CHAPTER 199

ARTIFICIAL SAND FILLS IN WATER

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1 Introduction

Experience has been obtained on the construction of sand fills in water as part of several types of structures in the Netherlands. These include the following: (closure) dams, artificial islands or coastal extensions, covering of pipelines, trench back fills and the foundation of submerged tunnels and caissons.
Rijkswaterstaat (Ministry of Transport, Public Works and Watermanagement) Dutch contractors, research institutes and consultancy firms have been involved in the research, design and construction of a large number of projects in the Netherlands and abroad.
In-depth research was carried out especially within the frame work of the preparations of a number of Delta closures constructed with sand.
After the completion of the Deltaworks it seemed important not to leave this knowledge scattered over many study reports and design and evaluation notes, but rather to summarize the data and experience in a manual (Van 't Hoff (ed.) et al, 1992) issued by the Council of the Centre for Civil Engineering Research, Codes and Specifications (CUR).
The theoretical section of this manual provides a description of the process phenomena for the

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construction with sand in water based on theory development of the physical processes supported by observations of these processes in the field and in the laboratory. In the practical section the design practice is highlighted with thirteen case histories. By means of a detailed elaboration of a practical case the theory is again more extensively verified with project experience. In this paper some results of the theory development are presented followed by an example of calculation results for a practical case.

2 Application of study results

The study provides a tool to predict the dimensions of a sand fill constructed in water as a function of the sand characteristics, the sedimentation processes on the fill area and method of sand placement.

3 Process phenomena

The processes related to the placement of sand for the construction of sand fills are shown in fig.1. After winning (I) the sand is transported to the fill area (II) by a hopper dredger or via a pipe line. Subject to the means of transport, the sand is either bottomdischarged or pipe line placed (III). The sand-water jet makes craters (IV) in the sand body under construction. A sand-water mixture flows across the edge of these craters. This overflow can occur above water (V) as well as under water (VI). Under water loss of sand (VII) to the surrounding water can occur. Sand in the mixture flow will settle rapidly to form the slope (VIII).

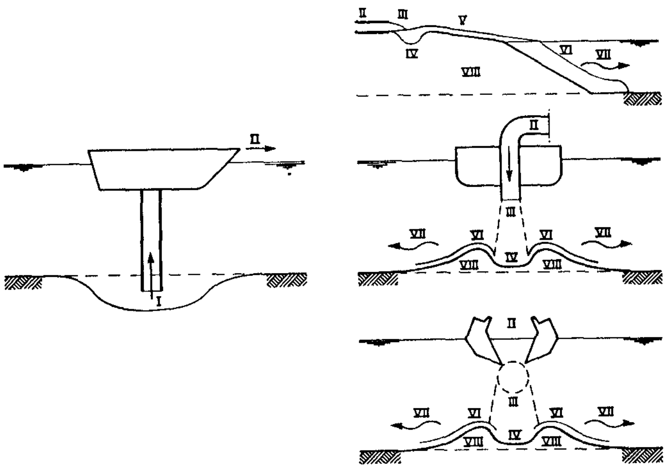


Fig.1 Phases of taking up, transporting and elementory methods of sand placement.

4 Dimensions of a sand fill

The dimensions of a sand fill (fig. 2) placed in water are determined by:

- the behaviour of a sand-water mixture after leaving the discharge pipe or hopper;
- the width of the crater developed during the discharging process as a result of the impact of a sand-water mixture plume or jet
- the sedimentation length
- the initial slope of the above and under water sand fill area directly after placing;
- the occurrence of flow slides;
- the water depth.

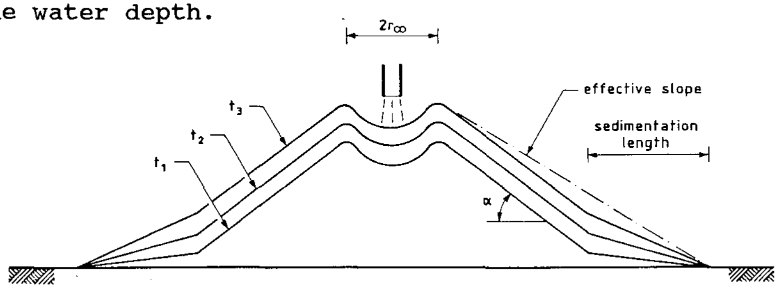


Fig. 2 Parameters determining the shape of a sand fill.

When placing sand in water the sand-water mixture forms a jet or plume with a certain initial flow rate and concentration at the point of discharge of the pipe line or hopper vessel. For a given shape and dimension of discharge opening and for given field conditions, the dimensions, concentrations and velocities along the trajectory of the jet or plume can be predicted as well as the traced path. From these characteristic parameters the dimensions of the crater, which develops when the jet hits the bottom, can be predicted.

5 Crater dimensions

The crater width can be determined using either the theory of Breusers (1991) for conical or round jets and Rajaratnam (1981) for vertical plane shaped jets or the theory of Heezen and Van der Stap (1988).
The theory of Breusers and Rajaratnam begins with a description of the erosion under a clear water jet followed by the determination of the influence of sand in the jet on the dimensions of the crater. With the theory of Heezen and Van der Stap the crater dimensions are directly determined from tests and experience with sand-water jets. Because of the limited available space within the context of this paper, only the results of Breusers theory will be presented briefly (fig. 3).

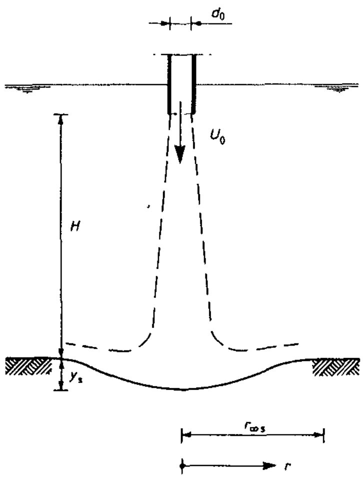


Fig.3. Erosion under a vertical jet.

Based on experiments Breusers recommends the following relations (see also fig. 4):

$$\frac{y_s}{d_0}=0.075\frac{U_0}{u_{*cr}} \quad \text{if} \quad \frac{U_0}{u_{*cr}}<100$$

$$\frac{y_s}{d_0}=0.35\left(\frac{U_0}{u_{*cr}}\right)^{2/3} \quad \text{if} \quad \frac{U_0}{u_{*cr}}>100 \qquad (1)$$

In which:
- d_0 = discharge pipe diameter (m)
- U_0 = discharge velocity (m/s)
- u_{*cr} = critical shear velocity according to Shields (m/s)
- y_s = crater depth for clear water (m)

The vertical distance H to the point of discharge has no influence within the application range of the formula:

$$4<\frac{H}{d_0}<12 \text{ @ } 20 \qquad (2)$$

The effect of the presence of sand in the jet or plume on the dimensions of a crater, can be found by assuming equilibrium between erosion and sedimentation. Because of the presence of sand in the flow, the velocity of the flow on the crater edge must be higher than for clear water in order to prevent sedimentation. As a result of this the crater edge will be closer to the center line of the jet.

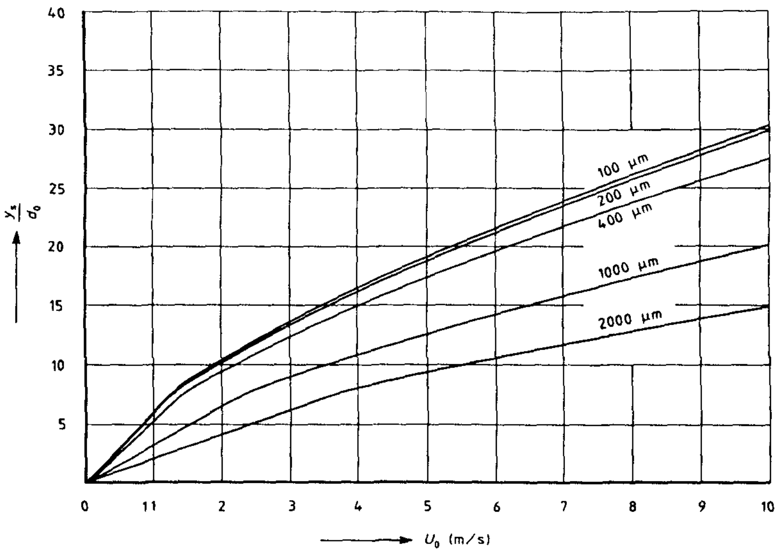


Fig.4. Depth of scour hole for clear water as function of U_0 according to Breusers.

The presence of sand can be accounted for, by reducing the crater dimensions, calculated with formula (1), using a reduction factor which depends on the grain size diameter D_{50} and on the sand concentration (c) in the jet. For jets with coarse sand a reduction of the dimensions of the crater upto a factor 5 is possible.

The ratio between radius and depth does not change, hence the following always applies:

$$\frac{r_\infty}{y}=\frac{r_{\infty s}}{y_s}=2.5 \qquad (3)$$

In which:
r_∞ = crater radius for sand-water mixture (m)
$r_{\infty s}$ = crater radius for clear water (m)
y = crater depth for sand-water mixture (m)
y_s = crater depth for clear water (m)

6 Mixture overflow from crater

Besides the grain diameter, for the determination of the slope gradient, the specific flow rate (q) is the most important parameter for the above water fill area and the specific sand production rate (s) for the underwater fill area. A large specific flow rate and a large specific sand production rate result in flatter slopes.
To be able to determine the values of q and s the width (B) across which the mixture will spread after passing the crater edge must be assessed.

The specific flow ratio q and specific sand production rate s for single point discharging in an under water fill area, follow from the equations:

$$q = U_b . \pi / 4 . d_b^2 / B \qquad (4)$$
$$s = \rho_s . q . c_b \qquad (5)$$

In which:

q = specific flow rate (m^2/s)
U_b = mixture velocity in centre of jet just above sea bed (m/s)
B = spreading width of mixture (m)
d_b = diameter of round jet just above sea bed (m)
s = specific sand production rate (solids) (kg/ms)
ρ_s = density of solids (kg/m^3)
c_b = volume concentration just above sea bed (-)

The question is, across what width B the mixture will spread. There is little known about this subject. For that reason the following approach must be regarded as a first attempt to estimate an upper limit B_{max} and a lower limit B_{min}. The upper limit is taken equal to the circumference of the crater edge. In principle B could become even larger after the mixture has passed the crater edge because the size of the crater increases continuously from the discharge point. However it seems very unrealistic that the mixture spreads more than the complete circumference of the crater edge. Hence, for a crater under a round (conical) jet the following applies:

$$B_{max} = 2\pi r_\infty \qquad (6)$$

and for a crater under a vertical plane shaped jet with a length equal to the curtain-length or the hopper-length of the vessel from which the sand is discharged, the following applies:

$$B_{max} = 2\pi r_\infty + 2 \text{ x curtain-length} \qquad (7)$$

However most likely the mixture will not spread across the complete crater circumference B_{max}, but will concentrate in a channel.

On the above water fill area the mixture flow can be distributed by means of bulldozers across the full width of the fill area determined by bunds. This is not the case on the under water fill area and hence channel formation cannot be prevented here.
The width B of this channel determines the specific flow rate q and the specific sand production rate s and therefore the under water slopes.

Based on the regime theory, the minimum width of a channel normalized for jet diameter d, can be derived from (8) (for a round jet, hence for single point discharging in an under water fill area):

$$\frac{B_{min}}{d} = 0.6\sqrt{\frac{U}{U_c}} \qquad (8)$$

In which:

B_{min} = lower limit of spreading width of mixture (m)
d = jet diameter (m)
U = mixture flow velocity in centre of jet (m/s)
U_c = mixture flow velocity for which erosion occurs, (Shields: $U_c \equiv \sqrt{(\Delta g D_{50})}$) (m/s)

In fig. 5 this relation is plotted as a function of the flow velocity in the centre of the jet and the grain size diameter.

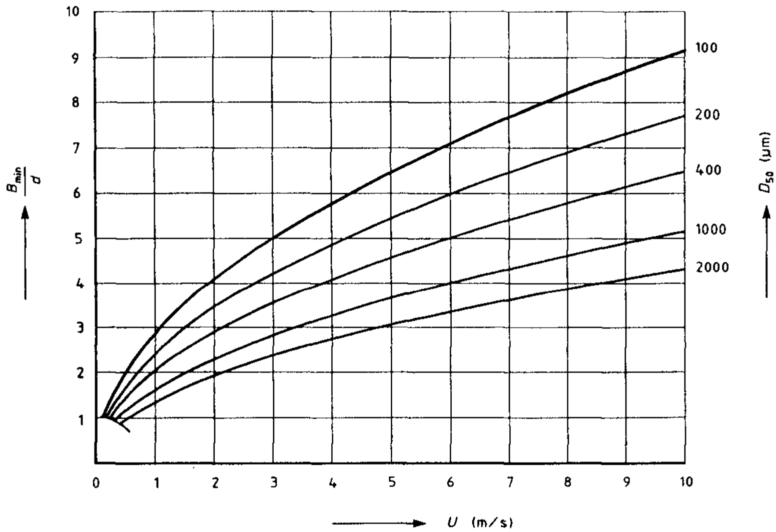


Fig.5. Minimum spreading width of mixture at overflow of crater edge.

7 Sedimentation and erosion processes

The extension of a hydraulically placed sand body is the result of sedimentation of sand from a sand-water mixture flow and in some cases the successive replacement of already deposited sand. These sedimentation and erosion processes can be determined in a quantitative way. In principle they are physically independent of each other. The net result can therefore be derived by superimposing the sedimentation- and erosion-velocity.

The sedimentation length is defined as the distance covered by the sand-water mixture flow before the volume concentration is reduced to 10% of the initial concentration. This sedimentation length can be read from fig. 6 as a function of the specific mixture flow rate, grain size and volume concentration. Because of the hindered settling effect, the sedimentation length is strongly influenced by the concentration.

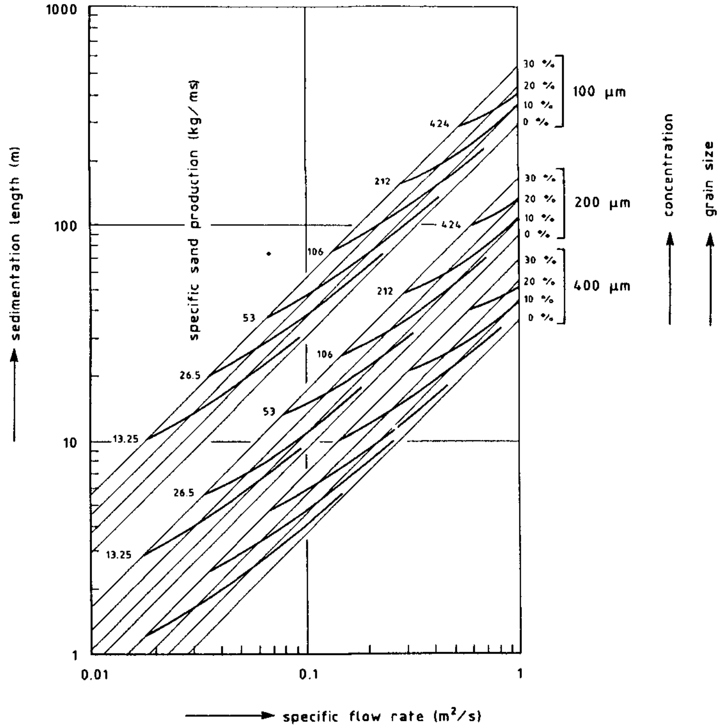


Fig.6. Sedimentation length as a function of specific flow rate, grain size and volume concentration.

8 Slope formation above water

The following bed-forms can be observed: terraces, cascades and channel formation.

Terraces and cascades

Terraces and cascades develop at moderate specific mixture flow rates of the order of 0.01 to 0.3 m^2/s (Winterwerp et al, 1992). The anti-dune like bed-form is composed of long, flat sloped terraces where the flow velocity is sub-critical and where sedimentation of sand takes place, see fig. 7. At the end of this terrace a steep cascade is present, where the flow velocity becomes super-critical and where erosion takes place. A hydraulic jump develops between this cascade and the next terrace at the transition of super-critical flow to sub-critical flow. Because of the erosion of the downstream side and sedimentation at the upstream side, the system of terraces, steps and cascades propagates slowly in upstream direction. A dynamic equilibrium situation can develop between sedimentation on the terraces and erosion on the cascades at a certain average bed slope.

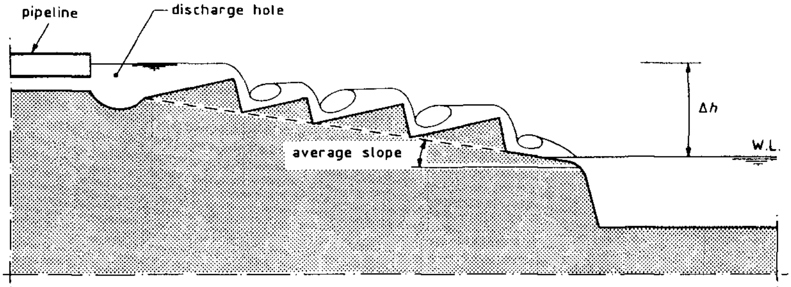


Fig.7. Terrace formation on fill above water level.

Channels
At high specific mixture flow rates the mixture concentrates in deep channels and the bed-form of terraces and cascades disappears.

Equilibrium slope above water level
The equilibrium slope is defined by the equilibrium between sedimentation and erosion. This slope is determined with field observations and large scale tilting flume tests as a function of the flow velocity, grain size and concentration (Winterwerp et al 1990). The following empirical formula for this equilibrium slope above water level could be inferred:

$$i=0.006\left(\frac{D_{50}}{D_0}-1\right)\frac{q^{-0.45}}{q_0} \qquad (9)$$

In which:
i = tangent of the average slope gradient (-)
D_{50} = medium grain size diameter (μm)
q = specific mixture flow rate (m^2/s)
D_0 = 65 μm
q_0 = 1 m^2/s

This equation was derived for specific mixture flow rates varying from 0.01 and 0.15 m^2/s and grain size diameters of respectively 120 and 225 μm. This relation is shown in fig. 8 together with the flume and field surveys. The equilibrium slope showed a strong relation with the specific mixture flow rate and the grain size. The concentration appears to be of minor importance, which can be explained by the effects of hindered settling.

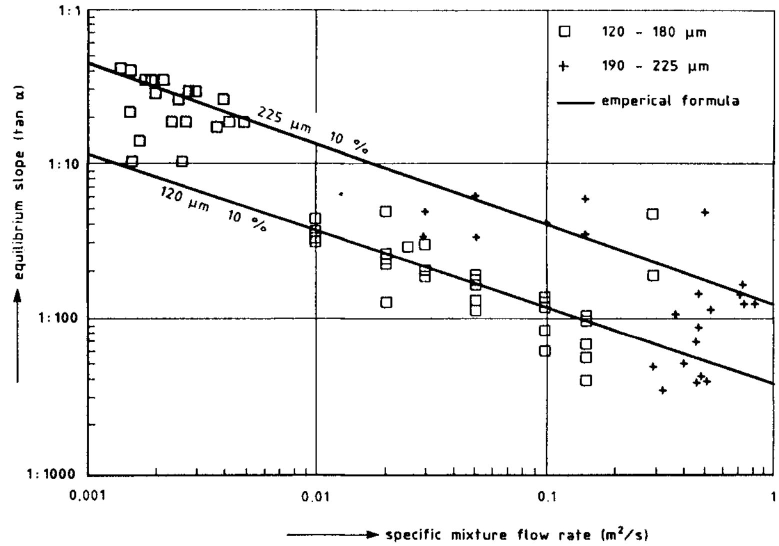


Fig. 8. Equilibrium slopes above water, results of flume tests and field observations and calculations using formula 9.

9 Slope formation under water

Compared to the circumstances above water, the soil mechanics properties of the sand body during sand placement under water have a much stronger influence on the development of the slope. Because the deposited sand is always very loosely packed, it is susceptible to liquefaction. Therefore under certain circumstances the slope of the sand body will not be stable and liquefaction may occur followed by a flow slide.
Whether flow slides occur directly after the sand has settled depends on the type of sedimentation. To predict which type can be expected depends on the sedimentation length (L), the critical slope height (h_{cr}) and the porosity (n).
The development of a sand slope under water is illustrated in figures 9a, -b and -c.

During hydraulic placement of sand at low to moderate specific sand production rates and with fine sand in shallow to fairly deep water, the development of the slope takes place in a discontinuous way. This has been observed during field surveys and during experiments in a large flume.
During the hydraulic placement of sand, sedimentation takes place within the first metres of the slope after the sand body has reached the water surface. It then starts to develop in horizontal direction. The slope

increases locally which may result in a critical situation and a flow slide. See fig. 9a. Sedimentation again takes place on the resulting flat slope. The alternating increase and decrease of the slope caused by sedimentation and flow slides, is a continuous process. The flow slides are now the dominating factor for the transportation of sand to the toe of the sand body.
For coarser sand and for the same low specific sand production rates and shallow water, however, flow slides will be observed less readily even when the sand is very loose and the porosity of the deposited sand is well beyond the critical value.
It was found that for horizontal slope development a critical slope height exists. Beyond this critical height flow slides occur. For coarse sand this critical slope height is larger than for fine sand. The values for h_{cr} are based on experience with the construction of sand fills with grain sizes between 100 and 500 μm. The critical slope height can be approximated by:

$$h_{cr} = 0.075D - 8.5 \quad (120\ \mu m < D < 500\ \mu m) \qquad (10)$$

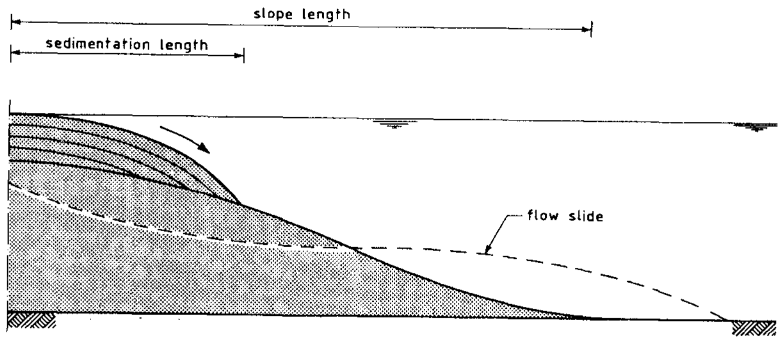
In which:
h_{cr} = critical slope height (m)
D = grain diameter (μm)

For $h < h_{cr}$ the under water sand slope increases up to a certain steep equilibrium angle. The development of the slope takes place in a very regular way and a kind of equilibrium situation establishes, see fig. 9b.

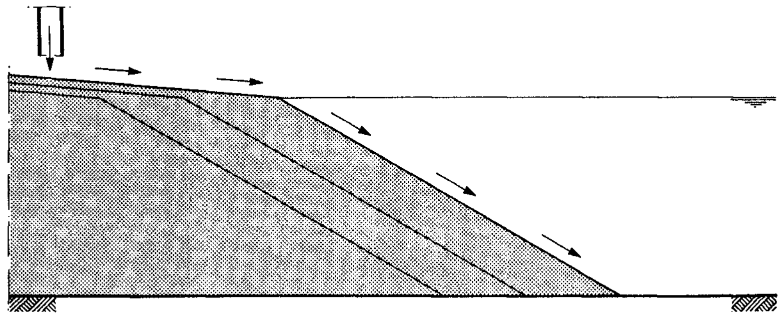
For high specific sand production rates (s > 25 kg/ms) a turbulent suspension flow will occur, for fine sand as well as for coarse sand, with hydraulic jumps propagating continuously in the upstream direction. This process is very similar to the type of mixture flow above water.
The suspension flow can extend far beyond the toe of the slope resulting in a decreasing under water slope. See fig. 9c. Although flow slides may be present these do not constitute a prevalent sand transport mechanism.

Equilibrium slope below water level
No unique value can be established for the slope of a hydraulically placed sand body because of the alternating increase and decrease of the slope. Flow slides or breach processes, if present, define the minimum slopes. The average under water sand slope is mainly defined by the grain size and the specific sand production rate.
Average under water slopes observed during the hydraulic placement of sand of various projects are shown in fig. 10 as a function of the specific production rate (s) and

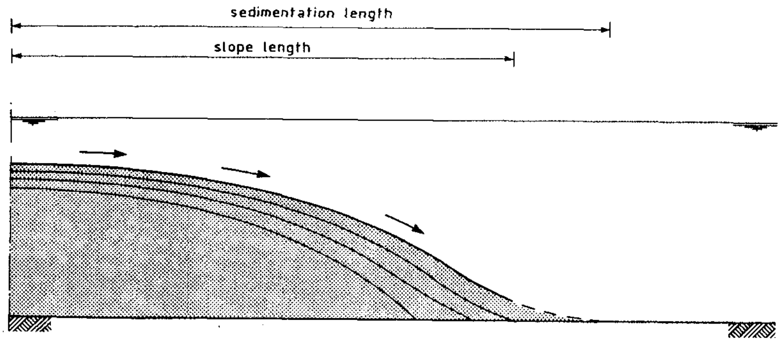
grain size. The results of flume tests with fine and medium coarse sand are given for various sand production rates, as well as the results of previously performed small scale flume tests. Since all types of measurements are collected a wide scatter is the result.



a) Small specific sand production rates; increasing slope and beginning of flow slides.



b) Constant slope.



c) High specific sand production rates; decreasing slope.

Fig.9 Development of under water sand slopes.

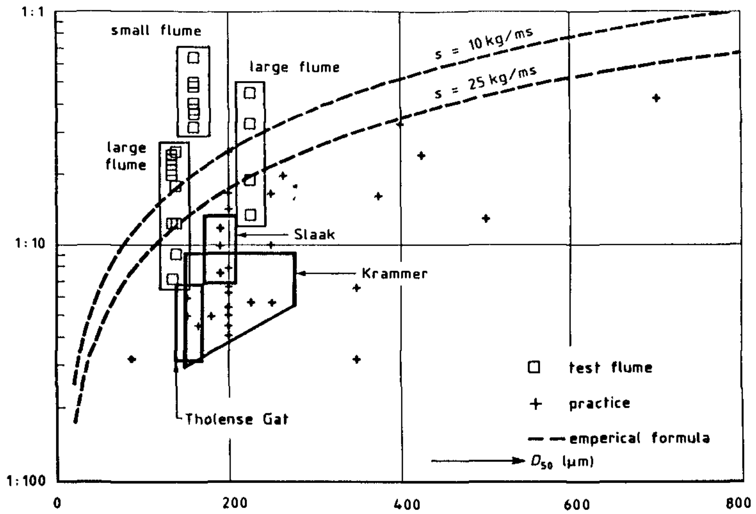


Fig.10. Underwater sand slopes measured in the field and in the laboratory as a function of D_{50}.

The following empirical formula applies to the average under water slope (i) when no flow slides occur:

$$i = 0.0032D.s^{-0.4} \qquad (11)$$

In which:
D = grain size (µm)
s = specific sand production rate (kg/ms)

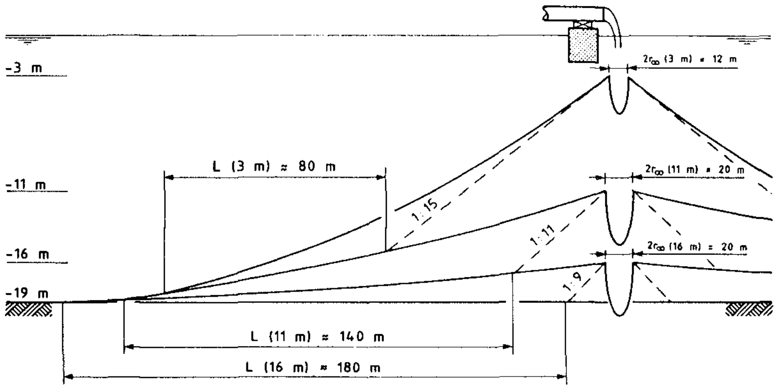


Fig.11 Building up of the artificial island Issungak for hydraulic discharging from the water surface.

It can be read from fig. 10 that in the field often flatter slopes are observed than according to formula (11). These are always practical situations for which flow slides govern the slope formation. In these cases it is recommended not to use formula (11) but to estimate the slope on the basis of the indicated field observations.

10 Prediction of sand fill dimensions

Typical computational results for the building up of an artificial island at varying discharge heights are shown in fig.11 and table 1.

Table 1 Crater dimensions and sedimentation length for discharging from the water surface (Issungak).

magnitude	unit	fall height 19 m	fall height 11 m	fall height 3 m
crater width $2r_\infty$	m	10-40	8-30	5-20
specific flow rate q	m^2/s	1.8-2.4	1.4-1.7	0.45-1.1
specific sand production rate s	kg/ms	45-200	70-350	170-550
sedimentation length L	m	150-250	120-170	50-130
equilibrium slope tan α	(-)	1:7-1:12	1:8-1:14	1:11-1:17

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