LECTURE NOTES ON FLUVIAL HYDRAULICS

Unit 1: INTRODUCTION (15Lectures)
Origin and properties of sediments-size, shape, fall velocity and its effects, orientation, grain size distribution. Difference between rigid and alluvial channels. Incipient motion of sediment particles: different approaches to study sediment motion- lift force approach, tractive force approach, theoretical and sub- theoretical analysis of Shields, White and others. Types of bed forms or regimes of flow.

TEXT BOOKS:

1. Graf, W.H. "Hydraulics of Sediment Transport", McGraw Hill International, 1984.
2. Garde, R.J. and Ranga Raju, K.G. "Mechanics of Sediment Transportation and alluvial stream Problems", New Age International (P) Limited Publishers, 2000.
3. van Rijn, L.C." Principles of Sediment Transport in Rivers, estuaries and Coastal Seas", Aqua Publications, Delft, The Netherlands, 1993.

REFERENCE BOOKS:

1. Raudkivi, A.J. "Loose boundary hydraulics" Pergamon Press, 1998
2. Bharat Singh" Fundamentals of Irrigation Engineering", Nem Chand and Brothers, Roorkee.
3. Chapter 8 of the book by Rajesh Srivastava, "Flow through Open Channels", Oxford University Press, New Delhi, 2008.
4. River Behaviour, Control and Training, 1971, CBIP Publication No.69.
5. River Behaviour, Management and Training, Volume-I, 1989, CBIP Publication No.204.
6. River Behaviour, Management and Training, Volume-II, 1994, CBIP Publication No.204.

URL

http://www.cbip.org

LESSON PLAN (1 hour each topic)

UNIT-1

1. Definition of Fluvial Hydraulics, its importance, complexities and historical developments.

2. Origin and formation of sediments in stream flows: Physical, Chemical and Organic weathering of rocks; erosion, transportation and deposition of soil by water and wind.

3. Properties of individual sediments - size and their effects.

4. Properties of individual sediments- shape and their effects.
5. Properties of individual sediments - fall velocity and their effects.
6. Orientation of sediment particles.
7. Bulk properties of sediments: grain size distribution
8. Bulk properties of sediments: porosity, specific gravity, angle of repose.
9. Difference between rigid and alluvial channels.
10. Incipient motion of sediment particles, Different methods to study sediment motion.
11. Competency approach, Lift concept, and Critical Tractive Force concept approach.
12. Theoretical and sub-theoretical analysis of Shields.
13. Theoretical and sub-theoretical analysis of White and others.
14. Types of bed forms or regimes of flow in rivers.
15. Mechanism of formation of different types of bed forms and regimes of flow in rivers.

UNIT-1: INTRODUCTION

Fluvial Hydraulics deals with science of flow of sediment-laden water through erodible non-cohesive bed and banks of natural streams and man-made channels (e.g. canal for irrigation, navigation, hydro-power generation, etc. usage) involving the processes of erosion, transportation and deposition of sediment particles.

(Knowledge of Fluid Mechanics, Geo-Science, Open Chanel Hydraulics and Soil Mechanics are pre-requisite to this course.)

Complexities involved with erodible boundary channels are:
(i) Changing cross section, spatially as well as temporally, due to erosion and deposition of sediment particles.
(ii) Additional resistance to flow due to presence of undulations on channel bed.
(iii) Additional expenditure of energy in carrying the sediments.
(iv) Wide variation in size of sediments.

IMPORTANCE:

Presence of sediment in stream flow creates following problems to Civil Engineers in performing their duties during flood as well as lean periods:
(i) operation and maintenance of turbines and pumps, (ii) treatment of water in Water Treatment Plants for domestic and industrial use, (iii) training and harnessing of river flows, (iv) aquatic animal and plant life (thin deposit or sludge seals the surface of bed against circulation of water and oxygen and may wipe out food species), (v) ecological considerations, (vi) silting of reservoirs, canals, formation of delta, etc. (vii) navigational channels, (viii) design of stable channels, (ix) degradation, aggradation, meandering, braiding of natural rivers , (x) local scour around bridge piers, and (xi) design of silt excluders and silt ejectors.

Efficiency of turbines of Khatima project was reduced due to abrasion of blades by coarse sand. More than 80% repairs in China's Yanguoxia help was for treatment of abrasion caused by sediments.Yasuoka reservoir on Tenrya river in Japan lost 80% of its capacity in 13 years. Ichari diversion dam (53m high) on river Yamuna was silted up to crest in 5 years (1972-77). Rate of silting Indian reservoirs varies from 0.2% to 1% of its capacity each year. Kosi river moved through a distance of 112 km westward during 200 years. Yellow river bed was lowered by an average of 4.5m along its reach of 50 km. At Lungmen the bed was lowered by 9m over a length of 2-4 km.

HISTORICAL DEVELOPMENT: Many of the earlier civilizations came into being in the alluvial fertile valleys of large rivers, e.g. Nile valley in Egypt, along Tigris and Euphrates rivers in Mesopotamia (Iraq), along Indus, Ganga, Yamuna, Gomti, Narmada, Sone, Tapi, Godavari, Cauveri, Brahmaputra, Barak, etc. river in India, and along Yellow river in China. Sage Vashishtha had mentioned in Yog Vashishtha that flowing water has an ability to carry gravel, sand, silt and clay and this ability decreases as the velocity of flow is decreased. Hence for sedimentation the flow velocity should be reduced and for scour it should be increased.

The first engineer to contribute in knowledge of science of fluvial hydraulics was Dominico Guglielmini through his book published in 1697. He realized that vertical velocity distribution in stream flow is not uniform and found, based on experiments that for scouring to occur the scouring force should be greater than the resistance of soil. A mathematician named as Paul Frizi published a book "Rivers and torrents with the method of regulating their courses and channels" in 1762 and translated by Major General John Garstin in English and published in London in 1818-based on laboratory experiments.

Lachalas in 1871 distinguished between transportation of solids by traction i.e. bed load and the in suspension i.e. due to action of eddies and vortices. French engineer Paul Francois Dominique du Boys in 1879 gave the equation for bed load transportation. Most of the development in the science of fluvial hydraulics occurred only recent.

ORIGIN AND FORMATION OF SEDIMENTS:

Weathering of rocks (a process by which solid rocks are broken up and decayed) and erosion of soil by action of precipitation, water, wind, gravity, land-slides and human activity are the origin of individual as well as bulk sediments transported by water as well as air through overland flow, rivulets, streams, rivers and deposited on stream beds or overland and also those found in deserts. Weathering can be grouped into: (i) physical/mechanical weathering, (ii) chemical weathering, and (iii) organic weathering.

PHYSICAL WEATHERING of rocks occurs due to (i) repeated freezing and thawing of rocks at high altitudes (volume of water increases by about 10% when it freezes and when water is confined , such expansion causes a considerable force and the water which enters the cracks and fissures and freezes tends to push the rocks apart), (ii) rolling of rocks, boulders, stones along flow of water, and their collision with each other and converting them into smaller and smaller in size as river proceeds from its origin towards its confluence with larger river because of gravity,(iii) overland, stream bed and bank erosion because of inertial forces of rain, water, and gravity, (iv) expansion caused by chemical changes, and (v) exfoliation (to remove dead cells from surface of skin to make it smoother) resulting from sudden changes in temperature- extreme heating followed by sudden cooling.

CHEMICAL WEATHERING of rocks occurs due to (i) their interaction with oxygen, carbon dioxide and water vapor present in atmosphere, (ii) carbonic acid and excess water act on granite, albite biotite, etc. and give free silica carbonate of alkali elements and other secondary minerals,(iii) secondary minerals , such as kaolinite formed by chemical weathering occupy a volume greater than the original mineral, (iv) hydration of minerals gives rise to new secondary minerals and increases their volume, (v) Iron ores are oxidized, and (vi) under the process of chemical exfoliation, the sheets are notably decayed and discolored. The work is performed by the solutions which penetrate slowly along the cleavage cracks of the crystals and between the grains and thereby induce the formation of new minerals of large volume which causes disintegration.

ORGANIC WEATHERING of rocks occurs primarily due to burrowing animals (earthworms, ants, rodents, etc.), and also due to roots and trunks of plants and trees which wedge the rock apart and break them into pieces. Man also breaks rocks by making road cuts, tunneling, and quarrying, mining and cultivating land.

All these processes loosen and break the rocks of the land surface and alter them to easily erodible material. Thereafter these sediment materials are transported from one place to another by rain water, torrents, streams, wind glaciers and gravity. The processes of erosion of soil from land surfaces, beds and banks of rivulets, streams, and rivers, transport of eroded material, deposition of partial of this material in lakes, streams ,rivers, flood plains, overland and such other processes depend on **characteristics of sediment, characteristics of fluid and flow and characteristics of channels, reservoirs**. The size, mineral composition, density, surface structure, etc. of sediment depend on its parent rocks.

TYPES OF SEDIMENTS BASED ON THEIR MODE OF TRANSPORT:

After the parent rocks are disintegrated, the material is transported from one place to another by rain water, torrents, stream flows, wind, glaciers and gravity and deposited on streambeds, flood plains and over land. The material is called **Alluvium** if transported and deposited by water through streams, **Loess** if transported and deposited by wind over land, and **Glacial Drift** if transported and deposited by glaciers.

WATER/STREAM EROSION AND DEPOSITION:

The major portion of the sediment load carried by streams comes from the erosion of soil in the drainage basin; a certain amount also originates as a result of weathering of rocks from the bed and banks of the stream. The amount of sediment load carried depends on the size of the material, discharge, slope, and channel and catchment characteristics. When there is sudden reduction either in the discharge or in the slope of an equilibrium stream, the stream cannot transport the material supplied to it and the excess material is deposited. These deposits give rise to various formations depending on the mode of deposition and they are called **flood plains**, **alluvial fans**, **delta**, etc.

WIND EROSION AND DEPOSITION:

Arid and semi-arid regions are characterized by relatively low and infrequent rainfall. As such, stream flows as well as stream erosion in these regions are small, generally. High velocity winds, carrying fine sand with them are effective agents of wind erosion. When wind blows over deserts and ploughed fields, fine sand and dust particles are carried away while the coarser material is left behind. This process is called **deflation**. If dust carried by the winds is transported to great distances, when the wind velocity is reduced, this material is deposited as **loess**.

GLACIAL EROSION AND DEPOSISION:

As big pieces of ice move over land surfaces they pick up loose rock, boulders, and sand along with them. This material acts as an abrasive agent to loosen other materials and reduce their sizes. The transporting capacity of glaciers is large enough to transport rocks of the size of a room. When the glacial melts most of the material that it has been carrying is dropped and deposited.

PROPERTIES OF SEDIMENTS: (a) Properties of individual sediments, such as size , shape, fall velocity, mineral composition, surface texture and orientation; (b) Properties of bulk sediments, such as grain size distribution, porosity, specific gravity, cohesion and angle of repose.

SIZE: Sediment size is usually defined by its volume, fall velocity, size of sieve mesh or by its intercepts. Measurements of its size by its volume and fall velocity are based on the premise that measurements can be made and expressed as the diameter of an equivalent sphere.

Nominal diameter, d_n of a sediment is defined as the diameter of a sphere which is having the same volume as that of the particle.

Fall diameter is defined as the diameter of a sphere of relative density 2.65 and having the same standard fall velocity as that of the particle. It is the terminal fall velocity of the particle in quiescent distilled water of infinite extent and at 24^0C.

Sieve diameter, d of a sediment particle is the size of the sieve opening through a given particle will just pass. Sieves are generally used to separate the particles larger than 0.0625mm in diameter. It has been found that for natural material, d=0.9da.

Tri-axial size of sediment particle: The tri-axial sizes of sediments are measured along the three mutually perpendicular axes of particles. If 'a' is the longest or the major axis,'b' the intermediate axis, 'c' the shortest or minor axis, then one can take 'b' as index of size, $b=K.d_n$, where K is a function of shape factor, known as Markwick's constant=$c/\sqrt{ab}$. Approximate values of K for various values of shape factors are given below:

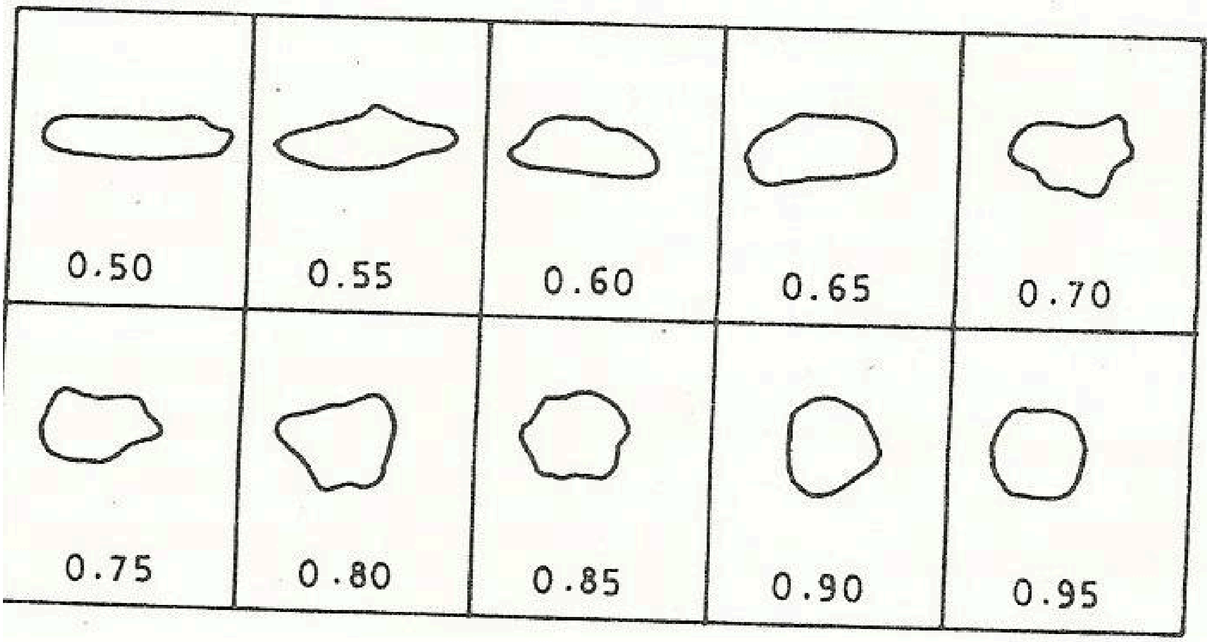
Shape factor ($c/\sqrt{ab}$)	K
0.3	1.27
0.5	1.13
0.7	1.05
0.9	1.00

Grade Scale for Sediment Size Terms

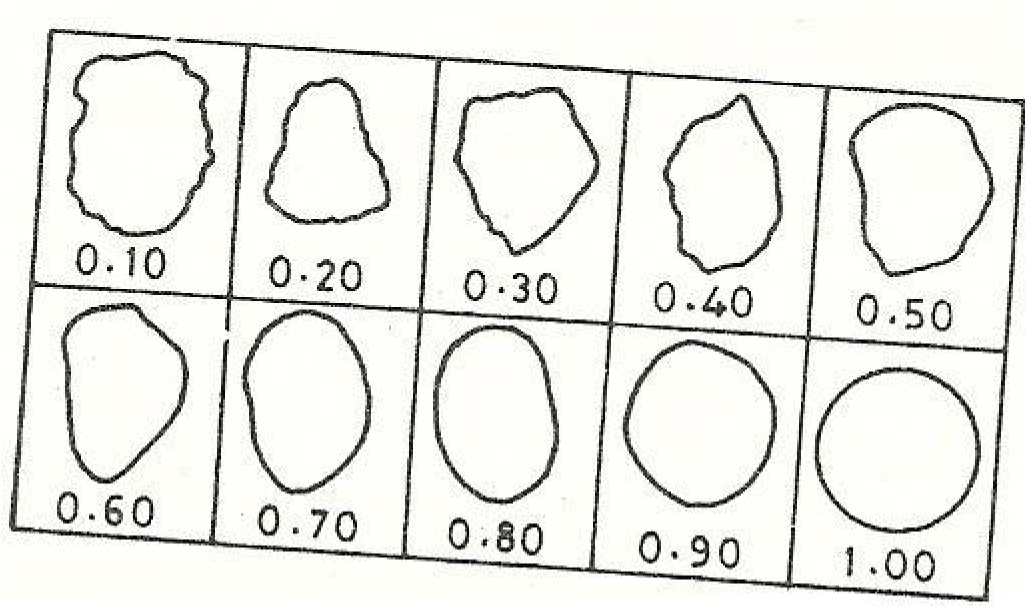
Sediment size (mm)	Class name	Sediment size(mm)	Class name
4096-2048	Very large boulders	1/2-1	Coarse sand
2048-1024	Large boulders	1/4-1/2	Medium sand
1024-512	Medium boulder	1/8-1/4	Fine sand
512-256	Small boulders	1/16-1/8	Very fine sand
256-128	Large cobbles	1/32-1/16	Coarse silt
128-64	Small cobbles	1/64-1/32	Medium silt
64-32	Very coarse gravel	1/128-1/64	Fine silt
32-16	Coarse gravel	1/256-1/128	Very fine silt
16-8	Medium gravel	1/512-1/256	Coarse clay
8-4	Fine gravel	1/1024-1/512	Medium clay
4-2	Very fine gravel	1/2048-1/1024	Fine clay
2-1	Very coarse sand	1/4096-1/2048	Very fine clay

SHAPE: Shape of a sediment particle depends on origin, abrasion, corrosion, breakage, crushing, and splitting, chipping, grinding and chemical weathering. Cubes, spheres, cylinders, elliptical shapes of sediments are rare. Shapes have been defined as coefficients based on volume, based on projected area, and based on major, intermediate and minor axes. If d is the diameter of the circle of area equal to projected area of the particle perpendicular to c-axis, following definitions may be used:

Volume constant=Volume of particle/d^3
Surface constant=Surface area of the particle/d^2
Andreasen's coefficiant=d/ (Volume of particle)$^{1/3}$
Markwick's coefficient=Volume of particle/abc
Markeick's surface constant=$b/d_n=K=c/\sqrt{ab}$
Sphericity=[Volume of particle/volume of circumscribing sphere]$^{1/3}$=d_n/a
Following figure gives a chart for determining the sphericity of coarse particles by visual observations:



Roundness is the ratio of the average radius of curvature of the several corners or edges to the radius of curvature of the maximum inscribed sphere or the normal radius of the particle. Following figure gives a chart for visual estimation of roundness of coarse material:

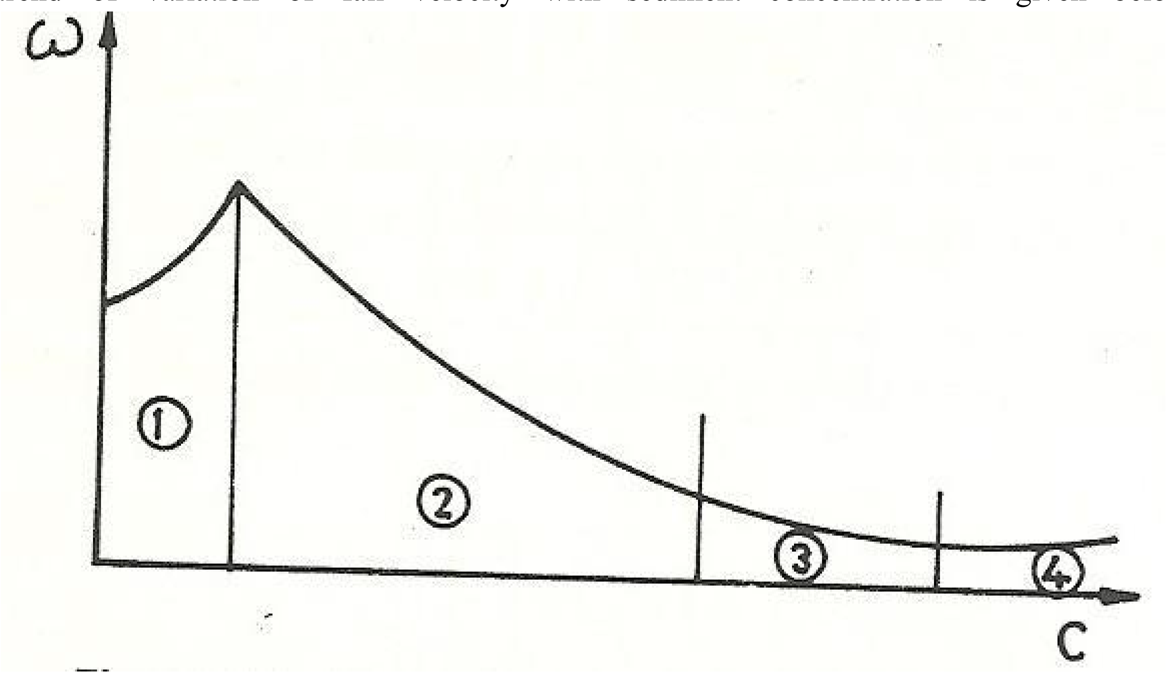


If r_1 is the smallest radius of curvature in the projected area, following definitions may be used:
Cox's coefficient of roundness=$r_1/(abc)^{1/3}$
Cailleux coefficient of bluntness=r_1/a
Tickell's coefficient of circularity=Projected area/Area of circle of diameter α
Shape factor=$c/\sqrt{ab}$
Flatness ratio= (a+b)/2c. (It varies from 1.05 to 10 for natural sediments)
Markwick's modulus of flatness=c/b and Markwick's modulus of length=a/b.
(If a/b≥1.8, the particle is long, while if c/b≤0.6, the particle is called flat.)
Uniformity coefficient=d_{60}/d_{10}
Kramer's uniformity coefficient, M=$\sum_{0}^{50} \Delta pidi / \sum_{50}^{100} \Delta pidi$
Arithmetic mean size diameter, $d_a=\sum_{1}^{n} fidi$, where fi is the probability of occurrence of size d_i as obtained from measured size distribution.
FALL VELOCITY: As sediment particle starts falling in a fluid from rest, its velocity increases because its submerged weight is the only force acting on it. As the velocity increases, the drag force on the particle also increases, which causes a decrease in the net force acting downward and a consequent decrease in acceleration. After some time, the submerged weight and the drag force become equal in magnitude and the sediment particle attains a constant velocity, known as terminal fall velocity, terminal velocity, or settling velocity.
Navier-Stokes solved this problem for laminar flow around a sphere equating the submerged weight of sphere with the viscous resistance, assuming negligible inertial forces as follows:
$\mu\ d^3\ (\Upsilon_s-\Upsilon_f)/6=3\pi d\mu\omega_0$
$\omega_0=d^2(\Upsilon_s-\Upsilon_f)/18\mu=2r^2\ (\Upsilon_s-\Upsilon_f)/9\mu$
where, d=diameter of sediment particle
r=radius of sediment particle
μ=dynamic viscosity of fluid
ω_0=terminal fall velocity of spherical sediment

Υ_s= specific weight of sediment particle
Υ_f= specific weight of fluid
ASSUMPTIONS: (i) Initial forces are neglected and therefore the law holds good up to Reynold's number, R_e ($=\omega_0 d\rho_f/\mu$) $\leq$0.10. As an approximation it can be used up to R_e=1.0.
(ii) Sediment is spherical in shape.
(iii) No slip occurs between fluid and surface of sediment particle.
(iv) Sediment particle falls in an infinite and calm fluid.

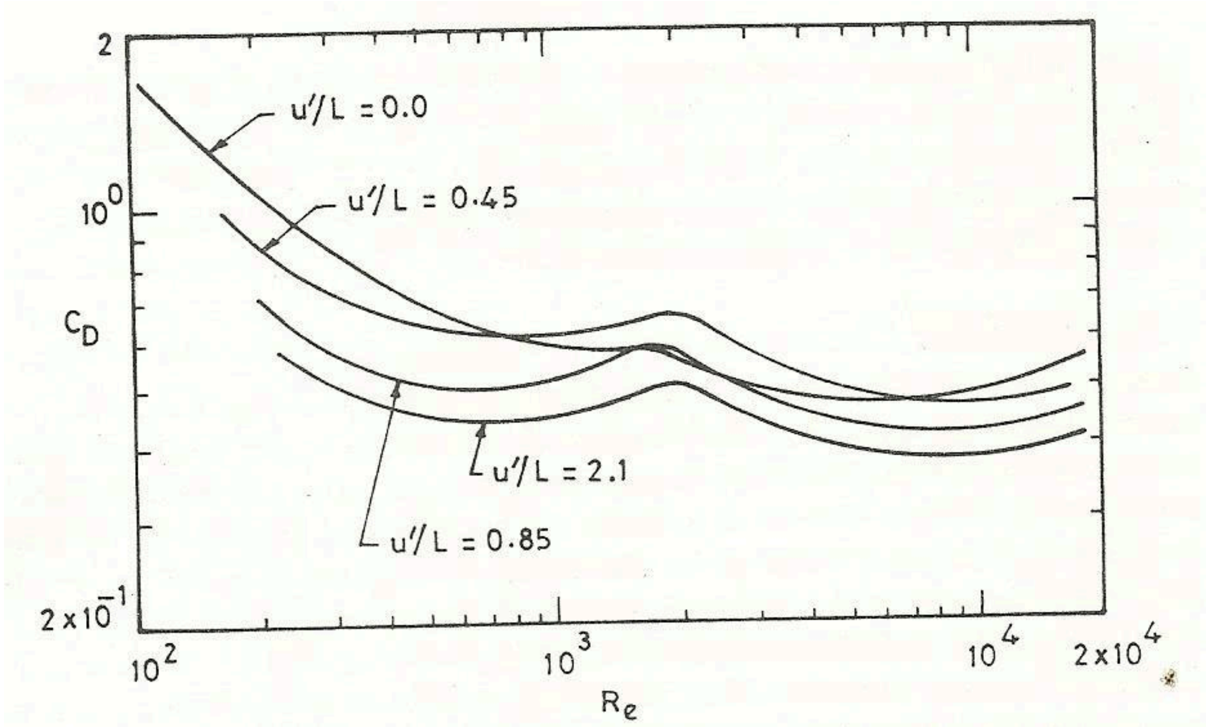
FACTORS AFFECTING FALL VELOCITY OF SEDIMENTS:
(i) Reynold's number (R_e)-when R_e is large turbulence will be created close to surface of the sediment particles.
(ii) Shape factor, (iii) Proximity to boundary, (iv) Suspended sediment concentration, (v) Turbulence, (vi) Vertical velocity distribution, (vii) Vertical sediment distribution, (viii) Non-uniformity of sediment in suspension, (ix) Horizontal velocity distribution, (x) Horizontal sediment distribution.

EFFECT OF CONCENTRATION ON FALL VELOCITY:
As sediments fall they enter in the regions of higher and higher concentration of sediments as a result fall velocity of the sediment decreases continually as it falls down. The qualitative trend of variation of fall velocity with sediment concentration is given below:



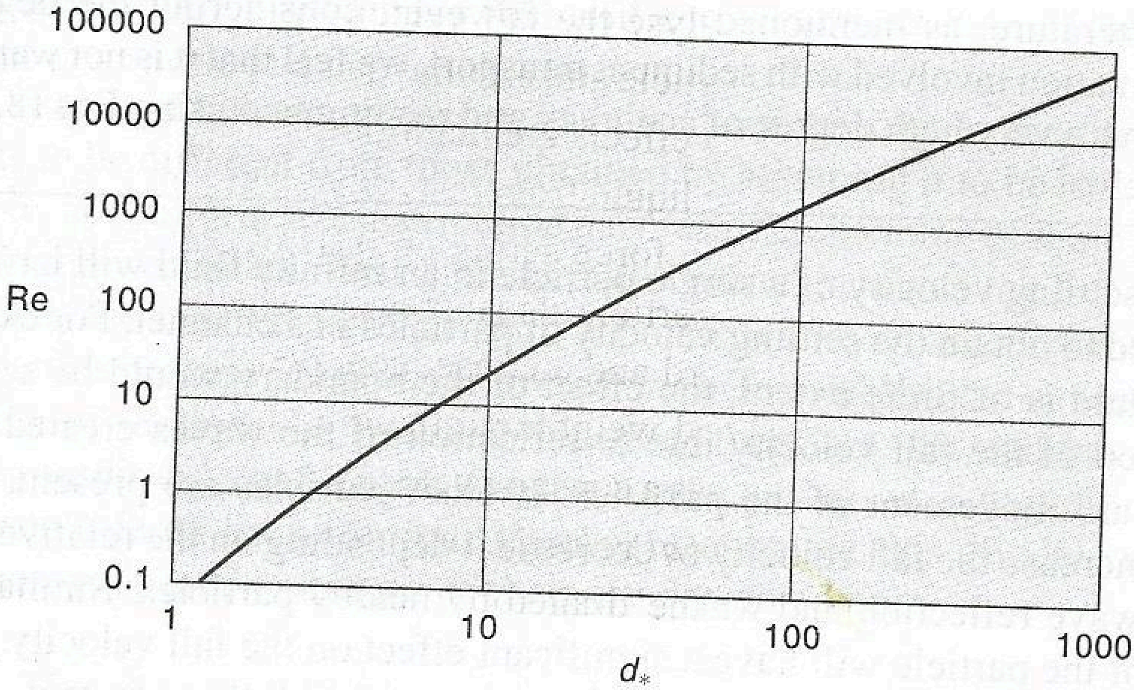
Region (1) is one of 'sparse settling' in which the concentration is low and the fall velocity increases with increase in concentration. Region (2) is the region of 'disturbance settling' in which the fall velocity decreases with increase in concentration, as indeed it does in regions (3) and (4) also which may be designated respectively as 'group settling' and 'dense settling'. The concentrations are extremely high in regions (3) and (4), whereas range of concentration is very small in range (1), generally up to 20ppm.

EFFECT OF TURBULENCE ON FALL VELOCITY:
The cases considered above were exclusively for the fall velocity of a particle in turbulence-free fluid. Open channel experiments done by Jobson and Sayre indicate an increase in fall velocity due to presence of turbulence fluctuations; the increase is more in case of fine sediments than in case of medium sediments. Experiments conducted by Boilat and Graf show that C_D is dependent on Re and u'/L, where u' is the root mean square value of the turbulent fluctuations and L is the macro scale of turbulence as shown below:



EFFECTS OF SEDIMENT PARTICLE SHAPE ON FALL VELOCITY:
The way in which the sediment particle orients while falling in a fluid depends on the R_e. For $R_e \leq 0.10$, any orientation is stable, but for $R_e \geq 0.10$ only one stable orientation is possible-that with the maximum cross sectional area normal to the direction of motion.
EFFECTS OF INERTIAL FORCES ON FALL VELOCITY: In 1933 Ruby suggested a formula for the fall velocity of coarse materials which fall beyond Stokes' range. He suggested that the total resistance to the motion of a particle is the sum of viscous resistance and the **impact resistance**, the latter being estimated to be $\boldsymbol{\pi d^2 \rho_f \omega_0^2/4}$.
Hence $\pi d^3(\Upsilon_s-\Upsilon_f)/6=3\pi d\mu\omega_0 +\pi d^2\rho_f\omega_0^2/4$
$\omega_0=\sqrt{[36\mu^2/\rho_f^2 d^2 +2(\Upsilon_s-\Upsilon_f)d/3\rho_f]}-6\mu/\rho_f d$

Stokes' law can be written in slightly different form. According to Newton, the resisting force can be expressed as, $F=C_D A\rho_f\omega_0^2/2$ in which C_D is the drag coefficient and A is the projected area of the sediment particle. However, according to Stokes $F=3\pi d\mu\omega_0$
Hence, $C_D A\rho_f\omega_0^2/2 =3\pi d\mu\omega_0$
Here $A=\pi d^2/4$, Therefore $C_D=24\mu/\omega_0 d\rho_f=24/R_e$
However, the equation $C_D=24/R_e +3/\sqrt{R_e} +0.34$ is found to agree closely with the experimental data in the range $0.50 \leq R_e \leq 10^4$
Equating the drag force and the submerged weight of sediment:
$C_D(\rho_f\omega^2/2)\text{x}(\pi d^2/4)=g(\rho_s-\rho_f)\pi d^3/6$
Since $R_e=\rho_f\omega d/\mu$, we can write this equation in dimensionless form:
$3C_D R_e^2/4=g\rho_f(\rho_s-\rho_f)d^3/\mu^2=d_*^3$ in which d_* is dimensionless grain diameter defined as $d_*=[g\rho_f(\rho_s-\rho_f)/\mu^2]^{1/3}\, d$
As an approximation, for estimation of fall velocity for $d_* \leq 2500$, which covers the Reynold's number range up to 2×10^5,
$R_e=d_*^3/(18+0.616 d_*^3/2)$
Typical values of fall velocities range from about 5 mm/second to about 20 cm/second for particle sizes ranging from 0.1mm to 2 mm. Following graph shows the relationship between Reynold's number and the dimensionless grain diameter, d_*:



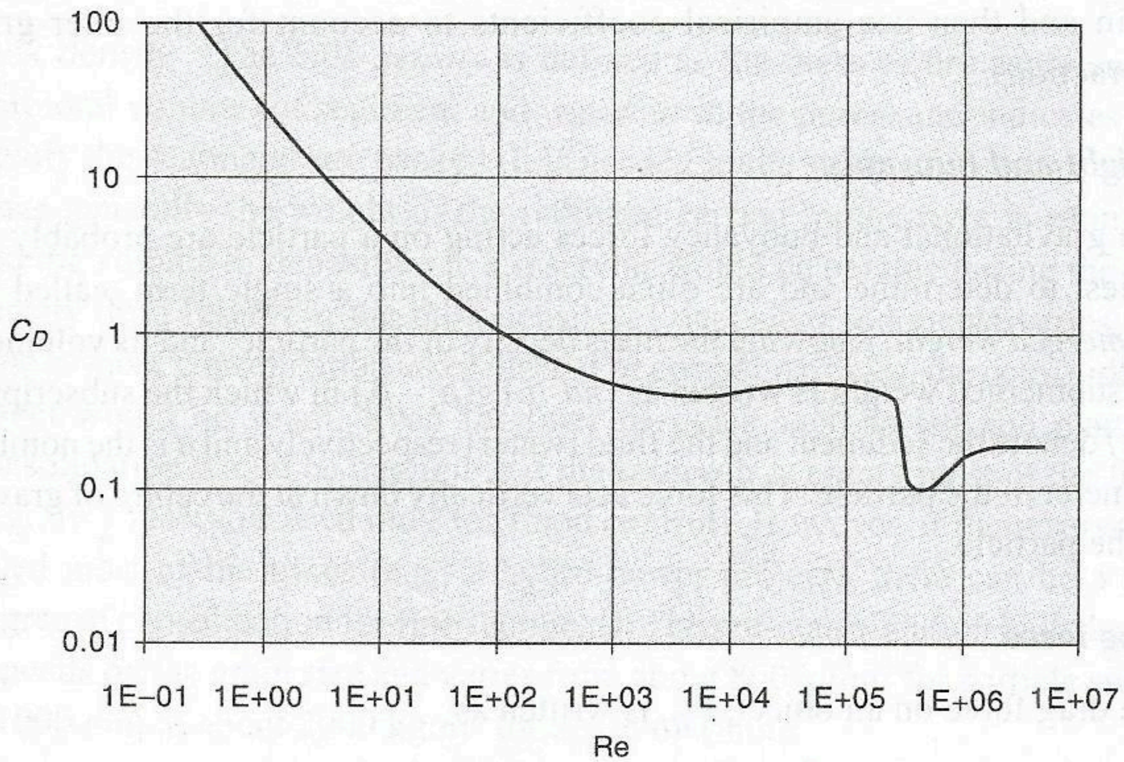
Swamee and Ojha (1991) have found that

$C_D=0.5[16\{(24/R_e)^{1.6}+(130/R_e)^{0.72}\}^{2.5}+\{(4000/R_e)^2+1\}^{-0.25}]^{0.25}$

Brown and Lawler (2003) provide a recent review, summary of previous work, and propose simple approximations for R_e up to $2x10^5$:

$C_D=24(1+0.0888\sqrt{R_e})^{2.24}$

Following figure shows the variation of the drag coefficient, C_D with the Reynold's number of the particles (E indicates as exponential):



ORIENTATION OF SEDIMENTS: (i) Orientation of sediment particle while it is falling in a fluid- known as Instantaneous orientation, and (ii) Orientation of the sediment particle after it has deposited on the bed- known as Fabric.

Instantaneous orientation depends on relative magnitudes of inertial and viscous forces, i.e. R_e and shape of sediment. Within Stokes's range any orientation is stable so that the particle retains its original orientation as it descends. After the inertial forces become significant, i.e. $Re \geq 0.10$, the particles tend to orient themselves in one stable position- the one the maximum cross sectional area normal to direction of motion. Beyond a certain Re, which is a function of shape, there is no stable orientation and the particle oscillates as it falls down. For values with higher values of shape factors, this limiting value of 1000 but for particles with low values of shape factor it can be as low as 100. Particles with small values of shape factor but reasonably symmetrical in shape can have stability up to $Re \geq 10000$.

Fabric is the orientation of sedimentary particle as it deposits on the bed depending on shape of particle, direction of current flow and relative magnitude of permeability in the vertical and horizontal directions. The flat pebbles deposit on bed of stream in such a way that the pebbles point upward in the direction of flow.

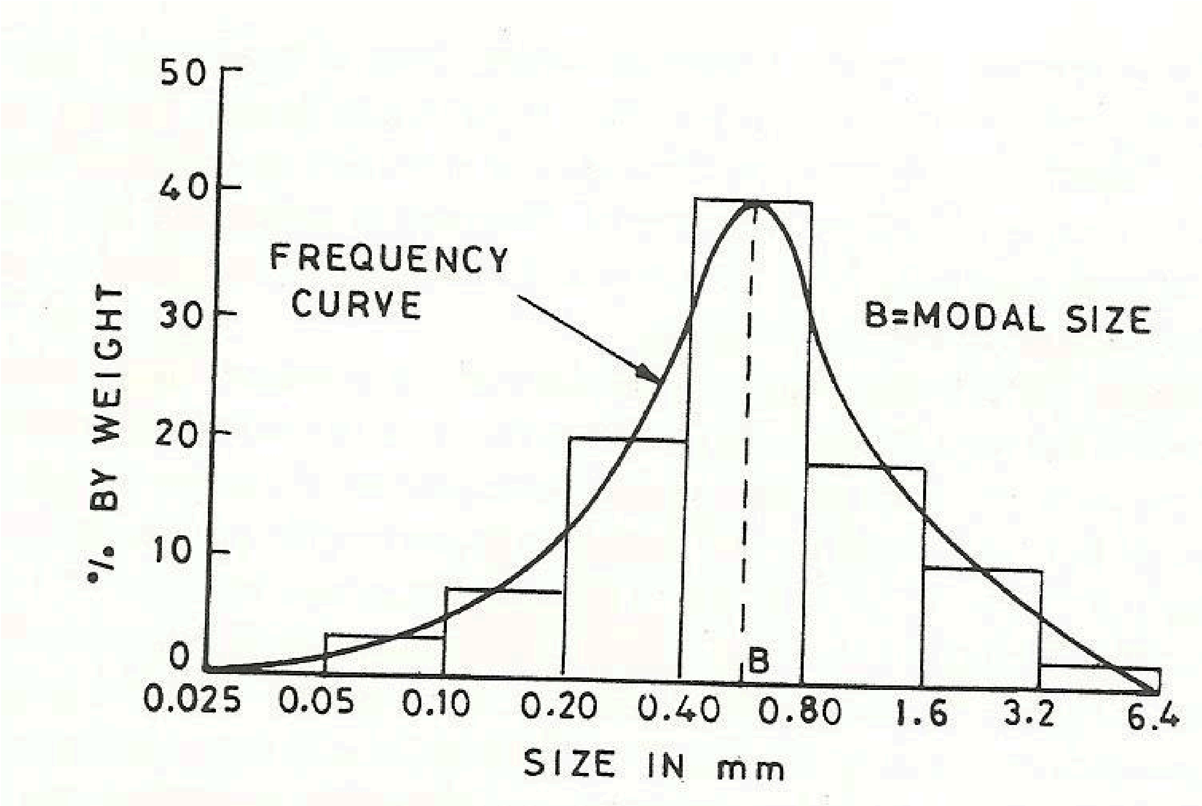
BULK PROPERTIES OF SEDIMENT: (i) Grain size distribution, (ii) Porosity, (iii) Specific weight, and (iv) Angle of repose.

GRAIN SIZE DISTRIBUTION: Knowledge of relative abundance of sediment particles of different size ranges is quite important since other bulk properties such as compactibility, porosity and permeability depend to a certain extent on the size distribution.

After sieve analysis has been carried out, the data obtained are in the form of amount of sediment retained over sieves of various sizes. These data are presented in various ways so as to draw definite conclusions and obtain definite information.

(a) Histogram with size grades on logarithmic scale.
(b) Frequency polygon and frequency curve.
(c) Cumulative frequency curve

The Histogram and frequency curve are shown below:



The central tendency of the frequency distribution curve can be described by parameters such as mode, median and mean.

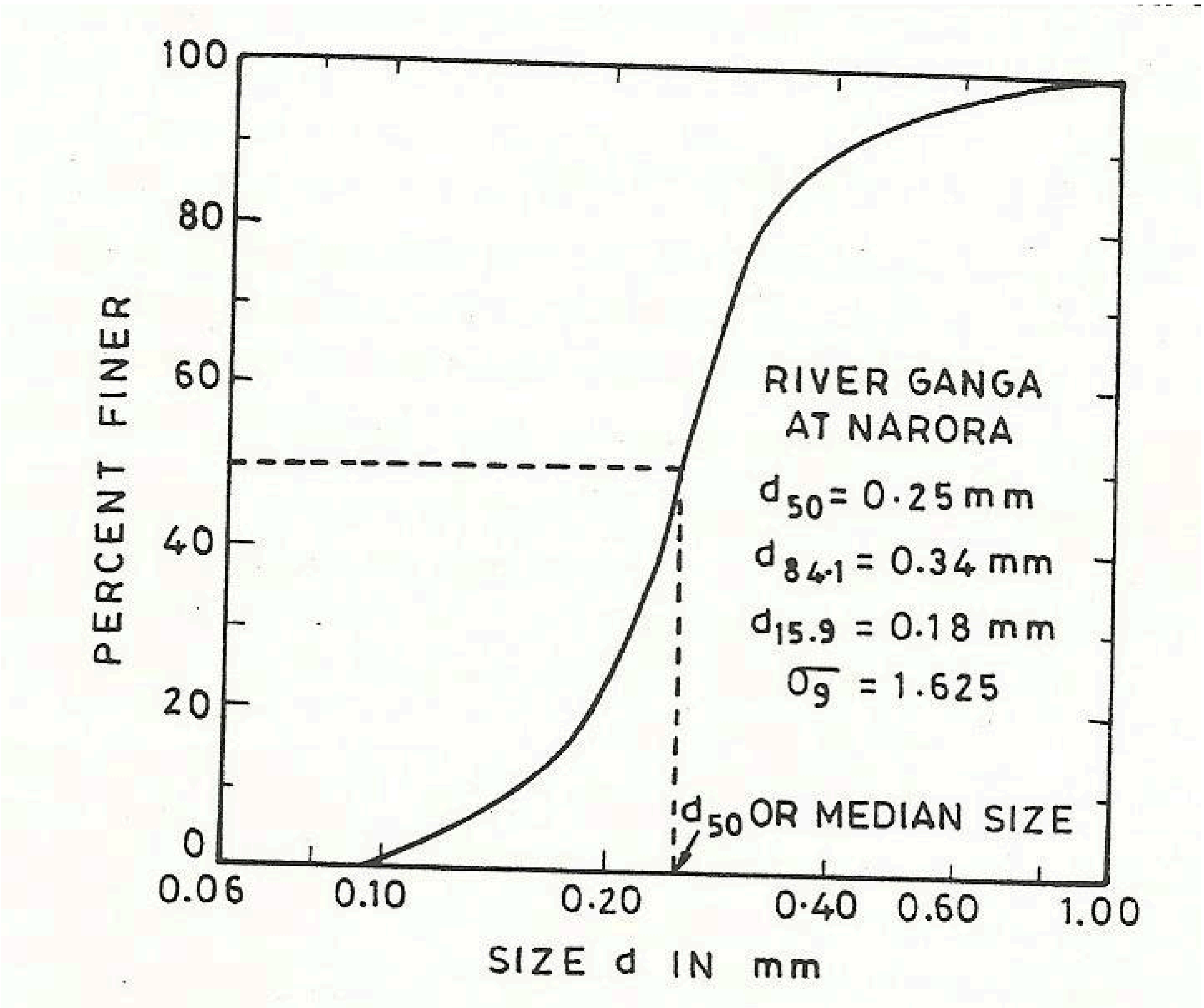
Mode is the most predominant size in the sample and is given by the size corresponding to the maximum ordinate of the frequency curve.

Median size d_{50} is the sediment size for which 50% of the material by weight is finer.

Arithmetic **mean** size d_a is defined as the distance from the y-axis of the centroid of area enclosed by frequency curve. The arithmetic mean d_a and the standard deviation can be obtained from the equation $d_a=\sum_{i=1}^{i=n} fidi$ and $б=\sum_{i=1}^{i=n}(di-da)^2$ fi}$^{0.5}$ in which f_i is the occurrence of size d_i as obtained from measured distribution.

The arithmetic mean value d_a can be obtained from the graph by reading the intercept of the line at 50%-also known as median size.

When the cumulative frequency curve for size distribution of sediment is plotted on ordinary or semi log papers, one usually gets an S–shaped curve as shown below:



A symmetrical S-curve on ordinary paper plots as a straight line on the arithmetic probability paper. Such a distribution is known as normal or Gaussian distribution which follows following law: $f(d_i)=(1/\sigma\sqrt{2\pi})exponential[-(di-da)^2/2\sigma^2]$ in which $f(d_i)$ is probability of occurrence of size d_i.

Standard deviation, $\sigma = (d_{84.1}-d_{50}) = (d_{50}-d_{15.9})$

For normal distribution, 68.2% of the values will be within the range of $(d_{50}\pm\sigma)$ while the corresponding percentages for the ranges of $(d_{50}\pm2\sigma)$ and $(d_{50}\pm3\sigma)$ will be 95.4 and 99.73 respectively. Many natural occurrences, such as errors in measurements, have a tendency to be normally distributed.

For a normal distribution curve, the arithmetic mean, median and the mode have the same value.

The spread of the frequency distribution curve can be expressed in terms of parameters such as sorting coefficient, arithmetic quartile deviation and standard deviation.

Sorting coefficient, $s_0=\sqrt{d_{75}/d_{25}}$. For a completely uniform material, the sorting coefficient will be unity.

Arithmetic quartile deviation is defined as $(d_{75}-d_{25})/2$. It is dimensional quantity.

For the data following normal distribution, the standard deviation is given as:

$\sigma = (d_{84.1}-d_{50}) = (d_{50}-d_{15.9})$

If the data follows log-normal distribution, the geometric standard deviation:

$\sigma_g=d_{84.1}/d_{50}=d_{50}/d_{15.9}$

Alternatively, $\sigma_g=1/2[(d_{84.1}/d_{50}) + (d_{50}/d_{15.9})]$

Kramer's Uniformity Coefficient: M= $\sum_{i=0}^{i=50} \Delta pi.di / \sum_{i=50}^{i=100} \Delta pi.di$

This parameter is used in studies of the critical tractive force of non-uniform materials.

Porosity= $\frac{Bulk\ volume - Grain\ volume}{Bulk\ volume}$ **x100**

Specific weight of sediment: Its knowledge is required to estimate the life of reservoirs. It may vary from 4.8kN/m^3 to 20 kN/m^3.

Name of reservoir	Specific weight of sediment, kN/m^3
Bhakra	10.40-15.80
Koyna	8.10-13.10
Mayurakshi	8.00-11.70
Hirakud	7.60-10.00
Matatila	5.20-6.40
Maithon	5.10-17.10
Panchet	5.60-17.60

Lane and Koelzer have shown that $W=W_0+K \log T$
where, W=specific weight of sediment in kN/m^3 at the end of T years
W_0= initial specific weight, normally taken as the value at the end of one year
K= function of sediment size and the method of reservoir operation.
Degree of consolidation of silt in dead storage depends on size of materials. Finer materials have low initial specific weights and they can be consolidated to much higher specific weights over a relatively long period. On the other hand, coarse sediments have higher initial specific weight but they consolidate very little over a relatively long period.

Median size,mm	0.0012	0.005	0.01	0.05	0.10	0.25	0.50	1.00
Initial sp.wt.kN/m^3	7.55	9.45	10.2	11.6	12.6	14.0	16.3	18.9

Angle of repose: This is important in study of critical tractive force, design of stable channels and other hydraulic problems like stability of side slopes of banks. Gibson has proposed the following:
$\tan \varphi = K\, d^{0.125}\, S^{0.19}\, \Upsilon^{0.25}$
where, d=mean grain diameter in mm.
S= relative density of the particle in water
ϒ=mean ratio of the longest to the shortest diameters
K=0.60

DIFFERENCE BETWEEN RIGID AND ALLUVIAL CHANNELS:

Rigid channels are those channels in which the boundary is not deformable in the sense that the shape, planiform and roughness magnitudes are not functions of flow parameters.
An alluvial channel, also known as mobile-bed channel or mobile boundary channel, comprises of alluvium deposited on the channel section having the same quality as that of the

sediment in stream flows. The materials on the bed and sides of such channels are loose and easily movable due to flow of water. Its geometry changes over time because of erosion and deposition processes.

However, in alluvial channels when velocity of flow is very small, the channel bed does not move at all, and channel behaves as rigid boundary channel. The processes of transportation, deposition, and the resulting additional resistance to flow may also occur in rigid boundary channels due to sediment inflow from elsewhere, e.g. from a river into a lined canal.

INCIPIENT MOTION OF SEDIMENT PARTICLES:

A number of forces act on the channel boundary. Some of these are stabilizing forces in the sense that they would oppose any tendency of the particle to move while others would be trying to dislodge the particle from its place. For example, the weight of the particle would prevent it from lifting into the flow while the buoyant force would try to lift it. Similarly, the shear force near the bed and the form drag due to particle shape would try to roll the particle along the flow while the friction force at the bed and shielding and anchoring by nearby particles would try to prevent this motion. The sediment particle will start to move when the balance of these forces favours the de-stabilizing forces. It is the stage of critical starting from zero or stopping of movement of a single sediment particle from zero, or that of a few particles, or general motion of sediments on the bed of the channel. There are two limiting conditions when the rate of sediment transport tends to zero, i. e. (i) slowly increase of drag force up to threshold condition of motion, and (ii) slowly decrease of drag force up to threshold stage of motion. This point at which this happens is called the incipient motion condition, threshold condition, or critical condition.

Different approaches to study the sediment motion have been proposed, both theoretical as well as based on empirical observations, to correlate the critical condition with the flow and sediment particle characteristics. Broadly, they can be grouped as follows:

i.) **Competent velocity approach**: Here the size of the bed material is related to either bed velocity or bottom velocity or mean velocity of flow, which just causes the particle to move.

ii.) **Lift force approach:** In this case it is assumed that when the upward force due to the flow (i.e. lift) is just greater than the submerged weight of the particle, the condition of incipient motion is established.

iii.) **Critical tractive force approach:** This approach is based on the idea that the tractive force exerted by the flowing water on a channel bed in the direction of flow is mainly responsible for the motion of the sedimentary particles.

Amongst these approaches, the critical tractive force approach is more rational and sounds better than others and is now used more often than the other two approaches.

Competent velocity approach: This concept was first, probably the earliest, used by du Buat in 1786 in which the critical velocity was correlated with the sediment size based on the laboratory and field observations. Later, researchers attempted to provide some theoretical justification to these observations based on a balance of driving force and resisting force on a particle. This approach is much simpler and is still used in river model studies and in the design of protection works. Assuming the drag coefficient to be a constant, the drag force would be proportional to the square of the velocity and also to the square of the grain diameter. If it has to balance the frictional resistance, which is proportional to the cube of the diameter, it follows that the critical velocity should be proportional to the square root of the

grain diameter as observed in a number of studies. R. J. Garde in 1970 expressed this relationship, after analyzing a large set of data, as
$v_c/\sqrt{g(s-1)d}=1.51$ in which v_c is the critical value of the grain-level velocity(i.e. at the top of the grain), and s is the specific gravity of the sediment. The following relationship for the critical velocity (also called the competent velocity due to it being competent in moving a particle) was also proposed:
$V_c/\sqrt{g(s-1)\,d}=0.6 \log (y/d) +1.63$ in which V_c is the critical value of the cross-sectional average flow velocity and y is the flow depth.
LIFT APPROACH (Theory based on the vertical motion): This approach was proposed in 1920s and considered the critical condition as the point at which the lift force acting on the particle is just equal to its submerged weight so that a slight increase in the flow rate would lift the particle up. The velocity at the bottom level of the grain is zero since the particle is not moving and the velocity at the top of the grain is greater than zero. As a result, there is high pressure under the particle and low pressure at the top of the sediment particle. This pressure difference creates an upward force. Analyzing the case of a cylindrical particle using the ideal fluid flow theory, it was shown by H. Jeffreys in 1920s that the critical value of the free-stream velocity is given by
$V_c/\sqrt{g(s-1)\,d} =0.59$
Assuming $g=9.81 m/sec^2$ and $(s-1)=1.65$, the above relationship becomes
$V_c^2=11.32r$ where V_c is expressed in cm/sec and r is the radius of the cylinder in cm.
For spherical particles, the lift force will be smaller since the fluid will also move around the bottom. Therefore, the critical velocity will have to be higher to be able to lift the particle. As the particle travels upwards, the velocity difference between the top and bottom of the particle will reduce thereby reducing the lift. After the particle reaches a certain height, the lift becomes smaller than the submerged weight. The particle then starts falling down during its transport in the forward direction. As the particle touches the bed the same sequence events described earlier would repeat. Thus the particle travels along a series of curved paths. Another result of the velocity difference is the spinning motion of the sediment particle.

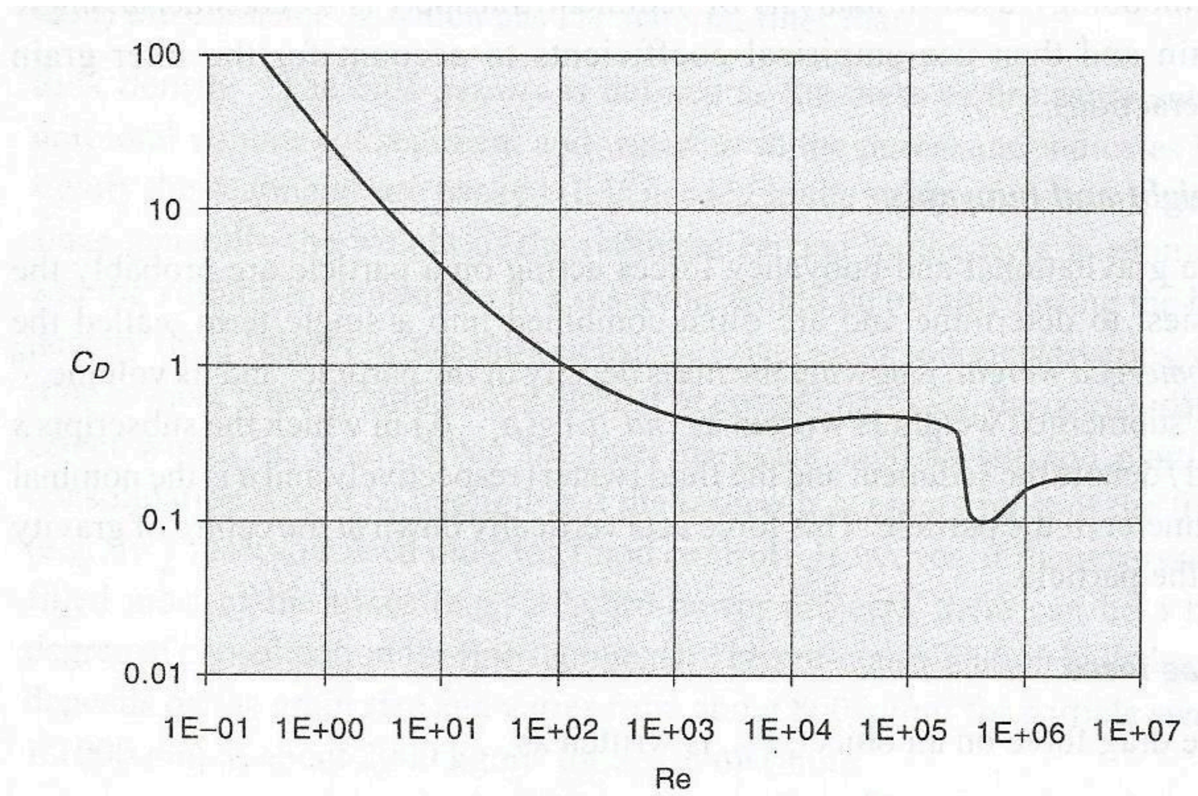
It may be noted that the competent velocity approach as well as that based on lift concept gives similar result, viz. that the square of the competent velocity is proportional to the diameter of the sediment particle.

However at present our knowledge of the role played by lift in the phenomenon of the sediment transport is inadequate and therefore extensive experimentation must follow to determine the magnitude of lift under various flow conditions.

CRITICAL TRACTIVE FORCE APPROACH (Theory based on horizontal motion):
This theory defines the critical condition as the point at which driving force (also called the tractive force) at the bed is just equal to the resisting force acting on a particle due to friction and a slight increase in the flow rate would cause the particle to move. Compared to the competent velocity approach and the lift approach, the critical tractive force approach has found favor with hydraulic engineers and is used quite often for design of erodible channels carrying clear water and the pattern of silting in reservoirs, apart from being the limit indicating the onset of sediment motion. The earlier studies attempted to obtain an empirical relation between the bed shear stress,τ_0, and the grain size of the sediment. For example the critical shear stress was found to increase from about $2N/m^2$ for a grain size of 0.5mm to

about $50 N/m^2$ for a 50mm size. H.Kramer in 1930s proposed the following equation to determine the critical tractive force:
$\tau_0/g(\rho_s-\rho_f)d=1.66x10^{-5}/M$ where M is the Kramer's uniformity coefficient.

EXPRESSION FOR AVERAGE SHEAR STRESS
Consider steady uniform flow in rectangular channel and consider equilibrium of a water prism abcd under various forces acting on it. Since there is no acceleration of the fluid, the summation of all the forces acting in the direction of flow must be zero.
$\sum F=F_1+W\sin\alpha-F_2-\tau_0 x$ wetted area=0
In which τ_0 is the average shear stress at the boundary, F_1 and F_2 are the hydrostatic forces, and W is the weight of water prism. Since the depth of flow is the same at the sections ab and cd, $F_1=F_2$, and $\tau_0= W \sin\alpha$/wetted area.
But wetted area is equal to (B+2D)x, in which B is the channel width, D as deph of flow, and x is the length of the prism. Also $W=Dx\Upsilon_f$, therefore τ_0 (i.e. tractive shear stress)= $BDx\Upsilon_f \sin\alpha/(B+2D)x=\Upsilon_f R\sin\alpha$ in which R is the hydraulic radius. For small α, $\sin\alpha = \tan\alpha=S$ i.e. the channel slope. Therefore, $\tau_0= \Upsilon_f RS$.
For very wide channels R=D. Hence $\tau_0=\Upsilon_f DS$ for such channels. The force exerted by water on the channel bed will have the same magnitude but will act in the direction of flow. This shear stress can directly be related to the velocity distribution near the boundary and the viscosity of the fluid.
THEORETICAL AND SUB-THEORETICAL ANALYSIS OF SHIELDS: Shields (1936) proposed a theory based on the tractive force approach that attempted to address the issue of the initiation of sediment motion on more rational grounds than previously used. Various modifications and improvements have been suggested in this theory but it remains essentially the same as that originally proposed.
He considered the resistance offered by a particle to be proportional to the submerged weight and the coefficient of friction between the particle and the channel bed. The submerged weight was considered to be proportional to the submerged specific weight and the cube of the sediment diameter, with the constant of proportionality dependent on the grain shape. Merging the constants in one, we may write the resisting frictional force as:
$F_f=\alpha_1 g(\rho_s-\rho_f)\ d^3$ in which d is the nominal diameter of the sediment particle and α_1 is an empirical constant.
The drag force applied by the flow on particle is written as:
$F_D=\alpha_2 C_D(\rho_f\ v^2)d/2$ in which α_2 is another empirical constant that depends on shape of the particle (such that $\alpha_2\ d^2$ is the projected area of the particle) and v is the velocity at grain level. The drag coefficient, C_D, will be a function of Reynold's number, $\rho_f vd/\mu$, as well as the shape of the particle as shown below:

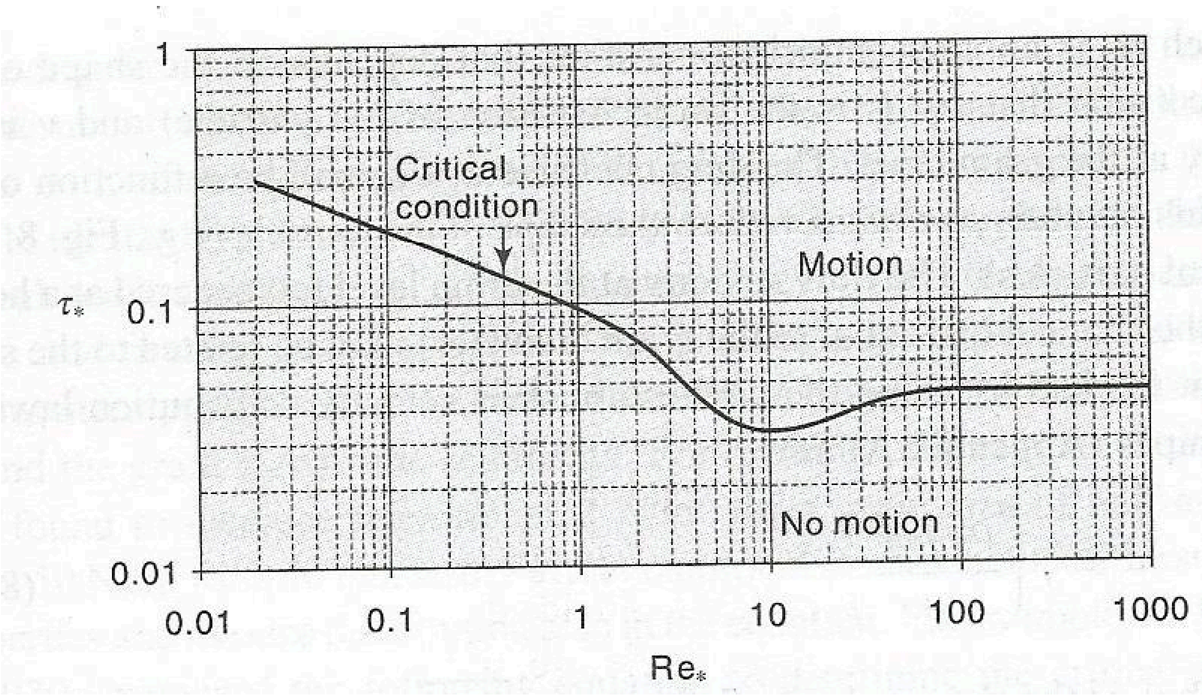


The flow velocity at the grain level (considered at a height above the channel bed equal to grain diameter) may be related to the shear stress at the bed by using the well-established vertical velocity distribution laws as:

$v/v_* = f[\rho_f v_* d/\mu]$ in which v* is shear velocity defined as $\sqrt{\tau_0/\rho}$. Thus the drag coefficient also becomes a function of shear Reynold's number (also called as the particle's Reynold's number), $R_{e*}(\rho_f v_* d/\mu)$, in addition to particle shape. The drag force equation may be re-written as:

$F_D = \alpha_3 f_1[\rho_f v_* d/\mu]\rho_f v_*^2 d^2 = \alpha_3 f_1(Re_*)\tau_0 d^2$

α_3 being another empirical constant and the function f_1 also depending on the shape. At critical conditions, the drag force will be just equal to the resistance, and we get $\alpha_3 f_1(Re_*)\tau_0 d^2 = \alpha_1 g(\rho_s - \rho_f)d^3$ which provides us the classical Shields relationship $\tau_{*c}[=\tau_{0c}/g(\rho_s - \rho_f)d] = f_2(Re_{*c})$ with the parameter τ_{*c} known as the Shields parameter. Shields plotted (the Shields diagram) a number of laboratory and field data sets in terms of variables, τ_* and Re_* and delineated the regions of no sediment motion and appreciable motion through a line, known as Shields curve. Since R_e* is proportional to the ratio of the sediment size to the laminar sub-layer thickness, the value of R_{e*} gives an indication of the type of boundary. The boundary is rough at large values of R_{e*} and τ_{c*} becomes independent of R_{e*} at high values of R_{e*}; at $R_{e*} \geq 400$, τ_{c*} remains constant at 0.06.According to him, for very coarse material at recipient motion $\tau_{0c}/(\Upsilon_s - \Upsilon_f)d = 0.06$. According to Neill this constant value of 0.06 is obtained for $\tau_{c*} \geq 600$ for completely rough boundary. Following figure shows a plot representing the above equation, which is based on slight modification the original Shields curve by Yalin and Karahan.



Once the critical shear stress is obtained, the corresponding flow depth can be obtained by using the relationship between the shear stress and the hydraulic radius, $\tau_0=\rho_f gRS_0$.

THEORETICAL AND SUB-THEORETICAL ANALYSIS OF WHITE:

C.M. White in 1940 considered a packing coefficient,η for the particles. Neglecting the lift component of the hydraulic forces, he equated the submerged weight of the particle,$\pi d^3 (\Upsilon_s-\Upsilon_f)/6$ with the fluid drag force on the particle in the direction of flow depending on whether R_{c*} $(=\rho_f v_* d/\mu)\geq 3.5$ (High speed case) or $Rc_*\leq 3.5$ (Low-speed case).

HIGH-SPEED CASE: When velocity is high and the particles are large, the tangential component of the drag on the particle is very small compared to the drag force due to pressure difference. If a spherical particle is considered, the resultant force (which would be wholly a pressure force in this case) would pass through the centre of gravity of the particle and would act in the direction of flow. If η is the packing coefficient defined as d^2 times the number of particles per unit area, the shear force per particle will be $\tau_0/N=\tau_0 d^2/\eta$ where N is the number of particles per unit area. Taking tan φ as the coefficient of friction (φ being the angle of repose), the condition of incipient motion of a particle located on a horizontal bed requires that $\tan\varphi=(\tau_{0c}\, d^2/\eta)/\pi d^3(\Upsilon_s-\Upsilon_f)/6$ or $\tau_{0c}=\eta(\pi/6)\, d(\Upsilon_s-\Upsilon_f)\tan\varphi$.

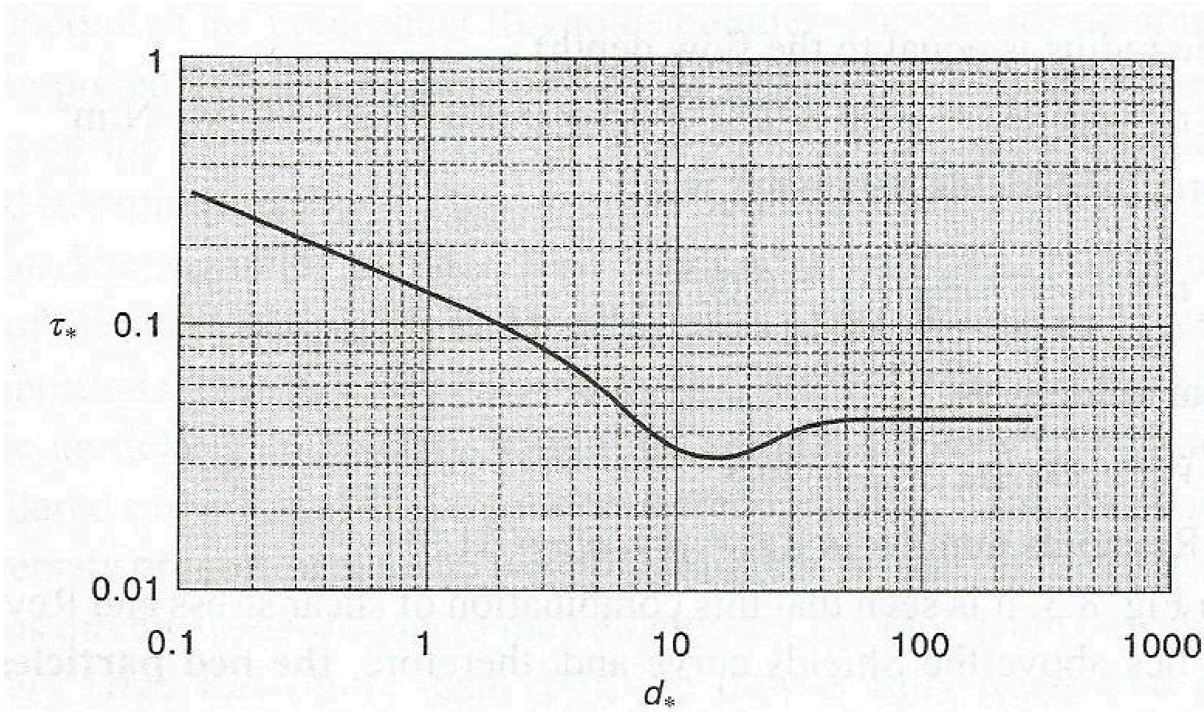
Assuming$\eta=0.4$, Turbulence factor, $T_f=4$ and $\tan\varphi=1$, for turbulent flow and $Rc^*\geq 3.5$, we obtain $\tau_{0c}/(\Upsilon_s-\Upsilon_f)d=0.052$.

LOW-SPEED CASE: At low velocities and with small particles pressure force on the particle is of very small magnitude and viscous force dominates. Since the upper part of the particle will be exposed to this tangential force, one would expect the force $\tau_{0c}\, d^2/\eta$ to pass through a point above the centre of gravity of the particle. If this effect is taken into consideration by introduction of a coefficient α, then the equilibrium condition for a particle on a horizontal bed requires that $\tau_{0c}\, d^2/\eta=\alpha(\pi/6)d^3(\Upsilon_s-\Upsilon_f)\tan\varphi$ or$\tau_{0c}=\alpha\eta(\pi/6)d(\Upsilon_s-\Upsilon_f)\tan\varphi$.

Experimental results show that $\alpha\eta$ varies from 0.31 and 0.29, thus taking its average value as 0.34, the above equation yields as:

$T_{0c}/(\Upsilon_s-\Upsilon_f)d=0.18\tan\varphi$.

THEORETICAL AND SUB-THEORETICAL ANALYSIS OF JULIEN:
Julien (1995) used non-dimensional diameter, d_*, defined earlier (sometimes called Rouse's auxiliary parameter) and obtained
$d_*=[g\rho_f(\rho_s-\rho_f)/\mu^2]^{1/3}=[g(\rho s-\rho_f)d^3\ \rho_f^2\ v_*^2/\tau_0\ \mu^2]^{1/3}=Re_*^{2/3}/\tau_{0*}^{1/3}$
Then, using the values of Reynold's number and the non-dimensional shear stress at the critical condition from the earlier figure, a plot of d_* versus the critical shear stress was prepared as shown below:

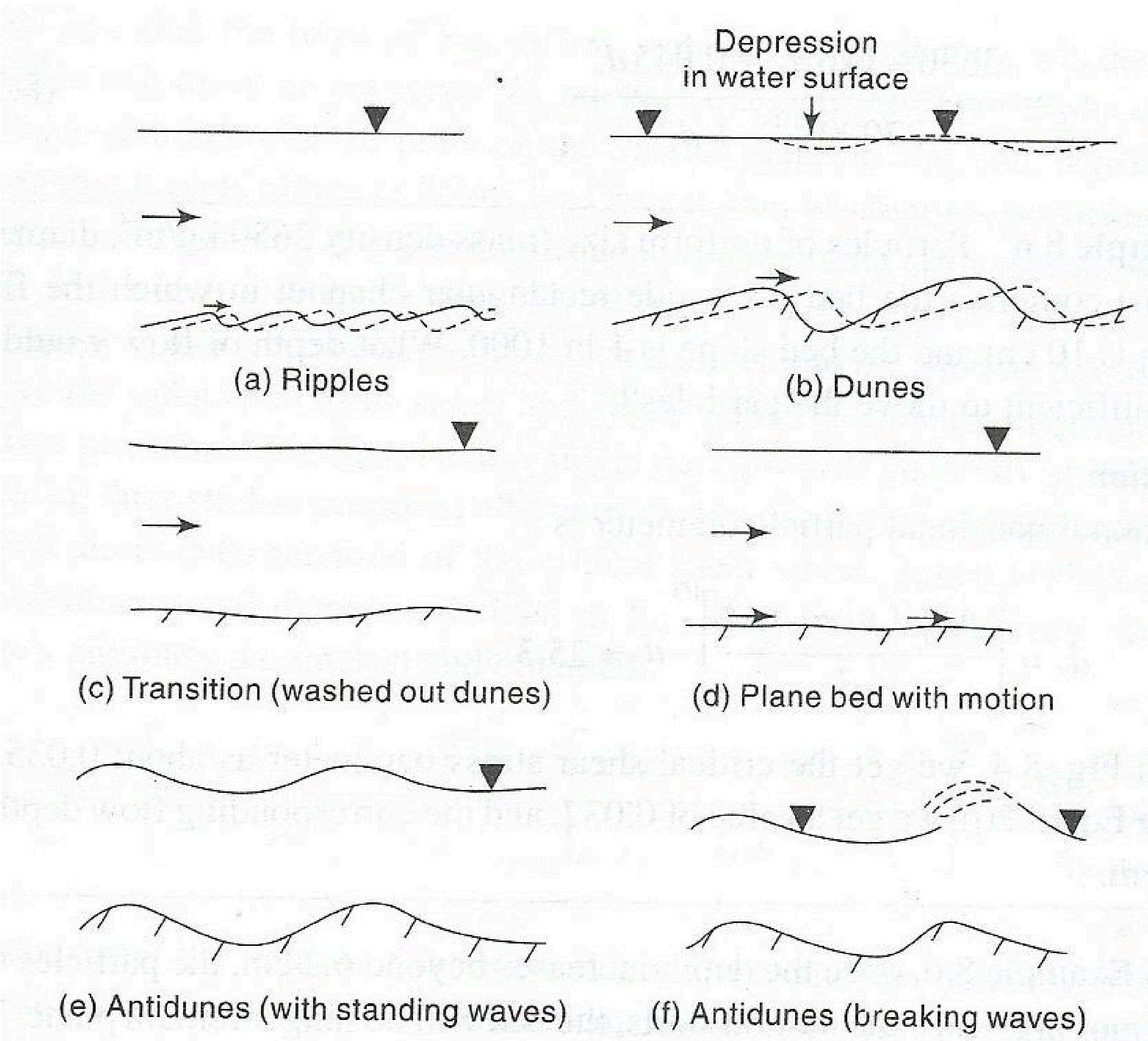


From this figure, for a given particle size, the critical shear stress may be directly obtained. The following approximation provides a reasonably accurate estimate of the critical shear stress:
$\tau_{*c}=3630-126d_*+0.045d_*^4/(27000d_*^{0.4}+d_*^4)$.
Effect of Sediment non-uniformity on Critical Tractive Stress: The criteria for initiation of motion discussed above cannot be easily applied for the different size fractions of the bed material in case of non-uniform sediments because of the effect of sheltering of the finer particles (size d_1) by the coarse ones ((size d_2) and the relatively larger exposure to the flow of the coarser ones themselves.
Egiazaroff, Ashida, Michiue and Hayashi found the dimensionless critical tractive stress for the arithmetic mean size. Egiazaroff assumed that the velocity at a distance of 0.63d is equal to the fall velocity of the sediment and expressed the dimensionless critical shear stress for any size d_i as
$\tau_{*ci}=0.10/(\log 19d_i/d_a)^2$ in which d_a is the arithmetic mean size of the sediment.
Ashida and Michiue proposed modification for above equation for $d_i/d_a\leq0.40$. Their equation is $\tau_{*ci}/\tau_{*ca}=0.85(d_i/d_a)^{-1}$ in which τ_{*ca} is the dimensionless critical shear stress for the arithmetic mean size.
Hayashi recommended that $\tau_{*ci}/\tau_{*ca}=(d_i/d_a)^{-1}$ for $d_i/d_a\leq1$ and
$\tau_{*ci}/\tau_{*ca}=(\log 8/\log 8\ d_i/d_a)^{-2}$ for $d_i/da\geq1$
Patel and Ranga Raju recommended approximate value of $\tau_{*ca}=0.45/\sigma_g^{0.60}$

DERIVATION OF CONDITIONS FOR STABILITY OF A SEDIMENT/ STONE OF CHANNEL LINING ON A STREAMBED AND OVER THE SIDE SLOPES BASED ON CRITICAL TRACTIVE FORCE CONCEPT:

Shields Entrainment Function, $F_s=\tau_{0c}/\Upsilon_f\,(\Upsilon_s/\Upsilon_f-1)\ d=0.06$ for $d \geq 6mm$ and $Re\geq400$,where τ0c=critical tractive shear stress in N/m^2, d=diameter of sediment in mm, Υ_f=specific weight of fluid, and Υ_s=specific weight of sediment. Generally $\Upsilon f=9.81N/m^3=1\ t/m^3$ or $1000Kg/m^3$
Iwagaki gave this value as 0.056, White gave this value as 0.052, Yalin and Karhan gave this value as 0.045 and Neill gave this value as 0.030 arguing that Shield should have taken time average of instantaneous bottom shear and critical tractive shear.
Average shear stress,$\tau_0=\Upsilon_f\,RS$
To ensure stability of the sediment on horizontal beds not to move,τ_0 should be lesser than τ_{0c}.
$\Upsilon_f\,RS\leq0.06\Upsilon_f(\Upsilon_s/\Upsilon_f-1)d\leq0.06x1(2.65-1)\leq0.099$
$d\geq RS/0.099\geq10.01RS$
For Fs=0.056, $d\geq11RS$
But on side slopes of channels, one more disturbing force, i.e. component of weight of the particle , also comes into picture.
$\tau'^2_c+(W\sin\theta)^2=[W\cos\theta.\ \tan\varphi]^2$
But $\tau_c=W\tan\varphi$
Therefore, $\tau'^2_c+(\tau_c\sin\theta/\tan\varphi)^2=[\tau_c\cos\theta.\ \tan\varphi/\tan\varphi]^2$
$\tau'^2_c+\tau_c^2\sin^2\theta/\tan^2\varphi=\tau^2_c\cos^2\theta$
$\tau'^2_c=\tau^2_c[\cos^2\theta-\sin^2\theta/\tan^2\varphi$
$\tau'^2_c/\tau^2_c=\cos^2\theta-\sin^2\theta/\tan^2\varphi=\cos^2\theta[1-\tan^2\theta/\tan^2\varphi]$
$\tau'_c/\tau_c=\cos\theta\sqrt{}1-\tan^2\theta/\tan^2\varphi$
$(\tau'_c/\tau_c)=[\cos^2\theta+(\sin^2\theta-\sin^2\theta)-\sin^2\theta/\tan^2\varphi]=[1-\sin^2\theta-\sin^2\theta/\tan\varphi]$
$[1-\sin^2\theta(1+1/\tan^2\varphi)]=[1-\sin^2\theta x(1+\tan^2\varphi/\tan^2\varphi)]$
$[1-\sin^2\theta.\ Sec^2\varphi/\tan^2\varphi]=[1-\sin^2\theta/\sin^2\varphi]$
$\tau'_c/\tau_c=\sqrt{}1-\sin^2\theta/\sin^2\varphi$
The above equation shows that the shear stress required moving a grain on the side slopes is less than the shear stress required to move the grain on the canal bed. Moreover on slopes the average value of actual shear stress generated by flowing water is equal to $0.75\Upsilon_f RS$.

TYPES OF BED FORMS: (i) Plane bed without motion of sediments, (ii) Ripples, (iii) Dunes, (iv) Dunes superimposed by small ripples, (v) Transition (washed out dunes), (vi) Plane bed with motion, (vii) Anti-dunes (with standing waves),and (viii) Anti-dunes (breaking waves).
Bed form is defined as the feature developed on the alluvial stream beds due to different flow and fluid characteristics. Since the flow resistance is significantly influenced by these bed forms, these are also called **regimes of flow** with ripples and dunes included in lower regime and occurring under sub-critical flow conditions, and others in upper regime occurring at Froude's number near or greater than 1. The various types of bed forms in alluvial streams are shown below:



When the average shear stress on the bed is not large enough to move the sediment particles, the bed form remains **plane**. When the average shear stress on the bed increases above critical, small undulations occur. When the discharge is further increased, small **ripples** are formed having long and flat upstream slope and a much steeper downstream slope with height less than 50mm and wave length less than 600mm. The material rolls along upstream face of ripples and then falls over downstream face. Due to continuous erosion and deposition of sediments over these ripples, it is observed that these ripples move downstream at a very slow rate. Height, length and speed of ripples depend upon flow, sediment and fluid characteristics. Amplification of slight perturbations in the bed profile which are created due to non-uniform and random motion of the eroded streambed is the main reason of formation of ripples.

As the flow rate is further increased, the size of the ripples increases and they are no longer small ripples and are classified as **dunes**. Perturbation of longitudinal distribution of suspended sediment load are the main reason causing dune formation and hence ripples are found superimposed on dunes when appreciable amount of suspended load is present, particularly in case of fine to medium sand when v^*/ω_0 is large. Dunes slope between 30^0 to 40^0.

Further increase in flow may lead to wash out of the dunes, if the bed material is fine enough, and will lead to formation of a plane bed but with considerable sediment motion. For coarser material, the flow may not have enough power to wash out the dunes. The presence of dunes causes the water surface to be wavy with crest and the trough in phase with those on the bed. It has been observed that if a disturbance is created on the water surface, scouring occurs in the troughs and deposition on the crest and it appears that the dunes are moving upstream. These bed forms are called **anti-dunes** and have a steeper upstream slope and flatter downstream profile. The growth of the size of anti-dunes leads to further perturbation in water velocities which, in turn, increases the size of the bed forms. However, as the anti-dunes reach a certain size, the water surface waves tend to break. All anti-dunes do not necessarily move in the upstream directions; sometimes they have been observed to move downstream or even stationary.

Bed forms having lengths of the same order as the channel width or greater and heights comparable to the mean depth of flow are known as **bars**. They are larger in size than dunes. Bars occur in natural streams. Point Bars are bars occurring on inside of the bend in rivers. Ripples and dunes are often superimposed on the upstream face of bars.

PREDICTION OF TYPE OF REGIME OF FLOW: Since the bed forms develop when the shear stress at the boundary increases beyond the critical shear stress, it is logical to relate the bed forms to a parameter representing the additional shear stress beyond its critical value. The two most obvious choices are: (i) using the ratio of actual shear stress and the critical shear stress, and (ii) using the difference of the actual shear stress and the critical shear stress.

(i) GARDE AND RANGA RAJU METHOD: This method, proposed in the 1960s (and a method proposed by S. Sugio around the same time) is based on the ratio of the actual and critical shear stresses. However, the non-dimensional critical shear stress is taken as constant at 0.05 rather than dependent on the particle Reynolds number. The ratio of shear stress is defined as:

$\tau_0/\tau_{0c}=\rho_f gRS/0.05g(\rho_s-\rho_f)d=RS/0.05d[(\rho_s/\rho_f)-1]$ and is plotted against the relative flow depth, R/d, with the lines of demarcation of different regimes located by the following expressions and figure:

τ_0/τ_{0c}	Flow Regime
≤ 1	No motion
Between 1 and $0.28(R/d)^{0.54}$	Ripples and dunes
Between $0.28(R/d)^{0.54}$ and $1.18(R/d)^{0.46}$	Transition
$\geq 1.18\,(R/d)^{0.46}$	Anti-dunes

For ripples, Mantz related the height (h) and length (l) of the ripples to the non-dimensional shear stress and shear Reynold's number as follows:

$h/d=195\tau_*^{\,0.55}\,Re_*^{\,-1.53}$

$l/d=2240\tau_*\,0.82\,Re_*^{\,-1.51}$

According to Mantz, the stream bed becomes flat for the bed shear≥15 times the critical shear stress.

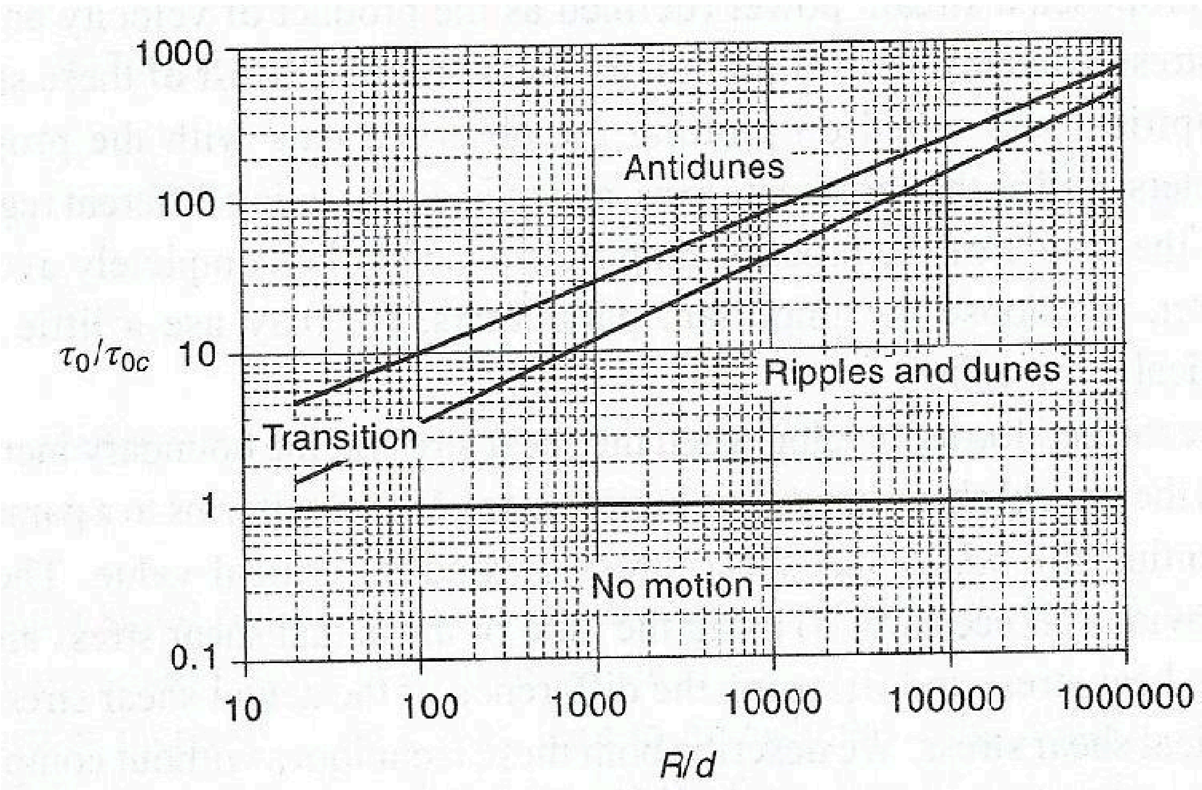
For dunes, van Rijn related the relative height, h/y (y being the flow depth), to the Transport parameter, $T=(\tau_0'-\tau_{0c})/\tau_{0c}$ as follows:

$h/y=0.11(d_{50}/y)^{0.3}\,[1-\exp(-0.05T)]\,(25-T)$

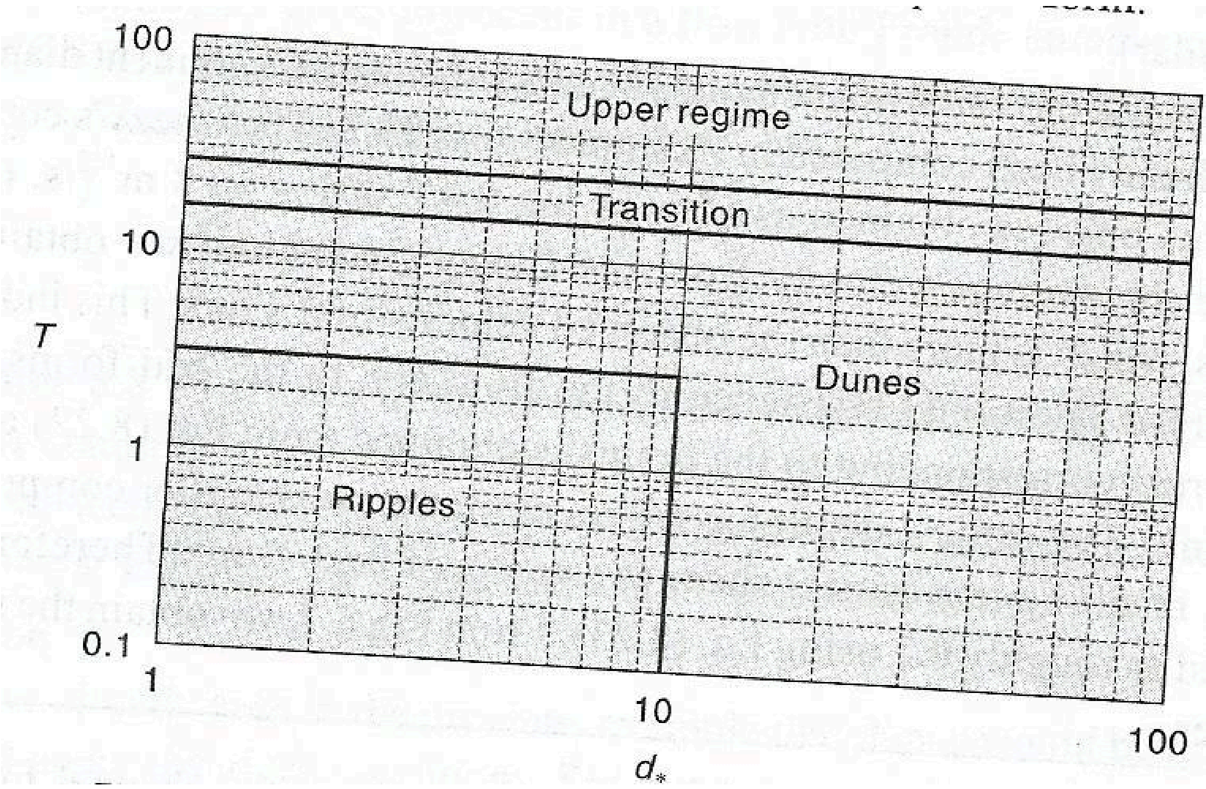
For T≥25, a flat stream bed is observed. The length of the dunes was found to be 7.3 times the flow depth. For large rivers, Julien and Klaassen suggested a more appropriate relationship as follows:

$h/y=2.5(d_{50}/y)^{0.3}$ and the length equal to 6.5 times the flow depth.

For anti-dunes, the geometry of the bed forms is a function of the Froude's number (anti-dunes generally occur in a flow with Froude number range from 0.8 to 1.8. The length of the anti-dunes has been proposed by J.F. Kennedy in 1960 as $l/y=2\pi F_r^2$.



(ii) VAN RIJN METHOD: This method originally proposed in the 1980s, is based on the difference of the actual and critical shear stresses. The shear stress is corresponding to the grain roughness only, without including effects of bed forms and is defined as:
$\tau'=\rho fRS'=\rho_f gV^2/C'^2$ in which the prime indicates that the values are corresponding the grains only, R is the hydraulic radius, Vis the average flow velocity, C' is the Chezy's coefficient, assumed as $18\log 4y/d_{90}$ (as based on experiments), with y being the flow depth and d_{90} the sediment size for which 90% of the material is finer. A transport stage parameter T is defined as:
$T=(\tau'_0-\tau_{0c})/\tau_{0c}$ representing the excess of shear stress nondimensionalized with the critical shear. The other parameter used by him was d_*. For $d_*\leq10$ ripples were observed when T was less than 3 and dunes were observed when T was between 3 and 15. For $d_*\geq10$, dunes were observed when T was less than 15. The zone of transition was observed when t was greater than 15, irrespective of d_*, and upper regime bed forms are likely to exist when $T\geq25$ as shown in the figure shown below:



TUTORIAL SHEET-1

Question No.1: Derive the conditions for the most efficient/economical trapezoidal section of an open channel to carry the maximum discharge.

Question No.2: Derive the conditions for the most efficient/economical angular section of an open channel to carry the maximum discharge.

TUTORIAL SHEET-2

Question No.1: If the lengths of major, intermediate, and minor axes of a sediment particle are 2.00mm, 1.5mm, and 0.5mm respectively, determine its:
(a) Shape factor, (b) Flatness ratio, (c) Markwick's modulus of length, and (d) Markwick's modulus of flatness.

Question No.2: Distinguish amongst nominal diameter, fall diameter, and sieve diameter of a sediment particle.

Question No.3: Distinguish amongst alluvium, loess, and glacial drift.

Question No.4: Define (a) volume constant, (b) surface constant, (c) sphericity, and (d) Cox's coefficient of roundness of a sediment particle.

Question No.5: Explain the characteristics of a falling sediment particle having instantaneous orientation.

TUTORIAL SHEET-3

Question No.1: What are the complexities involved with flow in erodible loose boundary channels?

Question No.2: What are the problems faced by Civil Engineers in dealing with sediment-laden flows in rivers and canals during floods as well as during lean seasons?

Question No.3: What are the origins of sediment particles found in stream flows?

Question No.4: What are the factors affecting fall velocity of sediment particles in natural stream flows?

Question No.5: How to determine the fall velocity of sediments in natural stream flows in terms of velocity of flow and diameter of falling sediment particles?

Question No.6: Explain fabric orientation of sediment particles.

Question No.7: Distinguish amongst mean, mode, and median sizes of sediment particles in natural rivers.

Question No.8: Define (a) arithmetical mean diameter, and (b) standard deviation of sediment particles.

Question No.9: Distinguish between (a) Hazen's uniformity coefficient, and (b) Kramer's uniformity coefficient.

Question No.10: Describe the procedure of determining specific weight of sediments deposited in reservoirs at the end of T years.

TUTORIAL SHEET- 4

Question No.1: At a particular time, a spherical sediment particle (mass density 2650 kg/m^3) of 1 mm diameter was observed to be falling in a stationary fluid (mass density 1000 kg/m^3, dynamic viscosity 0.001Ns/m^2) with a velocity of 5 cm/second. Find the drag force exerted by the fluid on the particle. What is the net force on the particle?

Question No.2: Find the terminal fall velocity of a spherical particle (mass density 2650 kg/m^3) of 1 mm diameter falling in a stationary fluid (mass density 1000 kg/m^3, dynamic viscosity 0.001Ns/m^2). Compute the drag force exerted by the fluid on the particle. What is the net force on the particle?

Question No.3: Explain the analysis of incipient motion of sediment particles as described by Shields, White, Iwagaki, Yalin & Karahan, and Julian.

Question No.4: Find the competent velocity of water for moving a spherical particle (mass density 2650 kg/m^3) of 1 mm diameter placed on the channel bed. The flow depth may be taken as 10 cm at the critical point.

Question No.5: Particles of uniform size (mass density 2650 kg/m^3, diameter 1mm) comprise the bed of a wide rectangular channel in which the flow depth is 10 cm and the bed slope is 1 in 1000. Would the channel behave as a rigid-boundary channel or a mobile boundary channel? What depth of flow would be just sufficient to move the particles? Assume mass density 1000 kg/m^3, dynamic viscosity 0.001Ns/m^2).

Question No.6: A channel is to be constructed in coarse alluvium gravel with d_{75} size of sediment as 5 cm. The channel has to carry a discharge of 3 cumec and longitudinal slope of the channel is 0.01. The banks of the channel will be protected by grass against scouring. Find the minimum width of the channel.

Question No.7: Water flows at a depth of 0.6m in a wide stream having longitudinal slope of 1 in 2500. The median size of the sandy bed is 1 mm. Determine whether the soil grains are stationary or moving, and comment as to whether the stream bed is scouring or non-scouring.

Question No.8: A canal is to be designed to carry a discharge of 56 cumec. The longitudinal slope of the bed of the canal is 1 in 1000. Assuming the canal to be unlimited and a trapezoidal channel section, determine a suitable section for the canal, angle of repose of the soil, $\varphi = 37^0$ and side slope, $\theta = 30^0$ from the horizontal.

Question No.9: Particles of uniform size (mass density 2650kg/m^3, diameter 1 mm) comprise the bed of a wide rectangular channel in which the flow depth is 10 cm, the bed slope is 1 in 1000, and the flow velocity was measured as 40 cm/second. What regime of flow is expected in such condition?

Question No.10: Particles of uniform size (mass density 2650kg/m^3, diameter 1 mm) comprise the bed of a wide rectangular channel in which the flow depth is 10 cm, the bed slope is 1 in 1000, and the flow velocity was measured as 40 cm/second. Estimate the height and length of the bed form.