THREE DIMENSIONAL SCOUR

Gijs HOFFMANS[1] and Henk VERHEIJ[2]

[1]Member of ISSMGE, Hydraulic Specialist, Deltares
(P.O. Box 177, 2600 MH Delft, The Netherlands)
E-mail:gijs.hoffmans@deltares.nl
[2]Lecturer, Delft University of Technology and Deltares
(E-mail:henk.verheij@deltares.nl

This study investigates propeller scour and 3D (three-dimensional) scour generated by free jets downstream of outlets. Jet velocities can reach 6 to 8 m/s and when scour is unacceptable this results in the need for robust and expensive bed protection. Here the time scale of propeller scour is approximated by applying the Breusers' time-dependent scour equation. For the maximum scour depth in the equilibrium phase for both propeller and 3D scour, an equation which is based on six equations including Newton's second law with six unknowns is deduced. Finally, the proposed equation is validated by using prototype scour caused by berthing along quay walls of the Dutch "Amsterdam-Rijn" channel.

Key Words : *3D Jet scour, Newton's second law, Propeller scour, Time-dependent scour, Validation*

1. INTRODUCTION

2D surface jets are symbolised by two different flow velocities occurring in the undisturbed flow and the deceleration or recirculation zone where the near-bed velocities are relatively small. At the interface, that is in the mixing layer where the velocity gradients and the turbulence intensities are at maximum, the flow is unstable. The surface jet flow has a potential core, a wedge-like region in which the flow velocity equals the efflux velocity, and a diffused jet.

Jets that are initiated by a propeller accelerate fluid in axial, radial and tangential directions. The flow behind a ship's propeller is similar to a flow in a free (or 3D) jet, because in both flows the jet diffuses. However, there are also differences. The rotation and whirl in a propeller jet is higher, resulting in different patterns for flow (Fig. 1) and turbulence (Fig. 2).

This paper provides an introductory discussion of turbulence and velocity parameters in a 3D scour hole. The time-dependent behaviour of scour is analysed in relation to the required dimensions of the bed protection when scour is not acceptable. Finally, a relation for the maximum scour depth in the equilibrium phase is derived by applying Newton's second law and verified with some prototype tests.

2. HYDRAULIC MODELLING

The depth-averaged relative turbulence intensity (r_0) and the local relative turbulence intensity (r_u) are defined as

$$r_0 = \frac{\sqrt{k_0}}{U_0} \quad \text{and} \quad r_u = \frac{\sigma_u}{u} \quad \text{with}$$

$$k_0 = \tfrac{1}{h}\int_0^h \tfrac{1}{2}\left(\sigma_u^2(z) + \sigma_v^2(z) + \sigma_w^2(z)\right)\mathrm{d}z \qquad (1)$$

in which h is the flow depth, k_0 is the depth-averaged turbulent kinetic energy, u is the mean local velocity in the x (= longitudinal) direction, U_0 is the depth-averaged flow velocity, σ_u, σ_v and σ_w are the standard deviations of the fluctuating velocities in the x, y (= transverse) and z (= vertical) directions respectively.

For uniform flow, r_0 (= $1.21g^{0.5}/C$ in which C is the Chézy coefficient representing the bed roughness and g is the acceleration due to gravity) varies from 0.08 to 0.12 and is somewhat smaller than r_u (= 0.15) at a reference level close to the bed.

The turbulent kinetic energy (k_{mix}) in a 2D mixing layer with U as the velocity in the undisturbed flow, is

$$k_{mix,2\mathrm{D}} = \left(r_{0,2\mathrm{D}}U\right)^2 \qquad (2)$$

According to Van Mierlo and De Ruiter (1988) who examined 2D flow velocities and turbulence patterns downstream of an artificial dune, $r_{0,2D}$ in the mixing layer increases in the x direction from 0.17 to 0.26, so $r_{0,2D,\max} = 0.26$, while the maximum value of r_u caused by propellers is larger, $r_{u,prop,\max} = 0.3$ (Verheij 1983).

The propeller jet can be schematised according to the actuator disc theory and can be considered as a submerged 3D jet discharging out of an orifice into an infinite fluid where the jet velocities are Gaussian distributed around the axis. As given by Albertson et al. (1948) the maximum velocity in the mixing layer (u_m) and the jet velocity ($u_{r,x}$) in the diffused jet (Fig. 3) are

$$u_m = (2c_1)^{-1} U_e (D_p / x)^{c_0} \quad \text{and}$$

$$u_{r,x} = u_m \exp\left[-\frac{1}{2c_1^2} \frac{r^2}{x^2} \right] \tag{3}$$

where c_0 and c_1 are coefficients, D_p is the 3D jet diameter (or propeller diameter), and r is the radial distance from the jet axis.

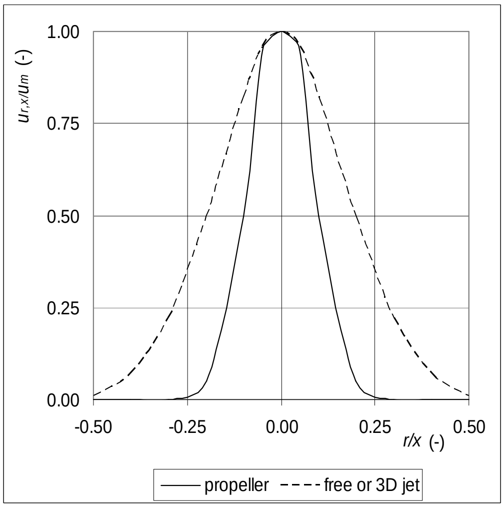

Fig. 1 Differences between velocities of propeller and free jets

The efflux velocity (U_e) reads (Blaauw and Van de Kaa 1978)

$$U_e = 1.15 \left[\frac{P}{\rho D_p^2} \right]^{1/3} \tag{4}$$

where P is the installed engine power and ρ is the density of water. The reattachment length (x_R) of the jet ranges from $4 < x_R / z_p < 10$, where z_p is the distance between propeller axis and bed level. The maximum near-bed velocity ($u_{b,m}$) occurs at $x_R / z_p = 5.6$, giving

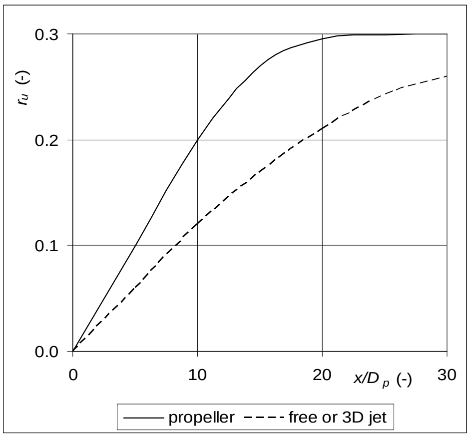

Fig. 2 Differences between turbulence of propeller and free jets

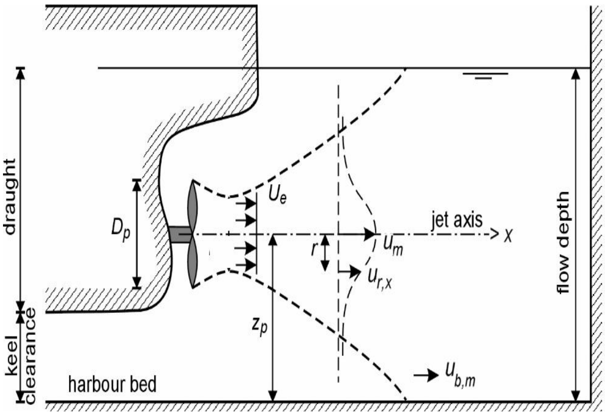

Fig. 3 Flow field behind a free propeller

$$u_{b,m} = c_2 U_e (D_p / z_p) \tag{5}$$

where c_2 is a coefficient. Fueher, Römisch and Engelke (1981), Blaauw and Van de Kaa (1978) and Verheij (1983) use both Eqs. 3, 4 and 5 to predict near-bed load caused by shipping manoeuvres. However, the German and the Dutch approaches apply different coefficients (Table 1).

3. STONE STABILITY

Although numerous stone stability equations have been discussed in the literature, the equation proposed by Brahms in 1767 is still valid

$$d_{50} = (\alpha_B)^{-2} u_{b,c}^2 \tag{6}$$

where d_{50} is the required stone diameter, $u_{b,c}$ is the critical near-bed velocity and α_B [m$^{0.5}$/s] is a dimen-

Table 1 Overview of 3D jet parameters in Eqs. 3 and 5

	Albertsen et al. 1948	Dutch(2) approach	German approach(3)
c_0	1	1	0.25 twin propeller 0.30 extra influence for lateral quay wall 0.60 influence of bed and water surface 1.62 for jets reflected by a quay wall
c_1	0.081	0.18	0.19 unobstructed jets $0.27\exp[0.092(z_p/D_p)]$ without central rudder $0.27\exp[0.161(z_p/D_p)]$ with central rudder 0.56 twin propeller
c_2	(1)	0.3(4)	0.25 inland vessels with a tunnel stern and a twin rudder configuration 0.42 sea borne vessels without rudder 0.71 sea borne vessels with rudder
(1) not specified (2) Blaauw and Van de Kaa (1978) and Verheij (1983) (3) Fueher, Römisch and Engelke (1981) (4) using $x_r/z_p = 5.6$			

sional coefficient which lies in the range of 4 to 5. Hoffmans (2006) extended his equation by

$$\Delta d_{50} = 0.7 \frac{(r_0 U_0)^2}{g \Psi_c} \tag{7}$$

where Δ (= $\rho_s/\rho - 1$) is the relative density, ρ_s is the density of sediment and Ψ_c is the critical Shields parameter. When it is acceptable that some erosion may occur, that is when $\Psi_c = 0.05$, and assuming that $r_0 U_0 = r_{u,prop,\max} u_{b,m}$ with $r_{u,prop,\max} = 0.3$, the strength of the bed protection must fulfil

$$\Delta d_{50} = 2.5 \frac{u_{b,m}^2}{2g} \tag{8}$$

resulting the need for large stones and thus an expensive bed protection.

4. TIME-DEPENDENT SCOUR

Usually propeller load is not continuous at one specific location. Therefore scour as function of time is considered. From experiments on different scales and with different bed materials, scour equations are derived between the time scale and the scales for velocity, turbulence, flow depth and material density. Based on the Dutch systematic research into scour, it appears that the shape of the scour hole is independent of bed material and flow velocity. In the development phase the scour as function of time is (Breusers 1966)

$$\frac{y_m}{\lambda} = \left(\frac{t}{t_1}\right)^{\gamma} \quad \text{with} \quad t_1 = \frac{K\lambda^2 \Delta^{1.7}}{(\alpha U_u - U_c)^{4.3}} \tag{9}$$

where K [= 330 hours $m^{2.3}/s^{4.3}$] is a dimensional coefficient, t [hours] is the time, t_1 [hours] is the characteristic time at which $y_m = \lambda$, and U_c is the critical depth-averaged flow velocity, U_u is the mean flow velocity upstream of the scour hole, y_m is the maximum scour depth as function of time, α (= $1.5 + 5r_0$) is a turbulence coefficient, γ is a coefficient representing the type of flow (for 2D $\rightarrow \gamma = 0.4$ and for 3D $\rightarrow \gamma = 0.8$) and λ is a characteristic length scale.

The size of bow thrusters and the engine power installed in ships have increased continuously over the past years. If $u_{b,m}$ is 2 m/s, thus U_e is about 6 m/s and assuming that $U_u = u_{b,m}$, $r_0 = 0.2$, $U_c = 0.5$ m/s, $\gamma = 0.8$ and $\lambda = z_p = 2$ m, the scour depth reaches a depth of 2 cm after 1 minute and 14 cm after 10 minutes.

Verheij (1983) investigated bed stability and scour caused by propellers in harbours. Figure 4 shows the time-dependent scour process for some experiments in which various hydraulic parameters were varied ($d_{50} = 0.0056$ m, $0.14 \text{ m} < h < 0.37$ m, $0.6 \text{ m/s} < u_{m,b} < 1.0$ m/s, $1.5 \text{ m/s} < U_e < 1.65$ m/s and $0.06 \text{ m} < z_p < 0.16$ m). Although the modelling shows a tendency to agree with the experimental results, it is recommended prototype tests be used to validate Eq. 9.

5. 3D-H EQUILIBRIUM SCOUR

For a long time the prediction of the localised scour geometry resulting from 3D-H flow has been an element of the culvert design process for determining erosion protection. Unprotected culvert outlets can induce substantial scouring which may lead to undermining of the culvert.

A method which is based on the momentum principle and in which some simplifications are made is discussed. Figure 5 shows a fluid element that is representative for the 3D scour process. The momentum fluxes and forces acting on this fluid element are the momentum flux ($M_1 = \rho Q U_1$) in the jet (section 1) the momentum flux ($M_2 = \rho Q U_2$) at the outflow sec-

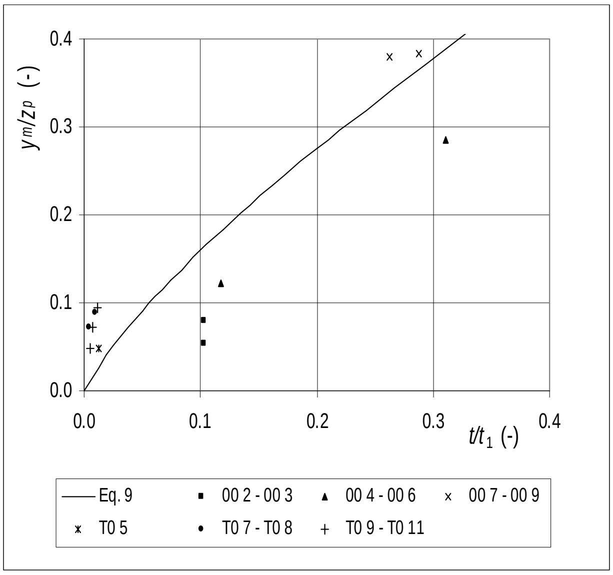

Fig. 4 Time-dependent scour (Verheij 1983); to compute t_1 in Eq. 9 the following assumptions are made: for sand U_c = 0.5 m/s, $U_u = u_{b,m}$, r_0 = 0.2, γ = 0.8 and $\lambda = z_p$

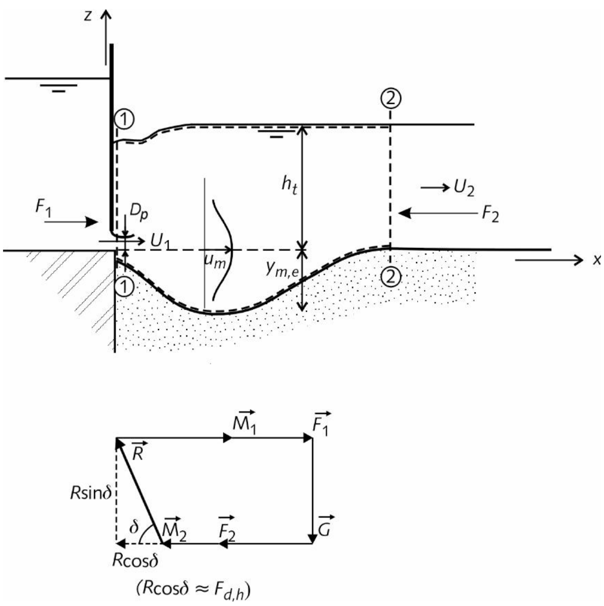

Fig. 5 Definition sketch of jet scour

tion (Section 2) with Q is the discharge, the hydrostatic forces (F_1 and F_2), the weight of water (G) and the resultant or dynamic force R exerted by the jet on the bed of the scour hole.

Applying Newton's second law to a fluid element in the horizontal direction, the maximum scour depth in the equilibrium phase ($y_{m,e}$) caused by 3D flow can be written as

$$F_1 - F_2 - R\cos\delta + \rho Q(U_1 - U_2) = 0 \tag{10}$$

This analysis results in one equation with two unknowns (R and δ). In principle, Eq. 10 can be solved if only one assumption is made for the unknown parameters, which must also be correlated to $y_{m,e}$. The latter correlation allows prediction of the scour hole dimensions.

Hoffmans (2008) showed that when using the momentum equation in the vertical direction, the closure problem for jet scour 2D-V is solved by using eight equations with eight unknowns. For 3D-H jets Eq. 10 is also used and is analysed further.

In general, the weight of water (G) may be written as

$$G = \rho g V \tag{11}$$

in which V is the volume of the fluid element and is proportional to the equilibrium scour depth and the tail water depth (h_t) as

$$V \equiv y_{m,e}^2 \left(y_{m,e} + h_t\right) \tag{12}$$

The unknown tanδ in Eq. 10 is the ratio of the vertical and horizontal resultant force, which can be quantified by first considering the ratio between the friction force (W) and the normal force (N), for uniform flow i.e.,

$$\frac{W}{N} = \frac{\rho g R_h S \ell}{\rho g R_h \ell} = S = f \tag{13}$$

in which f is a friction factor, ℓ is the length over which W is acting, R_h is the hydraulic radius and S is the energy slope.

If the bed shear stress (τ_0) is larger than the critical bed shear stress (τ_c) the dimensions of the scour hole will increase. An equilibrium phase of the maximum scour depth is achieved if $\tau_0 = \tau_c = \rho g R_h S_c$. Applying the Shields criterion $\tau_c = \Psi_c(\rho_s - \rho)gd$, when d is the particle diameter, the critical energy slope is $S_c = \Psi_c \Delta d / R_h$. Assuming that R_h is constant, the inverse of $(\tan\delta)_c$ is proportional to

$$(\tan\delta)_c^{-1} = f_c \equiv \Psi_c \Delta D_{90*} \text{ with } D_{90*} = d_{90}\left(\Delta g / \nu^2\right)^{1/3} \tag{14}$$

where D_{90*} is a dimensionless particle, f_c is the critical friction factor that represents the strength characteristics of loose material and ν is the kinematic viscosity.

For uniform flow the relative parameter R_h/d_{90} is usually applied to quantify the bed roughness. If R_h increases with respect to d_{90} the bed turbulence decreases, since the bed becomes smoother.

For non-uniform flow the bed turbulence is not only determined by d, but also by both vortices with horizontal and vertical axes. Raudkivi (1963) demonstrated that the turbulence downstream of an artificial dune is mainly caused by the turbulence generated in the mixing layer. Since the bed turbulence in the recirculation zone is much higher than the bed turbulence in uniform flow, R_h does not influence the bed turbulence in non-uniform flow like in uniform flow. Hence, R_h is not a representative parameter for the strength in non-uniform flow.

If both Δ and d increase f_c also increases in agreement with observations, since the dimensions of a scour hole are relatively larger for lighter and smaller material.

Assuming that $h_t << y_{m,e}$ and combining Eqs. 11, 12, 13 and 14, the critical external force is proportional to

$$(R\cos\delta)_c = \left(R\sin\delta(\tan\delta)^{-1}\right)_c = (Gf)_c \equiv \rho g y_{m,e}^3 D_{90*} \qquad (15)$$

If $F_1 = F_2$ and using Eqs. 10 and 15, $y_{m,e}$ reads (see also Hoffmans 1998)

$$y_{m,e} = c_{3H}\left(Q(U_1 - U_2)/g\right)^{1/3} \quad \text{with} \quad c_{3H} = 7(D_{90*})^{-1/3} \qquad (16)$$

in which c_{3H} is a parameter including several uncertainties. Calibration and verification of c_{3H} was based on approximately 120 flume experiments in which the hydraulic conditions were almost identical (Hoffmans 1994). Figure 6 demonstrates that $y_{m,e}$ slightly increases if the particle diameter decreases, which is in agreement with experimental results in which sand was considered in the range of 1 mm < d_{90} < 40 mm with g = 9.81 m/s^2, Δ = 1.65 and $\nu = 10^{-6}$ m^2/s.

The scour database, which has been used to calibrate and verify Eq. 16, contains little information with respect to the duration of the experiments. Usually researchers terminate their tests when the scour rate slows (stabilization phase), not when a stable scour hole is achieved. Part of the relatively large scatter in Fig. 6 can be ascribed to lack of definition of the equilibrium phase.

For horizontal jets, F_1 is assumed to be equal to F_2, which is a fair assumption only if the flow depth downstream of the hydraulic structure is about equal to the tail water depth. When the jump is unstable, i.e. when the jump is receding to a point far downstream of the outlet, the assumption $F_1 = F_2$ cannot be used.

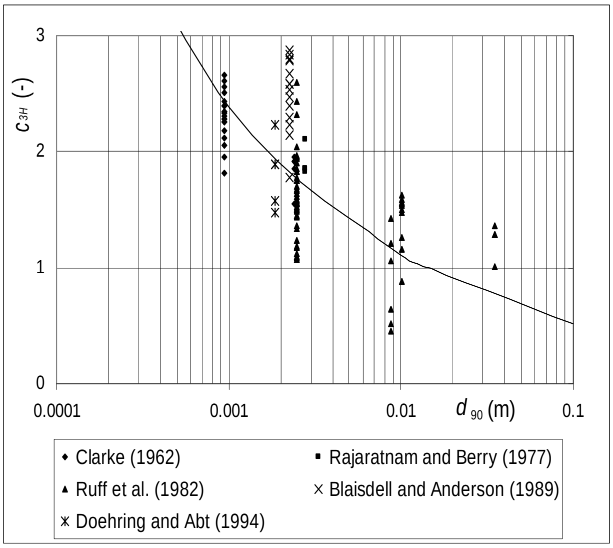

Fig. 6 c_{3H} as function of d_{90} (Hoffmans 1998)

6. VERIFICATION PROTOTYPE SCOUR

Recently the engine power installed in ships and the sizes of the main and bow thrusters has increased. Driven by large-diameter propellers or bow thrusters, velocities can reach 6 to 8 m/s, and the strong jet flow can last for the distance of several propeller diameters from the exit. In the intense jet flow, once the critical near-bed velocity is exceeded bed particles can be removed. The jet can lead to severe erosion and scour on the bed or bank of navigation channels and harbour structures.

3D scour holes were measured along quay walls in the "Amsterdam-Rijn" channel to investigate the influence of bow thrusters and main thrusters on scour (Schokking 2002). Different scour patterns were distinguished. Along short quays the length of which is shorter than 300 m, the scour holes were determined by the irregularity in berthing resulting in shallow and widespread scour. For long quays the scour pattern was more ordered. Along the quay at Maarsen, the averaged flow depth which was 5.75 m, the measured scour depth was approximately 0.9 m. The scour depths near the Plofsluis were 1.3 m (bow thruster) and 1.7 m (main thruster). Table 2 shows the characteristics of a Rhine-vessel and the computational results.

The calculations with c_{3H} = 2, which for fines is a reasonable value, shows that the predicted scour depth is greater than the measured scour depth. Geotechnical investigations have demonstrated that the subsoil in the channel consists of sandy-clay, thus it is more cohesive than sand and thus also less sensitive to scour. In addition to the strength parameters, the time-dependent behaviour of scour could also explain the differences, although the influence of time is of minor importance. Finally, owing to shipping manoeuvres, bed particles are always in suspension, so it is also possible that rather than creating them vessels could fill scour holes.

Table 2a
Details of large Rhine vessel

length	110 m
Beam	11 m
Draught	4 m
Manoeuvring power	10^3 kW
No. of main propellers	2
D_p of main thrusters	1.4 m
Draught main propellers	3.1 m
Power of bow thruster	200 kW
D_p of bow thrusters	0.8 m
Draught of bow thruster	3.5 m

Table 2b
Computational results Plofsluis

Main thrusters	
U_e (Eq. 4, efficiency 60%)	7.8 m/s
$u_{b,m}$ (c_2 = 0.3, Eq. 5)	1.8 m/s
$Q = ¼\pi(D_p)^2U_e$	11.9 m^3/s
$y_{m,e} = 2(Q\ u_{b,m}/g)^{0.33}$	2.6 m
Bow thrusters	
U_e (Eq. 4, efficiency 60%)	6.6 m/s
$u_{b,m}$ (c_2 = 0.3, Eq. 5)	1.5 m/s
$Q = ¼\pi(D_p)^2U_e$	3.3 m^3/s
$y_{m,e} = 2(Q\ u_{b,m}/g)^{0.33}$	1.6 m

7. CONCLUSION

This study shows that the time-dependent scour equation proposed by Breusers (1966) yields reasonable results for flume experiments (Fig. 4). It is recommended that Eq. 9 should be validated for tests at prototype scale.

The change in momentum per unit of time in the fluid element flowing in a channel is equal to the resultant of all the external forces that are acting on the element. Despite the simplifications made in applying the momentum principle to a short horizontal reach of a scour hole, this study has shown that the method, which is based on 6 equations (Eqs. 10, 11, 12, 13, 14 and 15) with 6 unknowns (f, G, R, V, $y_{m,e}$ and δ can be used to calcultate scour for sand and gravel caused by horizontal 3D jets within an accuracy of $0.5 < \xi < 2$ where ξ is the ratio between measured and calculated scour depth.

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