{3 C_L A} \frac{(\gamma_s - \gamma_f)}{\rho}}$$

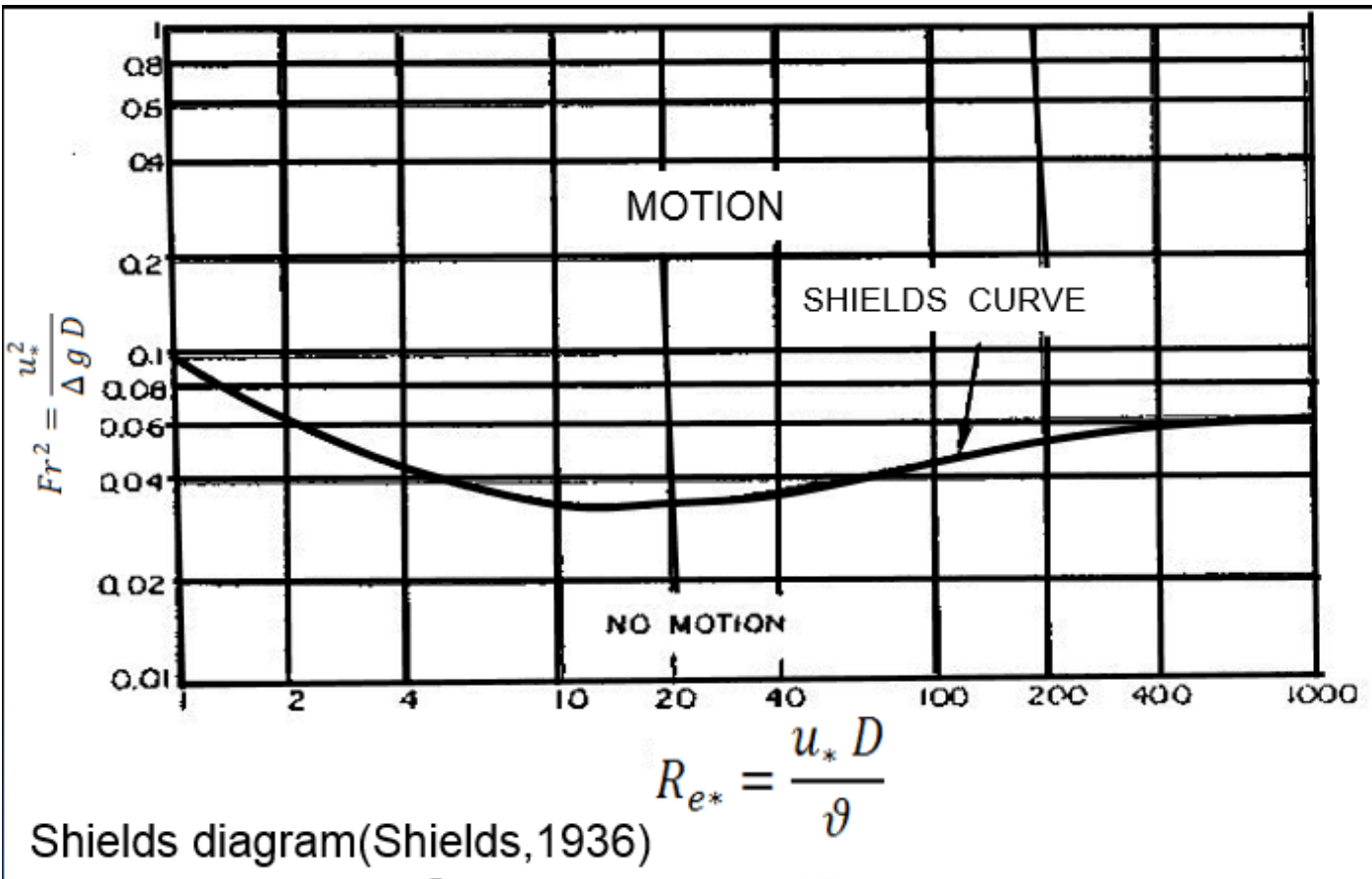
Sliding Threshold

$$*u_b^2 > B_S^2$$

B_S is the sliding threshold, which can be expressed as

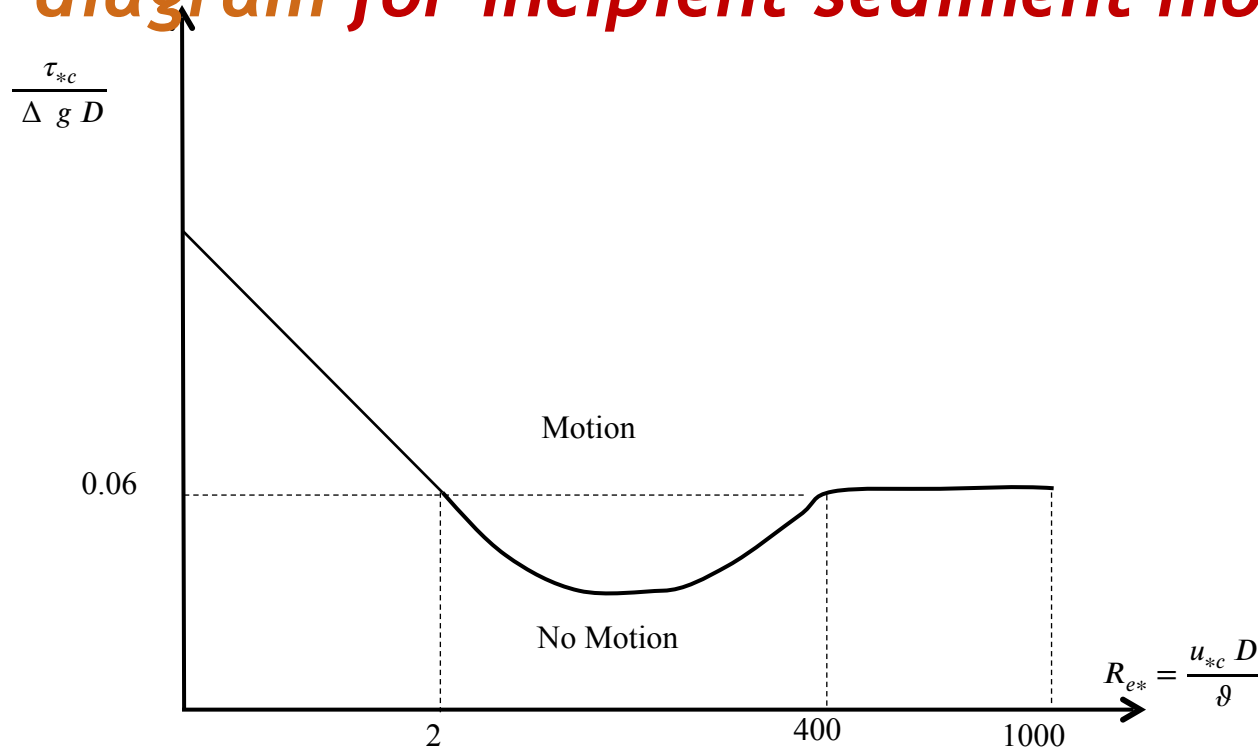
$$*B_S = \sqrt{\frac{k}{C_D + C_L} \frac{\pi D^3}{3 A} \frac{(\gamma_s - \gamma)}{\rho}}$$

Shields Diagram

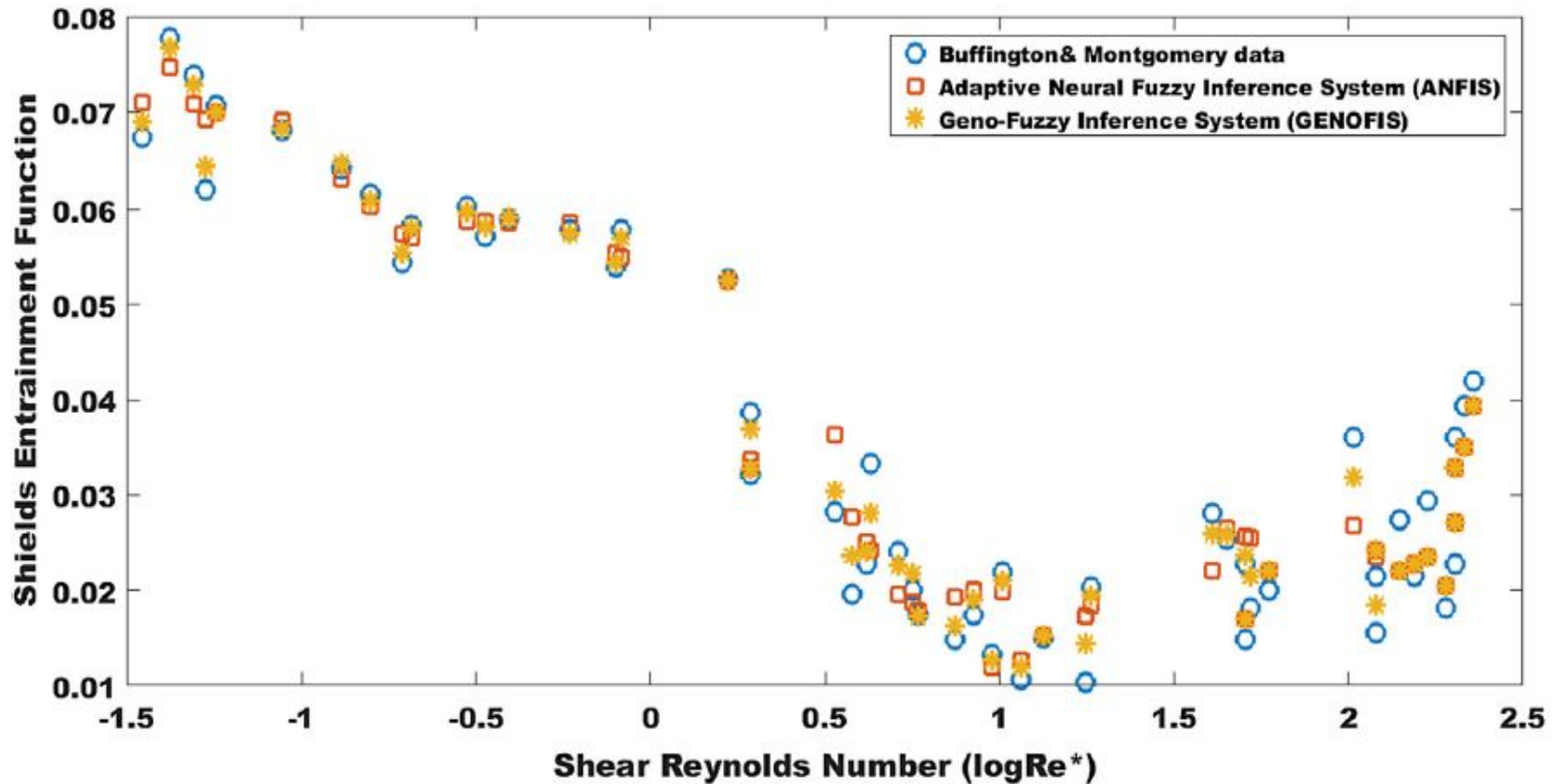


Modified Shields Diagram

- Yalin and Karahan (1979) modified Shields diagram for incipient sediment motion

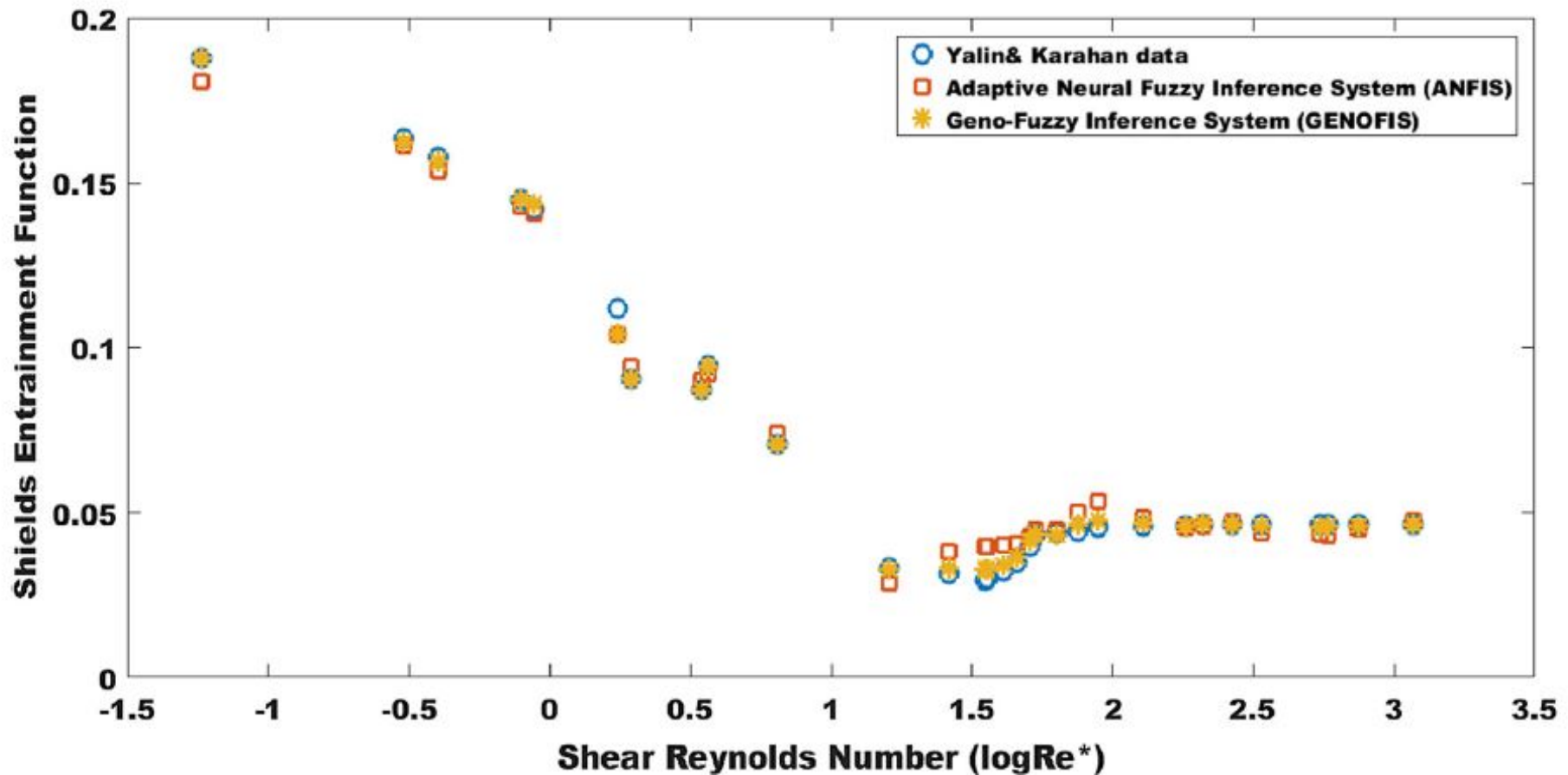


Shields Entrainment Function of observed and predicted dimensionless shear stress



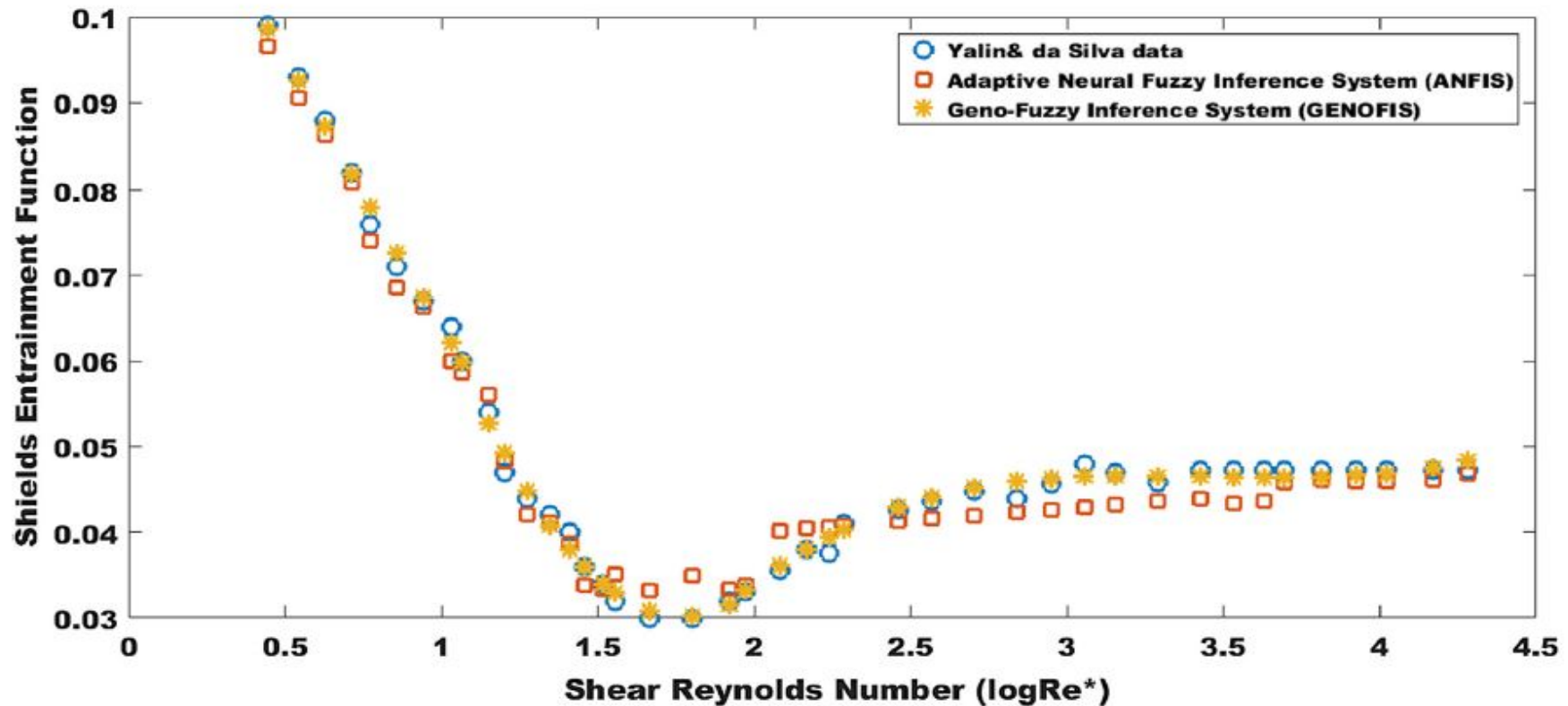
Shields Entrainment Function of observed and predicted dimensionless shear stress of the Buffington and Montgomery collective data for reference approach

Shields Entrainment Function of observed and predicted dimensionless shear stress



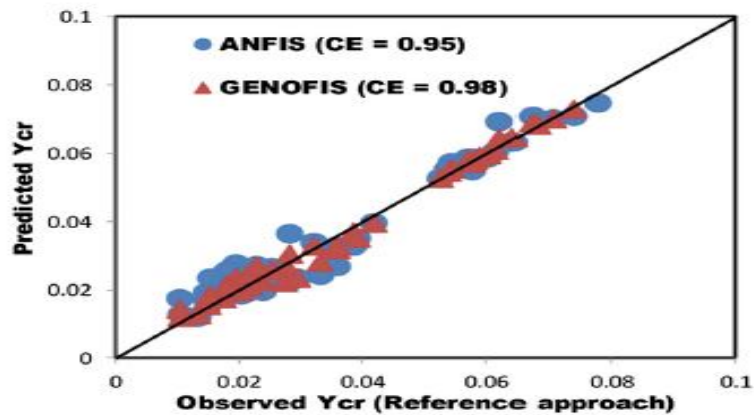
Shields Entrainment Function of observed and predicted dimensionless shear stress of the Yalin and Karahan collective data for visual approach

Shields Entrainment Function of observed and predicted dimensionless shear stress

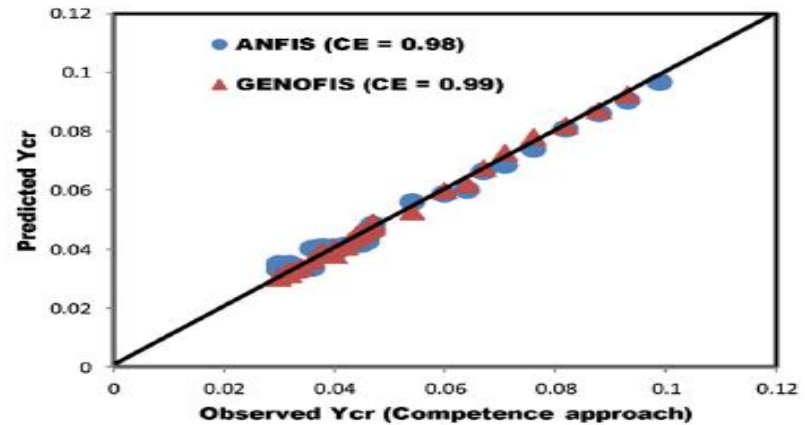


Shields Entrainment Function of observed and predicted dimensionless shear stress of the Yalin and da Silva data for competence approach

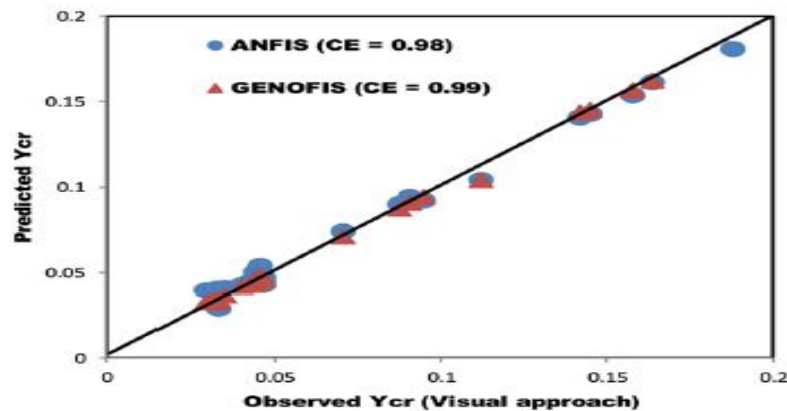
Comparison of Shields entrainment function results predicted by ANFIS and GENOFIS



a



b



c

Bizimana and Altunkaynak (2019). A novel approach for the prediction of the incipient motion of sediments under smooth, transitional and rough flow conditions using Geno-Fuzzy Inference System model. *Journal of Hydrology* , 577 :123952

Initiation of Particle Motion

For large Reynolds numbers ($Re^* > 400$), the value of Fr is constant as **0.06**.

$$\frac{\tau_{0c}}{(\gamma_s - \gamma) \cdot D} = \frac{\gamma \cdot R \cdot S_0}{(\gamma_s - \gamma) \cdot D} = 0.06$$

This range represents actual river flow conditions
Diameter of a sediment with $D = 1.65$ is subjected to incipient motion:

$$D = 10 R S_o$$

Initiation of Particle Motion

The turbulence intensity may reach *very high values* in rivers. S_o , *the size of sediment* which would *not* be *subjected to motion* may be *assumed* to be *twice* the size given as below (Bayazit, 1971):

$$D = 20 R S_o$$

Where R is *hydraulic radius* of the

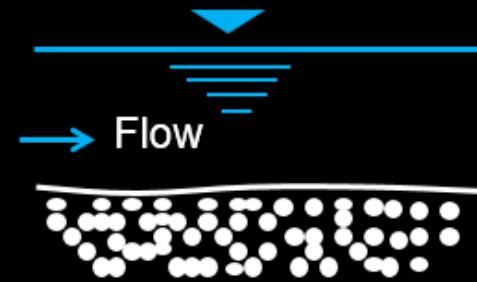


Formation of Bed Forms

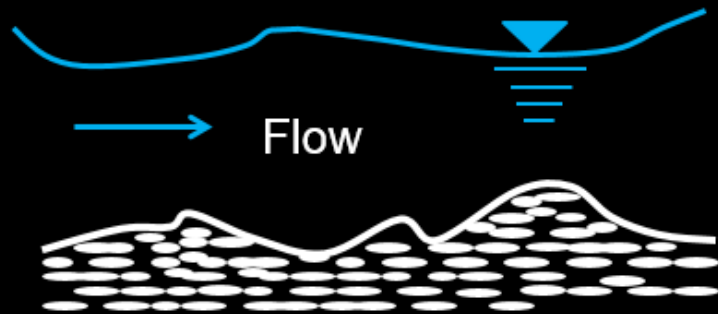
- *After the incipient motion is reached, in case of further increase in velocity (during the passage of a flood wave) the bed develops ripples*
- *At the higher velocities ripples grow in size and named as dunes.*
- *Dunes affect the water surface profiles when $Fr < 1$*



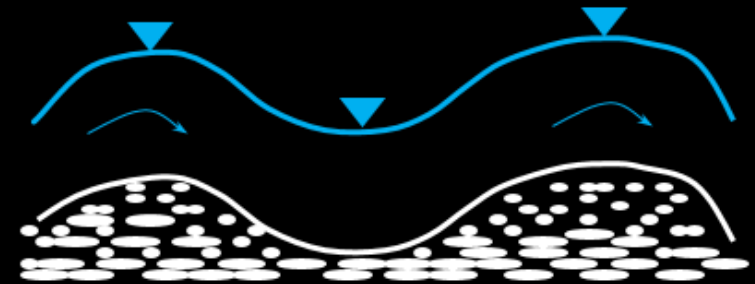
(a) Ripples, $Fr \ll 1$



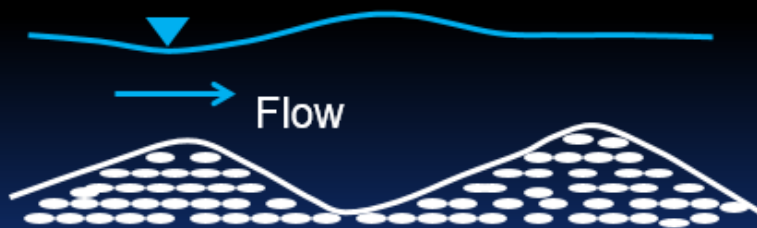
(d) Flat bed, $Fr < 1$



(b) Dunes with superposed ripples



(e) Standing waves, $Fr = 1$



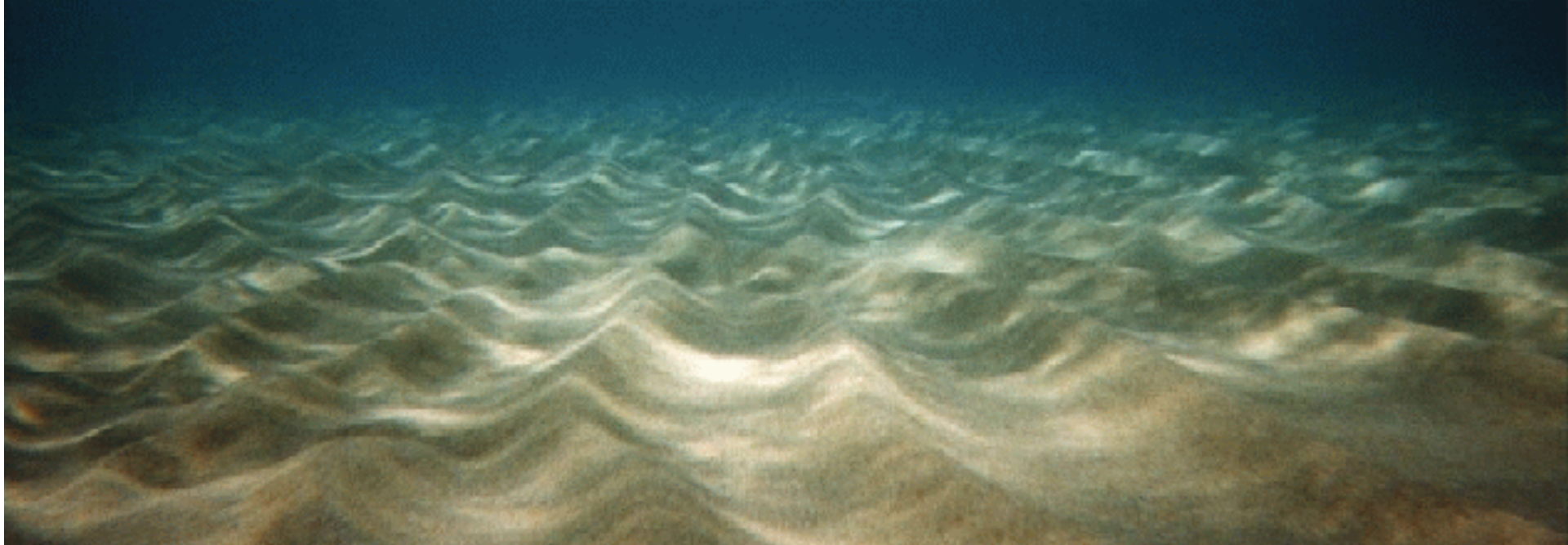
(c) Dunes $Fr < 1$



(f) Antidunes, $Fr > 1$

Bed forms developed in alluvial channels

altunkaynak.net







A photograph of a desert landscape. The foreground is filled with fine, parallel sand ripples. In the middle ground, there are several large, smooth sand dunes. The background shows a range of rugged, rocky mountains under a clear blue sky. The text "Ripples and dunes also exist in the deserts" is overlaid in the center in a light blue, italicized font.

*Ripples and dunes also
exist in the deserts*



Even in Mars...

Formation of Bed Forms

- *Propagation of a dune can be examined by Sediment Continuity Equation:*

$$K \frac{\partial u}{\partial x} + \frac{\partial z}{\partial t} = 0$$

K: *Parameter (sediment properties)*

u: *Average velocity*

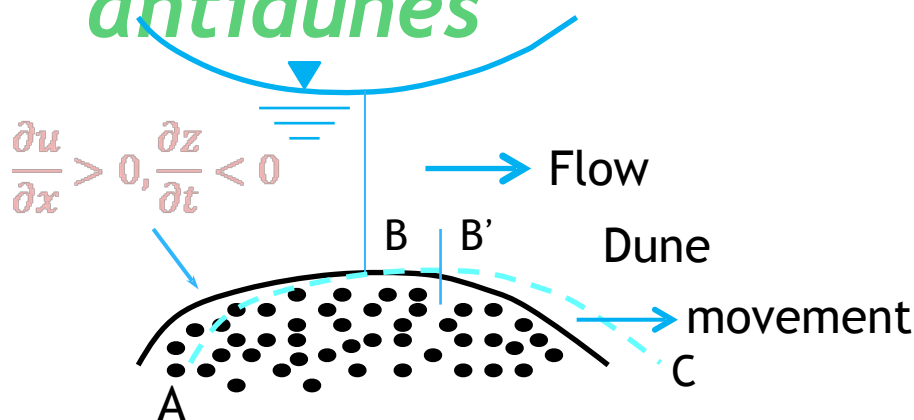
z: *Elevation of bed*

As both dunes and ripples migrate slowly downstream,
the next is the formation of **flat bed**

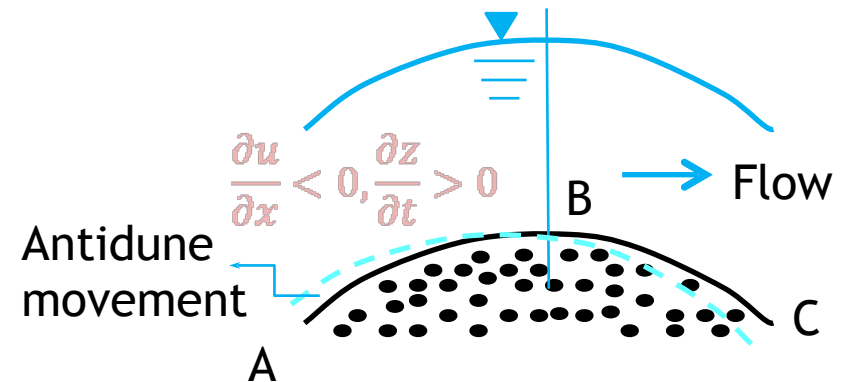
Formation of Bed Forms

- Further increase in the velocity, $Fr \geq 1$ (formation of sand waves in phase with the surface waves)
- Sand waves migrating upstream direction →

antidunes



(a) Dunes



(b) Antidunes

Flow conditions around a dune and

Suspended sediment load passing through the cross section of a river:

$$q_s = \int C(y) u(y) dy$$

Where

- q_s is the volumetric suspended sediment rate per unit width
- $C(y)$ and $u(y)$ are variation of sediment concentration and velocity with respect to depth respectively

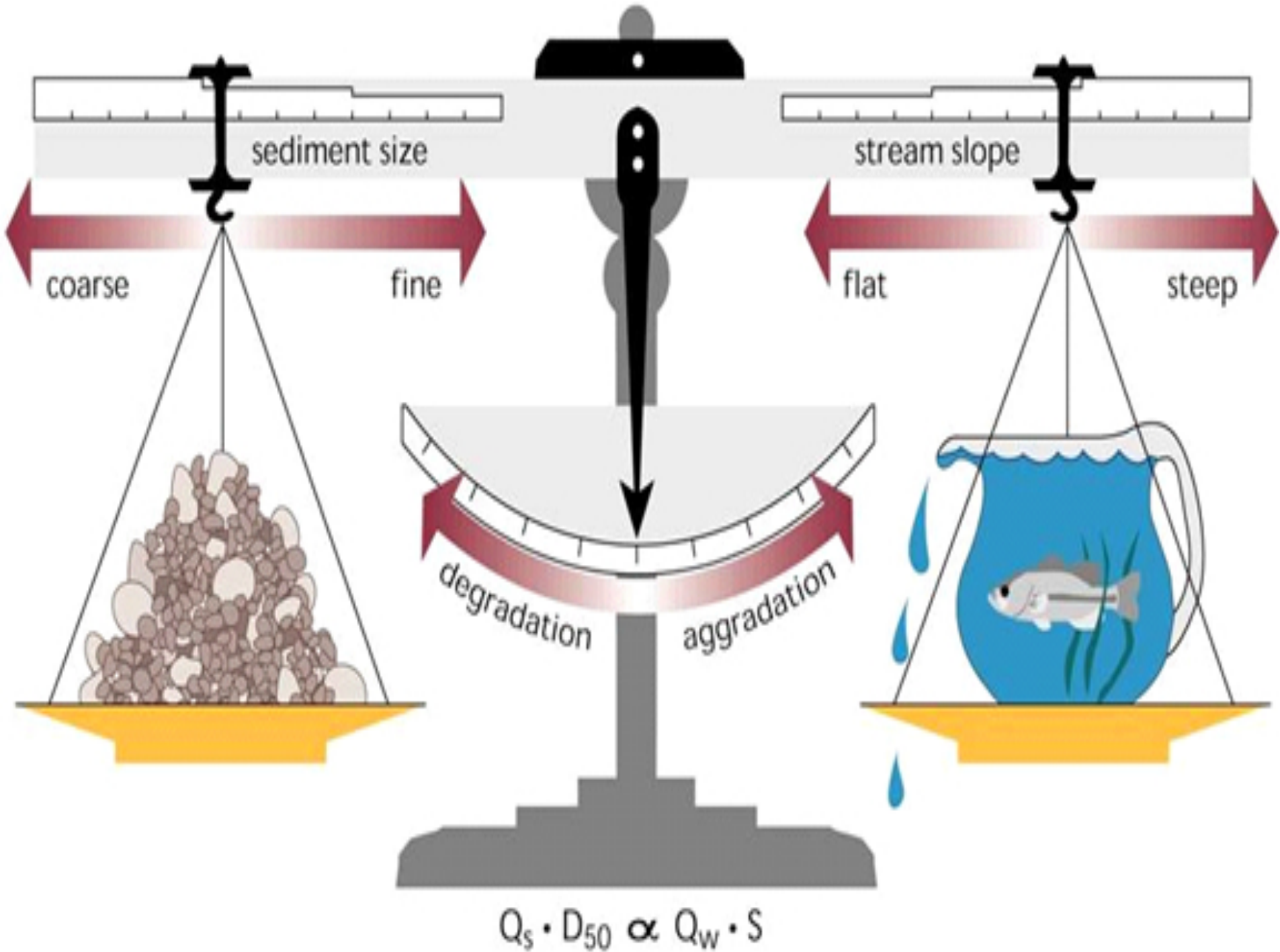
Computation of Sediment Load

➤ In practice,

- A river *cross-section* is divided into a *number of strips*
- The *mean values of velocity and concentration* at each strip are estimated using *field measurements* and *multiplied with each other*

➤ Depth integration method

- *Lowering* and *raising* the sampler *through the depth* during *a specified time interval*
- obtain *sediment rating curve*





Thank you ...

Abdüsselam ALTUNKAYNAK

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<https://upload.wikimedia.org/wikipedia/commons/5/58/>

Aerodynamic Drag of Car.jpg

<https://i.ytimg.com/vi/ukcSp14yWJk/>

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<http://blog.science-matters.org/wpcontent/uploads/2012/02/>

proportionalinverse.jpg