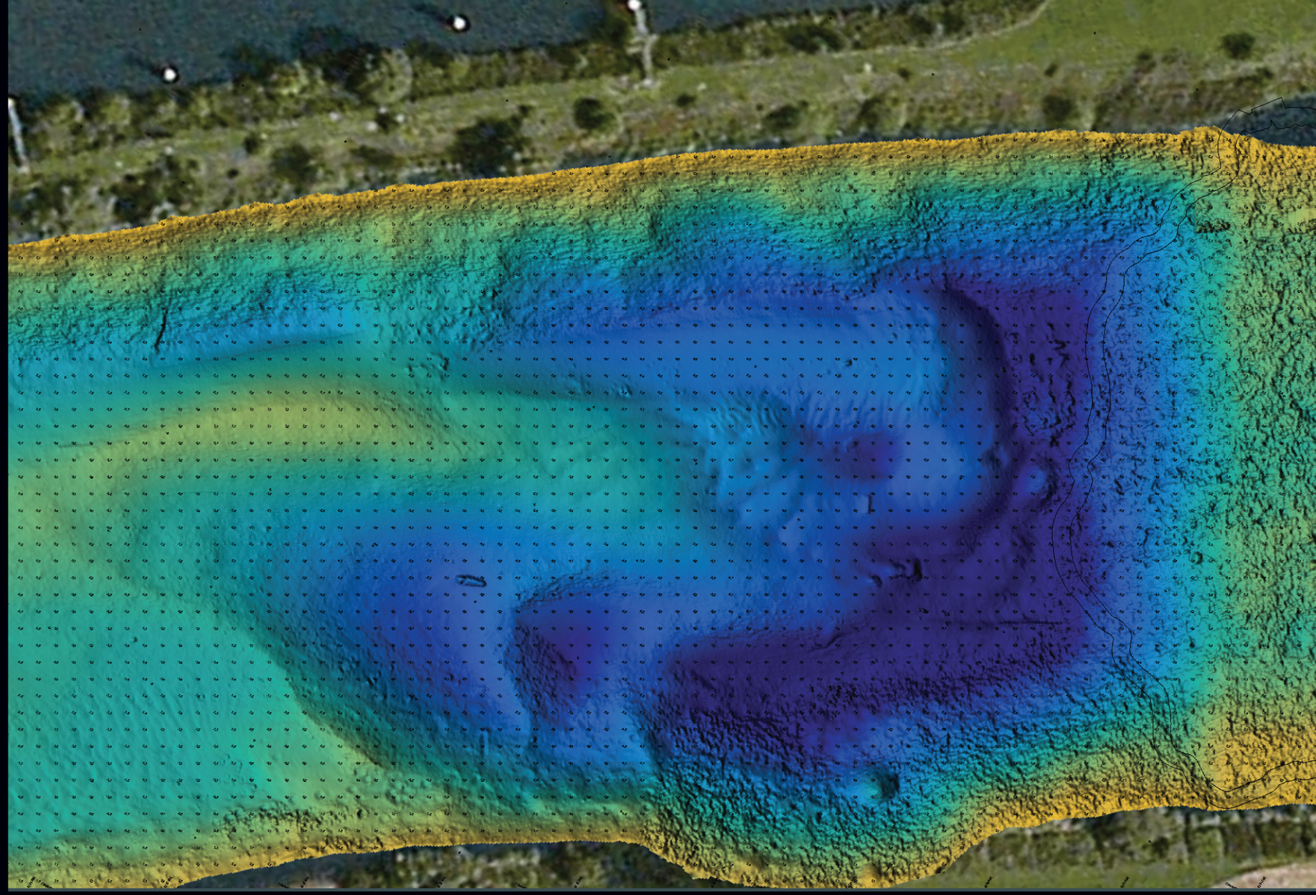

Scour Manual

Current-Related Erosion

SECOND EDITION

edited by

G.J.C.M. Hoffmans
H.J. Verheij

CRC Press
Taylor & Francis Group

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Contents

Foreword

This manual is an update of the internationally well-known Scour Manual, published in 1997, in which much of the knowledge and experience at that time on scour was captured. Knowledge that was gathered after the February 1953 disaster where many dikes in the south-western provinces of the Netherlands failed during a severe storm surge. As a consequence of this disaster, several hydraulic and soil mechanical issues had to be dealt with in order to be able to draw up appropriate solutions for the breaches in the flood defenses. In part the solutions consisted of repairing the dikes and in part of constructing closure dams in the estuaries. To study the effects of closures, small-scale experiments were carried out to obtain general information about the critical velocity for the stability of stones and concrete blocks, the overlapping of mattresses, the water movement, and the scouring effects downstream of revetments.

Based on a systematic investigation of the time scale for two- and three-dimensional scour in loose sediments, relations were derived for predicting the maximum scour depth as a function of time. In the 1990s, these scour relations were slightly modified and used for the design of the storm surge barrier in the Nieuwe Waterweg near Rotterdam and for the prediction of the scour process downstream of the barrier in the Eastern Scheldt.

Following the publication of the Scour Manual in 1997, more experience is acquired with existing formulas and the knowledge in the field has widened, especially related to turbulence. The original Scour Manual is partly rewritten to capture this information. Moreover, attention is paid to mathematical scour and erosion models, risk assessment and erosion of cohesive sediments. Some applications of this knowledge in projects are described in case studies at the end of the manual. In this update, it was chosen not to address coastal and offshore structures. For wave-induced scour reference is made to the 1997 version of this manual or to other international manuals.

This update of the Scour Manual concerns the scour processes and phenomena taking place near hydraulic structures due to currents. The manual is intended primarily for hydraulic engineers in the field; however, it may also have appeal to researchers in hydraulic engineering. The scour process has still not yet been explained in a generally accepted manner, and therefore it would be only appropriate to keep discussing their mechanism and formulations for the simpler cases.

The updated Scour Manual was prepared by the original authors and supervised by a CUR committee. The update is dedicated to Mr. G. Vergeer, a strong promotor of this update, who passed away in 2018.

I would like to thank all those who contributed their time and knowledge to the update of the Scour Manual and especially the companies that contributed to the cases.

I wish it will offer the practicing engineer again a guideline in the field.

Pieter van Berkum
Head of Hydraulic Engineering section, Rijkswaterstaat

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For this updated version of the scour manual, we would like to thank all members of the committee and the contributors for their support and especially Erik Mosselman for reviewing the document and Maarten van der Wal and Frans Buschman for leading the project at Deltares.

Also, the committee members and the contributors to the first version of the manual are acknowledged. They helped creating the basis for the update.

List of main symbols

a	factor, $a = \cot \beta_a + \cot \delta$	–
a	deck block height of a bridge	m
A	cross-section	m^2
A_a	cross-section area of abutment	m^2
A_b	two-dimensional blocking area of abutment	m^2
A_f	cross-section area upstream of abutment	m^2
A_r	cross-section area of the river	m^2
B	length of structure (perpendicular to flow direction), pier width	m
b	factor, $b = \cot \gamma_2 - \cot \gamma_1$ (–)	–
b_u	diameter of pipe or thickness of jet at $x = 0$ (m)	m
B	width of flow	m
B	load factor in propeller scour	–
B_c	stability factor in propeller scour equation	–
B_1	width of the river upstream of the constriction	m
B_2	width of the river at the constriction	m
c	parameter $c = 10^3\,N/m^3$	N/m^3
c	cohesion	N/m^2
c_a	shape factor of scour hole, $c_a = 22$	–
c_f	resistance coefficient, $c_f = 0.010$ (range 0.005–0.020)	–
c_s	coefficient of Schoklitsch, $c_s = 4.75\,m^{0.16}s^{0.57}$	–
c_v	velocity distribution coefficient, $c_v = 1.0$	–
c_o	coefficient, $c_0 = 0.29$ (sand) to 1.24 (gravel)	–
c_{2H}	dimensionless parameter for 2D-H jets	–
c_{2V}	dimensionless parameter for 2D-V jets	–
c_{3H}	dimensionless parameter for 3D-H jets	–
C	Chézy coefficient	$m^{1/2}/s$
C_f	fatigue rupture strength of clay, $C_f = 0.035C_o\ N/m^2$	N/m^2
C_k	constant that ranges from 0.030 (for scour slopes less steep than 1V:3H) to 0.045 (for backward facing step)	–
C_0	cohesion in the Mirtskhoulava formula	N/m^2
d	particle diameter	m
d_a	size of detaching aggregates, $d_a = 0.004\,m$	m
d_0	characteristic length, $d_0 = 1/2\ h_d$, h_d is the drop height	m
d_{50}	median particle diameter for which 50% of the mixture is smaller	m
d_{50f}	median filter size	m
d_{90}	particle diameter for which 90% of the mixture is smaller	m
D	height of sill, step height	m
D	thickness of cohesive layer	m
D	jet or pipe diameter	m
D_F	filter thickness	m
D_p	drop height of grade-control structure	m
D_r	relative soil density	–
D_{90*}	dimensionless grain diameter	–

D_*	sedimentological diameter, $d(\Delta g/\nu^2)^{1/3}$	–
e	actual void ratio, $e = V_v/V_s$	–
e_{max}	maximum void ratio	–
e_{min}	minimum void ratio	–
f_c	friction coefficient, g/C^2	–
f_c	roughness function, C/C_0, $C_0 = 40\,\mathrm{m}^{1/2}/\mathrm{s}$	–
f_u	undrained shear strength	$\mathrm{N/m^2}$
F	fraction of fines of soil smaller than 0.075 mm	–
F_{down}	downward force	N
F_{lift}	lift force	N
Fr	Froude number related to water depth, $Fr = U_0/(gh)^{1/2}$	–
Fr_s	Froude number related to pressure $Fr_s = \dfrac{V_{uc}}{\sqrt{g(h_u - h_b)}}$	–
Fr_1	Froude number just upstream of the hydraulic jump	–
Fr_1	Froude number in the jet, $Fr_1 = U_1/(\mathrm{g}\mathrm{b_u})^{1/2}$	–
Fr_1	Froude number, $Fr_1 = U_1/(\mathrm{g}y_1)^{0.5}$	–
g	acceleration due to gravity, $g = 9.78–9.83\,\mathrm{m/s^2}$	$\mathrm{m/s^2}$
G_B	width of scour hole at broken pipeline	m
G_L	length of scour hole at broken pipeline	m
h	flow depth	m
h_b	water depth under a bridge	m
h_e	critical water depth	m
h_c	equilibrium water depth after functioning of a falling apron	m
h_i	stages in the water depth during functioning of a falling apron	m
h_p	distance between propeller axis and bed	m
h_t	tailwater depth	m
h_u	upstream water depth	m
h_0	initial or average flow depth	m
$h_0(0)$	tide-averaged flow depth	m
h_1	average depth in contracted area	m
h_2	average depth in upstream section	m
H	height between head and tailwater levels	m
H	difference in height between upstream and downstream water levels	m
I	volume of scour hole per unit width	$\mathrm{m^2}$
k	turbulent kinetic energy	$\mathrm{m^2/s^2}$
k_m	mean turbulent kinetic energy where scour depth is at maximum	$\mathrm{m^2/s^2}$
k_s	Nikuradse bed roughness (rough: $k_s = 3d_{90}$, smooth: $k_s = 2d_{50}$)	m
k_{max}	maximum turbulent kinetic energy in mixing layer	$\mathrm{m^2/s^2}$
K	non-dimensionless constant, $K = 330\,\mathrm{m}^{2.3}/\mathrm{s}^{3.3}$	$\mathrm{m^{2.3}/s^{3.3}}$
K	factor for various influences, such as pier shape and flow angle	–
K_b	coefficient	–
K_1	coefficient, $K/(\mathrm{g}^{1.43}\mu^{0.43})$ (K in $\mathrm{m}^{2.3}/\mathrm{s}^{3.3}$)	–
l	length of structure parallel to the flow direction	m
L	length of bed protection	m
L_{ins}	bed protection length to prevent shear failure	m
L_{min}	minimum bed length	m
L_p	bridge pier length	m
L_r	length hydraulic jump	m
L_s	length of scour hole	m
L_s	failure length	m
L_s	ship length	m
LL	liquid limit	–
m	constriction ratio, $m = 1- B_2/B_1$	–
n	porosity, default 0.4	–
n	scale ratio	–
n	Manning's coefficient	$\mathrm{s/m^{1/3}}$
N	number of ship passages	–
$p(\xi')$	probability density function	–

$P(\xi')$	cumulative density function	–
P_f	failure probability	–
PI	plasticity index	–
q	discharge per unit width	m^2/s
q	discharge in a 2D-H jet	m^2/s
q_s	(reduced) sediment transport per unit width (including porosity)	m^2/s
Q	discharge	m^3/s
Q	discharge in a 3D-H jet	m^3/s
Q_c	discharge through main river (without floodplain), see Fig. 3.1	m^3/s
Q_f	discharge floodplain	m^3/s
Q_1	discharge in the upstream channel	m^3/s
Q_2	discharge in the contracted section	m^3/s
r	local turbulence intensity	–
r	discrepancy ratio	–
r_0	depth-averaged relative turbulence intensity, σ_u/U	–
$r_{0,m}$	depth averaged relative turbulence intensity when scour depth is maximal	–
R	strength component	Var.
R	hydraulic radius	m
R	radius of curvature of the centreline	m
R	erosion parameter	$kg/(m \cdot s^3)$
R	erosion rate	m/s
Re	Reynolds number, $Re = Uh/\nu$	–
$Re*$	Reynolds stress number related to particle diameter, $Re = U_*D/\nu$	–
s	specific density of bottom material	–
s_b	bed load	m^2/s
s_s	suspended load	m^2/s
S	load components	Var.
S_I	slope energy grade line	–
t	time	s
t_c	time referring to conditions where $q_s = 0$	s
t_p	time referring to live bed conditions	s
t_1	characteristic time at which the maximum scour depth equals h_0	s
t_1	characteristic time at which $y_m = \lambda(s)$	s
$t_{1,u}$	characteristic time at which $y_m = h_0(0)$	s
t_1	time at which αU_0 first exceeds U_c during flood tide	s
t_2	time at which αU_0 drops below U_c during ebb tide	s
T	half tidal period where $\alpha U_0 > U_c$ (s), $T = t_2 - t_1$	s
$T_{0,s}$	time scale for change of the cross-section profile	s
u	local longitudinal flow velocity	m/s
u	mean velocity in the x-direction	m/s
u_m	maximum velocity of u at any x-section	m/s
u_*	bed shear velocity	m/s
$u_{*,c}$	critical bed shear velocity	m/s
U	time-averaged velocity	m/s
U_b	water velocity just above the bed due to the return current	m/s
U_c	critical averaged flow velocity for uniform flow; U_c can be depth-averaged or the near-bed critical velocity	m/s
U_c	critical depth-averaged flow velocity	m/s
U_d	characteristic tidal mean flow velocity	m/s
U_g	mean gap velocity	m/s
U_h	horizontal component jet velocity	m/s
U_m	depth-averaged velocity where scour depth is at maximum	m/s
$U_{m,t}$	maximum velocity during a tide	m/s
U_{max}	maximum velocity	m/s
U_r	ship-induced return current below the ship's keel	m/s
U_v	vertical component jet velocity	m/s
U_0	depth-width-averaged flow velocity, Q/A	m/s

U_0	depth-averaged flow velocity upstream of scour hole	m/s
$U_{0,c}$	critical flow velocity	m/s
U_1	average flow velocity in the jet	m/s
U_1	jet velocity entering tailwater, $U_1 = \sqrt{2gH}$	m/s
U_1	efflux velocity at $x = 0$ (m/s)	m/s
U_2	average flow velocity downstream of the scour hole	m/s
V_s	ship speed (m/s)	m/s
V_s	volume of solids	m3
V_{uc}	critical velocity pressure scour	m/s
V_{ue}	effective velocity pressure scour	m/s
V_v	volume of voids	m^3
$V(t)$	volume of scour hole per unit width	m^3/m
$Vr(t)$	reduced volume of scour hole per unit width	m^3/m
w	water content	–
w_s	fall velocity	m/s
W_1	bottom width in the of the upstream main channel	m
W_2	bottom width in the contracted section	m
$\boldsymbol{x}$	longitudinal distance	m
$\boldsymbol{y}$	vertical distance	m
$\boldsymbol{y_c}$	critical scour depth	m
$\boldsymbol{y_d}$	depth after a sliding	m
$\boldsymbol{y_m}$	maximum scour depth	m
$y_m(t)$	maximum scour depth as a function of time	m
$\boldsymbol{y_{m,e}}$	equilibrium scour depth	m
$\boldsymbol{y_{m,e,max}}$	maximum equilibrium scour depth	m
$\boldsymbol{y_{m,e\|50\%}}$	equilibrium scour depth exceeded by 50% of the scour	m
$\boldsymbol{y_{ad}}$	bed elevation changes due to long-term deposition or bed erosion	m
$\boldsymbol{y_{be}}$	bend scour	m
$\boldsymbol{y_{bf}}$	bed form trough depth	m
$\boldsymbol{y_{cf}}$	confluence scour	m
$\boldsymbol{y_{cs}}$	constriction scour	m
$\boldsymbol{y_s}$	local scour	m
$\boldsymbol{y_{s,actual}}$	actual scour depth	m
$\boldsymbol{y_{ss}}$	equilibrium scour depth (static scouring)	m
$\boldsymbol{y_{tot}}$	total scour depth	m
$\boldsymbol{y_1}$	thickness of the jet at the vena contracta	m
$\boldsymbol{z}$	vertical distance from the axis of the jet at any section	m
$\boldsymbol{Z}$	reliability parameter	Var.
$\boldsymbol{Z}$	scour number	–
α	flow and turbulence coefficient (or angle)	–
$\boldsymbol{\alpha_F}$	turbulence coefficient, $\alpha_F = (1 + 3r_0)c_v$	–
$\boldsymbol{\alpha_g}$	gap coefficient, $\alpha_g = 2.4$	–
$\boldsymbol{\alpha_{ga}}$	abutment coefficient, $\alpha_{ga} = 1.0$ or 1.4	–
$\boldsymbol{\alpha_{RAJ}}$	constant, $\alpha_{RAJ} = 0.3$	–
$\boldsymbol{\alpha_1}$	turbulence coefficient, $\alpha_1 = 1.5 + 5r_0$	–
$\boldsymbol{\alpha_u}$	coefficient, to be determined as $\alpha_u = \alpha - U_c/U_0$	–
$\boldsymbol{\alpha_v}$	Veronese coefficient, $\alpha_v = 1.9$	–
$\boldsymbol{\alpha_1}$	angle upstream wing wall of abutment	°
$\boldsymbol{\alpha_2}$	angle downstream wing wall of abutment	°
$\boldsymbol{\beta}$	upstream scour slope (or angle)	°
$\boldsymbol{\beta}$	reliability index	–
$\boldsymbol{\beta}$	coefficient; $\beta = 0.67–0.8$	–
$\boldsymbol{\beta_a}$	average slope angle before instability	°
γ	coefficient (or angle)	–
γ	weight per unit volume, $\gamma = 10\ kN/m^3$	kN/m^3
γ	coefficient, $\gamma = 0.4–0.8$	-
γ	coefficient, $\gamma = 0.22–0.23$	-
$\boldsymbol{\gamma_s}$	safety factor	-
$\boldsymbol{\gamma_{wet}}$	wet weight per unit volume	kN/m^3

γ_1	sliding erosion slope angle after instability	°
γ_2	sliding deposit slope angle after instability	°
δ	slope angle downstream of the point of reattachment	°–
δ	slope angle downstream of the deepest point of the scour hole	°
Δ	relative density, $\rho_s/\rho - 1$	–
Δ_t	time step	s
η	$\eta = z/x$	–
η	coefficient, $\eta = 0.75–0.85$	–
η_b	coefficient	–
η_s	coefficient	–
θ	temperature	°C
θ	angle between two upstream branches of a confluence	°
θ	jet angle near surface	°
κ	constant of von Kármán, $\kappa = 0.4$	–
λ	characteristic length scale	m
μ	shape factor or roughness factor	–
μ	average value	Var.
μ_R	average value of the strength parameter R	Var.
μ_S	average value of the load parameter S	Var.
μ_Z	average value of the reliability parameter	Var.
ν	kinematic viscosity	m^2/s
ξ	ratio measured and calculated scour depth	–
ρ	fluid density	kg/m^3
ρ_b	density bed material	kg/m^3
ρ_s	material density	kg/m^3
σ	relative standard deviation	–
σ_g	sediment gradation, $\sigma_g = d84/d50$	–
σ_u	standard deviation of the instantaneous longitudinal velocity averaged over the depth	m/s
σ_v	standard deviation of instantaneous velocity in transverse direction	m/s
σ_w	standard deviation of instantaneous velocity in vertical direction	m/s
σ_Z	standard deviation of the reliability parameter $_Z$	Var.
τ_c	critical bed shear stress	$kg/m.s^2$
τ_0	bed shear stress	$kg/m.s^2$
φ	dimensionless transport rate	–
ϕ	angle of repose, $\phi = 40°$	°
φ'	angle of internal friction	–
χ_e	turbulence parameter	–
ψ	mobility or Shields parameter	–
ψ_c	critical Shields parameter	–
ω	angle of attack	°
ω	turbulence coefficient, $\omega = 1 + 3r_0$	–
ω	fall velocity	m/s
Ω	current-related sediment mobility, $= \psi/\psi_c$	–

List of main definitions

- General scour: degradation of the main channel bed due to an imbalance of the sediment transport entering and leaving a control volume. This occurs, for example, when the sediment transport capacity increases due to accelerating flow.
- Bend scour: local scour in the outer bend of a river due to helical flow; maximum scour depth usually at the downstream side of the bend.
- Constriction scour: local scour due to the transition into a narrower or shallower section of the river.
- Confluence scour: scour due to the confluence of flows from two upstream river branches.
- Non-uniform flow: flow where flow velocity and other hydrodynamic phenomena differ spatially.
- Equilibrium scour depth: constant scour depth reached after some time, when the conditions remain constant.
- Plunging jets: water jets that fall from a certain height onto a free water surface.
- Submerged jets: water jets with an outflow opening under water.
- Grade control structure: structure to control the water level where water flows over or through the structure.
- Shear failure: soil mechanical instability of non-cohesive soil.
- Flow slide: soil mechanical instability of loosely packed sand.
- Two-dimensional scour: scour as a result of a long (normal to the flow direction) sill or infinitely long outflow opening. The scour is equal over the full length or width. A typical example is an underwater sill in a closure of an estuary.
- Three-dimensional scour: scour downstream of a structure with a limited width (normal to the flow direction). At the sides of the outflow opening, eddies occur causing extra scour. Typical examples: spurs, outflow of culverts.
- Clear water scour: scour with transport of bed material only due to the presence of a structure. Without the structure, no bed load or suspended sediment transport would occur. This type of scour occurs in laboratory conditions and in areas with scour-resistant beds. It results in deeper scour holes.
- Live-bed scour: scour with supply of bed material from upstream.
- Bed load transport: sediment transport by rolling, sliding and saltating (jumping up into the flow, being transported a short distance then settling) of sediment particles mainly just above the river bed.

- Suspended load transport: transport of sediment that is suspended in the water column by turbulence. The suspended load usually consists of smaller sediment particles than bed load.
- Abutment: horizontal construction into the flow as part of an approach embankment for a bridge.
- Groyne or spur: horizontal constriction of a flow to train a river to provide sufficient depth for navigation and to prevent erosion of the river bank.

Chapter 1

Introduction

1.1 General

A hydraulic structure is generally intended to provide a practical measure to solve an identified problem. After problem identification, subsequent stages are determined by a series of decisions and actions culminating in the creation of a structure or structures to resolve the problem. Aspects that may affect the eventual outcome of the design process have to be assessed. In addition to hydraulic, geotechnical and engineering characteristics, aspects such as social conditions, economics, environmental impact and safety requirements also influence the design process.

Within the scope of the Dutch Delta works, the Dutch Ministry of Transport, Public Works and Water Management and Delft Hydraulics (now merged into Deltares) conducted systematic research with respect to the prediction of the formation of scour holes. After the catastrophic flood disaster in 1953, the Delta Plan was formulated to protect the Rhine-Meuse-Scheldt delta against future disasters. Dams with large-scale sluices were planned in some estuaries. The expected severe scour necessitated acquiring a better understanding of the scour process.

To obtain detailed information about the physical processes playing a role in scour development, Delft Hydraulics (Deltares) carried out many experiments in which several parameters of the flow and the scoured material varied. From the results of experiments in flumes, with obvious difficulties of scale effects and limitations in instrumentation, some semi-empirical relations were obtained that describe the erosion process as a function of time and position (Breusers, 1966, 1967; van der Meulen & Vinjé, 1975). In addition, design criteria were deduced for the length of bed protection. These were based on hundreds of shear failures and flow slides that occurred along the coastline in the south-western part of the Netherlands.

Understanding of the physical processes and mathematical modelling of the water and sediment movement in rivers, estuaries and coastal waters have made much progress in recent years. This has led to a number of more or less ready-to-use mathematical model systems, but it has also raised many new research questions. In the early 1990s, a morphological model for the generation of scour holes behind hydraulic structures was developed. This morphological model was based on the 2D Navier-Stokes and convection-diffusion equations and used for the calibration and verification of semi-empirical relations that predict the scour process. Nowadays sophisticated CFD (Computational Fluid Dynamic) models are available for scour computations.

This manual highlights the so-called Breusers method which describes the maximum scour depth as a function of time, including the practical equilibrium value near hydraulic structures. Scour due to three-dimensional flow can easily be predicted when this method is applied in combination with computational results of depth-averaged hydrodynamic models or with measurements obtained from scale models. The accuracy of the scour computation depends mainly on the accuracy of the flow velocities and the turbulence intensities just above the protected bed. According to Breusers (1966), the development of the scour process depends entirely on the average flow velocity and depth-averaged relative turbulence intensity at the transition from the fixed to the erodible bed. Applying this concept restricts the scour prediction to a single computation. No information is needed concerning the near-bed velocities and bed turbulence in the scour hole.

This manual is an update of the original book published in 1997. However, it deals only with scour due to currents. Scour due to waves is not addressed in this update. This manual addresses various new aspects, such as risk assessment, scour of rock and new theory-based formulas for the prediction of scour at hydraulic structures but also an update of the available mathematical scour and erosion models. Last but not least, a fully renewed chapter has been added with recent experiences of consultants and contractors with scour design.

1.2 Scope of this manual

The purpose of this scour manual is to provide the civil engineer with useful practical methods to calculate the dimensions of scour holes in the prefeasibility and preliminary stages of a project, and to furnish an introduction to the most relevant literature. The 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. A complete review of all the available references on scour is beyond the scope of this manual. The most relevant manuals are Breusers and Raudkivi (1991), Melville and Coleman (2000) and May et al. (2002). Furthermore, the International Conference on Scour and Erosion provides relevant information and is important for the most recent developments.

The scour depth as a function of time can be predicted by the so-called Breusers equilibrium method. Basically, this method can be applied to all situations where local scour is expected. However, the available knowledge about scour is not sufficient for applying the method to scour at each type of structure. Structure-specific scour prediction rules are presented then. The treatment of local scour is classified according to different types of structures. Each type of structure is necessarily schematised to a simple, basic layout. The main parameters of a structure and the main parts of the flow pattern near a structure are described briefly insofar as they are relevant to the description of scour phenomena. Detailed and theoretical descriptions of the flow phenomena are not included because at this stage, the consequences of such descriptions are minimal in relation to engineering practice. Nonetheless, Hoffmans (2012) developed new formulas for equilibrium scour. Evaluating a balance of forces for a control volume, he was able to develop scour equations for different types of flow fields and structures, i.e. jets, abutments 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 calculations of the maximum scour depth during the lifetime, the upstream scour slope and the failure length. Due to shear failures or flow slides, the scour process can progressively damage the bed protection. This will lead to the failure of hydraulic structures.

The presented Breusers equilibrium method 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 the Breusers equilibrium method, which can be considered as a continuation and an expansion of the work of Breusers (1966). In other words, one may speak of a revitalisation of the Breusers formula, with which a lot of experience has been gained, mainly in the Netherlands but also abroad.

1.3 Reading guide

The manual is divided into seven parts. The first three parts give a general introduction to the subject. The next four parts deal with calculation methods for predicting scour near hydraulic structures and, in the final part, some cases of scour at prototype scale are described. A brief summary of each chapter follows.

Chapter 2 – Design process

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. After having addressed the boundary conditions, we discuss the risk assessment and the fault tree analysis. Two methods are treated: one based on safety factors and the other 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. Examples show how to deal with these methods. Furthermore, protective measures are mentioned.

Chapter 3 – Design tools

The total scour which may occur at the site of a structure can be estimated with mathematical scour and erosion models. An overview is given of available tools. In principle, scour may be considered as a combination of general scour and local scour resulting from different processes. In addition, time phases can be distinguished in the scour process. We present these phenomena for currents.

A more or less continuous scouring process may suddenly be disturbed by the occurrence of geotechnical instabilities along the upstream scour slope. Shear failures and flow slides influence the stability of hydraulic structures. In the extreme case, these instabilities involve large masses of sediment and cause a major change of the shape of the upstream side of the scour hole in a relatively short period of time. Some design criteria based on storage models are presented.

Chapter 4 – Initiation of motion

Scour results from transport of bed materials. The non-uniform flow is responsible for this, which is usually expressed by either a turbulence coefficient or a dominating flow velocity, or by both. Turbulence is the most important phenomenon determining erosion. Relations for the turbulence intensity and the critical flow velocity are presented for various situations. The design graphs of Shields are presented for non-cohesive bed materials, such as sand and rock. For cohesive soils such as clay and peat, the method of Mirtskhoulava and also empirical relationships based on the plasticity index are given. In addition, erosion rate formulas are also presented.

Chapter 5 – 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. In addition, we treat the complex flow pattern of jets. We also address scour by ship-induced currents, scour due to propellers and scour due to jets in the case of broken pipelines. Semi-empirical and theory-based relations for the scour process behind a short-crested sill are presented. The semi-empirical relations are often used for grade-control structures, where the flow above the structure is supercritical, and for the time-dependent development of the maximum scour depth downstream of a hydraulic jump. The structure of the semi-empirical relations shows a good similarity with the Breusers approach. The new relations have a theoretical base as they have been derived using the balance of forces. However, both semi-empirical and theory-based relations must be clearly understood prior to any attempt to use them for design purposes.

Chapter 6 – Sills

We summarise calculation methods for sills. A distinction is made between sills with a broad or a sharp crest and between sills with and without bed protection. Usually, the flow above a sill is subcritical, but depending on the downstream water level, the flow may become supercritical. We discuss the time-dependent and equilibrium behaviour of scour holes in sandy beds in relation to closure works (broad-crested sills) in tidal channels. Special attention is paid to the effects of turbulence and flow pattern on the scour process.

We describe an approximate method (reduction method) for calculation of the maximum scour depth. This takes the influence of upstream sediment supply into account. In addition, we present a method to adjust this calculation method for unsteady flow, especially tidal flow. These methods were successfully applied during the design of the Eastern Scheldt Storm Surge Barrier. The upstream scour slope determines the stability of the upstream part of the scour hole and the adjacent bed protection. A relation for the upstream scour slope, based on a probabilistic model for bed load transport, is presented. Relations derived from systematic scour investigations are verified by two field experiments, among which the scour at the Eastern Scheldt Storm Surge Barrier.

Chapter 7 – Abutments and groynes

Relations are presented for predicting local scour at the head of abutments, for which several names are used (spurs, groynes, guide or river bunds) in the literature. We also present recently developed formulas based on a balance of forces. We briefly discuss the flow characteristics around blunt and streamlined abutments. Attention is also paid to the time scale of the scour process and to combined scour (e.g. local scour and bend scour or constriction scour). Since the literature contains many scour relations, a number of generally acceptable predictors have been selected for this manual. Finally, attention is paid to failure mechanisms and measures to mitigate scour near abutments.

Chapter 8 – Bridge piers

After discussing the flow characteristics at the pier and in case of a submerged bridge, relations for estimating scour around bridge piers are summarised. These relations are mostly empirical, but we also present a theoretical relation based on a balance of forces. Correction factors and design graphs for the equilibrium scour depth are discussed. Attention is paid both to the equilibrium scour depth and to the time scale of the scour process. Methods are given to predict scour at bridge piers with a footing or pile cap and for pressure scour. Indications are provided for determining the area to protect against scour.

Chapter 9 – Realised case studies on prototype scale

Nine realised case studies on the prototype scale, based on feasibility studies or design studies, are evaluated in order to determine the practical use of the scour relations in this manual. These cases are as follows:

- Four cases about bridge pier scour: Camden motorway bypass, crossing of a high-voltage power line, pier scour in bypass channel, and pressure scour;
- Two cases about culvert scour: Waterdunen project, and scour development in front of a culvert;
- Two cases about jet scour: propeller- and thruster-induced jet scour;
- One case about sill scour: weir at Grave.

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