CHAPTER 128

# SCOUR AROUND STRUCTURES

ECO W. BIJKER*, Member ASCE

## Abstract

The physics of scour around structures and especially underneath pipelines is discussed. It is demonstrated that a combination of current and waves with an equal bottom shear stress as a uniform current gives lower scour rates than a single current with the same bottom shear stress.

The principle of the performance of scale series is discussed and it is shown that this method has still some weak points.

## 1. Introduction

When a structure is placed in water on an erodable bottom and is subject to a current or wave field, scour will most likely occur around the structure. It is difficult to predict this scour because the scour process is even more complicated than the normal transport process. In this paper the various processes and prediction methods will be discussed for pipelines on a sandy bottom because a lot of data is available from an extensive research carried out within the framework of the Dutch Marine Technology Research (MaTS).

At present it is possible to predict the current pattern around a structure, c.q. the pipeline, by numerical models. These models can also calculate the rate of turbulence and the bottom shear stress. Modelling of transport processes is, however, still very difficult [Leeuwestein and Wind (1984) and Leeuwestein et al. (1985)]. Good progress is made in obtaining a reliable description of the transport and scour phenomena.

As long as the final goal is not yet reached, physical model tests can offer a solution, not only for predicting scour values but also for obtaining a better insight in the physical processes. However, with physical modelling serious and well known scaling problems will arise. A method to cope to some extent at any rate with that problem, is the application of scale series. In this procedure a set of models with varying scales is applied and the results, for instance measured values of the scour, are extrapolated to values for scale 1:1.

---

* Professor of Coastal Engineering, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands

This should give the correct answer. Since this extrapolation is rather difficult, often an attempt is made to determine for each test the best possible scale factor for the scour. In the ideal case all predicted scour values should give then the same value. Even in the case this ideal is not reached, the extrapolation of these 'up-scaled' values is much more easy than of the observed test values. This principle is demonstrated in Figure 1.

In this paper this procedure is worked out for the scour around pipelines and the possible deficiencies which are still inherent to this method are discussed.

## 2. Physics of scour

A basic difference exists between the scour caused by current and waves.

i. In a current field, normally a continuous transport exists. In this case the basic condition for the equilibrium situation in the immediate vicinity of the structure, so for the equilibrium scour hole configuration, is that the transport gradient, $dS(x)/dx = 0$. When the current is so low that in the undisturbed current field no transport occurs, the scour around the structure, c.q. underneath the pipeline, will develop until also in the vicinity of the structure the transport is zero. So again $dS(x)/dx = 0$. (See Figure 2.)

ii. Under the influence of an orbital wave motion hardly any continuous transport occurs. In this case the scour process is determined by the excursion distance of the sediment particles through the orbital motion. The amplitude of the sediment motion is closely related and even almost equal to the amplitude of the orbital motion of the water at the bottom. (See Figure 3.)

Moreover, another difference exists between the development of scour by only current or by waves. This is caused by the fact that in the case of only current, the scour will take place by an accelerated current which has subsequently a relatively low rate of turbulence. The bottom shear will be, however, higher than in the case of a uniform flow, since the boundary layer is not yet adjusted. This effect, of the adjustment of the boundary layer, does not occur for the situation with only waves, since the boundary layer under waves must be adjusted continuously. This effect is almost equal for the undisturbed wave motion and for the wave motion in the scour area.

For the combination of waves and current this effect is also noticeable. The bottom shear stress of the combined effect of waves and current can be written as

$$\tau_{cw} = \tau_c + \tfrac{1}{2}\,\hat{\tau}_w = \tau_c\left(1 + \frac{\hat{\tau}_w}{2\tau_c}\right) \qquad (1)$$

in which $\tau_c$ = bottom shear stress by current; $\hat{\tau}_w$ = amplitude of bottom shear stress by waves; $\tau_{cw}$ = combined bottom shear stress [Bijker (1966 and 1971)].

Since in the scour area $\tau_c$ increases relatively more than $\hat{\tau}_w$, the

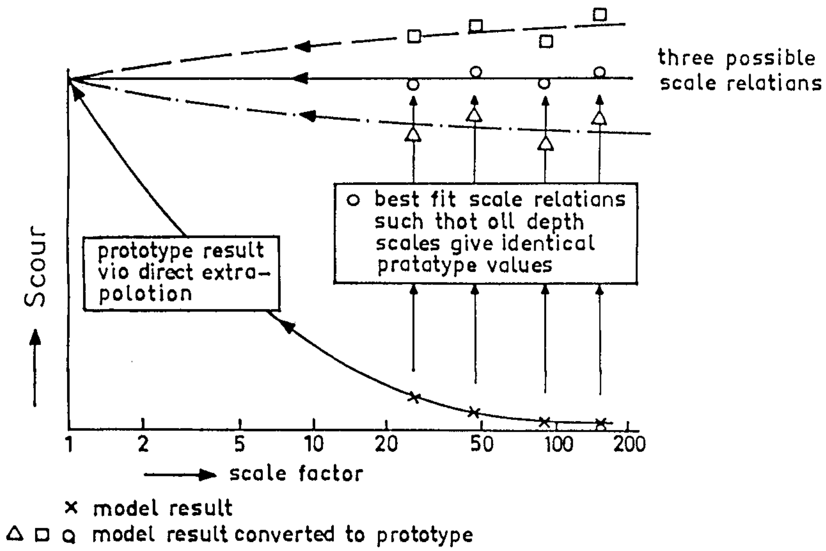


Fig. 1 Philosophy of a scale series

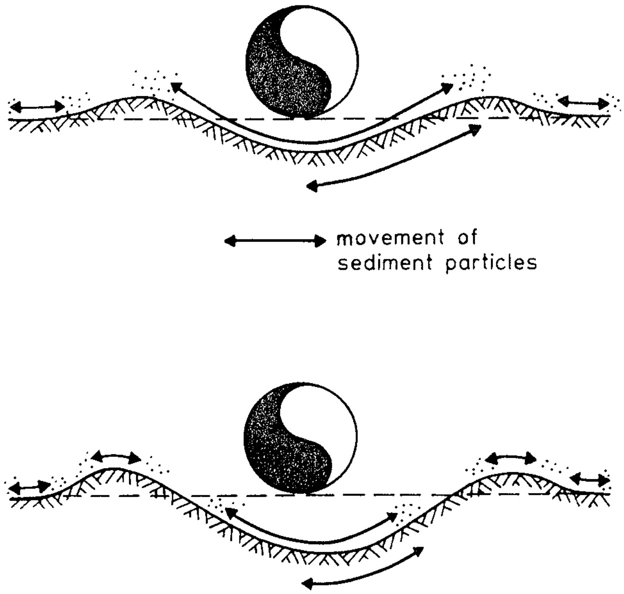


Fig.3 SCOUR DUE TO WAVES.

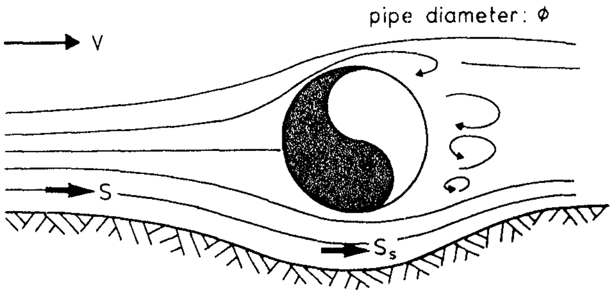


Fig. 2 SCOUR AS RESULT OF CURRENT

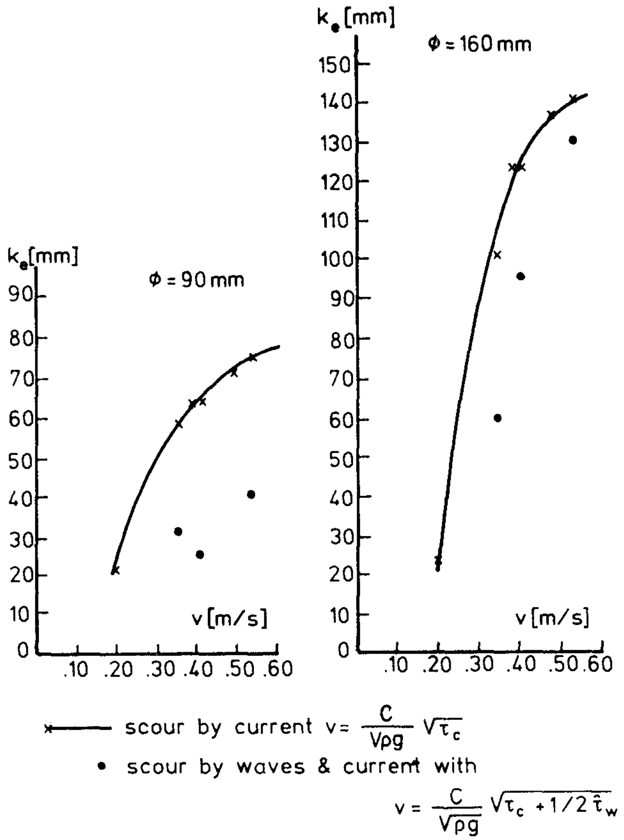


Figure 4. SCOUR FOR CURRENT AND CURRENT + WAVES.

factor by which the transport due to current is increased by wave motion is in the scour area less than in the undisturbed area.

The scour will be, therefore, less and this is demonstrated by tests in which scour has been subjected to a current and to a combination of current and waves with an equal bottom shear stress in the undisturbed area.

The velocity in the case of only current should be

$$v_1 = C\sqrt{\frac{\tau_{c,1}}{\rho g}} \tag{2}$$

in which C = the Chezy bed resistance factor.

In the case of the combination of a current and waves, the current should be less, resulting in a bed shear $\tau_{c,2}$ , so that

$$\tau_{c,w} = \tau_{c,1} = \tau_{c,2} + \tfrac{1}{2}\,\hat{\tau}_w \,. \tag{3}$$

The scour occurring under these conditions should be compared with scour $k_{e,1}$ occurring by the velocity

$$v_1 = C\sqrt{\frac{\tau_{c,2} + \frac{1}{2}\,\hat{\tau}_w}{\rho g}} \,. \tag{4}$$

The results are shown in Table 1 which gives the observed scour values for various combinations of waves and currents. The values $v_1$ of a single current giving the same resulting shear stress as the combination of waves and current are given with the corresponding scour values.

The results are also presented in Figure 4. Apart from the test with $v_2$ = 0.40 m/s and $\hat{u}_b$ = 0.15 m/s, the scour underneath a pipeline subjected to a combination of waves and currents is less than the scour when the pipeline is subjected to a single current $v_1$ with the same bottom shear stress as $v_2$ and $\hat{u}_b$ .

For a continuous transport the bottom changes can be described by

$$\frac{\partial}{\partial t}\left[\int_{z_b}^{z_s} c(x,z,t)\cdot dz\right] + \frac{\partial S(x,t)}{\partial x} + (1-p)\,\frac{\partial\, z_b(t)}{\partial t} = 0 \tag{5}$$

in which $c(x,z,t)$ is the sediment concentration at place x , height z and time t , $z_b$ is the height of the bottom, $z_s$ = height of the water level, or any level above which $\frac{\partial}{\partial t}\left\{c(x,z,t)\right\} = 0$; $S(x,t)$ is the total sediment transport per unit of width at place x and time t , and p = the porosity of bottom material.

Equation 5 demonstrates that scour will not only occur as a result of $\partial S/\partial x$ , but also because more sediment can go into suspension. This is especially important in those cases where the material brought into suspension can be transported outside the area of expected scour. This is of great importance for the scour around structures when locally material can be brought into suspension and then can be transported by a continuous current.

This phenomenon also explains the difference in scour patterns in front of a vertical wall with coarse and fine bottom material [de Best et al. (1971), Irie and Nadaoka (1984)] .

3. Formulation of sediment transport

Sediment transport formulae can be written in the following general form:

$$\phi = f\ (\psi), \tag{6}$$

in which $$\phi = \frac{S}{\sqrt{g\Delta D^3}}, \tag{7}$$

with S = transport per unit width; g = acceleration of earth gravity; D = grain size of sediment and $\Delta$ = relative density of sediment;

and $$\psi = \frac{\tau}{\rho g \Delta D}, \tag{8}$$

with $\tau$ = bottom shear stress.

For current $$\psi_c = \frac{\kappa\ v_t^2}{g\Delta D} = \frac{\bar{v}^2}{C^2 \Delta D}, \tag{9}$$

with $v_t$ = velocity just above laminar sublayer at er/33 and $\bar{v}$ = mean velocity, averaged over the depth

and for waves $$\psi_w = \frac{f_w\ \hat{u}_b^2}{2g\Delta D}, \tag{10}$$

with $\hat{u}_b$ = amplitude of the orbital velocity at the bottom and $f_w$ = bottom friction factor of Jonsson [Jonsson (1966)] .

For the case of a combination of current and waves, $\psi_c$ should be replaced by $\psi_{cw}$, which can be written as

$$\psi_{cw} = \psi_c + \tfrac{1}{2}\psi_w \tag{11}$$

[Bijker (1966, 1971)] .

Some sediment transport formulae are:

Meyer-Peter, Mueller

$$\phi = 13.3\ (\psi_c - 0.047)^{1.5} \tag{12}$$

Kalinske-Frijlink

$$\phi = 5\sqrt{\psi_c}\ e^{-0.27/\psi_c} \tag{13}$$

Paintal

$$\phi = 10.9\ 10^{18}\ \psi_c^{16} \quad \text{for } \psi_c < 0.05 \tag{14}$$

$$\phi = 21.7\ \psi_c^{2.5} \quad \text{for } \psi_c > 0.05 \tag{15}$$

Engelund and Hansen

$$\phi = \frac{C}{g} \psi^{5/2} . \qquad (16)$$

All above descriptions can, over a limited velocity range, be simplified to

$$S = \alpha v^{\beta} , \qquad (17)$$

in which $\alpha$ is a non-dimensionless coefficient. This simplification is used for the derivation of simple scale relations used in the scale series. A close analysis of the above quoted formulae shows that $\alpha$ is mainly determined by D and that the influence of the velocity and the type of transport, viz. : mainly bed load or mainly suspended load, or a combination of these two, are represented by the value of $\beta$ .

For low transport rates, mainly in the form of bed load, $\beta$ is larger, 0 (6), than for high transport rates with a large ratio of suspended load over bed load, 0 (2 or 3).

## 4. Prediction of scour by current through a scale series

In Chapter 1 it has been stated that, in order to be able to extrapolate the measured scour values for the various model pipes, c.q. structures to scale 1:1 , an as accurate as possible scale for the scour should be found. This requires a good choice for the velocity scale belonging to the various scales of the structure. The correct value of this scale is, moreover, at any rate necessary for a good performance of the model test. In the ideal case the transport scale is constant over the entire area, that is upstream and downstream and around the structure.

So, $n_S = n_{S_s}$ , (18)

in which $n_S$ = transport scale factor = prototype value over model value and the subscript s denotes the value at the place of maximum scour. This leads in this case through Equation (17) to

$$n_{(\alpha v^{\beta})} = n_{(\alpha_s v_s^{\beta_s})} . \qquad (19)$$

Equation (19) leads to a value of $n_v$ and in some cases also to a relation of $n_v$ to $n_1$ .

From the discussion in Chapter 3 , $\alpha$ proves to be determined mainly by the grain size of the sediment. Since the material in the scour area will not differ much from that in the undisturbed area; $n_\alpha = n_{\alpha_s}$ .

In order to make the computations not too complicated, $n_\beta$ and $n_{\beta_s}$ are assumed to be 1 . This is only so when the type of transport in the model is equal to that in the prototype. Since this is not completely true, the derived scale relation will not be the 'ideal' one. However, when the relation is consistent, extrapolation through a continuous curve to the prototype condition, $n_1 = 1$ , will be possible.

Equation (19) in this case can be written as

$$n_v^{\beta} = n_{v_s}^{\beta_s} \qquad (20)$$

Normally the relation between $v_s$ and $v$ is known. For a vertical pile $v_s = 2\ v$, which would lead to

$$n_v^{\beta} = 2^{\beta_s}\ n_v^{\beta_s} \ . \qquad (21)$$

For the tests with pipelines the situation differs somewhat since a pipeline with a larger diameter will force more water through the gap underneath the pipeline. The ratio between the velocity underneath the pipeline and the undisturbed velocity is, therefore, a function of the pipeline diameter $\phi$.

Tests have shown that this ratio can be described by

$$v_s/v = \phi^{0.2} \ . \qquad (22)$$

In this case Equation (20) [ Leeuwestein (1986) ] can be written as

$$n_v^{\beta} = n\left(v\,\phi^{0.2}\right)^{\beta_s} = n_v^{\beta_s}\ n_\phi^{0.2\ \beta_s} \ , \qquad (23)$$

$$\text{or} \quad n_\phi = n_v^{\ p} \ , \qquad (24)$$

$$\text{with} \quad p = \frac{\beta - \beta_s}{0.2\ \beta_s} \ . \qquad (25)$$

Reasonable values for $\beta$ and $\beta_s$ are 5 and 3 respectively. The value of $\beta_s$ is chosen lower than $\beta$ because a numerical analysis by the Delft Hydraulics Laboratory revealed that underneath the pipeline a greater ratio of suspended load over bed load exists than in front of the pipe [ Leeuwestein and Wind (1984) ] .

In that case $p = 3.3$ and subsequently

$$n_\phi = n_v^{3.3} \ . \qquad (26)$$

Another possible scale relation is based on Froude modelling of the flow pattern, so

$$n_\phi = n_v^{2} \ . \qquad (27)$$

The procedure to determine the scour underneath a pipeline of $\phi = 500$ mm for an undisturbed current velocity of 0.7 m/s is as follows.

For various pipe diameters $\phi$, ranging from 10 to 100 mm, the scour is measured for velocities of 0.2 , 0.3 , 0.35 and 0.4 m/s. The results are shown in Figure 5. For each value of the velocity, the velocity scale (with respect to $v = 0.7$ m/s) is determined and from that velocity scale the scale for the pipeline $n_\phi$ is calculated through Equation (24). When this exercise is performed for $p = 2$ and $p = 3.5$, a velocity in the test of $v = 0.35$ m/s, leading to $n_v = 2$, gives values of $n_\phi = 4$ and 11.3 respectively. In this way a set of scour values under pipelines with varying scales with regard to the pipeline of 500 mm and 'realistic' values of the tests-velocities is obtained. These points form the lower line of Figure 6. Exrapolation

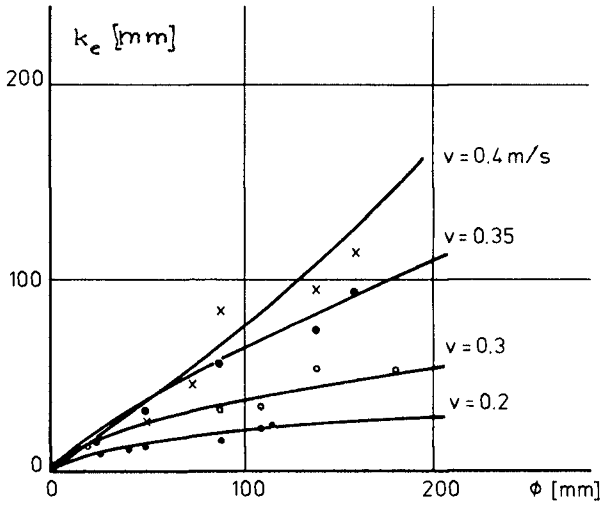


Figure 5. MEASURED SCOUR DEPTHS (CURRENT).

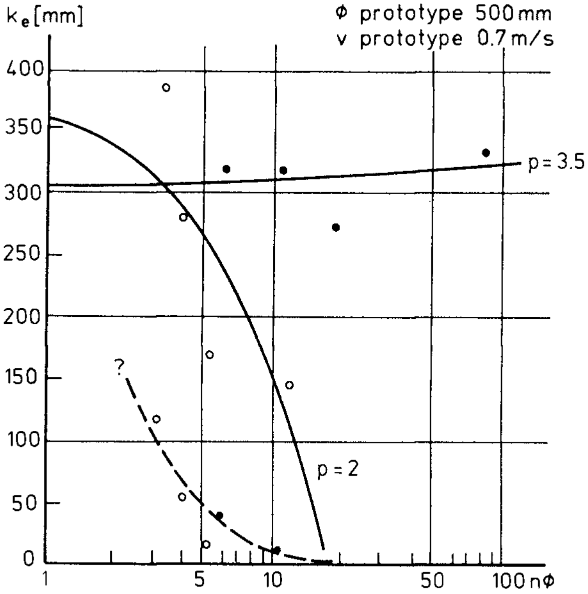


Figure 6. SCOUR BY CURRENT (MATS DATA).

of this line to $n_\phi = 1$ would give the expected scour for a pipe of 500 mm and a velocity of 0.7 m/s. This extrapolation is, however, easier when the observed scour values are multiplied with the expected scale factor of the scour. For the 'ideal' velocity scale this factor will be equal to $n_\phi$ . The lines obtained in this way for p = 2 and 3.5 are also given in Figure 6. Extrapolation is done by a linear regression analysis. In Chapter 6 the results will be discussed more in detail.

The same exercise has been done for the data of Kjeldsen, which are summarized in Figure 7. The final result is shown in Figure 8.

## 5. Prediction of scour by means of scale series for waves

In principle the same procedure as for a current is followed. However, in order to make a first estimate for p in $n_\phi = n_v{}^p$, a somewhat different procedure has to be followed, since the principle of scour around a structure by waves is basically different from that by current (see Chapter 2).

In the case of scour by waves no continuous transport of any importance exists. The criterium that $\partial S/\partial x = 0$ and, therefore, the requirement that $n_S$ in front of the structure should be equal to $n_{S_s}$ in the scour hole is irrelevant.

In the ideal situation $n_{k_e} = n_\phi$ and since the current pattern around the structure is determined to a great extent by the pressure around the structure, c.q. underneath the pipe, $n_\phi = n_{\hat{u}}^2$ .

According to the physics of the scour underneath a pipeline as discussed in Chapter 2, the amplitude of the orbital motion should be reproduced on the scale of the pipeline; $n_\phi$ . When the wave period is reproduced on $n_\phi^{\frac{1}{2}}$ , this requirement also leads to $n_{\hat{u}} = n_\phi^{\frac{1}{2}}$ .

The scale series have been performed with values of p = 1 , 1.5 and 2 . The original test results for scour by waves are given in Figure 9 and the final results for the scale series in Figure 10. The scour for the prototype pipeline of $\phi$ 500 mm and $\hat{u}_{b,pr}$ = 1 m/s then is 187 , 205 and 210 mm which is reasonable close together. These values are, as could be expected, much less than the values obtained for a steady current of comparable value.

## 6. Discussion

For the pipeline of 500 mm in a steady current of 0.7 m/s, data are available from full scale tests in the large flume of the Delft Hydraulics Laboratory. The MaTS data give for p = 2 a value of $k_e$ = 355 mm and for p = 3.5 a value of $k_e$ = 302 mm. As a matter of fact, these two values should have been equal. Moreover, the full scale test gives a value of only 220 mm.

One of the reasons for this 'low' value of 220 mm probably is that the tests in the large flume have not been run long enough. In Figure 11 the results of these tests are shown. These results indeed give the impression that extension of the test with v = 0.7 m/s would have given somewhat larger values for the scour.

Another reason could be the layout of the test as shown in Figure 12. The feeding of the sand by controlled dumping in the flume some 50 m upstream of the pipe, could have led to a too high suspended load and,

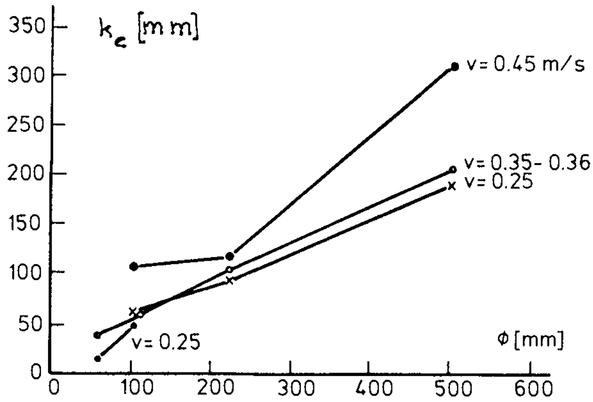


Figure 7. KJELDSEN SCOUR DATA.

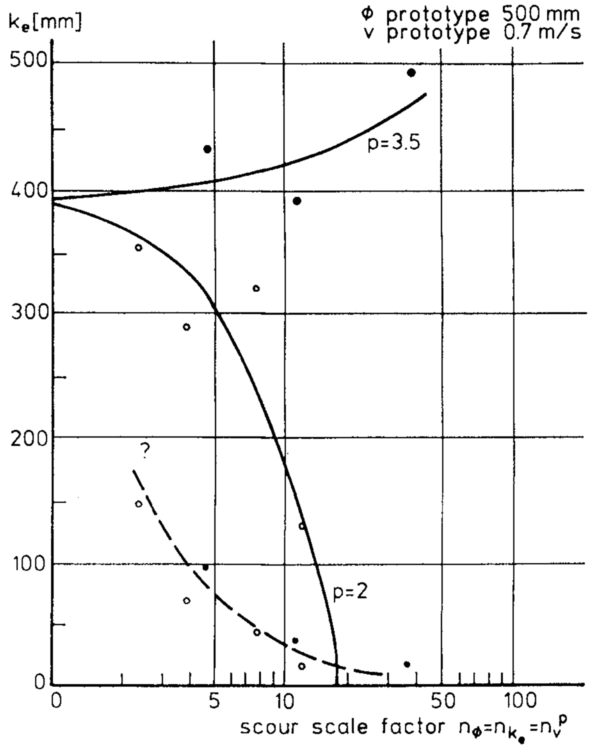


Figure 8. SCOUR BY CURRENT (KJELDSEN DATA).

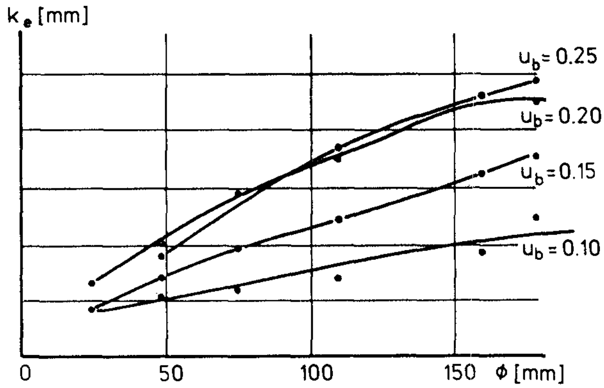


Figure 9. MEASURED SCOUR DEPTHS (WAVES).

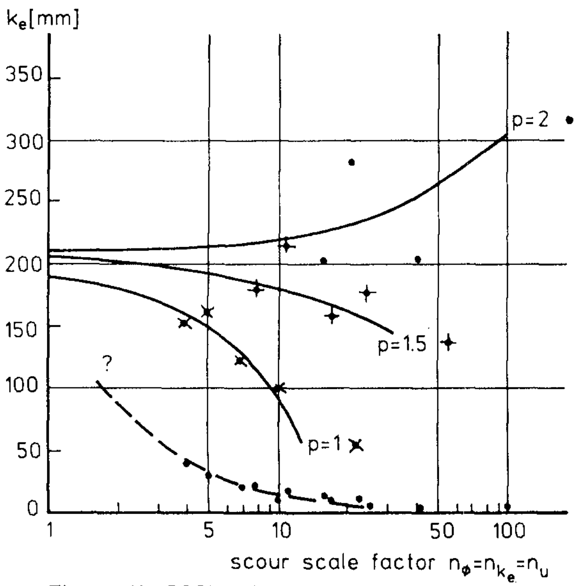


Figure 10. SCOUR BY WAVES:

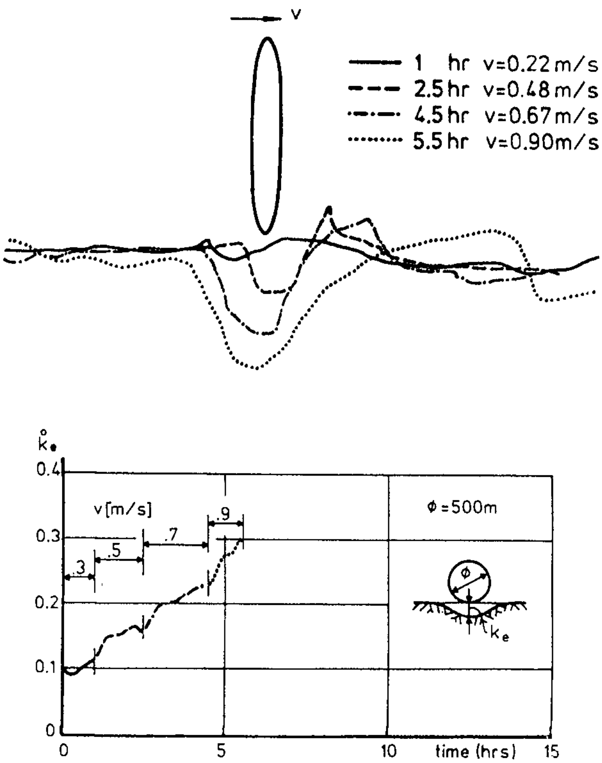


Figure 11. SCOUR MEASUREMENTS IN LARGE FLUME of D.H.L. (de Voorst).

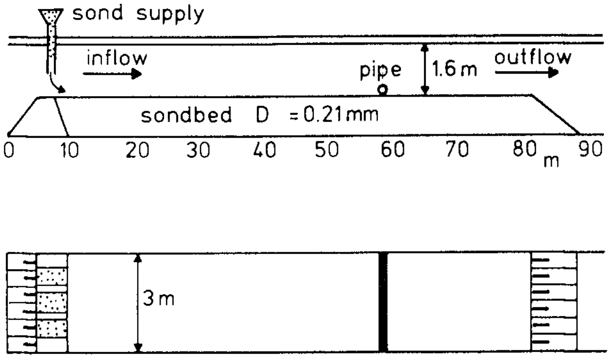


Figure 12. LARGE FLUME D.H.L. (de Voorst).

therefore, to too high sand supply to the scour hole. This also led in some cases to the formation of very large dunes.

Also the Kjeldsen data lead to values of the scour of the order of 390 mm, which is higher than predicted by the formula of Kjeldsen,

$$k_e = 0.97 \left(\frac{v^2}{2g}\right)^{0.2} \phi^{0.8} \tag{28}$$

This would give $k_e$ = 266 mm .

Of course, this value corresponds rather well with the direct extrapolation of the Kjeldsen data. However, it is not sure that this extrapolation is allowed, because the transport mechanism is changing when the velocity is increased so much from the values of the Kjeldsen data.

This also demonstrates the weak point of every scale series. It is well possible that extrapolation to the required prototype value will change the transport mechanism so fundamentally that extrapolation by a continuous curve is not allowed any more. Therefore, utmost care in the application of scale series is still necessary.

The ultimate procedure for scour prediction will be, therefore, in the nearby future the use of numerical models based on a description of the transport and scour processes through basic physical research.

| | | Measured values of $k_{e,2}$ [mm], for | | $\tau_{c.w}$ [N/m²] | $v_1$ [m/s] | Scour values $k_{e,1}$ [mm], for | |
|---|---|---|---|---|---|---|---|
| $v_2$ [m/s] | $\hat{u}_b$ [m/s] | $\phi$=90 mm | $\phi$=160 mm | | | $\phi$=90 mm | $\phi$=160mm |
| .20 | 0 | 20 | 24 | .13 | | | |
| .20 | .15 | 32 | 60 | .43 | .36 | 58 | 100 |
| .20 | .20 | 25 | 90 | .60 | .42 | 63 | 124 |
| .40 | 0 | 63 | 124 | .52 | | | |
| .40 | .15 | 90 | 140 | .82 | .50 | 70 | 136 |
| .40 | .20 | 40 | 130 | .97 | .55 | 75 | 140 |

Table 1 Scour values for only current and a combination of waves and currents

Appendix 1 - References

BEST, A. de, E.W. BIJKER and J.E.W. WICHERS
Scouring of a sand bed in front of a vertical breakwater.
Proc. 1st Int. Conf. on Port and Ocean under Arctic Conditions (POAC), Trondheim, 1971, Vol. II, pp. 1077-1086.

BIJKER, E.W.
The increase of bed shear in a current due to wave action.
Proc. 10th Int. Conf. on Coastal Engineering, Tokyo, 1966, Vol. I, pp. 746-765.

BIJKER, E.W.
Longshore transport computations.
Proc. ASCE, Journal of the Waterways, Harbors and Coastal Engineering Division, WW 4, November 1971.

IRIE, I. and K. NADAOKA
Laboratory reproduction of seabed scour in front of breakwaters.
Proc. 19th Int. Conf. on Coastal Engineering, Houston, 1984, Vol. II, pp. 1715-1731.

JONSSON, I.B.
Wave boundary layer and friction forces.
Proc. 10th Int. Conf. on Coastal Engineering, Tokyo, 1966, Vol. I, pp. 127-148.

KJELDSEN, S.P.
Experiments with local scour around submarine pipelines in a uniform current.
Technical University of Norway, Trondheim, 1974.

LEEUWESTEIN, W. and H.C. WIND
The computation of bed shear in a numerical model.
Proc. 19th Int. Conf. on Coastal Engineering, Houston, 1984, Vol. II, pp. 1685-1700.

LEEUWESTEIN, W., E.W. BIJKER, E.B. PEERBOLTE and H.C. WIND
The natural self burial of submarine pipelines.
Proc. 4th Int. Conf. on Behaviour of Offshore Structures (BOSS'85), Delft, 1985, pp. 717-728.

LEEUWESTEIN, W.
The natural self burial of submarine pipelines.
MaTS Stability of pipelines, scour and sedimentation.
PL4-2 DD, 1986.