

Samenvatting River Flow Processes

Hfst. 2; Turbulence and roughness

* Introduction

- Since the kinematic viscosity of water is relatively small ($\nu \approx 10^{-6} \text{ m}^2/\text{s}$), the water flow in rivers, estuaries and seas is generally turbulent ($Re > 2300$)

* General basic equations

- Conservation of mass; $\dot{m}_{in} - \dot{m}_{out} = \frac{dm}{dt}$

→ constant density of fluid and constant volume leads to constant mass of element;

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 = \text{continuity equation}$$

- Conservation of momentum; $\Sigma F_x = m a_x \rightarrow \frac{\Sigma F_x}{\Delta x \Delta y \Delta z} = \frac{d\rho u}{dt}$
 $\Sigma F_y = m a_y \rightarrow \frac{\Sigma F_y}{\Delta x \Delta y \Delta z} = \frac{d\rho v}{dt}$
 $\Sigma F_z = m a_z \rightarrow \frac{\Sigma F_z}{\Delta x \Delta y \Delta z} = \frac{d\rho w}{dt}$

- combined with external gravitational forces and internal shear and normal stresses;

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = g_x - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu_m \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

1.) temporal change of momentum (local acceleration)

2.) Net Flux of momentum through fluid element (convective acceleration)

3.) gravitational force

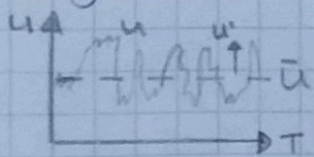
4.) net pressure force on fluid element

5.) net viscous forces on fluid element (caused by molecular interactions)

- Navier Stokes equation for water (in x-direction)

Week 11st 2

* Reynolds decomposition



$$u = \bar{u} + u'$$

$\swarrow$ turbulent velocity
 $\searrow$ time-averaged velocity
 $\swarrow$ instantaneous velocity

- Reynolds decomposition added to Navier Stokes equation to include fluctuating parts of the instantaneous velocity components (turbulence). added as normal and shear stresses
- Reynolds stresses $\gg$ molecular stresses

* Flow resistance

- Turbulence dissipates energy from the flow; transition from largest turbulent flow to smaller scales (energy cascade). From large to smaller eddies
- Balance between gravity that drives the flow in the river and bottom friction that dissipates energy;

$$\rho g i_b = \rho \frac{\partial \overline{u'w'}}{\partial z} \rightarrow \text{integrate over depth; } T_b = \rho g h i_b = \rho u_*^2 = \rho \overline{u'w'}$$

for $h \gg B$ if $B \gg h$

- shear stress has linear distribution across the flow depth ($\tau = (1 - z/h) T_b$)

* Roughness and the velocity profile

- Find out how turbulence affects the vertical profile of velocity;

$$T_b = \rho \left(l \frac{\partial \bar{u}}{\partial z} \right)^2$$

With;

$l = \text{mixing length} = Kz$

$$T_b = \rho u_*^2$$

$$u_* = Kz \frac{\partial \bar{u}}{\partial z} \xrightarrow{\text{integrate over depth from } z_0} \bar{u}(z) = \frac{u_*}{K} \ln \left(\frac{z}{z_0} \right)$$

$$z_0 = 0.11 (u/u_*) + 0.03 k_s$$

$k_s \approx D$ (= roughness height)

- $Re_* = \frac{u_* k_s}{\nu}$, if $Re_* > 70 \rightarrow$ hydraulic rough wall;

$$z_0 = k_s / 33 \rightarrow \bar{u}(z) = \frac{u_*}{K} \ln \left(\frac{33z}{k_s} \right)$$

Ver Hst. 2

- * Depth-averaged flow velocity and flow resistance
- For hydraulic rough wall;

$$\left. \begin{aligned} U &= \frac{u_*}{K} \ln \left(\frac{12h}{k_s} \right) \\ u_* &= u \frac{\sqrt{g}}{C} \end{aligned} \right\} \begin{aligned} C &= \frac{\sqrt{g}}{K} \ln \frac{12h}{k_s} \\ &\text{OR} \\ C &= 18 \log_{10} \frac{12h}{k_s} \quad (\rightarrow \text{or } R_h \text{ i.p.v. } h) \end{aligned}$$

- Manning; $U = (1/n) R_h^{2/3} i_b^{1/2}$ with $n = 0,04 k_s^{1/6}$
- Chezy; $U = C \sqrt{R_h i_b} \rightarrow U = 18 \log_{10} (12h/k_s) \sqrt{R_h i_b}$
- Darcy-Weisbach; $U = \sqrt{\frac{8u_*^2}{f_{bw}}}$ ($Q = U \cdot B \cdot h$)

- The higher the roughness height (k_s), the higher the hydraulic radius (or water depth h when $B \gg h \rightarrow R_h \approx h$)
- The higher the roughness height (k_s), the lower the velocities at the bed and will increase slower to the top than with lower roughness values.
- Shape of velocity profile;

$$\frac{u(z)}{u} = \frac{\ln(33.2 z/h) + \ln(h/k_s)}{\ln(12h/k_s)}$$

H/1st 3; Incipience of sediment motion and bed-load

* Sediment characteristics

- Dimension (size) $\rightarrow D_{50}$
- shape
- Density (bulk density; $\rho_b = \rho_s(1 - \epsilon)$)
- Fall velocity
- chemical composition
- pore content (porosity ϵ)

* Fall velocity

$F_{0z} = \frac{1}{2} C_D \rho A W_s^2 = \frac{1}{2} C_D \rho \frac{1}{4} \pi D^2 W_s^2$
 $\rightarrow$ Drag coefficient sphere

$F_{gz} = \frac{1}{6} \pi (\rho_s - \rho) g D^3$

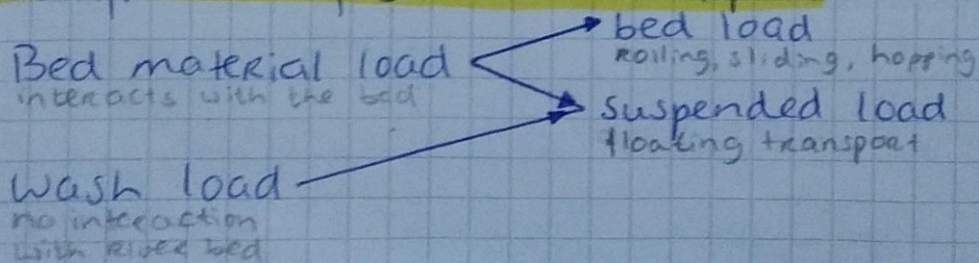
$\rightarrow$ at some point $F_{gz} = F_{0z}$ (constant W_s);

$\frac{1}{6} \pi (\rho_s - \rho) g D^3 = \frac{1}{2} C_D \frac{1}{4} \pi D^2 W_s^2 \rightarrow W_s = \sqrt{\frac{4 R g D}{3 C_D}}$ $R = \frac{\rho_s - \rho_w}{\rho_w}$

where; $Re_p = \frac{W_s D}{\nu_m}$ and $C_D = \frac{24}{Re_p} \rightarrow W_s = \frac{R g D^2}{18 \nu_m}$
within stokes regime ($Re_p < 1$)

- fall velocity, next to grain properties, also influenced by,
 - temperature fluid (included in viscosity)
 - vicinity of walls
 - Presence of other grains $\rightarrow$ hindered settling
 - cohesive sediment flocculation (aggregation of several small cohesive particles into bigger ones)

* Classification of sediment transport



Ver. Hfst 3

* Threshold of motion / incipient motion

- Particle will move when mobilizing forces (drag & lift forces) are bigger than stabilizing forces (gravity force)
- Ratio between mobilizing & stabilizing forces = Shields parameter / dimensionless shear stress:

$$\tau^* = \frac{|\vec{F}_0|}{|\vec{G}|} = \frac{\rho u_* D^3}{(\rho_s - \rho) g D^3} = \frac{\tau_b}{(\rho_s - \rho) g D} \quad \text{OR} \quad \tau^* = \frac{u_*^2}{g R D}$$

with; $u_* = \sqrt{g R h_b}$

→ movement of particle if $\tau^* > \tau_{cr}^* \rightarrow \tau_{bcr} = \frac{\tau_{bcr}}{(\rho_s - \rho) g D}$

* Bed forms and alluvial roughness

- With an alluvial soil (loose, unconsolidated soil or sediment that has been eroded and deposited by surface water), the sediment transport and bed forms depend on the flow.
- Since bed forms, and thus alluvial roughness, depend on flow conditions, it is no longer possible to determine bottom roughness in advance.
- Bed form → Chézy coefficient → bed shear velocity → sediment transport → bed form

$$\text{Total bed roughness} \quad \tau_b = \tau_b' + \tau_b''$$

skin friction drag from sediment of the bed = τ_b'

pressure drag caused by pressure differences due to bed forms = τ_b''

lower roughness regime - Form roughness dominant

- Ripples → dunes with ripples → dunes → washed-out dunes → plane bed → standing waves → anti-dunes (sand-bed or sand/gravel bed rivers)
- Pebble clusters → transverse ribs → steps

Ver. Hst. 3

* Sediment transport formulas

- used to calculate the volume or mass of sediment being transported under certain hydraulic conditions.
- sediment transport formulas are a function of;
 - gravitational acceleration (g)
 - fluid properties (ρ, ν_m)
 - sediment properties (ρ_s, D)
 - parameters regarding the flow (i.e. T_b)

$$q_s = f(g, \rho, \nu, \rho_s, D, T_b) \quad \left[\frac{\text{kg}}{\text{m}} \right]$$

width

- Sediment transport parameter;

$$\phi = \frac{q_s}{\sqrt{RgD^3}}$$

$$\rightarrow q_s = \phi \sqrt{RgD^3}$$

↳ calculated with specific formula (Meyer-Peter & Müller or Engelund & Hansen)

- Flow parameter;

$$\psi = \frac{\mu_r T_b}{\rho g R D} = \mu_r T^* = \mu_r \frac{h_i}{R D}$$

↳ slope of Energy head = i_b if flow is uniform

$$= f(C/C_{90})$$

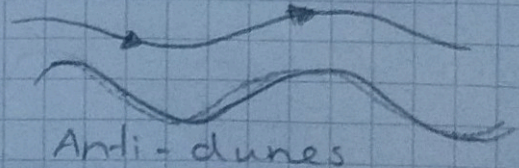
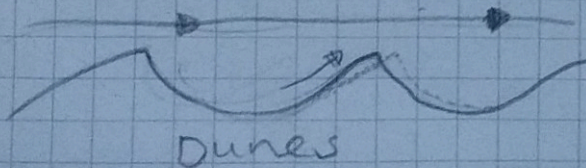
$$\rightarrow = 18 \log(12h/D_{90})$$

* Dunes

- like ripple; gentle upstream slope, steep downstream slope
- Height and wave length are related to water depth;
 - Height < 0,33 water depth
 - Length 8 to 4 times water depth
- Formed due to macroturbulent flow (turbulent eddies of the order of water depth)
- Dune height;

$$\Delta = 0,11h \left(\frac{D_{90}}{h} \right)^{0,3} \left(1 - \exp \left[-0,5 \left(\frac{T_b' - T_{bcr}}{T_{bcr}} \right) \right] \right) \left(25 - \frac{T_b' - T_{bcr}}{T_{bcr}} \right)$$

- Dune length; $\Lambda = 7,3h$



Hfst 4; Suspended sediment transport

* Settling and turbulent mixing

- When $F_0 = F_s$, a constant settling velocity occurs. This results in a downward/vertical sediment flux for a certain sediment concentration;

$$f_s = -w_s C \quad (\text{per unit bed area})$$

- Due to staneous forces (turbulence), the fluid drag force will increase and the sediment will move upwards. Due to those turbulent fluctuations, turbulent mixing takes place where the higher concentrations of sediment (from the bed) are being moved to the lower concentration levels (up in the water column) $\rightarrow$ smoothing sediment concentration profile of water column. The upward sediment flux (due to turbulent mixing) is described as;

$$f_0 = -E_s \frac{\partial C}{\partial z} \quad (\text{per unit bed area})$$

$\rightarrow$ turbulent mixing coefficient [L^2/T]

- In steady and uniform flow, there is an equilibrium situation where $f_s + f_0 = 0 \rightarrow w_s C + E_s \frac{\partial C}{\partial z} = 0$

* Concentration profile

- for constant vertical E_s -profile;

$$C(z) = C(z_a) e^{-6z \left(\frac{z - z_a}{h} \right)}$$

E_s -profile;
 $\rightarrow = \frac{K}{6} u_* h$

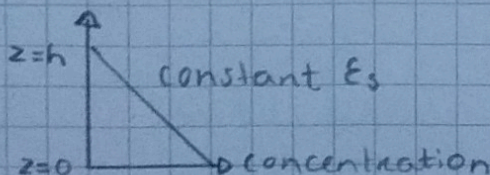
- for parabolic vertical E_s -profile;

$$C(z) = C(z_a) \left(\frac{h - z}{z} \frac{z_a}{h - z_a} \right)$$

$\rightarrow = K u_* z \left(1 - \frac{z}{h} \right)$

$$C(z) = C(z_a) e^{-\frac{w_s(z - z_a)}{E_s}}$$

With $Z = \frac{w_s}{K u_*}$



Ver. Hfst 4

* Bottom concentration $c(z_a)$

- calculated via empirical model;

$$c(z_a) = 0,015 \frac{D_{50}}{z_a} \frac{T^{1,5}}{D_x^{0,3}}$$

- calculated via a sediment transport formula;

$$q_{sus} = \int_h u(z)c(z)dz = c(z_a) \int_h \frac{u(z)c(z)}{c(z_a)} dz \rightarrow c(z_a) = \frac{q_{sus}}{\int_h \frac{u(z)c(z)}{c(z_a)} dz}$$

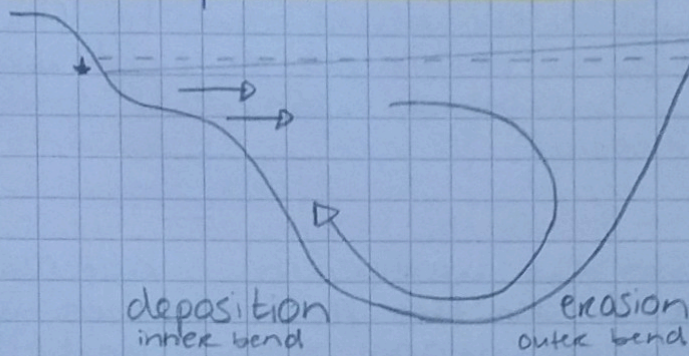
* Sediment concentration equation

$$\underbrace{\frac{\partial c}{\partial t}}_1 + \underbrace{u_f \frac{\partial c}{\partial x}}_2 + \underbrace{w_f \frac{\partial c}{\partial z}}_3 = \underbrace{w_s \frac{\partial c}{\partial z}}_4 + \underbrace{\frac{\partial}{\partial x} \left(\epsilon \frac{\partial c}{\partial x} \right)}_5 + \underbrace{\frac{\partial}{\partial z} \left(\epsilon \frac{\partial c}{\partial z} \right)}_6$$

1. Storage in water column
2. Horizontal advection term (sediment transport $\leftrightarrow$)
3. Vertical advection term (sediment transport $\updownarrow$)
4. Settling term
5. Horizontal diffusion term (gradual sediment transport $\leftrightarrow$)
6. Vertical diffusion term (gradual sediment transport $\updownarrow$)

H1st 5; Flow and morphology in river bends

* Process; flow in river bends



- Faster moving layers move to outer bend (due to inertia)
- slower moving layers are moved to the inside of the bend (due to mass continuity)
- Result; spiral flow through river bend

- Coarser sediment remains in the outer bend
- Finer sediment transported (with spiral flow) to inner bend

Hfst 6; Flow-cylinder interaction & local scour

* local scour

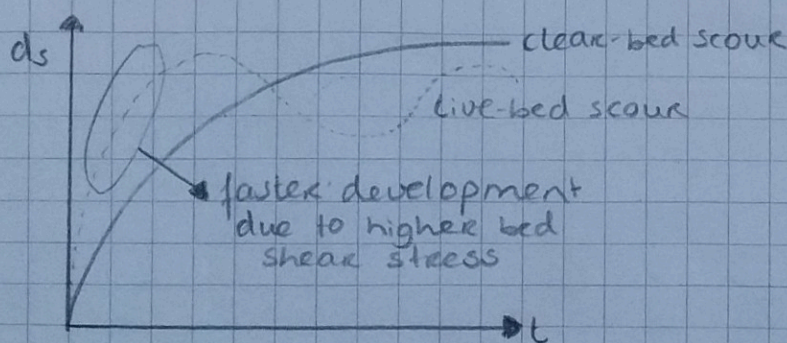
= localized erosion around a structure due to flow accelerations which leads to enhanced exerted bed stresses and thus sediment transport and development of local scour.

* Clear water scour

= Approaching flow from the upstream is not able to entrain sediment. When the flow arrives at the pier, local flow accelerations occur and the exerted bed shear stress will increase $\rightarrow$ local scouring. Sediment will settle again when flow conditions are the same as in front of the pier.
- Equilibrium conditions are reached when the scour hole obtains such a shape where the bed shear stresses can no longer entrain sediment ($T_b = T_{cr}$)

* Live-bed scour

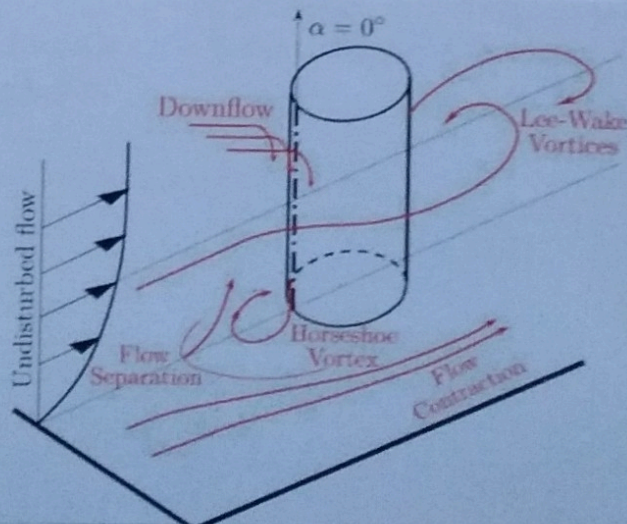
= The incoming flow induces sediment transport and the scour hole around the structure gets continuously supplied with sediment from upstream. At the same time, sediment is being removed from the scour hole due to the effect of the structure (local accelerations).
- Dynamic equilibrium is reached when the rate of upstream sediment supply becomes equal to the rate of sediment that is transported out of the scour hole.



Ver. Hfst. 6

* Flow cylinder interaction

- When undisturbed, steady and uniform flow reaches a cylinder, the flow gets decelerated
- A portion of the flow gets accelerated due to the contraction of streamlines and gets separated at the rear side of the cylinder due to **adverse pressure gradient** → **Lee-Wake vortices** and usually with the occurrence of vortex shedding and the significant increase of turbulence
- The other portion of the flow heads downward, forming a **downflow**. At the bed, the flow is affected by both the cylinder and the bed. Hereby, the so-called **horseshoe vortex** is formed in front of the cylinder due to incoming flow that gets separated from the bed in front of the cylinder due to **adverse pressure gradient** owed to the presence of the cylinder. Where the downflow meets the horseshoe vortex, the bed leads to a **vortical structure** around the upstream face of the cylinder that gets convected downstream increasing substantially the bed shear stress in front and around the cylinder. The vortical structures will eventually deform downstream, but until this happens, there is increased scour potential in the vicinity of the cylinder.
- Due to flow separation pressure differences occur which will cause increased turbulence which entrains sediment movement



Ver. Hst 6

* Boundary layer characteristics on a cylinder with flow separation

- The Reynolds number expresses the ratio of inertial forces to viscous forces; $Re = \frac{U_b}{\nu}$

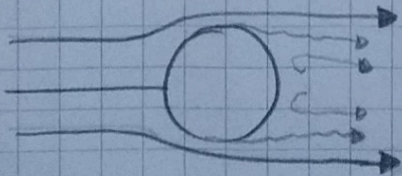
→ viscosity keeps the boundary layer attached to the cylinder

- At the front half of the cylinder, velocity increases and pressure decreases (favorable pressure gradient) → increase Re → increase inertial forces
- At the rear half of the cylinder, velocity decreases and pressure increases (adverse pressure gradient) → Bernoulli.
- At some point of the flow around the cylinder, the fluid inertia is such that the flow gets separated from the cylinder
- After separation flow recirculation is induced behind the cylinder and there is fluid flowing upstream
- separation occurs interchangeably at the two sides of the cylinder, leading to an oscillating flow pattern (vortex shedding)

* Flow pattern around cylinder various Re -numbers

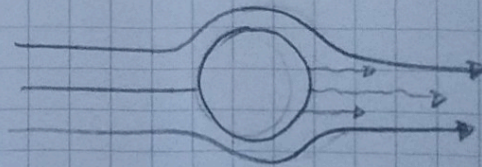
- Higher Re -number → lower drag coefficient (C_D)
- After a certain Re , drag gets reduced because of:
 - transition from laminar to turbulent boundary layer at the upstream side of the cylinder
 - This leads to a narrower wake (due to turbulence) and thus smaller pressure differences between the front and rear sides.

$$10^3 < Re < 10^5$$



laminar boundary layer, wide turbulent wake

$$Re \approx 7 \cdot 10^5$$

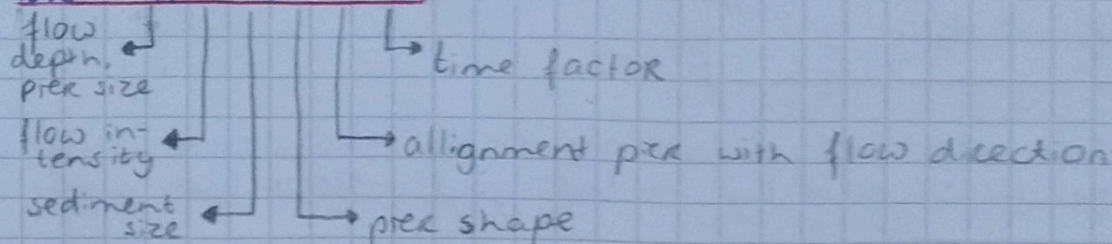


turbulent boundary layer, narrow turbulent wake

ver Hfst. 6

* Estimation of max scour depth at bridge piers

$$ds = K_n K_z K_a K_s K_e$$



→ When countering local scour, the goal is to reduce downflow so that no flow separation occurs at the bottom of the bridge pier.

* Scour below horizontal pipelines

→ may leave the pipeline unsupported by the bed → fatigue failure due to oscillate of pipe by vortex shedding which will cause the pipe to vibrate and enhance the pressure load on it.

1. Pressure difference in front and at the rear side of the cylinder induces subsurface flow below the pipe which increases with flow velocity.
2. As the velocity increases, at some point the sediment at the downstream side will begin to move (scour threshold) → piping.
3. Flow acceleration in piping gap enhances erosion and the gap becomes larger (tunnel erosion). This erosion gradually becomes less intense as the gap widens until an equilibrium is reached (exerted bed shear stress = critical bed shear stress).
4. When the gap below the pipe gets large enough, vortex shedding begins and the generated eddies entrain sediment at the downstream until an equilibrium is reached (lee-wake erosion).

→ for clear-water scour or when exerted upstream bed shear stress = exerted bed shear stress in scour hole for live-bed scour

Ver 11/5/16

clear-water
scour

* Estimation of max. scour depth at horizontal pipe

1. Estimate gap discharge per unit width;

$$q_s = 0.7819 \left(\frac{b}{h} \right)^{0.727}$$

2. Assume a value for max. d_s . Then calculate average flow velocity in the gap below the pipe;

$$U_g = \frac{q_g}{d_s}$$

3. Estimate the bed shear stress in the gap;

$$\tau_b = \frac{f_w}{8} \rho U_g^2$$

4. Compare τ_b to τ_{cr} obtained from Shields diagram

5. Now iterate till $\tau_b = \tau_{cr}$