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THE INFLUENCE OF UPSTREAM TURBULENCE ON LOCAL-SCOUR HOLES

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1. Introduction

Scour is the lowering of the sea or river-bed as a result of non-equilibrium sediment transport conditions and can be divided into several categories. Local scour, which may occur at the base of a structure because of the affected flow pattern, can severely endanger the stability of this structure. Many varieties of local-scour systems downstream from hydraulic structures exist, each with its own particular geometry and hence local scour mechanism.

The prediction of local-scour holes that develop downstream from hydraulic structures plays an important role in their design. Excessive local scour can progressively undermine the foundation of a structure. Because complete protection against scour is too expensive generally, the maximum scour-depth and the upstream slope of the scour hole have to be predicted to minimize the risk of failure.

In 1961 a systematical research with respect to scour holes started in the Netherlands at Delft Hydraulics within the scope of the Delta works. After the catastrophic flood disaster in 1953 the Delta plan was made to protect the Rhine-Meuse-Scheldt delta for future disasters. Dams with large scale sluices were planned in some estuaries. The severe scour expected necessitated a better understanding of the scour process.

To find detailed information about the physical processes playing a role in scour many experiments were carried out, in which various parameters of the flow and the scoured material were varied. From the results of experiments in flumes with all difficulties of scale effects and limitations in instrumentation some empirical relations were obtained, which describe the erosion process as function of time and place (Breusers, 1966).

In these empirical relations a not well defined turbulence coefficient was introduced. Up to now this coefficient was related to the geometry upstream of the scour hole, which relation was based on trial and error. Based on theoretical

grounds an analytical relation for the depth-averaged turbulence intensity is derived in this paper. This relation, which implies a modification of the turbulence coefficient in the Breusers scour formula, is verified using approximately 300 experiments.
The modified scour formula yields results that compare reasonably well to measured and computed developments of a scour hole in case of a uniform flow upstream of the scour hole corresponding with a large protected bed area. The computations were based on the two-dimensional Navier-Stokes and convection-diffusion equations (Hoffmans, 1992). The present paper aims at extension of the domain of application of the scour formula to non-uniform flow conditions upstream.

2. Semi-empirical scour approach

Generally the scour process is determined by flow and sediment characteristics. The sediment transport is mainly dependent on the bed shear-stress and the turbulence condition near the bed on the one hand and the density of the bed material, the sediment-size distribution and the porosity of the (non-cohesive) material on the other hand. Based on many clear-water scour observations Breusers (1966) reported that the scour process could be written as:

$$\frac{y_m}{h_0} = \left(\frac{t}{t_1}\right)^{\gamma} \quad \text{where} \quad t_1 = K_1 \frac{h_0}{\overline{U}_0} T_{\alpha}^{\beta 1} \Delta^{\beta 2} Fr^{\beta 3} Re^{\beta 4} \tag{1}$$

In equation (1) y_m is the maximum scour-depth, h_0 is the initial flow-depth, t is the time, t_1 is the characteristic time at which $y_m = h_0$, $\overline{U}_0 = Q/(B h_0)$ is the mean flow-velocity, Q is the discharge, B is the width of the flow, $T_\alpha = (\alpha \overline{U}_0 - \overline{U}_c)/\overline{U}_0$ is a transport parameter, $\overline{U}_c$ is the depth-averaged critical flow-velocity according to Shields, Δ is the relative density, $Fr = \overline{U}_0 (g h_0)^{-0.5}$ is the Froude number, g is the acceleration of gravity, $Re = \overline{U}_0 h_0 / \nu$ is the Reynolds number, ν is the kinematic viscosity and γ , K_1 , $\beta 1$ to $\beta 4$ and α are coefficients (table 1). In the transport parameter T_α , which can be interpreted as a measure for the erosion capacity in the scour hole, the turbulence is represented by the turbulence coefficient α . According to Breusers the turbulence coefficient α is related to r_0 (relative turbulence intensity, section 3.3) at the transition of the fixed to the erodible bed. Hence the local bed-turbulence in the scour hole is not included in α . Though this is somewhat con-

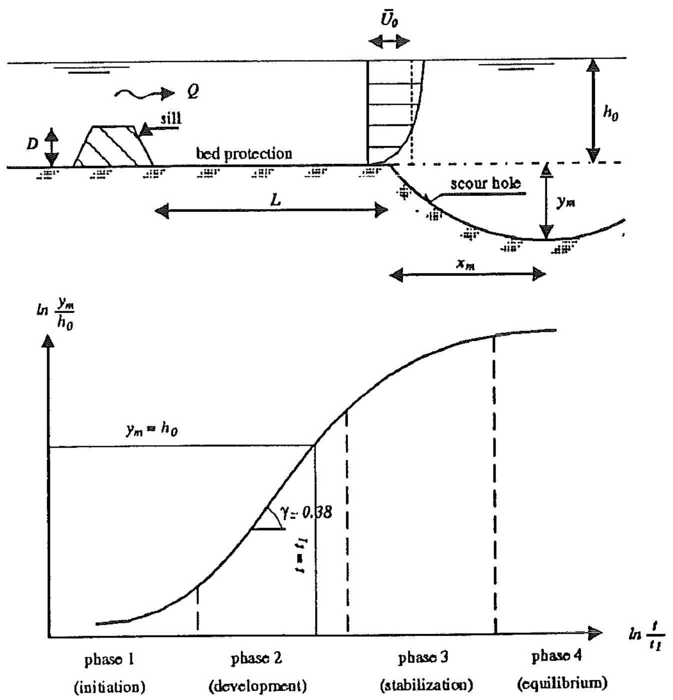

Figure 1 Development of the scour process

troversial, the used approach is followed because of its simplicity.
The definition of the exponent γ in equation (1) is not obtained unambiguously. Only in the development phase (phase 2) a more or less constant value of γ applies, figure 1.
After a further extensive evaluation of the enormous amount of data of both two and three-dimensional scour experiments the coefficients in the scour relations were readjusted (Jorissen and Vrijling, 1989). Besides these Dutch research activities many other investigators e.g. Dietz (1969) and Zanke (Hoffmans, 1992) contributed to the scour research. These research activities confirmed the empirical relations of Breusers, although with different values for the empirical coefficients (table 1).
The differences between the coefficients obtained by calibrating the measurements are generally small and may be due to the different method calculation. Also the number of experiments and the reach of the hydraulic and material parameters prove not to be insignificant considering the 'improved' constants.

	$K_1/10^6$	$\beta 1$	$\beta 2$	$\beta 3$	$\beta 4$	α
Breusers (1966)	0.94	-4.0	1.62	-2.7	-0.3	$1+3r_0$
Dietz (1969)	9.95	-4.0	1.75	-2.5	-0.5	$1+3r_0$
Jorissen and Vrijling (1989)	17.1	-4.3	2.0	-2.87	-0.43	$1.5+5r_0$

Table 1 Empirical coefficients in scour formula (equation 1)

3. Turbulence parameters

3.1 General

Usually a sill has the function of a foundation for a closure dam in an alluvial river or estuary. In a river the flow over a sill is mostly unidirectional. Sills with a broad or a sharp crest and sills with and without a bed protection can be distinguished. Normally the flow above a sill is subcritical, but depending on the waterlevel downstream from the sill the flow can become supercritical. In this study only subcritical flow is considered.

3.2 Nature of the flow

In analogy of the distribution of characteristic flow patterns in scour holes (Hoffmans, 1992) the following flow zones can be distinguished downstream from a sill: a mixing layer, a recirculation zone, a relaxation zone and a new wall-boundary layer, figure 2.
In the deceleration zone, the separated shear-layer appears to behave much like an ordinary plane mixing layer. A recirculating flow develops behind the sill. The underside of the shear layer curves sharply downwards to the point of reattachment. Both in the mixing layer and in the recirculation zone the

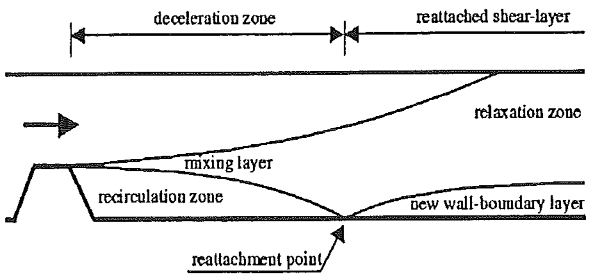

Figure 2 Flow regions

flow is very unsteady and highly turbulent. Downstream from the point of reattachment, the turbulence energy and the dissipation rate of the turbulence energy decay rapidly. Simultaneously, a new wall-boundary layer develops and spreads into the relaxation zone (the outer part of the reattached shear-layer). Measurements of Troutt et al (1984) have shown that behind a backward-facing step the flow in the relaxation zone still has most of the characteristics of a free shear-layer flow as much as 50 step heights downstream from reattachment. This observation demonstrates the persistence of the large-scale eddies, which are developed in the mixing layer.

3.3 Turbulence energy and relative turbulence intensity

Based on theoretical grounds a relation is derived for the turbulence coefficient α in the transport parameter in equation 1 (section 3.4). In this relation α is related to r_0 at the transition of the fixed to the erodible bed. The parameter r_0 is the depth-averaged relative turbulence intensity of the longitudinal turbulence velocity component. The longitudinal component is only considered because this was the only component measured in general.

Before examining the turbulence energy downstream from a sill in more detail some definitions are given. The (kinetic) turbulence energy k and r_0 respectively are defined by (Hinze, 1975):

$$k = \tfrac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right) \tag{2}$$

$$r_0 = \frac{1}{\overline{U}_0 h_0} \int_0^{h_0} \sqrt{\overline{u'u'}(z)}\, dz \tag{3}$$

in which the terms u' , v' and w' are the fluctuating flow-velocities in the longitudinal, transverse and vertical direction respectively.

Combining equations 2 and 3 and using measurements of Nezu (1977) the turbulence energy averaged over the depth is for uniform-flow conditions:

$$\frac{1}{h_0} \int_0^{h_0} k(z) dz \simeq \left(r_0 \overline{U}_0\right)^2 \tag{4}$$

For non-uniform flow, measurements of van Mierlo & de Ruiter (1988) have shown that the turbulence energy k_m in the centre of the mixing layer grows rapidly to a maximum. Downstream from the point of reattachment this turbulence energy in the relaxation zone decreases gradually again and becomes small compared to the turbulence energy generated by the bed in the developing new wall-boundary layer. The turbulence energy generated in the mixing layer vanishes for relatively large values of x , i.e., where the new wall-boundary layer is well developed. Then the turbulence energy tends to an equilibrium value, which largely consists of turbulence generated at the bed.

To analyze the decay of the turbulence energy in the relaxation zone k_η an analogy with the decay of k and the dissipation in grid turbulence can be used. When the zone downstream of the point of reattachment is considered and the production and diffusion terms in the transport equations of the turbulence energy and the dissipation are neglected, k_η can be given by (Hoffmans, 1992):

$$k_\eta(x) = k_m \left[\frac{x - x_R}{\lambda} + 1 \right]^{\alpha_k} \quad \text{for} \quad x \geq x_R \tag{5}$$

in which x is the longitudinal coordinate, x_R is the x-coordinate where the flow reattaches the bed, λ is a relaxation length and α_k (=-1.08) is a coefficient, which is directly related to the turbulence coefficients used in k-ε-models.

The hypothesis of self-preservation requires a constant turbulence energy in the mixing layer up to the point where the boundaries have reached the surface and the bed. An appropriate value is (Hoffmans, 1992):

$$k_m = C_k \overline{U}^2 \tag{6}$$

in which C_k (=0.045) is a coefficient and $\overline{U}$ is the depth-averaged flow velocity above the sill.

The turbulence energy averaged over depth from which r_0 can be determined, downstream from a sill can be given by:

$$\frac{1}{h_0} \int_0^{h_0} k(x,z) dz = \beta_k k_\eta(x) + c_0 u_*^2(x) \tag{7}$$

in which u_* is the bed shear-velocity and β_k (=0.5) is a coefficient (Hoffmans, 1993). Actually the bed shear-velocity varies in the streamwise direction. In the recirculation zone the bed shear-velocity is relatively small and even zero in the reattachment point. Downstream from the point of reattachment the bed shear-velocity tends rapidly to the equilibrium value corresponding to uniform-flow conditions for which applies $c_0 = 1.45$.

The length of the bed protection L will for safety reason always extend beyond the point of reattachment. Combining equations (3) to (7) in the zone downstream from the point of reattachment only shows r_0 can be represented by:

$$r_0 = \sqrt{\beta_k C_k \left[1 - \frac{D}{h_0} \right]^{-2} \left[\frac{L - 6D}{\lambda} + 1 \right]^{\alpha_k} + c_0 \left[\frac{u_*}{\overline{U}_0} \right]^2} \tag{8}$$

in which D is the height of the sill.

More than 250 experiments (Hoffmans, 1993) were used to verify the model equation for the relative turbulence intensity. In these laboratory experiments the hydraulic conditions $(\overline{U}_0, h_0, k_s)$ as well as the geometrical parameters (L, D, B) were varied. Moreover tests were executed with an abutment in permanent flow introducing three-dimensional scour. In these tests the width of the abutment measured $b = 0.1B$, figure 3.

Figures 4 to 8 presents the results of the measured and calculated values of r_0 , where the influence of both the height of the sill and the length of the bed protection can be observed.

The standard deviation of r_0 for three-dimensional experiments (figures 5 and 7) is somewhat larger than for two-dimensional ones (figures 4 and 6). This can

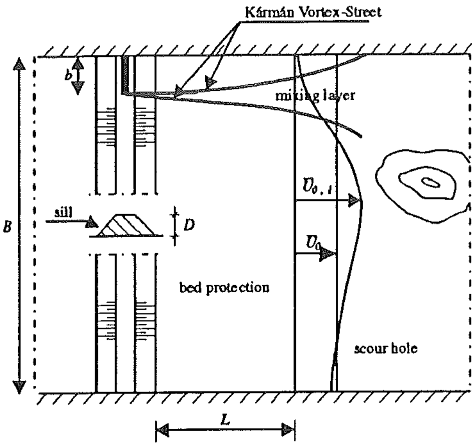

Figure 3 Definition sketch of $U_{0,t}$

partly be ascribed to periodical vortices, which can occur at the boundaries of the mixing layer in the transverse direction known as a Kármán Vortex-Street and partly to the measuring procedure.

In the two-dimensional experiments the velocities in the main direction of the flow were measured with a propellor-type current meter and were taken at about 10 points along the vertical axis in the centre of the flume. In the case of three-dimensional scour the longitudinal flow velocities were also measured at several locations along the transverse axis. However, the data given in figures 5 and 7 are not averaged values over the width of the flume, but concerns measurements carried out in the axis, where the depth-averaged flow velocity is at maximum.

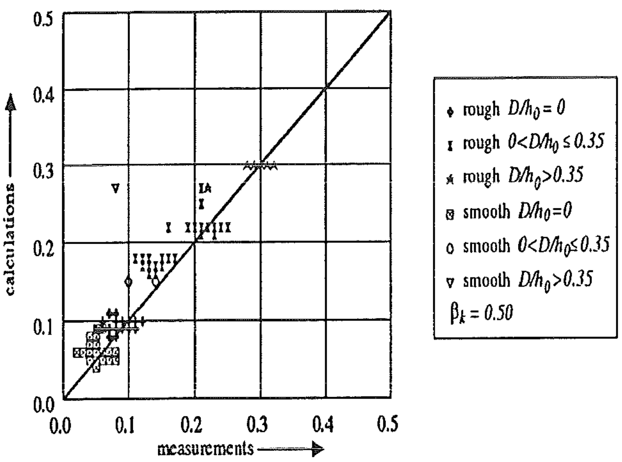

Figure 4 Relative turbulence intensity (2-D experiments)

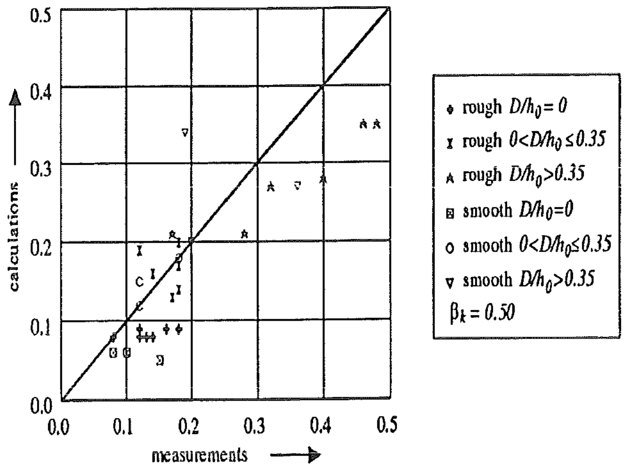

Figure 5 Relative turbulence intensity (3-D experiments)

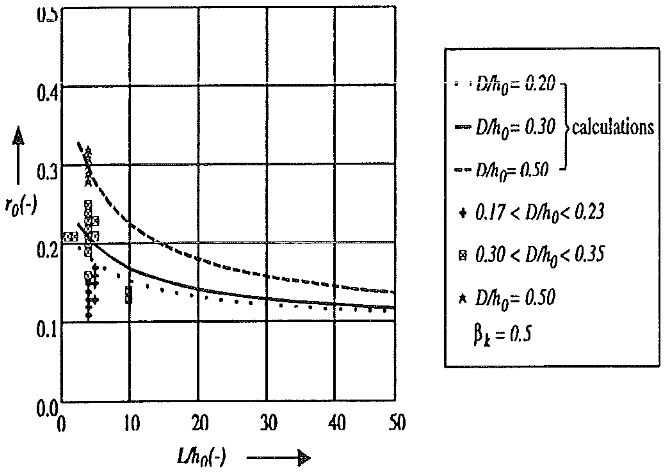

Figure 6 Relative turbulence intensity as function of L/h_0 (2-D experiments; rough)

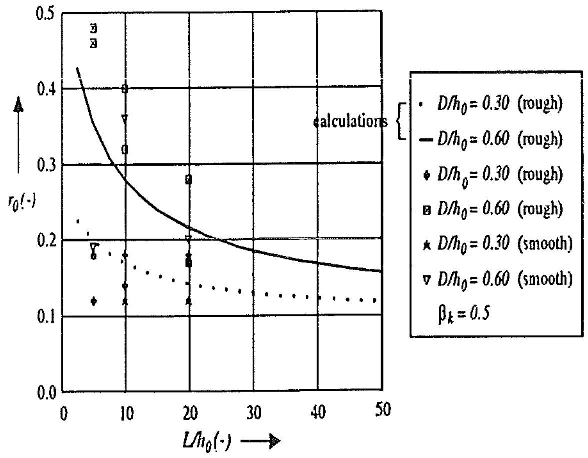

Figure 7 Relative turbulence intensity as function of L/h_0 (3-D experiments)

The measurements of the longitudinal flow-velocity near the bed, where large gradients occur, were inaccurate due to the relatively large dimensions of the measuring instrument. Also the number of measuring points in the vertical was not large enough especially in the mixing layer to calculate r_0 from the measurements accurately (figure 6).

3.4 *Turbulence coefficient in the scour formula*

The value of α in the scour formula can be obtained using the relation between α and r_0 from Jorissen and Vrijling (1989) $\alpha = 1.5 + 5r_0$ (table 1). This value is based on the use of a local depth-averaged velocity $\overline{U_{0,\ell}}$ in the scour formula. If a three-dimensional flow is considered and the mean flow-velocity $\overline{U_0}$ (figure 3) is used in the scour formula, the value of α has to be multiplied by $\overline{U_{0,\ell}}/\overline{U_0}$.

A re-examination of more than 250 experiments (Hoffmans, 1993) shows that reasonable results are then achieved for both two and three-dimensional experiments.

Already Hinze in 1961 remarked that not only the influence of the relative turbulence intensity but also the influence of the flow-velocity profile near the bed is significant for the development of the scour process. To include the influence of a smooth bed a simple expression is introduced, which is verified applying about 550 experiments (Hoffmans, 1993):

$$\alpha = 1.5 + 5 r_0 f_C \tag{9}$$

in which $f_C = C/C_0$ represents a roughness function, C is the Chézy coefficient related to the bed protection upstream from the scour hole and $C_0 = 45\,\mathrm{m}^{1/2}/\mathrm{s}$. For hydraulically-rough conditions $C \leq 40\,\mathrm{m}^{1/2}/\mathrm{s}$ regarding the fixed bed before the scour hole $f_C \simeq 0.9$.

Though the influence of three-dimensional effects are not included in the model equation for r_0 (equation 8) satisfactory results are obtained, especially for two-dimensional scour.

4. Conclusions

A model equation is given for the relative turbulence intensity (equation 8), which is based on theoretical grounds and fitted to results of velocity measurements. This study shows a way to calculate the relative turbulence intensity at the transition of the fixed bed to the erodible bed, which can be used to predict two-dimensional scour downstream from a sill.

The particular case of scour of three-dimensional flow considered here is flow around an abutment with consequent scour development downstream. Although some characteristics of three-dimensional flow and additional phenomena such as vortices with a vertical axis in particular have not been taken into account in the model equation for the relative turbulence intensity, promising results regarding three-dimensional scour are obtained. For example, in the centre of the flow where the scour depth is about at maximum, the influence of the Kármán Vortex-Street can be neglected. However, prudence has to be called for complex hydraulic structures. Then it is recommended to carry out experiments using a scale model to find detailed information about the development of a scour hole.

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