Hydraulics of Mobile Bed Channels

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Sediment Transport

- Phenomena of Waters flowing in natural streams and rivers ability to scour channel beds, to carry particles (heavier than water) and to deposit materials, hence changing the bed topography.

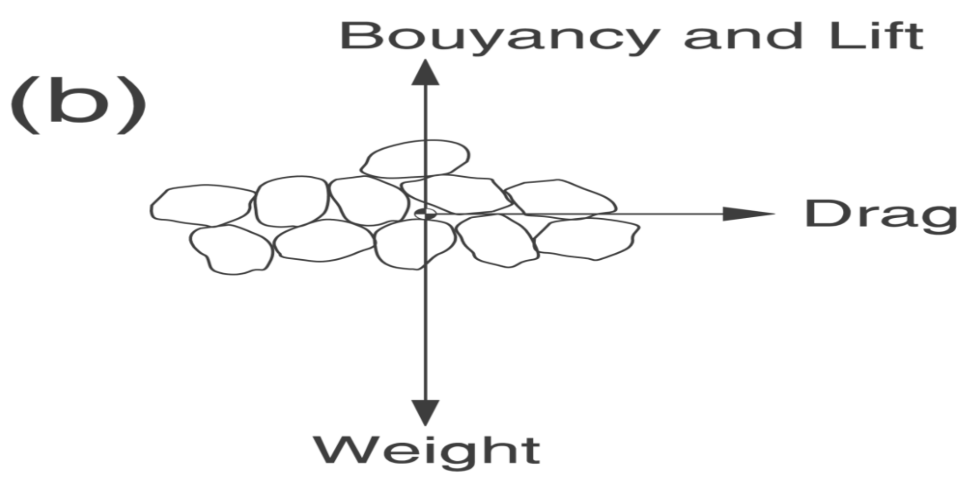
Sediment Transport

- Sediment transport has great economical importance:
  - to predict the risks of scouring of bridges, weirs and channel banks;
  - to estimate the siltation of a reservoir upstream of a dam;
  - to predict the possible bed form changes of rivers and estuaries.

- Sediment transport is the general term used for the transport of material (e.g. silt, sand, gravel and boulders) in rivers and streams.
- The transported material is called the **sediment load**
  - *bed load*
  - *suspended load*.

Forces Acting on a Sediment Particle

- Gravity force ($W_s = \rho s\ gVs$), *is the weight of the particle.*
- Buoyancy force ($F_b = \rho\ g\ Vs$) *The upward force that a fluid exerts on an object less dense than itself.*
- Drag force ($F_D = Cd\ \rho\ As\ V^2/2$), *which results from resistance to turbulent flow around the particle in the horizontal direction.*
- Lift force ($F_L = CL\ \rho\ As\ V^2/2$), *results from resistance to turbulent flow around the particle in the vertical direction.*
- Reaction forces



Initiation of motion

- The condition of flow at which the bed particles will just begin to move is known as ***critical motion or incipient motion*.**
- The bed shear stress corresponding to incipient motion is known as ***Critical Shear stress or Critical tractive force and designated as*** τ_c.
- No sediment motion, until the shear stress (τ_o) exceeds a critical value (τ_c)
- For τ_o larger than the critical value (τ_c), bed load motion takes place.

Initiation of motion

- The relevant parameters for the analysis of sediment transport threshold (initiation of motion) are:
  - the bed shear stress τ_o,
  - the sediment density ρ_s,
  - the fluid density ρ,
  - the grain diameter d_s,
  - the gravity acceleration g and
  - the fluid viscosity μ:

$$f_1(\tau_o, \rho, \rho_s, \mu, g, d_s) = 0$$

$$f_2\left(\frac{\tau_o}{\rho g d_s}; \frac{\rho_s}{\rho}; \frac{d_s\sqrt{\rho\tau_o}}{\mu}\right) = 0$$

- Introducing the *shear velocity V_** defined as $V_* = \sqrt{\frac{\tau_o}{\rho}}$
- the above equation is transformed into

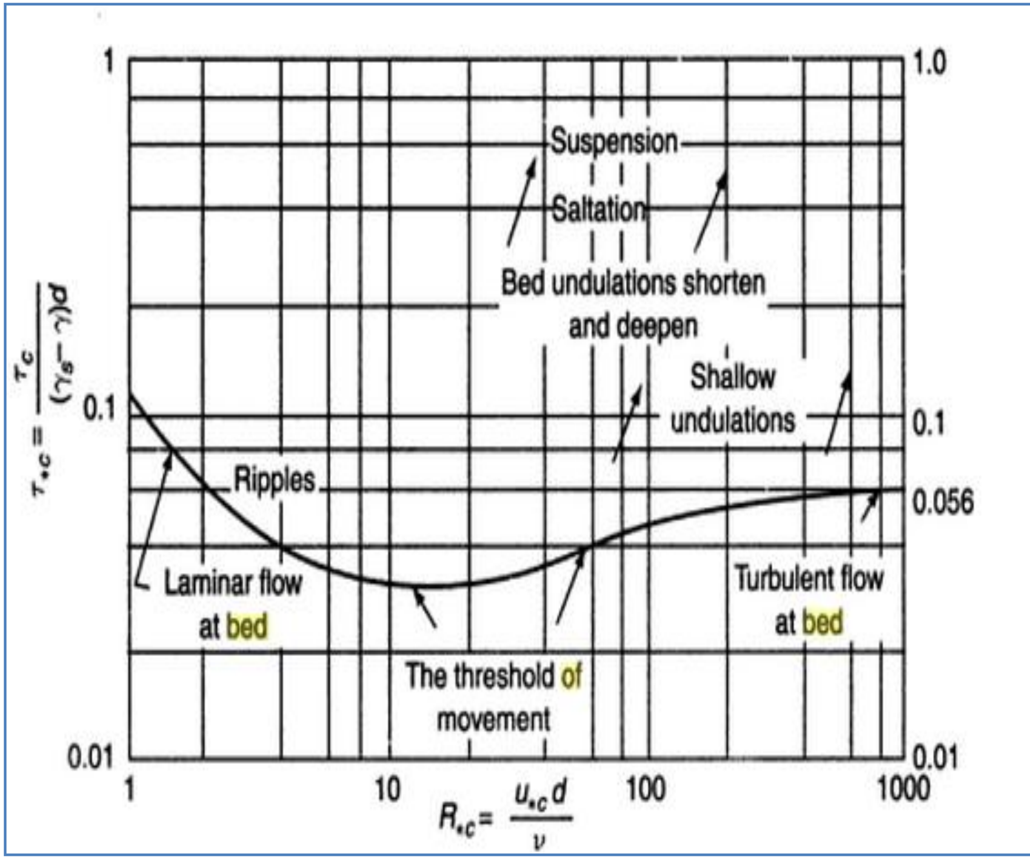
$$f_3\left(\frac{V_*}{\sqrt{g d_s}}; \frac{\rho_s}{\rho}; \rho\frac{d_s V_*}{\mu}\right) = 0$$

1. Froude number.
2. Relative density (specific gravity).
3. Reynolds number defined in terms of the grain size and shear velocity.

Reynolds number is often denoted as R_c and called the ***shear Reynolds number* or *particle Reynolds number*.**

Initiation of motion

At the stage of **initiation of motion** the functional relationship between **Critical Shear stress (τ_c)** and **shear Reynolds number (R_c)** expressed with a curve is called Shield Curve/shields diagram



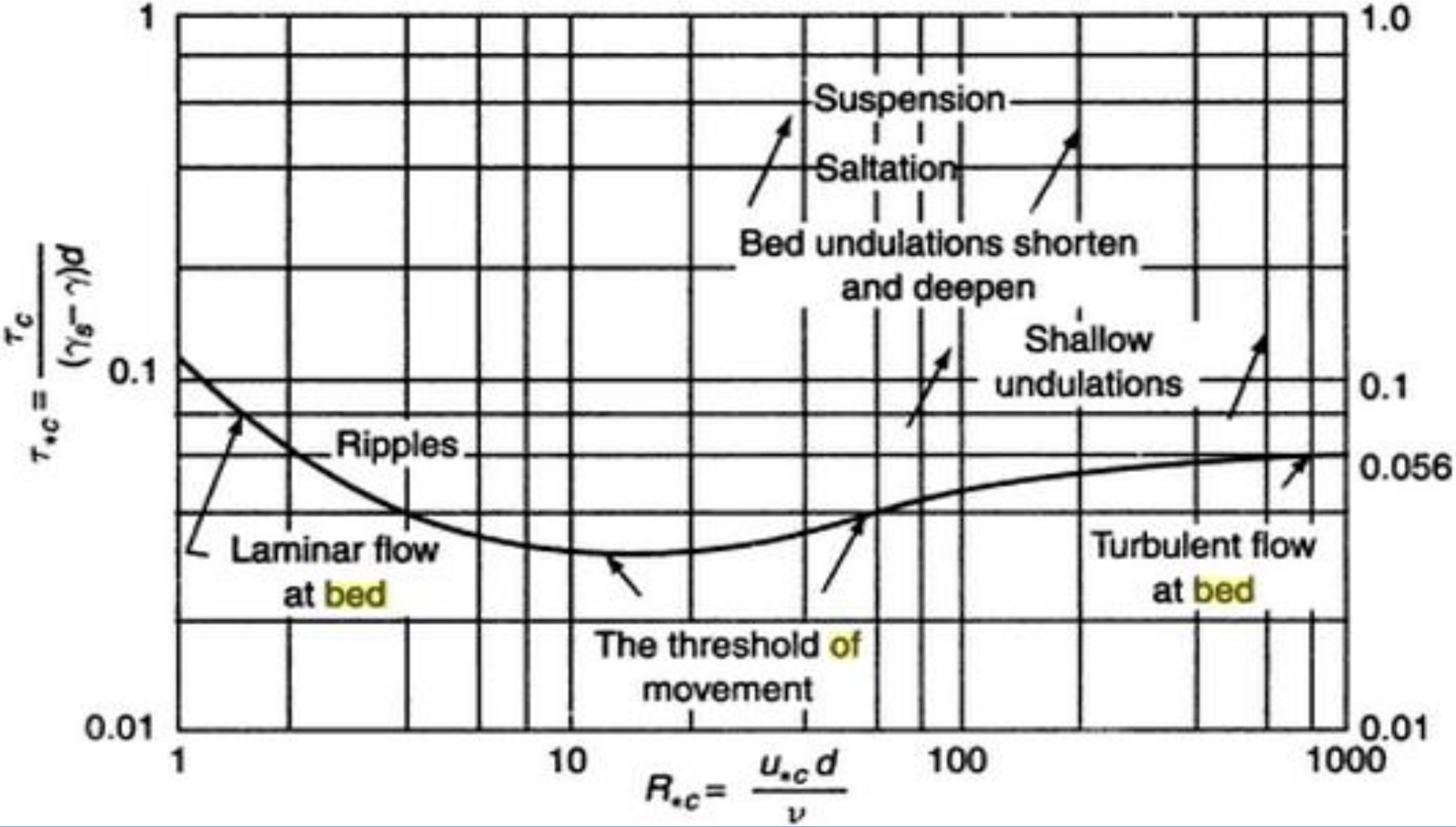
Swamee and Mittal(1976) explicit relationship between τ_c and **d** by an empirical non-dimensional formula.

For the specific case of water at 20^0c ($\nu = 1X\ 10^{-6}\ m^2/s$) and sediment of relative density 2.65mm

$$\tau_c = 0.155 + \frac{0.409 d_{mm}^2}{\left[1 + 0.177 d_{mm}^2\right]^{1/2}}$$

Where, d_{mm} is the particle size in mm

τ_c is in N/m^2


Suspension
Saltation
Bed undulations shorten and deepen
Shallow undulations
Ripples
Laminar flow at bed
Turbulent flow at bed
The threshold of movement
$\tau_{*c} = \frac{\tau_c}{(\gamma_s - \gamma)d}$
$R_{*c} = \frac{u_{*c} d}{\nu}$
1
0.1
0.01
1.0
0.056
10
100
1000

Initiation of motion

Consider an alluvial channel with Rc > 400 (i.e. having sediment particles of size greater than 6.0mm). The shields' curve approximates the values of

$$\frac{\tau_c}{(\gamma_s - \gamma)d} = 0.056$$

If d_c is size of a particle that will just remain at rest in a channel of bed shear stress τ_o then

$$d_c = \frac{\tau_o}{0.056(\gamma_s - \gamma)}$$

but for a uniform flow channel flow of hydraulics radius R and bed slope S_o

Thus $$d_c = \frac{\gamma R S_o}{0.056(\gamma_s - \gamma)}$$

Taking relative density $\gamma_s/\gamma = 2.65$, the equation for dc reduced to

$$d_c = 10.82 R S_o \approx 11 R S_o$$

This equation is valid for $d_{mm} \geq 6.0$mm and provides a quick method for estimating the size of a sediment particle that will not be removed from the bed of a channel

Example

A wide rectangular channel in alluvium of 3mm median size, which has relative density of 2.65, has a longitudinal slope of 0.0003. Estimate the depth of flow in this channel which will cause incipient motion

Bed Forms

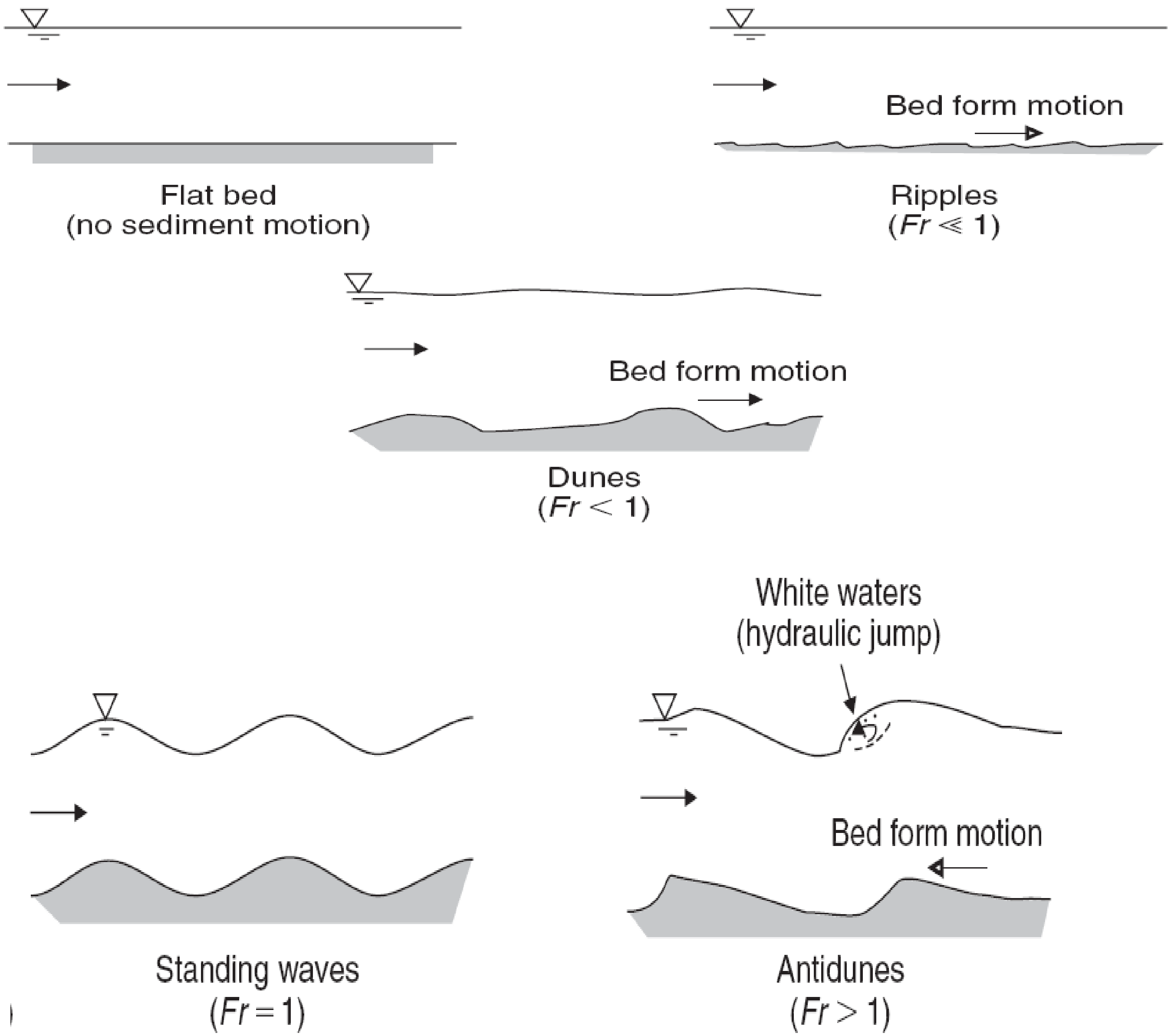
- In most practical situations, the sediments behave as a non-cohesive material (e.g. sand and gravel) and the fluid flow can distort the bed into various shapes.

- The ***bed form*** results from the drag force exerted by the bed on the fluid flow as well as the sediment motion induced by the flow onto the sediment grains.

- The predominant parameters which affect the bed form are the ***bed slope, the flow depth and velocity, the sediment size and particle fall velocity***

- The basic bed forms which may be encountered are:
  - R*ipples* (usually of heights less than 0.1 m),
  - *Dunes*,
  - *Flat bed*,
  - *Standing waves* and *anti-dunes*.

Bed Forms



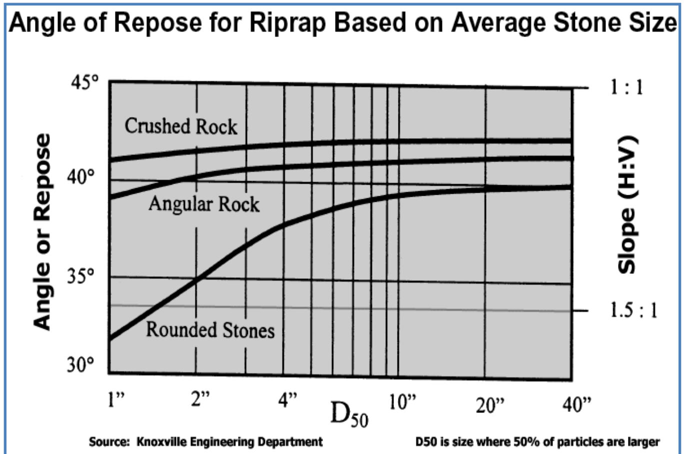
Flat bed
(no sediment motion)
Bed form motion
Ripples
(Fr ≪ 1)
Bed form motion
Dunes
(Fr < 1)
White waters
(hydraulic jump)
Bed form motion
Standing waves
(Fr = 1)
Antidunes
(Fr > 1)

Table 7.1 Basic bed forms in alluvial channels (classification by increasing flow velocities)

Bed form (1)	Flow (2)	Bed form motion (3)	Comments (4)
Flat bed	No Flow (or $Fr \ll 1$)	NO	No sediment motion
Ripples	$Fr \ll 1$	D/S	Three-dimensional forms; observed also with air flows (e.g. sand ripples in a beach caused by wind)
Dunes	$Fr < 1$	D/S	Three-dimensional forms; sand dunes can also be caused by wind
Flat bed	$Fr \leq 1$	NO	Observed also with wind flow
Standing waves	$Fr = 1$	NO	Critical flow conditions; bed standing waves in phase with free-surface standing waves
Antidunes	$Fr > 1$	U/S	Supercritical flow with tumbling flow and hydraulic jump upstream of antidune crests
Chute-pools	$Fr > 1$	U/S	Very active antidunes
Step-pools	$Fr > 1$	–	Cascade of steps and pools; steps are often caused by rock bed

Design of Stable Channels

- There are two basic types of design procedures
  - **Critical tractive force method:** - attempts to restrict the shear stress anywhere in the channel to a value less than the critical shear stress of the bed material.
  - **Regime channel method**:- design a channel under dynamic equilibrium while the channel is carrying a small amount of sediment. Design of a non-scouring and a non-silting channel is the objective of the regime approach.
- **Design Procedure with Critical tractive force method**
  1. The angel of response (φ) of the sediment is determined by laboratory tests. For preliminary design



and

Design of Stable Channels

2. The longitudinal slope of the channel is established from topographical considerations. The side slope of the channel is established from practical and construction aspect.
3. Use Stricker's formula to estimate Manning's coefficient (n) for the channel $n = \frac{1}{21.1} d_{50}^{1/6}$
4. Take $\tau_b = K_2 \tau_c$ to avoid any sediment motion in the channel, where $\tau_c =$ critical shear stress and K2= a coefficient of value less then unity. Then $\tau_w = K_1 K_2 \tau_c$.
5. The critical shear stress of the particle is determined by Shields curve or appropriate and equivalent empirical formula.
6. Finally the non-erodible channel be designed to withstand the maximum shear stress that may occur anywhere in the perimeter of the channel.

$$(\tau_w)_{\max} = 0.75 \gamma y_o s_o \qquad (\tau_b)_{\max} = \gamma y_o s_o$$

for non-erodiblity

$$\tau_w \le (\tau_w)_{\max} \Rightarrow k_1 k_2 \tau_c \le 0.75 \gamma y_o s_o$$

$$\tau_b \le (\tau_b)_{\max} \Rightarrow k_2 \tau_c \le \gamma y_o s_o$$

Example

Design a stable non-erodible channel to carry 10m3/sec of clear water through a 10mm bed of rounded gravel. A longitudinal slope of 0.0008 and side slope of 2 H:1 V are to be adopted

Scour

- The process of removing of the bed material from the natural or man made channels is called scouring

- The scour which may occur at a structure can be divided into three categories:
  - ***General scour***: occurs in a river or stream as the result of natural processes irrespective of whether a structure is there.
  - ***Constriction scour:*** occurs if a structure causes the narrowing of a water course or the rechanneling of bed or flood plain flow.
  - ***Local scour:*** results directly from the impact of the structure on the flow. This scour, which is a function of the type of structure, is superimposed on the general and constriction scour.

- Scour can also be classified based on the different conditions of transport as;
  - ***Clear-water scour:*** occurs if the bed material in the natural flow upstream of the scour area is at rest. The shear stresses on the bed some distance away from the structure are thus not greater than the critical or threshold shear stress for the initiation of particle movement.
  - ***Live-bed scour***, also referred to as scour with bed material sediment transport, occurs when the flow induces a general movement of the bed material. That is, the shear stresses on the bed are generally greater than the critical one.

Scour

- General scour occurs because of the increased capacity of a river to carry sediment during flood flows or as the consequence of various man-made alterations. Some examples of the latter are:
  - erosion downstream of reservoirs due to the interception of sediment,
  - transfer of water from one basin to another which alters the sediment carrying capacities of both rivers,
  - mining of sand and gravel in rivers and on flood plains,
  - cut-off of meanders,
  - Decrease in effective boundary roughness and cross-section through channel regulation.

- *Local scour:* Structures such as **dikes, guide banks, abutments and piers** are often required in river banks in conjunction with river training or road construction works. All such works concentrate the river flow and can therefore cause *local scour*.