

4. Scouring

4.1 Introduction

Scour is the enlargement of a cross section by the removal of boundary material through the action of the fluid in motion. Scour is a natural phenomenon caused due to the erosive action of flowing stream on alluvial beds which removes the sediment around or near structures located in flowing water. It means the lowering of the riverbed level by water erosions such that there is a tendency to expose the foundations of a structure. It is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges. Scour has been the main cause for failures of marine structures throughout the world.

Scour can be long term erosion such as bank or channel erosion due to meandering processes or local erosion caused by an increase of the sediment transport capacity due to an increase of the local velocity and/or turbulence intensity.

Examples of local scour are:

- Scour near bridge piers
- Scour near bridge abutment, groynes and marginal bunds
- Scour downstream of weirs, barrages, dams

Local scour is herein considered to be the lowering of the bed in the direct vicinity of a structure due to local accelerations and decelerations of the near-bed velocities and the associated turbulence (vortices) leading to an increase of the local sand transport capacity. Once a scour hole is formed, flow separation will take at the edge of the hole and a mixing layer will develop increasing the turbulence intensities and stimulating further scour of the bed (self-intensifying process). Excessive scour close to the structure may ultimately lead to instability/failure of the structure.

Various mitigating measures are available to reduce or prevent local scour processes, such as: bottom/bank protection by means of rip-rap material (stones) dumped on geotextile filter material, by flexible mats or mattresses filled with gravel/sand, by sand bags, by artificial mats, by concrete slabs and by grout injections.

4.2 Local scour near structures

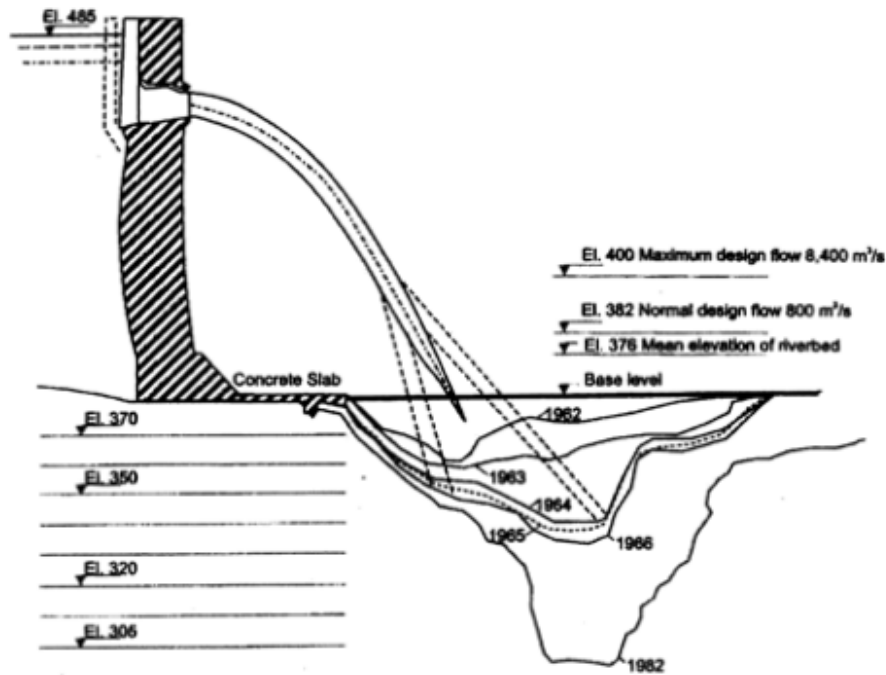
Scour is the local lowering of the stream bed around a hydraulic structure. Scour takes place around bridge piers, abutments, spurs and breakwaters due to modification of flow pattern causing increase in local shear stress which, in turn, leads to removal of material and hence scour.

Generally, scour could be two types, clear water scour (no upstream sediment transport, $u < u_{cr}$) and live bed scour which relates to upstream sediment transport $u > u_{cr}$.

4.2.1 Jet scour

(a) Plunging jet scour

Determination of the extent of scour is an important factor in the design of a dam whether it is during an overtopping event or from flows discharged through the spillway. Often times a plunge pool is used as a cushion to dissipate energy from the falling jet of water.

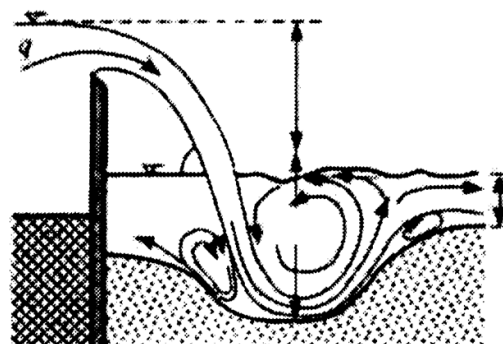


Scour hole formation at Kariba dam

The scour depth Δz below plunging jets can be estimated from the empirical equation of Fahlbusch as a function of unit discharge q , the jet velocity V_1 entering the tail water depth h_t at an angle θ_j measured from the horizontal at the water surface, and gravitational acceleration g .

$$\Delta z = K_p \sqrt{\frac{qV_1}{g}} \sin \theta_j - h_t$$

The coefficient for plunging jet K_p depends on grain size with $K_p \cong 20$ for silts, $5 < K_p < 20$ for sand, and $3 < K_p < 5$ for gravel

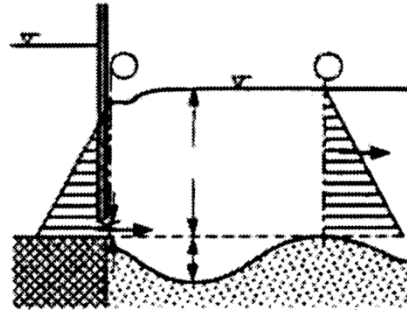


(b) Submerged jet scour

Hoffmans and Verheij applied Newton’s second law to a control volume and found the equilibrium scour depth Δz from

$$\Delta z = K_{sj} y_j \left(1 - \frac{V_2}{V_1} \right)$$

where V_2 is the outflow velocity, V_1 is the inflow velocity, y_j is the inflow jet thickness, and K_{sj} is a scour coefficient for submerged jets



The value of K_{sj} depends on particle size and varies from $K_{sj} \cong 50$ for silts, to $20 < K_{sj} < 50$ for sand, and to $7 < K_{sj} < 20$ for gravel.

(c) Grade-control structure scour

Scour below grade-control structures and also sills and drop structures can be estimated from the method of Bormann and Julien as

$$\Delta z = \left\{ 1.8 \left[\frac{\sin \phi}{\sin(\theta_j + \phi)} \right]^{0.8} \frac{q^{0.6} V_1 \sin \theta_j}{[(G - 1)g]^{0.8} d_s^{0.4}} \right\} - D_p$$

Where

Δz = scour depth below the grade-control structure

D_p = drop height of the grade-control structure

q = unit discharge

V_1 = approach velocity

d_s = particle size

g = gravitational acceleration

G = specific gravity of bed material

ϕ = angle of repose of the bed material

θ_j = jet angle measured from the horizontal



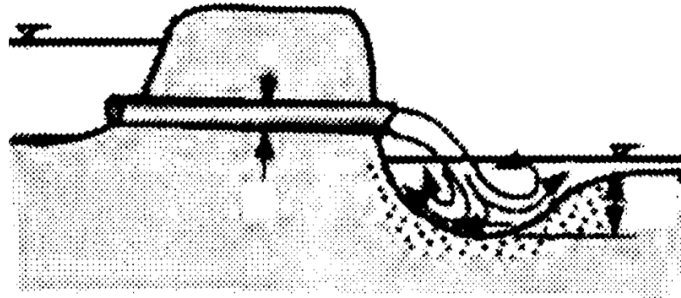
(d) Culvert scour

Local scour below circular culvert outlets has been studied by Ruff et al. (1982). The scour depth Δz can be predicted as

$$\Delta z = 2.07D \left(\frac{Q}{\sqrt{gD^5}} \right)^{0.45}$$

Where Q is the discharge, D is the culvert diameter, and g is the gravitational acceleration

The local scour depths predicted from the empirical relationships are subjected to improvements as more field and laboratory data become available.

**4.2.3 Bridge scour**

Majority of bridge failures were due to scour of foundation material.

Such failure is primarily due to three causes:

- Inadequate knowledge about scour phenomenon when the bridge was constructed
- Inadequate data and knowledge about design flood
- Increase in the loading on bridges due to increase in the size of trucks and wagons and frequency of loading

Protecting embankments and piers against scour requires consideration of the following items:

- 1) General scour due to progressive degradation
- 2) Contraction scour
- 3) Abutment scour
- 4) Pier scour

The total scour depth is obtained from the sum of all components. It should be remembered that all scour estimation procedures serve as approximations and engineering judgment should be exercised.

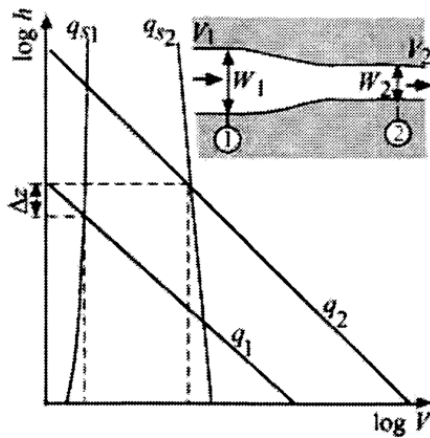
a. Contraction scour

Contraction scour results from flow acceleration in river contractions.

- The approach flow depth h_1 and average approach flow velocity V_1 result in the sediment transport rate q_{s1}
- The total transport rate to the contraction is $W_1 q_{s1}$, in which W_1 is the width of the approach
- If the water flow rate $Q_1 = W_1 q_1$ in the upstream channel is equal to the flow rate at the contracted section, then, by continuity,

$$q_2 = \frac{W_1}{W_2} q_1$$

Where $q_1 = h_1 V_1$, $q_2 = h_2 V_2$, and the subscript 2 refers to conditions in the contracted section



The sediment-transport rate at the contracted section after equilibrium is established must be

$$q_{s2} = \frac{W_1}{W_2} q_{s1}$$

The depth of scour Δz that is due to the contraction is then,

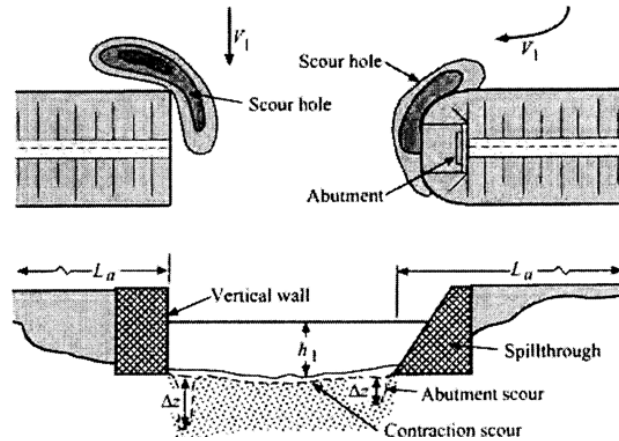
$$\Delta z = h_2 - h_1$$

Here h_1 , V_1 , and W_1 are the depth, velocity, and width of the approach flow, respectively, and h_2 is the contracted flow depth at the bridge.

The contracted scour depth represents an average over the channel width, and symmetry is assumed in the calculation. When only one side is being contracted, the abutment scour equation of the following subsection should be considered.

b. Abutment scour

Abutments, as well as spur dykes, can have different shapes, and they can be set at various angles to the flow.



Local scour at abutments depends on the amount of flow intercepted by the bridge abutments. The equilibrium scour depth for local live-bed scour in sand near a spill-through abutment under subcritical flow is given as

$$\frac{\Delta z}{h_1} = 1.1 \left(\frac{L_a}{h_1} \right)^{0.4} Fr_1^{0.33}$$

Where Δz = equilibrium depth of abutment scour

h_1 = average upstream flow depth in the main channel

L_a = abutment and embankment length measured at the top of the water surface and normal to the side of the channel from where the top of the design flood hits the bank to the outer edge of the abutment

$Fr_1 = V_1 / [(gh_1)^{0.5}]$, upstream Froude number

If the abutment terminates at a vertical wall and the wall on the upstream side is also vertical, then the scour hole in sand calculated by above equation nearly doubles as follows.

$$\frac{\Delta z}{h_1} = 2.15 \left(\frac{L_a}{h_1} \right)^{0.4} Fr_1^{0.33}$$

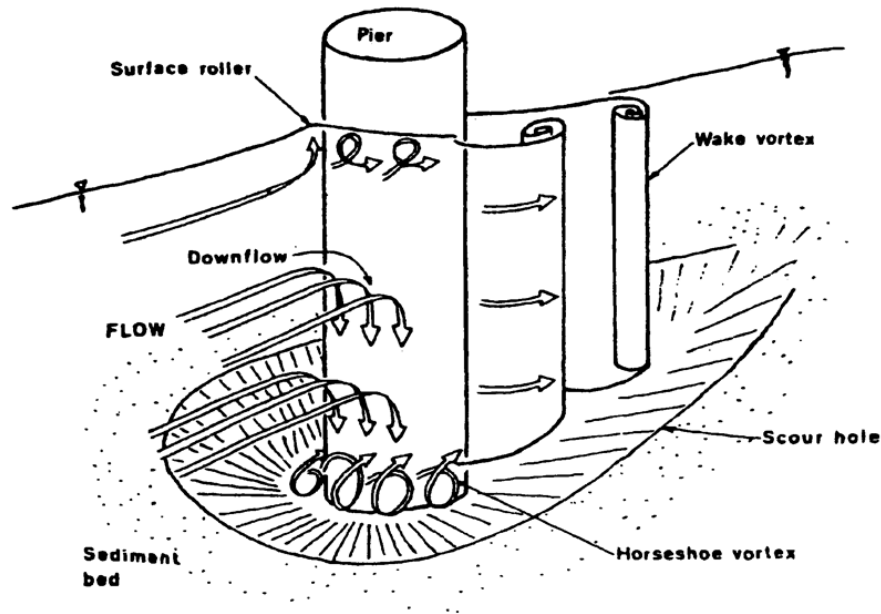
c. Pier scour

The total lowering of stream bed at any site can take place due to four reasons

1. Degradation taking place at bridge site due to dam upstream
2. Reduction in width in the vicinity of the bridge by providing embankments and guide bunds can lead to lowering of bed level
3. Lowering of bed level that takes place due to modification of flow pattern

4. Additional lowering of bed level can take place due to concentration or non-uniform flow distribution across the river width at the bridge

Earlier studies have indicated that depending on the type of pier and free stream conditions, an eddy structure comprising all or anyone or none of the vortex systems can be formed. These include horseshoe vortex system, the wake vortex system, and/or the trailing-vortex system.



Based on analysis of field and flume data, Breusers et al. have found for a single pier in uniform bed material:

$$h_{s,\max} = \alpha_1 \alpha_2 \alpha_3 \alpha_4 b$$

$h_{s,\max}$ = maximum scour depth below original river bed

b = width of pier in plane of river cross-section

α_1 = coefficient related to \bar{u} / \bar{u}_{cr}

α_2 = coefficient related to h_0/b

α_3 = coefficient related to shape of pier

α_4 = coefficient related to angle of attacking flow

\bar{u} = depth-averaged flow velocity upstream of pier

\bar{u}_{cr} = critical depth-averaged flow velocity (upstream)

$\alpha_1 = 0$ for $\bar{u} / \bar{u}_{cr} < 0.5$ (no upstream transport)

$\alpha_1 = 2(\bar{u} / \bar{u}_{cr} - 0.5)$ for $\bar{u} / \bar{u}_{cr} = 0.5$ to 1 (no upstream transport)

$\alpha_1 = 1$ for $\bar{u} / \bar{u}_{cr} \geq 1$

h_0 = flow depth (upstream)

$\alpha_2 = 2 \tan h (h/b)$ yielding $\alpha_2 = 2$ for $h/b \geq 3$

$\alpha_2 = 1.5$ for $h/b < 1$

$\alpha_3 = 1$ for circular and round-nosed piers

$\alpha_3 = 0.75$ for streamlined piers

$\alpha_3 =$ for rectangular piers

$\alpha_4 = 1$ for flow normal to bridge piers

$\alpha_4 = 1.3$ for flow under angle of 15° and length-width ratio of 4

$\alpha_4 = 2$ for flow under angle of 15° and length-width ratio of 8

Length of the score hole $\cong 1b$ (upstream of the pier)

$\cong 5b$ (upstream of the pier)

Width of the score hole $\cong 2b$ on each side of the pier where b = pier width

4.2.4 Scour near groynes, spur dikes, bridge abutments

The flow pattern around groynes is characterized by curvature of the streamlines resulting in a spiral type motion like flow in a river bend. The figure presented below shows the velocity vectors computed by two-dimensional horizontal mathematical model.

The conditions were as follows

- The approach depth-averaged velocity is 0.67m/s.
- The water depth upstream of the groyne is 6m.
- The maximum velocity near the groyne is about 2m/s.
- The length L_1 over which the flow field is disturbed in the contracted cross-section is approximately equal to the length of the groyne ($L_1 \approx L$) when the total river width is larger than twice the groyne length.

Based on the analysis of field data, Breusers (1988) proposed

$$h_{s,max} = \alpha (q_1)^{2/3} - h_1$$

Where,

$h_{s,max}$ = maximum scour depth near groyne

h_1 = mean water depth of contracted section before scour

q_1 = discharge per unit width in contracted section

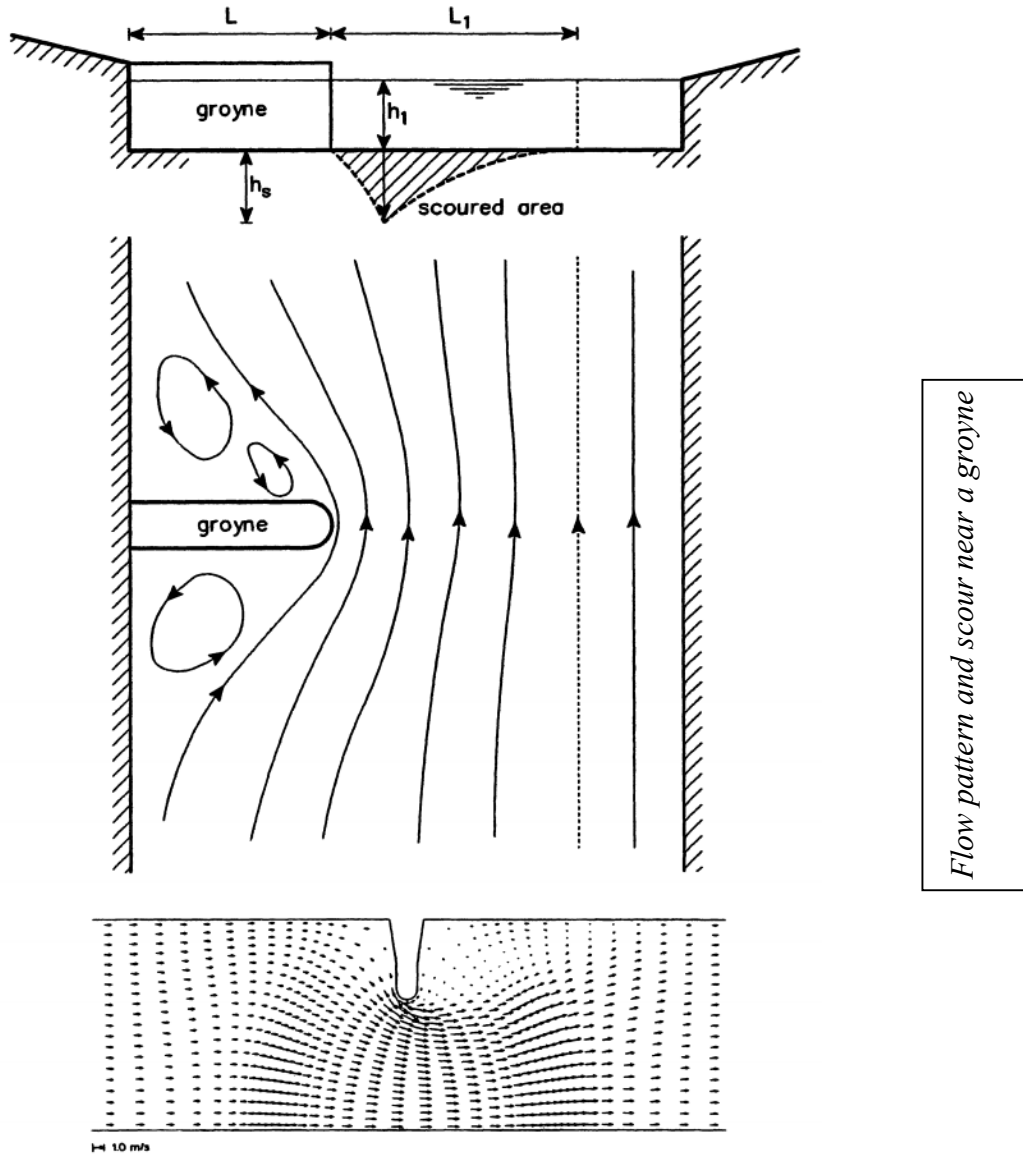
α = coefficient depending on groyne and river geometry (≈ 2 for straight channel and groyne normal to bank).

Another method is to assume that the cross-section area of the contracted section ultimately will be equal to that without the groyne. This means that the scoured area (A_s) will be equal to the area blocked by the groyne. Thus $A_s = h_1 L$.

Assuming that $A_s \approx \frac{1}{3}(h_{s,max} L_1)$ for long groynes ($L > 10h_1$) and $L_1 \approx L$, it follows that

$$h_{s,max} = 3h_1 \text{ for } L > 10h_1$$

This equation is valid for relatively long groyne ($\frac{L}{h_1} \geq 10$), resulting in a significant increase of the velocity in the contracted section. The channel bed is assumed to be composed of sandy material and the approach velocity is assumed to be larger than the critical velocity for initiation of motion (\bar{u}/\bar{u}_{cr}). Armouring which may occur in coarse bed material will result in reduced scour depths.



Flow pattern and scour near a groyne

The scour near a short groyne will be considerably smaller and can be given as:

$$h_{s,max} = 0.5 \text{ to } 1.5 h_1 \text{ for } L = 1 \text{ to } 3h_1$$

The shape of the groyne will also affect the scour depth. scour is maximum near a vertical wall (rectangular cross section). the scour depth may be reduced with about 30% in case of a rock-type groyne with trapezoidal cross-section.

Model studies are recommended for complicated groyne geometry and river alignment (bends). Bed protection measures should be considered to ensure the stability of the groyne head whenever necessary.

4.2.5 Scour downstream of weirs and barrages

The maximum scour depth in the equilibrium situation as well as the development in time of the scour depth has been studied. Based on experimental research in flumes the time dependent development of the scour depth in clear water flows was found to be:

$$\frac{h_s(t)}{h_o} = \left(\frac{t}{T}\right)^{0.38}$$

In which $h_s(t)$ is the maximum depth at time t

h_o is the upstream water depth

T is the time at which $h_s = h_o$

The above equation is not valid close to the equilibrium situation.

The time scale is found to be

$$T = \frac{330 (s - 1)^{1.7} (h_o)^2}{(\alpha \bar{u}_o - \bar{u}_{cr})^{4.3}}$$

\bar{u}_o = depth-averaged velocity just upstream ($x=0$) of scour hole

\bar{u}_{cr} = critical depth-averaged velocity (initiation of motion)

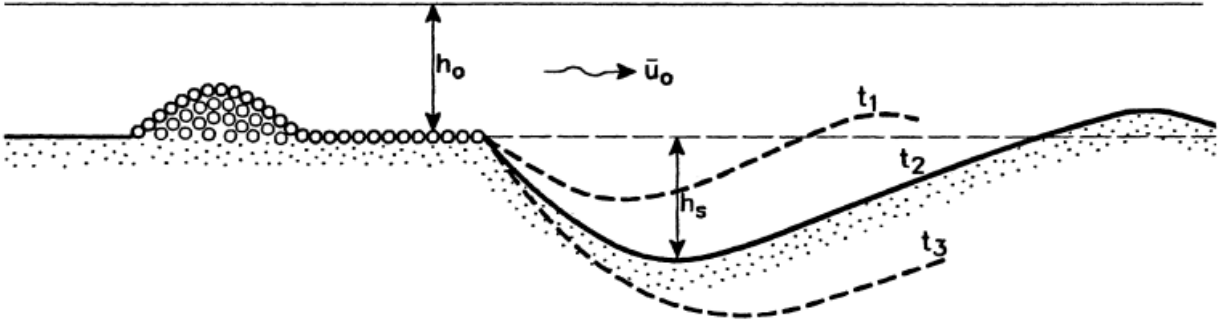
S = specific density (ρ_s/ρ)

α = coefficient depending on flow and turbulence structure at the upstream end of scour hole ($\alpha = 1.5$ for two dimensional flow without structure, $\alpha = 3$ for every violent three dimensional flow).

Generally-accepted formulas for the maximum scour depth in the equilibrium situation are not available. But, rough estimate can be found as:

$$h_{s,max} = \left(\frac{\alpha \bar{u}_o - \bar{u}_{cr}}{\bar{u}_{cr}}\right) h_o$$

Usually, the river bed downstream of a weir or barrage is protected over a certain distance to reduce the maximum scour depth which is strongly dependent on the α -factor (α decreases with distance due to the decay of turbulence). The bed protection length is of the order of 10 to $20h_o$.



Two dimensional scour downstream of structure