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Morphology of Pits, Channels and Trenches

Part I: Literature Review and Study Approach

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Contents

1 Introduction

For several years the large-scale mining of sand from the Dutch Sector of the North sea is in discussion related to the need of sand for shoreface, beach and dune nourishment and large-scale engineering works at sea (Maasvlakte extension, airport at sea). The mining methods considered basically fall into two categories: wide, shallow or small, deep mining pits. Presently, shallow pits not deeper than about 2 m are excavated beyond the 20 m depth contour to obtain sand for beach nourishments. Deep mining pits have not yet been made extensively. A temporary pit with a depth of about 20 m (below surrounding bed surface) has been excavated close to the shore in a water depth of about 10 m, but this pit was refilled shortly (a few months) after construction to prevent damage to the coastal system (Punaise project).

The mining of sea sand will affect both the ecology and morphology of the coastal system. The ecology is affected in the sense that the flora and fauna of the system is destroyed by the mining activities, whereas also the release of very fine sediments (silt and clay) from the bed into the water column may have a direct influence on the ecological system. The local bed fauna is almost completely destroyed by the mining activities. This also has a direct negative effect on all living creatures which are for their food dependent on the bed fauna. The recovery period of shallow mining areas is of the order of 5 years, but the recovery period may increase considerably with increasing excavation depth (dead water zone at bottom of deep pit). Additional negative effects may occur due to increase of the turbidity of the water phase above the bed due to fines from the bed layers brought into the water phase by the mining activities (stirring).

The morphology is affected in the sense that locally the bed level is lowered substantially in the form of a borrow pit (or channel), which may influence the local flow and wave fields and hence the sand transport rates due to modification of shoaling, refraction and reflection patterns. The pit area (slopes) may migrate towards the shore over time and/or may act as a sink (trapping) for sediments from the nearshore system. On long term (100 years) the area of influence may extend over tens of km's outside the original mining area. Furthermore, the small-scale and large-scale bed forms (from megaripples to sand waves) may be destroyed locally, which may also have an effect on the hydrodynamic system (less friction and turbulence). Various studies of the morphological consequences of sea sand mining have been performed, but most of these consequences can not yet be fully overseen and further studies are required to line up the positive and negative effects of sea sand mining, so that a rational decision with respect to location and quantity of future sea sand mining can be made. This literature review presents an overview and inventory of the most relevant studies performed up to now, covering:

- regulations on sea sand mining (Chapter 2),
- morphodynamics of offshore mining areas (Chapter 3),
- sediment transport and ecological processes in marine conditions (Chapter 4),
- mathematical description of sediment transport and available models (Chapter 5),
- data sets and hindcast studies (Chapter 6),
- mathematical studies related to pits in the North Sea (Chapter 7).

Finally, recommendations for additional research efforts are given and discussed in Chapter 8. This chapter also contains an outline of the study approach for the subsequent phases of the present project in Section 8.2.

The study has been done within the Cooperation Framework of Rijkswaterstaat/RIKZ and Delft/Hydraulics for Coastal Research (VOP Project 2).

2 Regulations for mining of sand in Dutch sector of North Sea

2.1 Introduction

Concessions for the mining of sea sand in the North Sea are bound to regulations. Points of attention in formulating these regulations are:
- ecology (bottom fauna, algae, bird habitat)
- dispersion of mud,
- morphology of shoreface and coastline,
- morphological interaction with existing and future engineering works (navigation channels to ports of Rotterdam and Amsterdam, pipelines, Maasvlakte extension, airport in sea, etc.).

2.2 Mining regulations

Regulations on mining activities in the Dutch Sector of the North Sea are formulated in: “Regionaal Ontgrondingsplan Noordzee” 2 (RON 2). These regulations mainly concern mining depth and mining area in relation to the water depth on the mining location. The maximum mining depth for the present mining activities is 2 m. In the present report, only the regulations for deep sand mining pits (deeper than 2 m) are considered. For these deep pits, the following regulations are given (p. 48 and 49 of RON 2):
- sand mining in deep pits, outside the NAP - 20 m depth contour is conditionally allowed if the presence of sufficient amounts of course sand is made plausible first.
- At granting a permit, a monitoring program, aimed at the effects of the mining activities may be required;
- inventory of the environmental effects of the proposed mining activities (EIA).

No specific regulations with regard to the maximum mining depth are given in the RON 2 document. The maximum depth is restricted in the sense that irreversible negative effects on the environment are not allowed. Some criteria given for the maximum depth, are:
- the new surface sediments should not deviate too much from the original ones;
- at the bottom of the pit no reduction of the water exchange is allowed, in order to prevent reduction of the oxygen content;
- ecological recovery of the mining region within a reasonable amount of time (say 10 years).

3 Morphodynamics of offshore mining areas

3.1 Transport processes and morphological evolution

Backfilling process

The morphological behaviour of a deepened mining area (pit, channel, trench) in coastal flow (with or without waves) shows the following basic features, depending on the orientation of the pit to the flow direction.

The following three cases are herein distinguished (Figure 3.1.1):

- **Unidirectional flow perpendicular or oblique to the main channel/pit axis:** deposition at the upstream slopes and erosion of the downstream slopes of the pit resulting in migration of the deepened area in the direction of the dominant flow (mainly bed load transport); deposition in the deeper area of the pit by reduction of the sand transport capacity (mainly suspended load transport);
- **Tidal flow perpendicular or oblique to the main channel/pit axis:** erosion of both side slopes due to bi-directional flow; deposition in the deeper area of the pit by reduction of the sand transport capacity (mainly suspended load transport);
- **Tidal flow parallel to the main channel/pit axis:** flattening of the slopes by transport of sediment from the slopes into the deeper area of the pit by gravitational slope effects (mainly bed load transport in parallel flow).

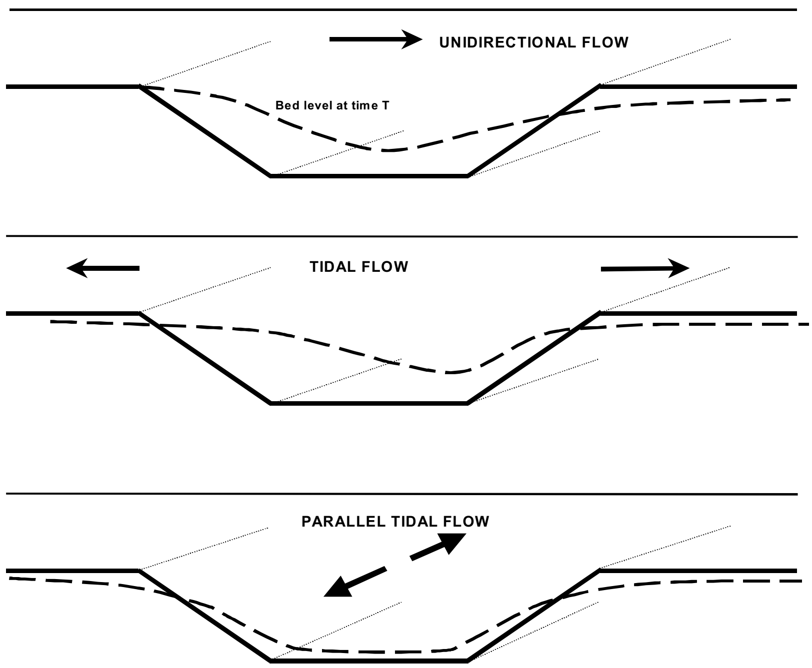


Figure 3.1.1 *Morphological development of channel*
Top: Migration in unidirectional flow perpendicular to main axis
Middle: Deposition and erosion in tidal flow perpendicular to main axis
Bottom: Flattening of slopes in tidal flow parallel to main axis

When a current passes a pit or channel, the current velocities decrease due to the increase of the water depths in the pit or channel and hence the sediment transport capacity decreases. As a result the bed-load particles and a certain amount of the suspended sediment particles will be deposited in the pit. The settling of sediment particles is the dominant process in the downsloping (deceleration) and in the middle section and of the pit. In the case of a steep-sided pit with flow separation resulting in the generation of additional turbulence energy, the settling process may be reduced considerably. In the upsloping (downstream) section of the pit the dominant process is sediment pick-up from the bed into the accelerating flow, resulting in an increase of the suspended sediment concentrations. The most relevant processes in the deposition and erosion regions are: convection of sediment particles by the horizontal and vertical fluid velocities, mixing of sediment particles by turbulent and orbital motions, settling of the particles due to gravity and pick-up of the particles from the bed by current and wave-induced bed-shear stresses. The effect of the waves is that of an intensified stirring action in the near-bed region resulting in larger sediment concentrations, while the current is responsible for the transportation of the sediment. The stirring effect diminishes with increasing water depth. Thus, this effect is less important in the pit itself. These processes are schematically shown for cross flow over a long, narrow channel in Figure 3.1.2.

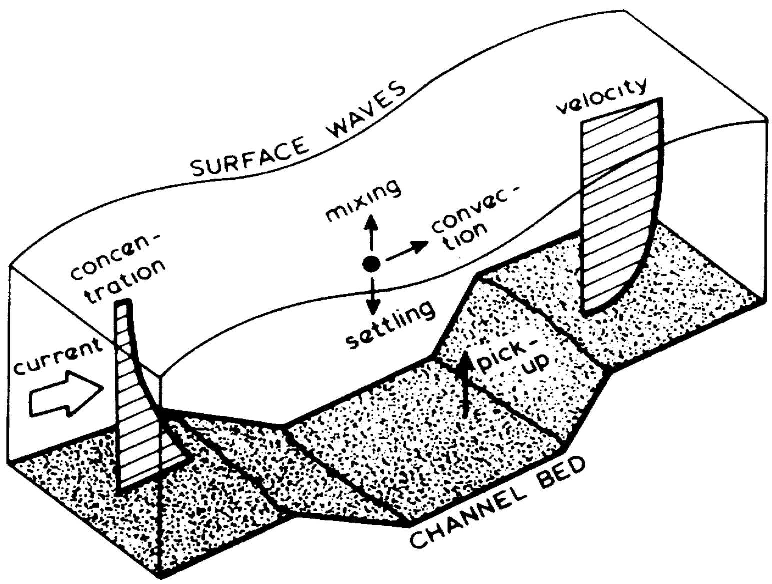


Figure 3.1.2 *Sediment transport processes in a channel perpendicular to the flow*

In case of oblique flow over a channel/pit the sediment transport in longitudinal direction may increase considerably with respect to the undisturbed longitudinal transport outside the channel. Jensen et al. (1999) reports an increase of a factor 2 for an approach angle of 45^o.

In case of flow parallel with the channel axis, the side slopes of the channel are flattened and smoothed due to gravitational effects. When a sediment particle resting on a side slope is set into motion by waves or currents, the resulting movement of the particle will, due to gravity, have a component in downwards direction. By this mechanism sediment material will always be transported to the deeper part of the channel yielding reduced depths and smoothed side slopes. These effects are particularly important in conditions with a relatively narrow channel and flow parallel to the longest axis of the channel.

The prediction of sedimentation in mining pits (backfilling) basically consists of two elements:

- sediment transport carried by the approaching flow to the channel, depending on flow, wave and sediment properties;
- trapping efficiency of the pit, depending on pit dimensions, channel orientation and sediment characteristics.

Effect of sand waves

Sand waves can affect the behaviour of navigation channels in two ways:

- generation of sand waves inside the channel thereby reducing the depth;
- sand waves and shoals on bed just outside channel and migrating towards the pit causing infill of the pit.

Katoh et al. (1998) studied the generation and migration of sand waves over a shoal inside a navigation channel (Bisanseto channel, Japan). The sand waves had a height of about 5 m and a length of about 100 m and were most pronounced and mobile in depths of about 15 to 25 m. The crestlines of the sand waves are essentially normal to the direction of the predominant tidal currents. The bed consisted of sand in the range of 0.5 to 2 mm. The sand wave crests were removed in the period 1981-1983 by dredging to obtain a larger depth for navigation (dredged volume of about 2 million m^3). During a period of 10 years after dredging the sand wave pattern was restored similar to the initial situation. Based on analysis of regular sounding data, the following observations were derived:

- gradual reduction of the mean depth (spatially averaged) in the most shallow area of the shoal (depths of 15 to 20 m) by about 0.7 m over 10 years over an area of about five wave lengths due to sand transport towards the shallow part of the shoal;
- gradual increase of the sand wave height by about 3 m over a period of 10 years (reduction of minimum depth);
- sand wave migration (about 5 m/yr in depths of 25 to 30 m up to 15 m/yr in depths of 15 to 25 m) from both sides of the shoal towards the most shallow part of the shoal in the direction of the predominant currents.

Katoh et al. suggest to perform pocket dredging at intermediate depths to intercept the transport of sands to the shallow part of the shoal.

Effect of mud

In muddy conditions, high concentrations of mud in suspension with accompanying high settling rates and relatively thick deposits may exist along the bed. These deposits appear to be due to the deposition of fluid mud flocs convected into the region from both upstream and downstream as a result of drifts near the bed. These drifts can be set up by wave-driven forces, and/or horizontal density gradients induced by differences in salinity between the fresh water flow and sea water. The vertical distribution of the sediment concentrations can be characterized as a three-layer system with clear interfaces (lutoclines), as follows (Van Rijn, 1993):

- consolidated mud at the bottom with concentrations largber than about 300 kg/m^3; flocs and particles are supported by drag forces exerted by the escaping fluid (hindered settling effects);
- mobile (fluid) mud suspension layer (0.1 to 1 m) with concentrations in the range between 10 and 300 kg/m^3; the fluid mud can be transported by tide-, wind-, wave- and gravity-driven forces (near-bed drift velocities of 0.05 to 0.5 m/s);
- mobile dilute mud suspension (up to water surface) with concentrations in the range between 0.1 and 10 kg/m^3; the flocs and particles are supported by turbulence-induced forces; the mud suspension can be transported by tide-, wind-, wave-driven forces (velocities of 0.3 to 1 m/s)

When the sea bed contains relatively large muddy and silty sediment fractions, cohesive forces become important. Generally, the strength of the consolidated soil against erosion increases depending on the type of clay minerals, the presence of organic materials, the stage of consolidation, etc. Flume experiments show that the sand concentrations are significantly reduced (factor 30) in conditions with wave motion over a bed consisting of 25% mud and 75% sand compared to the sand concentrations above a 100% sand bed (Van Rijn, 1993). The stage of consolidation of the mud bed is an important factor in the erodibility of the bed material. Fresh mud deposits have a very loose texture of mud flocs which already have a low density themselves. The wet bulk density of fresh mud deposits is in the range of 1050 to 1100 kg/m^3 (95% water). The cohesive forces in fresh deposits are still very low and the material can easily be eroded. The density of fresh deposits gradually increases as interstitial water is pressesd out by gravity forces. This process of consolidation initially goes relatively fast, but gradually slows down. The strength against erosion increases with increasing consolidation and density.

Wave action over a muddy bed may generate a high-concentration fluid mud layer close to the bed. The sediment concentrations in this layer may be of the order of 100 to 300 kg/m^3. The sediment concentrations above this layer generally are an order of magnitude smaller. Tide-driven, wave-driven, wind-driven or gravity-driven (on slopes) currents are able to transport the fluid mud layers towards the channel resulting in excessive deposition on short term time scales (storms, monsoon waves). A fluid mud layer with a thickness of 0.1 m, a concentration of 100 kg/m^3 and a horizontal velocity of 0.1 m/s, yields a transport rate of 1 kg/m/s or 0.002 m^3/m/s (assuming a dry bulk density of 500 kg/m^3), which is equivalent to about 175 m^3/m/day. Thus, a channel with a cross-section of 1000 m^3/m will be completely filled in about 5 to 6 days (storm time scale) by fluid mud carried into the channel.
Information on modelling of fluid mud transport is given by Odd and Cooper (1989), Kranenburg and Winterwerp (1997), Ali et al., (1997) and Winterwerp et al. (2002).

Recent studies (Winterwerp, 1999, 2001, 2002) suggest that the formation of fluid mud from suspensions of cohesive sediments in depressions in the sea bed (channels or pits) or in harbour basins is the result of supersaturation of the suspension, that is that the transport capacity of the flow is exceeded. These studies also suggest that the generation of fluid mud already takes place at relatively small concentrations (< 1 kg/m^3). Winterwerp et al. (2001) estimate that the saturation concentration in the Dutch coastal zone amounts to a value in the range of 0.1 to 0.5 kg/m^3. The saturation concentration C_s scales more or less with:

$C_s \approx \rho\ U^3/((s\text{-}1)g\ h\ w_s)$ where ρ= water density, s-1= relative sediment density, g= gravity acceleration, U= flow velocity, h = water depth and w_s= setting velocity.
Measurements performed at anchor stations a few km's offshore in the vicinity of the Euro-Maas Channel, carried out in the framework of the SITLMAN project, revealed depth-mean suspended sediment concentrations up to 0.5 kg/m^3 during storm conditions, with occasional near-bed concentrations during slack water exceeding 20 kg/m^3 (Kok, 2000). Simulations with a mathematical point model made it plausible that these suspensions may collapse under certain conditions, leading to the formation of a turbidity current and deposits of fluid mud (Winterwerp et al., 2001; Winterwerp and van Kessel, 2002).
The transport capacity (or saturation concentration) in a 20 m deep sandpit, located at 20 m water depth, would decrease by a factor 5 to 10 as a first estimate, assuming a decrease in velocity proportional to the increase in cross section (continuity considerations). This would imply that fluid mud may already be formed in such pits at concentrations of about 0.05 kg/m^3. Assuming a fluid mud concentration of 100 kg/m^3, such a suspension would yield a fluid mud thickness in the range of 0.01 to 0.02 m. Hence, these sediment deposits may become significant due to accumulation in time. If the hydrodynamic conditions favour the formation of such fluid mud layers, it is not likely that the tidal flow will be able to re-erode these deposits. However, waves may do so– whether this will occur is not known at present. If these layers are not eroded anymore, they will consolidate, resulting in bed concentrations in the range of 100 to 500 kg/m^3.

At present, the occurrence of saturation conditions, and the subsequent formation of a turbidity current and layers of fluid mud can be simulated with the DELFT3D model system (Winterwerp and van Kessel, 2002). Also the movements of the fluid mud layers themselves and their possible erosion or entrainment by flow and/or waves can be computed with the DELFT3D-fluid-mud model.

3.2 Currents

The influence of the deepened area (pit) on the local current pattern (tide and wind driven) is determined by the:

- pit dimensions (length, width, depth),
- angle between the main pit axis and direction of approaching current,
- strength of local current,
- bathymetry of local area (shoals around pit).

Generally, the dimensions of the deepened area are so small that there is no significant influence of the deepened area on the macro-scale current pattern. In most cases the current pattern is only changed in the direct vicinity of the area concerned.
Basically, three situations can be distinguished:

1. Main channel/pit axis parallel to current

When the deepened area is situated parallel to the local current, the velocities in the deeper zone may increase considerably due to the decrease of the bottom friction, depending on the length and width of the deeper zone. Just upstream of the channel, flow contraction will occur over a short distance yielding a local increase and decrease of the flow velocity (order of 10% to 20%, depending on channel width W and upstream flow depth h_o). Flow contraction will be minimum for $W>>h_o$. The flow velocity in the contraction section can be estimated from ($h_1>h_o$):

$$u_{con}=[2h_o/(h_o+h_1)]u_o \qquad (3.2.1)$$

The length of the contraction section is of the order of the channel width W. Similarly, flow contraction will occur just before the downstream end of the channel. The flow velocity distribution along the main axis of the channel is shown schematically in Fig. 3.2.1.

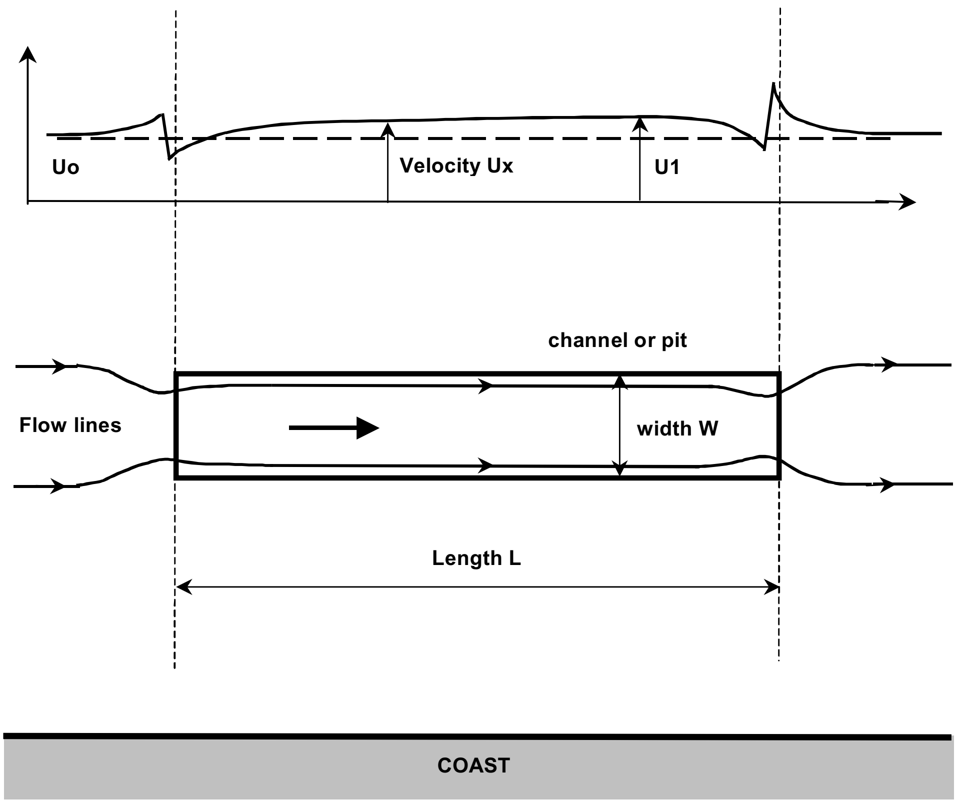


Figure 3.2.1 *Main channel/pit axis parallel to current*

Assuming the water surface slope to be constant, the equilibrium flow (u_1) inside the channel can be described by the Chézy equation, yielding the following far-field expression ($h_1>h_o$):

$$u_1=u_o(C_1/C_o)(h_1/h_o)^{0.5} \qquad (3.2.2)$$

with u_1=equilibrium flow velocity inside channel and u_o= equilibrium flow velocity upstream of channel, h_1= water depth in channel. Generally, the flow inside the channel is somewhat larger than outside the channel ($u_1>u_o$), except when the length of the channel is relatively small (L<2W). The adjustment length λ of the flow to the new equilibrium value inside the channel is of the order of $C_1^2h_1/(2g)$, yielding values of 3 to 4 km (De Vriend, 1996). The exponential adjustment process can be expressed as:

$$u_x^2=u_l^2+(u_o^2-u_l^2)e^{-x/\lambda} \quad (3.2.3)$$

Generally, the new equilibrium flow velocity in the channel is reached for L>10W and W>>h_o.

2. Main channel/pit axis perpendicular to current

When the deepened area is situated perpendicular to the local current, the velocities in the deeper zone are reduced due to the increased water depth. This influence is most significant in the near-bed layer of the deceleration zone where adverse pressure gradients are acting, causing a strong reduction of the flow. In case steep side slopes (1:5 and steeper) flow separation and reversal will occur introducing a rather complicated flow pattern. The velocities in the recirculation zone are small compared with those in the main flow. The flow velocities in the near-water surface layers are hardly influenced by the presence of the channel (inertial effect).
The depth-averaged flow velocity inside the channel (u_l) can be determined from the continuity equation (q is constant):

$$u_l=u_o(h_o/h_l) \quad (3.2.4)$$

The layer between the near surface region and the recirculation region is dominated by production of turbulence energy (mixing layer). When the deepened area is wide enough, the flow will reattach at the end of the downsloping side, as shown in Fig. 3.2.2. More uniform velocity profiles will be present at the upsloping (downstream) side of the channel. In case of a narrow channel the flow pattern will be completely dominated by flow separation and flow reversal phenomena. Most probably, a large vortex will generated in the channel. Detailed mathematical studies have been done by Alfrink and Van Rijn (1983) and recently by Jensen et al. (1999). The latter studied the morphological behaviour of small scale, steep-sided pipeline channels using a full 3D model for oblique flow conditions. The flow in these types of channels can only be described by a detailed 3D model as the flow pattern is strongly dominated by the flow separation zone in the steep-sided channel, often extending onto the downstream side slope. The separation zone is largest for an approach angle of 90° but becomes weaker for smaller angles.

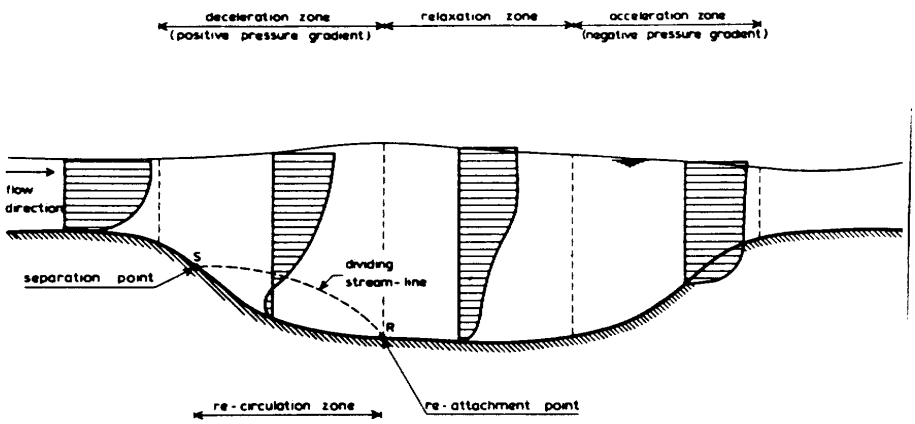


Figure 3.2.2 *Channel perpendicular to current*

3. Main channel/pit axis oblique to current

When the deepened area is situated <u>oblique</u> to the local current, the effects of parallel and perpendicular flow patterns are occurring simultaneously. The velocity component perpendicular to the channel is inversely proportional to the local water depth, while the velocity component parallel to the channel may increase due to a reduction of bottom friction. As a result, the streamlines show a refraction-type pattern in the channel (see Fig. 3.2.3). This effect is more pronounced in the bottom region where the velocities are relatively small. Usually, there is an overall increase of the velocities in the channel when the angle α_o between the approaching current and the channel axis is smaller than about 20^o to 30^o, depending on channel dimensions and bottom roughness.
The equilibrium (depth-averaged) flow velocity vector in the channel v_1 can be estimated as (Jensen et al., 1999):

$$v_1 = v_o \, [(h_o \sin\alpha_o)/(h_1 \sin\alpha_1)] \qquad (3.2.5)$$

with v_o=equilibrium approaching flow velocity, h_o=water depth upstream of channel, h_1=water depth in channel, α_o=approach angle, α_1= equilibriun angle in channel (Jensen et al., 1999). The equilibrium values will be reached if the cross channel width W is larger than approximately $500h_o$, ($W>500h_o$). The equilibrium flow velocity will exceed the upstream velocity if the channel depth is relatively large and the approach angle is relatively small ($<30^o$).

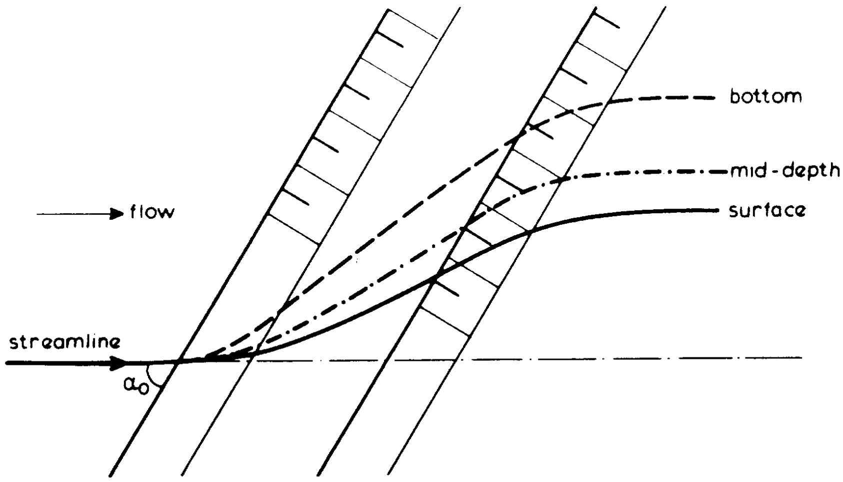


Figure 3.2.3 *Channel parallel to current*

Physical model studies have been performed at the Hydraulic Research Station Wallingford (HR Wallingford, 1973) and at Delft Hydraulics (Boer, 1985). The tests at HRS Wallingford were conducted in relatively wide channels inclined to the current at angles of 0^o to 30^o. The water depth on the banks ranged from 0.015 to 0.1 m and the difference in the depth between the channel and the banks was 0.02 m. Based on these results, it can be concluded that for angles smaller than 30^o, the velocity in the channel is generally larger than that outside the channel.
The tests at Delft Hydraulics were conducted in relatively wide channels inclined to the flow at angles of 45^o to 90^o. The water depth outside the channel ranged from 0.1 to 0.2 m. The

difference in depth between the channel and the banks was 0.1 m. In all cases, the measured velocities inside the channel were smaller than those outside the channel. Boer (1985) has shown that the depth-averaged velocity in an oblique channel of infinite length can be computed by the following relatively simple mathematical model.

Continuity: $\partial(hu)/\partial x=0$ (3.2.6)

Motion: $u\partial u/\partial x + \tau_{b,x}/(\rho h) + g\partial(h+z_b)/\partial x=0$ (3.2.7)

$u\partial v/\partial x + \tau_{b,y}/(\rho h) + g\partial(h+z_b)/\partial y=0$ (3.2.8)

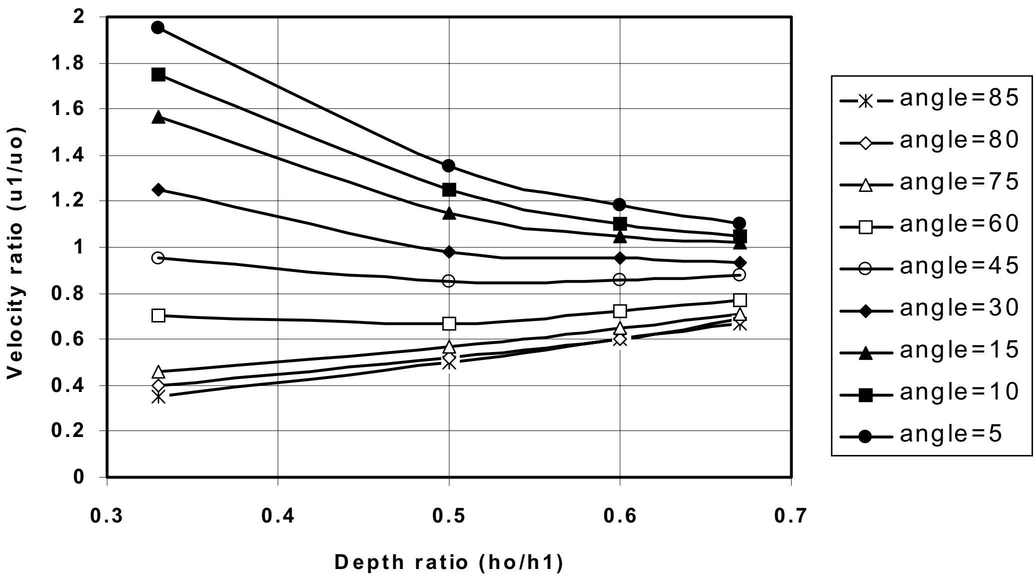
with: u, v= depth-averaged velocities in x, y directions, h= water depth, z_b= bed level to datum, τ_b= bed shear stress, x= coordinate normal to channel axis, y= coordinate parallel to channel axis, ρ= fluid density.

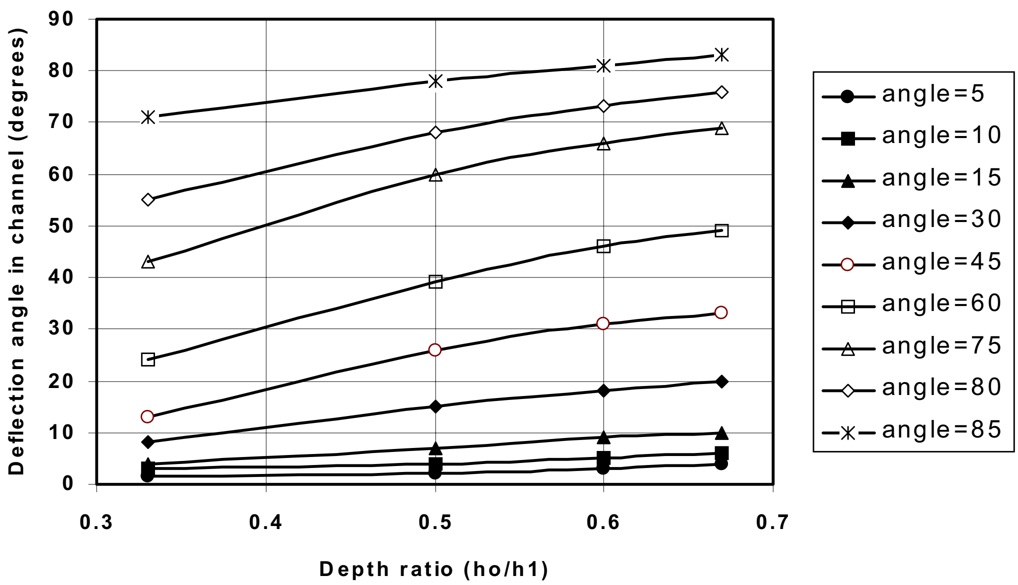
Based on a numerical solution of this set of equations, Boer has presented design graphs for the current velocity and deflection angle in the middle of a channel oblique to the flow (Fig. 3.2.4). The water depth outside the channel is in the range between 2.5 and 10 m. The channel depth with respect to the surrounding bottom is 5 m. The side slopes of the channels are 1 to 10. The bottom width is 200 m. The approach velocity is 2 m/s. The bed roughness is k_s= 0.1 m. Figure 3.2.4 shows that $u_1>u_0$ for approach angles < 15^o.

Jensen et al. (1999) has studied the oblique flow over a channel using a 3D mathematical model (rigid lid approach), including a 3D turbulence model (K-Epsilon model). The equations are transformed onto a curvilinear coordinate system and solved using the finite volume method. The model was verified using the experimental results of HR Wallingford (1973). The model was found to satisfactorily represent the effect of refraction increasing towards the bottom.

Figure 3.2.5 shows the refracted streamlines for two situations. The streamlines represent the paths of three fluid particles released at three different heights above the bed (just above the bed, at mid-depth and near the water surface). The streamline near the bed has the largest deflection. The variation of the current refraction (deflection) over the vertical may be seen as a secondary motion coexisting with the depth-averaged flow. The strongest secondary motion (strongest fraction effect) occurs for approach angles in the range of 60^o to 80^o. In that case the difference between the depth-averaged flow angle and the angle of the bed-shear stress reaches values up to 30^o.

In Figure 3.2.5 a fourth streamline is shown for a fluid particle inside the flow separation zone. The slope of the channel is relatively steep; thus a large separation zone is generated. The fluid particle inside the separation zone is carried in the longitudinal direction of the channel.





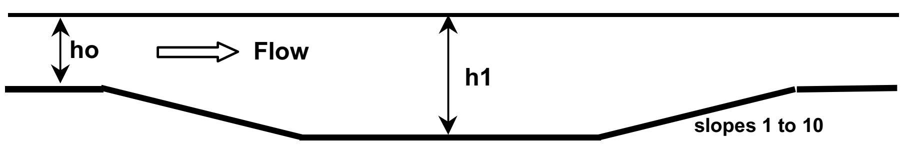


Figure 3.2.4 *Velocity and deflection angle in middle of channel for oblique flow*
h_0=water depth outside channel; h_1= water depth inside channel;
u_0=depth-averaged velocity outside channel;
u_1=depth-averaged velocity in middle of channel

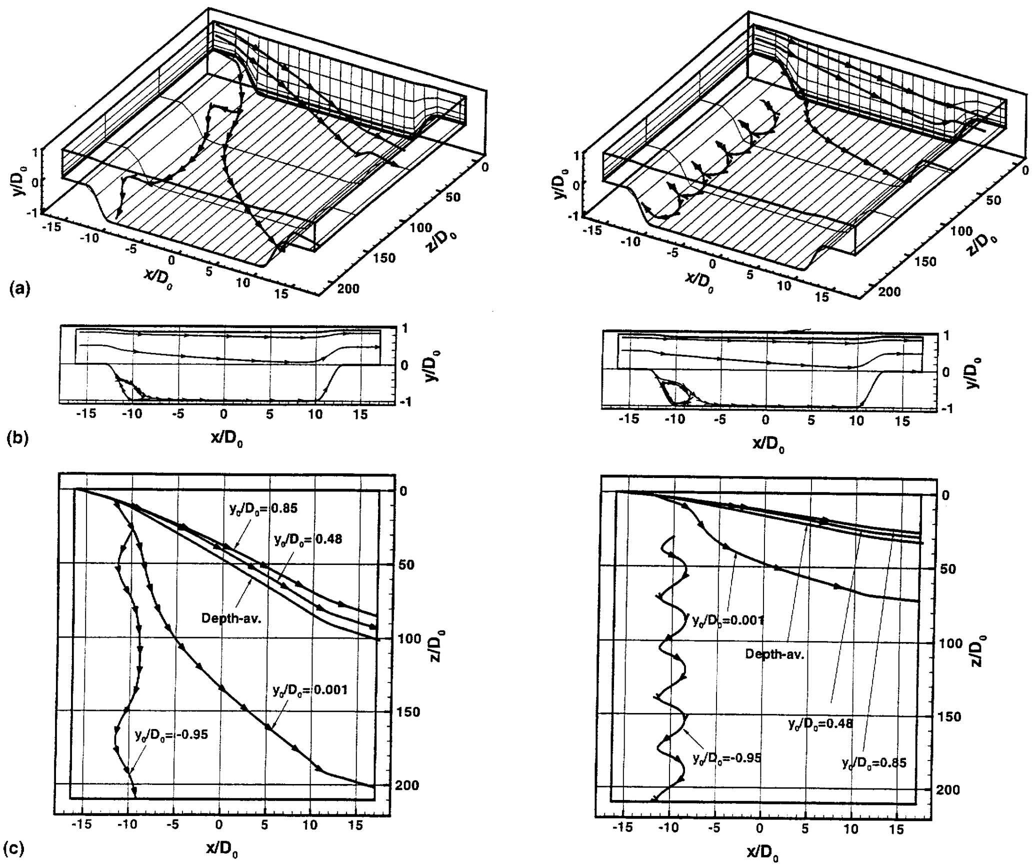


Figure 3.2.5 *Visualisation of refracted streamlines;*
Ratio of depth in channel (D_1) and depth outside channel (D_0)=2;
Ratio of channel width (W) and depth outside channel (D_0) =23
Left: Approach angle=30^o
Right: Approach angle=60^o

3.3 Waves

Waves are important for the sediment transport processes due to the stirring action of the orbital fluid motions on the sediment particles. This effect is most pronounced in shallow depths where the wave motion penetrates to the sea bottom. Wave motion in the nearshore zone is influenced by refraction, diffraction, shoaling, and energy dissipation by wave breaking and bottom friction. Wave breaking in the nearshore zone may result into the generation of additional currents. Waves breaking outside the channel results in a wave-induced set-up on both sides of the channel generating a flow towards the channel. Due to the presence of the coast the flow in the channel will be deflected in offshore direction (similar to rip currents, see Fig. 3.3.1).

Three situations of wave propagation over the channel are herein distinguished:

1. Main channel/pit axis parallel to waves
When the waves are propagating parallel to the main axis of the deepened area, the wave height in the deeper area will be reduced somewhat due to the increased water depth. The wave celerity will increase in the deeper area yielding curved wave crests. Wave energy on the side slopes will be reduced by diffractional effects. Waves with a very small approach angle entering the deeper area will be refracted out of the area, see Figure 3.3.1.

2. Main channel/pit axis perpendicular to waves
When the waves are propagating perpendicular to the main axis of the deepened area, the wave height in the deeper zone will reduce due to the increased depth. Secondary effects are reflection phenomena at the edges of the side slopes. This effects are however of minor importance for gentle side slopes (less than 1:7).

3. Main channel/pit axis oblique waves
When the waves are propagating oblique to the main axis of the deepened area, shoaling and refraction effects will occur and a rather disturbed wave pattern may be generated above the deeper zone depending on the depth and wave approach angle. In case of a relatively small approach angle, the incoming waves may be trapped (refracted/reflected backwards) on the slope of the deepened area resulting in a significantly smaller wave height in the deepened area, see Figure 3.3.1. A cross wave pattern consisting of incoming and outgoing waves will be generated outside the channel. The critical wave approach angle (with respect to the channel axis) is about 25^o to 30^o for wave periods of 7 to 9 s, depths of 15 to 20 m, side slopes of 1 to 7 and channel depth of 5 to 10 m. Incoming waves with an approach angle larger than the critical value will cross the deeper area; the wave direction of the waves leaving the channel will more or less the same as that of the incoming waves due to compensating refractional effects on both side slopes (in case of a relatively narrow channel, Fig. 3.3.1). Linear or weakly non-linear wave theory can be used to estimate these effects for each particular case.

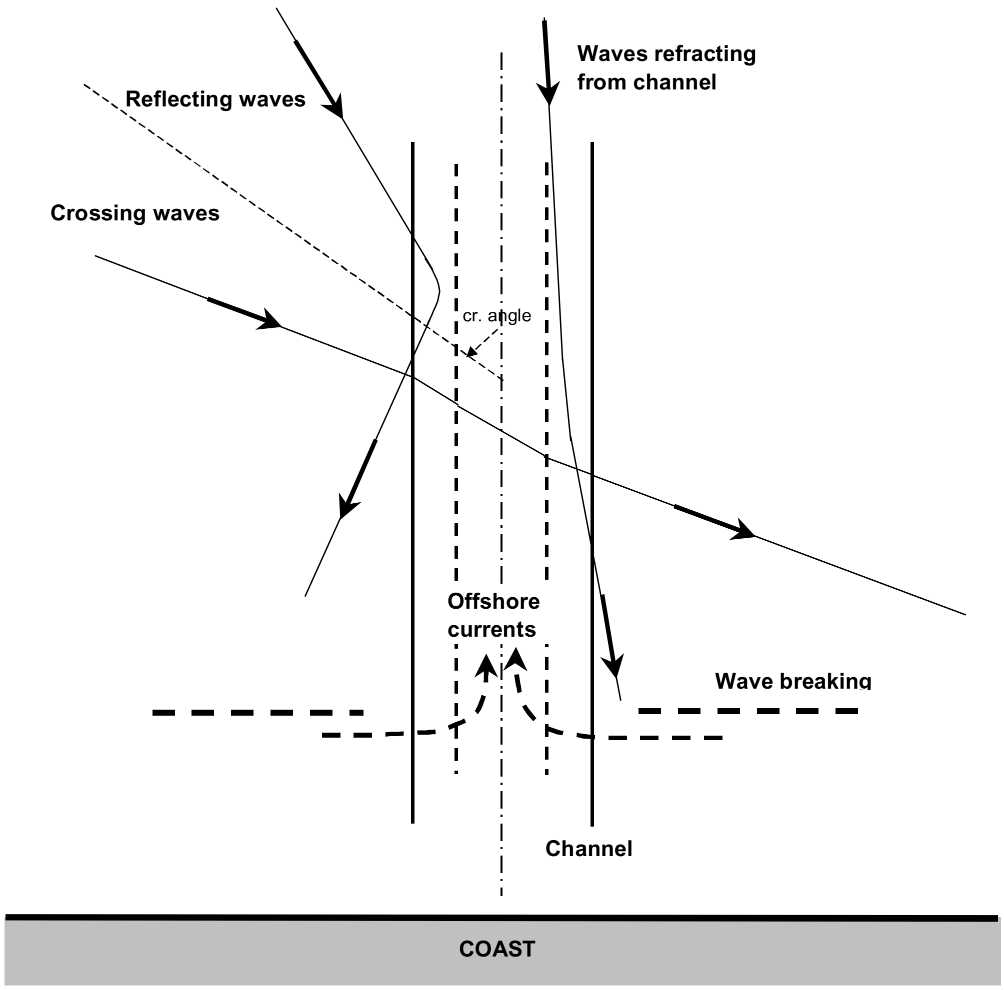


Figure 3.3.1 *Effect of deeper area (channel) on wave propagation*

3.4 Slope instability

The side slopes of a dredged pit, channel or trench should remain stable after construction.

Based on research at Delft Hydraulics, it is concluded that three mechanisms of slope instability can occur, depending on local conditions (Figure 3.4.1):

- slope collapse,
- liquefaction and successive flow slide,
- breaching and retrogressive slope erosion

The maximum slope is a function of depth or slope height, grain size and density or porosity but also to operational aspects concerning for instance the dredging activity.
Slope collapse can only occur at very steep slopes (<1:2 to 3). Liquefaction can occur in loosely packed sand layers only, and may result in a instantaneous mass flow creating very gentle slopes (> 1:10 to 15). If sufficient geotechnical data are available, the risk for slope instability can be computed (Geodelft, 1994). Retrogressive breaching is well known in the dredging practice, as mentioned in relation to deep suction dredging, but as a mechanism of

slope instability in densely packed sand it is not commonly recognised so far (Van den Berg et al., 2002).
Breaching also occurs at dam bursts (Zwinproef, 1994, Delft University of Technology), a research program is carried out on this topic already, but the breaching mechanism has been incorporated recently in order to improve models (Delft Hydraulics, 2000b).
Breaches under water produce a quasi-steady turbidity current, that may be the origin of massive sands deposited in channels and in some deep marine environments, sometimes over more than 3 km. Characteristic profile in the case of breaching is a steep top and successive gentler slopes decreasing with slope height.
Risk on slope instability and slope development due to breaching, which may be of importance for mining of sand in deep pits, can be simulated with a 1D stationary model (Mastbergen en Van den Berg, 2002).

Summarising, it can be concluded that side slope instability depends on: (i) dredging method applied, (ii) excavation depth and (iii) sediment properties of the deeper layers.

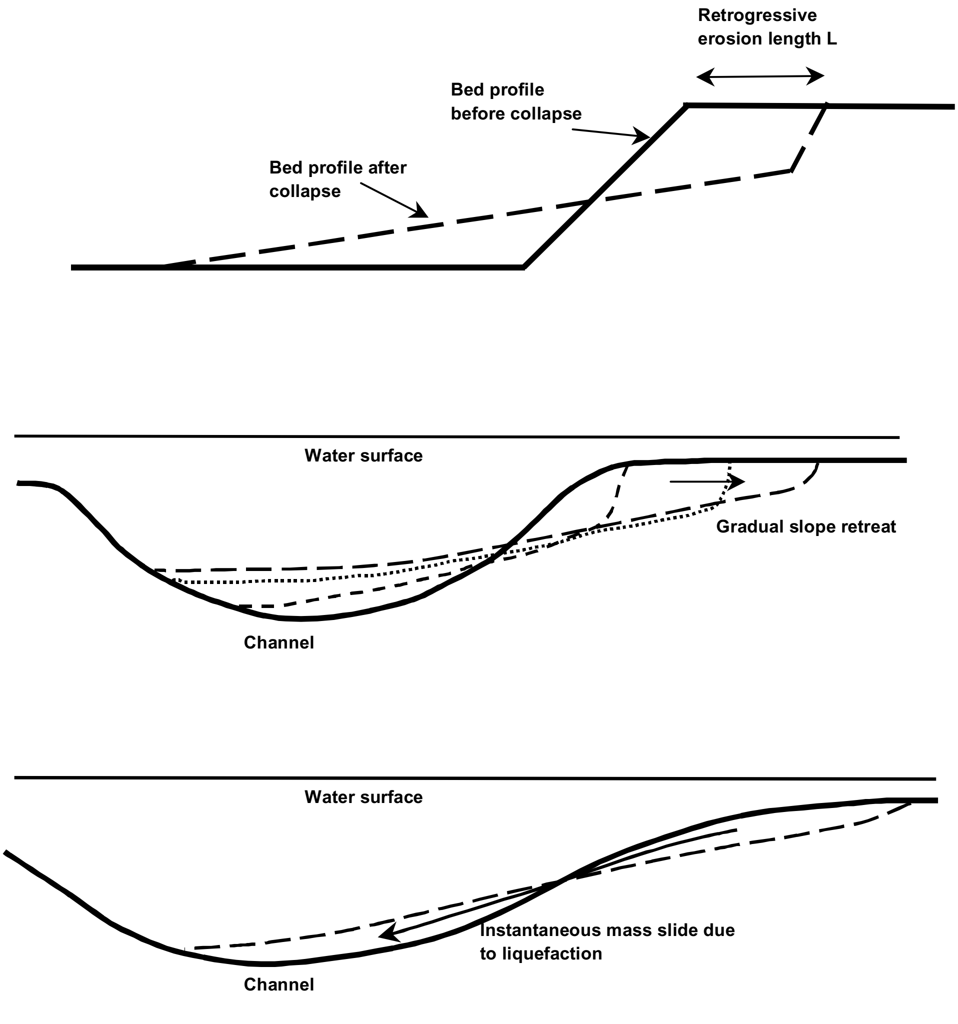


Figure 3.4.1 *Slope failure mechanisms*
Top: Slope collapse
Middle: Slope breaching and retrogressive erosion
Bottom: Slope liquefaction and mass slide

Dredging methods

Generally applied are: trailing suction hopper dredges, cutter suction dredges and deep suction dredge.

The most suitable method is dredging with large capacity trailing suction hopper dredges, nowadays operational at large water depths. The new generation of jumbo trailing hopper dredges has a capacity of over 20 000 m^3. Cutter suction dredges are applied only in shallow water in rehandling areas. The most efficient way of sand mining, however, is the stationary or slowly displaced deep suction dredge, creating a deep, crater-like sand pit. However, its application is restricted to on-shore locations or well protected off-shore areas only, due to intolerable wave action at sea. The deep suction dredge benefits of the unique self eroding and transporting property of sand along the resulting slope due to gravity and density differences (breaching). For this reason sand and gravel extraction in lakes (IJsselmeer), along the rivers (Rijn, Maas) and even on land borrowing areas (Overijssel, Drente, Gelderland) is performed hydraulically with deep suction dredges.

New technology is being developed, but still not fully operational (fluidisation and sand by-passing systems, punaise system being a submerged deep suction dredge, not affected by surface waves).

Excavation depth

Until recently the excavation depth allowed on the Dutch area of the North Sea is not more than 2 m. This implies that for large quantities of sand, very large sea bottom areas have to be explored.

Theoretically, very deep sand extraction depths are feasible at the North Sea with deep suction dredgers until -75 m NAP as shown schematically in Figure 3.4.1 (60 m excavation depth; Van ‘t Hoff et al., 1996). After construction of a wave breaking sand fill dam, a protected area can be created, allowing application of deep suction dredges. The breaching mechanism taking place at the side slopes in the case of deep suction has been investigated and modelled by Delft Hydraulics and Delft Geotechnics in the framework of the Dredging Research Association in which the Dutch contractors and Rijkswaterstaat (WODCON, 1992) participate. Predicted slopes are, as follows:

Sand	Water depth (m)	Slope
0.2 mm	25	1:4
	50	1:11
0.08 mm	25	1:6
	50	1:20

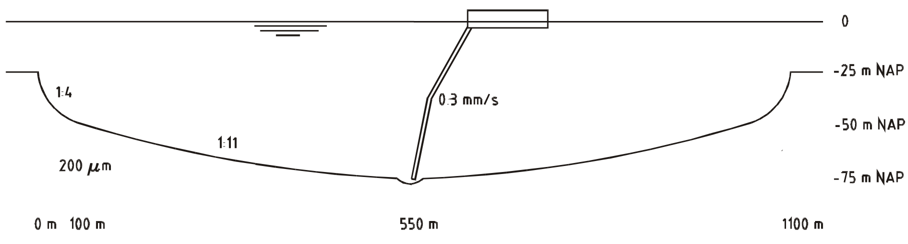


Figure 3.4.2 *Deep sand pit mining*

Sand properties in deep layers

Important properties of the sand and gravel natural resources in the North Sea regarding mining and processing are layer thickness, grain size distribution, composition (presence of clay, silt or peat) and the in-situ density or porosity of the sand layers. At present, sand extraction activities on the North Sea yields medium fine to medium coarse sand quality (0.15 to 0.3 mm), suitable for sand fills, construction and concrete industry.

Maps of the Dutch NITG-TNO (Netherlands Institute of Applied Geoscience) give the distribution of the main sea bed properties to a limited depth (Laban, 1995, NITG-TNO). For some locations deep geotechnical explorations have been performed (cone penetration tests Gemeentewerken Rotterdam, 1996, with maximum depth -95 m, location Europahaven North-West corner Maasvlakte). Assuming that this location is as a characteristic location, the following depth profile can be derived (Van 't Hoff et al., 1996):

Depth of layer	**Type of sediment**
-15 to -23 m NAP	Holoceen medium fine sand 150 μm with clay and peat layers
-23 to -25 m NAP	clay /peat layer of about 2-3 m
-25 to -45 m NAP	Pleistoceen I medium coarse sand 200 - 500 μm
-45 to -80 m NAP	Pleistoceen II very fine sand 80 μm with clay layers
-80 to -84 m NAP	clay with sand layers
-84 to -95 m NAP	fine sand

Table 3.4.1 *Characteristic geologic profile North Sea*

It can be concluded that good quality sand resources are present to in depths up to -45 m NAP depth and less quality still in depths between -45 and -80 m NAP.

Based on results from ongoing sampling and boring programmes, the database of sediment properties of the North Sea bottom is continuously updated (Nederlands Instituut voor Toegepaste geowetenschappen, NITG-TNO, Utrecht).

Slope stability

To obtain a license for construction or extension of a sand borrowing area on land, soil investigation and a geotechnical advice concerning slope stability by an independent consultant is required (deep cone penetration tests and borings). In order to establish the production capacity of the location and to maintain the safety of the surrounding land, restrictions are formulated regarding the allowed slopes and excavation depth. The restrictions for deep suction dredging sand borrowing pits should be mentioned here (Provincie Overijssel, 1997, 2001, Delft Hydraulics, 2001).

Generally speaking, the present experience in Overijssel where rather coarse, densely packed sand layers are encountered until 40 m depth, points out the following:

- maximum slope 1:3 for 10 m slope depth
- maximum slope 1:4 for 20 m slope depth

Since in recent years borrowing pits are extended and the excavation depth is increased to maximum 40 m, frequently slope instabilities have been encountered. The retrogressive erosion length L (see Fig. 3.4.1, Geodelft 1994) due to slope instabilities was in the order of the sand slope height h.

Sand deposits

In the case of (submerged) sand deposits, sand rehandling areas, artificial islands, etc. slope stability also plays an important role. Hydraulically placed sands but also freshly sedimentated natural sands, are loosely packed and therefore susceptible to liquefaction. This has been investigated at Delft Hydraulics and Delft Geotechnics (SOWAS, 1988) and field research has been carried out during major sand fill closures in the Eastern Scheldt (Krammer, Slaak), part of the Delta works. The research results were summarised in Artificial sand fills in water, CUR, 1992. In the case of deep suction dredging and slope instability due to breaching, sand is transported and resedimentates downslope, creating large zones of loosely packed sand. Similar processes take place in natural circumstances on large scale such as turbidity currents in submarine canyons (Mastbergen en Van den Berg, 2002) on the Continental slope, subaqueous deltas such as river Nile in Mediterranean and Rhone in Lake Geneva.

The underwater slope development (De Groot et al., 1988) turned out to be a function of grain size and sand supply per unit width and by the slope height, defining if liquefaction is likely to occur, reducing the slope dramatically.

Slopes encountered at various measurements in loosely packed sands are (see also CUR 1992):

- flume tests (Delft Hydraulics), slopes of 1:6 to 1:14 in depth of 2.5 m for 0.135 and 0.225 mm sand;
- Eastern Scheldt sand fill closures Slaak, Krammer, slopes of 1:7 to 1:33 in sand of 0.18 mm (liquefaction);
- drilling islands Northern Arctic Sea, slopes of 1:5 in 0.32 mm sand and slopes up to 1:12.5 in 0.26 mm sand.

Conclusions and recommendations

The following conclusions are given:

- deep sand extraction on the North Sea is feasible in depths down to about -75 m NAP;
- trailing suction hoppers can be generally applied, but to create a deep sand mining pit deep suction dredges are most efficient, but require wave protection;
- slope stability restrictions are defined by provincial government for deep hydraulic sand mining on land;
- slope development in densely packed sand due to breaching is dependent on grain size and in-situ density and decreases with height from about 1:4 tot 1:12;
- in the case of artificially placed sand, liquefaction can occur, resulting in very gentle slope (> 1:10).

Recommendations for further research activities are:

- time-dependent modelling of the breaching process in the case of slope instability for deep sand mining pits.

4 Sediment transport and ecological processes in marine conditions

The knowledge of sand transport and ecological processes on the middle and lower shoreface (seaward of the -8 m depth contour) is summarised herein.

4.1 Sand transport processes

4.1.1 Definitions and general characteristics

The shoreface is defined, as follows see Fig. 4.1.1):

- upper shoreface landward of the -8 m depth contour; where wave-driven processes (shoaling and wave breaking) are dominant; this zone is also known as the surf zone;
- middle shoreface between -8 and -20 m depth contours, where wind-, density- and tide-driven flows are controlled by bottom friction; the currents generally are parallel to the coast with during storms a secondary circulation (in transects normal to coast) superimposed on the main longshore current yielding a spiral type of fluid motion with landward flow in the surface layers and seaward flow in the near-bed layers;
- lower shoreface seaward of -20 m contour, where the currents are controlled by pressure gradients and wind forces in combination with Coriolis forces (Ekman spiral, geostrophic flows).

The fluid in the shoreface zone may be homogeneous (well-mixed) or stratified with a surface layer consisting of relatively low fluid density (fresh warmer water in summer) and a bottom layer of relatively high density (saline colder water in summer). Strong horizontal density-related pressure gradients may occur in regions close to a river mouth. In micro-tidal environments (such as Atlantic Shelf, Gulf of Mexico Shelf) the tidal currents generally are less important (<0.5 m/s) than wind-driven currents. In meso-tidal environments like the North Sea both tide- and wind-induced currents are important.
Sand can be transported by wind-, wave-, tide- and density-driven currents (current-related transport; Van Rijn 1984a,b,c; Van Rijn and Kroon, 1992; Van Rijn, 1993), or by the oscillatory water motion itself (wave-related transport). The waves generally act as a sediment stirring agent, whereas the sediments are transported by the mean current. Wave-related transport may be caused by the deformation of short waves (wave asymmetry) under the influence of decreasing water depth. Low-frequency waves interacting with short waves may also contribute to the sediment transport process (wave-related transport), especially in shallow water in the surf zone.
In friction-dominated deeper water on the lower shoreface zone the transport process generally is concentrated in a layer close to the sea bed and mainly takes place as bed-load transport in close interaction with small bed forms (ripples). Bed-load transport is dominant in areas where the mean currents are relatively weak compared to the wave motion (small ratio of depth-averaged velocity and peak orbital velocity). Net sediment transport by the oscillatory motion is relatively

small in depths larger than 15 m (Van Rijn, 1995, 1997; Van Rijn et al., 1995), because the wave motion tends to be more symmetrical in deeper water.

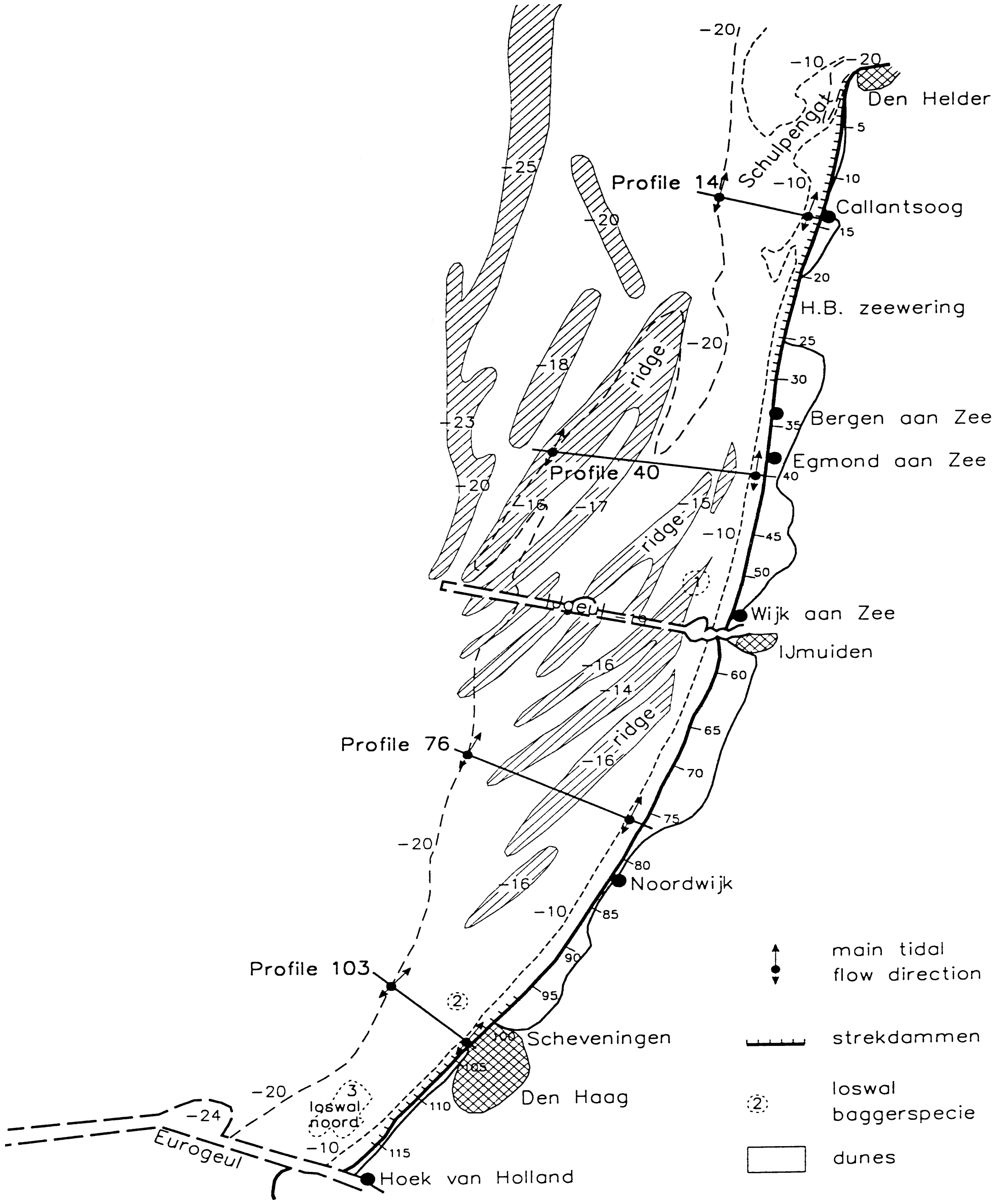


Figure 4.1.1 *Plan view of bottom (Dutch Sector) of North Sea*

Suspension of sediments on the lower shoreface can be generated by ripple-related vortices. Suspended load transport will become increasingly important with increasing strength of the tide- and wind-driven mean currents due to the turbulence-related mixing capacity of the mean current (shearing in boundary layer). By this mechanism the sediments will be mixed up from the bed-load layer to the upper layers of the flow. On the lower shoreface the suspended sand transport may be dominant during storm conditions, depending on conditions (wave height in relation to water depth; additional wind-driven flow).

Soulsby (1987) concluded that the most important contributions to the long-term sediment transport are made by fairly large (in relation to depth) but not too infrequent waves, combined with tidal currents between mean neap and maximum spring tide. Weak currents and low waves in relation to water depth give a small contribution, because their potential for sediment transport is low, although their frequency is high. Extreme conditions also are relatively unimportant, since their frequency is too low, although their transport potential is high.

Characteristic morphological features occurring on the shoreface are breaker bars in the nearshore zone and large sand banks, ridges or shoals on the middle and lower shoreface, which are at some places connected to the shore. Small-scale bed forms may be superimposed on these large scale features ranging from wave-induced micro ripples to mega-ripples.

Herein , the following terminology is used:

- *shoreparallel breaker bars;* linear sand bars in the surf zone with heights of the order of 3 m and spacings of the order of 100 m, which are generated by breaking wave processes;
- *sand banks*; large linear sand bodies with spacings up to 30 km, crest lengths up to 70 km, heights up to 40 m and which are believed to be maintained by tidal currents larger than about 0.7 m/s (including Coriolis effect); they occur at the edges of broad shallow seas; their crest lines may be oriented slightly anti-clockwise (20^o to 40^o on northern hemisphere) with respect to the dominant tidal current direction; often they are covered by transverse sand ridges, transverse sand waves and mega-ripples; linear sand banks (banner banks) may also occur at erodible or inerodible headlands; banks in deltas are excluded here;
- *oblique sand ridges*; linear ridges oblique (20^o to 40^o) to the main (tide-or wind-driven) current direction and often connected to the shoreface: spacings of about 5 km, crest lengths up to 20 km; heights up to 10 m; migration rates up to 3 m/year; occurring in seas with (North Sea) and without tidal currents (North American shoreface);
- *sand shoals*; these are isolated irregular underwater bodies of sand without the typical sequential characteristics of banks and ridges (spacing and orientation); inlet-associated shoals occur near the inlets/mouths of major estuaries; ebb-tidal deltas in the entrance of inlets/estuaries can be seen as large shoals; headland-attached shoals occur on the shoreface of prominent headlands (southeast Australia) where they form shore-parallel sand deposits of 20 to 30 m thick, 2 to 5 km wide and extend alongshore for distances of 5 to 30 km in depths of 25 to 80 m; shoals in shallow areas serve to naturally limit the wave energy approaching the shore (bottom friction, reflection and wave breaking);
- *transverse sand waves*; sand bodies transverse to the main current direction; spacings up to 1 km, crest lengths up to 5 km; heights up to 5 m; migration rates up to 10 m/year; their shapes are often asymmetric; covered by mega-ripples.

Generally, the sand bodies consist of well-sorted, medium-grained sand with fragmented shell debris. Core analyses reveal cross-bedding features and a coarsening-upward sequence due to winnowing of fines from the ridge/bank crest and deposition of fines in the troughs.

4.1.2 Net annual sand transport along the Dutch coast based on model computations

The semidiurnal tide along the Holland coast of the North Sea propagates northwards and the tidal range roughly varies between 1 and 2 m (meso-tidal). The horizontal tide becomes more asymmetric in northern areas; the peak flood and peak ebb depth-averaged velocity are about 0.6 and 0.5 m/s in depth of 20 m near Hoek van Holland (Table 4.1.1) and about 0.75 and 0.45 m/s near Den Helder. The flood duration is about 5 hours and the ebb duration is about 7 hours along the Holland coast (Van Rijn, 1995); these values are reasonably constant along the coast.

The wave climate is rather constant along the Holland coast; the dominant wave direction is south-west. Some values of the probability of occurrence (duration in % of time) for waves in deep water are:

- south-west (180^o-270^o): 15% waves of 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5 m;
- north-west (270^o-360^o): 10% between 1-2 m, 4-5% between 2-3 m, 1-2% between 3-5 m.

The median size of the bed material (Van Rijn, 1995) on the lower shoreface (20 m depth) varies between 0.15 mm (near Den Helder) and 0.25 mm (near Hoek van Holland). On the upper shoreface (depth of 8 to 10 m) these values vary between 0.15 mm (Noordwijk) and 0.2 mm (Egmond).

Van Rijn (1995, 1997) presented estimates (and variation ranges) of the net annual longshore and cross-shore transport rates at the -20 m depth contour at several stations along the coast (sand size of d_{50}= 0.25 mm), based on state of the art mathematical computations.

The results and error ranges (based on sensitivity computations varying input parameters) are given in Table 4.1.2. The peak depth-mean velocities due to tide plus wind effects used to determine the transport rates are given in Table 4.1.1. The peak tidal velocities increase along the shore in northern direction.

The sediment transport rates (bed load plus suspended load transport) were computed by the UNIBEST-TC model (Delft Hydraulics, 1997) using schematised wave and current conditions. Tidal averaging was applied to obtain the tide-averaged transport rate for each wave direction and wave height class. The tide-averaged transport rate is multiplied by the percentage of occurrence of each specific wave condition, resulting in the weighted transport rate. Adding all individual weighted values, yields the mean annual sediment transport rate.

Profile (km alongshore from Den Helder)	Wind velocity (m/s)	Water depth (m)	Max. flood velocity (m/s)		Max. ebb velocity (m/s)		Local wave height H_{rms} (m)
			Long-shore	Cross-shore	Long-shore	Cross-shore	
14	0	20	0.65	0.05	-0.50	-0.05	0
	15 m/s	20	0.80	0	-0.30	-0.05	1.9
40	0	20	0.65	0.15	-0.55	-0.15	0
	15 m/s	20	0.75	0.20	-0.40	-0.10	1.9
76	0	20	0.65	0	-0.55	0	0
	15 m/s	20	0.75	0	-0.45	0	1.9
103	0	20	0.65	0.05	-0.55	0	0
	15 m/s	20	0.75	0.05	-0.45	0	2.0

(+ north/flood, onshore; - south/ebb, offshore; wind 15 m/s from south-west)

Table 4.1.1 *Peak longshore and cross-shore depth-averaged tide- and wind-induced velocities (based on model computations) for profile 14, 40, 76 and 103 along the coast of Holland*

Cross-shore profile (km alongshore from Den Helder)	Net annual sand transport rates (m^3/m/year, incl. pores)	
	Cross-shore at depth of 20 m	Longshore at depth of 20 m
14, Callantsoog	5 ± 10	75 ± 30
40, Egmond	15 ± 10	60 ± 25
76, Noordwijk	10 ± 10	35 ± 15
103, Scheveningen	0 ± 10	25 ± 15

+ north/onshore; - south/offshore

Table 4.1.2 *Best estimates of net annual sand transport rates at a depth of 20 m in profiles 14, 40, 76 and 103 along coast of Holland (all values incl. pores of 40%)*

4.1.3 Net annual sand transport derived from morphological data along the Dutch coast

The computed transport rates (see previous section) are compared with transport rates derived from available field data of the middle and lower shoreface (dumping Hoek van Holland 1982, dump site Wijk aan Zee 1982, trial trench Scheveningen 1964, Simon Stevin pit 1981).

Dump site near Hoek van Holland

Information of net sand transport rates can be derived from the morphological behaviour of sand dump sites related to the maintenance of navigation channels near the port of Rotterdam. During the period 1982 to 1991 an artificial sand ridge was made by dumping sand over a length of about 3600 m normal to the shore (location Hoek van Holland) in an area with depths between 15 m and 23 m on the northern side of the navigation channel. In all, 3.5 million m^3 of sand was dumped over the period 1982 to 1991 (Rijkswaterstaat, 1996; Delft Hydraulics, 1998).
The ridge dimensions are: length of about 3,600 m; toe width between 250 m and 370 m; height between 1.3 m and 4 m; slopes between 1:50 and 1:100 on the south flank and between 1:20 and 1:50 on the north flank; d_{50} between 0.15 mm and 0.45 mm. The landward end of the ridge is about 6,300 m from the shoreline.

Based on the analysis of detailed volume calculations (per unit length of the ridge), the increase of the net annual longshore sand transport from the ridge toe to the ridge crest was found to be 20±5 m^3/m/year (including pores). A clear effect of the water depth and/or ridge height could not be determined. A bed-load transport model was used to compute the net annual longshore sand transport rates across the ridge in two sections, taking tidal velocity and orbital velocity variations over a representative year into account. Wind-induced velocities were neglected. The model was calibrated by varying the bed roughness (k_s) to give the observed increase of the net annual longshore transport rate at the ridge crest. The contribution of cross-shore transport was neglected. Optimum agreement was found for k_s=0.005 m.

The calibrated model was applied to compute the total net annual longshore transport rates in two sections, yielding:

- about 65 m^3/m/year (incl. pores) at ridge crest in water depth of 15 m (section 4);
- about 50 m^3/m/year (incl. pores) at ridge crest in water depth of 19 m (section 20).

The total transport rates are about 2 to 3 times larger than the transport increase rates (between toe and crest of ridge) derived from the morphological data.

The result of section 20 of about 50 m^3/m/year at depth of about 19 m is in reasonable agreement with the net annual longshore transport rates of Profile 103 (depth of 20 m; about 15 km north of Hoek van Holland) given in Table 4.1.2, the latter being in the range between 10 and 40 m^3/m/year.

Dump site near Wijk aan Zee

Another dump site of sand off the coast of Holland (location Wijk aan Zee, north of approach channel to port of Amsterdam) is located in relatively shallow water with depths between 13 and 15 m. An artificial shoal with a height of about 1.2 m was made in 1982 by dumping sand (about 1 million m^3), which was sounded regularly over a period of 8 years without any additional dumpings (Rijkswaterstaat, 1992). Based on the analysis of the sounding data, the crest was found to migrate at a rate between 25 and 40 m/year in the direction of the dominant flood tidal current (in north-eastern direction) over a period of 8 years. The peak flood current is about 0.65 m/s; the peak ebb current is about 0.55 m/s, both parallel to the shore. The increase of the net annual longshore sand transport rate due to the presence of the shoal can be roughly estimated to vary between 40 and 50 m^3/m/year. The actual transport rates will be a factor of 2 to 3 larger (say 80 to 150 m^3/m/year), because the net annual longshore transport entering the sections has to be added (see results of dump site near Hoek van Holland).

These values are somewhat larger than those of Table 4.1.2, yielding net annual longshore transport rates between 35 and 60 m^3/m/year for profiles 76 and 40 km at a depth of 20 m. The larger transport rates at the dump site near Wijk aan Zee can be explained by the smaller depth (13 to 15 m).

Trial trench near Scheveningen

A trial trench was dredged in the North Sea bed (sand between 0.2 and 0.3 mm) near Scheveningen in March 1964 to obtain information of deposition rates with respect to the construction of a future sewer-pipeline trench. The trial trench was dredged perpendicular to the shoreline between 1 km (local depth of about 7 m below MSL) and 1.7 km (local depth of 10.5 m) from the RSP-baseline on the beach. The length of the trench along the main axis of the trench was about 700 m; the bottom width of the trench was about 10 m; the side slopes of the trench were about 1 to 10 and the trench depth below the surrounding sea bed was about 2 m. In all, about 30,000 m^3 was dredged. The local peak flood and ebb currents are estimated to be in the range of 0.4 to 0.6 m/s parallel to the shoreline (perpendicular to the trench axis).
The trench was sounded regularly in the period between 7 March and 27 August 1964. Analysis of the bed profiles showed:

- almost symmetrical filling of the trench; net migration was not observed;
- deposition of about 20 to 25 m^3/m over 173 days (7 March-27 Aug. 1964) or about 40 to 55 m^3/m per year (for currents without waves, summer conditions);
- assuming that all incoming sediment is trapped in the trench, the gross transport rates (sum of net flood and ebb transport) will be about 40 to 55 m^3/m/yr for tidal currents without waves (calm weather).

These values represent short term transport rates, which can not be compared to the yearly-averaged values given in Table 4.1.2. Additional transport computations for tidal flow made by Delft Hydraulics (1998) showed computed transport rates (TRANSPOR model) in the range of 25 to 70 m^3/m/yr for input values: h= 7 to 10 m, peak velocity v= 0.5 to 0.6 m/s (effective duration of 8 hours per day; velocities are larger than initiation of motion during 8 hours per day), d_{50}= 0.00025 m, k_s=0.05 m (no waves). These latter computed values of 25 to 70 m^3/m/yr are in reasonable agreement with the observed transport rates of 40 to 55 m^3/m/year (calm weather).

Mining pit Simon Stevin

The pit was dredged on 26/27 may 1981 (Rijkswaterstaat, 1986) northwards of a dump site (Loswal Noord near Hoek van Holland) for dredging material from the harbour of Rotterdam. The sea bed is about 15.5 m below MSL; the pit had a depth of about 6.5 m with respect to the surrounding bed and side slopes between 1 to 5 and 1 to 15. The area of the pit was about 100x100 m^2. The local peak tidal velocities parallel to the coast are about 0.5 to 0.6 m/s. The local bed material is fine sand (median size between 0.1 and 0.2 mm).

Analysis of regular soundings showed a natural deposition rate of about 45,000 m^3 (mixture of sand and mud) over the first 520 days immediately after dredging, which is equivalent to about 320 m^3/m per year. The deposition rates may be relatively high due to the fact that during the flood current the pit is situated some kilometres downstream of the Loswal Noord dump site.

Analysis of samples of the deposited material showed the presence of 40% to 60% of sand, yielding a deposition rate of sand of about 130 to 200 m^3/m/yr. Assuming that the pit trapped all incoming sand transport from both the flood and ebb directions, the gross sand transport rates will be about 130 to 200 m^3/m/yr. These latter values representing conditions with tidal currents and waves are about 3 to 4 times larger than the values for calm weather (observed near Scheveningen), which seems reasonable.

Conclusions

Estimates (based on model computations) of net annual longshore and cross-shore sand transport rates (at a depth of 20 m) in various stations (sand size of d_{50}= 0.25 mm) along the coast of Holland vary in the range between 25 and 75 m^3/m/yr, depending on location along the coast (Den Helder to Hoek van Holland). The net annual cross-shore transport rates at a depth of 20 m are onshore-directed and vary in the range between 0 and 15 m^3/m/yr, depending on the location along the coast. Net annual longshore transport rates derived from sand dump sites near Hoek van Holland and near Wijk aan Zee are in the range of 30 to 100 m^3/m/yr for depths between 10 and 20 m. The results obtained from model computations and from both dump sites are of the same order of magnitude.
The data of the trial trench near Scheveningen at depths between 7 and 10 m represent gross transport rates of about 40 to 55 m^3/m/yr for tidal currents without waves (calm summer weather). The results are in reasonable agreement with transport estimates based on the TRANSPOR model using tidal current velocities as input.
The data of the mining pit Simon Stevin at a depth of about 15 m represent gross annual transport rates of about 130 to 200 m^3/m/yr (current and wave conditions).

The applicability and validity of practical sand transport models are largely based on the quality and quantity of the underlying data sets. Therefore, it is extremely important to have information provided by available data sets from large-scale laboratory and field experiments. An overview of field data sets of sand transport in the coastal zone is presented by Van Rijn et al. (2001). A reasonable number of data sets is available for the shallow surf zone. Some data sets are available for the depth zone from 3 to 10 m. Hardly any data sets are available for deep water with depths larger than 10 m. Sand transport under storm wave conditions has only been measured at the Duck site (USA) in the period 1994-1998, on the Flemish sand banks of the southern North Sea in the period 1992-1995 and in the surf zone of Egmond site (North Sea) in 1998. Most of the data refer to the current-related suspended transport component; the wave-related suspended transport has only been measured in the Deltaflume of Delft Hydraulics and at the Egmond site (The Netherlands). There are few reported measurements of bed forms and associated bed load transport, particularly for the deeper parts of the shoreface. Our present sand transport formulations have been calibrated on the basis of the available surf zone data (in the shallow zone from 1 to 3 m). It has yet to be proved that these formulations yield good predictions for the deep water zone. The predicted sand transport rates for deep water (middle and lower shoreface) may suffer from serious errors due to scale effects (water depth effects). Additional field experiments focussing on sand transport in deep water (15 to 20 m) are highly recommended.

4.2 Mud transport processes and effect of mining activities

The natural flux of fine sediments (size<0.05 mm) in the Dutch sector of the North Sea is concentrated in a relatively narrow coastal zone of about 20 km due to geostrophical effects. Field observations show that there is a pronounced cross-shore gradient in suspended sediment concentration, with the larger values occurring near the coast (FLYLAND-study, MARE 2001). The total (gross) flux of fine sediments is about 20 10^6 ton/year or 50,000 ton/day (Skalden, 1998). Assuming a uniform cross-shore distribution of the longshore mud transport, this is equivalent to about 2.5 ton/day/m or 0.03 kg/s/m. Taking a mean discharge of about 3 m^3/s/m (depth of 10 m and current of 0.3 m/s), the mean sediment concentration is about 0.01 kg/m^3 or 10 mg/l.

The sand mining activities affect the volume, transport and fate of fine grained sediments in the Dutch coastal zone in two ways:

- large amounts of fines can be mobilised and released in the environment during the sand mining activities,
- fine grained sediments may accumulate temporarily or permanently in the resulting deep sand pits in the sea floor.

The sediments of the North Sea bed contain a few percentage of fines (between 1% and 3 %) in the Dutch coastal zone.
Suppose that the sand mining is carried out with a modern, large suction hopper dredger with a capacity of 20,000 m^3/hr in a sandpit with a diameter of 300 m. This would imply a sand production of 60,000 to 120,000 m^3/day, i.e. 0.1 to 0.2 10^6 ton/day, yielding 1,000 to 6,000 ton of fines per day. This amount of fines is mobilised by:

- breaching of the sea bed during the suction activities,
- overflow of fines during the filling of the hopper.

The amount of fines released in the environment can be controlled by strict working procedures. However, if no regulations are set, it is estimated that 10% to 50 % of the fines present in the seabed sediments can be mobilised, as a result of the breaching processes and/or the overflow. Hence, it is estimated that for a sand mining production of 60,000 to 120,000 m^3/day, an amount between 100 and 3,000 ton per day of fines is released in the environment.
This amount should be compared to the natural flux of fine sediments in the Dutch coastal zone, which is currently estimated at about 20 10^6 ton/yr, or 55,000 ton/day. Considering the width of the sandpit of 300 m and assuming a uniform cross-shore distribution, the natural fine sediment flux per 300 m width is estimated at about 900 ton/day. Hence it is concluded that the amount of fines mobilised (100 to 3,000 ton) by the sand mining can be of the same order of magnitude as the local natural sediment flux, depending on the location of the mining pit from the shoreline and the dredging technique applied.

The overflow plume from the dredging vessel may be released in clouds of sediment, or either be mixed with the environmental water, or behave as a density current over the seabed. The behaviour of the sediment in the vicinity of the mining activities, released through one of these three modes is considerably different. Clouds of sediment can behave as individual entities; within these clouds, segregation of coarse and fine sediment material may take place. This effect is also known as convective settling (e.g. Darcovich et al., 1996 and Tacker and Lavelle, 1997).
Whether the overflow behaves as a plume that is rapidly mixed with the environment, or as a density current over the sea floor, is governed by a bulk Richardson number and a velocity parameter (Winterwerp, 2002). In the latter case, the impact in the direct vicinity of the dredging vessel is the largest.
The fine sediments mobilised during breaching are for the major part directly mixed over the water column, as the breaching process generates additional turbulence.

At present, it is not known whether all or part of the sediments, released during the sand mining process, will be reworked into the seabed, either temporarily, or permanently.
Part of the released sediments will accumulate in the sandpit. Whether this accumulation is either temporarily or permanently, depends on whether local waves can stir up these sediments or not. This on its turn is dependent on the relative depth of the mining pit with respect to the undisturbed seabed, which is also a function of the location of the sand mining from the shoreline.

The sand pit can also collect sediments from the natural flux, through direct settling or super-saturation. In the latter case the transport capacity of the flow for fine sediment in the mining pit is exceeded, as a result of which a high-concentrated near-bed suspension is formed, resulting in a very efficient trapping of fine sediments in the pit (Winterwerp et al., 2001). Whether these sediments are re-eroded again, or are accumulated in time, depends again on the local wave activity. In the FLYLAND-study related to the construction of an airport at sea (MARE, 2001), it is estimated that up to about 0.1 m of fines may settle per year in the sand mining pits (see Section 7.4).

4.3 Ecological processes

4.3.1 Overview of processes

Sand mining/dredging and dumping have various direct and indirect short and long term effects on marine and coastal benthic communities of plants and animals. The ecological impacts depend on complex and dynamic interactions of abiotic and biotic factors including:

- composition and dynamics of the sediment (Fig. 4.3.1),
- methods of dredging and dumping and the sediment spill,
- the occurrence and sensitivity of seagrass and macro-zoobenthic communities and the rate of recovery of the communities affected.

An important problem of sand mining may be the release of fine sediments (silt and mud) in the environmental system during the dredging process. Roughly about 1% to 3% of the substratum of the North Sea consists of fine to very fine sediments. One of the consequences of massive sand mining will be the production of an enormous amount of fine sediment, which can be carried over large distances to the coasts and shores of the countries surrounding the North Sea, threatening the environmental system at those places.
In general, the diversity of zoobenthic communities in dynamic sandy bottoms is lower compared to more stable environments. The sensitivity and the rate of recovery are important factors in order to maintain the structure and function of benthic communities and sustainable exploitation of the sand resources. It is necessary to make an inventory of the ecological aspects resulting in a 'state of the art' description of the ecological aspects.
The attention needs to be focussed on the influence of mining/dredging/dumping on local turbidity patterns, local bathymetry and substratum, and local flora and fauna. This will require:

- description of the state of the natural environment (without proposed activities), its function in the natural system and the expected future development of the natural environment, with special emphasis on benthic communities, spawning and nursery grounds, fish, birds and marine mammals,
- description of the expected environmental effects of the proposed activities,
- identification of the least intrusive sand mining/dredging/dumping methods with respect to environmental effects.

The occurrence of species and communities of species in the Northsea and on the Northsea floor is not homogeneous. This distribution is dependent on the species, the lifestage of the species, the season and the physical environment. The most important physical factors governing the distribution are depth, substrate type, exposure to currents and waves and water chemistry. Important human influences on the distribution of species are disturbances of sediments by dredging, dumping or fishing.
Due to its hydrodynamical, geological and climatological characteristics, the North Sea encompasses a large variety of habitats. In the Dutch part of the North Sea, large sandy areas are found. Also, we find silty areas and some gravelbeds (Fig. 4.3.1). The deeper areas and the shallow coastal areas create habitat variety. This variety is further enhanced by the sand ridges that are found perpendicular to the shore and by many wrecks creating artificial hard substrate. For example, see Figures 4.3.2 and 4.3.3.

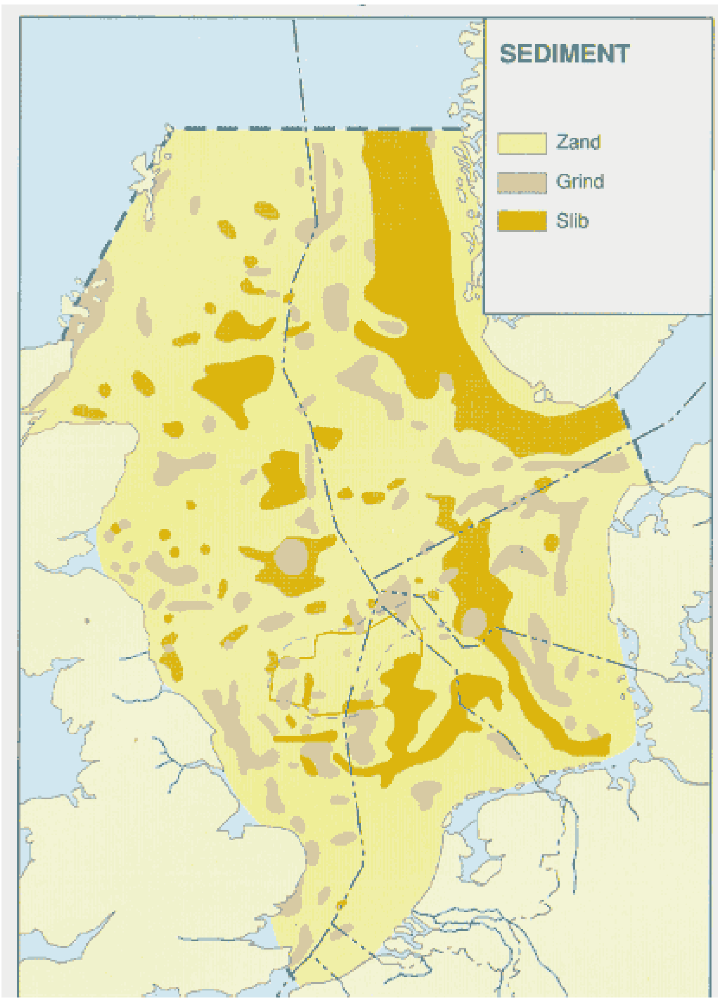


Figure 4.3.1 *Sediment composition of the Northsea (Laane et al. 1996)*

Figure 4.3.2 *The bivalve Tellina fabula (Holtmann et al., 1996)*

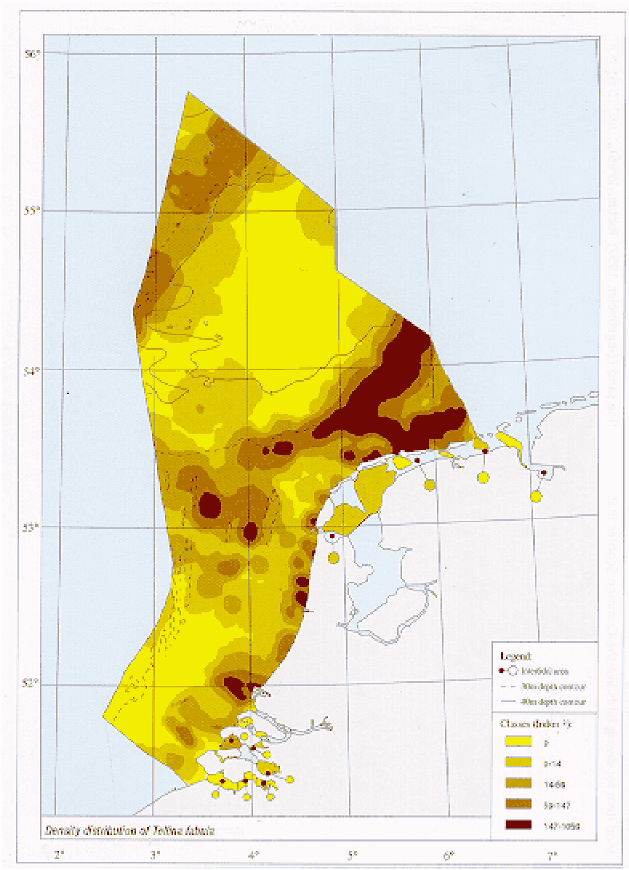


Figure 4.3.3 *Distribution of Tellina fabula in the Dutch part of the Northsea (Holtmann et al., 1996)*

Sand mining causes direct and indirect effects on the ecology of the North Sea. Main causes are the mining of the seabed, the production of silt in the water column, the increased deposition of silt on sediment and the disturbance of morphological and hydrodynamic processes. These causes have an impact on the ecology on different temporal and spatial scales. For instance, mining of the seabed causes direct mortality of bottom species. In contrary, enhanced silt concentration in the waterphase can cause long term (months), large scale (regions of the North Sea) impacts on primary production by reduction of the light climate. The main ecological impacts are listed below.

Bottom

- Loss of bottom-habitats at the mining location. Direct mortality of bottom dwelling species (Figure 4.3.4).
- Burial/smothering of bottom-habitats due to increased siltation rates.
- Morphological and hydrodynamical changes with impacts on the occurrence and quality of habitats of bottom species.

Waterphase

- Reduction of primary production by increased turbidity due to production of silt during sand mining and transportation. Left-over nutrients can cause increased production in areas further away from the site.

- Alteration of chemical and physical characteristics in sand mining pits such as reduced current speeds, stratification and changed oxygen and nutrient availability. This could have an effect on the primary production.

Foodweb

- Various direct and indirect impacts on mobile species such as fish, birds and mammals due to loss of feeding and spawning areas, increased turbidity, loss of food production, disturbance by noise and transport activities.

Other

- Fishery activities can be influenced by direct loss of fishing grounds and reduction of fish production.

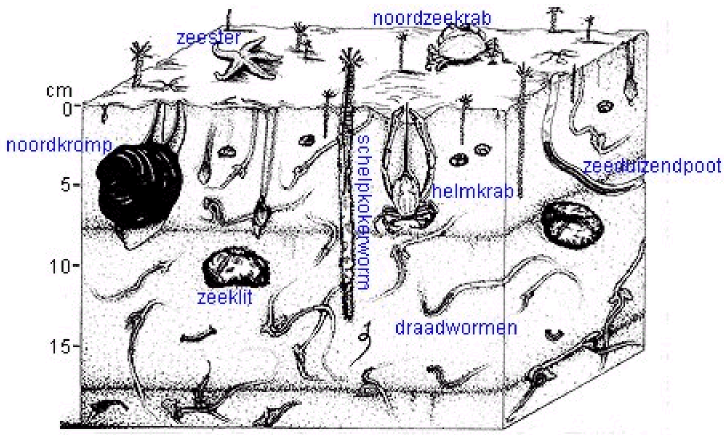


Figure 4.3.4 *Example of animals living in a typical North Sea sediment*

The ecological impacts cannot be quantified or in some cases even cannot be qualitatively described due to lack of knowledge. The disturbance of the physical, chemical and biological processes in the ecosystem is globally described in the first phase of the Flyland project (Los, 2001; Leopold, 2001; Poot, 2001 en Witte, 2001). A relevant quantitative result of this study is the tentative conclusion that the production of silt during sand mining can lead to large impacts on the primary production in parts of the North Sea (10% to 30%). Another conclusion is that impacts on fish, bird and mammal species cannot be ruled out but cannot be quantified due to lacking knowledge.
During sand mining, the species living on or in the seabed will be killed. This impact may be temporary, because after mining, the ecology of the seabed will be restored (if governing factors do not change permanently). Some bottom species will recuperate within some years due to their short life cycles and their large larvae production. Opposite, some species can get very old (the bivalve *Arctica islandica* (Noordkromp): 100 years see Holtmann et al., 1996; Zeedahlia: 200 tot 300 years). It will therefore take a very long time to re-establish these populations, once lost. The amount of impact therefore is dependent on the typical habitats that are lost. If it takes place in already disturbed areas (for instance intensively trawled areas), the impact to bottom species could be relatively small. However, the impact to fishing activities is then expected to be larger.

Figure 4.3.5 *Acorn barnacle*

The sensitivity of species to burial or smothering is dependent on the species and its ability to move or grow through the sediment. Species that are attached to a substrate, such as oysters, mussles and barnacles (Figures 4.3.5 and 4.3.6) will be more susceptible to smothering or burial. Other mobile species will be able to move upward to compensate for burial. Macro-algae or macrophytes will try to grow back to the surface. The maximum layer thickness of added sediment that can be coped with is called the 'fatal depth' (Essink, 1993; Bijkerk 1988). This depth is dependent on both the species- and sediment characteristics. This depth seems correlated to the (dis)similarity of the characteristics of the deposited sediment in relation to the original sediment. It was found that species in a sandy sediment are more sensitive to burial with silty material than species in a silty sediment.

By distribution of free floating larvae or eggs, a swift recolonization of the disturbed area is possible. This so called 'pelagic' state of many bottom species can cover weeks to months, enabling the distribution of a species over a large area. Many species reproduce in two periods each year, in spring and in the autumn.

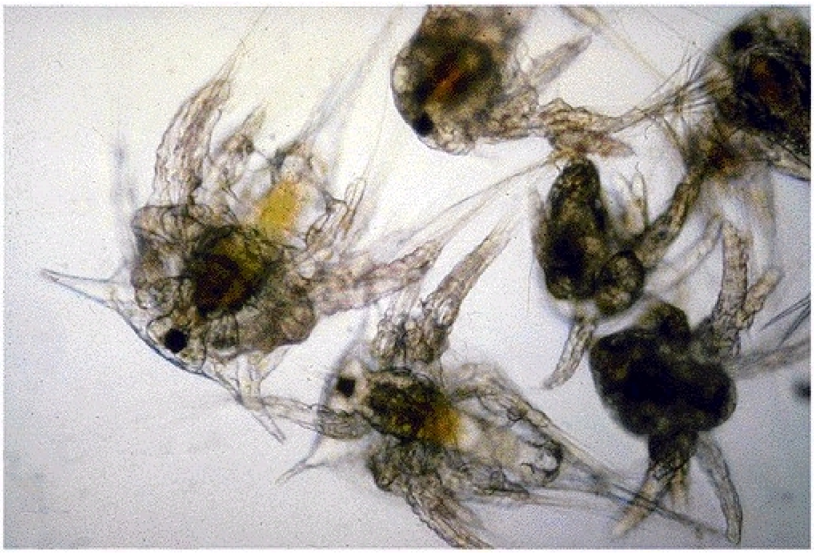


Figure 4.3.6 *Acorn barnacle larvae*

After settling of larvae, some species such as the bivalve Abra alba and the sea urchin Echinocardium cordatum (Figure 4.3.7) achieve high densities, high growth rates and high biomass in one year. However, most bottom species live three years to ten years and are slow growing. Disturbance of populations of these species will therefore take many years to recover.

Figure 4.3.7 *Echinocardium cordatum*

Another impact that can be found is the negative effect of increased suspended matter concentrations on the functioning of gills of fish. The sensitivity to this effect is species dependent. It is expected that pelagic species are more sensitive than bottom dwelling species such as flat fish. No observations are known of fish mortality near dredging works (Essink,1993). Fish, of course, will try to evade bad environmental conditions. For fish, birds and mammals it is assumed that turbidity, noise and transport activities in the area can disturb natural behaviour. A foodweb impact can be that schools of prey-fish will evade the disturbed area and therefore reduce feeding opportunities for predator-species.

4.3.2 Quality of water phase in deep pits

Oxygen cycle
The quality of the ecological processes in the marine environment strongly depend on the biological and chemical properties of the water phase.

One of the most important chemical parameters in the water column in pits is the dissolved oxygen level.

The dissolved oxygen cycle consists of the following basic terms:

Positive terms
- Primary production (photosynthesis)
- Re-aeration over the atmosphere-water interface (in case of undersaturation)

Negative terms
- Respiration by organisms
- Re-aeration over the atmosphere-water interface (in case of oversaturation)
- Decay of organic material
- Oxidation of reduced substances such as ammonium (nitrification), sulphides and methane
- Sediment oxygen demand

In equilibrium with the atmosphere the dissolved oxygen concentration ranges from 6 to 14 mg/l. The lower value can be found in warm, marine waters; the higher value in cold, fresh water. Oxygen is produced by photosynthesis by algae and plants resulting in an oversaturation as compared to the equilibrium or '*saturation*' concentration. Oxygen is consumed by 'reduced' substances of which organic matter is generally by far the most important. This results in undersaturation as compared to the saturation concentration. Reaeration always strives for the saturation concentration. If the water is oversaturated with oxygen, it will escape to the atmosphere; in case of undersaturation, oxygen will be imported from the atmosphere.

As long as the water column is unstratisfied or well-mixed, oxygen depletion will be very unlikely. After all, oxygen that is consumed, can be replenished easily by reaeration from the atmosphere.

In general, oxygen depletion of the water column can only occur under stratified conditions. Possibly the best-known example is the Black Sea, where a permanent pycnocline exists at approximately 200 meters depth. The hypolimnion is permanently anoxic (dissolved oxygen concentration is 0 mg/l). In other water bodies stratification is only seasonal. For example in subtropical regions during the monsoon season the high riverine discharge of fresh water results in a low saline surface layer on top of a high saline bottom layer (e.g. the Pearl River in China). In fresh water lakes, stratification is only temperature induced. The surface layer is heated during summer, while the bottom layer remains cool. The water column is destratified in winter time, when the surface water cools again.

In all cases the mechanism for oxygen depletion is equal. Since stratification only occurs in deep water, shallow areas are not considered and photosynthesis by plants can be considered as minor except maybe in very clear water. Photosynthesis by algae occurs near the water surface where light is still available. Algae convert light (energy), carbondioxide and other nutrients to organic matter, thereby releasing dissolved oxygen. When algae die, a part of the organic matter sinks towards the sediment. On its way down organic matter decays in a reversal of the photosynthesis reaction: oxygen is consumed. When the organic matter has settled through the pycnocline, it will still decay, but oxygen can not be replenished from the atmosphere as the stratification prevents the exchange over the pycnocline. The dissolved oxygen concentration in the hypolimnion will start to decrease. If the amount of organic matter reaching the hypolimnion is large enough, oxygen can be depleted completely. Oxygen consumption will continue after the organic matter has settled to the sediment, which is referred to as the Sediment Oxygen Demand (SOD).

Apart from primary production external sources form a second major source for organic matter. External sources are rivers and streams or sewage discharges.

Summarising, whether or not oxygen depletion in deep pits occurs depends on a number of things:

1. Does stratification occur - will the pit be sealed off from the atmosphere?
    - If no → oxygen depletion unlikely,
    - If yes → how long does the stratification last? To what extent is exchange between surface and bottom layer reduced?

Then, if stratification occurs:

2. What is the influx of organic matter into the pit? The higher the influx, the higher the change of oxygen depletion. In case there is a high primary production in the vicinity of the deep pit, the influx of organic matter will be higher.
3. What is the Sediment Oxygen Demand? For example, a peaty sediment has a high SOD and may thus results more easily in oxygen depletion than a sandy sediment.
4. Is there an external source of organic matter nearby?

The dissolved oxygen concentration in a pit depends on the combination of the components described above. The processes can be excellently simulated by numerical models such as Delft3D-WAQ. Even with some rudimentary information on stratification and organic matter concentration a first estimate of the oxygen concentration in a pit can be made relatively easily.

Pollutants

Pollutants are carried by the fine-grained sediment fractions (silt, clay, mud; particles smaller than 50 μm) carried by the fluid phase, but also, in dissolved form by the fluid phase (surface water, pore water).

Surface waters receive a substantial part of their dissolved load from atmospheric fall-out (blown soil and dust, biological emissions from living vegetation, burning of organic matter, vulcanic emissions) and anthropogenic emissions. Biological processes in the aquatic system will also affect the dissolved load (uptake by aquatic organisms).

Depressions in the sea bed such as pits, channels and trenches generally are sinks for suspended sediments and may therefore also act as sinks for pollutants. The deposited sediments may be stirred up by wave action during storm periods and transported by tide- and wind-induced drift currents.

4.3.3 Research questions

In case of large scale sand mining (hundreds of millions of cubic meters of sand) over a long period (5 to 10 years) it is necessary to study the quantitative impacts on the ecology of the North Sea. In the next table relevant outlines of research questions are defined. For each research question the most suitable type of research (either field study, laboratory study, modelling study or literature study) is suggested. More detailed definition and prioritisation of research will be elaborated later.

Physical effect	bottom	waterphase	foodweb
Present situation For the quantification of a significant effect, research into the present situation at the sand mining location is needed. see NB1	What habitats are found where. What bottom species are found, in what season/lifestage, in what densities and biomass. *field study*	What species (algae, zooplankton, larval stages of other species) are found in what season. What densities and biomass. What is the primary production. What are the macro-chemical characteristics (temperature, redox, oxygen, nutrients, suspended sediment, etc.) *field study*	What species of fish, birds and mammals are found in the area. In what season. What densities and biomasses. What is the habitat function of the area for these species (feeding, spawning, wintering, etc.). What is the structure of the local foodweb? What are the carbon fluxes in the foodweb? *field/model study*
Sand mining	What habitats will disappear. How long will they take to recover Are there any wrecks that will be lost. How do we define recovery of habitats. *field study*	How does the macro-chemistry change (temperature, redox, nutrients and oxygen) by mixing with porewater. What are the impacts on primary and secondary producers. *model/field study*	What species will be influenced by disturbance and loss of habitat.In what season. What timescale is needed to recover. Are there any ‘red list’ species that will be impacted. What are the foodweb effects. *field/literature study*
Burial	Some area will experience increased sedimentation rates. What are the impacts on species composition, densities and biomasses of impacted habitats. *lab/field study*		A change in composition and densities of bottom species might impact on the feeding behaviour of fish, birds and mammals. *field/literature study*
Hydro-morphological changes	Some areas will be deeper after mining. Current speeds will have changed. Sediment composition might have changed. Sedimentation rates may change. Polluted sediments may deposited. What are the impacts on species composition, biomass and densities.	Some areas will be deeper after mining. Current speeds will have changed. If stratification will exist, the impact on macro-chemistry and on primary and secondary producers should be checked.	Changes in species composition and productivity will impact on birds, fish en mammals.

	lab/field study	*model/field study*	*field/literature study*
Production of silt	What amount of what type of silt can be found in the mining location *field study*	What amount of silt will be released. What are the specific extinctions and settling rates. How will this impact primary and secondary production *lab/field study*	What are the impacts of increased turbidity on predators. How are changed primary and secondary production influencing the remainder of the foodweb *model/field study*
Mining method	What method will result in the smallest impacts (area, morpho-dynamics, silt production, duration). What are mitigating measures. *model/field study*	What method will result in the smallest impacts (macro-chemistry, turbidity, duration). What are mitigating measures *model/field study*	What method will result in the smallest impacts (turbidity, noise, disturbance, duration). What are mitigating measures *literature/field study*
Criteria for evaluation	Definition of recovery and impacts. Definition of critical thresholds.	Definition of impacts. Definition of critical thresholds.	Definition of impacts. Definition of critical thresholds.

NB1: The choice of the most appropriate temporal and spatial scales is important for modelling and field studies. These scales will depend on the process that is studied. This will differ for waterphase and bottom. Furthermore, for biology seasonal and yearly variations are normal. These long term natural variations have to be known to allow detection of the impact of the sand mining operation.

5 Mathematical description and available models of sand transport and morphology

5.1 Introduction

This section gives an overview of the available models at WL | Delft Hydraulics to simulate sediment transport and morphodynamic behaviour of mined (deepened) areas on the lower shoreface.
Various methods are discussed: simple engineering rules, analytical models, mathematical models such as: SUTRENCH, UNIBEST-TC, LOMOR and DELFT3D-MOR.

For each model an overview is given of the modelled processes, the basic simplifications and the types of boundary conditions which have to be specified. Furthermore, the suitability of the models for the various characteristic morphological areas (e.g. surfzone, lower shoreface) is indicated.

5.2 General mathematical description and simplifications

The most general description of the transport processes and associated morphological bed evolution (deposition, erosion and migration) can be obtained by a three-dimensional approach (see Figure 5.2.1) based on numerical solution of the advection-diffusion equation, which reads as (Van Rijn, 1987; Van Rijn and Meijer, 1991; Toro et al., 1989; Van Rijn, 1993; Jensen et al., 1999; Lesser, 2000):

$$\partial c/\partial t+\partial(uc)/\partial x+\partial(vc)/\partial y+\partial((w-w_s)c)/\partial z-\partial(\varepsilon_{s,x}\partial c/\partial x)/\partial x-\partial(\varepsilon_{s,y}\partial c/\partial y)/\partial y-\partial(\varepsilon_{s,z}\partial c/\partial z)/\partial z=0 \quad (5.2.1)$$

with: c=suspended sediment concentration, u,v,w= fluid velocities in x,y and z-directions, z=vertical direction, w_s= settling velocity, $\varepsilon_{s,x}$, $\varepsilon_{s,y}$, $\varepsilon_{s,z}$= sediment mixing coefficients in x, y and z-directions.

The depth-integrated (from the top of the bed load layer to the water surface) suspended transport rates in x and y-directions are defined by:

$$q_{s,x}=\int(uc-\varepsilon_{s,x}\partial c/\partial x)dz \text{ and } q_{s,y}=\int(vc-\varepsilon_{s,y}\partial c/\partial x)dz \quad (5.2.2)$$

The bed level evolution follows from:

$$\partial z_b/\partial t+\partial(q_{t,x})/\partial x+\partial(q_{t,y})/\partial y=0 \quad (5.2.3)$$

with z_b= bed level to horizontal reference plane, $q_{t,x}$=total depth-integrated sediment transport (bed load plus suspended load transport) in x-direction, $q_{t,y}$= total depth-integrated sediment transport (bed load plus suspended load transport) in y-direction.

These equations can be solved for given flow velocities, sediment mixing coefficients, settling velocity, sediment concentrations at all boundaries and at initial time (t=0).

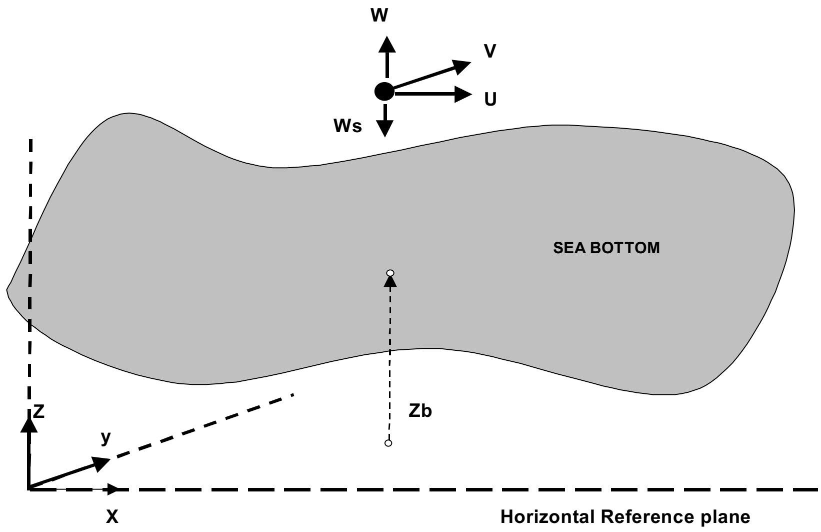


Figure 5.2.1 *Definition sketch for three-dimensional conditions*

A two-dimensional vertical approach can be applied in case of a relatively long deepened area (channel or trench). This situation basically refers to the modelling of one streamtube crossing the channel (see Figure 5.4.1). The advection-diffusion equation reads as (Van Rijn, 1986a,b; 1987, 1993):

$$\partial c/\partial t+\partial(buc)/\partial x+\partial(b(w-w_s)c)/\partial z-\partial(b\varepsilon_{s,x}\partial c/\partial x)/\partial x-\partial(b\varepsilon_{s,z}\partial c/\partial z)/\partial z=0 \quad (5.2.4)$$

with: b=width of the streamtube.

The SUTRENCH model is based on this approach, see Section 5.4.1.

5.3 Simple engineering rules

Deposition formula

The reduction of the suspended sediment in a relatively long channel (1D approach) due to decrease of the transport capacity can schematised quite simply by an exponential decay curve. Assuming an oblique flow direction and a rectangular cross-section (Figure 5.3.1), the reduction of the suspended sediment transport ($q_{s,x}$) is:

$$q_{s,x}= (b_0/b_1)q_{s,0} - [(b_0/b_1)q_{s,0} - q_{s,1}](1-e^{-Ax})= (b_0/b_1)q_{s,0} (e^{-Ax})+q_{s,1}(1-e^{-Ax}) \quad (5.3.1)$$

with: b_0= streamtube width of approaching flow; b_1=streamtube width in channel, $q_{s,0}$= suspended transport capacity of approaching flow (per unit width), $q_{s,1}$= suspended transport capacity in channel (per unit width), x= coordinate along streamtube, A=coefficient.

This approach has been frequently used to estimate the backfilling of relatively narrow navigation channels and pipeline trenches (Mayor et al, 1976; Lean, 1980; Bijker, 1980 and Eysink-Vermaas, 1983). The trapezoidal cross-section is schematised to a rectangular cross-section making intersections halfway the side slopes. The effective deposition length is the length between the intersection points, yielding $L=B/(\sin\alpha_1)$. Jensen et al. (1999) have compared the transverse component of the sand transport distribution in an oblique channel (approach angle=60^o, h_1/h_o=1.5) using the engineering method of Mayor et al. (1976) and a full 3D model. The results show that the exponential decay function of Mayor et al. (1976) considerably overestimates the adjustment process to the new equilibrium sand transport inside the channel.

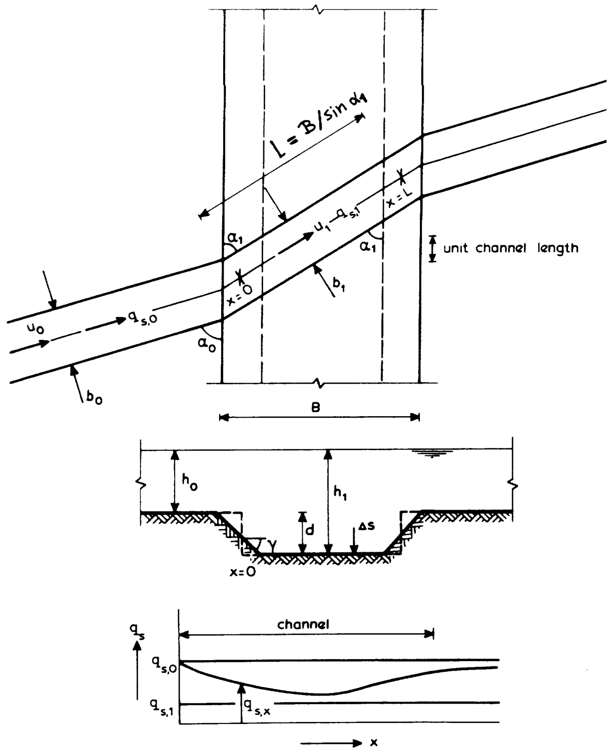


Figure 5.3.1 *Definition sketch*

Trapping efficiency graphs

Van Rijn (1987) has introduced two graphs, which can be used to determine the trapping efficiency of sediments from oblique and cross flow over an infinitely long channel. The graphs are based on simulations using the SUTRENCH model (see Section 5.4.1) using current velocities according to Eqs. 3.2.6 to 3.2.8. The definition sketch is shown in Figure 5.3.1.

The trapping efficiency (e) is defined as the relative difference of the incoming suspended load transport ($q_{s,o}$) and the minimum suspended load transport in the channel ($q_{s,1,minimum}$).

$$e=(b_o q_{s,o}-b_1 q_{s,1,minimum})/(b_o q_{s,o}) \quad (5.3.2)$$

The basic parameters determining the trapping efficiency of a channel, are: approach velocity ($v_{r,o}$), approach angle (α_o), approach depth (h_o), approach bed-shear velocity ($u_{*,o}$), particle fall velocity (w_s), wave height (H), channel depth (d), channel width (B), channel side slopes ($\tan\gamma$) and bed roughness (k_s).
In all, 300 computations have been made using:
- approach velocity $v_{r,o}$= 1 m/s and approach water depth h_o= 5 m,
- approach angles $\alpha_o = 15^o$ to 90^o,
- channel depths d= 2 to 10 m,
- channel width (normal to axis) B= 50 to 500 m,
- particle fall velocity w_s= 0.0021 to 0.036 m/s,
- bed roughness k_s= 0.2 m.

The influence of the relative wave height (H/h) and relative bed roughness (k_s/h) on the trapping efficiency (e) is relatively small and has therefore been neglected. The error of the e-parameter is about 25% for an approach velocity in the range of 0.8 to 1.2 m/s, H/h varying in the range of 0 to 0.3 and k_s/h varying in the range of 0.02 to 0.06.
The trapping efficiency (e) values are shown in Figures 5.3.2 and 5.3.3. The e-values increase with increasing approach angle and are maximum for an approach angle of 90^o (maximum reduction of current velocity in channel). The graphs should only be used to get a rough estimate of the sedimentation.

The sedimentation rate (ΔS) per unit channel length immediately after dredging can be determined from:

$$\Delta S= (e_s\, q_{s,o} +\ e_b q_{b,o}) \sin\alpha_o \qquad (5.3.2)$$

with: e_s= trapping efficiency for suspended load (Figs. 5.3.2 and 5.3.3), e_b= trapping efficiency (about 1) for bed load, $q_{s,o}$ = incoming suspended load transport per unit width, $q_{b,o}$ = incoming bed load transport per unit width.

As a computation example, the following values are used:
- approach velocity $v_{r,o}$= 1 m/s and approach water depth h_o= 5 m,
- approach angle $\alpha_o = 30^o$,
- channel depth d= 5 m,
- channel width (normal to axis) B= 200 m,
- particle fall velocity w_s= 0.01 m/s,
- side slope $\tan\gamma$=0.1,
- approach bed-shear velocity $u_{*,o}$= 0.05 m/s.

The dimensionless parameters are: $w_s/u_{*,o}$= 0.2, d/h_o= 1, B/h_o= 40, yielding e= 0.5 from Figure 5.3.2. Assuming an incoming suspended load transport of 1 kg/s/m, the sedimentation rate per unit channel length is: ΔS= 0.5x1x sin 30^o=0.25 kg/s/m.
The total sedimentation (mass) in one month in a channel with a length of 1000 m is:

M_s=0.25x(30x24x3600)x(1000)= 648 10^6 kg.

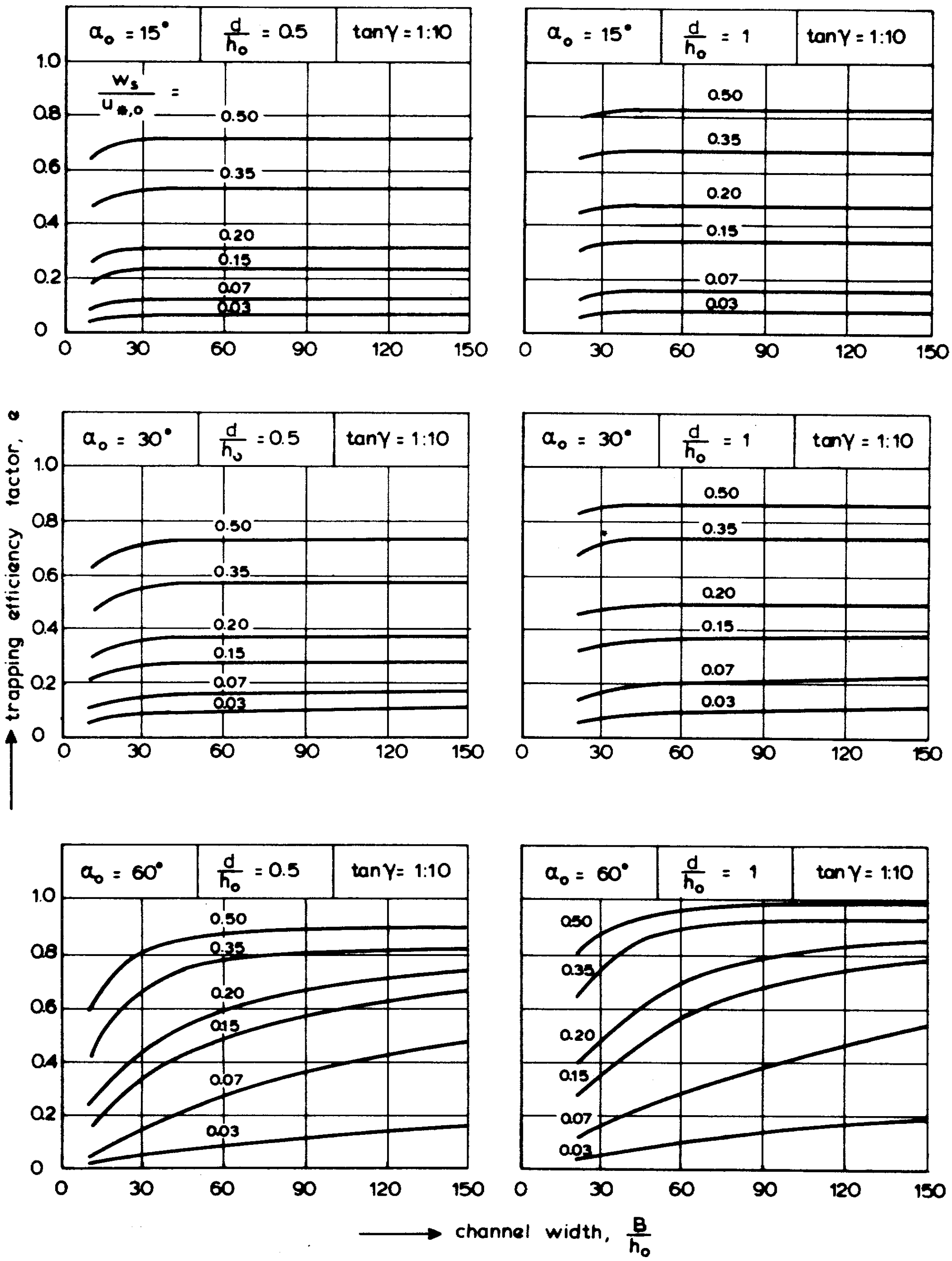


Figure 5.3.2 *Trapping efficiency (e) for approach angles of α_o= 15^o, 30^o and 60^o*

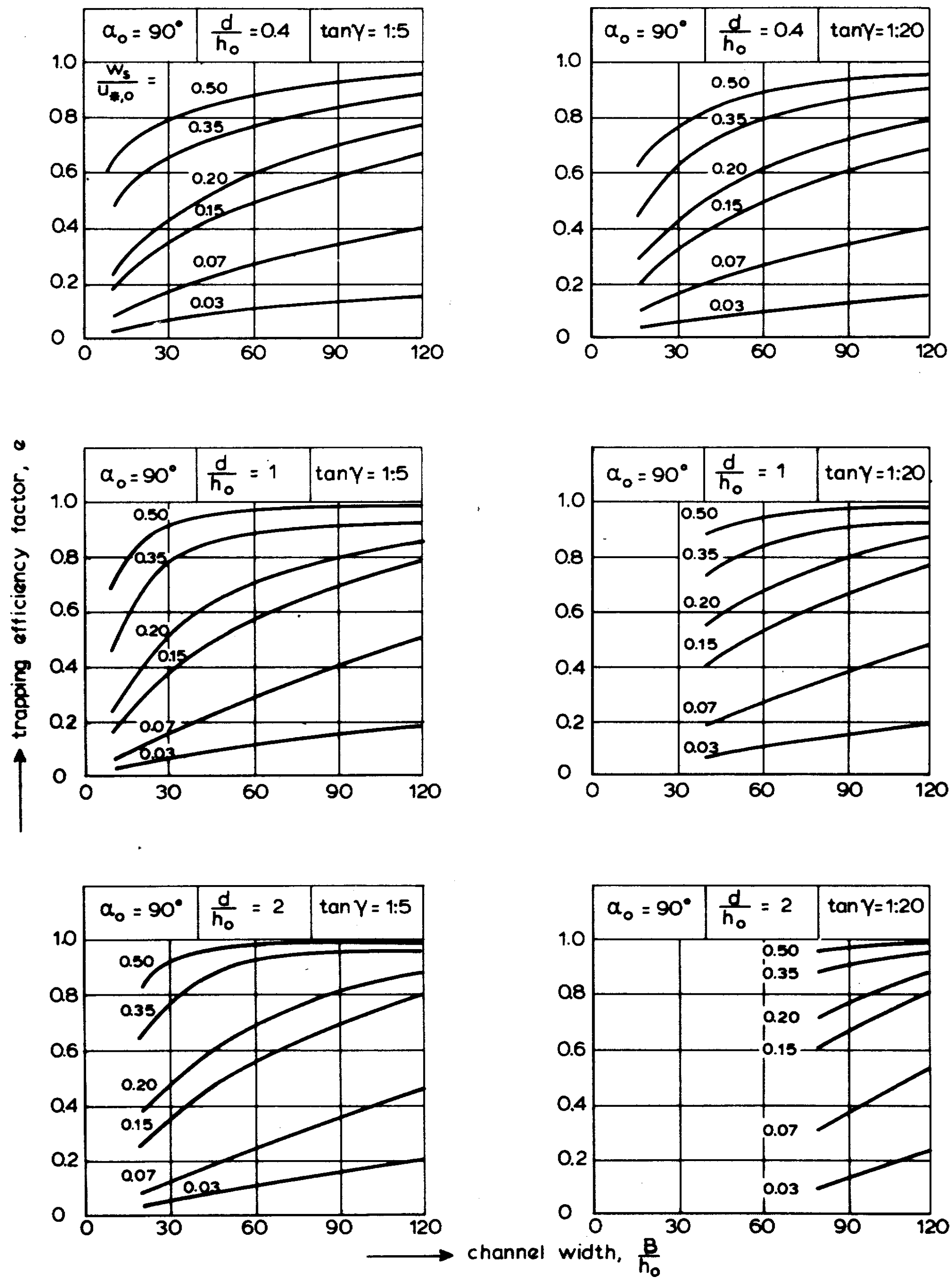


Figure 5.3.3 *Trapping efficiency (e) for approach angles of $\alpha_o = 90^o$*

5.4 Analytical models for flow perpendicular to channel

Analytical models based on relatively simple equations representing the basic physics have been developed to study the morphological behaviour of schematised channels, trenches and mining pits.
Van der Kreeke et al. (2001) have studied the morphological behaviour of a channel (initial cross-section schematised as Gaussian function, see Figure 5.4.1), which is subject to tidal currents and waves. The tidal currents are rectilinear and perpendicular to the longitudinal axis of the channel. The tidal velocity comprises the residual velocity M_0 and the harmonic constituents M_2 and M_4. Separate equations have been derived for bed load and suspended load transport.
In case of dominant bed-load transport conditions the bed level changes are represented by:

$$\partial a/\partial t+\partial q_b/\partial x=0 \qquad (5.4.1)$$

with a=channel depth below the surrounding bed and q_b= bed load transport.
The bed load transport (q_b) is represented by:

$$q_b=fU^3[(1+|U|)\lambda\partial a/\partial x] \qquad (5.4.2)$$

with U= depth-averaged current velocity, f= coefficient (including friction effect), λ= coefficient. The effect of waves on the sediment transport is incorporated by use of a stirring term. The equations are averaged over the tidal time scale assuming that the morphological time scale is large compared to the tidal period. To determine the leading order terms, the variables are scaled and the equations are written in dimensionless form. The relative magnitude of the terms is determined by a small parameter, being the ratio of channel depth and undisturbed water depth. Retaining only leading order terms, the equation for the bed level reduce to an advection-diffusion equation with constant coefficients:

$$\partial a/\partial t+c(\partial a/\partial x)-K(\partial^2 a/\partial x^2)=0 \qquad (5.4.3)$$

with c= migration velocity and K=diffusion coefficient. The initial Gaussian cross-section (see Figure 5.4.1) migrates with speed c and the width σ increases (widening) at rate $d\sigma/dt=(0.5K/t)^{0.5}$.

In case of dominant suspended load transport the bed level changes are represented by:

$$\partial a/\partial t+\alpha(E-S)=0 \qquad (5.4.4)$$

with E= erosion function, S= deposition function, E-S= $w(c_a-c)$, c_a= near-bed concentration, c= concentration, w= fall velocity, α= coefficient (including sediment density and porosity). The settling term is described as: $wc_a=\gamma U^2$ with γ=coefficient.
The suspended load transport is modelled as:

$$\partial c(h+a)/\partial t+\partial Uc(h+a)/\partial x-D(h+a)\partial^2 c/\partial x^2=E-S \qquad (5.4.5)$$

with D= dispersion coefficient (about 10 m^2/s). The first order solution can also be described by an advection-diffusion equation with constant coefficients.

The analytical solution shows that the channel cross-section migrates, widens and shallows. The velocity of migration is a function of the residual velocity and the amplitudes and phases of the M_2 and M_4 constituents. Widening and shallowing is a result of diffusion. For bed-load transport, diffusion derives from the effect of the bed slope on the sediment transport. For suspended load transport, diffusion is assumed to be the result of velocity shear and vertical turbulent mass exchange (shear dispersion). When accounting for higher order non-linear terms, an initially symmetric cross-section becomes asymmetric. Application to the access channel (water depth h= 17 m, maximum channel depth a_{max}= 3 m, U_{max}= 0.55 m/s, fall velocity= 0.02 m/s) to the port of Amsterdam yields channel displacement velocities of c= 1.3 m/year for bed-load transport case and c= 1.8 m/year for suspended load transport case. The diffusion coefficient is about K= 300 m^2/year.

Summarising, an analytical solution is proposed for two cases: bed-load and suspended load transport. It is shown that for both transport modes, to a leading order the evolution of the cross-section is governed by an advection-diffusion equation with constant coefficients. This implies that the cross-section of the channel migrates, shallows and widens. An initially symmetric cross-section remains symmetric. Migration is the result of tidal residual velocities and tidal asymmetry. Shallowing and widening is the result of a diffusion process. For bed-load transport the diffusion enters through the slope term in the sediment transport equation. For suspended load transport, diffusion enters by introducing a gradient- type suspended sediment transport with a diffusion coefficient D. For both transport modes holds that only the M_2 velocity constituent plays a role in the diffusion process.
When including higher order terms, the governing equations become analytically intractable and recourse has to be taken to numerical solutions. Only when introducing simplifications, the equations can be solved analytically as shown for bed-load transport when neglecting the slope term in the sediment transport equation. In that case the updrift slope of the channel becomes steeper and the downdrift slope becomes gentler. The result is that an initially symmetric cross-section no longer remains symmetric.

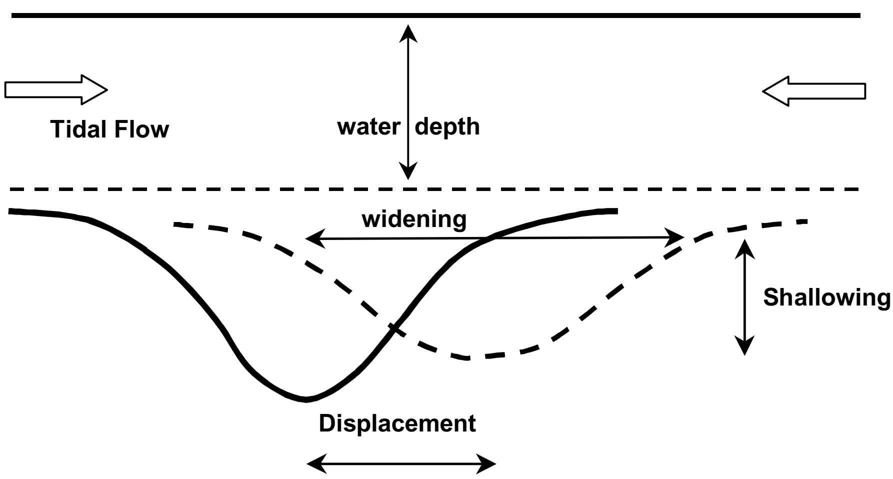


Figure 5.4.1 *Migration of Gaussian-shaped channel*

5.5 Analytical models for flow parallel to channel

Fredsøe (1978) has proposed a method to compute the morphological behaviour of a channel parallel to the flow by considering the effects of gravity forces and drag forces on the bed-load particles moving on the side slopes of the channel. The resulting force is inclined towards the channel bottom and thus causes infill of the channel (see Figure 5.5.1). The angle ψ between the direction of the force on the particle and the flow line is assumed to be equal to the ratio of the transverse side slope angle γ and the dynamic friction angle ϕ of the bed material particles, which reads as:

$$\tan \psi = \tan \gamma / \tan \phi \qquad (5.5.1)$$

Assuming that the variation of the bed-load transport over the side slope is relatively small, a diffusion-type equation for the bed level can be derived, as follows:

$$\partial z_b/\partial t= \zeta\, \partial^2 z_b/\partial x^2 \qquad (5.5.2)$$

with: $\zeta=q_{bo}/[(1-p)(\tan \phi)]$= constant diffusion coefficient (in m^3/ms), q_{bo}= bed-load transport in flow direction on middle of slope (in m^3/ms), $\tan \phi$=dynamic friction angle (about 1.5), p= porosity factor (0.4), x=coordinate transverse to channel axis, z_b= bed level to channel bottom (Fig. 5.5.1).

The volume of sand transported from the side slopes into the channel after time t can be expressed as:

$$\Delta S= 2d\, (\zeta/\pi)^{0.5} [(t+t_o)^{0.5} - t_o^{0.5}] \qquad (5.5.3)$$

with ΔS= infill volume of sand (in m^3/m) after time t, d= initial channel depth (below surrounding bottom), $t_o=(\pi d^2)/(64\ \zeta\ \tan\gamma)$=coefficient (in seconds), γ= initial transverse side slope angle, t= time (in seconds).

According to Fredsøe (1978), this approach is also valid for currents crossing a channel under a small angle relative to the channel axis. In that case the longitudinal component of the bed-load transport on the side slope should be used into the equation for channel sedimentation.

Another approach is based on the transverse bed-load transport ($q_{b,n}$) on the side slope of a straight channel. This was studied by Ikeda (1982), yielding the following formula:

$$q_{b,n}=[1.5(\tau_{b,cr}/\tau_b)^{0.5} \tan\gamma]q_{bo} \qquad (5.5.4)$$

with $\tau_{b,cr}$= critical bed-shear stress and τ_b= bed-shear stress exerted by the flow (and/or waves).

The sedimentation (in m^3/m) in the horizontal bottom section of the channel by lateral bed-load transport from two side slopes after time t (in s) can be determined as:

$$\Delta S= 2\, (1-p)^{-1}\, t\, [1.5(\tau_{b,cr}/\tau_b)^{0.5} \tan\gamma]q_{bo} \qquad (5.5.5)$$

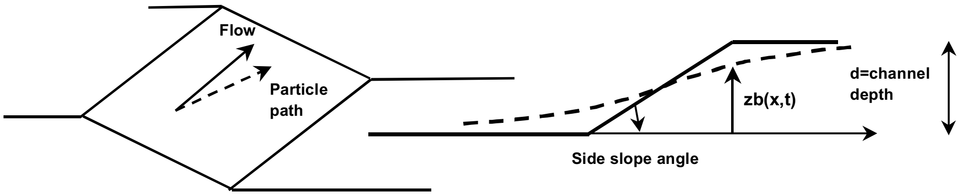


Figure 5.5.1 *Morphological behaviour of side slope in parallel flow*

5.6 Mathematical models

5.6.1 Two-dimensional vertical model for oblique flow conditions: SUTRENCH model

The SUTRENCH model (Van Rijn and Tan, 1985; Van Rijn, 1986a,b; Delft Hydraulics, 1985) is a two-dimensional vertical (2DV) mathematical model for the simulation of bed-load and suspended load transport under conditions of combined quasi-steady currents and wind-induced waves over a pit/channel/trench oblique to the flow, see Figure 5.6.1. All processes (parameters) in the direction normal to the streamtube direction are assumed to be constant.

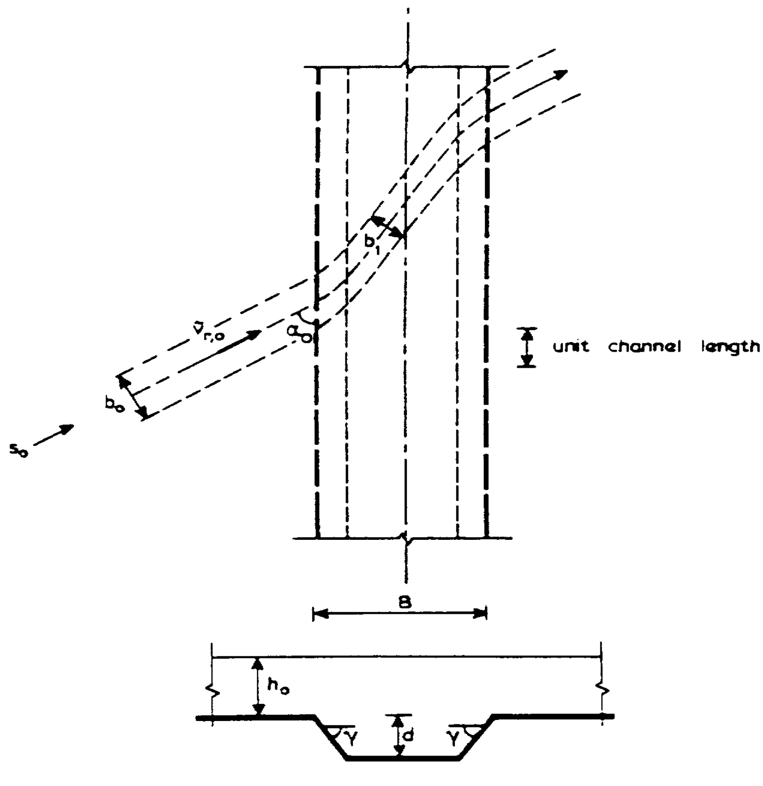


Figure 5.6.1 *Oblique flow and transport across a channel/pit (two-dimensional streamtube approach)*

Basic processes taken into account:

Hydrodynamics
- modification of velocity profile and associated bed-shear stress due to presence of waves,
- modification of velocity and associated bed-shear stress due to the presence of sloping bottom,

Sediment transport
- advection by horizontal and vertical mean current,
- vertical mixing (diffusion) by current and waves,
- settling by gravity,
- entrainment of sediment from bed due to wave- and current-induced stirring,
- bed-load transport due to combined current and wave velocities (instantaneous intra-wave approach),
- slope-related transport components (bed load),
- effect of mud on initiation of motion of sand,
- non-erosive bottom layers.

Basic simplifications are:

Hydrodynamic
- logarithmic velocity profiles and associated bed-shear stress in conditions with waves (steep-sided trenches and channels can not be modelled),
- shoaling and refraction of wind waves is not implicitly modelled, these effects can be taken into account by the input data,
- current refraction (veering) is not implicitly modelled,

sediment transport
- steady state sediment mass conservation integrated over the width of the flow (stream tube approach),
- no longitudinal mixing (diffusion),
- no wave-related suspended sediment transport (no oscillatory transport components),
- uniform grain size (no mixtures),

Numerical
- forward-marching numerical scheme (transport due to near-bed return currents can not be modelled),
- explicit Lax-Wendorf numerical scheme for bed level changes (smoothing effects may occur).

Boundary conditions to be specified, are:
- water depth, flow width (stream tube width, discharge is constant) and bed level along computation domain,
- wave heights along computation domain,
- equilibrium or non-equilibrium sediment concentrations at inlet (x= 0); model has option to generate equilibrium concentrations,
- bed concentration or bed concentration gradient is prescribed as function of bed-shear stress and sediment parameters,
- sediment, settling velocity, and bed roughness.

The SUTRENCH model is a process-based model to be applied at a space-scale of 1 to 5 km and at a time scale of 1 to 100 years (imposed by computation time and available computer memory). Practical application requires detailed knowledge of the sediment composition along the bed and the incoming sediment transport (at inlet boundary x=0).

The SUTRENCH model is applicable in regions outside the surfzone where wave breaking is limited. Since it is a 2DV model all processes normal to the computational direction are assumed constant. This can impose limitations to the applicability of SUTRENCH if 2DH or 3D effects play a dominant role.

The sand transport model (TRANSPOR, submodule of SUTRENCH model) can be used to generate equilibrium sand transport rates at the inlet boundary (x=0).

5.6.2 Two-dimensional vertical model for oblique wave conditions: UNIBEST-TC model

The UNIBEST-TC 2.0 model is a two-dimensional vertical (2DV) cross-shore mathematical model for the simulation of bed-load and suspended load transport and associated morphological changes under conditions of wind-induced (breaking) waves over a shoreparallel pit/channel/trench, see Figure 5.6.2. All longshore processes (parameters) are assumed to be constant (uniform coast).

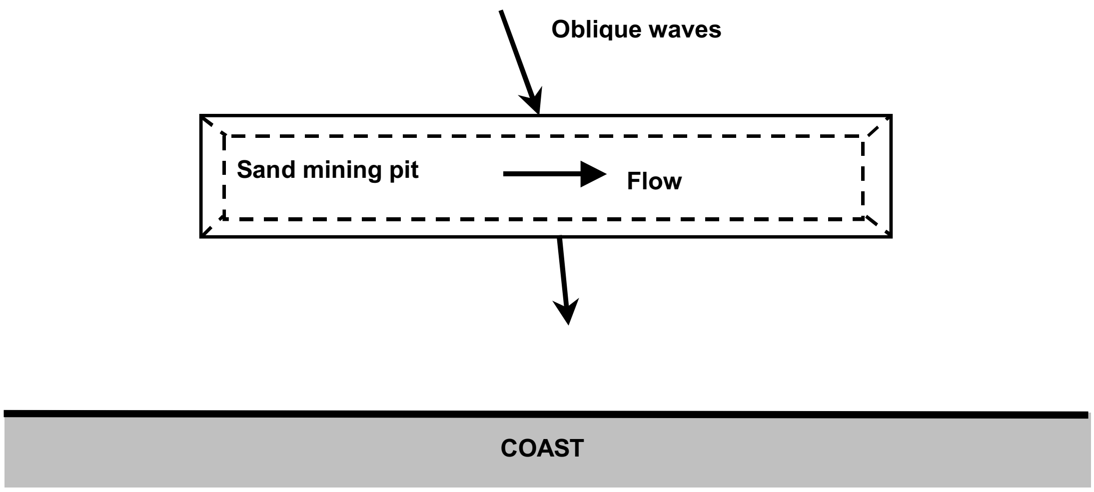


Figure 5.6.2 *Oblique waves over a channel/pit in cross-shore direction (alongshore uniform conditions)*

Basic processes taken into account, are (Delft Hydraulics, 1997):

Hydrodynamic

- wave energy propagation, shoaling and refraction,
- wave energy dissipation by bottom friction and wave breaking,
- longshore tidal current including bottom friction,
- near-bed currents and asymmetry of orbital velocities,
- bound-long waves related to wave groups,
- modification of velocity profile and associated bed-shear stress due to presence of waves,

Sediment transport

- vertical mixing (diffusion) by current and waves (suspended load transport),
- entrainment of sediment from bed due to wave- and current-induced stirring (suspended load transport),
- horizontal advective transport (suspended load transport),
- bed-load transport due to combined current and wave velocities (intra-wave approach),
- slope-related transport components (bed load).

Basic simplifications are:

Hydrodynamic

- deterministic spectral approach for wave field,
- linear wave theory,
- parameterised approach for long-period waves,
- no effect of pit on longshore tidal current,
- quasi-steady approach for mean currents,

Sediment transport

- no longitudinal mixing (diffusion),
- no wave-related suspended sediment transport,
- uniform grain size (no mixtures),

Numerical

- implicit scheme for bed level changes.

Boundary conditions to be specified, are:

- mean water depth and bed level along computation domain,
- rms-wave height and period at inlet (x=0),
- mean longshore current at inlet,
- sand transport at outlet (beach boundary),
- sediment, bed roughness and calibration parameters.

The UNIBEST-TC 2.0 model is a process-based model to be applied at a space-scale of 1 to 5 km and at a time scale of 1 to 10 years. UNIBEST-TC is a so-called profile model. It has primarily been designed to model the (cross shore) morphodynamic behaviour of the surfzone under the influence of (breaking) waves, wind and tidal currents.

A detailed overview of the formulations is given in Delft Hydraulics (1997). The sand transport model (submodule of UNIBEST-TC 2.0 model) is based on the TRANSPOR model (Delft Hydraulics, 2000a).

5.6.3 Two-dimensional model for shoreparallel conditions: LOMOR-model

The LOMOR model is a two-dimensional horizontal (2DH) mathematical model for the simulation of bed-load and suspended load transport and associated morphological changes under conditions of shoreparallel flow in a pit/channel/trench, see Figure 5.6.3. All cross-shore processes (parameters) are assumed to be constant (horizontal bottom).

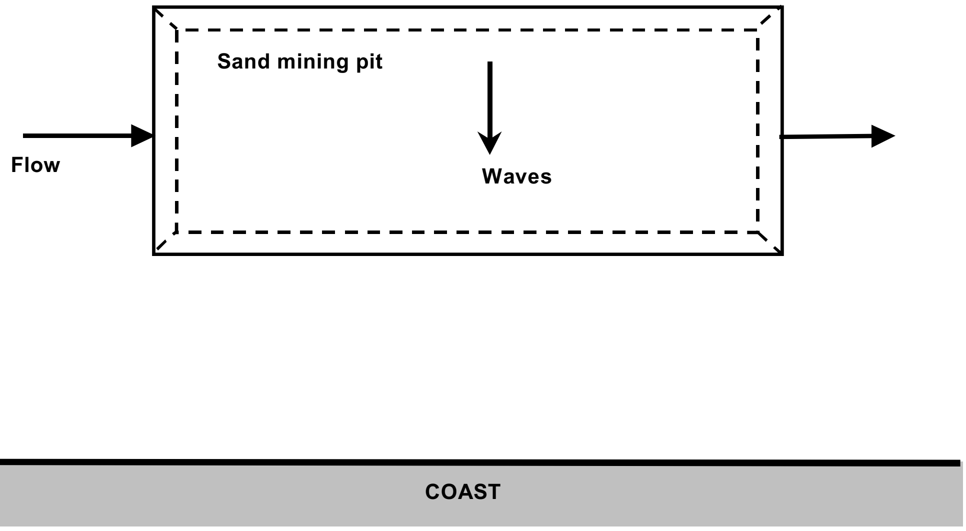


Figure 5.6.3 *Shoreparallel flow over channel/pit in longshore direction (cross-shore uniform conditions)*

Basic processes taken into account, are (Rijkswaterstaat, 1990):

Hydrodynamic
- depth-averaged longshore tidal flow including advection and bottom friction effects,
- acceleration and deceleration effects at upstream and downstream slopes,
- constant wave height, near-bed orbital velocity based on linear wave theory.

Sediment transport
- bed-load transport due to combined current and wave velocities based on Bailard-Bagnold approach,
- horizontal advective suspended load transport,
- equilibrium suspended load transport based on Bailard-Bagnold approach,
- spatial lag effects (Galapatti method).

Basic simplifications are:

Hydrodynamic
- constant wave height in pit,
- depth-averaged flow without wave-current interaction,
- quasi-steady approach for mean currents (tidal cycle schematised into quasi-steady periods),

Sediment transport
- no vertical and longitudinal mixing (diffusion),
- no wave-related transport (no oscillatory transport components),
- no slope effect on bed load transport,
- uniform grain size (no mixtures),

Boundary conditions to be specified, are:

- mean water depth and bed level along computation domain,
- mean longshore current at upstream boundary (x=0),
- rms-wave height and period,
- sediment, bed roughness and calibration parameters.

The LOMOR model is a process-based model to be applied at a space-scale of 1 to 10 km and at a time scale of 1 to 50 years.

The model has been used to compute the morphological development of mining pits over 40 years in the North Sea.

5.6.4 Two-dimensional horizontal and three-dimensional models

The DELFT-MOR model is a universal field model, simulating waves, currents, sand transport and bed evolution on a 2DH or 3D grid.

The model package DELFT-MOR is based on the numerical solution of the hydrodynamics and sediment dynamics on short time scales (seconds to hours) and associated morphological bed level changes in a loop (feed back) system.

The model system consists of four main modules: Flow, Wave, Transport and Bottom.
The sand transport computations can be operated either in an ‘off-line’ or an ‘on-line’ mode.

In the offline mode the transport rates are computed in the subroutine Transport; various sand transport capacity formulations for bed-load and suspended load transport can be applied; lag effects (non-local response) of the suspended load transport can be taken into account using the Galapatti method.

A new functionality, ‘sediment on line’ has been introduced in the Flow module, so that the transport components can be calculated during the ‘Flow’-run. In this ‘on-line’ mode the transport rates can be computed using:

- a multi-layer model approach (three-dimensional; 3D) based on the numerical solution of the 3D advection-diffusion equation (see Lesser, 2000);
- a one layer model approach (depth-averaged horizontal; 2DH) based on sand transport capacity formulations for bed-load and suspended load transport excluding or including the Galapatti method to account for the lag effects of the suspended load transport (see van Rijn et al., 2001).

The total transport in the current direction (‘sediment on-line’ approach) consists of bed-load and suspended load transport. The total transport in the wave direction is described in a similar way. Both transport components (in current and in wave direction) are transformed into the local coordinate system of the curvilinear grid to determine the spatial gradients of the total transport rate.

Using this detailed approach, the prediction horizon is limited to a few years at present stage of research (Walstra, 1994; Roelvink, 1999; Steijn et al., 1998; Wang et al., 1995; De Vriend et al., 1993). An efficient method to increase the prediction horizon is the integration of the sediment transport processes over longer time scales, as used in the DELFT-RAM model approach (Roelvink et al., 1998; Roelvink et al., 2001).

Basic processes taken into account, are:

Hydrodynamic
- wave energy propagation, shoaling, diffraction and refraction,
- wave energy dissipation by bottom friction and wave breaking,
- wave growth by wind input,
- non-steady fluid motion (homogeneous and non-homogeneous) based on continuity and momentum equations,
- advanced turbulence models for modelling of internal shear stresses,
- modification of bed-shear stress due to presence of waves,

Sediment transport
- vertical mixing (diffusion) by current and waves (suspended load transport),
- entrainment of sediment from bed due to wave- and current-induced stirring (suspended load transport),
- horizontal advective and diffusive transport (suspended load transport),
- bed-load transport due to combined current and wave velocities,
- slope-related transport components (bed-load).

Basic simplifications are:

Hydrodynamic
- deterministic spectral approach for wave field,
- linear wave theory,

Sediment transport
- uniform grain size (no mixtures), but a spatially non-uniform grain size can be described.

The DELFT-MOR model is a process-based model to be applied at a space-scale of 10 to 100 km and at a time scale of 1 to 10 years.

5.6.5 Evaluation of models

The SUTRENCH, UNIBEST-TC 2.0, LOMOR and DELFT-MOR models are all process-based models, simulating bed-load and suspended load transport and associated bed level changes.

The SUTRENCH-2DV quasi-steady state model is based on detailed modelling of the sand transport processes, which are represented by expressions representing diffusive, advective and settling processes (lag effects). The bed-load transport takes all transport components into account. The wave-related (oscillatory) suspended load transport is not modelled. The hydrodynamics are not modelled, but have to be given as input data (wave height along domain, discharge, width of streamtube). The model is applicable to sedimentation and erosion problems, provided that the hydrodynamic data are known.

UNIBEST-TC 2.0 is a 2DV model, which gives a detailed description of the hydrodynamic processes (waves and currents) in cross-shore direction, assuming invariant conditions alongshore. The bed-load and suspended load transport processes are represented by assuming local equilibrium conditions (no lag effects). The bed-load transport takes all transport into account. The wave-related (oscillatory) suspended load transport is not modelled. The model is only applicable for simulation of cross-shore profile evolution.

LOMOR is a 2DH model, which gives a detailed description of the flow in longshore direction, assuming invariant conditions in cross-shore direction. The bed-load and suspended load transport processes are based on the Bailard-Bagnold approach. Spatial lag effects on the suspended load transport are taken into account using the Galapatti method. The wave-related (oscillatory) transport components are not modelled. The model is only applicable for simulation of longshore bed evolution of mining pits.

The DELFT-MOR non-steady model is a universal field model, simulating waves and currents on a 2DH or 3D grid; the bed-load and suspended load transport can be simulated by using a local equilibrium or non-equilibrium (lag effects) approach.

6 Data sets and hindcast studies

6.1 Introduction

In this Chapter an inventory is given of the available data sets and hindcast studies related to sedimentation in channels, trenches and pits. The data sets are described in terms of:

- steady and non-steady flow,
- steady and non-steady flow superimposed by waves.

The measured parameters generally are:

- **laboratory cases**: flow discharge, incoming sand transport (sand feed in flume), water depth, wave height, flow velocity and sand concentration profiles at start of test, bed level changes as function of time, bottom samples, suspended sand samples;
- **field cases**: flow discharges, (tidal) water depths, tidal levels, wave heights, bed level changes, bottom samples, flow velocity and suspended sediment concentrations in some cases.

The data sets are mentioned in Sections 6.2 and 6.3. It is highly recommended to make a database of the available data sets.

6.2 Steady and non-steady flow

6.2.1 Data sets used in hindcast studies

The following hindcast studies (laboratory and field conditions) have been performed:

1. migration and sedimentation of a trench in a laboratory flume;
   (water depth= 0.39 m, current velocity= 0.51 m/s, sand= 0.16 mm),
2. sedimentation of a trial dredge channel in Western Scheldt estuary;
   (water depth= 7.5-10.5 m, current velocity= 0.5-1.1 m/s, sand= 0.18 mm),
3. Sedimentation of a trial dredge channel in Eastern Scheldt Estuary;
   (water depth= 20-22 m, current velocity= 0.7-1.15 m/s, sand= 0.3 mm);
   These cases (1 to 3) are described in:
   - Delft Hydraulics, report R975 part II, 1977: Numerical model for non-steady suspended transport (in Dutch),
   - Journal of Hydraulics Division, ASCE, Hy 5, 1979: Model for suspended sediment transport, by Kerssens, PJ.M, Prins, A. and Van Rijn, L.C.,
   - Delft Hydraulics, report R1267 part V, 1980: Computation of siltation in dredged trenches,
   - Delft Hydraulics, report S488 part IV, 1985: Sutrench-model; Two-dimensional vertical mathematical model for suspended sediment transport by currents and waves,
   - Rijkswaterstaat Communications, No. 41, 1985: Sutrench-model; Two-dimensional vertical mathematical model for sedimentation in dredged trenches by currents and waves, by L.C. van Rijn and G.L. Tan,
   - Journal of Hydraulic Engineering, ASCE, Vol. 112, No. 6, 1986: Mathematical modelling of suspended sediment in nonuniform flows, by L.C. van Rijn,
   - Delft University of Technology, Doc. Thesis, 1987: Mathematical modelling of morphological processes in the case of suspended sediment transport, by L.C. van Rijn,

4. trial dredge pit near Barrow in Furness, England
   (water depth= 3-9 m, current velocity= 0.5-0.7 m/s, sand= 0.1-0.2 mm)
   - Delft Hydraulics, Report H1208, 1991, Design of the Access channel to Barrow in Furness, Task 5,

5. sedimentation in a trial dredge channel in Asan Bay, Korea
   (depth= 7-11 m, current vel.= 0.7-0.8 m/s, sand= 0.2 mm),
   - Delft Hydraulics, report S488 part IV, 1985: Sutrench-model; Two-dimensional vertical mathematical model for suspended sediment transport by currents and waves,

6. siltation in a trial dredge channel near Bahia Blanca, Argentina,
   (depth= 11 m, current vel.= 0.3 m/s, mud),
   - Delft Hydraulics, report S488 part IV, 1985: Sutrench-model; Two-dimensional vertical mathematical model for suspended sediment transport by currents and waves,
   - Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 112, No. 5, 1986: Sedimentation of dredged channels by currents and waves, by L.C. van Rijn,
   - Sedimentation computations for the access channel to the port of Bahia Blanca, Argentina, by Van Overeem, J., 1985, In: Acces Channels Ports, Post Academic Course (PATO), Civil Engineering, Delft University of Technology, Delft, The Netherlands.
7. sedimentation in trial dredge channel in River IJssel near Deventer, Netherlands
   - Van Rijn, L.C., 2001. Lecture notes on morphology, IHE, Delft.

6.3 Steady and non steady flow with waves

6.3.1 Data sets used in hindcast studies

1. migration and sedimentation of a channel in a laboratory flume,
(water depth= 0.24 m, current vel.= 0.18 m/s, waves= 0.1 m, sand= 0.1 mm),
- *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 112, No. 5, 1986: Sedimentation of dredged channels by currents and waves, by L.C. van Rijn,*
- Delft Hydraulics, report S488 part IV, 1985: Sutrench-model; Two-dimensional vertical mathematical model for suspended sediment transport by currents and waves,

2. sedimentation in trench in laboratory wave-current basin
(water depth=0.4 m; waves=0.1 m, current vel.=0.25 m/s, sand=0.1 mm)
- Delft Hydraulics, Report Z2378, 1998, Sand transport at the middle and lower shoreface of the Dutch coast; Simulations of SUTRENCH-model and proposal for large-scale laboratory tests, by D.J.R. Walstra, L.C van Rijn and S.G.J. Aarninkhof

3. sedimentation in navigation channel Eurochannel near Rotterdam,
(water depth= 19-22 m, current vel.= 0.7-1.1m/s, waves= 0.5-4 m, sand= 0.21 mm)
- University of Twente/Delft Hydraulics, Report Z2268, 1997, 1998. Morphological impact of large-scale marine sand extraction, by T. Hoitink.
- Delft Hydraulics, Report Z2255, 1997, Long term effects of Maasvlakte-2 and associated sand mining on the Dutch coast, by D.J.R. Walstra and others.

4. sedimentation in navigation channel to Suez Canal, Egypt,
(water depth= 10 to 20 m, current velocity=0.1 to 0.5 m/s, waves= 1 to 3 m, sand=0.1 to 0.15 mm)
- Hassan, R., Sadek, E., and Van Rijn, L.C., 1992. Prediction of the Siltation in the Northern Entrance of the Suez Canal for the Second Development Stage, Second Int. Conf. on Hydr. Modelling, Bradford, United Kingdom.

5. sedimentation in pipeline trench in surf zone near Kærgaard Plantation, Denmark
(water depth= 3 to 5 m, current =0.5 to 1 m/s, waves= 0.5 to 3 m, sand=0.2 to 0.25 mm)
- Delft Hydraulics, Report Z2378, 1998, Sand transport at the middle and lower shoreface of the Dutch coast; Simulations of SUTRENCH-model and proposal for large-scale laboratory tests, by D.J.R. Walstra, L.C van Rijn and S.G.J. Aarninkhof.

The main conclusion from the results of these simulation runs is that the sedimentation in channels, pits and trenches can be quite well simulated, provided that representative incoming transport rates are known. The evolution of the downstream slope can only be accurately modelled if the acceleration effects on the velocity profile are taken into account (non-logarithmic profiles). Neglecting these effects, the computed erosion and migration rate of the slope are too small.

So far, only two field data sets for combined current and wave conditions has been used for testing of models (cases 3 and 5).

6.3.2 Data sets not yet used in hindcast studies

Between October 1999 and March 2000 an extensive measuring campaign (PUTMOR data) was held to collect data concerning water movement, water quality and morphology in and around a large sand pit at the North Sea some 10 km off the Dutch coast near Hook of Holland. The dimensions of the pit are 1300 m x 500 m x 10 m (relative to the seabed at an approximate depth of 24 m water depth). The measurements comprise bathymetry, flow velocities, water levels, temperature, conductivity, turbidity, oxygen content and sampling of seabed material.
The preparation and execution of the measuring campaign as well as the processing and analysing of the measurements, are part of the PUTMOR project initialised by Directorate North Sea (DNZ) in co-operation with the National Institute for Coastal and Marine Management (RIKZ). The programme was initiated in view of large dredging and reclamation activities that may occur in the North Sea in the future, like for instance 'Maasvlakte 2' or for the extraction of concrete sand. The aim of the measurements was to assess the impact of a large-scale sand pit on water movement, water quality and morphology.

Figures 6.3.1 to 6.3.5 show the environmental conditions, which can be used to determine suitable conditions for testing of models.
Calm periods with relatively small wave heights (<1.5 m) are given in Figures 6.3.1 and 6.3.2.
Storm periods with relatively large wave heights (up to 5 m) are given in Figures 6.3.3 and 6.3.4.
The period between 25 November and 25 December 1999 is characterised by stormy weather conditions (Figure 6.3.5).

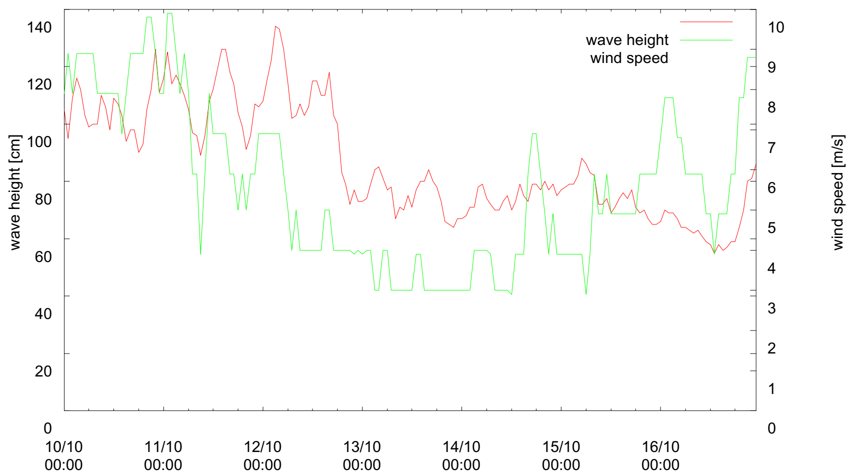


Figure 6.3.1 *Calm periods: wave heights between 12 and 16 October 1999 at LEG Station*

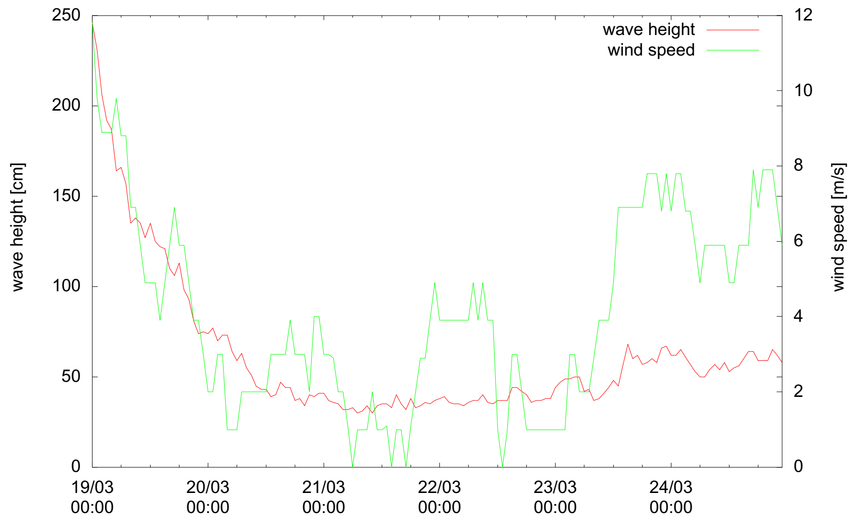


Figure 6.3.2 *Calm periods: wave heights between 19 and 24 March 2000 at LEG Station*

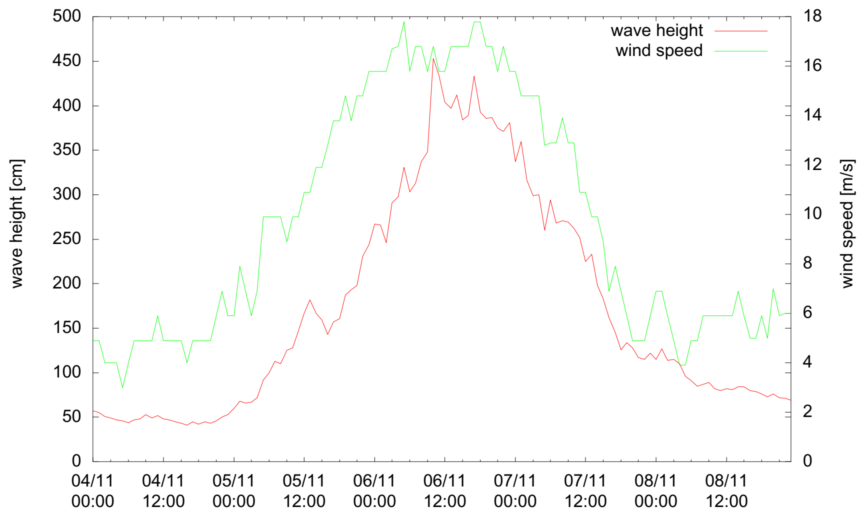


Figure 6.3.3 *Storm periods: wave heights between 5 and 8 November 1999 at LEG Station*

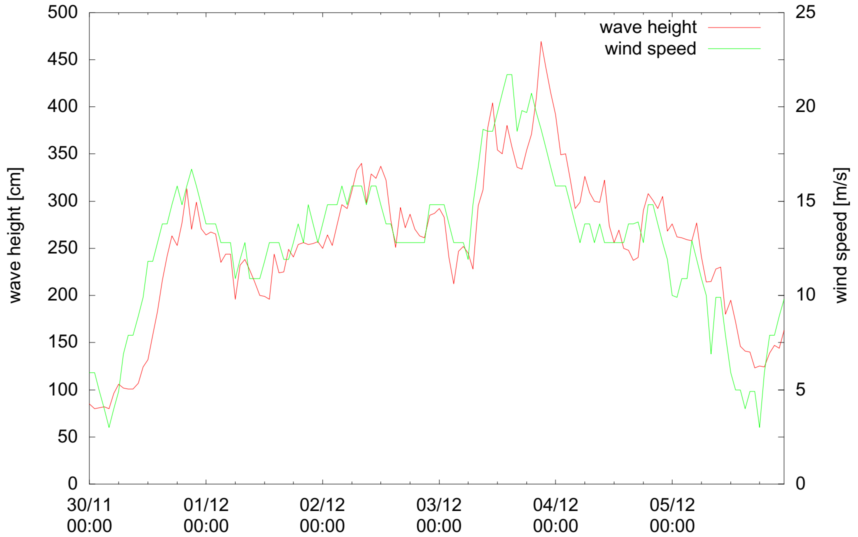


Figure 6.3.4 *Storm periods: wave heights between 30 November and 5 December 1999 at LEG Station*

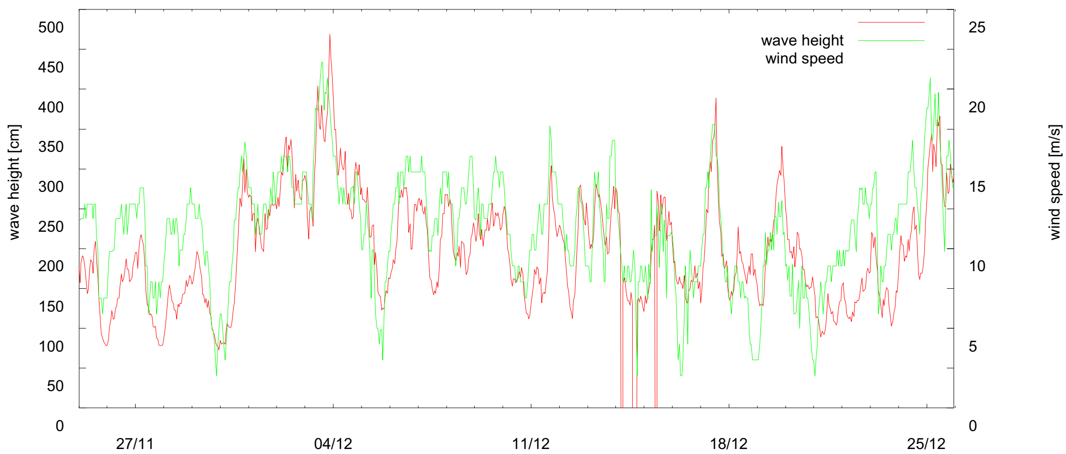


Figure 6.3.5 *Storm periods: wave heights between 27 November and 25 December 1999 at LEG Station*

7 Mathematical model studies related to pits in North Sea

7.1 Introduction

Several studies have been performed related to the behaviour of navigation channels and sand mining pits in the North sea, being:

1. morphology of mining pits and mining from IJ-channel; Rijkswaterstaat, 1989;
2. morphology of mining from EURO-MAAS channel, Delft Hydraulics, 1992;
3. morphology of large scale mining pits near EURO-MAAS channel; Delft Hydraulics-Alkyon, 1997;
4. flow in large scale mining pits; Svasek, 1998;
5. morphology (2DV) of mining pits, Delft Hydraulics, 1998;
6. flow and morphology (2DH) in large scale mining pits; Klein, Delft University of Technology, 1999;
7. morphology (2DH) of large-scale mining pit using stability analysis, University of Twente, 2001.

7.2 Morphology of mining pits and mining from IJ-channel; Rijkswaterstaat, 1990

This study was focussed on the mining of seasand in deeper water and its effects on the shoreline of the Dutch coast.
Two aspects were studied:

- effects of sand mining from pits at various depths (between 10 and 20 m) on the shoreline at four alongshore locations (Scheveningen, Bergen, Texel and Ameland),
- effects of sand mining from the IJ-channel (near IJmuiden) on the shoreline.

The following mining pit dimensions were studied.

Depth contour (m)	**Cross-shore width of pit (m)**	**Alongshore length of pit (m)**	**Depth of pit (m)**	**Volume of pit (10^6 m^3)**
10	100	2000	1	0.2
10	500	2000	1	1
16	100	2000	1	0.2
16	500	2000	1	1
16	1000	2000	5	10
16	1000	5000	2	10
20	1000	2000	5	10
20	1000	5000	2	10

The UNIBEST-model was used to estimate the cross-shore morphological bed evolution; the LOMOR model was used to estimate the longshore morphological bed evolution.
Based on the model computations, it was concluded that:

- the flow pattern outside the pit is modified over a distance of maximum twice the pit width and length;
- the flow velocity in the pit is reduced by about 10% for a pit depth of 5 m and by about 5% for a pit depth of 2 m;
- the cross-shore morphological changes are relatively small; the migration rates are mainly affected by the local water depth and not by the pit dimensions (depth, width, length); the landward side slope of the pit shows net onshore migration of the order of 0.2 m/year at the -20 m NAP depth contour, 0.5 m/year at the -16 m NAP depth contour and 1.5 m/year at the -10 m NAP depth contour; the pit will be filled up in about 100 year; the maximum migration in that period will be about 1500 m at the -10 m depth contour; the effect on the shoreline depends on the distance of the pit to the shoreline, yielding time scales of centuries;
- the longshore morphological changes are relatively small; the side slopes are flattened over a length equal to the pit length (a few km's); the pit will be filled up in about 100 years; the longshore migration length in that period is of the order of the pit length (say 5 km).
- the uncertainty ranges are relatively large (factor 5) due to lack of field data for verification.

Mining of sand from the IJ-channel (navigation channel to Port of Amsterdam) by widening and/or deepening of the channel has no significant effect on the far-field shoreline. The local shoreline close to the breakwaters may be modified slightly due to changes of the local wave-current conditions.

7.3 Morphology of mining from Euro-Maas channel, Delft Hydraulics, 1992

Mining of seasand from the EURO-MAAS channel (approach navigation channel to Port of Rotterdam) was studied. The options considered were: widening (from 600 m in present situation to maximum 2700 m in future situation) and deepening (maximum 20% of the present depth) of the cross-section of the channel; the cross-section modifications were assumed to be situated between 5 and 20 km from the shoreline.
The study comprised the following elements:

- analysis and description of the physical system (tides, currents, waves, sediments, transport rates);
- determination of alternative cross-sections for mining of sand;
- estimation of morphological effects:
  - deposition in channel due to reduction of sand transport capacity (maximum 0.2 m/year);
  - flattening of side slopes in longshore direction (maximum 2 km);
  - migration of slopes in cross-shore direction (maximum 1km);
- estimation of trapping of mud in channel (maximum 5% of the amount of mud passing the channel).

Overall, the morphological changes are found to be limited to an area of one or two kilometres on both sides of the widened channel. The effects on the local wave and current patterns are so small, that appreciable effects on the shoreline are not to be expected. The uncertainty ranges are relatively large due to lack of field data.

7.4 Morphology of large scale mining pits near EURO-MAAS channel; Delft Hydraulics-Alkyon, 1997

Delft Hydraulics and Alkyon (1997) studied the overall long-term morphological impact on the Dutch coast of the Maasvlakte-2 extension and associated sand mining areas in the North Sea.

The study consisted of the following elements:

- determination of morphological tide to represent the neap-spring tidal cycle using DELFT 2DH model runs;
- determination of representative wave conditions using SUTRENCH-2DV model runs based on annual wave climate;
- initial sand transport computations using DELFT-2DH model for schematised tide and wave conditions to determine annual mean residual transport rates;
- long-term morphological computations (50 years) using DELFT-2DH RAM model based on annual mean residual transport rates;
- long-term morphological computations (300 years) using ASMITA model based on the quasi-equilibrium bathymetries produced by RAM model.

Two alternative sand mining scenarios have been studied:

- wide and shallow mining pit (approx. 7x20 km^2, depth of 2 m) north of EURO-MAAS channel;
- narrow and deep mining pit (approx. 3x7 km^2; depth of 10 to 15 m) north of EURO-MAAS channel.

Based on the long-term morphological model results, the migration velocity of the mining pits was found to be 10 to 15 m/year. The morphological changes remain within the local surrounding of the mining pits. On the time scale of 100 years the overall migration of the mining pit will be of the order of 1 to 2 km, which is smaller than the width (about 3 km) of the deep mining pit. The effect of the mining pit scenarios on the nearshore coastal zone is found to be negligibly small. The morphological effect of the construction of the MAASVLAKTE 2 extension on the nearshore coastal zone is found to be substantially larger than the effects of the sand mining pits.

7.5 Flow in large scale mining pits; Svasek, 1998

Svasek has studied the flow in large-scale mining pits (rectangular planform) situated in the Dutch sector of the North Sea.

The base case is a shoreparallel pit with a length of L= 20 km, a width of W= 2 km and a depth in the pit of h_1= 30 m; the water depth outside the pit is h_o= 20 m. The Chézy value is set to 50 $m^{0.5}$/s.

The study comprised the following elements:

- theoretical analysis of the flow phenomena involved for stationary and non-stationary (tidal) flow focussing of far-field effects and in/outflow effects (flow contraction);
- model computations using a 2DH approach;
  - stationary flow with u_o= 1m/s,
  - tidal flow with u_o varying between -0.6 and +0.6 m/s; water level between -1 and +1 m,
  - channel lengths between 2 and 20 km, channel width between 2 and 20 km,
  - water depth in channel between 22 and 40 m,
  - approach angles (between flow direction and main axis) of 0^o, 30^o and 60^o.

The most important conclusions of the numerical flow computations are:

Stationary flow

- the maximum flow velocity in the middle of the pit increases (10% to 20%) with increasing L/W ratio, in case of constant pit depth;
- the maximum flow velocity in the middle of the pit increases (10% to 20%) with decreasing W/h_1ratio, in case of a constant pit length,
- the maximum flow velocity in the middle section (longitudinal) of the pit increases with decreasing Chézy value (more rough bed) due to decrease of the adjustment length (dominant effect),
- the maximum flow velocity in the middle section of the pit is smaller than the upstream velocity for a pit length smaller than two times the pit width (L<2W);
- the flow in a long and small (narrow) pit can be reasonably well represented by the far-field expressions for stationary flow.

Tidal flow

- the maximum flow velocity in the pit has a small time lag of about 15 minutes with respect to the maximum flow velocity upstream of the pit; the time lag decreases with increasing W/h_1 ratio;
- the residual (time-averaged over the tidal period) velocities are largest (order of 10% of main flow) near the inflow and outflow areas of the pit; the residual velocities are directed toward the outside area;
- the maximum flow velocity in the pit decreases for approach angles of 30^o and 60^o; the residual velocities at the inflow and outflow sections are largest for an angle of 60^o.

7.6 Morphology (2DV) of mining pits, Hoitink, University of Twente, 1997

Hoitink (1997, 1998) has studied the longshore and cross-shore morphology of mining pits situated in the Dutch sector of the North Sea.

The study comprised the following elements:
- analysis of the hydrodynamics and bathymetry of the EURO-MAAS Channel (approach channel to Port of Rotterdam);
- application of SUTRENCH model to various sections of the EURO-MAAS Channel;
  - calibration of model based on observed bed profile changes of the channel (bottom width of approx. 600 m, maximum width of approx. 1000 m, channel depth of approx. 7 m) based on a simulation over 5 years;
  - application of model to deepened and widened channel sections based on simulations over 50 years.
- application of UNIBEST-TC model to estimate the cross-shore development of mining pits (depth of 2 m) in water depth of 20 m (depth contour -20 m NAP) due to waves up to H_{rms}=2.25 m and tidal flow up to 0.65 m/s.

The SUTRENCH runs (sand of about 0.2 mm; bed roughness in range of 0.001 to 0.5 m) show that the net displacement of centre of the side slopes is of the order of 500 m, while the total area of influence in the direction of the tidal flow is approximately 10 km on a time scale of 50 years.
The UNIBEST runs show cross-shore migration rates of the pit (with depth of 2 m) of maximum 2 m/year.

7.7 Morphology (2DV) of mining pits, Delft Hydraulics, 1998

The 2DV development of sand mining pits in the North Sea (perpendicular to the flow) was studied using the SUTRENCH model. The model was first tested by comparing computed and measured results for two cases concerning combined current and wave conditions: (i) small-scale channel perpendicular to flow and oblique to waves in laboratory wave-current basin and (ii) morphological development (over period 22 March to 14 April 1982) of pipeline trench in Danish littoral zone. After testing, the model was applied to determine the most important model and input parameters (sensitivity study). Finally, the long-term morphological evolution of various pit cases was determined.

The representative tidal flow characteristics (19 quasi-steady flow blocks) are:
Flood: maximum water level of 1.4 m above MSL (NAP); peak flow of 0.9 m/s to north; duration of 6 hrs;
Ebb: maximum water level of -0.5 m below MSL (NAP); peak flow of -0.7 m/s to south; duration of 6.5 hrs.

The representative wave characteristics are:

Significant wave height: H_s= 2.25 m during 84% of the time,
Peak wave period: T_p= 6.6 s,
Wave direction: 315 degrees with respect to North.

The representative sediment characteristics are:
Bed material: d_{50}=0.21 mm, d_{90}= 0.31 mm,
Fall velocity of suspended sediment: w_s= 0.0275 m/s,
Bed roughness: $k_{s,c}$= 0.05 m, $k_{s,w}$= 0.01 m,
Reference level: a= 0.05 m,
Correction factor for reference concentration: γ= 0.7.

Given the input data for tidal flow, waves and sediment, the reference concentrations at the bed boundary were calibrated (correction factor of 0.7) to obtain a net annual sand transport rate at the inlet boundary of about 50 m^3/m/year to the north. This latter value is the characteristic net annual transport rate for North Sea conditions at a depth of about 20 m.

The channel depth (below surrounding bed surface) was varied in the range between 2 and 14 m; the width was varied between 300 and 2400 m; the side slopes were 1 to 12.5 and 1 to 50. The upstream water depth to MSL was varied between 15 and 25 m.

Summarising:
- water depth outside pit between 15 and 25 m (20 m in base run);
- tidal flow with depth-averaged flood velocity of 0.9 m/s and ebb velocity of 0.7 m/s;
- representative wave height of H_s= 2.25 m (varied between 1.125 and 3.375 m), wave period of 6.6 s, wave direction of 315^o;
- wave-related bed roughness between 0.005 and 0.05 m;
- current-related bed roughness between 0.025 and 0.075 m;
- sediment size d_{50} between 0.1 and 0.3 mm, d_{90} between 0.2 and 0.45 mm;
- net annual sand transport at upstream boundary (inlet, x=0 m) of about 50 m^3/m year;
- pit width between 300 and 2400 m, depth between 3.5 and 14 m, slopes between 1:12.5 (8%) and 1:50 (2%).

Model appraisal
The results for the laboratory basin experiment show good agreement with the measurements. The migration of the trench is modelled accurately, the morphological development of the trench slopes is not modelled satisfactory. The upstream slope is generally predicted too steep whereas the erosion of the downstream slope is under-predicted. From the basin experiment it is found that the trench slope development is influenced by varying the roughness heights. Varying the sediment fall velocity mainly influences the sedimentation (and migration) of the trench. An optimal fit to the upstream boundary velocity and concentration profiles resulted in a good representation of the measured trench development. An accurate hindcast of the Danish field experiment was not possible due to the fact that current data was not available for the simulated period. The migration and sedimentation of the trench over a period of 3 weeks show reasonable agreement with the observed morphological developments by using reasonable estimates for the tide-and wind-induced currents.

Overall it is concluded that the deposition in trenches and channels can be simulated quite well, provided that the incoming sediment transport is known.

Influence of dominating parameters on morphological evolution of pit

A sensitivity study using the SUTRENCH 2DV model has been performed, focussing on deposition and migration of the EURO-MAAS channel. Based on model runs varying process and model input parameters, it is found that the tide and wave climate should be accurately schematised to obtain reliable and accurate morphological results. Small variations of the current velocity have a relatively large effect, because the transport rates in deep water are relatively small (close to the initiation of motion). Furthermore the model is found to be very sensitive to variations of the sediment characteristics, calibration and validation of the transport functions for fine sediment is necessary. The sensitivity of SUTRENCH results to variations in the wave-related mixing parameters illustrates the need to validate the model for deep water conditions as the referred parameters have only been validated for shallow water conditions.

Long term (50 years) morphological evolution of various mining pits

The water depth outside the mining pit has the largest influence on the morphological evolution of the pit owing to the effect of the water depth on the sand transport capacity. The pit geometry and dimensions have much less effect on the morphological evolution of the pit. The maximum initial total trapping efficiency of the pit is about 75% for the simulation with a reduced water depth. The minimum trapping efficiency is about 35% for the shallow pit with a depth of 2 m. The maximum migration of the pit in longshore direction over 50 years is 800 m for the decreased water depth case. The minimum migration is about 250 m for the increased water depth case. The relative volume decrease of the pit after 50 years is highest for the reduced water depth case, minimum relative sedimentation occurs for the pit with a width of 2400 m.

A deep pit of 14 m (twice as deep as base run) has a time scale of 800 years (extrapolation to zero trapping efficiency) whereas a wide pit of 2400 m (four times as wide as base run) only has a time scale of about 500 to 600 years.

The morphological development is mainly influenced by the lag of the settling and picking up of the suspended sediment. If most of the sediment has settled on the pit bottom before the toe of the upstream slope, both slopes will develop almost independently from each other. This so-called morphological interaction between the pit slopes mainly occurs for the wide and deep pits. In case of reduced width or depth an increasing interaction between both slopes can be seen which results in an increasing sedimentation at the toe of the upstream slope. Wide pits have a relative short morphological time scale whereas deep pits have a relative long morphological time scale but also a relative small migration rate, which is favourable in relation to effect on the coastline.

The longshore morphological evolution of the pits is assumed to be driven by longshore currents (pit axis perpendicular to longshore current). In the cross-shore direction tidal currents are of a smaller order. The transport capacity of waves however increases if the water depth decreases. A decrease of 25 % in water depth (from 20 to 15 m) results in an increase of the migration rate of almost a factor 2. The morphological time scale (first order estimate of when the dredging trapping efficiency reaches zero) is also halved. It illustrates that the dynamic behaviour of a pit changes dramatically if it is located in or migrates to shallower waters.

The results are summarised in Figure 7.7.1, focussing on: (i) horizontal displacement of centre of gravity of channel (relative to upstream water depth of 20 m) after 50 years and (ii) ratio of channel depth (below the surrounding bed) at deepest point after 50 years and initial channel depth.

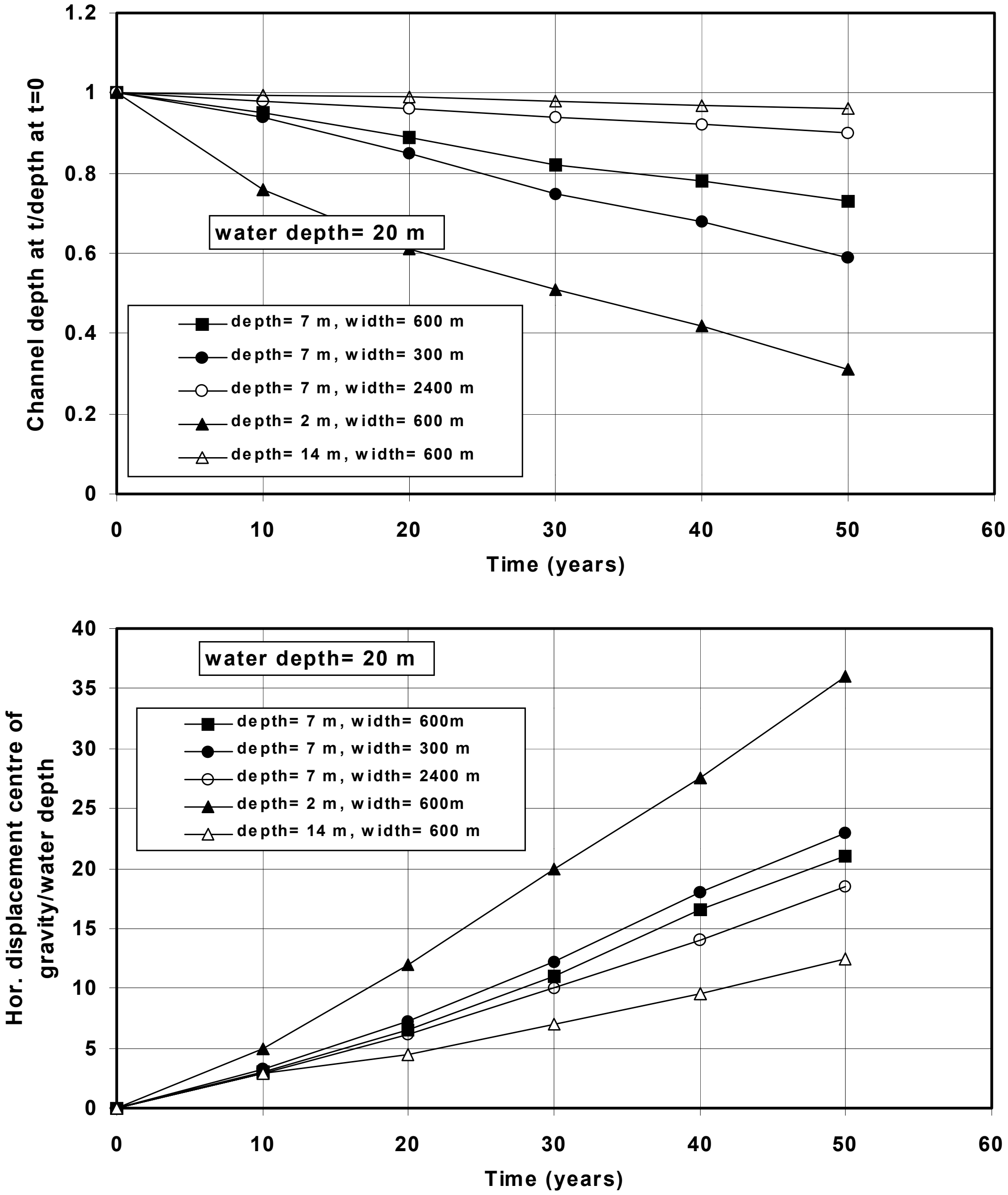


Figure 7.7.1 *Influence of channel dimensions on sedimentation and horizontal displacement of channel after 50 years*
Top: Ratio of channel depth (deepest point) and initial channel depth as function of time
Bottom: Ratio of horizontal displacement of centre of gravity of channel and upstream water depth as function of time

The following features can be observed:

- a shallow channel of 2 m is characterised by a relatively large horizontal displacement ($35h_o$ with h_o= upstream water depth) and relatively large sedimentation (channel depth is reduced by about 70%) after 50 years;
- a deep channel of 14 m is characterised by a relatively small horizontal displacement ($12h_o$) and sedimentation (channel depth is reduced by about 5%) after 50 years;
- a wide channel (1200 and 2400 m) is characterised by sedimentation on the upstream side slope and erosion on the downstream slope; the sedimentation in the middle of the channel is minimum after 50 years;
- a relatively narrow channel of 300 m shows a horizontal displacement of about $20h_o$; the channel depth is reduced by about 40% after 50 years;
- a channel with a side slope of 1:50 yields a wider channel and hence less sedimentation in the middle of the channel compared to a channel with a slope of 1:12.5;
- the water depth outside the channel has a relatively large effect on the channel sedimentation; a small depth of 15 m yields a much larger wave effect resulting in a significant increase of the incoming sand transport (80 m^3/m/year); a water depth of 25 m results in a decrease of the net annual transport (40 m^3/m/year) at the inlet boundary.

7.8 Flow and morphology (2DH) in large scale mining pits; Klein, Delft University of Technology, 1999

Klein has studied the flow in large-scale mining pits (rectangular planform).

The study comprised the following elements:

- stationary flow;
  - pit length L between 2 and 100 km;
  - pit width W of 5 and 10 km;
  - water depth h_1 in pit between 22 and 30 m; water depth outside the pit is h_o= 20 m;
  - approach angles of 0^o and 45^o;
  - approach velocity of 0.5 m/s;
  - Chézy value of 65 $m^{0.5}$/s.
- stationary flow with Coriolis effect;
  - length L between 10 and 40 km;
  - width W of 5 and 10 km;
  - water depth h_1 in pit of 30 m; water depth outside the pit is h_o= 20 m;
  - approach angles of 0^o, -22.5^o, -45^o, 22.5^o and 45^o;
  - approach velocity of 0.5 m/s;
  - Chézy value of 65 $m^{0.5}$/s.
- tidal flow with and without Coriolis effect;
  - length L between 10 and 40 km;
  - width W of 5 and 10 km;
  - water depth h_1 in pit of 30 m; water depth outside the pit is h_o= 20 m;
  - approach angles of 0^o, -45^o, and 45^o;
  - upstream flow velocity varying between about 0.67 and -0.52 m/s;
  - water level variations of about 0.75 m;
  - Chézy value of 65 $m^{0.5}$/s.

- morphology;
  - pit length of 25 km, pit width of 5 km;
  - water depth in pit of 22 and 30 m, water depth outside pit of 20 m;
  - approach angles of 0^o, -45^o and 45^o;
  - sediment size of 0.2 mm;
  - bed load and suspended load transport capacity (no lag effects);
  - model was tuned based on a comparison with SUTRENCH model results;
  - morphological time scale of 1000 years for pit evolution (Coriolis effect included).

The most important conclusions are:

Stationary flow

- the maximum flow velocity in the pit is larger than the flow velocity outside the pit for a length-width ratio larger than 3 (L/W>3);
- the equilibrium flow velocity in the pit (width of 5 km and a water depth of 22 m) is only reached if the pit length is larger than 60 km (L/W>12); the equilibrium depth-averaged flow velocity can be reasonably well described by the Chézy equation;
- the adjustment length scale increases with increasing pit depths; the model values are somewhat larger (50%) than the theoretical values;
- the Coriolis force has a significant effect on the flow pattern due to the asymmetrical inflow of the pit; the Coriolis force opposes and follows the inertial force in different areas of the pit; the maximum flow velocity in the pit increases (5% to 10%) taking the Coriolis effect into account for approach angles of $+22.5^o$ and 45^o and decreases for angles of -22.5^o and -45^o.

Tidal flow

- the maximum flow velocity in the pit is larger than the flow velocity outside the pit for a length-width ratio larger than 4 (L/W>4);
- time lag effects are present for cases with L/W>>4;
- the residual velocities show circulation patterns near the corner areas of the pit for approach angles of 22.5^o and 45^o; the circulation cells increase in size for increasing approach velocity (1 m/s).

Morphology

- the side slopes of the pits are flattened (erosion);
- a pit parallel (0^o) to the flow or under a positive angle (45^o) migrates in the direction of the main longitudinal axis; the maximum migration distance after 1000 years is about 5 km (approximately 250 h_0);
- a pit under a negative angle of -45^o migrates in the direction normal to the main longitudinal axis (Coriolis effect); the maximum migration distance after 1000 years is about 3 km (approximately 150 h_0);
- the depth of a pit parallel to the flow or under a positive angle (45^o) tends to become somewhat larger; deposition is remarkably small after 1000 years
- the rectangular and square planforms of the pits are transformed into less regular shapes.

Table 7.8.1 summarises the most important morphological indicators for the mining pits considered. The upstream side slope is defined as the side slope upstream of the dominant flow.

An example of the computed morphology of a pit of 25x5 km^2 is given in Figure 7.8.1.

Pit Dimensions **(length in km, width in km, depth in m, angle)**	**Maximum deposition (+) or erosion (-) in middle of pit** **(m)**	**Lateral (cross) direction**		**Longitudinal direction**	
		Maximum migration of upstream side slope (km)	**Maximum erosion length at upper corner of side slope (km)**	**Maximum migration of upstream side slope (km)**	**Maximum erosion length at upper corner of side slope (km)**
LxW=25x 5 d=10 m, 45^o	-1	0	3	5	10
LxW=25x 5 d=10 m, 0^o	-0.5	0	1	3	10
LxW=25x 5 d=10 m, -45^o	1	3	5	3	3
LxW=10x 5 d=10 m, 0^o	-0.5	0	5	5	10
LxW=25x 5 d=2 m, 45^o	-0.5	3	5	3	20
LxW=25x 5 d=2 m, 0^o	-0.5	0	1	3	10
LxW=25x 5 d=2 m, -45^o	0.5	3	10	3	10
LxW=10x 5 d=2 m, 0^o	-0.5	1	1	3	10
LxW=25x 5 d=10 m, 0^o (net residual velocity increased to 0.1 m/s)	2	complete filling of original planform	complete filling of original planform	10	20

Table 7.8.1 *Characteristic indicators of long term (after 1000 years) mining pit evolution; tidal flow (-0.5 to 0.5 m/s) including Coriolis effect, upstream depth=20 m, sediment of 0.2 mm*

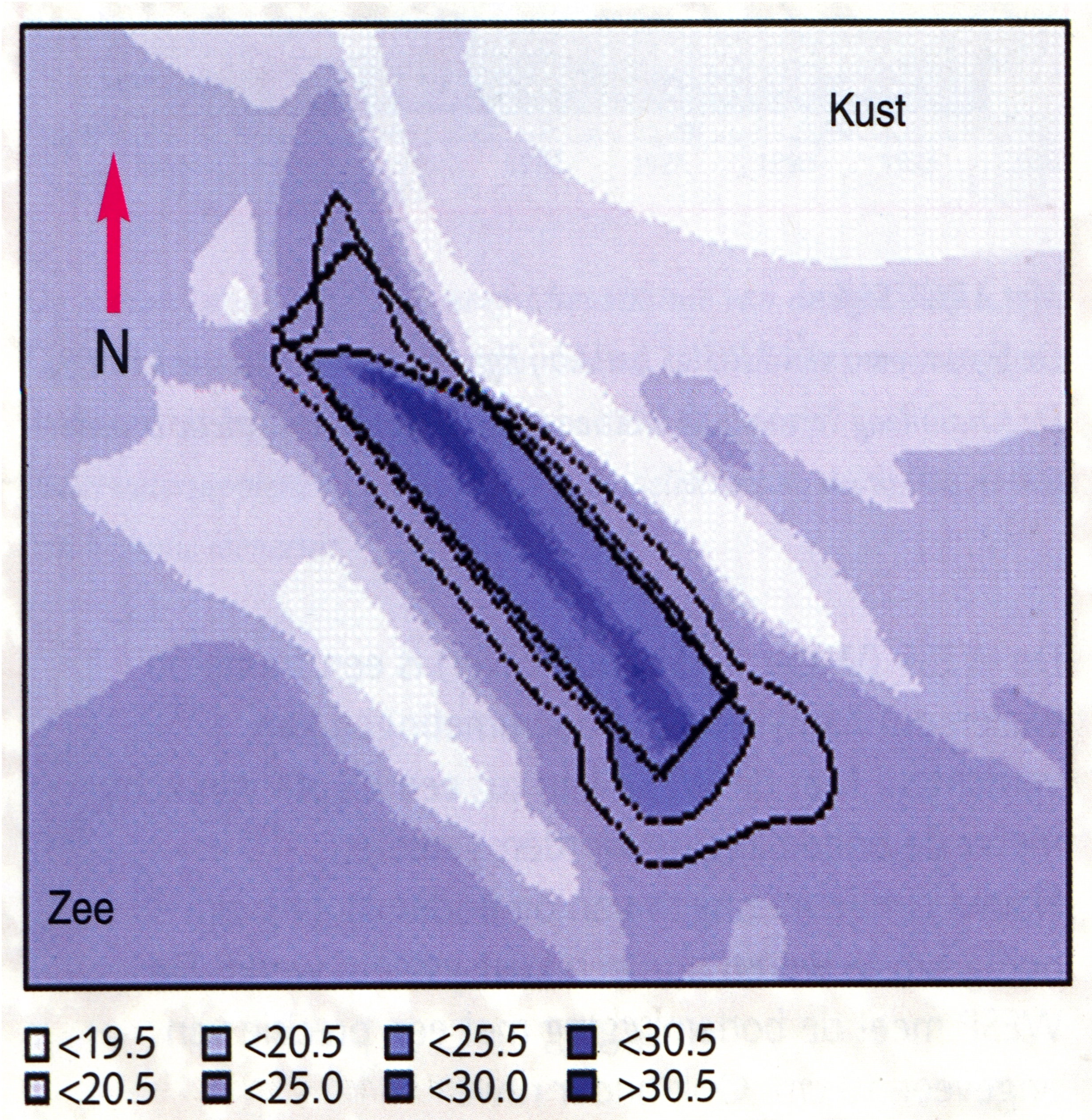


Figure 7.8.1 ***Computed morphology of sand mining pit after 50 years*** *(colours represent water depth in m to NAP; contour lines represent the 22.5 m depth and 25 m depth); coast on right side and sea on left side;*
Initial pit characteristics: *25x5 km^2, water depth in pit of 30 m, water depth outside pit of 20 m, angle of 45^o with respect to main flow direction;*
Tidal flow: *peak flow of 0.52 m/s to north; peak flow of 0.67 m/s to south;*
Pit characteristics after 50 years: *erosion of side slopes; deposition outside pit on both long sides; deepening (erosion) in middle of pit; migration of downstream side slope in direction of main axis.*
(from: Kust en Kennis, Rijkswaterstaat-RIKZ)

7.9 Morphology (2DH) of large scale mining pits, University of Twente, 2001

The behaviour of a sand pit has been studied by representing the pit as a morphodynamic instability of a sandy bed subject to asymmetric tidal motion (Roos et al., 2001; Németh, 1998; Peters, 2000). The starting point is the linear stability analysis proposed by Hulscher et al. (1993), focussing on the response of small wavy bed perturbations under the influence of an M_2 tidal component. The fastest growing mode of the bed perturbations in an otherwise flat bed is assumed to represent the dominant wave length and orientation of the large scale sand bed features which are present in the system. More realistic conditions were simulated by including the M_0 and M_4 tidal components. The model consists of the 2DH flow equations (including Coriolis effect and linear bed friction) in combination with a simplified sand transport equation (including a bed slope term). Tidal asymmetry causes migration of the bed features.

The sand pit is represented as a superposition of wavy bed perturbations of small amplitude. The sand pit considered has a depth of 2 m in a water depth of 30 m and a Gaussian plan shape, given by $h_{pit}=-\exp(-\pi/L^2(x^2+y^2))$ with L=nondimensional diameter. The pit effect is isolated from the growth of rhythmic patterns on the surrounding flat bed, assuming that these latter patterns represent a higher order effect compared to the pit effects.

The presence of a sand pit triggers the formation of circulation cells resulting in the development of a sand bank pattern, see Figs 7.9.1 and 7.9.2. As time evolves, the sand bank pattern spreads out and migrates, alternatingly generating trough and crest zones. The pit itself deepens and the pattern spreads at a rate of 10 to 100 m/year. The migration rate of the centre of the pit is of the order of 1 to 10 m/year.

An explanation of the hydrodynamic response to the presence of the pit can be found in terms of the vorticity dynamics. Vorticity is generated either by Coriolis and streamwise bed slopes or by bottom friction and transverse bed slopes.

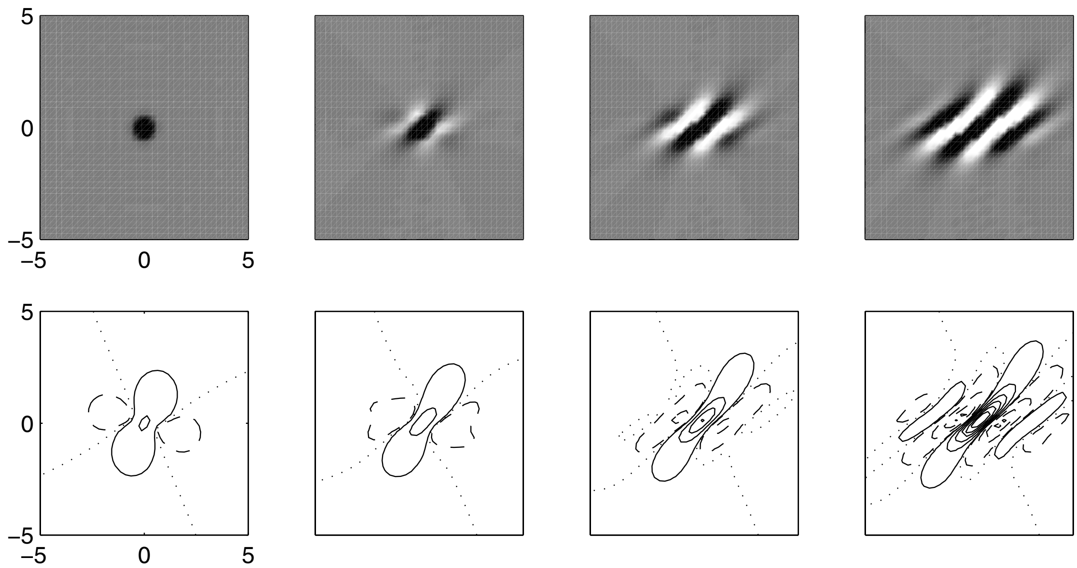


Figure 7.9.1 *Evolution of pit under tidal flow (M_2 and M_4 components) in x-direction over time scale of about 1000 years (Top right); Area covers 70x70 km²*
Top: bed evolution (troughs=black; crests=white; undisturbed=grey)
Bottom: residual current patterns (solid streamlines= counterclockwise rotation; dashed lines= clockwise rotation)

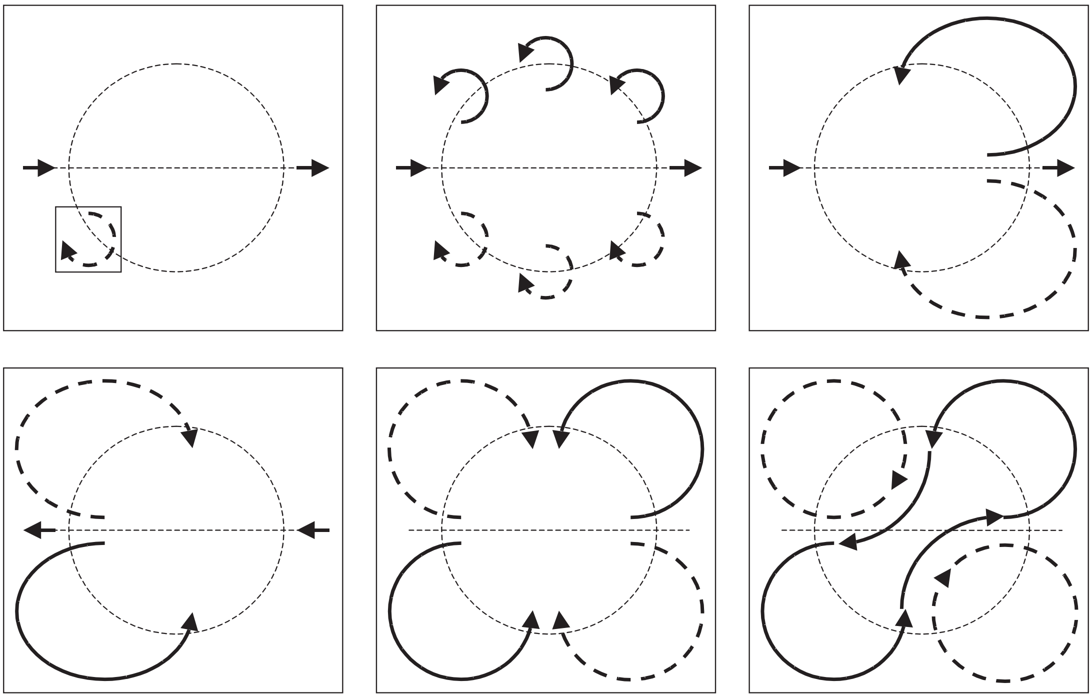


Figure 7.9.2 *Physical mechanisms explaining secondary flow in circular sand pit (one depth contour is shown).*

Top left: *Flow from left to right (no Coriolis); small fluid column is on slope of pit; flow velocity and bottom friction is smaller on deeper side of column; column experiences a torque, which tends to bend the flow to the right.*

Top middle: *Fluid below pit axis experiences a clockwise rotation and a counterclockwise rotation above the pit axis (no Coriolis).*

Top right: *Generated vorticity induces residual cells that are carried slightly downstream by advection (no Coriolis).*

Bottom left: *Flow is from right to left (no Coriolis). Conversely, two other residual cells are generated on other side of pit.*

Bottom middle: *A four-cell pattern emerges after tidal averaging showing lateral inflow and longitudinal outflow with respect to tidal flow direction.*

Bottom right: *Coriolis force is included (northern hemisphere). The two clockwise cells are amplified, which leads to the merging of the slightly damped counterclockwise cells into one larger elongated cell.*

8 Summary, conclusions and recommendations

8.1 Summary and conclusions

The literature review comprised the following elements:

- regulations for sea sand mining in the Dutch sector of the North Sea,
- morphodynamics of offshore mining areas,
- sediment transport and ecological processes in marine conditions,
- mathematical description of sand transport and morphology,
- data sets and hindcast studies,
- mathematical model studies related to pits in North Sea.

For several years the large-scale mining of sand from the Dutch Sector of the North sea is in discussion related to the need of sand for shoreface, beach and dune nourishment and large-scale engineering works at sea (Maasvlakte extension, airport at sea). The mining methods considered basically fall into two categories: wide, shallow or small, deep mining pits. Presently, shallow pits not deeper than about 2 m are excavated beyond the 20 m depth contour to obtain sand for beach nourishments. Deep mining pits have not yet been made extensively. A temporary pit (Punaise project) with a depth of about 20 m (below surrounding bed surface) has been excavated close to the shore in a water depth of about 10 m, but this pit were refilled shortly (a few months) after construction to prevent damage to the coastal system. Experience sofar seems to indicate that the negative environmental effects increase with increasing excavation depth (RON 2).
The mining of sea sand will affect both the ecology and morphology of the coastal system. The ecology is affected in the sense that the flora and fauna of the system is modified by the mining activities, whereas also the release of very fine sediments (silt and clay) from the bed into the water column may have a direct influence on the ecological system.
The morphology is affected in the sense that locally the bed level is lowered substantially in the form of a borrow pit (or channel), which may influence the local flow and wave fields and hence the sand transport rates due to modification of shoaling, refraction and reflection patterns.

Regulations for mining of sand

Regulations for mining activities in the Dutch Sector of the North Sea are formulated in: "Regionaal Ontgrondingsplan Noordzee" 2 (RON 2). These regulations mainly concern mining depth and mining area in relation to the water depth on the mining location. The maximum mining depth for the present mining activities is 2 m. Regulations for deep sand mining pits (deeper than 2 m) are not very specific. Sand mining in deep pits, outside the -20 m NAP depth contour is conditionally allowed. The environmental effects should be evaluated (EIA procedure). Monitoring programs, aimed at the effects of the mining activities generally are required.

Morphological behaviour of mining pits

The morphological behaviour of a deepened mining area (pit, channel, trench) in coastal flow (with or without waves) shows some basic features, depending on the orientation of the pit to the flow direction. When a current passes a pit or channel (perpendicular or oblique), the current velocities decrease due to the increase of the water depths in the pit or channel and hence the sediment transport capacity decreases. As a result the bed-load particles and a certain amount of the suspended sediment particles will be deposited in the pit. The settling of sediment particles is the dominant process in the downsloping (deceleration) and in the middle section and of the pit. The most relevant processes in the deposition and erosion regions are: convection of sediment particles by the horizontal and vertical fluid velocities, mixing of sediment particles by turbulent and orbital motions, settling of the particles due to gravity and pick-up of the particles from the bed by current and wave-induced bed-shear stresses. The effect of the waves is that of an intensified stirring action in the near-bed region resulting in larger sediment concentrations, while the current is responsible for the transportation of the sediment. In case of flow parallel or almost parallel with the channel axis, the side slopes of the channel are flattened and smoothed due to gravitational effects. When a sediment particle resting on a side slope is set into motion by waves or currents, the resulting movement of the particle will, due to gravity, have a component in downwards direction. By this mechanism sediment material will always be transported to the deeper part of the channel yielding reduced depths and smoothed side slopes. Slope instability may occur in case of relatively steep slopes immediately after (capital) dredging. This may especially occur in deep mining pits and more research into the breaching process in deep pits is recommended.

The prediction of sedimentation in mining pits basically consists of two elements:

- sediment transport (mud, silt and sand) carried by the approaching flow to the channel, depending on flow, wave and sediment properties;
- trapping efficiency of the pit, depending on pit dimensions, channel orientation and sediment characteristics.

Sediment transport processes

An overview of the sediment transport processes in undisturbed marine conditions has been given, focussing on sand and mud transport.

Sand can be transported by wind-, wave-, tide- and density-driven currents (current-related transport), or by the oscillatory water motion itself (wave-related transport). The waves generally act as a sediment stirring agent, whereas the sediments are transported by the mean current. Wave-related transport may be caused by the deformation of short waves (wave asymmetry) under the influence of decreasing water depth. Low-frequency waves interacting with short waves may also contribute to the sediment transport process (wave-related transport), especially in shallow water in the surf zone.

In friction-dominated deeper water on the lower shoreface zone the transport process generally is concentrated in a layer close to the sea bed and mainly takes place as bed-load transport in close interaction with small bed forms (ripples). Bed-load transport is dominant in areas where the mean currents are relatively weak compared to the wave motion (small ratio of depth-averaged

velocity and peak orbital velocity). Net sediment transport by the oscillatory motion is relatively small in depths larger than 15 m, because the wave motion tends to be more symmetrical in deeper water.
Suspended load transport will become increasingly important with increasing strength of the tide- and wind-driven mean currents due to the turbulence-related mixing capacity of the mean current (shearing in boundary layer). By this mechanism the sediments will be mixed up from the bed-load layer to the upper layers of the flow. On the lower shoreface the suspended sand transport generally is dominant during storm conditions only.
Net annual sand transport rates are given based on model computations and derived from morphological data in the North Sea (behaviour of artificial shoals and pits)
The sediments of the North Sea bed contain a few percentage of fines (between 1% and 3 %) in the Dutch coastal zone. The natural flux of fine sediments (size<0.05 mm) in the Dutch sector of the North Sea is concentrated in a relatively narrow coastal zone of about 20 km due to geostrophical effects. The total flux of fine sediments is about 20 10^6 ton/year or 50,000 ton/day. The mean annual sediment concentration is about 0.1 kg/m^3 or 10 mg/l.
The sand mining activities affect the volume, transport and fate of fine grained sediments in the Dutch coastal zone in two ways: (i)large amounts of fines can be mobilised and released in the environment during the sand mining activities and (ii) fine grained sediments may accumulate temporarily or permanently in the resulting deep sand pits in the sea floor.

Ecological processes

Sand mining/dredging and dumping have various direct and indirect short and long term effects on marine and coastal benthic communities of plants and animals (ecological processes). The ecological impacts depend on complex and dynamic interactions of abiotic and biotic factors including: (i)composition and dynamics of the sediment, (ii) methods of dredging and dumping and the sediment spill and (iii) the occurrence and sensitivity of seagrass and macro-zoobenthic communities and the rate of recovery of the communities affected. An important problem of sand mining may be the release of fine sediments (silt and mud) in the environmental system during the dredging process. Roughly about 1% to 3% of the substratum of the North Sea consists of fine to very fine sediments. One of the consequences of massive sand mining will be the production of an enormous amount of fine sediment, which can be carried over large distances to the coasts and shores of the countries surrounding the North Sea, threatening the environmental system at those places. Many of the processes involved are unknown and should therefore be studied more intensively focussing on the bed, water phase (oxygen cycle) and foodweb by both laboratory and field experiments.

Mathematical models

The models available for mathematical simulation of the sand transport processes and associated morphological changes related to the behaviour of mining pits have been summarized. Various models are discussed: simple engineering rules, analytical models and detailed mathematical (numerical) models. For each model an overview is given of the modelled processes, the basic simplifications and the types of boundary conditions which have to be specified. Furthermore, the suitability of the models for the various characteristic morphological areas is indicated.

Data sets and hindcast studies

An inventory is given of the available data sets and hindcast studies related to sedimentation in pits, channels and trenches. The data sets are described in terms of steady and non-steady flow with and without waves. The main conclusion from the results of the hindcast studies is that the sedimentation in pits, channels and trenches can be quite well simulated, provided that representative incoming transport rates are known. The evolution of the downstream slope can only be accurately modelled if the acceleration effects on the velocity profile are taken into account (non-logarithmic profiles). Neglecting these effects, the computed erosion and migration rate of the slope are too small. So far, only three field data sets for combined current and wave conditions have been used for testing of models.

Mathematical model studies of mining pits in North Sea

Finally, several studies related to the behaviour of sand mining pits in the North sea have been evaluated and summarised. These studies generally focus on the flow and morphology of mining pits in the North Sea using, 2DV, 2DH and 3D hydrodynamic and morphodynamic models, as used by Delft Hydraulics, Svasek and University of Delft. Bed instability models were used by the University of Twente.
The outcome of these studies generally is that the flow and morphodynamics can be simulated quite well provided that the boundary conditions of flow, waves and sediment transport at the model inlet are accurately known. In the absence of such data the uncertainty margins are relatively large (up to factor 5). Furthermore, the models have not yet been verified extensively due to lack of field data. Field data sets at deeper water are almost completely missing.

8.2 Recommendations for further studies

8.2.1 Study approach

To be able to estimate the long-term morphological behaviour of sand mining pits in deeper water, the following basic hydrodynamic and sand transport processes should be known:

- direction and magnitude of the flow, wave and sand transport fields outside the pit area (undisturbed conditions);
- modification of the flow, wave and sand transport fields due to the presence of the mining pit;
- representation of these processes in a mathematical model capable of making long-term simulations.

Field data of sand transport rates in deeper water are almost completely missing, so that the available models can not be properly calibrated. The best strategy to extend the knowledge of sand transport processes and morphology in deeper water would therefore be to perform a detailed field study of these processes in and near a test pit (process measurements and monitoring of morphological behaviour) in combination with model simulations to interpret the results of the field experiment. Based on that, the improved models can be used to estimate the long-term behaviour of future sand mining pits and their effects on the nearshore zone.

8.2.2 Motivation for model improvement and verification

Based on earlier research using 'state of the art' mathematical models (Van Rijn, 1995), estimates and variation ranges of the net annual cross-shore and longshore transport rates in the North Sea have been obtained. These results show that the variation range of the cross-shore transport rates is considerably larger than those of the longshore transport rates, because the cross-shore transport rate is a delicate balance of onshore and offshore-directed (opposite) transport processes. At present state of research the net annual transport rates and direction along the cross-shore profile can not be determined with sufficient accuracy.

Recent model sensitivity computations (Delft Hydraulics, 1998) show that the present-day models are rather sensitive to specific wave-related sediment parameters, which are of importance for the vertical distribution of the sediment concentrations. The uncertainty ranges of these parameters are too wide; more process data are required to improve these parameters. Furthermore, the model results are quite sensitive to the suspended sediment size, which is often relatively small on the shoreface (<0.2 mm). This means that the winnowing of finer sand fractions (particle size effects) in relation to wave conditions should be studied in more detail (experimentally by field data sampling). It may even be necessary to implement a multi-fraction method to compute the sand transport rates.

Another problem of 2DH and quasi-3D models is the assumption/application of logarithmic velocity profiles. This leads to under-estimation of near-bed velocities and bed-shear stresses and hence the transport gradients in the acceleration zone of the pit. As a result the scour of the bed in this zone of the pit (migration of the downstream slope) is also under-estimated.

Given these results, the available mathematical models can not yet be applied to accurately estimate the morphological behaviour of sand mining pits. Further model testing and improvement is required focussing on the flow modification due to the presence of the pit and the effect of particle size and wave-related parameters on the pick-up and vertical mixing of the suspended sediment.
It is proposed to improve the available models with respect to:
- flow simulation by using the PUTMOR data set (see Section 8.2.3);
- wave-related sand transport processes and associated morphology by performing a test pit experiment in a large-scale wave flume (see Section 8.2.5);
- wave-related and current-related sand transport processes and associated morphology by performing a large-scale test pit experiment in the North Sea (see Section 8.2.4).

8.2.3 Model improvement based on existing hydrodynamic PUTMOR data

Field experiments related to hydrodynamics (PUTMOR experiment, 1999) were performed in a temporary pit in deep water of the North Sea (location Hoek van Holland). The experiments were focussed on the measurement of local flow patterns in and around the pit (Svasek, 2001). The hydrodynamic data sets should be used to verify and improve the available models. The study approach will be:
- analysis of available datasets,
- selection of data sets for verification (mean to spring tide period in calm conditions; mean to spring tide period in storm conditions),

- selection of statistical parameters for presentation of results (test bank parameters)
- simulation runs for selected periods,
- analysis and presentation of results (model performance).

8.2.4 Model improvement based on field test pit in North Sea

Objectives of field test pit
The objectives concerning the sand transport processes are similar to those of the large-scale flume experiments (see next section). Furthermore, the long-term morphology (infill and migration, slope behaviour) of a pit can be studied under realistic conditions. The results will be used to verify and improve the available models.

Design of test pit
The existing models will be used to determine the optimum location and dimensions of the test pit. Wide and shallow as well as deep and narrow pits will be studied. Furthermore, the morphological behaviour of the pit (including uncertainty ranges) will be predicted on a time scale of 50 years.

8.2.5 Model improvement based on large-scale laboratory experiment

It is proposed to perform large-scale wave flume experiments with the objective of improving the process knowledge of cross-shore sand transport and morphology. This can be achieved by studying the morphological behaviour of a pit under conditions of non- or weakly breaking storm waves. The hydrodynamic conditions should be such that the filling and onshore migration of a pit will take place, simulating the behaviour of a sand mining pit in water with depths between 10 and 20 m migrating to the shore.

The objectives of large-scale experiments in a wave flume are:
- measurement of sand concentration profiles to derive the wave-related mixing parameters under non-breaking waves in relatively deep water outside the surf zone; based on this the validity range of the process models can be extended to deeper water;
- measurement of bed and suspended sand composition to study the effect of winnowing processes on the concentration profiles, sand transport rates and bed evolution and to evaluate whether the sand transport rates should be computed by using a single fraction method or a multi-fraction method;
- measurement of near-bed orbital velocities and mean current velocities and associated oscillatory and mean transport components to determine their relative importance to the net transport rates; these parameters can be measured at close spacing along the flume so that the cross-shore gradients can be determined accurately; based on this the measurement locations during future field measurements can be better determined;
- measurement of cross-shore pit morphology and associated net transport rates to improve process models and behaviour-related models, so that the cross-shore behaviour of sand mining trenches and pits in the nearshore zone (especially between 10 and 20 m depth contours) and their influence on the shoreline can be described;
- indirect evaluation of the relative importance of the bed load transport (verification of wave tunnel results), using infill rates of pit and measured suspended transport upstream of pit (diagnostic modelling using data and models).

This proposal for experimental work should be integrated within the planned flume experiments of the SANDPIT Project.

Design of test pit in flume
The basic features of sand transport and morphology in coastal seas (current and waves) can be characterised by a series of dimensionless numbers being: the relative wave height, the Froude number, the suspension number and the particle mobility number
Simulation of field conditions in a laboratory flume or basin requires that these characteristic numbers have approximately the same values in the field and in the laboratory.
Based on this approach, the wave conditions and optimum pit dimensions can be determined.

8.2.6 Knowledge improvement of Ecological processes

One of the consequences of massive sand mining will be the production of an enormous amount of fine sediment, which can be carried over large distances to the coasts and shores of the countries surrounding the North Sea, threatening the environmental system at those places. Many of the processes involved are unknown and should therefore be studied more intensively focussing on the bed, water phase (oxygen cycle) and foodweb by both laboratory and field experiments. Suggestions for further research are given in Section 4.3. An extensive literature study summarizing and evaluating all available knowledge is highly recommended as a starting point for further studies. Research on the impact of fine sediments on the water phase and the foodweb must have the highest priority.

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