New Developments in Scour Modelling

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ABSTRACT

The updated Scour Manual (Hoffmans & Verheij, 2021) presents scour prediction methods and deals with practically current related scour problems. The original Scour Manual (Hoffmans & Verheij, 1997) is partly rewritten to capture the experience with the existing formulas and the knowledge in the field, especially related to turbulence. Attention is paid to mathematical scour and erosion models, risk assessment and erosion of cohesive sediments. The Breusers equilibrium method has a central role which can mostly be used to all situations where local scour is expected. The method allows to predict the scour depth as a function of time. New scour formulas for the equilibrium scour have been developed. Evaluating a balance of forces for a control volume, it is possible to develop scour equations for different types of flow fields and structures, i.e. jets, abutments and bridge piers. We will highlight these new developments during the conference.

INTRODUCTION

The Scour Manual contains guidelines which can be used to solve problems related to scour in engineering practice and also reflects the main results of all research projects in the Netherlands in recent decades. Obviously, also the so-called Breusers equilibrium method, is discussed. It allows to predict the scour depth as a function of time, however, the available knowledge about scour is not sufficient for applying the method to predict scour at each type of structure. Structure-specific scour prediction rules are presented then.

The treatment of local scour is classified according to the different types of structures. The main parameters of a structure and the main parts of the flow pattern near a structure are described briefly insofar they are relevant to the description of scour phenomena. New scour formulas for the equilibrium scour have been elucidated**.** Evaluating a balance of forces for a control volume, it is possible to develop scour equations for different types of flow fields and structures, i.e. jets, abutments, sills and bridge piers.

As many scour problems are still not fully understood, attention is paid to the validity ranges and limitations of the formulas, as well as to the accuracy of the scour predictions. This information can also be used to carry out a risk assessment using a safety philosophy based on a probabilistic analysis or an approach with a safety factor. Moreover, the information on the strength of soils is extended and aspects are addressed such as scour due to shear failures or flow slides, that can progressively damage the bed protection which might lead to the failure of hydraulic structures.

DESIGN PROCESS

General. It is crucial to design hydraulic structures that are reliable and safe during their life cycle. To ensure safe long-term functioning of hydraulic structures, it is necessary to consider boundary conditions, risk assessment and measures to prevent scour. We discuss the risk assessment and the fault tree analysis. Two methods are treated: 1) one based on safety factors and 2) one on failure probability. When applying these techniques one should keep in mind what the goal is of the design: a pre-feasibility study or a final design. We also discuss different design tools.

Risk Analysis. The main dimensions of a scour hole can be characterized roughly by the maximum scour depth expected during the lifetime of the structure and by the upstream scour slope. Not only the hydraulic and geotechnical characteristics influence these two design parameters, but also the presence of a bed protection. Figure 1 demonstrates that scour assessment is multidisciplinary in character, especially in the technical sense, with all relevant interactions between soil, water and structure.

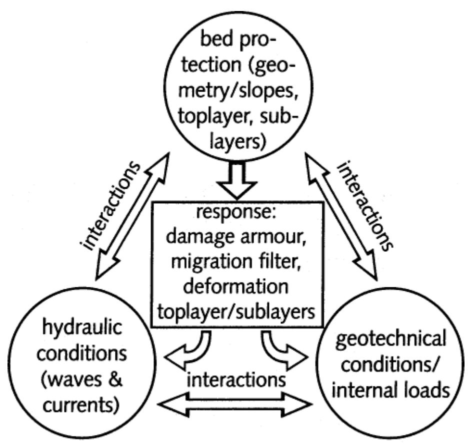


Figure 1 Soil-water-structure interaction.

During the design process of hydraulic structures various stages can be recognized: 1) pre-feasibility stage (often the tender phase), 2) preliminary stage (often the tender phase), and 3) final or executional stage. The pre-feasibility and the preliminary stages require a rough estimate of the dimensions of the scour holes and analytical and empirical formulae can be applied. Usually the upper limit will be used, because time is limited and not all aspects can be studied in detail. In the final stage a better estimate has to be made and it is recommended to use a risk based approach. Then, mathematical scour and erosion and physical models can be applied.

It is recommended to perform a risk assessment to establish the risks that need to be managed and to identify means to control them to acceptable levels. Therefore, it is necessary to consider all failure mechanisms, e.g. by using a fault tree. Prior to making a risk assessment a safety philosophy needs to be chosen. For various structures (sluices, sills, bridge piers, abutments) formulas to estimate the time-dependent scour process including the equilibrium scour depth. Sometimes, these formulas are best-guess predictors; sometimes they give an upper limit.

According to Breusers et al. (1977) the averaged scour depth at circular bridge piers is given as 1.5 times the pier diameter: $y_{m,e} = 1.5b$. Based on a systematic research on scour Melville and Coleman (2000) found an upper limit of $y_{m,e,max} = 2.4b$. Hence, the ratio between the maximum and mean value is about 1.6 which is comparable with the value (= 1.5) in Figure 2 showing that 50% of the results is larger than predicted.

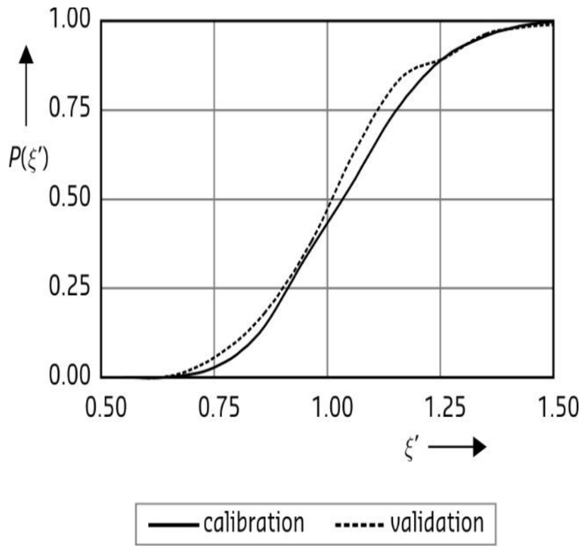


Figure 2 Cumulative density function for the equilibrium scour for pool plunge experiments (Hoffmans, 2012)

A considerable improvement could be obtained if the formulas are based on a safety philosophy. An example of a risk assessment including a safety philosophy is presented by Johnson (1992; Table 1), showing for bridge piers a safety factor as function of the failure probability based on Monte Carlo simulations.

Table 1 Relation between safety factor and probability of failure for bridge piers

Probability of failure	0.1	0.01	0.001	10^{-4}	10^{-5}
Safety factor	1.2	1.4	1.6	1.75	1.85

A safety philosophy for scour issues has been followed in the Eurocodes NEN-EN-1991 that specify how structures should be designed within the European Union. In principle, two approaches can be used for the safety philosophy:

1. Using a “fixed” safety factor, for example a value of 2, to be defined preferably using a failure requirement.
2. Applying a (semi-) probabilistic approach.

Obviously, option 2 is preferred over option 1, because all uncertainties can be considered individually but it is also time consuming. However, option 1 is simpler and quicker and should be considered as a fall-back option.

To produce a safe and reliable design, the total reliability as a function of all modes of failure should be approximated. A fault-tree can be very helpful, moreover it makes it possible to incorporate the failure due to human errors in the management and maintenance of the structure. For instance, the safety of a sluice can be dramatically improved by regular echo-sounding of the bed protection and by subsequent maintenance if the initiation of a scour hole is discovered.

The total scour depth applying the method with a safety factor (*SF*) needed for a design may be computed by summing all the components of vertical bed change:

$$y_{tot} = SF\sum_{i=1}^{n} y_i \quad (1)$$

where y_{tot} is the total scour depth inclusive a safety factor and y_i is scour due to various influences such as bend scour, bed elevation changes and local scour depth associated with a structure.

Methods to determine the failure probability with a (semi-) probabilistic approach are for example a Monte Carlo simulation, the FORM method or numerical integration. The reliability function Z (strength R minus load S) is the central point:

$$Z = R - S \quad (2)$$

The failure probability P_f can be determined if the reliability index β is computed as:

$$\beta = \mu_Z / \sigma_Z \quad (3)$$

in which μ_z and σ_z are the values of the average and standard deviation of the reliability parameter Z. The Eurocode distinguishes three safety levels in which the RC (Reliability Class) and the CC (Consequence Class) are described for a reference period of 50 years. Table 2 provides values for the safety requirements as well as descriptions of the consequences. The ratio RC1/CC1 means in case of a failure that the consequences are very limited; for RC2/CC2 the consequences are moderate, and for RC3/CC3 they are severe. In general, hydraulic structures must be designed on the RC3/CC3 level.

Table 2 Safety levels according to the Eurocode

Reliability Class / Consequence Class	Reliability index β	Failure probability P_f	Consequences in terms of loss of human life	Economic, social or environmental consequences
RC1/CC1	3.3	4.83E-04	Low	Small or negligible
RC2/CC2	3.8	7.23E-05	Medium	Considerable
RC3/CC3	4.3	8.54E-06	High	Very great

Applying Equation (1) requires computing each component of scour and relevant formulae are provided in the recently updated Scour Manual. Using the probabilistic approach means that for all parameters an average value and a standard deviation must be known or estimated beforehand (assuming all parameters fulfil the standard normal distribution). This requires a lot of information. Furthermore, mutual correlations between various parameters should be taken into account when relevant as this may influence the failure probability.

Design Tools. The total scour which may occur at the site of a structure can be estimated with 1) analytical/(semi-)empirical formulae, 2) mathematical/numerical models (= scour and erosion models), and 3) physical or laboratory models. Some analytical models are discussed in the next Sections. Physical models are a valuable tool and help us to understand the complex hydrodynamic processes occurring in the vicinity of hydraulic structures. Moreover, they provide reliable and economic engineering design solutions.

At present several mathematical models are available to predict two and three-dimensional scour. A first more or less traditional category of these models consists of two separated sub-models: a flow model and a morphological model which are connected to one model. The flow model calculates the flow velocities and the morphological model predicts the sediment transport and the bed level changes as function of time.

Although these models predict scour parameters they do not always predict the scouring process correctly due to the poor modelling of the turbulence in the scour hole, and the interaction between water and soil that govern the erosion processes. Examples are: RANS models (Reynolds-Averaged Navier–Stokes), DNS (= Direct Numerical Simulation) and LES (Large-Eddy Simulation) models. Figure 3 shows the differences between the models.

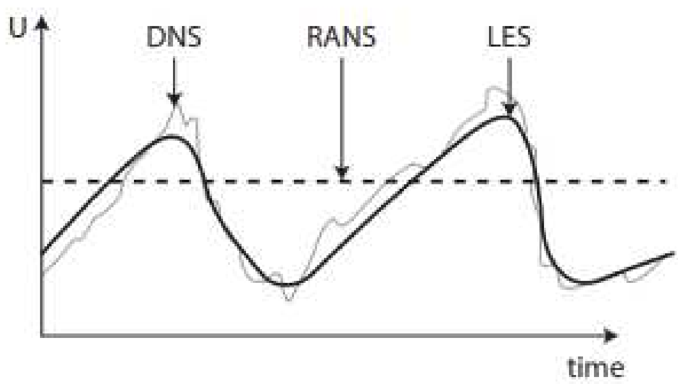


Figure 3 Principle of RANS, LES and DNS approaches.

A second category of mathematical models consists of particle-based models or multiphase models, where flow and sediments are solved together as different phases. They are mesh-free approaches, where flows and sediments are calculated as particles. An example of such an approach is a two-phase numerical model using Smoothed Particle Hydrodynamics, which is used for scour frequently.

Another example with possible application to scour modelling is the MPM (= Material Point Method) which has been developed for geotechnical applications. Also MPM is applicable for modelling complex soil-water interactions that determine scour. Nevertheless, mathematical models provide very qualitative results with respect to scour.

SCOUR PHENOMENA

General. Hinze (1975) developed an idealized model of bed turbulence. A horseshoe-shaped vortex is beginning to form locally at the bed. This vortex is deformed by the flow into a more and more elongated U-shaped loop in the streamwise direction. Where the instantaneous near-bed velocity (continuous profile) is at its maximum, there is an outward flow between the legs of the U-loop, also known as an ejection. This location is of interest to describe bed erosion.

The flow in a river is highly turbulent and is composed of eddies of different scales. This wide range of length scales is bounded from above by the flow depth (integral scale) and from below by the diffusive action of molecular viscosity, known as the Kolmogorov scale. The Taylor scale is the intermediate length. When eddies at integral scale, hereafter called as large eddies, have a large flow velocity fluctuation and low frequency, they contain the most energy, about 70% of the depth-averaged turbulent kinetic energy (Nezu, 1977 and Graf, 1998).
Scour occurs if the bed shear stress exceeds its critical value (Shields, 1936). Since the bed shear stress is proportional to the turbulent kinetic energy through the bed shear velocity (Hoffmans, 2012), large eddies are representative for bed erosion. Therefore, we use a control volume of two eddies, both of which have a length scale that approximately equals the flow depth; one eddy rotates clockwise and the other anticlockwise (Figure 4).

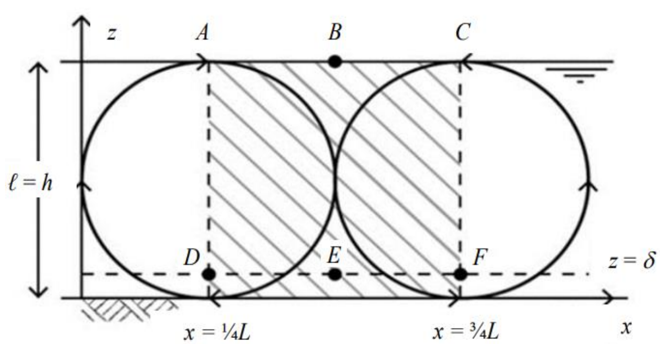


Figure 4 Two eddies in a uniform flow.

Uniform flow equilibrium. Uniform flow is defined as a flow in which each particle moves along its streamline with constant velocity and in which the cross sectional area remains unchanged. In uniform flow, the water flow is driven by gravity. The flow will reach exact equilibrium between the gravity force component in the streamwise direction and the shear force. The water depth and velocity become independent of time and position at uniform equilibrium. The bed shear stress, τ_0, for this type of flow can be written as:

$$\tau_0 = \rho g R S \tag{4}$$

in which g is the acceleration of gravity, R is the hydraulic radius, S is the energy slope and ρ is the water density. Equation (4) represents the well-known equilibrium equation based on Newton's first law. Using Chézy's equation the bed shear stress can also be given by (Hoffmans, 2012):

$$\tau_0 = 0.7\rho\left(r_0 U_0\right)^2 \tag{5}$$

with $$r_0 = \sqrt{k}/U_0 = 1.2\sqrt{g}/C \tag{6}$$

in which C is the Chézy coefficient which for rivers varies from 30 $m^{0.5}\ s^{-1}$ to 50 $m^{0.5}\ s^{-1}$, yielding the following range for the relative mean turbulence intensity: $0.075 < r_0 < 0.125$, k is the mean turbulent kinetic energy and U_0 is the mean flow velocity. The equilibrium conditions of uniform flow is considered by two large eddies which are representative for bed erosion (Figure 4). Figure 5 demonstrates the acceleration and deceleration zones and the profiles of the instantaneous and time-averaged flow velocities.

Along the reference level at sections AD (overpressure) and CF (under pressure) and accounting for bed friction the maximum bed shear stress is (Hoffmans, 2012): $\tau_{max} = 18\tau_0$. This approach of considering a control volume in non-uniform flow and selecting the relevant forces of over- and under pressures has been used to determine the equilibrium scour depth around hydraulic structures, such as wide and slender bridge piers, abutments and downstream of sills.

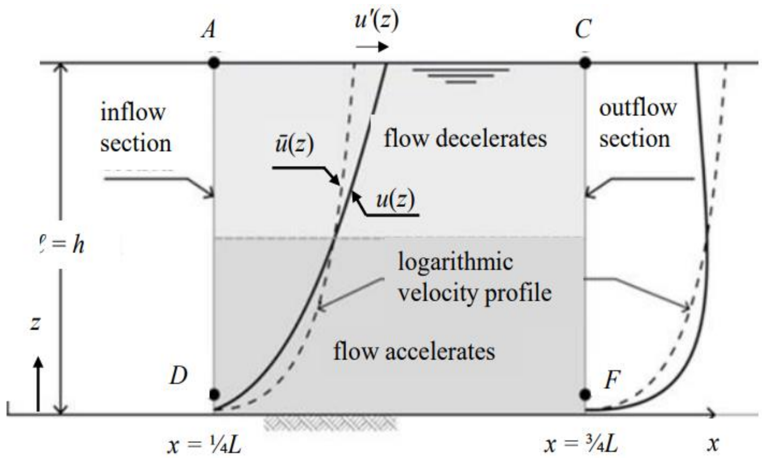


Figure 5 Flow velocities in two rotating eddies (see also Figure 4).

General and local scour. The time scale to reach equilibrium for general scour is generally longer than the time scale for local scour. Commonly occurring examples of general scour are the long-term change in the bed level of a river, scour due to a long constriction, scour in a bend or scour at a confluence. Local scour results directly from the impact of the structure on the flow. Local scour is the erosion occurring over a region of limited extent due to local flow conditions, such as may be caused by the presence of hydraulic structures.

Time-dependent scour. Based on clear-water scour experiments using scale models with small Froude numbers Zanke (1978) distinguished four phases in the evolution of a scour hole (Figure 6): an initial phase, a development phase, a stabilization phase and an equilibrium phase.

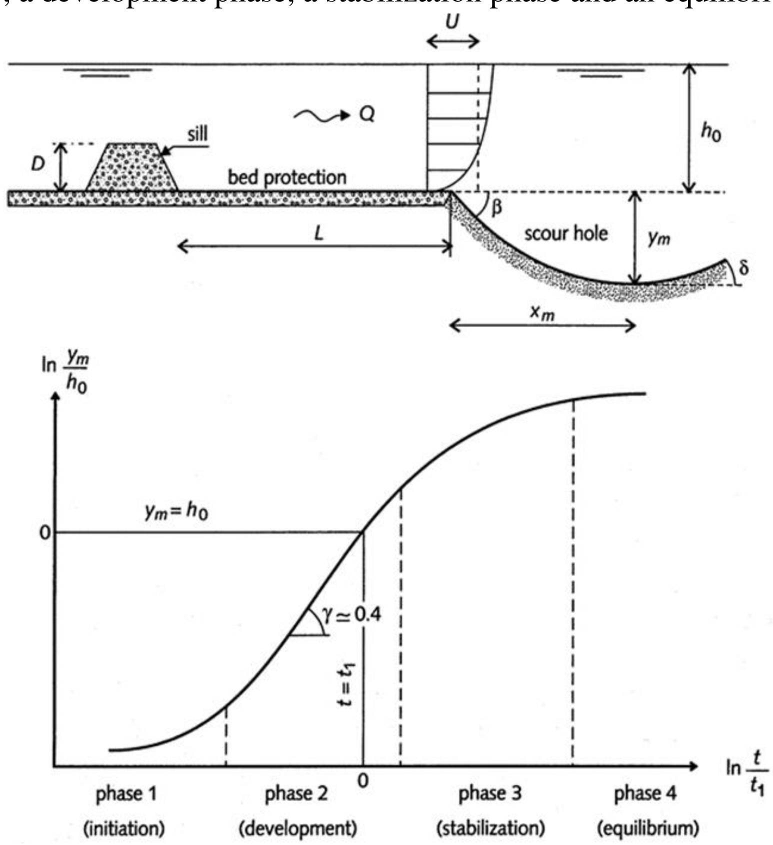


Figure 6 Time-dependent scour process downstream of sill.

In the development phase the scour depth can be estimated by:

$$\frac{y_m}{\lambda} = \left(\frac{t}{t_1}\right)^{\gamma} \quad \text{for} \quad t < t_1 \tag{7}$$

in which t is the time, t_1 is the characteristic time at which $y_m = \lambda$, y_m is the maximum scour depth, γ (= 0.4–0.8) is coefficient and λ is the characteristic length scale. Following Breusers (1966) the characteristic time is proportional to:

$$t_1 \propto \lambda^2 \left(\rho_s/\rho - 1\right)^{1.7} \left(\alpha U_0 - U_c\right)^{-4.3} \quad \text{for} \quad t < t_1 \tag{8}$$

in which U_c is the critical flow velocity, α (= 1.5 + 5r_0) is the turbulence coefficient, and ρ_s is the density of sediment. Equation (8) essentially shows the relation between the scour hole volume and the sediment transport. However, the sediment transport description does not fulfil the

Partheniades erosion law. A better equation for the time scale, though not calibrated and validated, reads (Hoffmans, 2012):

$$t_1 \propto \lambda^2 \left(\alpha' U_0^2 / U_c^2 - 1\right)^{-2} \quad \text{for} \quad t < t_1 \tag{9}$$

Equilibrium scour. The Breusers equilibrium method, which is important for safe designs, can be applied directly in engineering practice for nearly all types of structures. Accurate local flow velocities and turbulence intensities resulting from three-dimensional flow models can act as inputs for this scour method, which can be considered as a continuation and an expansion of the work of Breusers (1966). Next, we discuss innovative formulas, which are based on an analysis of equilibrium scour depths.

STRUCTURE-RELATED SCOUR

General. With respect to scour all hydraulics structures can be summarized into 4 types: bridge piers, abutments/groynes, sills and jets. The flow at jets differ from the flow at other structures because it is nearly always supercritical, although also supercritical flow at sharp-crested sills is possible, see Figure 7. Therefore, jets are treated separately. The Scour Manual also discus other types of scour such as pressure scour at bridges and scour downstream of permeable abutments.

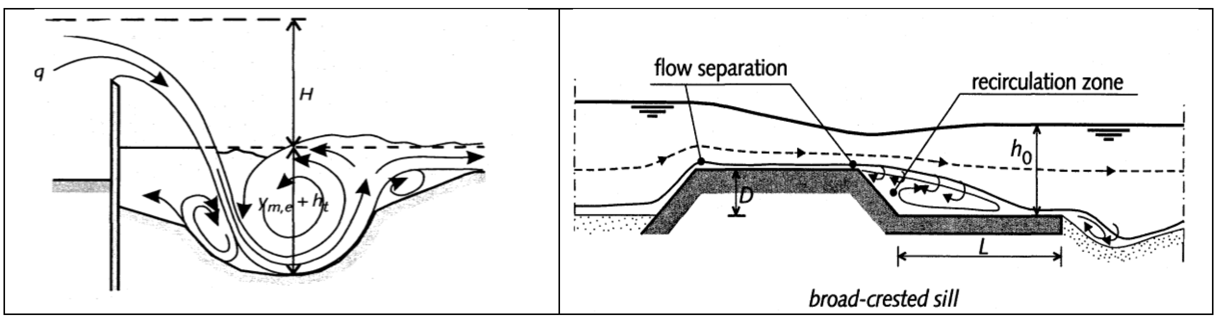
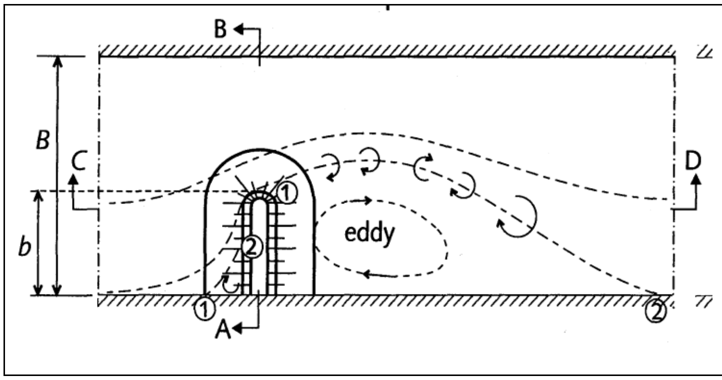


Figure 7 Supercritical jet due to overflow (left), and subcritical flow over a sill (right).

Bridge piers, abutments/groynes and sills. The flow fields at bridge piers and abutments /groynes are comparable. At both hydraulic structures the flow is forced to flow around the structure. Next to the structure the flow accelerates and behind the structure eddies can be observed, see Figure 8. Obviously, there are also differences such as the sloped head of an abutment, see Figure 9, which with respect to scour reduces the depth of the scour hole but also results in smoother flow lines.

A sill is a horizontal, structural part of a structure near bed level on a foundation or pilings that has to be constructed on a bed of alluvial material. In an estuary a sill has to be designed for flow in two directions: flood flow and ebb flow. In rivers, for example, a sill may be used as part of a scheme to maintain a minimum water level. Relatively small weirs on sills can be found in agricultural areas. A well-known prediction formulae for time-dependent scour at sills is the Breusers equation, see the Scour Manual (Hoffmans & Verheij, 2021).



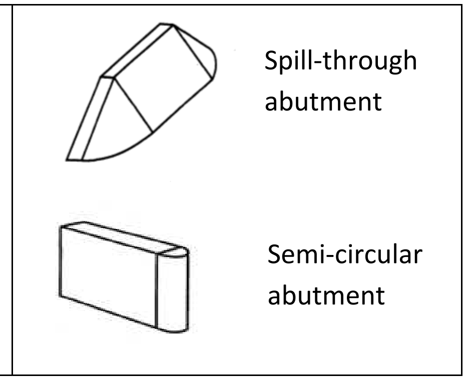


Figure 8 Flow around abutment head **Figure 9 Examples of abutment forms**

For bridge piers mostly empirical prediction formulae exist with correction factors for various influences and mostly developed from laboratory tests. Based on experimental data, Breusers et al. (1977) concluded that for live bed scour, the scour depth may be described by:

$$y_{m,e} = 1.5 K_i b \tanh\left(h/b\right) \qquad (10)$$

in which b is the pier diameter, h is the flow depth, and K_i is a correction factor (circular piers: K_i = 1.0). Hence, for slender circular bridge piers it follows: $y_{m,e} = 1.5K_ib$. Methods are also available for pressure scour in case of submerged bridges and for scour at bridge piers with a footing or pile cap, see Hoffmans & Verheij, 2021).

Also for abutments many empirical formulae are presented. Note that several names for abutments are used (spurs, groynes, guide or river bunds) in the literature. Abutments can be considered as single structures, i.e. as approach embankment for bridges, whereas groynes are supposed to protect the banks. Special attention requires permeable abutments, see Figure 10. Hoffmans et al. (2022) presented a scour equation for abutments that is based on a combination of Newton’s second law and a turbulence model comprised of a pair of isotropic vortices.

Figure 10 Pile screen as permeable abutment (Jamuna River, Bangladesh).

In this paper, we present recently developed theoretical relations based on a balance of forces (Hoffmans, 2012). The new equations read, also see Table 3 which provides per type of structure values for the parameters A and B:

$$\frac{y_{m,e}}{\lambda} = A\chi_e \left(\frac{U_0}{U_c}\right)^2 - B \quad \text{for clear water scour: } U_0 < U_c \tag{11}$$

$$\frac{y_{m,e}}{\lambda} = A\chi_e - B \quad \text{for live bed scour: } U_0 \geq U_c \tag{12}$$

with $$\chi_e = \frac{1+6.3r_0^2}{1-6.3r_{0,m}^2} \tag{13}$$

Table 3 Length scales and values for parameters *A* and *B*
(*h* = initial water depth and *b* = width of bridge pier (m))

Structure	λ	A	B
Sills	h	1.0	1.0
Abutments	h	1.4	1.0
Bridge piers (wide)	h	1.4	1.0
Bridge piers (slender)	b	1.6	1.3

In the deepest part of the scour hole, $r_{0,m}$ can be approximated by:

$$r_{0,m} = \sqrt{\tfrac{1}{2}C_k}\left(\frac{y_m}{h}+1\right) \quad \text{for} \quad 0.1 < \frac{y_m}{h} < 2 \tag{14}$$

where C_k is a constant dependent on the steepness of the upstream slope, 0.03 to 0.045. Values of the critical flow velocity U_c can be computed for alluvial bed material with:

$$U_c = 2.5\sqrt{\Psi_c\left(\rho_s/\rho - 1\right)gd}\,\ln\frac{12h}{k_s} \tag{15}$$

in which d is the particle diameter, and Ψ_c is the critical Shields parameter or via the critical shear stress (see Equation 5). However, the Shields approach cannot be applied for cohesive materials, such as clay and peat. Peat soil occurs in many areas and generally originates from plant and animal remains. It is considered partly as decomposed biomass. Due to this composition, the structure of this soil differs from inorganic soils like clay, sand and gravel. Peat has a high compressibility, low shear strength, high moisture content and low bearing capacity.

General values for the critical flow velocity for cohesive soils varies between 0.3 and 2.0 m s^{-1} (hard clay or peat with cohesion). Mirtskhoulava (1991) presented a method to compute the critical flow velocity, but this method requires information about various soil parameters. Hoffmans (2012) derived for clay and peat based on the equilibrium of uplift and downward forces the critical shear stress.

Using Equation (12) and assuming that $\chi_e = 1.75$ ($r_0 = 0.1$ and $r_{0,m} = 0.25$) the equilibrium scour depth is: $y_{m,e} = 1.5b$ which is equal to Equation (10) for slender bridge piers ($K_i = 1$). It should be remarked that for uniform flow conditions the turbulence intensity varies from 0.08 to 0.12 with a mean value of $r_0 = 0.1$. In the deepest part of the scour hole the turbulence intensity varies from 0.2 to 0.3 depending on the shape of the bridge pier. According to Dey and Barbhuiya (2006) the local turbulence intensities measure at a wing wall abutment: $r_{0,m} = 0.25$.

For abutments in which the width is larger than the flow depth Equation (10) reduces to: $y_{m,e} = 1.5K_i h$. Applying Equation (12) and assuming again that $\chi_e = 1.75$ ($r_0 = 0.1$ and $r_{0,m} = 0.25$; see Dey and Barbhuiya, 2006) the equilibrium scour depth is: $y_{m,e} = 1.5h$. Consequently, we have engineering tools which we can use in relation to turbulence models to predict the scouring process at hydraulic structures.

Jets. We discuss scour due to several jet forms, such as plunging jets, submerged jets, horizontal and vertical jets, and two- and three-dimensional jets, Figure 11. We present new relations having a theoretical base as they have been derived using the balance of forces.

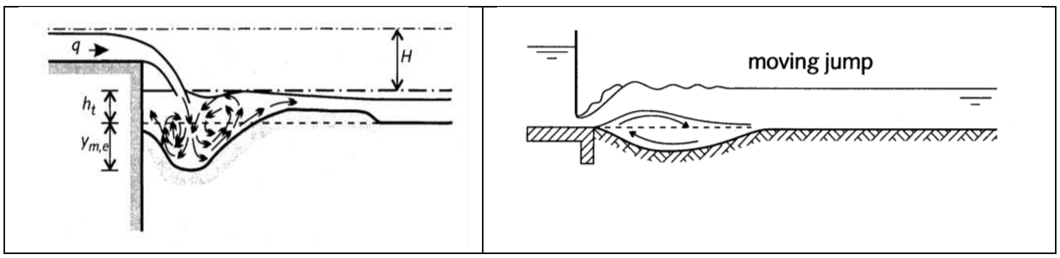


Figure 11. Examples of jets.

Most scour relations are not based on theoretical backgrounds, but are regressed relations calibrated by applying experiments in which the range of hydraulic conditions was restricted. Literature reviews of scour relations caused by plunging jets are given by Whittaker & Schleiss (1984). Schoklitsch (1932) proposed one of the earliest relations defining the scour depth as:

$$y_{m,e} + h_t = \alpha_S d_{90}^{-0.32} H^{0.2} q^{0.57} \tag{16}$$

in which α_S [$s^{0.57}$ $m^{-0.02}$] is a dimensional coefficient, d_{90} is the particle diameter for which 90% of the sediment grains is finer than d_{90}, h_t is the tailwater depth, H is the difference between head and tailwater levels (drop head), q is the discharge per unit width and $y_{m,e}$ is the equilibrium scour depth. The Veronese (1937) equation is comparable to Equation (16).

Other relations vary both in form and in the magnitude of the coefficients, e.g., Breusers and Raudkivi (1991) showed that the exponents of the drop head for these relations vary from 0.05 to 0.5. Further investigation of existing relations indicates that they do not include all the factors influencing the formation of a scour hole, i.e. the critical relation between hydraulic and geologic factors. Hoffmans (2009) used Newton's second law and modified the starting points of Fahlbush (1994) and arrived at the following relation for the equilibrium scour depth:

$$y_{m,e} + h_t = c_{2V} \sqrt{qU_1 \sin\theta / g} \tag{17}$$

with c_{2V} is a dimensional coefficient which decreases with an increasing particle size and for gravel c_{2V} is constant and θ is the jet angle with the horizontal. Combining the jet velocity as given by

Torricelli: $U_1 = (2gH)^{0.5}$ and Eq. (16) the total water depth is proportional to: $y_{m,e} + h_t \propto (qU_1)^{0.5}$. Hence, the scour equations as proposed by Schoklitsch and Veronese are physical-based.

Horizontal 2D flows are considered to be flows under barriers/gates which are sufficiently wide. Following Schoklitsch (1935) it is possible to distinguish attached jets (or wave or plunging jumps) and surface jets (or moving or inverted jumps) in which the jet form depends on a number of factors such as submergence flow and turbulence patterns. As there is a variety of different relations for this type of scour (Hoffmans, 1995), we discuss here some equations with a high predictability.

Qayoum (1960) studied the scour resulting from flow under gates with no bed protection. Several tests were performed in which the discharge, the head and the sediment size were varied. Using dimensional analysis Qayoum obtained the following relation:

$$y_{m,e} + h_t = 2.78 \frac{h_t^{0.4} H^{0.22} q^{0.4}}{d_{90}^{0.22} g^{0.2}} \tag{18}$$

Hoffmans and Verheij (2011) applied Newton's second law to a control volume in the horizontal direction and found for the equilibrium scour depth:

$$y_{m,e} + h_t = c_{2H} \sqrt{q(U_1 - U_2)/g} \tag{19}$$

in which c_{2H} is a dimensional constant representing the strength. Note that with Torricelli's law Qayoum's equation is comparable to Equation (19).

Martins (1973) analyzed about 100 scour experiments of 3D jet falling on a rocky river bed, which consisted of equal cubic blocks systematically arranged without cohesion. Ruff et al. (1982) examined the scour process downstream of circular culverts. Abt et al. (1984) and Breusers and Raudkivi (1991) analyzed these tests. They all arrived at the following proportionality, also see Hoffmans (2012):

$$y_{m,e} \propto (QU_1/g)^{1/3} \tag{20}$$

in which Q is the discharge. Hoffmans and Verheij (2011) applied Newton's second law and found for the equilibrium scour depth downstream of horizontal 3D jets a similar relation. Therefore, for jets we have also engineering tools to predict scour.

CONCLUSIONS

In this paper, we discuss innovative approaches to calculate the scour depth and the relevance of risk analysis. Usually we predict the equilibrium scour depth using a safety factor in relation to the ratio between the reliability class and the consequence class. However, we can also apply a probabilistic approach, for example, when we deal with (very) complex hydraulic structures.

We summarize new insights in the modelling of scouring downstream of sills/dams, due to different types of jets and at bridge piers and abutments. We use the change in momentum per unit of time in the control volume flowing in a channel. The sum of external forces acting on the element equals nil in the equilibrium phase. Despite the simplifications made the method can be used to calculate scour for sand and gravel within a reasonable accuracy. The maximum and minimum predictions of the equilibrium scour depth equal about 1.5 and 1/1.5 = 2/3 of the mean value respectively.

The basic conclusion is that local scour at hydraulic structures such as abutments (groynes), spurs or guide bunds, bridge piers in alluvial rivers depends on the geometry of the structure, the geometry of the surrounding river area, the approach depth, the dimensions of the bed protection and the time. The magnitude of the equilibrium scour depth is mainly determined by the geometry of the structure.

Though we discuss innovative approaches to calculate the scour depth as function of time, in the practical equilibrium phase there are still uncertainties in the scour prediction. Therefore, we recommend to analyze scour/erosion with physical and mathematical turbulence models in relation to analytical scour equations as discussed. In this way, we can understand the physics and improve our engineering tools for scour prediction. Hopefully we can derive one formula to calculate scour regardless the type of hydraulic structure.

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