1 INTRODUCTION

This note deals with the prediction of scour in a total of 8 cases consisting of 6 flume test predictions and 2 actual case studies. The Committee of the First International Conference on Scour of Foundations has delivered the cases to the participants of this conference to be held on November 17-19, 2002.

Van Oord ACZ is pleased to contribute to the understanding and prediction of scour of foundations.

2 FLUME TEST PREDICTIONS

2.1 SOIL PROPERTIES AND FLOW DATA

Information provided by the Committee of the ICSF-1 on the soils used in the flume test predictions has been summarised in Table 1 and 2. The relevant flow data as used in the experiments is listed in Table 3.

Table 1: Soil properties porcelain clay

w_L	w_P	w_N	PI	LI	ρ_s	d_{50}	s_u
[%]	[%]	[%]	[%]	[%]	[kg/m^3]	[μm]	[kPa]
33	17	24.2	16	35	2700	3	23.3

w_L liquid limit PI: Plasticity Index
w_P plastic limit LI: Liquidity Index
w_N water content

Table 2: Soil properties mortar sand

ρ_s	d_{50}
[kg/m^3]	[μm]
2600	300

Table 3: Flow data

Water temperature	Flow depth	Flow width	Diameter pile
[°]	[m]	[m]	[m]
25	0.375	2	0.160

2.2 METHODOLOGY

The first step in the scour calculations consists of the assessment of the critical mean velocity U_0, which can then be used to determine the calculation method. For the fume test predictions, the approach to the scour prediction by Breussers[1] and Teramoto[2] has been used. These methods are valid for a pile or pier diameter b versus flow depth h_0 ratio of $b/h_0 < 1$.

2.2.1 Critical velocity

Based on the character of the soil, (1) non-cohesive and (2) cohesive, a distinction in methodology has to made the assessment of the critical velocity:

(1) Non-cohesive soils

According to Shields[3], critical mobility factor Ψ_c is equal to:

$$\psi_c = \frac{u^2{}_{*,c}}{\Delta g d_{50}} \qquad [1]$$

In which:
- $u_{*,c}$ = critical bed-shear velocity [m/s]
- g = acceleration of gravity [m/s^2]
- Δ = relative density (=$\rho_{solid}/\rho_{water} - 1$) [-]
- d_{50} = median grain size [m]

For a uniform flow on a hydraulically rough surface the mean critical velocity equals

$$U_c = u_{*,c} \frac{C}{\sqrt{g}} \qquad [2]$$

Where the Chézy coefficient is given by

$$C = \frac{\sqrt{g}}{\kappa} \ln\left(\frac{12 h_0}{k_s}\right) \qquad [3]$$

In which:
- U_c = mean critical velocity [m/s]
- κ = constant of Karman = 0.4 [-]
- h_0 = flow depth [m]
- k_s = equivalent roughness of Nikuradse. Rough flow, k_s=3d_{50} and in case of a smooth flow, k_s=2d_{50} [m]

If the width B of the flow is large in comparison to the flow depth h_0, the first equation can be rewritten as:

$$U_c = 2.5\sqrt{\psi_c \Delta g d_{50}} \ln\left(\frac{12 h_0}{k_s}\right) \qquad [4]$$

With the use of the sedimentological diameter D_* (Van Rijn[4]) equation 4 can be solved by using the relation between Ψ and D_* listed in Table 4.

$$D_* = d_{50}\left(\frac{\Delta g}{\upsilon}\right)^{1/3} \text{ with } \upsilon = \frac{40.10^{-6}}{20+T} \qquad [5]$$

In which: ν = kinematic viscosity $[m^2/s]$
T = water temperature [°]

Table 4: Relation of sedimentological diameter D_* with critical mobility factor Ψ_c

Relation	In case of
$\Psi_c=0.24D_*^{-1}$	$D_* \le 4$
$\Psi_c=0.14D_*^{-0.64}$	$4 < D_* \le 10$
$\Psi_c=0.04D_*^{-0.10}$	$10 < D_* \le 20$
$\Psi_c=0.013D_*^{0.29}$	$20 < D_* \le 150$
$\Psi_c=0.055$	$D_* > 150$

(2) Cohesive soils

Based on the work of Mirtskhoulava[5], the mean critical velocity for cohesive soils equals:

$$U_c = \log\left(\frac{8.8h_0}{0.004}\right)\sqrt{\frac{0.4}{\rho_{water}}\left(0.004g\left(\rho_{solid}-\rho_{water}\right)+0.021C_0\right)} \qquad [6]$$

In which: C_0 = cohesion $[N/m^2]$
ρ_{solid} = density solid material $[kg/m^3]$
ρ_{water} = density water $[kg/m^3]$

2.2.2 Scour calculation

The time dependent relation for clear water scour can be calculated using the equations developed by Teramoto and Breussers. Both methods are valid for slender bridge piers in which the pier diameter b versus flow water depth h_0 ratio $(b/h_0) < 1$.

Teramoto

$$y_m = 0.072h_0\left(\frac{u_*}{u_{*,c}}\right)^{2.75}\left(\frac{Fr^2U_0t}{h_0}\right)^{0.364} \quad with\ Fr=\frac{U_0}{\sqrt{gh_0}} \qquad [7]$$

In which: Fr = Froude number [-]
U_0= depth average flow velocity [m/s]
$u_{*,c}$= critical bed-shear velocity [m/s]
g = acceleration of gravity` $[m/s^2]$
h_0 = water flow depth [m]
t = time [s]
y_m= maximum scour depth at time [m]

This equation is only valid for situations where the flow velocity is relatively small, ergo $U_0/U_c < 1$.

Breussers

The following relation, providing that the equilibrium scour depth exceeds the diameter of the bridge pier can describe the maximum scour depth.

$$y_m = y_{m,e}\left(1 - e^{\ln\left(1-\frac{b}{y_{m,e}}\right)\left(\frac{t}{t_1}\right)^{\gamma}}\right) \quad [8]$$

In which:

y_m=	maximum scour depth at time t	[m]
$y_{m,e}$=	maximum scour depth in equilibrium phase	[m]
t =	time	[s]
t_1=	characteristic time at which $y_m = b$	[s]
b =	width of pier	[m]
γ =	Coefficient between 0.2 and 0.4	[-]

The characteristic time can be written as:

$$t_1 = 29.2\frac{b}{\sqrt{2U_0}}\left(\frac{\sqrt{\Delta g d_{50}}}{\sqrt{2U_0 - U_c}}\right)^3\left(\frac{b}{d_{50}}\right)^{1.9} \quad [9]$$

In which:

U_0=	depth average flow velocity	[m/s/
U_c =	mean critical velocity	[m/s]
g =	acceleration of gravity	[m/s^2]
Δ =	relative density (=$\rho_{solid}/\rho_{water} - 1$)	[-]
d_{50} =	median grain size	[m]

The relation of the ratio U_0/U_c with the equilibrium scour depth can be described for the following three conditions:

1. $\frac{U_o}{U_c} \leq 0.5$

   No scouring will occur.

2. $0.5 < \frac{U_o}{U_c} < 1$

   The equilibrium scour depth $y_{m,e}$ can be described with:

$$y_{m,e} = 2K_i b\left(\frac{2U_0}{U_c} - 1\right)\tanh\left(\frac{h_0}{b}\right) \quad [10]$$

In which: K_i = Correction factor for pier shape, bed gradation, flow direction and pier group. This factor is in case of the flume tests equal to 1 [-].

3. $\frac{U_o}{U_c} > 1$

The equilibrium scour depth can be described with:

$$y_{m,e} = 1.5 K_i b \tanh(\frac{h_0}{b}) \quad [11]$$

2.3 CALCULATION RESULTS

The calculation results have been summarised in Table 5. The scour has also been calculated using the SRICOS method as described by Briaud, Chen and Ting[6].

From the results it can be deduced that the "conventional methods" of Breussers and Teramoto are in the same order as the results obtained with the SRICOS method.

Table 5: Results scour depth predictions of flume tests

Test description	**Maximum depth of scour hole when the flume test stops [mm]**		
	Breussers	**Teramoto**	**Sricos**
Flume case 1: 160 mm diameter circular pier placed in clean sand deposit and subjected to a constant velocity over a period of one day.	230	N/A Approach velocity is too high	190
Flume case 2: 160 mm diameter circular pier placed in a clean sand deposit and subjected to a multi-velocity hydrograph over a period of 4 days.	233	N/A Approach velocity is too high	191
Flume case 3: 160 mm diameter circular pier placed in clay deposit and subjected to a constant velocity over a period of 30 days.	N/A Approach velocity is too low	38	182.6
Flume case 4: 160 mm diameter circular pier placed in a uniform clay deposit and subjected to a multi-velocity hydrograph over a period of 4 days.	N/A Approach velocity is too low	14.3	109.2
Flume case 5: 160 mm diameter circular pier placed in a sand over clay layered soil and subjected to a constant velocity flow over a period of 10 days.	Combined: first Breussers and than Teramoto 105.6		233.3
Flume case 6: 160 mm diameter circular pier placed in a clay over sand layered soil and subjected to a constant velocity flow over a period of 10 days.	N/A Approach velocity is too low	25.6	281

3 BRIDGE SITES PREDICTION

3.1 CASE 7: MISSISSIPPI RIVER BRIDGE

3.1.1 Soil and flow properties

The soil and flow properties during the 8/3/93-flood event have been summarised in the Tables 6 and 7.

Table 6: Soil properties sand riverbed Mississippi

ρ_s	d_{84}	d_{50}	d_{16}
[kg/m^3]	[μm]	[μm]	[μm]
2600	1300	600	300

Table 7: Flow data

Date	Water temperature	Approach depth	Approach velocity	Skew angle	Sediment Transport	Flow width	Width pile
[-]	[°]	[m]	[m/s]	[°]	[-]	[m]	[m]
8/3/93	15	22.52	2.429	11	Life bed	518	7.32
8/12/93	15	22.37	2.000	4	Life bed	518	7.32
9/13/93	15	16.70	1.838	4	Life bed	518	7.32

3.1.2 Calculation method

For life bed scour, the equilibrium scour depth $y_{m,e}$ can be described according to Breussers:

$$y_{m,e} = 1.35 K_i b^{0.7} h_0^{\ 0.3} \qquad [12]$$

In which:
- b = width of pier [m]
- h_0 = water flow depth [m]
- K_i = correction factor for pier shape, bed gradation, flow direction and pier group [-]

The factor K_i consists of four different correction factors:

$$K_i = K_s K_\omega K_g K_{gr} \qquad [13]$$

In which:
- K_s = pier shape factor [-]
- K_ω = factor for orientation of pier to the flow [-]
- K_g = factor for the influence of groups an piers [-]
- K_{gr} = factor for the influence of the bed material grading [-]

Pier shape
The pier shape factor K_s can be deduced from Table 8 after Laursen & Toch[7]., Neill[8] and Dietz[9].

Table 8: Pier shape factor K_s

Form of cross section	K_s
Horizontal	
Lengticular	0.7 to 0.8
Elliptic	0.6 to 0.8
Circular	1.0
Rectangular	1.0 to 1.2
Vertical	
Pyramid	0.76
Inverted pyramid	1.2

The pier shape factor K_s equals 0.75 for this type of lengticular pier.

Orientation
The relation of skew angle and flow can be expressed as the factor K_ω and has been described by Froehlich[9]:

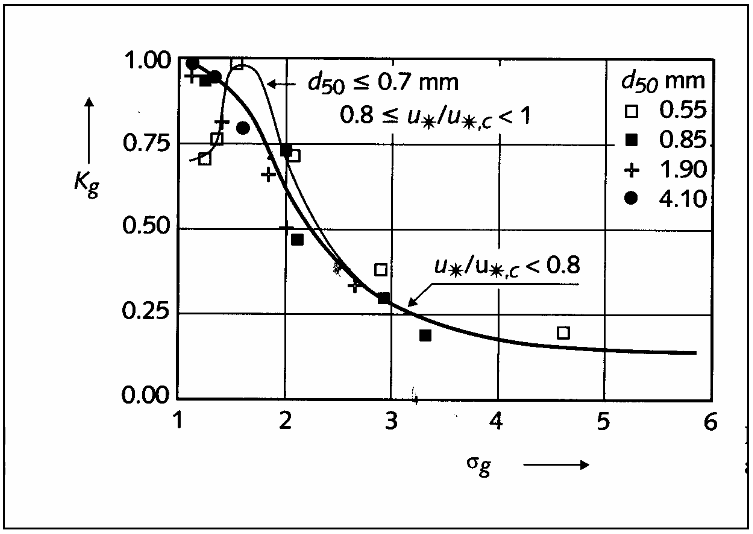
$$K_\omega = \left(\cos\omega + \frac{L_p}{b}\sin\omega \right)^{0.62} \qquad [14]$$

In which:	ω =	skew angle	[°]
	L_p=	length of pier	[m]
	b =	width of pier	[m]

With a skew angle of 11 degrees, the factor K_ω is equal to 1.23.

Gradation bed material
The influence of the bed gradation has been investigated by Vanoni[9] and can be expressed as the (graphical) relation of σ_g (equal to the ratio of d_{84}/d_{50}) shown in Figure 1.

Figure 1: Graphical relation K_g with ratio of d_{84}/d_{50}



The bed material of the riverbed near pier 11 has a σ_g equal to 4.3 and thus a factor K_g of 0.18.

Group of piers
Breussers and Raudkivi[11] have described the influence of the spacing between circular piers on the scour depth. In general, if the spacing is more than 8b, in which b is the pier width, the influence can be ignored and K_{gr} = 1, see Table 10.

Table 10: Factor K_{9r} for a group of circular piers

	Configuration			Pier spacing	Front pier K_{9r}	Rear pier K_{9r}
1				[m]	[-]	[-]
	O		O	1b	1.0	0.9
				2 to 3b	1.15	0.9
				> 15b	1.0	0.8
2		O		1b	1.9	1.9
			O	5b	1.15	1.2
				> 8b	1.0	1.0
3	O		O	1b	1.9	1.9
				2 to 3b	1.2	1.2
				> 8b	1.0	1.0

The pier spacing is approximately 9 times b so that K_{gr} = 1.

3.1.3 Calculation results

The scour created by the 8/3/93-flood event is according the calculations equal to 9 m.
After the water discharge decreases, the approach velocity and water flow depth will decrease to the average approximately 1.8 m/s and 16.7 m. The scour depth according to the latter averages equals 7.3 m.

The flood-induced scour is therefore equal to 1.7 m.

Additional data required:
- None when using the above-mentioned method.

3.2 CASE 8: PEARL RIVER BRIDGE

3.2.1 Soil and flow properties

The nature of the soil samples taken from the vicinity of pier 17 can not be clearly assessed from the provided data. For the scour calculations, we assume that the riverbed in the vicinity of pier 17 consists of sand.

The soil and flow properties of the riverbed in the vicinity of pier 17 have been summarised in the Tables 10 and 11.

Table 10: Soil properties sand riverbed Pearl River

Sample	ρ_s	d_{84}	d_{50}	d_{16}	Location sample
[-]	[kg/m^3]	[μm]	[μm]	[μm]	[-]
1	2600	1200	540	360	Mid-span piers 16 and 17
2	2600	900	390	260	Vicinity of piers 17 and 18

Table 11: Flow data

Date	Approach depth	Approach Velocity	Sediment Transport	Width pile	Event
[-]	[m]	[m/s]	[-]	[m]	[-]
05/1/95	6.9	1.2	Unknown	3.35	5/1/95 flood
N/A	8.9	1.5	Unknown	3.35	50 yr flood event

3.2.2 Calculation method

The provided data leads to the assumption of a non-existing bed load implying that the equilibrium scour depth can be described according to Breussers using equation 10 and 11 depending on the critical velocity.

The critical velocity, based on the data of the 5/1/91-flood event is equal to 0.38 m/s, which implies a ratio of U_0/U_c of 4 so that equation 11 has to be used.

Since the approach flow velocity in case of a 1 to 500 year flood is even larger than the velocity measured at during the 5/1/91-flood event, equation 11 can also be used to predict the scour depth.

The K_i factor has a lower and upper limit of 0.25 and 0.20 due to the large difference in the gradation in the bed material, expressed in the parameter d_{84} and d_{50}. The K_i factor has been calculated from the following values:

Pier shape factor K_s: 0.75 (lengticular pier shape)
Orientation factor K_ω: 1.0 (skew angle =0)
Bed gradation factor K_g: 0.25 for sample1 and 0.20 for sample 2
Group factor K_{gr}: 1.3 (configuration 1 with pier spacing of 1.7b)

3.2.3 Calculation results

Based on the data mentioned above, the scour depth during the 5/1/91-floodevent equals 0.9 to 1.2 m, depending on the coarseness of the bed material. Since there is no flow data for an average situation, the extra scour induced by this flood event can not be calculated.

During a 50-year period incorporating a 1 to 500 year flood event, the maximum scour depth is equal to 1.0 to 1.3 m, depending on the coarseness of the bed material.

Additional data required:

- Average flow velocities and flow depth averages during normal conditions. Also, EFA experimental data could improve the assessment of the final scour depth.

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