Dynamics of the closed coastal system of Holland

DELFT HYDRAULICS, report H2129, project kustgenese

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1 Introduction

The coastal defence policy in The Netherlands is primarily aimed at protection against flooding of the lowland areas situated behind the coastline, which upto 1960 has been achieved by building groynes, dikes and seawalls. Since then, beach nourishment has become a keystone of coastal defence to further reduce the retreat of the coastline in the eroding sections.

In 1990 a historic decision was made to maintain the coastline at the position of that date by all means, as published in an official document: "Coastal defence after 1990". Since then a program of massive and continuous beach nourishment has been initiated to compensate the loss of beach and dune sediments as caused by natural erosion processes.

A basic element of an effective coastal defence policy is the stimulation of research related to a better understanding of the physical processes involved and the behaviour of the coastline on larger scales with the objective to predict future developments related to natural processes and to human interferences. Therefore, in 1985 a multi-disciplinary research program entitled: "Coastal Genesis" was initiated to extend the knowledge of physical processes and coastline behaviour and to predict future coastline developments as required for an efficient management of the coastal zone. Especially, the large-scale and long-term coastal behaviour is of importance in relation to changes in exogeneous conditions such as sea level rise, changes in wave climate and in tidal ranges. These effects may result in the necessity of large-scale and long-term dumping of sand in the beach zone (beach nourishment) and associated mining of sand in offshore areas. The long-term consequences of these measures are of vital importance for coastal management and coastal defence.

The first phase (1985-1990) of the Coastal Genesis Project resulted in 1990 in the publishing of the document: "Coastal defence after 1990", based on a series of detailed technical reports. An important aspect of the underlying studies was the quantification of the large-scale sediment budget of the coastal system. During these studies many uncertainties in the knowledge of the physical processes were identified and, based on this, new research questions were formulated to be studied in the second phase (1990-1995) of the Coastal Genesis Project, as follows:

- what is the exchange of sediment between the lower, middle and upper shoreface? or more precise: what is the net yearly-averaged sand transport rate passing the –20 m and –8 m N.A.P. depth contours?
- what is the behaviour of the cross-shore profile in the surf zone in relation to sea level rise?, or more precise: is there a quasi-instantaneous response of the morphology of the surf zone to changes in sea level?

Besides these specific questions, more general questions were formulated:

- what are the causes of cyclic coastline behaviour?
- what are the conditions of onshore and offshore sand transport?
- what is the geological and historical development of the coastline?

To address these questions, it is of essential importance to better understand the physical processes in the surf zone, middle and lower shoreface zone.
The available knowledge of the physical processes should be operationalized in detailed mathematical hydrodynamic and sand transport models, which in turn should be properly verified based on the results of field and laboratory experiments. Given representative wind and wave climates, the models can be used to predict yearly-averaged transport rates, sediment budgets and cross-shore profile changes or coastline changes.

Coastal research in the period of 1990-1995 was continued along the following lines:

- analysis of physical processes in field and laboratory conditions;
- operationalization and verification of physical processes in process-related and behaviour-related mathematical models.

Applying this research strategy, a balanced combination of knowledge extension and operational models was obtained. The results of this new research effort will be used to evaluate the coastal defence policy of 1990.

The research in the period 1990-1995 was organized in a working group: Closed Coastal System of Holland; the research was subdivided in process-related and behaviour-related research projects coordinated by dr. L.C. van Rijn of DELFT HYDRAULICS. Most of the research projects are imbedded in the Centre of Coastal Research in The Netherlands (NCK) and in the G8-morphodynamics group of the European MAST-program. A summary of the research projects is given in Table 1.1.

Many research results have already been published in doctoral theses (Roelvink, 1993; Al-Salem, 1993; Van de Meene, 1994; Kroon, 1994) and in reviewed journal papers. In this report the results of the research efforts during the period 1990-1995 will be evaluated, missing knowledge of the physical processes will be identified and suggestions for further research will be recommended.

The present report has been composed by dr. L.C. van Rijn of DELFT HYDRAULICS in close cooperation with the staff of RIKZ of Rijkswaterstaat.

The outline of the report is, as follows:

- process-related and behaviour-related research and models;
- description of closed coastal systems;
- process-related research and small-scale modelling;
- behaviour-related research and large-scale modelling;
- recommendations for further research 1995-2000.

Type of research	Subject	Institute
Process-related research	High-frequency wave propagation	Delft Hydraulics
	Low-frequency wave propagation	Delft Hydraulics
	Wave-current interaction	Delft Hydraulics
	Vertical structure of mean flow	Delft Hydraulics
	Sediment transport	Delft Hydraulics Utrecht University Delft University of Technoloy
	Integrated modelling (yearly-averaged transport rates)	Delft Hydraulics
	Surf zone and shoreface dynamics near Egmond	Utrecht University Rijkswaterstaat
	Shoreface-connected ridges near Zandvoort	Utrecht University Rijkswaterstaat
Behaviour-related research	Statistical analysis of morphological data (JARKUS)	Rijkswaterstaat, RIKZ Utrecht University Delft University of Technology
	Sediment budget analysis (multi-line model)	Delft Hydraulics Delft University of Technology Rijkswaterstaat, RIKZ

Table 1.1 Summary of research projects

2 Process-related and behaviour-related research and models

2.1 Introduction

One of the most basic features of the hydrodynamic and sediment transport processes in the coastal zone is *three-dimensionality*, which is caused by the existence of different types of driving forces related to tide, wind, density-differences and Coriolis-effects, all acting in the lower and middle shoreface as well as in the surf zone where the breaking waves are dominant.
Even at a uniform beach with oblique incoming waves a cross-shore undercurrent is generated in combination with a longshore drift current. Very close to the bed in the wave-boundary layer onshore-directed streaming may occur due to an unbalance of the local shear stresses. Longshore variability of breaker bars may result in the generation of localized seaward-going currents, known as rip currents which are fed by the longshore currents. These rip currents spreading out in the deeper surf zone in combination with adjacent landward-going surface currents (mass transport) can be interpreted as horizontal circulation cells moving gradually along the coast.
The morphological development of the shoreface, beach and dunes in this battlefield of waves and currents is generally known as coastal behaviour.

Simulation and prediction of coastal behaviour at a certain level of accuracy require the use of mathematical models representing the basic hydrodynamic and sediment transport processes. Essentially, the models are the reflection of our knowledge of the processes.

In recent years a range of useful mathematical model concepts has been developed, which can be classified into two broad categories:

- process-related models,
- behaviour-related models.

2.2 Process-related models

Generally, these types of models are based on a detailed description of all relevant processes by implementation of a series of submodels representing wave propagation; tide, wind, wave and density-driven currents; sediment transport rates and bed-level changes combined in a loop system to effectuate the dynamic interaction of the processes involved.

Examples of process-related models are:

- 2DV-coastal profile models
- 2DH-coastal area models.

Coastal profile models consider the physical processes in a cross-shore direction, assuming longshore uniformity, so basically a two-dimensional vertical approach. All relevant transport components in cross-shore direction are represented such as wave randomness and irregularity, wave asymmetry, mean cross-shore and longshore currents, streaming in the wave boundary layer, bound long waves and wave stirring of sediments. Bed level changes follow from numerical solution of the mass conservation balance.

The hydrodynamic submodels usually are time-averaged models based on equations for individual waves (wave by wave approach) or equations for integral properties of the wave spectrum giving a characteristic wave height, wave-induced set-up and mean currents (cross-shore undertow and longshore drift).
Sediment transport (bed load and suspended load) is calculated by using a wave-averaged or an intra-wave approach neglecting horizontal convection and diffusion (local approach).
In principle, the profile models are capable of simulating the generation, migration and degeneration of pronounced breaker bars under irregular wave conditions. Generally, the models operate best in the central part of the surf zone with spilling breakers.

The profile models are useful for the short-term simulation and prediction of the profile characteristics, in particular bar development during storm conditions. Meso-term profile recovery under non-storm conditions with net onshore transport processes related to wave asymmetry and near-bed streaming is less well represented by the models; the models are not yet validated for these conditions. The basic physical processes acting in the dune, beach and swash zone need to be implemented in the model formulations. Other deficiencies are wave propagation and reflection on relatively steep slopes, wave breaking on barred profiles, long wave effects relevant for sediment transport processes and the mean current field in breaking wave conditions. All these aspects need further attention.
Although the concept of process modelling in a pure two-dimensional domain may not always be realistic, even in case of a uniform beach, it is of great value for the understanding of the cross-shore transport processes.

Coastal area models herein distinguished are two-dimensional horizontal models and (quasi) three-dimensional models.
The 2DH-models which are widely used, generally consist of:

- wave field model,
- tide, wind, wave-driven current model,
- sediment transport model (formula-type or depth-integrated model),
- bed evolution model (sediment balance).

Stable and realistic results require accurate modelling of the slope-related gravitational transport components and efficient time-stepping procedures and numerical schemes.
The 2DH-models are useful in conditions where the near-bed currents have the same direction as the depth-averaged currents, which is hardly the case in the nearshore coastal zone. Rather a complicated three-dimensional flow and transport system will exist as a result of the combined effect of the various driving forces (tide, wind, waves, density-differences, Coriolis).
Two options are available to model the three-dimensional processes:

- quasi-3D approach,
- full-3D approach.

The quasi-3D approach generally is a combination of 2DH modelling and 1DV modelling to represent the vertical structure of the flow related to bottom friction, wind, wave and density effects. Depth-integrated equations based on vertical equilibrium profile shapes are available to represent the vertical distribution of suspended sediment concentrations and hence the sediment transport field. Full 3D-models describing the currents on a three-dimensional grid, are in a very early stage of development. Full 3D-sediment concentration models are already available and operational; the wave-driven sediment transport processes in the bed-load layer including gravitational slope effects should be included using a local intra-wave approach.

Validation of process-based models requires analysis of the results of both laboratory and field experiments over a range of conditions. Laboratory data of experiments performed under controlled conditions should be used as a first check on model confidence. Ultimately, the models should be validated against field data, requiring synoptic information; whereas most field experiments are point-oriented and of short duration, hampering a thorough field verification of the models. New promising techniques such as remote sensing techniques should be introduced to provide synoptic data of waves, surface currents and seabed topography.

Process-based models are of vital importance in coastal research for the following reasons:

- Computation of yearly-averaged transport rates to be used in large-scale sediment budget models;
- Analysis of small-scale processes and their relative contribution to net effects (diagnostic modelling);
- Analysis of laboratory and field data producing information of higher spatial resolution; identification of spurious data;
- Identification of appropriate measurement locations and required parameter accuracy for field experiments;
- Evaluation of morphological effects related to extreme (catastrophic) events.
- Sensitivity analysis of morphological changes related to time-varying input conditions.

2.3 Behaviour-related models

Behaviour-related models describe the behaviour of morphological features or systems using relatively simple expressions formulated to represent the phenomena at the larger scales of interest. Hence, the basic phenomenological behaviour of the system is described neglecting unnecessary details. All process-related information and additional empirical information is represented by coefficients, parameterized functional relationships or by stripped process-based submodels. Longterm datasets are indispensable for calibration of the model coefficients and functional relationships. In this way the behaviour-related models can integrate the process-related information representing the basic driving forces and the long-term phenomenological behaviour based on field observations.

In principle, the behaviour of any morphological feature can be modelled by use of an advection-diffusion equation to represent the migration and smoothing effects during the course of events. Quantitative results require the specification of the advection and diffusion coefficients as a function of space and time, which might be an insolvable problem, even with process-based models at hand.

Numerous examples of behaviour-related models are available:

- Linear and non-linear extrapolation models;
- Descriptive beach-state models;
- Equilibrium cross-section models based on a relationship between the cross-sectional area of a tidal channel and the tidal volume passing that cross-section;
- Parametric cross-shore profile evolution models based on expressions for typical erosion and deposition events;
- Line-segmented cross-shore profile models based on schematization of the coastal zone in an active surf zone and passive middle and lower shoreface zones represented by line segments which may translate and/or rotate depending on deposition or erosion events;
- Coastline models (one- or multi-line approach) describing the behaviour of characteristic coastlines based on longshore transport variations as a function of local coastline orientation; cross-shore exchange of sediments between adjacent zones can be taken into account by using the multi-line approach, similarly the effect of tidal inlets can be included provided that the transport patterns are known.

2.4 Short-term and long-term modelling

The ultimate objective of morphological modelling is the long-term behaviour of morphological features or systems in relation to human interference and autonomous processes (climate changes).
Large-scale and long-term morphological behaviour is not a vague and mysterious phenomenon but simply the result of a sequence of erosional and depositional events due to variations of hydrodynamic and transport processes. This does, however, not imply that the natural processes should be modelled to the smallest possible scales to arrive at the same overall result.

The hydrodynamic driving forces are a combination of:

- Deterministically varying short-term and medium-term processes (oscillatory and unidirectional flow, tidal variations such as flood, ebb, neap and spring tide and seasonal variations);
- Deterministically varying long-term processes (sealevel rise due to climatic changes);
- Stochastically varying processes at all time scales (turbulence, irregular waves, wind-driven currents, wave climate variations).

The resulting coastal behaviour can be subdivided according to the various scales involved, as follows:

- Large-scale coastline changes related to structural erosion and deposition due to the interaction with neighbouring sediment-importing tidal inlet systems (10 to 100 km; 10 to 100 years).

- Meso-scale, cyclic coastline changes related to the cyclic behaviour of morphological features such as sand banks, sand waves, rip and tidal channels and meso-scale decaying coastline changes related to a transition to a new equilibrium, often induced by man-made structures (1 to 10 km, 1 to 10 years).

- Small-scale fluctuating coastline changes related to stochastic and deterministic variations of morphological features such as beach cusps, swash bars etc. (0 to 1 km; 0 to 1 year).

The relative contribution of the different types of driving processes to the long-term morphological behaviour is not very well known.

A basic question in relation to large-scale and long-term modelling is the type of approach to be used: upscaling or downscaling?

The upscaling approach is based on the application of detailed process-based small-scale models and the integration of the results to the larger scales of interest.
The process-based models are typical short-term models at the scale of the neap-spring tidal cycle or the storm cycle. At best these types of models can produce the yearly-averaged transport patterns to feed a sediment budget model, which still is a great benefit of process-based models. Generally, the applied submodels describing the hydrodynamic and transport processes, are not yet detailed enough to allow accurate and reliable long-term morphological predictions (error accumulation!). Furthermore, many runs are required to represent the stochastic variations of the input data, which is still a constraint in relation to the available computer power. Hence, the upscaling approach is not yet an attractive solution for the modelling of large-scale coastal behaviour.

In the downscaling approach the morphological system is formulated in terms of the behavioural characteristics of the system by means of parameterized input-output relationships or by stripped process-based submodels describing the basic physics as simple as possible to minimize the computational efforts in relation to the updating of the variables.
This latter approach requires appropriate understanding of the dominant generic physical processes at the scales of interest, which can to some extent be effectuated by scale analysis to identify the processes operating at large scales. It must be realized, however, that presently the level of understanding is still very much at an early stage.
Another basic problem of large-scale prediction is the schematization of the time-varying boundary data (input data), which are by definition unknown. The sequence of mild, moderate, extreme and catastrophic events, which is stochastic by nature, will have a dominant effect on the long-term behaviour of the morphological system. This addresses the subject of predictability of morphological systems. The only option here is to run the models for a series of most probable input scenarios and present the output results in terms of variation ranges rather than as absolute values.
The best-established downscaling approach for long-term predictions is that of the coastline and sediment budget models (one or multi-lines), as has been used for the long-term prediction of the closed central coast and the northern barrier island coast of The Netherlands.

3 Description of closed coastal systems

3.1 Longshore and cross-shore scales

The geomorphic closed coastal system may be described as consisting of a hierarchy of compartments, each with its own spatial and temporal scale. A compartment of a higher order includes the compartments of lower order.
Examples of longshore spatial scales (from large to small) are (see also Figure 3.5.2):

- coastal cell consisting of outer and inner breaker bars and associated rip current systems (length scale of 0 to 1 km),
- coastal section consisting of various cells (length scale of 1 to 10 km)
- coastline consisting of various connected sections (length scale of 10 to 100 km).

In cross-shore direction the coastal system between the shore and the shelf may be divided in following subzones (see Figure 3.1.1):

- upper shoreface; surf zone with breaker bars between 3 m and - 8 m depth contours with mean bottom slopes varying between 0.005 and 0.015.
- middle shoreface; zone between -8 m and -20 m depth contours with mean bottom slopes varying between 0.003 and 0.001; sand ridges may be present.
- lower shoreface; zone between -20 m contour and the shelf with mean bottom slope of about 0.001 and lower; sand ridges and sand banks may be present.

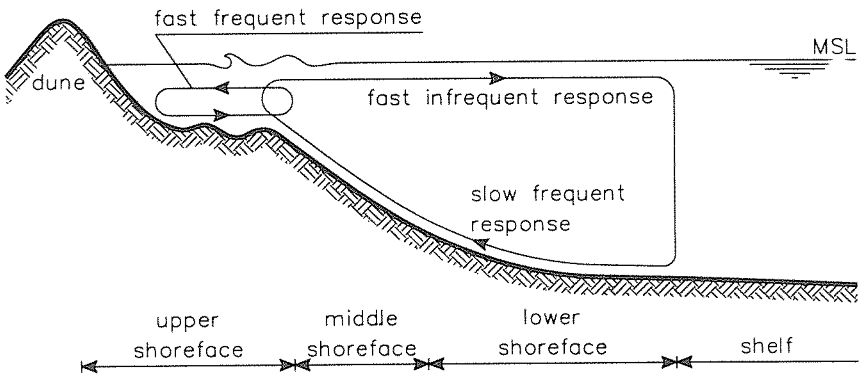


Figure 3.1.1 cross shore spatial scales

The basic elements of each zone and compartment are the hydrodynamics, the sediment transport processes and the morphology in a strongly coupled non-linear interaction.
The hydrodynamic variables mobilize the sediments when threshold values are exceeded; gradients of sediment transport rates lead to changes of morphology which in turn will affect the hydrodynamic variables.
In a dynamic coastal system there is almost instantaneous equilibrium between the processes on the smaller scales and quasi-equilibrium on larger scales because of the time required to adjust large-scale morphological features by erosion and deposition events. Before the new equilibrium is developed, the hydrodynamic conditions may have changed again.

In the lower and middle shoreface zone the transport rates are small and hence the response time of the morphology is generally assumed to be slow (passive behaviour). In the surf zone the transport rates are relatively large and the response time of the morphology is fast, almost on the scale of the events (active behaviour), see also Figure 3.1.1.
Alongshore the coastline may show slow large-scale changes due to the presence of sediment-importing tidal inlets; meso-scale cyclic changes related to the cyclic behaviour of morphological features such as sand banks and sand waves; meso-scale decaying changes related to a transition to a new equilibrium (often induced by man-made structures) and small-scale fluctuating changes related to stochastic and deterministic longshore variations of beach cusps and swash bars etc.

3.2 Hydrodynamics

The hydrodynamic phenomena in the shoreface zone are characterized by different types of motions on different types of scales. Basic wave motions associated with these scales are wind-generated and tide-generated waves.

Wind-generated waves with typical periods of 5 to 15 seconds propagating into shallow water are affected by reflection, refraction and shoaling phenomena and finally by wave breaking in the surf zone. Especially in the shoaling phase before breaking, the wave profile is highly distorted associated with bound higher harmonics (wave asymmetry). Wave breaking inside the surf zone results in the generation of organized mean cross-shore and longshore currents as well as in the generation of chaotic high-frequency and small-scale turbulence.

The incident short waves carry a small forward mass flux in the near water surface region to the shore, increasing in magnitude through the breaking zone and finally piling up at the beach (set-up of mean water level). As a consequence of the presence of a cross-shore water surface gradient, a near-bed return current (undertow) is generated, balancing the onshore mass flux. Oblique incident waves also generate a longshore mean current. Very close to the bed in the wave-boundary layer onshore-directed streaming may occur due to an unbalance of the local shear stresses and other fluid stresses.

Longshore variability of breaker bars may result in the generation of localized seaward-going currents, known as rip currents which are fed by onshore mass transport and longshore currents. These rip currents spreading out in the deeper surf zone in combination with adjacent landward-going surface currents (mass transport) can be interpreted as horizontal circulation cells, moving gradually along the coast.

Low-frequency wave motions with periods in the range of 10 to 100 seconds have been observed outside and inside the surf zone, especially during rough weather conditions. Their importance is enhanced through the surf zone as a result of wave breaking (surf beat). Cross-shore and longshore wave propagation modes have been identified in the coastal zone. Cross-shore modes are associated with forced long waves which are bound to short wave groups or to long-period variations in the break locations of irregular short waves. Longshore low-frequency waves may be progressive or standing edge waves trapped in the surf zone.

Tidal waves have typical periods in the range of 12 to 24 hours, which is related to the gravitational interaction between the sun, the earth and the moon. Tidal waves in coastal seas are originating from tidal forces generated in the deep oceans. Phenomena like reflection, refraction and shoaling affect the tidal waves during propagation to the shore resulting in variations of the tidal range and the generation of amphidromic systems. Wave damping by bottom friction and wave deformation due to differences in the crest and trough propagation speeds become more important in the shallow shoreface leading to wave asymmetry and phase differences between the vertical (surface elevation) tide and the horizontal (current) tide. Geostrophic forces related to the rotation of the earth (Coriolis effect) are of importance in areas further offshore (lower shoreface).
In the nearshore zone the tidal currents tend to be shore parallel; the current vector rotates in a flattened elliptical pattern. Residual currents usually are small (order of 0.1 m/s) and may be enhanced by wind-induced currents, density-induced currents and by local topographical effects (islands, headlands, sand banks).

Besides tidal effects, the large-scale shoreface circulation is driven by wind-induced and density-induced forces with bottom friction as the main controlling parameter.
Wind blowing in a certain direction will induce currents in that direction and in various other directions due to Coriolis forces resulting in a spiral-type turning of the velocity vectors at different elevations above the bed, which is known as the Ekman spiral. In shallow water near the shore the currents respond rapidly to the wind stresses and tend to be aligned with the wind direction. The shore-normal component of the wind stress and the related surface current causes a set-up (or set-down) of the water surface against the shore. As a consequence a cross-shore pressure gradient is generated yielding an onshore (or offshore) bottom current. Longshore winds and associated longshore currents also induce cross-shore currents by the action of Coriolis forces yielding a set-up or set-down of the water surface near the shore depending on the wind direction and corresponding bottom currents are generated.
Density-induced currents are related to spatial gradients of the fluid density due to variations of the salinity, temperature or sediment concentration. Usually, the fluid density related to salinity variations is decreasing in landward direction as a result of river (fresh water) outflow. The density-gradient effect is most pronounced in the near-bed region yielding relative large onshore near-bed velocities during the flood tide and relatively small offshore velocities during the ebb tide. As a consequence a near-bed residual current (landward) is generated, which may cause a net landward transport of sediments.

3.3 Transport processes

Wave motion over an erodible sand bed can generate a suspension with large near-bed concentrations, as shown by laboratory and field measurements. Mean currents such as tide-, wind- and density-driven currents are carrying the sediments in the direction of the main flow; this type of transport usually is termed as the current-related transport.
Wave-induced transport processes are related to the oscillating and mean currents generated by high- and low-frequency waves. Net onshore transport may be dominant in non-breaking wave conditions, whereas net offshore transport is dominant in the surf zone with breaking waves.

The transport components contributing to the wave-induced transport processes in non-breaking waves, are:

- net onshore-directed transport due to asymmetry of the near-bed orbital velocities with relatively large onshore peak velocities under the wave crests and relatively small offshore peak velocities under the wave troughs,
- net onshore-directed transport due to the generation of a quasi-steady weak current in the wave boundary layer,
- net offshore-directed transport due to the generation of bound long waves associated with variations of the radiation stresses under irregular wave groups (peak velocities and concentrations are out of phase).

The transport components in breaking wave conditions in the surf zone are:

- net offshore-directed transport due to the generation of a net return current (undertow) in the near-bed layers balancing the onshore mass flux between the wave crest and trough,
- net onshore-directed transport due to asymmetric wave motion,
- longshore and offshore-directed transport due to the generation of meso-scale circulation cells with longshore wave-driven currents and local offshore rip currents,
- gravity-induced transport components related to bed slopes.

During conditions with low non-breaking waves, onshore-directed transport processes related to wave-asymmetry and wave-induced streaming are dominant, usually resulting in accretion processes in the beach zone.
During high-energy conditions with breaking waves (storm cycles), the beach and dune zones of the coast are heavily attacked by the incoming waves, usually resulting in erosion processes. The sediments are carried in offshore direction by wave-induced near-bed return currents (undertow) and in longshore direction by wave-, wind- and tide-induced currents, which may feed locally generated rip currents. The undertow currents bring the sediments to the nearshore breaker bar systems, whereas the rip currents carry the sediments over longer distances to the edge of the surf zone. The three-dimensional flow pattern is dominant in the inner surf zone, whereas vertical circulations are dominant in the outer surf zone. These processes proceed relatively fast (see Figure 3.1.1) indicated by relatively large short-term variations (on the scale of events) of breaker bars and rip channels.
Low-frequency waves such as bound long waves and surf beat may have a specific role in the shoreface and surf zone. Although the associated net transport directions are partly unknown, these types of waves may be of importance for the position of the inner breaker bars.

In deeper water (-20 m depth contour) the cross-shore transport processes are dominated by the tide-, wind- and density-driven cross-shore mean currents. Most probably, the overall net transport is in the onshore direction with values in the range of 0 to 10 m^3/m^1/year.

In shallow water at the edge of the surf zone (-8 m depth contour) all cross-shore transport components are of importance; onshore- as well as offshore-directed components do exist. Relatively fine sediment material may result in net offshore-directed transport, whereas more coarse material and heavy minerals may result in net onshore-directed transport. Overall, the net cross-shore transport rate is close to zero with variation ranges of $\pm$ 5 m^3/m^1/year.

3.4 Morphology

The transport processes in the shoreface zone are strongly influenced by the presence of small-scale (ripples), meso-scale (bars), and large-scale (ridges and banks) morphological features developed under the prevailing hydrodynamic regime.

Ripples usually are the dominant type of small-scale bed forms in the lower and middle shoreface zone. Both symmetrical wave-induced ripples and asymmetrical current-induced ripples may be generated depending on the relative strength of the wave and current motion. As the current component gains in strength, the ripples become more asymmetrical and larger in height and length (megaripples), especially in case of an opposing current.

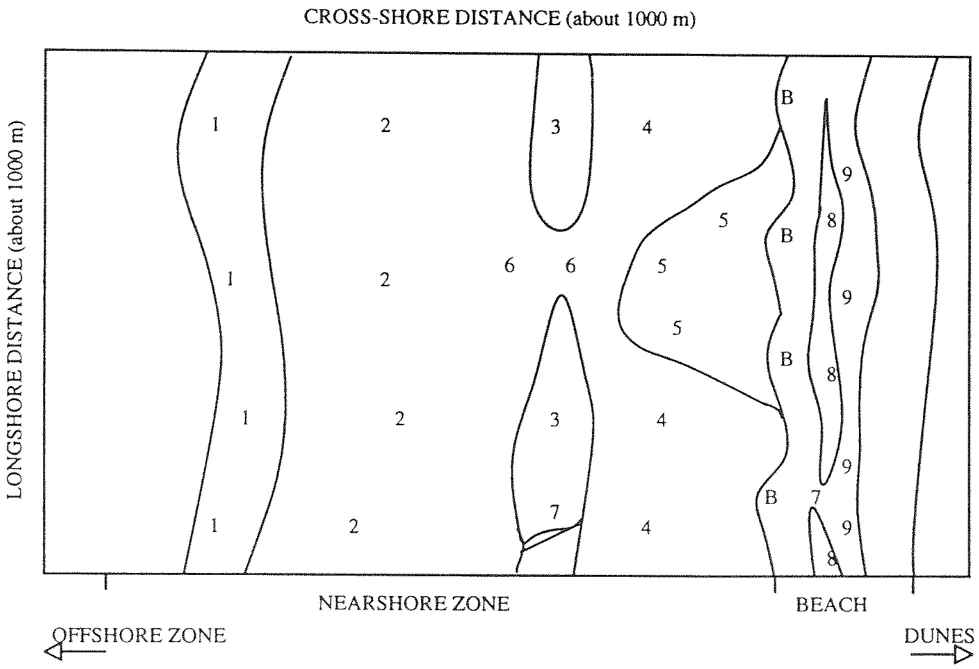
Large-scale sand waves with a length much larger than the water depth and their crest perpendicular to the main current direction are sometimes developed in strong tidal currents ($>$ 0.65 m/s) superimposed by weak orbital velocities. They are found in areas with sufficient quantities of sediments and could have grown up from a flat bed or be the relicts of former hydraulic regimes. At high current velocities the crest of the sand waves is partly eroded similar to that of dunes in the upper river flow regime. Megaripples are often migrating over the back of the sand waves, whereas small-scale mini-ripples are migrating over the back of the megaripples, especially during rough weather conditions with sufficient orbital motion.

Sand ridges and banks are the largest sedimentary features (width of order of 1 km and length of order of 10 km) which can be found in the shoreface zone. Their parallel spacing is of the order of the width. Generally, these features consist of medium coarse sand and are large sources of sediment. Sand banks are quite stable features with smaller sand waves and ripples migrating over the bed surface in regions where the current velocities are large enough to generate particle motion. Closely related to the strength and direction of the currents, the sediment particles are circulating round and over the bank. The crest axis of the bank typically deviates about 10° to 20° from the direction of the peak tidal current, which may be caused by Coriolis effects giving an anticlockwise rotation (on the northern hemisphere). Sand ridges and banks have been observed in the North Sea and in the East China Sea and in many other shelf seas.

Breaker bars covered by wave-induced ripples in the crest regions and by current-related asymmetrical megaripples in the trough regions are the dominant morphological features in the surf zone. The ripples may be washed away during strongly plunging breaking wave conditions (storm events), characteristic of the flat bed sheet-flow regime.
Breaker bars with their crests parallel to the shoreline are found in the zones with spilling and plunging breaking waves. The basic generic mechanism may be the generation of net onshore-directed velocities seaward of the breaker zone and net offshore-directed velocities (undertow) in the breaker zone. Often multiple bars are present in conditions with a relatively flat bed surface in the upper shoreface zone.

The typical morphological features of the surf zone are shown in Figure 3.4.1, classified according to their distinct spatial scales.
The micro-morphology represents the smallest scale of the wave- and current-related ripples. The dynamics of these features is high; relaxation times are short (minutes to hours).

The meso-morphology deals with features like beach cusps along the beach and is assumed to be related to low-frequency phenomena (edge waves). The relaxation times are of the order of days.
The macro-morphology consists of features such as erosion rips, accretion rips and swash bars, bar-trough systems and low-tide terraces. Relaxation times vary from days to years. The overall composition of the micro-, meso- and macro-morphology is characteristic of the beach state.



LEGEND:

MACRO-MORPHOLOGY
1. OUTER NEARSHORE BAR
2. OUTER NEARSHORE TROUGH
3. INNER NEARSHORE BAR
4. INNER NEARSHORE TROUGH
5. LOW-TIDE TERRACE
6. ACCRETION RIP (low mobility)
7. EROSION RIP (high mobility)
8. SWASH BAR (RIDGE)
9. FEEDER CHANNEL (RUNNEL)

MESO-MORPHOLOGY
A. MEGA-RIPPLE: AT 2,4,9
B. BEACH CUSP

MICRO-MORPHOLOGY
f. FLOW RIPPLE: AT 2,4,6,7,9
w. WAVE RIPPLE: AT 1,2,3,4,5,9

Figure 3.4.1 Morphological features of the nearshore zone (Kroon, 1994)

3.5 Closed coastal system between Den Helder and Hoek van Holland, The Netherlands

3.5.1 Historical developments

Since 1600 the central coast of The Netherlands between Den Helder and Hoek van Holland (see Figure 3.5.1) behaves as a closed coastal system in a strong interaction with the interrupted barrier island coast in the north and the interrupted delta coast in the south.
For hundreds of years the northern (north of Egmond) and the southern (south of Scheveningen) sections of the central closed coastal system are suffering from structural erosion because of the sediment-importing capacity of neighbouring tidal inlets.

During the period between 1600 and 1800 the retreat of the coastline in the eroding sections was of the order of 3 to 5 m/year caused by the eroding capacity of the flood and ebb currents near the tidal inlets in the south and in the north and intensified by the stirring action of shoaling and breaking waves (and breaking associated currents).
From 1800 onwards the coastline was more actively defended by building groynes and seawalls. The number of groynes was gradually extended and the length of the groynes was enlarged to about 350 m, almost upto the -4 m N.A.P contour at some locations. Long harbour dams normal to the shore were built around 1870 near Hoek van Holland and IJmuiden to ensure a safe approach of larger vessels to the port of Rotterdam and Amsterdam. As a result of these man-made structures, the retreat of the coastline in the eroding sections was considerably reduced to about 0.5 to 1.5 m/year. Around 1910 some negative effects related to the construction of relatively long groynes and harbour dams were first noticed, being the erosion and associated profile steepening in the deeper surf zone and shoreface zone because of the wave- and tide-induced longshore currents forced to flow around the structures at higher velocities.

3.5.2 Hydrodynamic and sediment characteristics

The coastline between Den Helder and Hoek van Holland has a length of about 118 km and consists of sandy beaches. The coastline is shown in Figure 3.5.1.

The main sediment sizes are in the range of 100 to 500 μm. Two types of mineralogical sediment were identified by Eisma (1968). North of Bergen aan Zee (33 km from Den Helder) the origin of the sediments is related to Saalian glacial deposits and river sand deposits (Meuse and Rhine). South of Bergen aan Zee the sediments mainly consist of Rhine sand deposits. South of IJmuiden the sediments are somewhat finer than those north of IJmuiden.

Man-made structures have a significant influence in this part of the Dutch coast. Most dominant are the relatively long harbour dams of Hoek van Holland and IJmuiden. The seadike of Petten protects the coastal section between 20-26 km (from Den Helder) against wave attack. Due to local erosion the seadike protrudes into the surf zone over a cross-shore distance of about 200 m. Groynes with a length of 200 to 300 m and spacings of 200 to 500 m are present in the sections 0-30 km and 100-118 km.

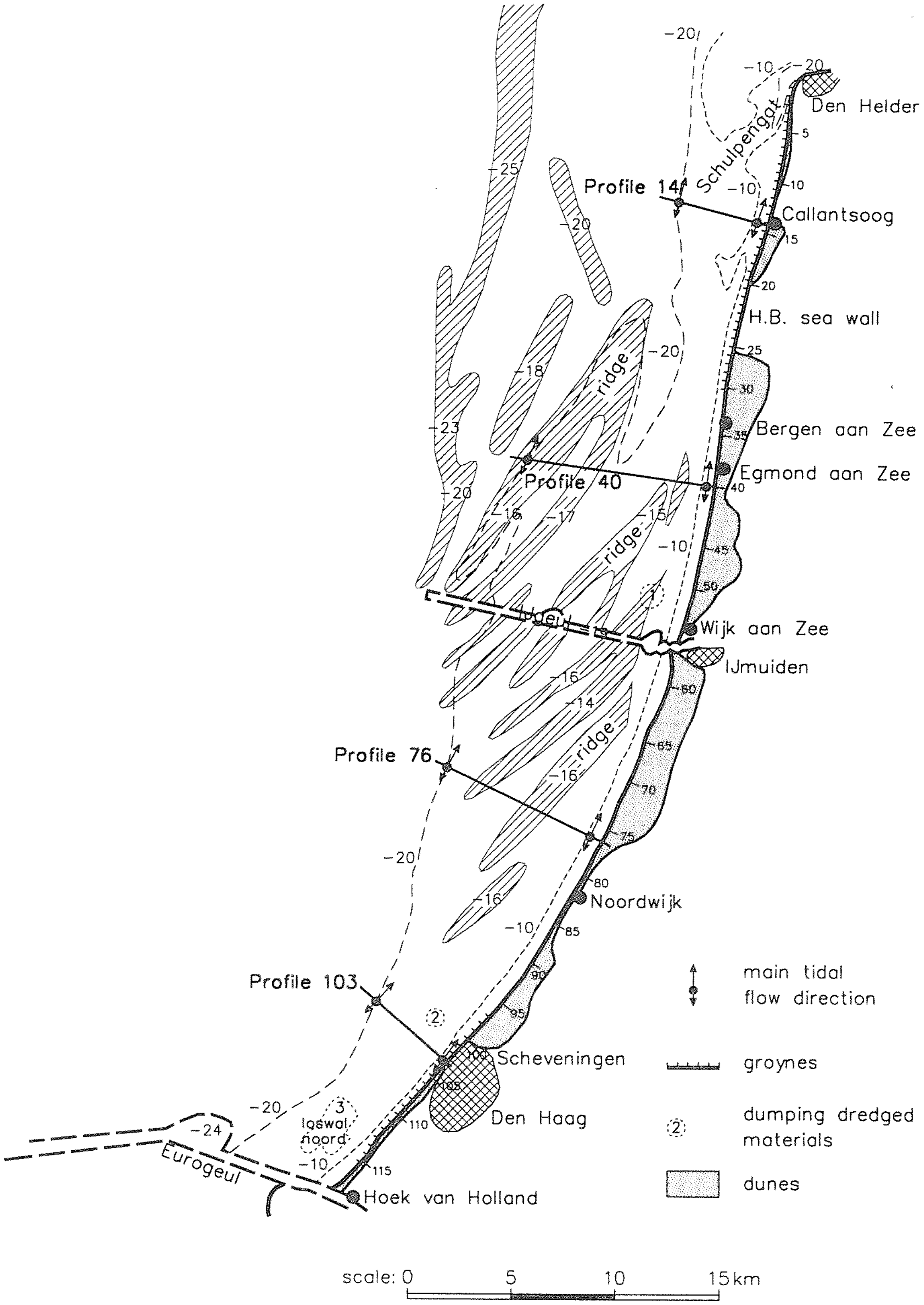


Figure 3.5.1 Closed coastline between Den Helder and Hoek van Holland, The Netherlands

Tidal surface waves, tidal currents, wind-induced currents, storm surges and wind waves do occur and contribute to the local coastal processes.
The tidal ranges along the coast range from 1.4 m near Den Helder to 1.7 m near Hoek van Holland. Tidal currents are dominant along the coast; the flood currents to the north have maximum values of about 0.8 m/s during spring tide, whereas the ebb currents to the south

have lower maximum values of about 0.7 m/s resulting in residual current velocities of the order of 0.1 m/s to the north.

The wind climate of the North Sea generates most of the waves arriving at the Dutch coast. Most important for the coastal morphology is the highly variable (seasonal effects) wave climate near the coast. The highest waves in the Dutch sector of the North Sea are recorded at the K13 station located 110 km off Texel. The lowest waves in the offshore area are recorded on MPN station located 10 km off Noordwijk in 18 m water depth. At the outer edge of the surf zone the waves will be somewhat lower than those in offshore areas due to energy dissipation by bottom friction.
The wave climate at the breaker zone is dominated by waves of moderate height (about 1.5 m) and relatively short period (about 5 s). Waves offshore exceed 2 m approximately 10% of the time and 3 m approx. 2% of the time. Most waves arrive from the southwest to the northwest directions. The highest waves are from the northwest direction because of the longer fetches in this sector. Swell is also dominant from the northwest direction. The waves are highly variable in height and frequency, oscillating between extremes on a period of several days, with the actual extreme height varying considerably between storms, seasons and years. Summer is the period of lowest waves. The winter period has the highest waves with maximum values in January.

3.5.3 Morphological characteristics

The nearshore bed profiles show a system of bars and troughs, see Figure 3.5.2. Generally, a swash bar attached to the beach and two or more breaker bars are present in the central sections north and south of IJmuiden. Near Den Helder and Hoek van Holland only one breaker bar is present.

Large sand ridges are present in the lower and middle shoreface; the latter are almost connected to the shore (see Figure 3.5.1).

Detailed analysis of short-term and long-term morphological data of the central zone between Den Helder and Hoek van Holland shows the following basic features:

- systematic retreat of the coastline north of Egmond and south of Scheveningen;
- erosion of the middle and lower shoreface zone (-8/-12 m N.A.P.); minor erosion in the central sections; increasing erosion towards the harbour dams and the Marsdiep channel (tidal inlets);
- steepening of the cross-shore profile in the surf zone north of Callantsoog and south of Scheveningen and in the middle shoreface zone near Bloemendaal; most probably related to accelerating longshore tidal currents (passing around groynes and dams);
- absence of major breaker bars in the eroding sections north of Callantsoog and south of Scheveningen.

Based on the available morphological data (1964-1992), the net yearly-averaged sand volume change in the surf zone between 3 m and -8 m N.A.P. depth contours between Den Helder and Hoek van Holland was found to be 125.000 m^3/year (sedimentation).

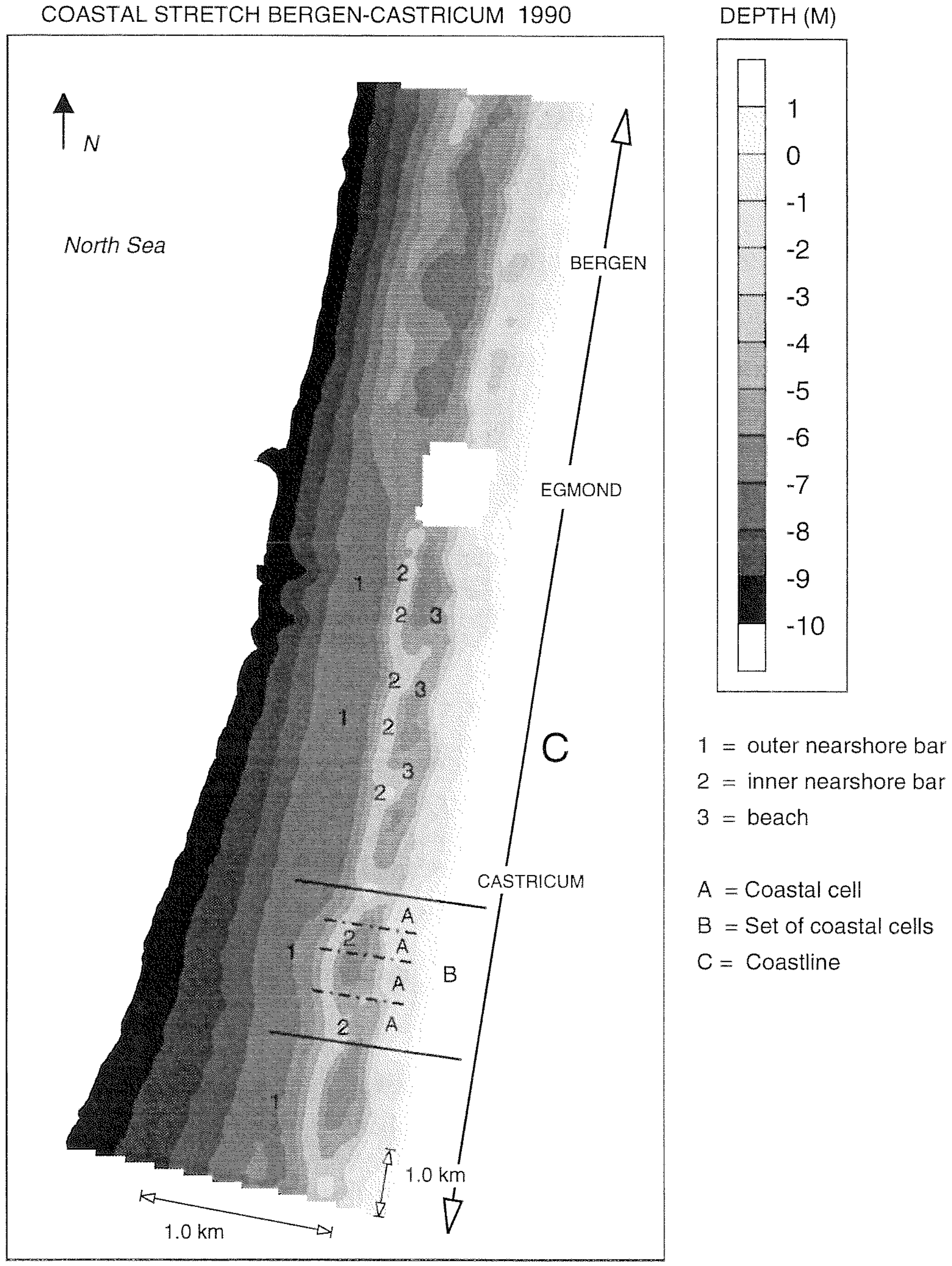


Figure 3.5.2 Coastline near Egmond, The Netherlands (Kroon, 1994)

The components contributing to this yearly-averaged sedimentation volume in the surf zone are:

- net longshore transport near Den Helder,
- net cross-shore transport across 3 m and -8 m N.A.P. contours,
- nourishment and dredging volumes.

The net longshore transport near Hoek van Holland is assumed to zero due to the presence of the harbour dams extending beyond the surf zone (-8 m N.A.P.). Similarly, the net longshore transport rate near IJmuiden is assumed to be zero.

The net longshore transport near Den Helder is estimated to be about 500.000 m^3/year (including pores) in northward direction (based on model computations).

The net onshore wind-blown sand transport across the 3 m N.A.P. contour is estimated to be 280.000 m^3/year between Den Helder and Hoek van Holland, according to the results of De Ruig (1989).

Taking the nourishment and dredging volumes and the above-given volumes into account, the net cross-shore transport over -8 m N.A.P. contour is found to be 490.000 m^3/year in onshore direction (closing volume).

The corresponding sand budget for the surf zone is (3 m/-8 m depth contours), as follows:

In:	nourishment	= 440.000 m^3/year
	net onshore transport (-8 m N.A.P.)	= 490.000 m^3/year
Out:	net longshore transport (Den Helder)	= 500.000 m^3/year
	net onshore transport (+3 m N.A.P.)	= 280.000 m^3/year
	dredging Scheveningen harbour	= 25.000 m^3/year
In-Out:	resulting sedimentation	= 125.000 m^3/year

Based on detailed analysis of the JARKUS-data of the subsections along the coast, the distribution of the net longshore transport rate along the coast was obtained. South of IJmuiden the net longshore transport rate in the surf zone was found to increase from zero near Hoek van Holland to about 500.000 m^3/year near IJmuiden. North of IJmuiden the net longshore transport is directed southward in section 35-55 km and northward again in section 0-35 km with a maximum value of about 500.000 m^3/year near Den Helder. The net southward transport just north of the harbour dam is related to the presence of the dams reducing the wave energy flux from southwest directions.

Reliable sand volume data of the lower and middle shoreface zone (-8/-20 m N.A.P.) are only available for the subzone between -8 m and -12 m N.A.P. contours. A total yearly-averaged erosion volume of about 700.000 m^3/year was found for the sections 8-50 and 60-68 km; all subsections along the coast except those adjacent to the harbour dams of IJmuiden show erosion, minor erosion in the central sections, increasing erosion volumes are found towards the harbour dams and the Marsdiep channel which is most probably related to accelerating longshore tidal currents.

Crucial assumptions in the overall sand balance of the surf zone (3/-8 m N.A.P.) are:

- the net longshore transport rate of 500.000 m^3/year near Den Helder (loss to Waddenzee through the Marsdiep channel), and
- the net onshore transport rate of about 500.000 m^3/year across the -8 m N.A.P. contour between Den Helder and Hoek van Holland.

This latter value corresponds to an onshore transport rate per unit length of 4 to 5 m^3/m^1/year; the onshore transport rate in the central sections further away from the harbour dams was estimated to be somewhat smaller (2 to 3 m^3/m^1/year).

The overall sand balance of the large-scale shoreface zone (-8 m/-20 m N.A.P.) was determined by using the computed yearly-averaged transport rates according to the applied mathematical models. Hence, the accuracy of the sand balance results is strongly related to the accuracy of the computed transport rates. Verification of the computed transport rates is essential.

4 Process-related research and small-scale modelling

4.1 Introduction

The process-related research of the Coastal Genesis Project was aimed at obtaining a better understanding of the physical processes involved (extension of knowledge) and at the operationalization of process knowledge in mathematical models (integrated modelling).
Theoretical work as well as practical work in laboratory and field conditions has been performed. The field experiments are related to the physics of the shoreface-connected ridges near Zandvoort and the surf zone and shoreface zone dynamics of the coastal zone near Egmond, The Netherlands.

The subjects herein discussed, are:

- high-frequency wave propagation
- low-frequency wave propagation
- mean current field and vertical structure
- sand transport processes
- integrated modelling.

Research developments elsewhere are also discussed where necessary and appropriate.

4.2 High-frequency wave propagation

4.2.1 Introduction

Incident waves coming from the sea to the shore can be divided into two categories:

- Wind waves and swell; these are the most energetic and readily visible waves.
- Long waves, which can be subdivided in:
  - Bound long waves; these are long waves associated with modulations in the wind waves and are travelling at the group velocity of wind waves; regions of high waves carry along a depression of the mean level, called "set-down" by Longuet-Higgins and Stewart (1964).
  - Free long waves; edge waves may be incident from the adjacent coastal regions.

In this section the propagation and transformation of high-frequency waves is considered. Waves play a dominant role in the nearshore zone. Wave processes are responsible for large fluid motions which drive currents, sediment transport and bed level changes.
During its propagation to the shore, the relatively well-organized motion of offshore waves is transformed into several motions of different types and scales, including small-scale turbulence, large-scale coherent vortex motions and oscillatory low-frequency wave motion. Their interactions (mostly nonlinear) are still poorly understood.

4.2.2 Wave breaking

Wave breaking and energy dissipation play an essential role in the surf zone dynamics because they induces a gradient of the radiation stresses driving the set-up of the mean water level and the longshore currents. The surf zone shoreward of the breaking point can be roughly divided in three subzones (Svendsen, 1984): outer breaking zone, inner breaking zone and swash zone.
In the outer breaking zone or transition zone the breaking waves are transformed into turbulent bores with a rapid transition of the wave shape including the generation of a surface roller. Most of the potential energy lost in breaking is first converted into kinetic energy of organized large vortices.
In the inner breaking zone the kinetic energy of the organized vortex and roller motions is dissipated into small-scale turbulent motions. Longshore currents, cross-shore return currents and mean water level set-up are generated. The process of energy transfer causes a lag between wave breaking and the generation of mean flow, especially in case of a barred bed profile.
In the swash zone near the water line the run-up of plunging breaking waves in combination with significant low-frequency motions is dominant.

The wave breaking process and associated energy transfer from potential energy into kinetic energy are still at an early stage of understanding, especially for profiles with major breaker bars. Experimental research has been carried out in a small-scale flume (wave breaking over a movable bar in the DUT-flume) and in the Delta flume of Delft Hydraulics (LIP-experiments). High priority should be given to further analysis of these experiments with respect to the breaking-related phenomena (further research).
Also the wave-flume experiments of Klopman (1994) should be further analyzed focussing on the breaking wave zone.

4.2.3 Wave shoaling and asymmetry

The horizontal near-bed peak velocities under the crest and the trough of shoaling and breaking waves show a significant asymmetry increasing with relative wave height (H/h), which is of fundamental importance with respect of the net onshore-directed transport processes causing accretion of beaches.
The results of laboratory experiments show that the asymmetry reaches a maximum value near the breaking point and then decreases in the surf zone. Asymmetry values in field conditions (Egmond, The Netherlands) were presented by Houwman and Hoekstra (1993) and are shown in Figure 4.2.1. In water depths larger than about 7 m the asymmetry factor remains relatively small with maximum values of about 0.55 ($\hat{U}_{on} \approx 1.2\ \hat{U}_{off}$) under storm conditions. In the shallow surfzone the maximum asymmetry factor is about 0.65 ($\hat{U}_{on} \approx 1.8\ \hat{U}_{off}$) under strong plunging breaking waves ($H_s/h = 1$).
Many higher-order wave theories are available to determine the asymmetry of the near-bed velocities. The most popular wave theories have been derived by assuming potential flow over a flat bed. Analytical solutions have been derived by making expansions in a small parameter yielding solutions upto the 5th-order for deep water (Stokes-solutions) and shallow water (Cnoidal-solutions). Numerical methods based on Fourier approximations give solutions in the form of truncated Fourier series (Sobey and Bando, 1991).
Parameterized solution methods based on an empirical wave shape for any depth over a horizontal bottom (Vocoidal theory) and later over a sloping bottom (Covocoidal theory) have been introduced by Swart and Loubser (1978) and Swart and Growley (1988).

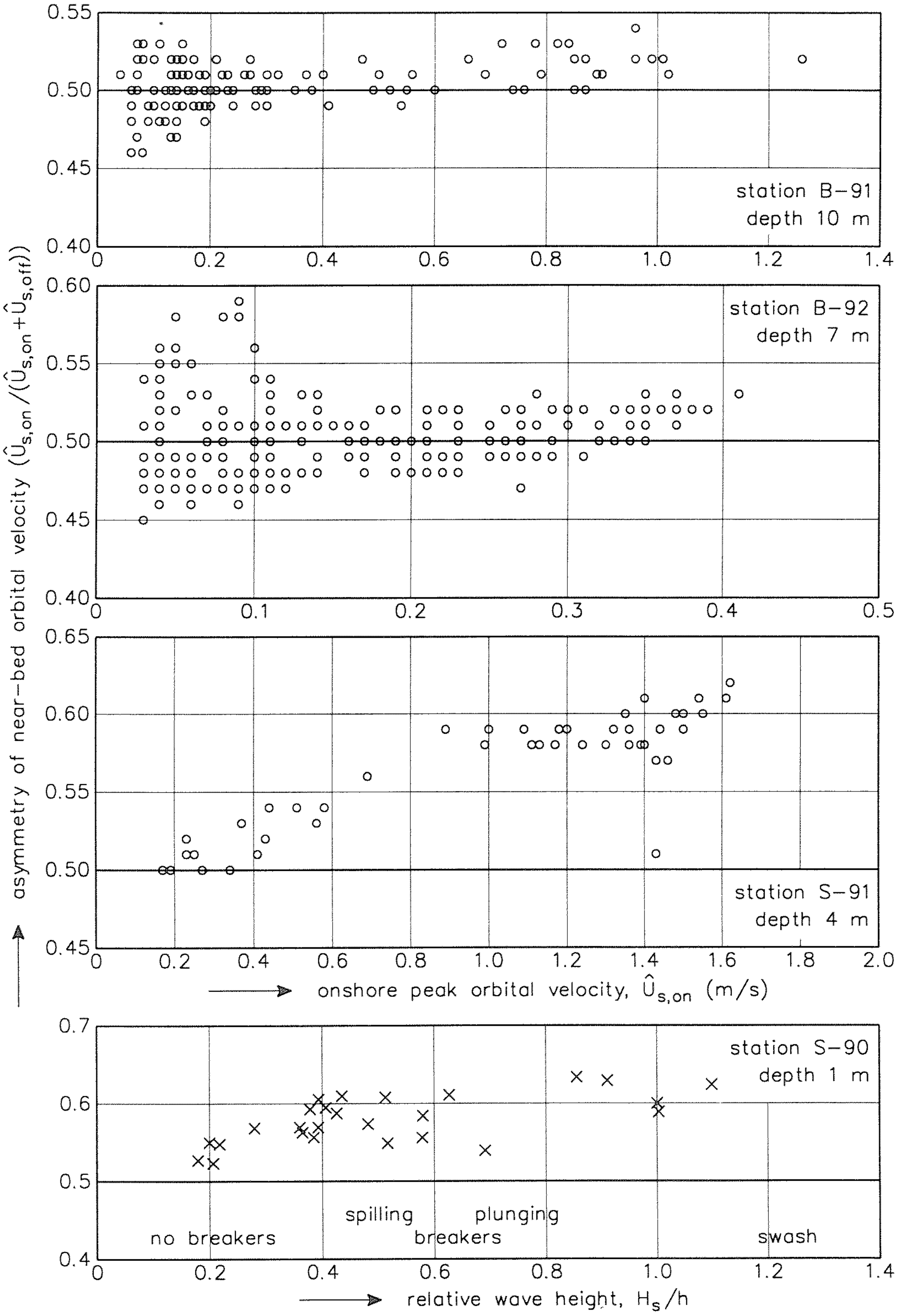


Figure 4.2.1 Asymmetry of near-bed orbital velocity in four stations in cross-profile near Egmond, The Netherlands

$\hat{U}_{sig,on}$ = significant near-bed onshore peak orbital velocity

$\hat{U}_{sig,off}$ = significant near-bed offshore peak orbital velocity

Figure 4.2.2 shows asymmetry factors of three wave theories in water depths of 5, 3 and 1 m for a wave period of 7 s. In case of a depth 5 m the three methods produce similar results. For a depth of 3 and 1 m the Cnoidal theory and the Rienecker-Fenton Fourier approximation theory (1981) yield similar results; the Covocoidal theory gives significantly larger values. Compared to the asymmetry factors for field conditions (see Figure 4.2.1), the applied wave theories produce relatively large values, especially in shallow water and even for low velocity values (low waves).

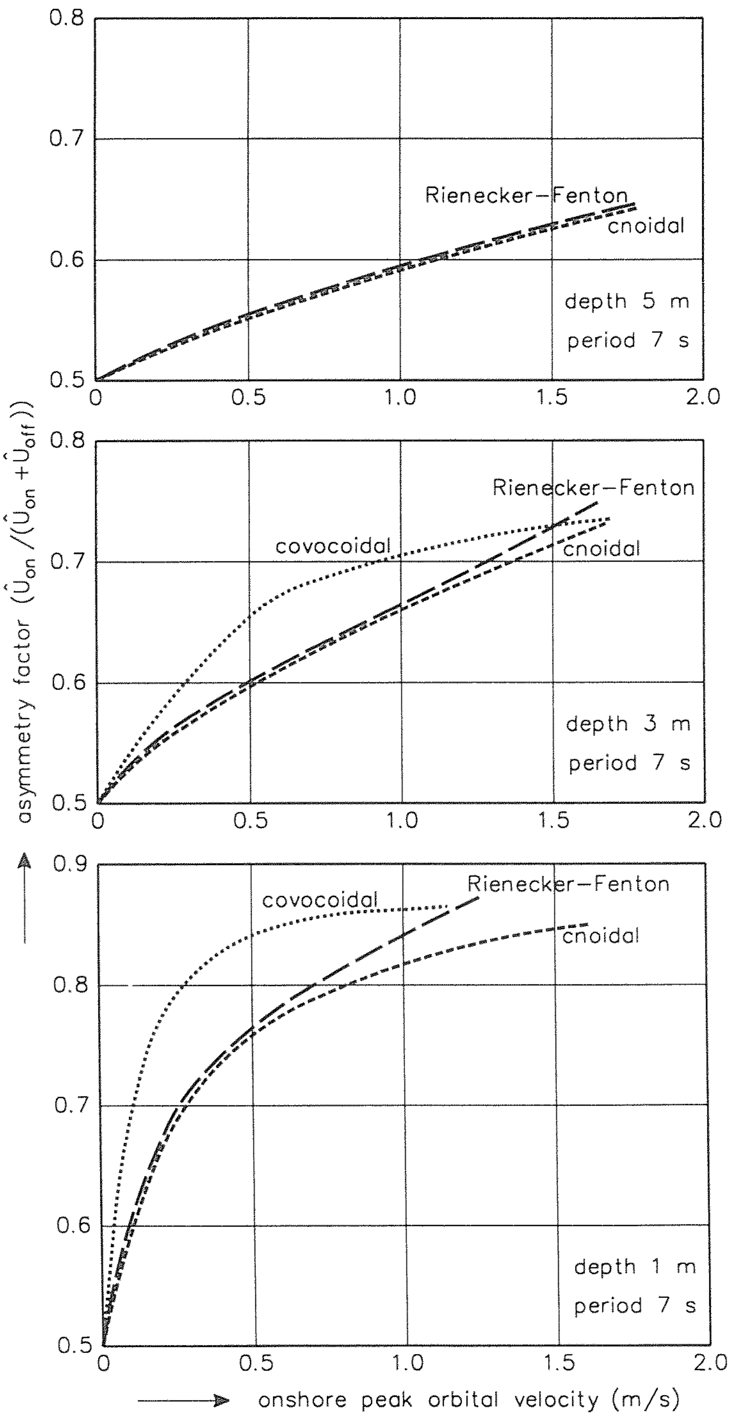


Figure 4.2.2 Asymmetry factor of near-bed orbital velocity according to three higher-order waves theories (Cnoidal theory, Covocoidal theory, Rienecker-Fenton Fourier approximation theory)

Figure 4.2.3 shows a comparison of measured and computed peak onshore and offshore velocities for a large-scale flume experiment (Roelvink, 1987). The measured data were corrected for the effect of the mean current generated by the wave motion and the effect of low-frequency waves. The peak onshore velocities under the wave crests are reasonably well described by linear wave theory (Stokes 1st order), the Rienecker-Fenton Fourier approximation theory and the covocoidal theory, even at relatively high waves ($H_s/h = 0.6$). The peak offshore velocities under the wave troughs are overpredicted by linear wave theory (about 20%) and underpredicted by the Rienecker-Fenton and covocoidal wave theories, even at relatively low non-breaking waves ($H_s/h = 0.3$).

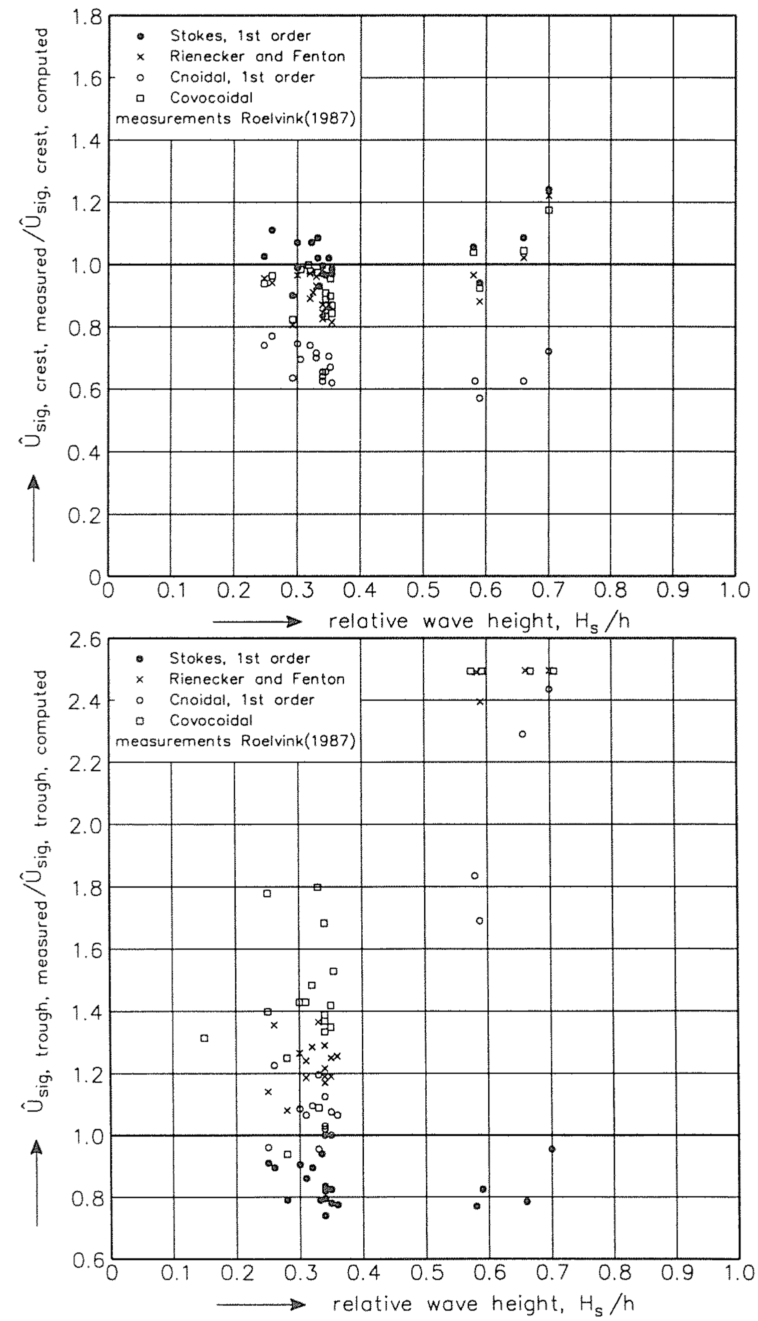


Figure 4.2.3 Measured and computed near-bed peak onshore and offshore velocities, Delta flume experiment (Roelvink, 1987)

In case of combined breaking and non-breaking waves in the surf zone different methods should be used for both types of waves. Resulting velocities can be obtained by multiplying with the fractions of breaking and non-breaking waves. Exploring studies have been done by Roelvink et al. (1995), but the agreement between computed and measured wave velocity asymmetry is not yet satisfactory (see, for example, the wave asymmetry effect (D) in Figure 4.6.1). Further research is required to come up with a universal and generally-accepted method to be used for waves (in combination with currents) in the surf zone. Kroon (1994) as many others has found that the peak onshore velocity can be reasonably well described by linear wave theory, even for breaking waves. The peak offshore velocity can also be described by linear wave theory using a simple empirical correction factor. Further research is required to verify the validity of this concept.

Non-linear wave effects on a sloping bottom can be represented by Boussinesq-type models, consisting of a continuity equation and a depth-averaged momentum equation (Boussinesq, 1872).
Dingemans (1994) made a comparison between the results of various Boussinesq-type models and laboratory measurements. Based on this, he concluded that the frequency-dispersion modelling is much more important than the modelling of the higher harmonics.

4.2.4 Wave modelling

In morphodynamic models the wave information is generally obtained by using the following procedure:

- wave propagation and transformation (including breaking) in the nearshore zone and
- wave kinematics (asymmetry) computation using an appropriate wave theory.

The most important phenomena to be represented in wave propagation and transformation models are:

- randomness and directionality of the waves
- refraction of waves over horizontally sheared currents
- nonlinear wave mechanics of shoaling waves just before breaking
- wave breaking and energy dissipation in the surf zone.

The traditional approaches of wave field modelling make use of the separation of vertical, horizontal and time variables. Wave-averaged energy conservation laws can be derived by integrating the basic equations of fluid motions over depth and averaging over the wave-period. This integrated approach forms the basis of pure refraction wave ray models. The other classical derivation introduces a velocity potential by assuming the irrotationality of wave motions. Euler equations are linearized and the method of separation of variables is applied by assuming a vertical distribution of the velocity potential and harmonic time functions of wave components. This has led to the mild-slope equation in which diffraction effects are included and wave energy flux is no longer conservative along rays. This aspect is quite attractive in the nearshore zone where significant diffraction is expected over complex bathymetries.

Two types of models are commonly used to describe the propagation and transformation of waves over a (barred) nearshore bed profile for uniform beaches: parametric models and probabilistic models.

A parametric model was used by Roelvink (1993) and updated by Roelvink and Reniers (1994). A probabilistic model was recently presented by Van Rijn and Wijnberg (1994). Many other models of both types have been presented in the literature (see Hamm et al, 1993).
The parametric models are based on the wave-energy or wave-action balance in terms of the root-mean-square wave height (H_{rms}) and the peak period to represent the (single peaked) wave spectrum. The energy dissipation of breaking waves is modelled in analogy with the energy dissipation of a propagating bore. A popular method is that proposed by Battjes and Janssen (1978) which is based on a Rayleigh-distribution of wave heights, truncated at the breaker (maximum) wave height. Functions are specified to determine the maximum wave height and the percentage of breaking waves.

The probabilistic models are based on propagation and transformation of individual waves (wave by wave approach). The probability density function of the wave height in deep water is schematized into a discrete series of wave height classes- and corresponding periods. Each wave height class is assumed to propagate shoreward independently of the other classes by solving the wave-energy balance separately. The individual waves shoal until an empirical criterion for breaking is satisfied. Wave height decay after breaking is modeled by energy dissipation methods or by exponential adjustment to a stable wave height. At any location the wave statistics such as the root-mean-square wave height (H_{rms}) or the significant wave height ($H_{1/3}$) can be calculated from the predicted individual wave heights.

Figures 4.2.4 and 4.2.5 show measured and predicted wave heights for the LIP-1B experiment in the Deltaflume of DELFT HYDRAULICS (Arcilla et al, 1994).

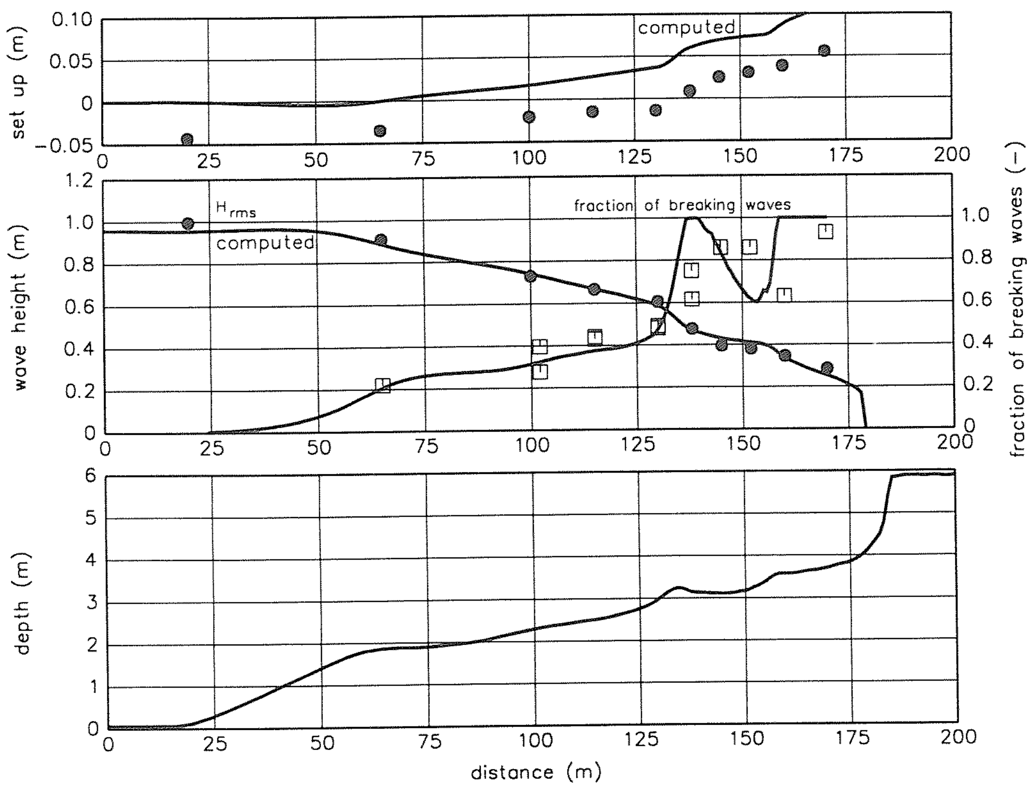


Figure 4.2.4 Measured and computed wave height using parametric model (UNIBEST), LIP-1B experiment

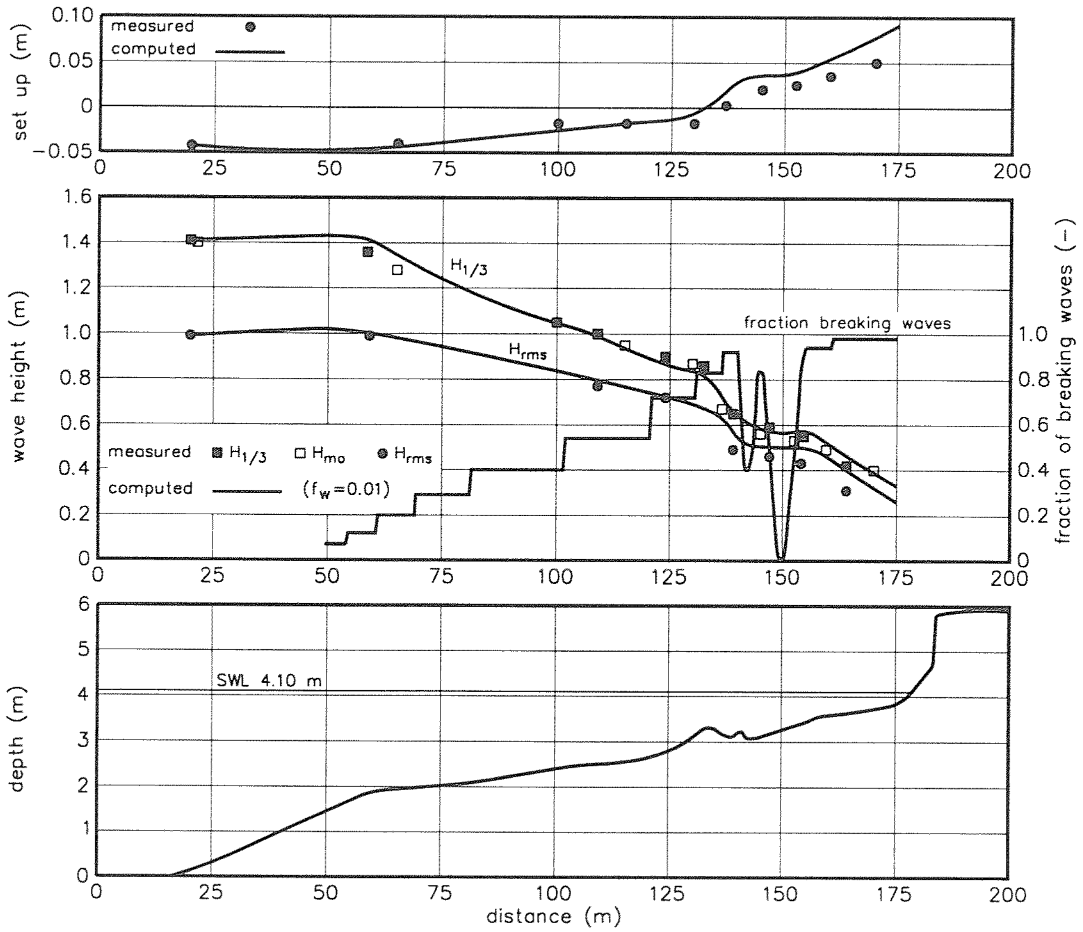


Figure 4.2.5 Measured and computed wave height using probabilistic model (WAVIS), LIP-1B experiment

Both types of models can predict the wave height distribution quite well in case of monotonically sloping bed profiles, even with small breaker bars. When large-scale bars are present, the predicted wave heights are less good. Wave breaking ceases landward of the bar and the bore model cannot be used any further.
The probabilistic models may offer the most promising results for accurate determination of the sand transport rates because of a better representation of the higher waves.

Further research of high-frequency wave models should be focused on wave breaking and wave shoaling over barred profiles. Finite amplitude shoaling and wave mechanics in the swash zone are features to be included in the models.

4.2.5 Further research

The following subjects should be adressed:

- Wave breaking and energy dissipation over barred profiles (lag effects);
- Asymmetry of near-bed orbital velocity in breaking and non-breaking waves;
- Modification of wave period in breaking waves;
- Wave propagation modelling using parametric and probabilistic models;
- Wave mechanics in the swash zone;
- Finite-amplitude wave shoaling of low-steepness (swell) waves over a relatively steep bottom.

4.3 Low-frequency wave propagation

4.3.1 Introduction

A review is given by Hamm et al (1993) and Roelvink (1993). A summary of their review is given below.

Interaction of all incident wind-waves (see Section 4.2.1) in the nearshore zone generates long period motions. The interaction with bed topography, and with wave-generated and other currents is of dominant importance. The long period motions can be subdivided into low-frequency waves (LFW) and vortical motions, such as longshore currents and rip currents. The term "infragravity waves" is also used to describe LFW, but since LFW are essentially gravity waves "infragravity" seems inappropriate. On a plane beach, the LFW motion is often described and analysed in terms of certain modes of motion, edge wave modes and reflective or "leaky" modes. For direct onshore-offshore motion, the only free modes are those corresponding to waves coming into the beach and being reflected there.

Normally most LFW motion is within the range where linear theory can be expected to hold, however if the beach profile has some sort of bar so that a region of full or partial resonance can occur, then LFW waves of large amplitude can grow and form substantial bores.

For gently sloping beaches, where most LFW activity is thought to originate, those waves which have variation along the shore are often trapped within the shallower region and are best described in terms of edge waves.
Edge waves have modes which are numbered according to the number of zeros of wave elevation between the shore and the outermost part of the wave which decays exponentially seawards. For the higher modes of edge waves, refraction of waves away from deeper water is seen to be responsible for their confinement to shallower regions.
For beaches bounded by headlands or by an entrance to a bay, standing edge waves corresponding to the modes fitting the beach length are the most likely to be observed. On long uniform beaches progressive edge waves may be more likely but standing edge waves are also observed.
The vortical long period motions have a different character since there is no significant variation of surface elevation associated with them. They are also often strongly affected by the bed topography. Longshore currents and rip currents are the best known examples. These are typically modelled as steady flows driven by the incident short waves.
LFW can generally be expected to be well described by linearised equations but there are certainly cases where the LFW properties are influenced by vortical motions such as longshore currents.

There is general agreement and all observations indicate that long period motions are caused by short waves incident on the coast. The major process involved is also clear. Short waves lose much or all of their energy by breaking. This dissipation differs strongly in its effects from the more commonly studied dissipation of fluid flows by frictional drag effects at boundaries. Breaking usually leads to little or no stress on the boundary and hence there is little or no loss of momentum. It is this momentum carried into the surf zone by the short waves and deposited there, that drives both LFW and vortical motions. It is best formulated in terms of the momentum flux tensor, which is usually described as "radiation stress".

In the simplest case of a uniform short-wave train normally incident on a plane beach, there are no mean currents and the progressive transfer of momentum from the short waves breaking in the surf zone balances the pressure gradient due to wave-induced set-up of the water level. Any variation from non-uniformity in the incident wave train may lead to the generation of long wave motion.
The simplest case is that of free long waves. These are normally sufficiently small in amplitude that near-perfect reflection can be expected. However their interaction with the incident short waves may be quite significant.
During half the long wave period, the short waves are "compressed" and during the other half they are expanded. Thus the dissipation of their energy, and hence transfer of momentum, is modulated in space and time by the long waves.
This must lead to generation of further long-waves at the same frequency as the incident waves. Whether the effect is to amplify or destructively interfere with the incident long wave depends on their relative phases and is hence likely to depend on the width of the surf zone. This topic awaits further study.

Most study has been given to the case of modulated short waves. Offshore there is a bound long wave accompanying such modulations. The magnitude of the bound wave changes as the water depth changes which implies that free long waves are being created to balance the changes in the bound wave. Then, as the short waves break two features affect the transfer of momentum to long waves. Higher waves break first in deeper water, and lead to a greater set-up, thus modulation leads to a variation of the width of the surf zone and to the magnitude of set-up. The break-point moves back and forth; in this region there is a radiation stress gradient varying in time. This gradient acts as a local forcing, comparable to a wave maker which generates waves both in onshore direction and (with opposite sign) in offshore direction. The onshore directed wave is subsequently reflected off the beach and interferes with the offshore directed wave. Depending on the dimensionless width of the surf zone, the relative phase of the two free outgoing wave components changes, resulting in an enhancing or damping of the total free wave radiated from the surf zone. Bound long waves may also be made free in the surf zone and will be reflected off the beach.
In reality, a combination of LFW and vortical motions are generated. Also as the short waves decrease in amplitude near the shore line, they are more strongly affected by the LFW. At the shore line short waves reach zero amplitude, yet the LFW are near maximum. This is very evident in the size of swash zone across which the instantaneous shoreline moves; for a regular uniform wave train this zone is often very small, yet for any variation from uniformity its width grows rapidly.
Modulations in the longshore direction will lead to excitation of both edge-wave modes and vortical motions.

In the past, almost all theoretical modelling has involved an approximation of linear waves, both short and long, with the radiation stress of the averaged short waves as the main interaction between the two. Typically the major nonlinear part of these models is the representation of wave breaking. Commonly waves are represented as breaking with a limiting amplitude which is a certain fraction of the water depth. Some numerical models include more or less other details (see Roelvink, 1993).

Among recent developments is the inclusion of non-linearity in the incident short waves by modelling the full wave motion. Outside the breaking zone Boussinesq equations provide an accurate modelling of the non-linear transformation of irregular wave trains including wave-wave interaction and the propagation of bound long waves.

The hypothesis that low-frequency waves have an important effect on cross-shore bed profiles originates from the fact that the typical length scales of many morphological features on natural beaches are similar to the length scales of long waves. Two types of explanations have been offered for the influence of long waves.

In the first explanation the long wave motion itself is responsible for introducing net transport effects through drift velocities that occur in the case of standing long waves. In cross-shore direction, it is quite likely for standing waves to occur, since most of the long waves incident on a beach will be reflected almost fully. Often, long waves are trapped in the nearshore zone on a sloping beach as "edge waves", which form a cross-shore standing wave pattern which propagates in longshore direction. For a standing wave pattern in longshore direction to be possible, different edge waves of the same frequency must occur simultaneously. In this case, net drift velocities are again possible. Most existing bar patterns have been explained by various combinations of edge waves.
Another explanation was first pointed out by Shi and Larsen (1984). An important effect of short waves is that the amount of suspended sediment is related to the amplitude of the short waves and therefore varies on the time-scale of the wave groups. Since the long waves act on the time-scale of the wave groups, and often are caused directly by these groups, a strong correlation between the suspended load and the long wave velocity is found to exist, and thus a significant net transport effect. This effect scales with the short wave velocity variance times the long wave velocity amplitude and must therefore be much larger than the effect of the drift velocities in standing long waves.

4.3.2 Bound long waves

Bound long waves may exist in the shoreface zone near Egmond, The Netherlands, during storm events (Houwman and Hoekstra, 1993). Figure 4.3.1 shows the cross-correlation between the short wave envelope curve and the long wave elevation assuming a zero time lag. Correlation coefficients between -0.5 and -1 are an indication for the presence of bound long waves related to wave groups.

Low-frequency wave propagation was studied in detail by Roelvink (1993). The aim of the study of Roelvink (1993) was to develop a predictive model of the propagation and decay of groups of short waves and the long wave generated by these groups and to investigate with this model the effect of long waves on the development of cross-shore profiles for the case of normally incident waves.

The model formulations of Roelvink are based on the short wave averaged conservation equations for mass, momentum and wave action. Closure relations are derived from linear theory, except for those concerning dissipation terms. A new formulation for the time-varying, short wave averaged wave energy dissipation due to breaking is proposed.

This formulation plays a key role in solving the conservation equations. Special attention is paid to the calibration of the parameters in the breaker formulation, and a set of constant parameter values is found for which the formulation is valid over a wide range of conditions.

A numerical method was designed to solve the non-linear system of conservation equations. In order to avoid a complicated treatment of the water line, the system of equations is transformed from a non-equidistant and time-varying physical domain to an equidistant and constant computational domain. A standard scheme of second-order accuracy is used to solve the transformed equations.

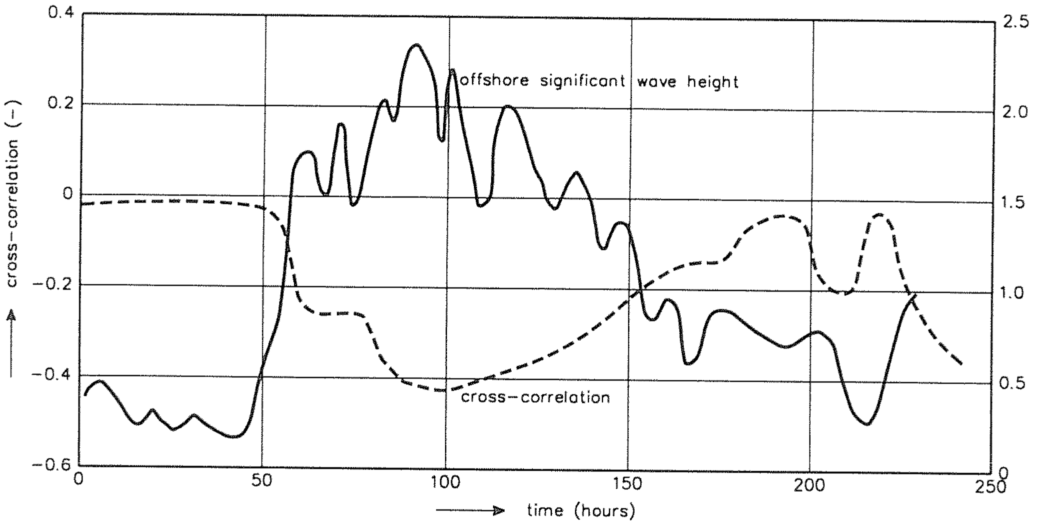


Figure 4.3.1 Cross-correlation between wave envelope and low-frequency pressure in water depth of 7 m near Egmond, The Netherlands

The applied numerical method has been tested against known analytical solutions of the non-linear shallow water equations. These solutions are reproduced accurately. The scheme is capable of accurately representing bore solutions of the shallow water equations; hence the model automatically represents the breaking of long waves.

The complete model is validated against data from three different wave flume experiments with regular and irregular waves.
Based on this, it was concluded that the proposed model is an accurate enough predictive tool for the propagation and decay of normally incident random wave groups and their associated long wave motions over an arbitrary beach profile. The use of the non-linear shallow water equations for the long wave motion enables application of the model to severe conditions where the long waves have high amplitudes or may even be breaking.

The sensitivity of the transport pattern due to the interaction between short and long waves to changes in the bar topography was studied by schematizing the profile shape to a realistic, parametric form of which the parameters can be varied in a systematic way. By means of numerical simulations the sensitivity of the long wave - short wave interaction term to the spacing, position and amplitude of longshore bars has been studied, in relation to the basic pattern on an unbarred "equilibrium" profile.

This was carried out for two typical wave conditions. Separately, the sensitivity of the result for a typical barred profile to incident wave conditions was investigated, in order to verify that the conclusions are generally valid, and to identify the most important parameters of the incident wave field.

The main conclusions regarding the long waves themselves are that the most important incident wave parameters are wave height and period (see Figures 4.3.2 and 4.3.3). Long wave amplitudes increase strongly near the shore, as opposed to short wave amplitudes. Long wave amplitudes keep increasing for increasing short wave period; with increasing wave height for a constant wave period the long wave amplitudes first increase strongly, after which a saturation takes place. However, since generally the wave period increases with increasing wave height, the long wave amplitudes on the beach will keep growing with increasing wave height.

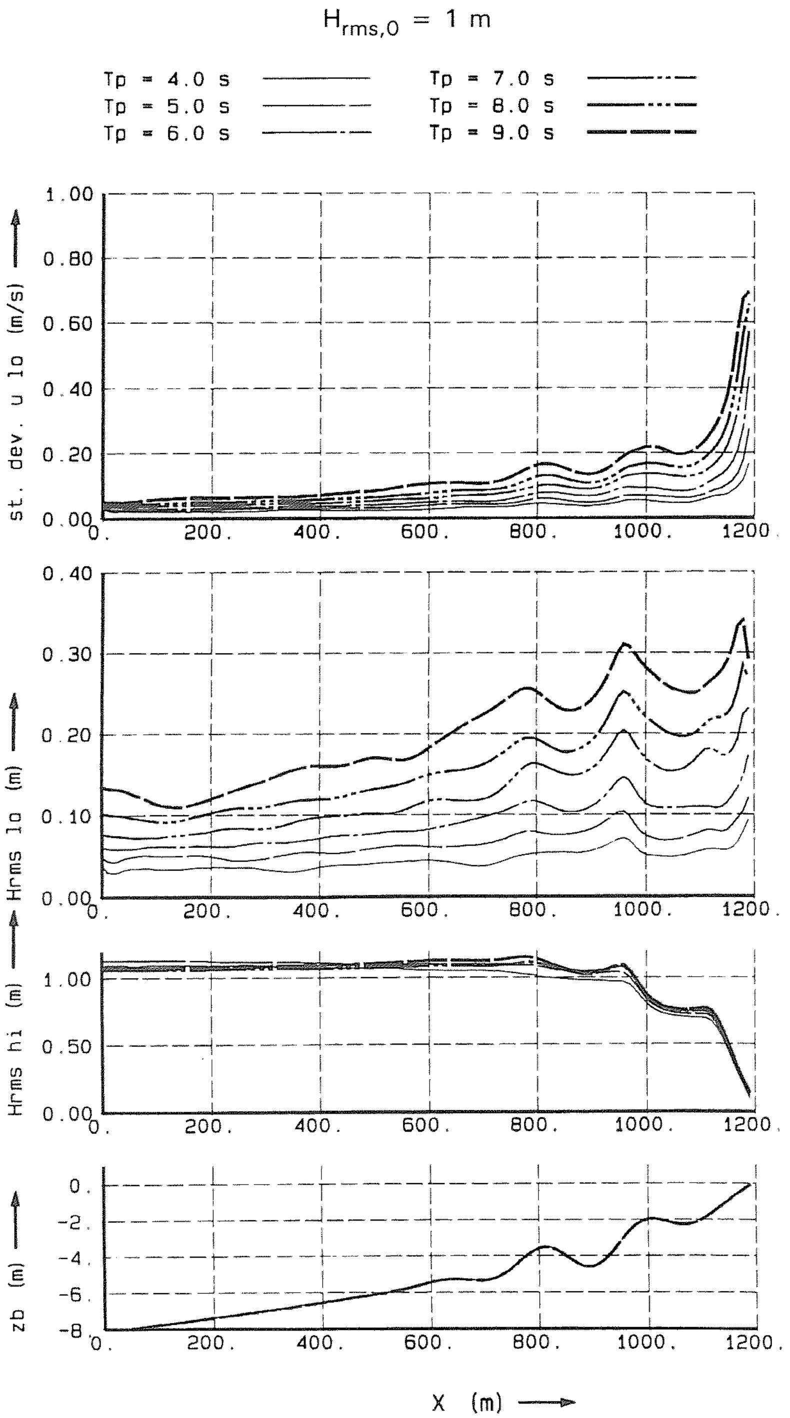


Figure 4.3.2 Influence of T_p on short wave height $H_{rms,hi}$ on long wave height $H_{rms,lo}$ and on standard deviation of long wave velocity $\sigma_{u,lo}$

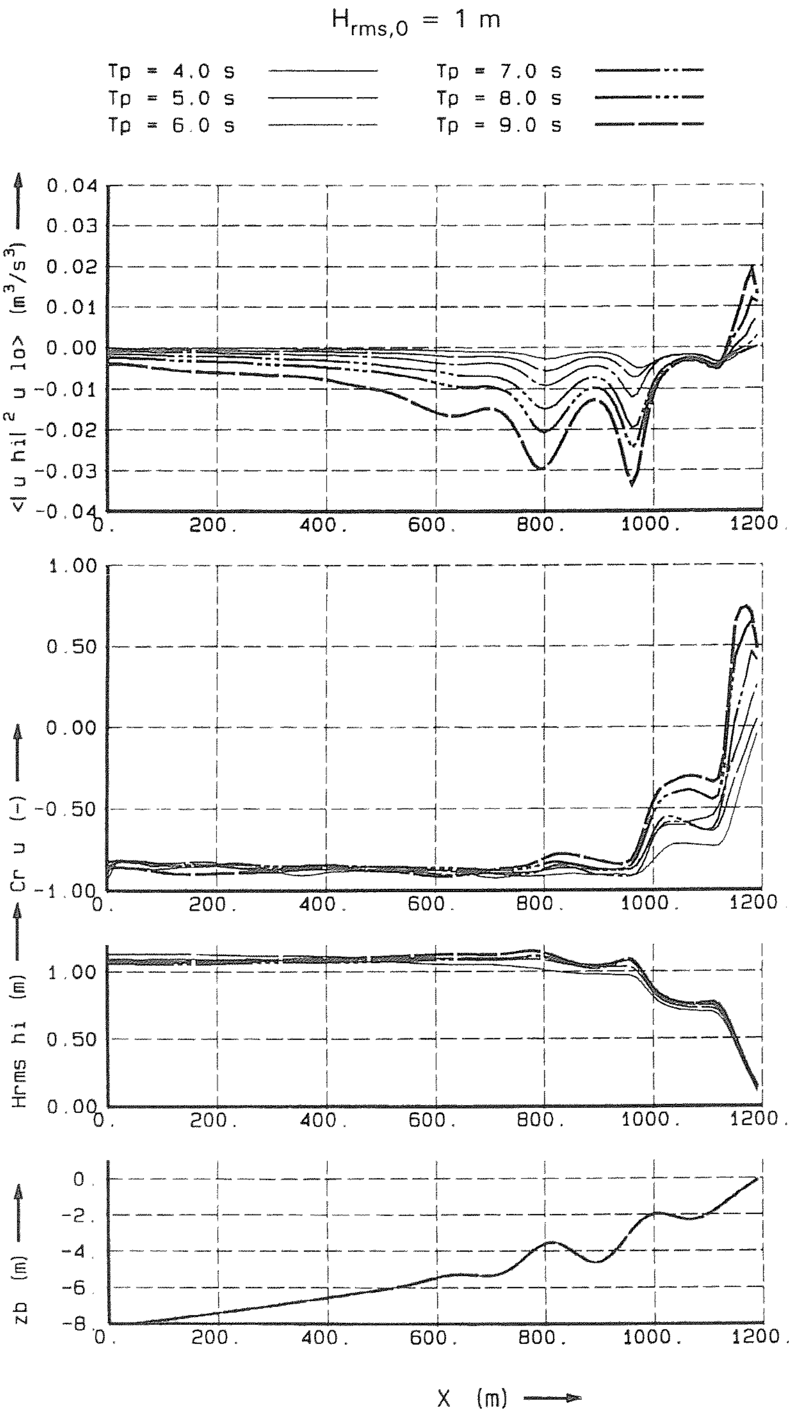


Figure 4.3.3 Influence of T_p on short wave height $H_{rms,hi}$, on correlation coefficient of long-short waves and on long-short wave interaction term $<|u_{hi}|^2 u_{lo}>$ (negative means net seaward transport)

Over a wide range of realistic wave and profile characteristics, no evidence of resonance conditions was found.

Due to the absence of strong resonance effects on time-averaged long wave parameters on the barred profiles considered and due to the broad-bandedness of the low-frequency spectrum, phase coupling between the short wave envelope and the *reflected* long waves is generally very weak. As a result, the velocity moments are dominated by the phase coupling between *incoming* long waves and the short wave envelope. This phase coupling results in a seaward directed effect, except very near the shoreline. Since both long wave velocity and short wave velocity variance increase over bar crests, the velocity moments are strongest on or just seaward of the bar crests. This effect increases for increasing bar amplitudes, and is found irrespective of bar length and location.

The morphological effect of cross-shore long waves is therefore generally to increase offshore transport, except very near the shoreline, and to move bars in seaward direction, while reducing their amplitude.

The most important incident wave parameters governing these processes are the wave height, and to an even greater extent, the wave period, while the spectral shape has a very limited effect.

The hypothesis that bar formation is to an important extent related to cross-shore long waves is not supported by the study of Roelvink. Although the cross-shore long wave motion plays an important role in bar evolution, it is generally a destructive role.

O'Hare (1994) agrees with the results and conclusions presented by Roelvink, when the wave group spectrum is broad-banded and the bound long wave dominates. However, if the breakpoint-forced long wave is sufficiently large relative to the bound long wave, multiple bars may be formed, particularly if the group spectrum is more narrow-banded.

4.3.3 Further research

Further studies recommended are:

- More detailed study of conditions with dominant break-point forced long waves.
- Improvement of the accuracy of the time series of short wave energy and long wave elevation by allowing the short wave frequency to vary slowly and by taking into account the effect of the long wave velocity on the propagation of the short wave groups.
- Extension of the model to the two-dimensional horizontal case (edge waves).
- Execution of two-dimensional wave basin experiments to generate a database for model validation.
- Verification of surf-beat model in field conditions (Nourtec Terschelling).

4.4 Mean current field dat and a vertical structure

4.4.1 Tide, wind and density-induced currents

A summary of available field data has been made by Rijkswaterstaat (1994), focussing on the near-bed current velocities which are of most importance for the sediment transport processes and hence morphological behaviour. The data considered are related to automatic velocity recordings in cross-shore profiles near Noordwijk, Scheveningen, Zandvoort, IJmuiden and Callantsoog in the period 1979 to 1991. In 1993 field data were obtained in an offshore station near Noordwijk using an Acoustic Doppler Current Profiler (ADCP) placed at an elevation of 1 m above the bed (Rijkswaterstaat, 1994a). In 1993 velocity data were measured by Houwman and Hoekstra (1993) at a depth of about 9 m in a station near Egmond using an Electromagnetic current meter in a stand-alone tripod.

Some of peak tidal velocities in longshore direction are given in Table 4.4.1 and in Figures 4.4.1 and 4.4.2. Both figures show the presence of a dominant flood current and the marked effect of the wind on the tidal current velocity forcing the current to move in the direction of the wind.
Analysis of residual cross-shore current velocities in the near-bed region shows a systematic longterm onshore-directed residual current velocity in the range of 0 to 0.05 m/s in water with depths larger than 15 m (Rijkswaterstaat, 1994b). In shallow water onshore-directed as well as offshore-directed residual velocities may occur depending on the water depth and on the wind conditions. Generally, offshore-directed current velocities do occur in shallow depths during onshore-directed storm winds. For example, the Egmond data of 1993 show offshore-directred near-bed velocities of about 0.15 m/s in the waning phase of a storm (Figure 4.4.3). Van de Meene (1994) concludes that the residual circulation at the shoreface-connected ridges near Zandvoort is dominated by a very delicate balance between tide, wind and density-induced effects, especially in cross-shore direction. The balance appeared to be very sensitive to varying hydrodynamic and meteorological conditions. His observations showed that close to the bed the onshore-directed density effect is dominant most of the time. Only during very strong onshore winds an offshore-directed residual current was observed.

The two-dimensional horizontal tidal current velocities are reasonably well represented by the depth-averaged coastal zone model of Rijkswaterstaat (1993), see Table 4.4.1. The wind effect is somewhat underestimated, as shown in Figure 4.4.2.

The vertical structure of the flow was studied in detail by Zitman (see Van Rijn et al, 1994), using a one-dimensional vertical approach. The Vertical Structure model computes the vertical distribution of the horizontal flow velocities for a given depth-averaged velocity vector, horizontal fluid density-gradient and wind-shear stresses at the water surface, taking the Coriolis effect into account. The effects of wave breaking causing a longshore current and a cross-shore return current (undertow) can also be represented by the Vertical Structure model.

Station	Depth (m)	Measured longshore velocity (m/s)	Computed longshore velocity (m/s)
Noordwijk Rijkswaterstaat, 1994a	20	$U_{max,flood}$ = 0.7 $U_{max,ebb}$ = 0.6 (low spring tide)	0.65 0.55 (representative tide)
Zandvoort v.d. Meene, 1994	18	$U_{max,flood}$ = 0.7 $U_{max,ebb}$ = 0.6 (low spring tide)	- -
Egmond Houwman, 1993	9	$U_{max,flood}$ = 0.6 $U_{max,ebb}$ = 0.4 (high neap tide)	0.55 0.45 (representative tide)

Table 4.4.1 Maximum velocities in stations Noordwijk, Zandvoort and Egmond

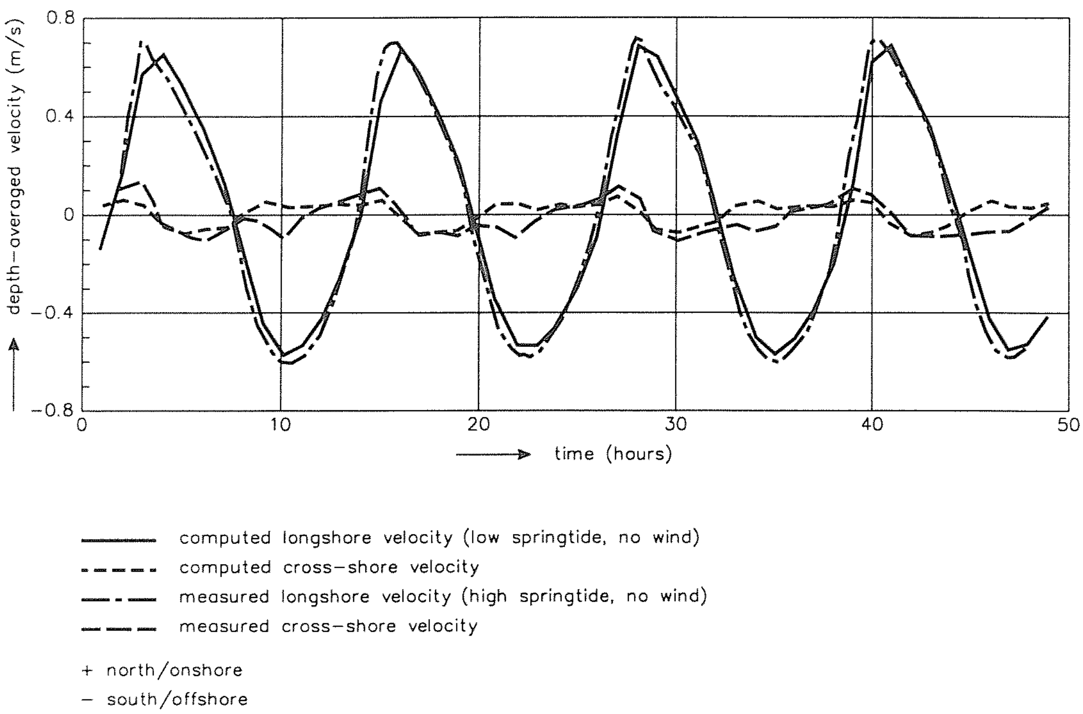


Figure 4.4.1 Measured and computed depth-averaged tidal velocities, water depth 20 m, offshore station Noordwijk

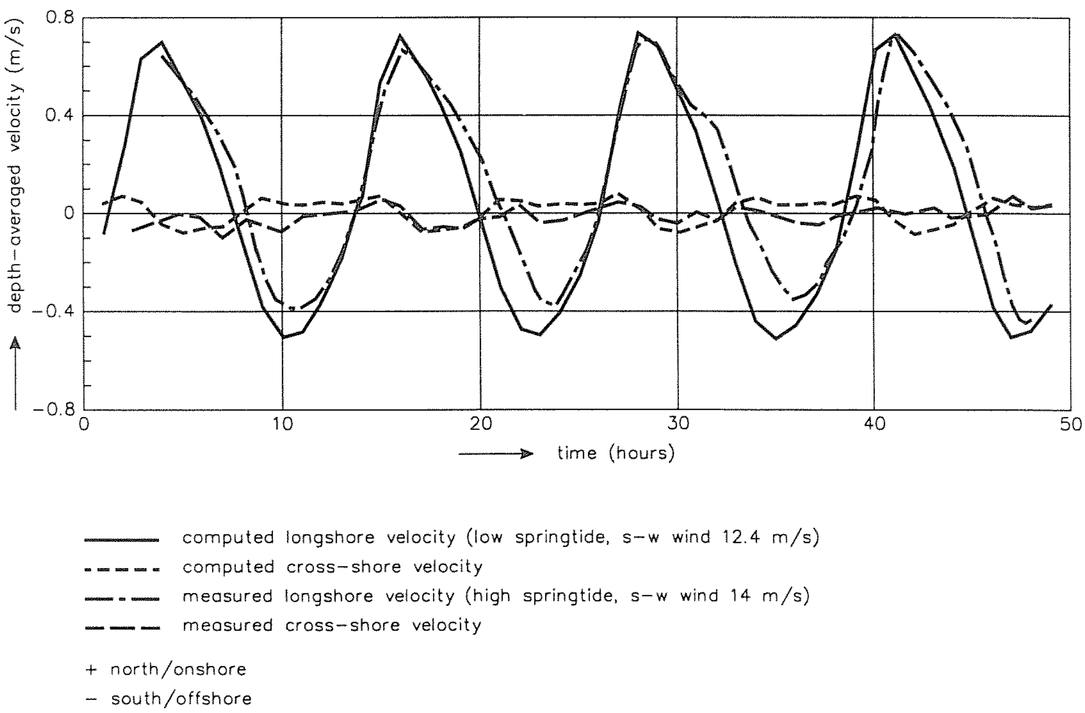


Figure 4.4.2 Measured and computed depth-averaged tidal velocities, water depth 20 m, offshore station Noordwijk

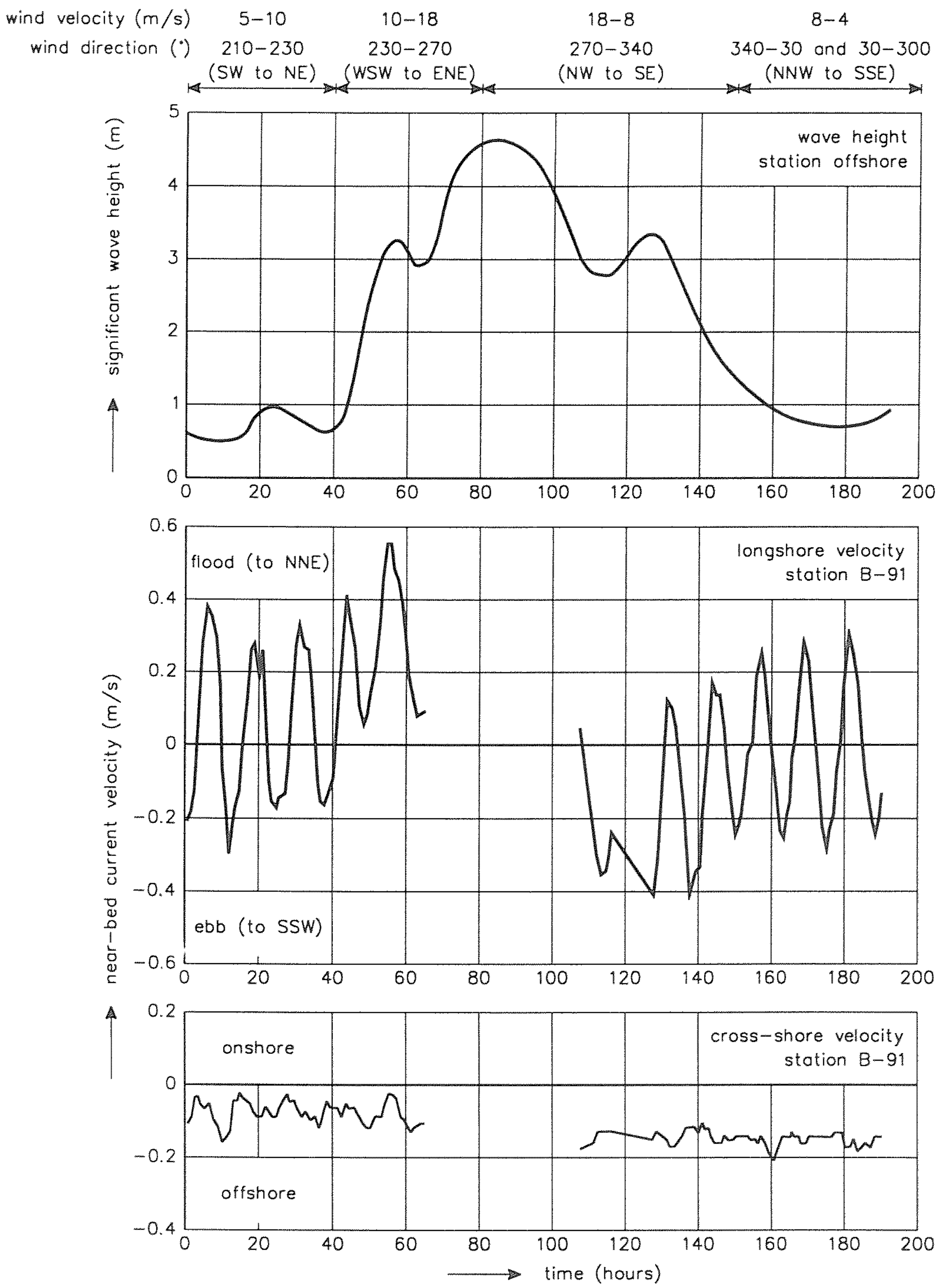


Figure 4.4.3 Measured near-bed current velocities, station B-91, water depth 9 m, Egmond

The Vertical Structure model is based on the horizontal momentum balance for quasi-steady flow neglecting the horizontal convective acceleration terms. Quasi-steady flow has been assumed because the time-scale of adjustments over the depth is much smaller than the time-scale of horizontal adjustment of the flow pattern. Furthermore, it has been assumed that the flow is locally uniform in the horizontal plane. The inertia effects and the lateral dependencies (horizontal advection and diffusion) are assumed to be adequately represented by the depth-averaged model from which the depth-averaged velocity vector is used.
A basic parameter of the Vertical Structure model is the eddy viscosity coefficient (turbulence closure) and its distribution over the depth, which is represented by a parabolic function using

a virtual depth to obtain finite eddy-viscosity values at the bed and at the water surface.
Another important aspect is the representation of the bottom boundary condition for the horizontal velocity. A no-slip condition specifying a zero velocity at the level $z = z_0$ (z_0 = zero velocity level = $k_s/33$ with k_s = effective bottom roughness) is the most appropriate schematisation, but it requires an extremely fine grid near the bed and hence extensive computational effort. To overcome this latter problem, a two-layer approach was used. The near-bed layer covers the high-shear region near the bottom and is represented by a logarithmic function whereas the other layer covers the upper part of the depth.
In order to check the accuracy of the Vertical Structure model, results of the model are compared to measurements. Data for this validation were available from an Acoustic Doppler Current Profiler (Rijkswaterstaat, 1994a). This ADCP-instrument was situated 10 km offshore, at the 20 m depth contour in front of the coast near Noordwijk. From 1 m above the bottom upto 18 m above the bottom the water velocity was measured at each meter. The total mean water depth at the measuring location was 20 m. The validation focussed especially on the near-bottom effect due to the horizontal density gradient. To exclude the wind-driven currents, a period of a few days in which there was almost no wind was selected from the total time series. In this time interval the Vertical Structure model was run in order to calculate the vertical structure of the flow at each hour. The results of the Vertical Structure model are compared to the velocity measurements.
In most of the calculations the model results resembled the measurements reasonably well. The effect of the horizontal density gradient was evidently well reproduced by the model, as shown by Figure 4.4.4 (time 36 and 40).
In some other calculations however the results were rather disappointing. The calculated effect of the density gradient was strongly underestimated or the velocity was opposite to the measured velocity (see Figure 4.4.4, time 38).

The horizontal density gradient is specified as a function of the discharge of the river Rhine, the wind velocity and the wind direction. This means that the density gradient is assumed to be constant in a tidal cycle. The results suggests that this assumption is not justified. One reason could be that in the VS-model inertial terms are neglected. Another possible explanation is the density gradient variation over a tidal cycle. Therefore, the model was run again, but a routine was added that searched for the density gradient needed for the best fit with the measurements. It must be realized that this optimized density gradient also reflects the inertial term which is not incorporated in the VS-model.
The optimized density gradient and the standard density gradient are in the same order of magnitude and have most of the time the same sign.
Further research is necessary to represent the effect of density gradient variations over the tidal cycle in the Vertical Structure model. The eddy-viscosity coefficient related to wave-, wind-, tide- and density-driven flow should be studied by using higher-order models (K-epsilon models). Theoretical research should be combined with more practical research parameterizing the results to improve the Vertical Structure model.

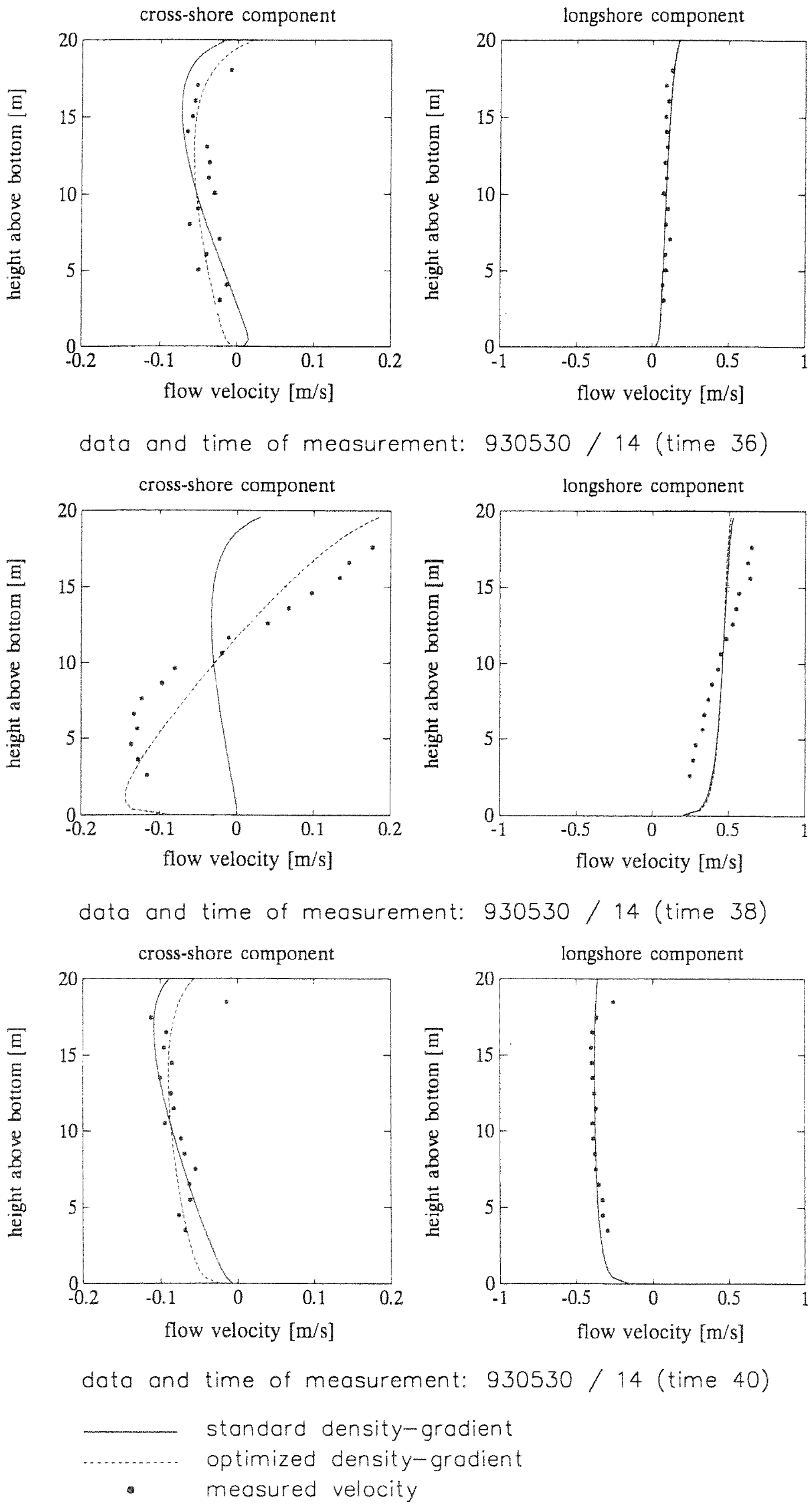


Figure 4.4.4 Measured and computed flow velocity profiles, water depth 20 m, offshore station Noordwijk

4.4.2 Wave-induced currents

Stokes (1847) first pointed out that the fluid particles do not exactly describe closed orbital trajectories in case of small-amplitude sinusoidal surface waves in perfect irrotational (non-viscous) conditions. The fluid particles have a second-order mean Lagrangian velocity (called Stokes-drift) in the direction of wave propagation resulting from the fact that the horizontal orbital velocity increases slightly with distance above the bed. Consequently, a particle at the top of an orbit beneath the wave crest has a greater forward velocity than it has at the bottom of the orbit beneath the wave trough. The depth-integrated mass flux associated with waves propagating in a horizontally unbounded domain is given by $M = E/c$ with E = wave energy and c = wave propagation velocity. As the waves enter shallow water the orbits become more elliptical and the drift velocities increase to appreciable values (order 0.1 m/s). Assuming a zero mass flux (bounded domain) over the water depth, the Lagrangian onshore mass flux concentrated in the upper layers is balanced by an Eulerian return flow in the lower part of the water column.

Longuet-Higgens (1953) has shown that for real fluids with viscosity ν there is a time-averaged net downward transfer of momentum into the wave boundary layer by viscous diffusion producing a mean Eulerian streaming in addition to the Stokes drift. The maximum wave-induced streaming in the boundary layer is onshore directed and of the order of $(\hat{U}_\delta)^2/c$ with $\hat{U}_\delta$ = peak orbital velocity at the edge of the boundary layer.

A detailed experimental flume study of wave-induced streaming in non-breaking waves over horizontal and sloping bottoms was performed by Klopman (1994a) using Laser-Doppler velocimetry. Monochromatic and random waves were generated. Active wave-absorption boards were used to eliminate wave reflection and resonance. The flume bottom consisted of gravel particles (0.002 m) with an effective Nikuradse roughness of 0.0012 m.
Figures 4.4.5 and 4.4.6 show the mean horizontal velocities over a horizontal and a sloping bottom, as measured by Klopman.

In case of monochromatic waves over a horizontal bottom the wave-induced streaming shows maximum values of about 0.01 m/s (approx. 6% of peak orbital velocity of 0.18 m/s) in the wave propagation direction. The thickness of the layer with wave-induced streaming is about 0.02 m which is about 4 times the wave boundary layer thickness. Above the streaming layer a return flow layer balancing the onshore mass-flux can be observed.
In case of random waves over a horizontal bottom maximum streaming velocities of about 0.012 m/s can be observed; but the thickness of the streaming layer shows a significant increase to about 0.1 m.
In case of monochromatic and random waves (non-breaking) over a plane sloping bottom the maximum streaming velocities are smaller (0.004 to 0.009 m/s). The layer thickness is about 0.01 m which is considerably smaller than that in case of a horizontal bottom.
The experimental results of Klopman (1994a) confirm the theoretical results of Longuet-Higgens (1953) yielding onshore-directed streaming near the bed.
In strongly asymmetric (shoaling) waves over steep sloping bottoms the net velocities in the streaming layer may be offshore-directed due to an unbalance of the fluid shear-stresses in the wave-boundary layer.

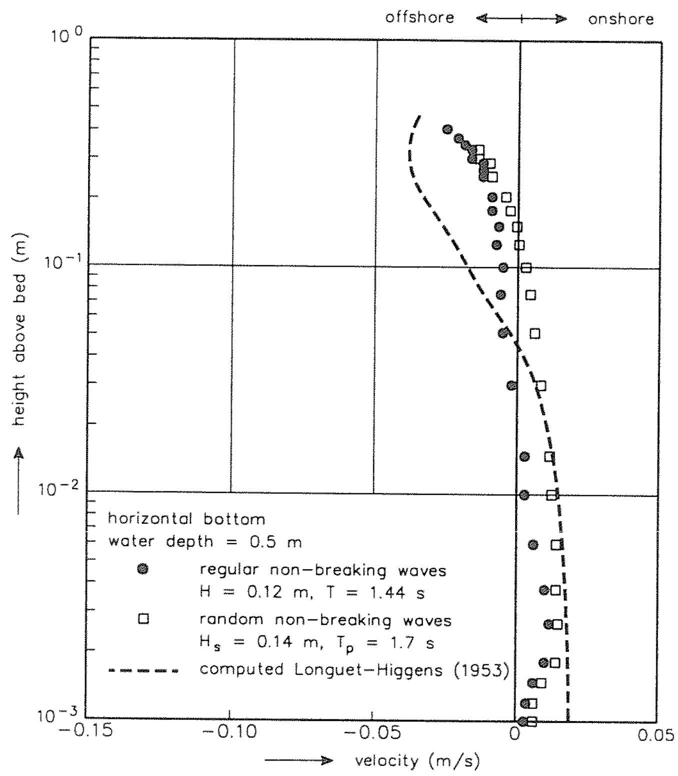


Figure 4.4.5 Wave-induced streaming velocities in case of monochromatic and random waves over a horizontal bottom (Klopman, 1994a)

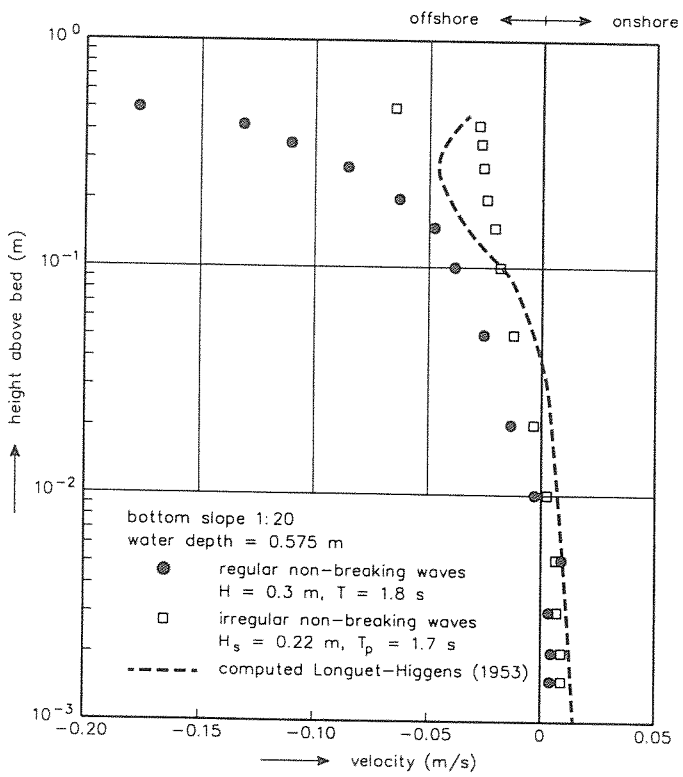


Figure 4.4.6 Wave-induced streaming velocities in case of monochromatic and random waves over a plane sloping bottom (Klopman, 1994a)

Comparison of measured streaming velocities and theoretical values according to Longuet-Higgens (1953) show qualitative agreement with onshore-directed velocities near the bed and offshore-directed velocities at higher levels compensating the mass flux. In quantitative sense the overall agreement is less good, although the near-bed velocities have the right order of magnitude.

Mass transport in the upper part of the water column (including roller effect) is considerably enhanced in breaking wave conditions. When oblique incident waves break in the nearshore zone, a complicated current pattern is generated in the surf zone, consisting of a longshore current and an offshore return current in the near-bed region (undertow).

Figure 4.4.7 shows the vertical structure of the mean currents in the surf zone (Svendsen and Lorenz, 1989). The mean currents interact with the instantaneous wave-related orbital motions yielding a complicated time-dependent three-dimensional pattern.

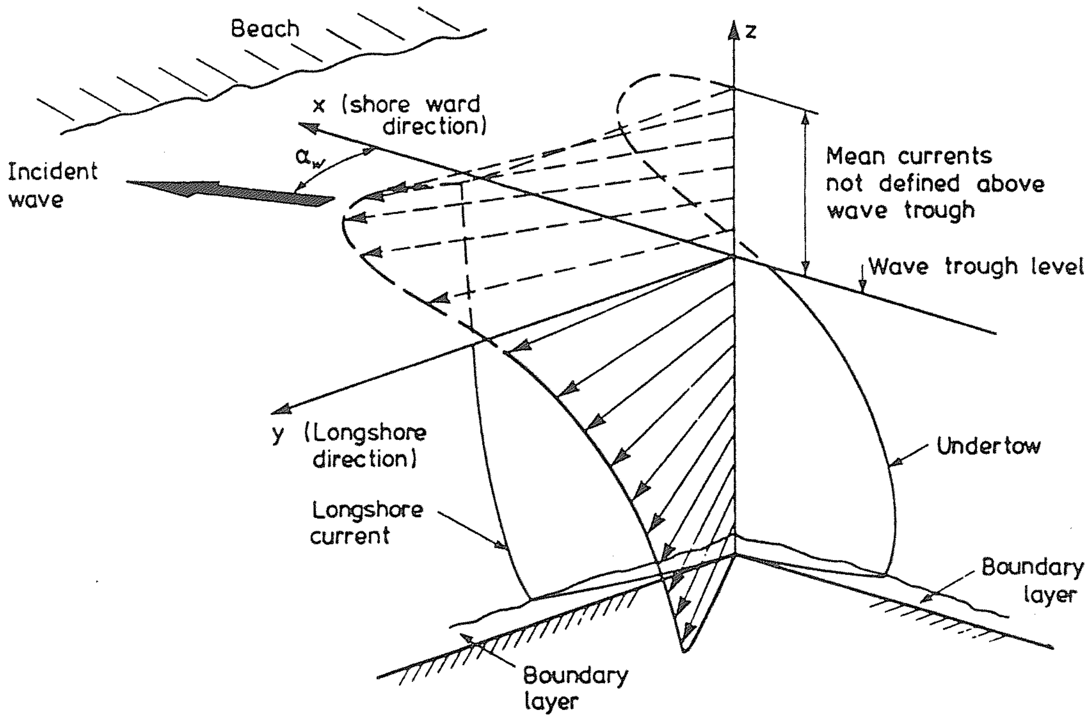


Figure 4.4.7 Three-dimensional structure of velocity profile in the surf zone

The generation of the longshore and cross-shore mean currents can be explained by the radiation stress concept which describes the momentum flux associated with the waves.
In the surf zone along a uniform coast the decaying incident waves generate an onshore gradient of the onshore component (S_{xx}) and the longshore component (S_{xy}) of the radiation stress. The gradient of the onshore radiation stress component is balanced by a pressure gradient related to the mean water surface yielding a set-up in the surf zone. As a result of the onshore mass transport in the near-surface region and the shoreward increasing mean water surface slope, an offshore return current (undertow) below the trough level is generated. De Vriend and Stive (1987) introduced a quasi-threedimensional approach to model the flow structure in the surf zone.

Figure 4.4.8 shows measured undertow velocities for Test 1B of the LIP-experiments in the Delta flume of DELFT HYDRAULICS (Arcilla et al, 1994).

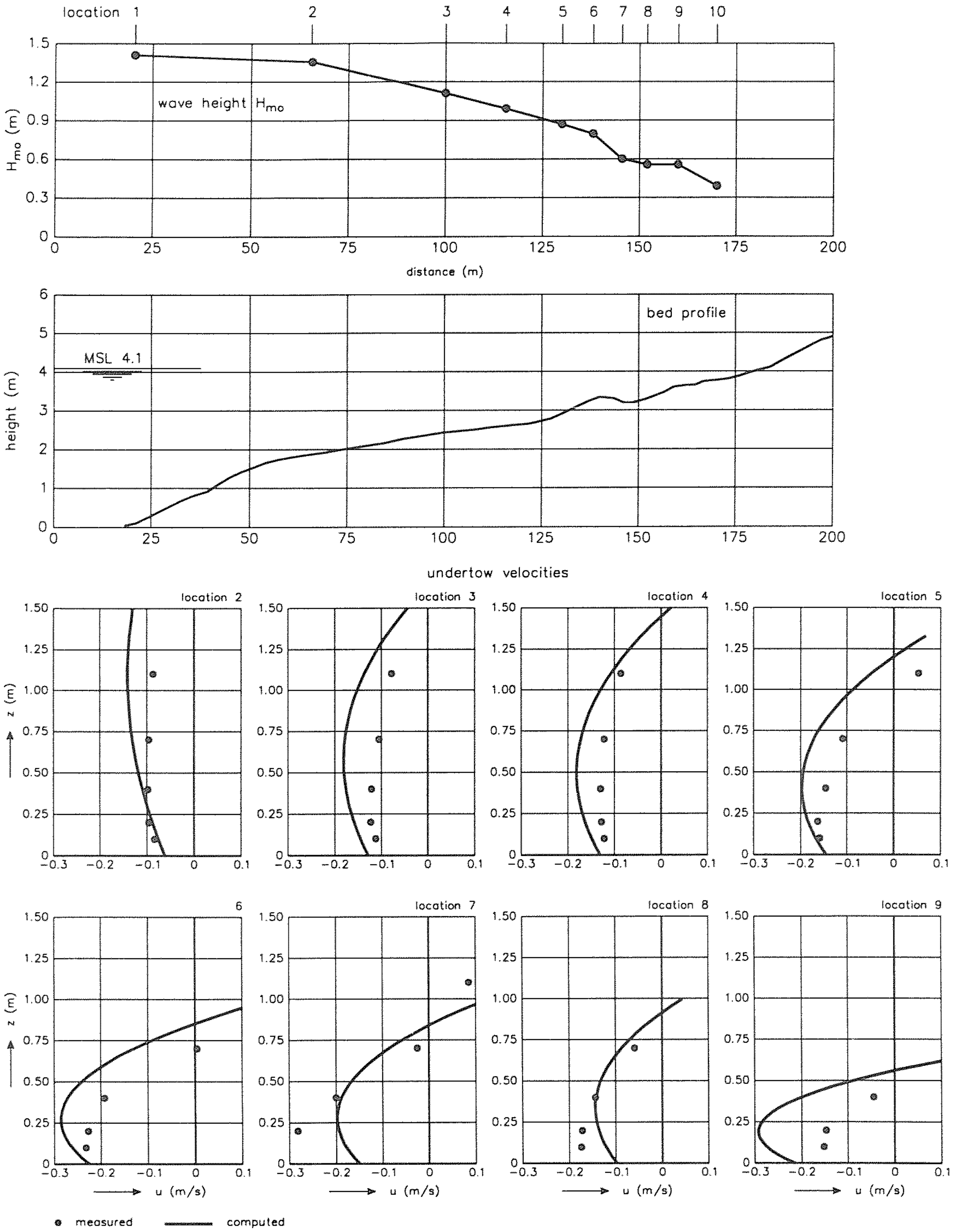


Figure 4.4.8 Measured and computed undertow velocities, Test 1B, Delta flume experiment

Computed undertow velocities are also shown in Figure 4.4.8, based on the concept $M = \phi_b M_b + (1-\phi_b) M_{nb}$ with M = total mass flux, M_b = mass flux in breaking waves according to Svendsen (1984) and ϕ_b = percentage of breaking waves (see Roelvink and Reniers, 1994; Van Rijn et al 1994) and M_{nb} = mass flux in non-breaking waves. Reasonably good agreement can be observed for most locations in the surf zone. Figure 4.4.9 shows measured and computed depth-mean undertow velocities for a station in the inner surf zone near Egmond (Kroon, 1994). Generally, the computed undertow velocities according to the concept of Svendsen (1984), also used in the UNIBEST-model, are much too small for velocities larger than 0.2 m/s. The reason for these discrepancies is not yet clear. Further research is required.

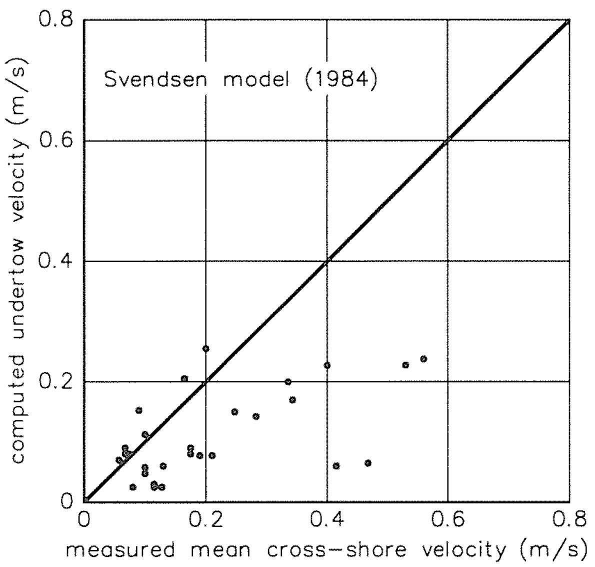


Figure 4.4.9 Measured and computed depth-mean undertow in inner surf zone near Egmond

The driving force of the longshore current is the onshore gradient of the longshore radiation stress component which is balanced by bottom friction and dispersive shear stresses. The longshore current is largely confined to the surf zone, rapidly decreasing in velocity seaward of the breaker line. The longshore velocity is found to be strongly related to the wave height decay in the surf zone and the orientation of the wave crests (angle of wave approach). In nature the wave-induced longshore currents are often enhanced by wind-induced currents. Analysis of field data has shown that the cross-shore distribution of the longshore current is rather insensitive to the contributions of individual waves in a random wave field.

Figure 4.4.10 shows examples of mean longshore and cross-shore velocities measured under storm conditions in shallow water (depth = 4 m) in a station (S-91) near Egmond along the Dutch coast (Houwman and Hoekstra, 1994). The velocities were measured by an electro-magnetic current sensor mounted in a stand-alone tripod at about 0.5 m above the bed. The velocity data in the surf zone show maximum longshore velocities of about 1.4 m/s and maximum undertow velocities of about 0.8 m/s. These values are considerably larger than those in deeper water (see Figure 4.4.3) which are dominated by tide- and wind-effects.

Information of the cross-shore and the longshore current velocities in the surf zone of the Dutch coast is not available. Hence, the model formulations (UNIBEST) have not been verified properly. Data of other locations (Duck beach, 1990; Church and Thornton, 1992) with a barred cross-shore profile show the presence of relatively large longshore velocities in the trough zone between the bars (see Figure 4.4.11). This latter effect may be related to:

- non-local energy transfer from breaking waves to kinetic energy of longshore current (lag effect),
- horizontal (cross-shore) mixing and

- longshore gradients in wave set-up related to variations in breaker type (spilling, plunging) and longshore bar variability,
- development of rip currents.

The longshore velocities measured in the Duck Beach case were modelled by Van Rijn and Wijnberg (1994) using a wave by wave approach (WAVIS-model). Reasonable agreement between measured and computed longshore velocities could only be obtained by introducing a longshore water surface gradient in the inner surf zone (see Figure 4.4.11a). It is not known whether this is a realistic physical phenomenon. Similar results have been obtained by using the UNIBEST model (Figure 4.4.11b). The computed velocities above the bar crest and in the trough zone are much smaller than the measured longshore velocities.

High priority should be given to further research of the wave-induced longshore velocities both by field experiments and mathematical modelling.

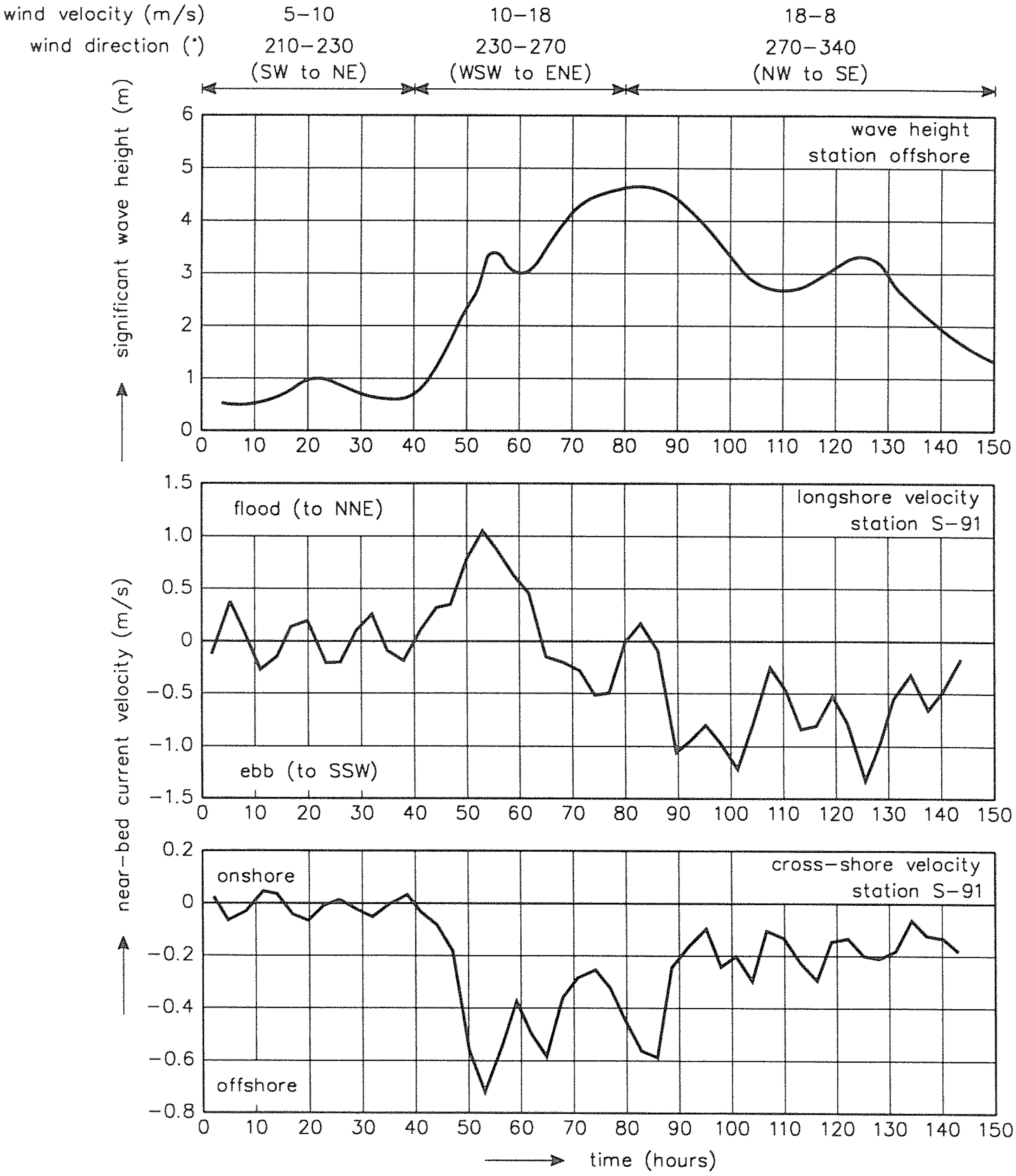


Figure 4.4.10 Measured near-bed current velocities, station S-91, water depth 4 m, Egmond

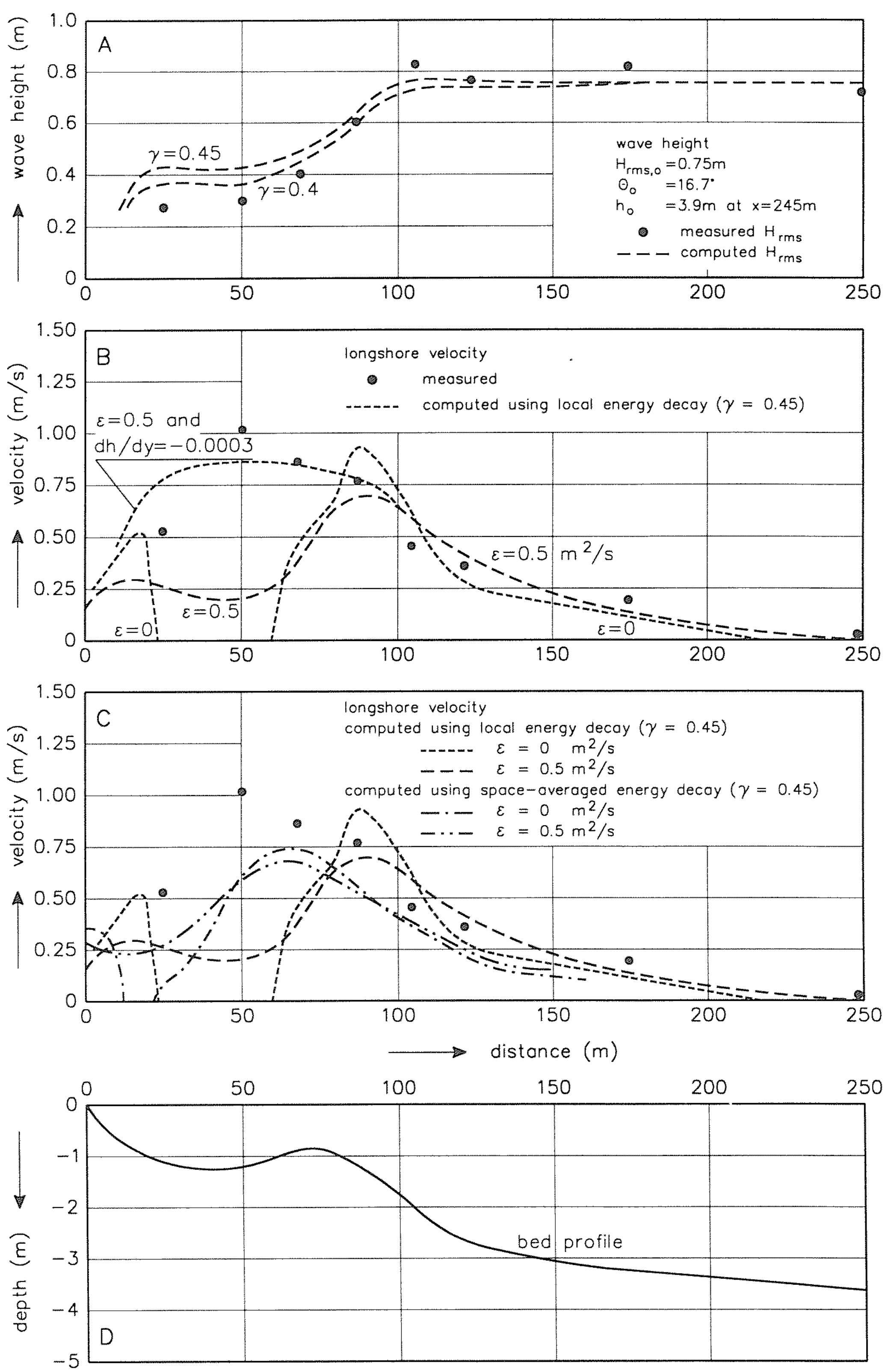


Figure 4.4.11a Longshore velocities, Duck Beach, USA; results of probabilistic WAVIS-model

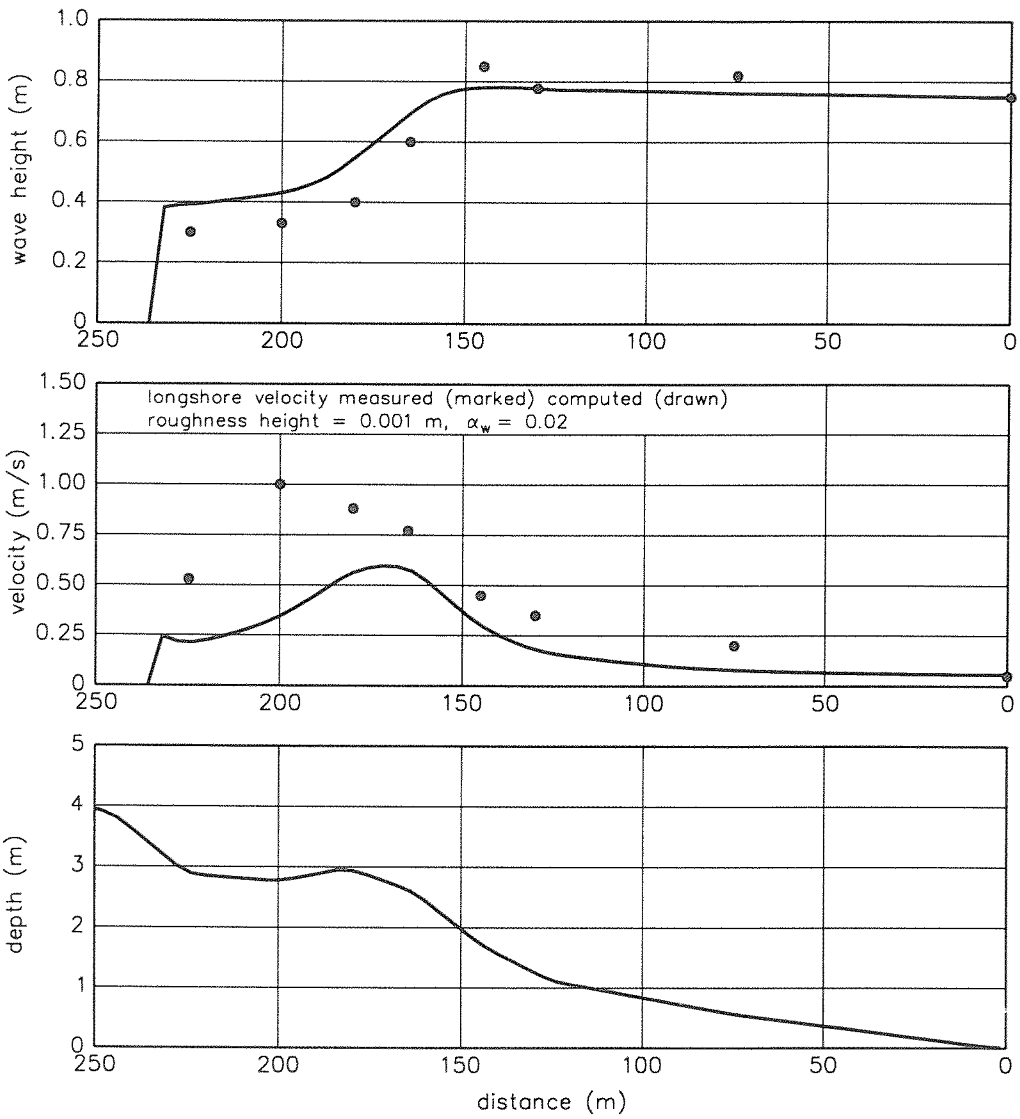


Figure 4.4.11b Longshore velocities, Duck Beach, 1990, USA; results of parametric UNIBEST-model

Observations along uniform and non-uniform coasts show that the longshore currents are turned seaward at regular intervals, yielding circulation cell systems. Rip currents are relatively strong narrow currents that flow seaward through the surf zone affecting the approaching waves and altering refraction patterns. Rip currents are fed by the longshore currents, whereas the longshore currents are in turn fed by the onshore mass transport due to breaking waves in the surf zone. The circulation cells thus consist of an onshore mass transport of water, longshore currents and seaward-turning rip currents which spread out into rip heads.

Longshore currents may be enhanced by longshore variations of set-up caused by longshore variations of the bottom topography (shoals), incident wave heights and/or the type of wave breaking (spilling, plunging). As a result water may be driven from regions of high waves towards regions of less high waves in the surf zone. The generation of standing edge waves trapped in the surf zone may also produce regular patterns of high and low wave heights along the beach providing a mechanism for regularly spaced circulation cells, especially in steep, reflective beach conditions.

Wave trains approaching the beach at different angles (intersecting waves) may also create regular longshore variations of the mean water level and wave height.

4.4.3 Wave-current interaction

The wave and current fields interact mutually through a number of mechanisms (Soulsby et al, 1993):

- refraction of the waves by horizontally sheared currents,
- modification of the wave kinematics by the currents,
- modification of the vertical flow structure by the waves,
- generation of streaming by the waves,
- generation of longshore currents by breaking waves,
- enhancement of the bottom friction felt by the currents due to interaction with the wave boundary layer,
- enhancement of the bed shear-stresses and energy dissipation of the waves due to interaction with the current boundary layer.

Herein, the attention is focussed on wave-current interaction effects in the vertical plane and, in particular, on those aspects which are most relevant to sediment transport processes.
Most of the theoretical effort in wave-current interaction has been restricted to non-breaking waves. Soulsby et al (1993) conclude that very good estimates of the wave length and near-bed peak orbital velocity can be obtained using linear wave theory relative to a coordinate system moving with the current.

The vertical structure of the flow is significantly modified by the wave motions, as shown by many laboratory experiments (for example, Van Rijn, 1993; Van Rijn et al, 1993; Van Rijn and Havinga, 1995).
The current velocities in the near-bed region are reduced by the wave-induced vortices generated in the wave boundary layer (see Figure 4.4.12), which can be modelled as an apparent bed roughness effect. The reduction of the near-bed velocities is most pronounced in case of a relatively weak current and relatively high waves. In case of an opposing current the reduction of the near-bed velocities is somewhat larger than in case of a following current.
When the wave direction is perpendicular to the current direction, the reduction of the near-bed velocities was found to be largest based on experiments in a laboratory basin with a rippled bed (Van Rijn and Havinga, 1995).
The current velocities in the upper layers show an increase in case of opposing waves and waves perpendicular to the current. When the waves are in the same direction as the current (following), the velocities near the surface are reduced.
The basic equations describing these processes have been formulated by Klopman (1994b), using a multiple-scales perturbation-series technique. The zeroth-order equations have been solved numerically. Numerical solution of the equations including first- and second-order terms has not yet been succesfull. Further research is necessary.
According to a study of Dingemans (1992), the most appropriate method for wave-current interaction is the generalized Lagrangian-mean formulation (GLM-method). He presented a derivation of the equations for the mean flow in three dimensions. In the general case of finite-amplitude disturbances on a stratified mean flow, these equations are very complicated and difficult to interpret physically. A more simplified approach is discussed by Radder (1994).

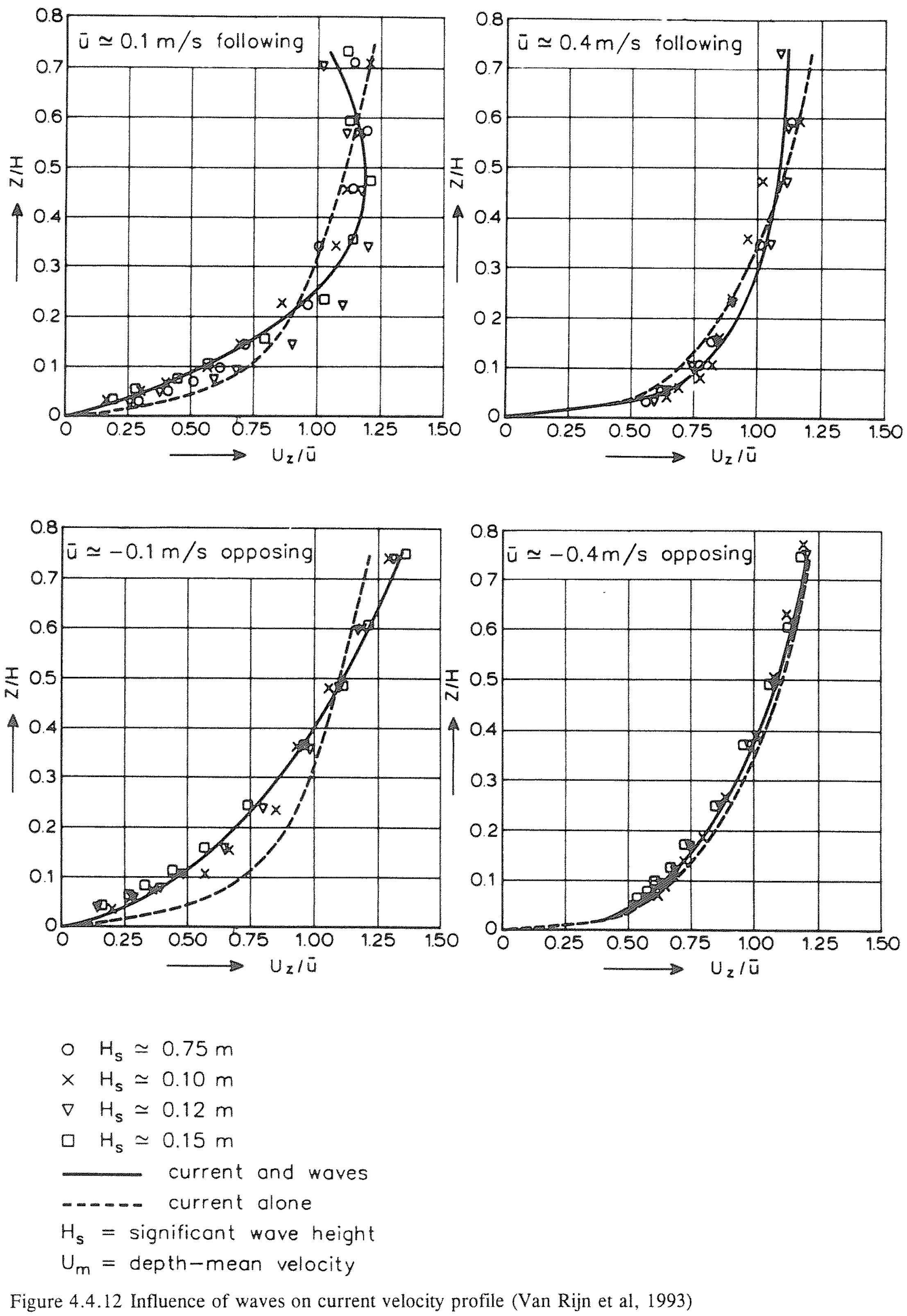


Figure 4.4.12 Influence of waves on current velocity profile (Van Rijn et al, 1993)

To determine the bed-shear stresses in combined current and wave conditions, the physics of the boundary layer should be better understood.

The boundary layers near the bed associated with the waves and the current interact nonlinearly, because they are dominated by turbulent stresses and turbulence generation is a nonlinear phenomenon. This has the effect of enhancing both the mean and oscillatory shear-stresses (see Figure 4.4.13). In addition, the current profile is modified, because the extra turbulence generated close to the bed by the waves appears to the current as an enhanced bottom roughness. Many mathematical models have been put forward to describe the combined boundary layer (see Soulsby et al, 1993). For sediment transport purposes it is important to predict the time-mean bed shear-stress (τ_m) and the maximum bed shear-stress (τ_{max}) in the combined wave-current flow (Figure 4.4.13). The entrainment of sediment particles is determined by τ_{max} while the current velocity and the diffusion of suspended sediment into the upper part of the flow are determined by τ_m.

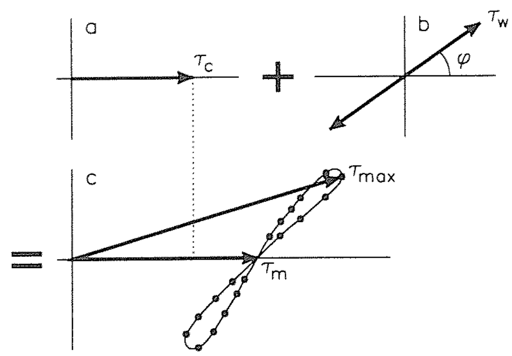


Figure 4.4.13 Schematic representation of bed-shear stresses

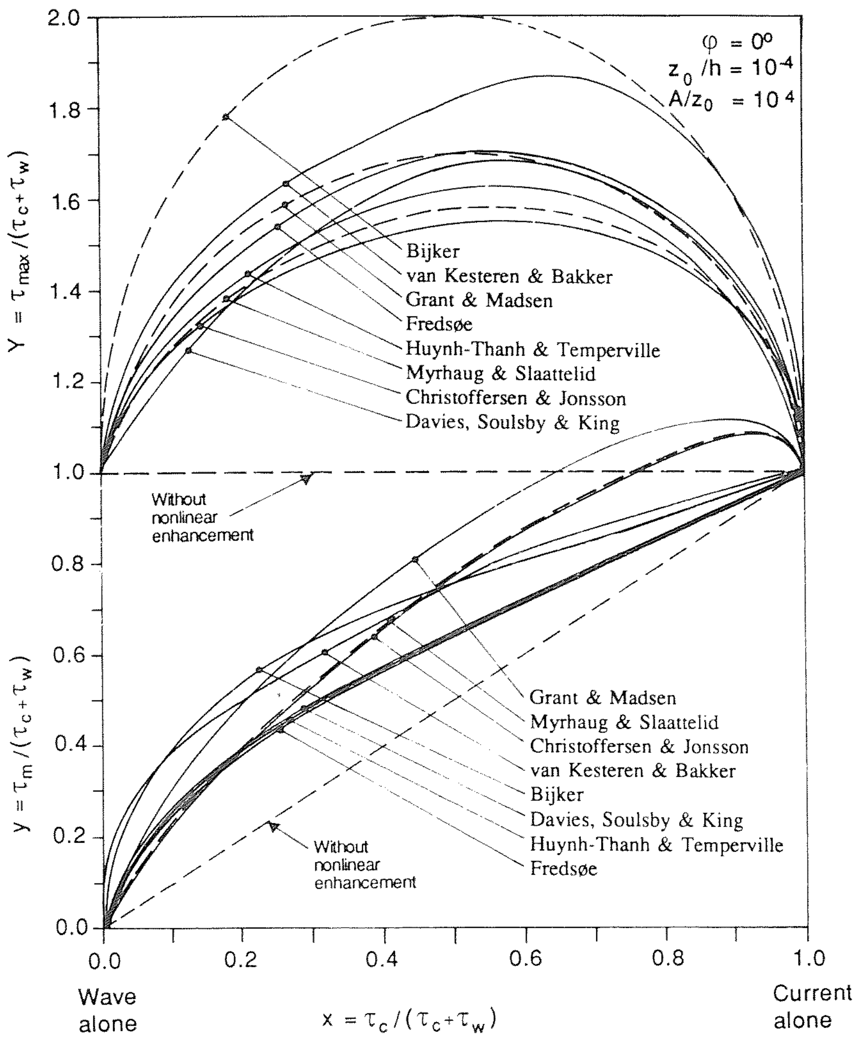


Figure 4.4.14 Intercomparison of model results

It is convenient to distinguish between bed shear-stresses which would occur if nonlinear interaction did not take place, so that the shear-stresses generated by the wave-alone and the current-alone could be summed linearly, and the nonlinear enhancement which is the primary purpose of the model, to predict.

Soulsby et al (1993) have plotted the results of many models in terms of the nondimensional parameters $y = \tau_m/(\tau_c+\tau_w)$ and $Y = \tau_{max}/(\tau_c+\tau_w)$ as a function of $x = \tau_c/(\tau_c+\tau_w)$, the latter being a measure of the relative strengths of the current and the wave (τ_c = current-alone bed shear-stress, τ_w = peak orbital bed shear-stress).

Inter-comparison of the results of the models shows that the general forms of the predictions of the mean (τ_m) and the maximum (τ_{max}) bed-shear stress are broadly similar, see Figure 4.4.14. However, variations between model results of up to 30% in τ_{max} and up to a factor of 4 in τ_m were found.
Reliable data against which the wave-current models can be validated are rather scarce. From the data available it was concluded that nonlinear interaction is of most importance under wave-dominated conditions, less so for relatively stronger currents. Experimental data for τ_m show some of the broad features predicted by the models, but support for the detailed behaviour is not apparent. Measurements of τ_{max} seem to indicate that the oscillatory part of the bed-shear stress is not significantly affected by a perpendicular current.

Soulsby et al have presented a standard formulation of the results of the models, with each model having its own set of fitting coefficients.
Further research of near-bed velocities, eddy-viscosity coefficients and shear stresses using higher-order turbulence closure models (K-epsilon model) is necessary. Theoretical research should be combined with practical work parameterizing the results of the sophisticated models to be implemented in 2DV profile models (UNIBEST).

Engineering methods are also available to compute the effect of the wave motion on the flow resistance (see Van Rijn, 1993). In this approach the effect of the wave on the near-bed current velocities and hence the resistance is represented by introducing an apparent bed roughness (k_a), being a function of the physical bed roughness (k_s), the relative strength of the wave and current motion and the angle between the current and wave direction. The friction due to both effects can be modelled as a combination of the values for wave-alone and current-alone, for example $f_{cw} = (1-\alpha)\ f_w + \alpha\ f_c$ with $\alpha = v/(v+\hat{u})$, v = current velocity, $\hat{u}$ = peak orbital velocity. The accuracy of this type of approach is discussed by Koelewijn (1994).

4.4.4 Further research

The following subjects should be further studied:

- Longshore and cross-shore currents related to breaking waves, especially for barred profiles.
- Streaming induced in the wave-boundary layer of irregular waves over sloping bottoms.
- Three-dimensional circulation patterns in the surf zone along uniform coasts (field data and laboratory data).

- Vertical structure of velocities and turbulence (eddy viscosity) in tide-, wind-, wave- and density-driven currents; data analysis and mathematical modelling using higher-order models and more simple parametric models.
- Effective roughness and bed-shear stress in wave-current systems using higher-order models and engineering methods.
- Variation of density-gradient over tidal cycle along coast (field data).

4.5 Sand transport processes

4.5.1 Introduction

Sediment transport in a coastal environment generally occurs under the combined influence of a variety of hydrodynamic processes.
In the surf zone of sandy beaches the transport is generally dominated by the waves through wave breaking and wave-induced currents in longshore and cross-shore direction. The breaking process as well as the near-bed wave-induced oscillatory water motion can bring sand into suspension (stirring) which can be transported by net (i.e., wave-cycle averaged) currents. Sand can also be transported by the oscillatory water motion itself, for example, caused by the deformation of waves under the influence of decreasing water depth (wave asymmetry). Also low-frequency waves interacting with short waves may have important contributions to the sediment transport.
Outside the breaker zone the transport process is generally concentrated in a layer close to the sea bed and takes place in close interaction with small bed forms (ripples) and larger bed structures (dunes, bars). The physical processes taking place near the sea bed (typical layer thickness of 0.1 m) play a key role in the bed-load transport of sand as well as in the transport of suspended sediment at higher elevations in the water column.

The net depth-integrated sand transport rate can be decomposed in a current-related part and a wave-related part (Van Rijn, 1993).
The current-related sediment transport is defined as the transport of sediment particles by the time-averaged (mean) current velocities (longshore currents, rip currents, undertow currents). The current velocities and the sediment concentrations are affected by the wave motion. It is known that the wave motion reduces the current velocities near the bed, but the wave motion strongly increases the near-bed concentrations due to its stirring action.
The wave-related sediment transport is defined as the transport of sediment particles by the oscillating fluid components (cross-shore orbital motion).
Herein, the wave-related sediment transport is assumed to be dominated by the transport of bed-load particles, whereas the current-related transport component is assumed to consist of suspended load particles.

Sand transport research in the Coastal Genesis Project was primarily aimed at deriving predictive and practical formulations for bed-load and suspended load transport in breaking and non-breaking wave conditions with or without a current superimposed. Laboratory experiments were performed by Ribberink and Al-Salem (1994) and by Van Rijn et al (1993) and Van Rijn and Havinga (1995). Field experiments were performed by Kroon (1994) in the surf zone near Egmond and by Van de Meene (1994) in the shoreface zone near Zandvoort.

The research related to sand transport performed by Delft Hydraulics in combination with the universities of Utrecht and Delft has played a leading international role. Three thesis (Al-Salem, 1993, Kroon, 1994 and Van de Meene, 1994) and many reviewed journal papers have been published.

4.5.2 Bed-load transport research in wave tunnel

The wave-related bed-load transport in oscillatory boundary layers over rippled and plane sheet flow beds has been studied in detail by Ribberink and Al-Salem (1994).
During moderate wave conditions, ripples can be formed on the seabed and the transport process is generally dominated by the cyclic development and convection of vortices near the ripples. Quantitative models for the description of these processes are still poorly developed.
In more extreme wave conditions and/or more shallow water the seabed becomes plane and sheet flow becomes the dominant transport mode. Most of the available intrawave theories of sediment transport are developed for plane-bed conditions. Generally a boundary layer schematization is used in which the near-bed flow is described as a horizontal oscillatory flow and vertical orbital velocities as well as horizontal advective terms are neglected. Distinction can be made between quasi-steady transport formulas and more detailed boundary layer models.
In the quasi-steady models it is assumed that the instantaneous transport adjusts itself immediately to the variable conditions within the wave cycle. The existing quasi-steady transport formulas generally have a semi-empirical character and are based on a limited number of measurements using oscillating plates or small oscillating water tunnels. Recently, King (1991) presented an extensive experimental study in the large tunnel at Scripps Institution of Oceanography and showed some of the shortcomings of quasi-steady theories and the importance of acceleration effects.
In the boundary layer models the vertical structure of the boundary layer transport process is described during the wave-cycle and, for example, phase differences between the bed-shear stress and the free stream velocity and the delayed response of suspended sediment are included.

Ribberink and Al-Salem (1994) studied the wave-related sand transport processes in the large-scale wave tunnel of Delft Hydraulics in the period 1988 to 1991. In this facility the oscillatory near-bed conditions as induced by moderate to extreme (nonbreaking) waves can be simulated at full scale for a wide range of relevant coastal conditions.
Two large sets of experiments with 210 μm sediment were conducted. Series A was aimed at bedform types and transport regimes in sinusoidal oscillatory flow with a specific interest in the relatively unknown large-velocity/large-period regime. The experimental conditions of series B were selected in order to simulate the near-bed cross-shore sediment motion in various wave conditions on the upper shoreface. In this coastal zone the process of cross-shore sediment transport is substantially influenced by the non-linearities (e.g. wave asymmetry) and randomness of the wave motion. During experiment series B, regular and random asymmetric oscillatory flows were imposed and bed forms, wave-cycle averaged sediment concentrations and net (wave-cycle averaged) transport rates were measured. Using the new data set, a number of intrawave (quasi-steady) transport formulas were verified. Special attention was paid to the validity of the assumption of quasi-steadiness of the transport process and the necessity of using intrawave boundary layer models.

Bed forms showed a strong sensitivity of the type of oscillatory flow in the high-velocity regime. For sinusoidal flows, increasing velocities did not lead to the expected decrease of ripple dimensions. Instead the ripple height and length showed a continuous linear increase with the horizontal excursion length of the water. This continuation of ripple growth in the high-velocity regime was also observed in large (prototype) wave flumes. During the series B experiments with asymmetric (regular and random) oscillatory flows the transition from rippled to plane-bed/sheet flow did occur. In these conditions the reduction in ripple dimensions could roughly be described with the available empirical relations.
The physical mechanisms which are involved in the process of sediment suspension during the wave cycle are different in rippled bed and plane-bed/sheet flow conditions.

In case bed ripples are present, the process of sediment suspension is generally dominated by the cyclic development and convection of large vortices. During most of the experiments in series A and part of the series B experiments, vortex ripples were observed, and the flow and suspension process along the ripples was dominated by the dynamics of the vortices. Vortices are developed in the ripple troughs and generate sediment clouds during each half cycle of the wave motion. Approximately at the moment of flow reversal of the free stream, the sand clouds are convected upward to higher elevations above the bed and are then transported in the opposite direction (during the next half cycle), while part of the sand is settling back to the bed. At the same time new vortices are developed in the ripple troughs, and the process repeats itself. The vertical distribution of the time-averaged and bed-averaged suspended sediment concentration under waves is often described with an advection-diffusion model in which the vertically downward sediment flux induced by gravity is balanced by an upward flux induced by the vertical mixing process.

In case of sheet flow the suspended sediment is confined to a layer of a few centimeters close to the bed, despite the presence of relatively large flow velocities.
All measured plane-bed experiments during series B show concentration profiles with a concave upward shape on a log-linear scale, which however, transform into straight lines when plotted on a log-log scale (see Figure 4.5.1).
This is an indication of a linearly increasing mixing coefficient with distance from the bed. The concentration decay parameter was found to be constant for all 14 experiments (parallel concentration profiles, see Figure 4.5.1).

In the transition regime from rippled bed to plane-bed/sheet flow conditions the character of the vertical mixing process of sediment changed strongly.
The influence of the oscillatory flow parameters on the behaviour of suspended concentration profiles is clearly different for both regimes. In the rippled bed regime the bed form dimensions are strongly reduced by the asymmetry and irregularity of the flow (especially in the transition regime), and consequently, also the suspended sediment mixing decreases considerably (see left part of Figure 4.5.2, U_{rms} = 0.22 m/s, T = 6.5 s). In the plane-bed regime the concentration profiles are not affected by the irregularity of the flow (see right part of Figure 4.5.2, U_{rms} = 0.5 m/s, T = 6.5 s).
In plane-bed conditions an increased U_{rms} leads to an increased suspended load, and no influence of the wave period is observed. However, in rippled bed conditions an increase of U_{rms} (for constant period T = 6.5 s) and an increase of T (for constant U_{rms} = 0.25 m/s) lead to a decrease in suspended load (see Figures 4.5.3 and 4.5.4). The latter phenomena are again directly related to the decrease in ripple dimensions (transition to plane bed).

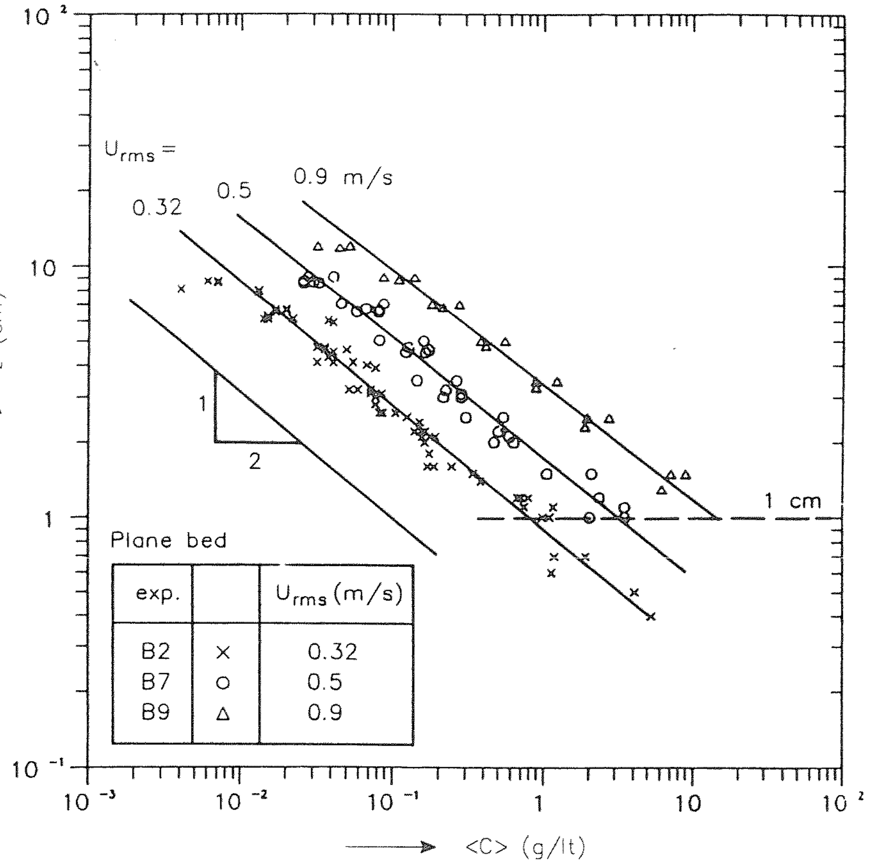


Figure 4.5.1 Near-bed sediment concentration profiles in plane-bed and sheet-flow conditions

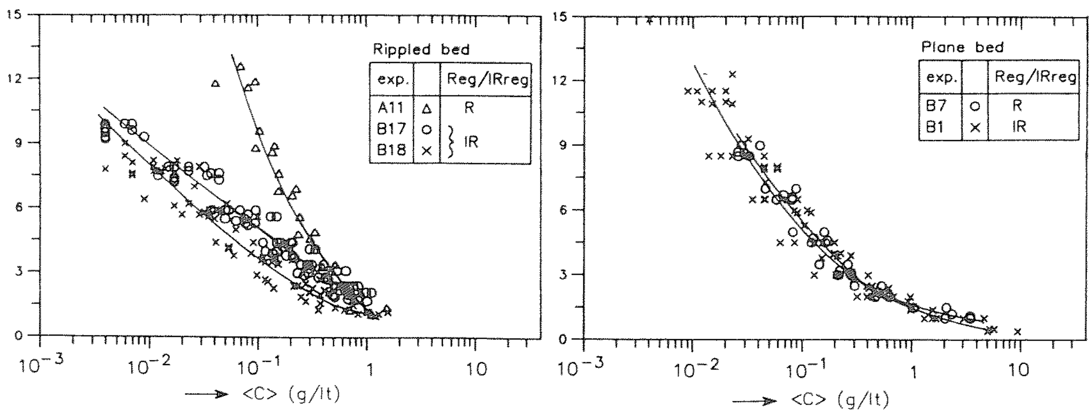


Figure 4.5.2 Near-bed sediment concentration profiles: influence of wave irregularity

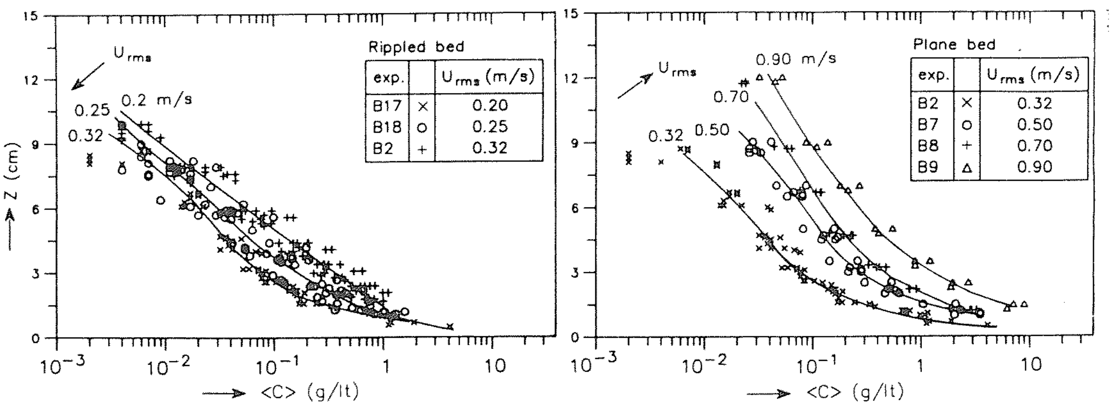


Figure 4.5.3 Near-bed sediment concentration profiles: influence of velocity

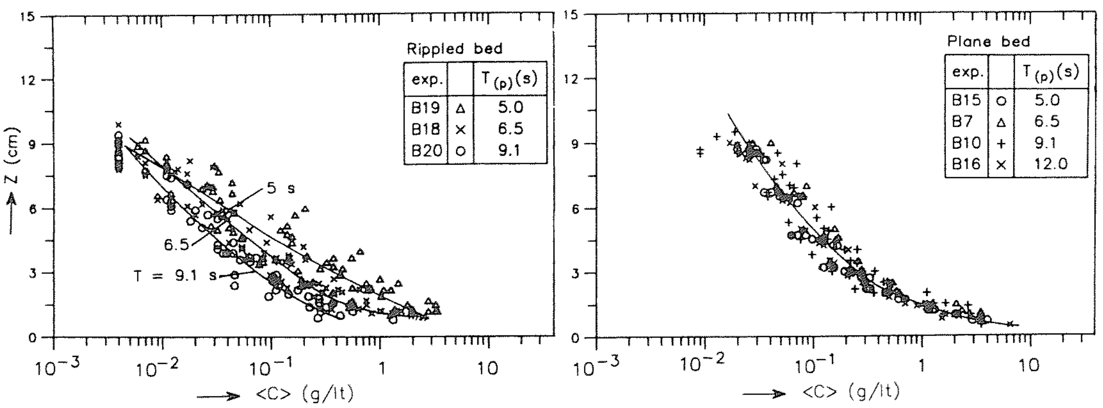


Figure 4.5.4 Near-bed sediment concentration profiles: influence of wave period

Cross-shore sediment transport under (nonbreaking) waves is generally described with bed-load transport formulas which are applied within the wave cylce (intrawave) assuming quasi-steadiness of the transport process. The instantaneous intrawave transport rate (expressed in sediment volume per unit width and time) is assumed to be a function of the instantaneous velocity above the boundary layer (or the instantaneous bed-shear stress) and other parameters such as the sediment grain size and the density of water and sediment.

In this quasi-steady approach, memory effects, acceleration effects, suspension delay effects, and hysteresis effects, which are all related to the unsteadiness of the flow (intrawave effect), are not accounted for. In general terms it can be expected that the quasi-steady approach can be succesfull if, during the wave cycle, sand grains are mainly confined to elevations close to the seabed from which settling to the seabed can take place within fractions of the wave period. During the series B-experiments the net wave cycle-averaged transport rate was measured for a wide range of asymmetric wave conditions using a sand balance method, based on measuring the bed elevations along the test section before and after each test. In all cases the net transport rate was directed onshore (in the direction of wave propagation caused by the asymmetry of the wave velocity motion).

Based on the analysis of the measured net transport rates and other available data, Ribberink proposed a new formulation for the net bed-load transport in oscillatory flow with or without a mean current superimposed, as shown in Figure 4.5.5 (see Ribberink in Van Rijn et al, 1994).

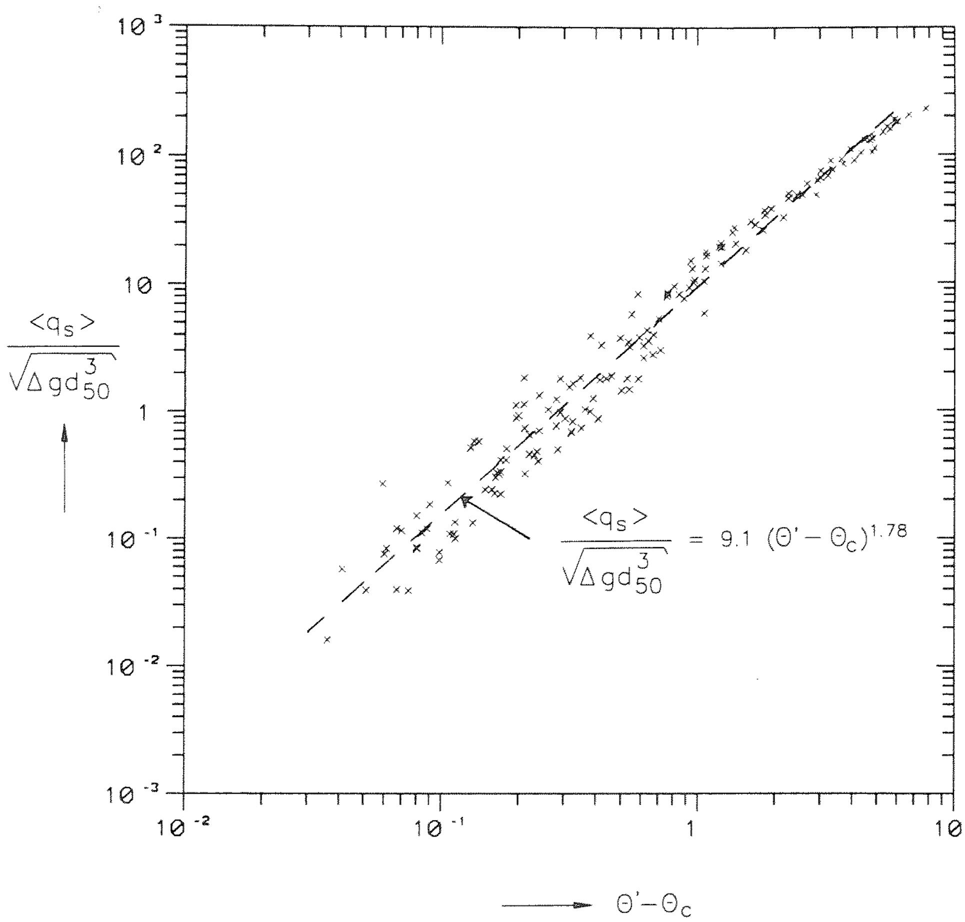


Figure 4.5.5 Net bed-load transport for steady and oscillatory flows

4.5.3 Suspcnded load transport research in laboratory facilities

The current-related suspended-load transport under non-breaking waves with and without a current over a rippled bed was studied by Van Rijn et al (1993) in a flume and by Van Rijn and Havinga (1995) in a laboratory basin. Many details of the various transport components in combined current and wave conditions are given by Van Rijn (1993).

The current-related suspended load transport is defined as the integration over the water depth of the product of the time-averaged flow velocities and sediment concentrations.
Time-averaged sediment concentrations measured over a rippled bed in laboratory conditions show the following phenomena (see also Figures 4.5.6, 4.5.7 and 4.5.8): (1) rapid decrease of the concentrations from the bed upward for waves alone, (2) upward transport by mixing processes in combined current and wave conditions, (3) mixing effects are relatively small for a weak current and relatively large for a strong current, and (4) the influence of the current velocity on the near-bed concentrations is only significant for low waves.
Based on the experimental results of Van Rijn et al (1993), no clear effect of the current direction (following or opposing) on the transport rate was found. The data of Van Rijn and Havinga (1995) for combined current and wave conditions with wave-current angles between 60° and 120° showed, however, an increase of the concentrations and transport rates for a wave direction perpendicular to the current direction, as shown in Figures 4.5.8 and 4.5.9.

The reason for this behaviour is not yet clear but the apparent bed roughness was also found to be largest under the same conditions, which may lead to a larger entrainment rate and mixing effect.

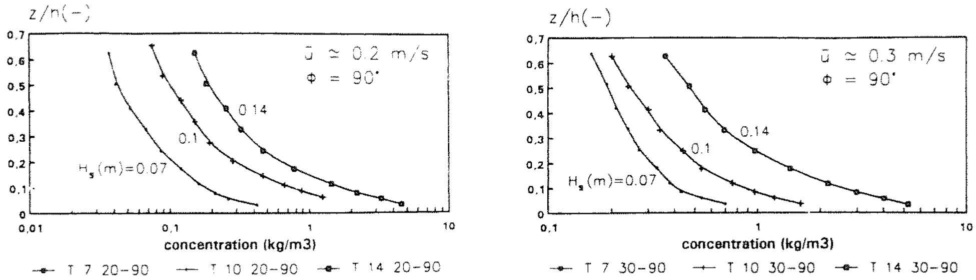


Figure 4.5.6 Influence of wave height on sediment concentration profile

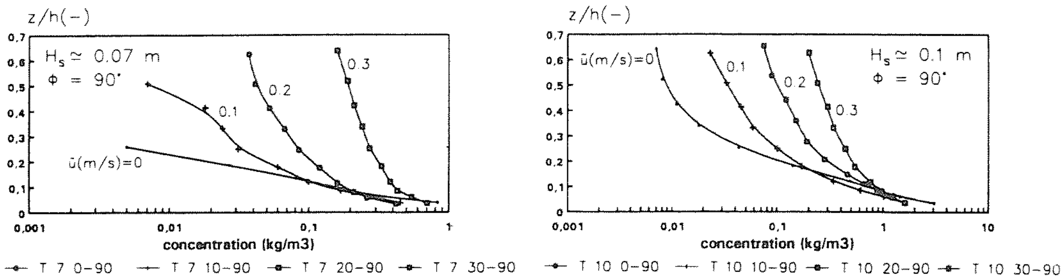


Figure 4.5.7 Influence of current velocity on sediment concentration profile

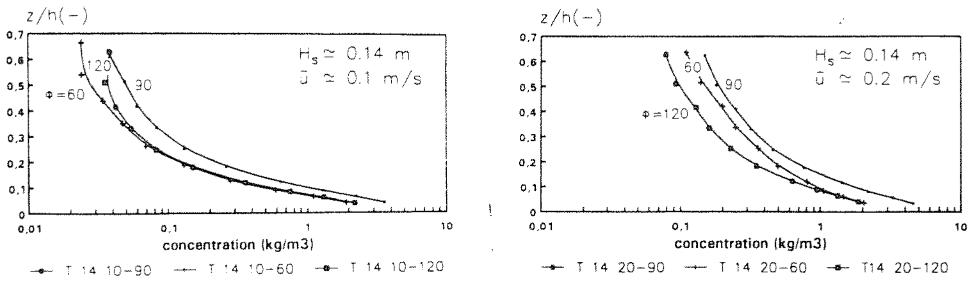


Figure 4.5.8 Influence of wave-current angle on sediment concentration profile

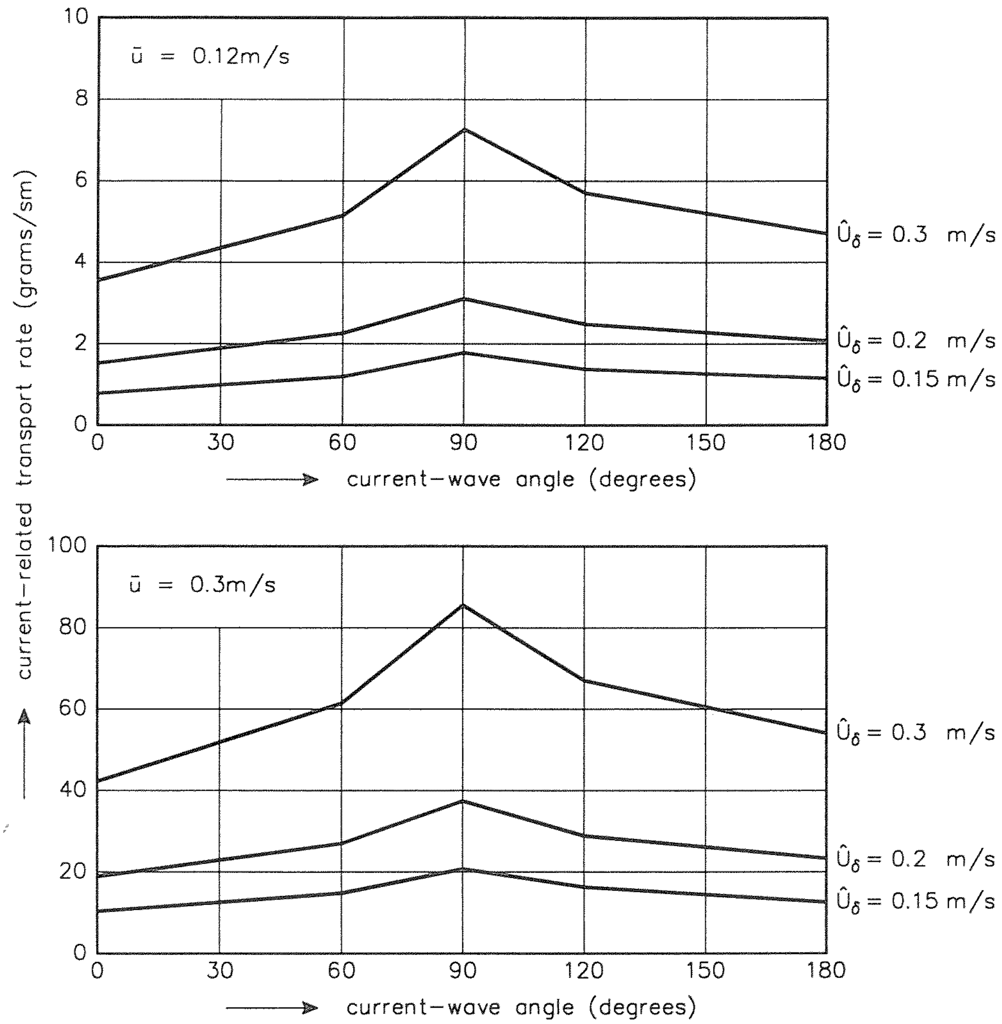


Figure 4.5.9 Suspended load transport as a function of wave-current angle (Van Rijn and Havinga, 1995)

All available laboratory and field data were used to verify the available prediction method for current-related suspended load transport. Good agreement between measured and computed values in longshore and cross-shore direction was obtained (Van Rijn, 1993). Most of the computed values were found to be within a factor of 2 of the measured values, except for the transport rates measured in the swash zone with plunging breaking waves ($H_s/h \geq 0.75$). In this zone the computed transport rates were systematically too small (factor 2 to 5). Further research is required.

In case of non-breaking waves over a rippled bed consisting of very fine sediments resulting in dominant suspension of sediments, the wave-related transport components due to high and low-frequency effects in cross-shore direction may not be neglected, as shown by Van Rijn and Havinga (1995). The depth-integrated wave-related transport rates due to high-frequency waves were found to be onshore-directed (wave asymmetry effect) similar to the results of Ribberink and Al-Salem (1994). The depth-integrated wave-related transport rate due to low-frequency waves was found to be offshore-directed in all experiments. The most plausible explanation for the presence of the this latter mode of transport is the generation of bound long waves. The slow variation of the low-frequency concentration and the velocity are both the result of the same driving mechanism and are therefore correlated.

Further research should be focussed on the effect of breaking waves on the suspended sediment concentrations and transport over rippled and plane beds. This type of research has just been initiated and should be continued with priority.

4.5.4 Sediment transport in field conditions

The sediment transport processes under various conditions in the area of the shoreface-connected ridges near Zandvoort, The Netherlands were studied by Van de Meene (1994) using a variety of instruments and modelling methods. The observed sediment transport rates indicate that under fair-weather conditions, sediment is transported only during the (maximum) tidal flood current. The sediment transport is highly intermittent under these circumstances, with bed load being the dominant mode of transport. Under storm conditions sediment is transported predominantly in suspension. Wave stirring and advection by the mean currents are the dominant sediment transporting agents. Wave oscillatory fluxes, directed both with and against the propagation direction of the waves, are important as well. This means that waves do not act only as a stirring agent. Although long periodic waves (periods in the order of 100 seconds) were clearly visible in the water motion, they were not found to have any net effect on the sediment motion.
A two-dimensional vertical sand transport model (SUTRENCH, Van Rijn, 1986) was used by Van de Meene to compute the transport gradients and hence bed level changes under various hydrodynamic conditions. A range of growth rates and migration rates of the sand ridge system was obtained. The growth rates were found to depend on the intensity of the flow; positive as well as negative values (between 0.015 and -0.002 m/year) were obtained. Computations based on measured flow velocities resulted in a growth rate of about zero and migration rates in the order of 0.5 to 1 m/year in seaward direction. The migration rate of the ridges appears to be determined by a very delicate balance between tidal current asymmetry, wave climate and tidal water level variations.

Sediment concentrations and transport rates under breaking and non-breaking waves in the inner surfzone (shallow depths) near Egmond were studied by Kroon (1994) and by Van Rijn and Kroon (1992).
In conditions with breaking waves the sediment concentrations are rather uniformly distributed over the water depth, especially in plunging breaking waves. The uniformity of the concentration profiles increases with increasing relative wave height, as shown in Figure 4.5.10.

The net suspended transport rates in the surf zone were found to be dominated by the mean current-related transport components. The wave-related components were of secondary importance, especially the low-frequency components. In cross-shore direction the high-frequency transport component is directed onshore (wave asymmetry effect). The mean current transport component is directed offshore (undertow current).

Sediment concentrations and transport rates in the shoreface zone were studied by Houwman and Hoekstra (1994) using an instrumented stand-alone tripod. The net transport rates were found to be dominated by the mean current effect (undertow) resulting in offshore-directed net transport rates. The waves act as a sediment stirring mechanism in the shoreface zone.

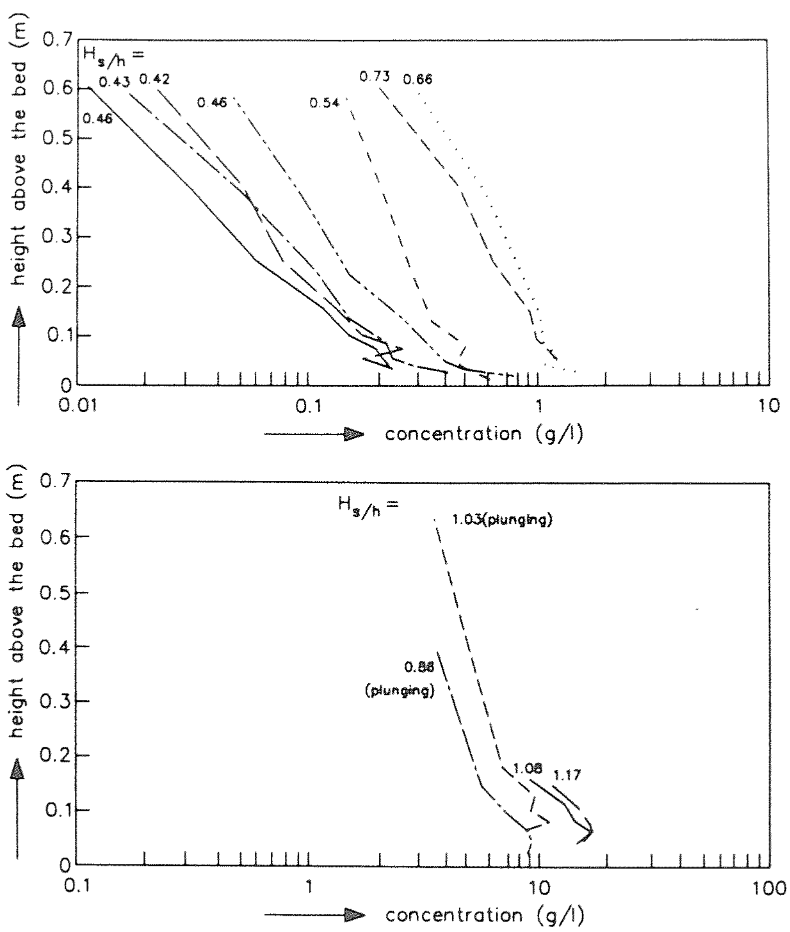


Figure 4.5.10 Time-averaged concentrations in breaking waves near Egmond, The Netherlands (Van Rijn and Kroon, 1992)

4.5.5 Further research

Further research of sediment transport processes should be focused on:

- Measurement and analysis of bed-load and suspended load transport processes in field conditions (shoreface and surf zone).
- Effect of non-steady fluid motion phenomena in the wave boundary layer on the bed-load transport process, especially for fine sediments (100-200 μm) and irregular waves.
- Effect of hindered settling and turbulence damping on sediment concentrations in sheet flow layer, using higher-order models and available wave tunnel data for verification.
- Influence of near-bed currents on the wave-related bed-load transport in the wave-boundary layer.
- Effect of non-breaking and breaking waves on suspended sediment concentrations and transport over plane bed (further analysis of LIP-experiments Delta-flume).
- Influence of strongly breaking waves on the wave-related and current-related suspended load transport, especially in the presence of breaker bars.
- Multi-fraction modelling of bed-load and suspended-load transport for non-uniform sediments.

4.6 Integrated modelling

4.6.1 Model concept

Simulation and prediction of coastal processes require the use of mathematical models representing the basic hydrodynamic and sediment transport processes. Essentially, the models are the reflection of our knowledge of the physical processes.
The mathematical models are based on a detailed description of all relevant processes by implementation of a series of submodels representing wave propagation; tide, wind, wave and density-driven currents; sediment transport rates and bed-level changes, combined in a loop system to effectuate the dynamic interaction of the processes involved.

The research in the Coastal Genesis Project was primarily related to the morphological behaviour of cross-shore profiles for coastal sections which are reasonably uniform in longshore direction. In that case a two-dimensional vertical approach (2DV) can be used, representing the basic processes along the cross-shore bed profile and neglecting the longshore gradients of the processes involved (UNIBEST-model).

This latter model consists of 3 sub-models:

- wave propagation model,
- vertical flow structure model,
- sand transport model.

The wave propagation model computes the wave energy decay along a wave ray based on shoaling, refraction and energy dissipation of bottom friction and wave breaking.
The effect of the wave asymmetry in shoaling waves on the instantaneous and on the time-averaged near-bed velocities is taken into account. The effect of bound long waves on the near-bed velocities is also represented using recently developed expressions for narrow banded wave spectra. The near-bed instantaneous velocities are computed as time series representing irregular wave groups (including wave asymmetry and bound long wave effects).

The vertical flow structure model computes the vertical distribution of the horizontal flow velocities for a given depth-averaged velocity vector, wave height and period, fluid density gradient and wind-shear stresses (surface). The effect of wave breaking resulting in a longshore-current and a cross-shore return current (undertow) and the Coriolis effect are taken into account.

The sand transport model computes the magnitude and direction of the bed load and suspended load transport. The bed-load transport is computed by using the instantaneous near-bed velocities (intra-wave modelling, Van Rijn et al, 1994) which are transferred to bed-shear stresses (within the wave period). Input parameters are the time-series velocity data and the time-averaged velocity data computed by the wave model and the vertical structure model. The suspended load transport is computed from the time-averaged velocity and concentration profile.

Roelvink et al (1995) have studied the performance of the various submodels of the UNIBEST-model in comparison to the available data from the LIP-experiments carried out in the Delta-flume of Delft Hydraulics. The attention was focussed on the cross-shore processes in the (surf) zone with breaking waves.

Figure 4.6.1 shows measured and computed wave heights, undertow velocities, bound-long wave effects, short wave-asymmetry effects and sediment transport rates. Good agreement of measured and computed wave heights can be observed. The undertow velocities are overpredicted in the zones landward and seaward of the breaker bars and underpredicted in the zone between the bars. The wave-asymmetry effect is strongly overpredicted. The net sediment transport rate is also strongly overpredicted.
Based on these results, it can be concluded that most of the relevant cross-shore hydrodynamic and transport processes are not represented with sufficient accuracy.
Further research of undertow velocities, wave velocity asymmetry and sediment transport processes in the surf zone with breaker bars is strongly recommended.

The updated 2DV-profile model UNIBEST has been used to estimate the yearly-averaged sand transport rates at various stations along the Dutch coast (see Section 4.6.2 and 4.6.3).
The potential of these types of models to compute the morphological development of the cross-shore profile is discussed in Section 4.6.4.

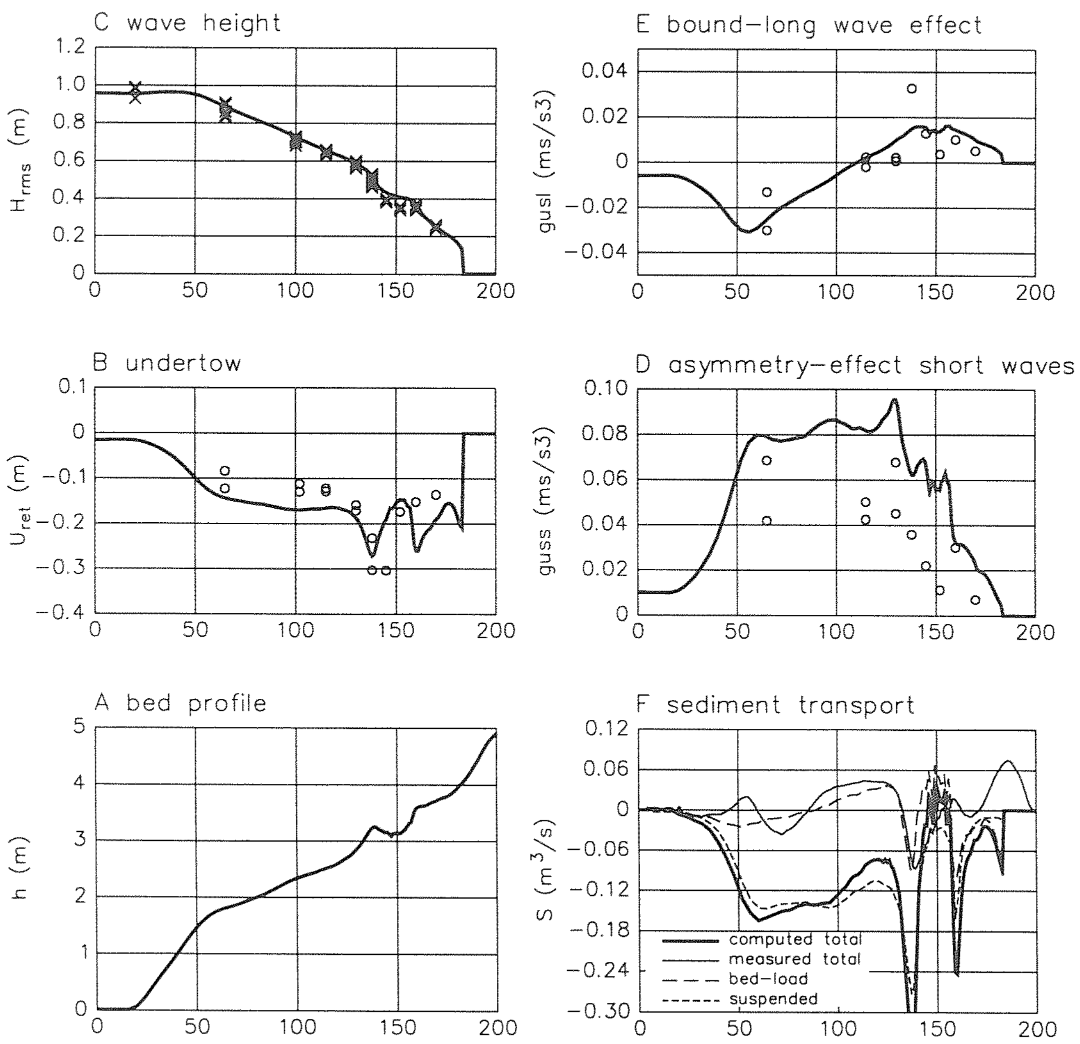


Figure 4.6.1 Comparison of UNIBEST-model results with data of LIP-1B experiment
(guss = third order high-frequency velocity moment, $<u_s|u_s^2|>$)
(gusl = third order low-frequency velocity moment, $3<u_L|u_s^2|>$)

4.6.2 Yearly averaged transport at -20 m and -8 m N.A.P. depth contour along the Dutch coast

Delft Hydraulics has made a hindcast study of the coastline development between Den Helder and Hoek van Holland in the period 1964-1992, using a sand budget model based on most recent knowledge of the hydrodynamic and sediment transport processes (Van Rijn et al, 1994).

Sand budget studies require knowledge of the yearly-averaged transport rates as input data at the boundaries of the budget compartments. These net transport rates have been computed at the -20 m and -8 m N.A.P. contours along the Dutch coast by use of various models of DELFT HYDRAULICS.

The sediment transport rates are computed for schematised wave and corresponding current conditions. Tidal averaging is 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 yearly-averaged sediment transport rate.

The tidal water levels and depth-averaged flow velocities (including wind effect) in the stations of interest were derived from computations made by the Department RIKZ of Rijkswaterstaat using the two-dimensional horizontal version of the TRIWAQ-model (Rijkswaterstaat, 1993).
The neap-spring tidal cycle (tidal range of about 1.3 m for neap, and about 1.9 m for spring) was represented by one representative tide. The tidal range of this latter tide was selected to be 10% larger than the mean tidal range (about 1.6 m) near the Dutch coast to account for the non-linear relationship between sand transport and depth-averaged flow velocity. This representative tide is approximately equivalent to a low spring tide.

Computations were made for 8 wind directions and 4 wind velocities (per direction) being:

- wind velocity of 0 m/s (no wind),
- wind velocity corresponding to wave height 1.25 m,
- wind velocity corresponding to wave height 2.75 m,
- wind velocity corresponding to wave height 4.25 m.

The median diameter of the sediments in the profiles of interest are in the range of 150 to 500 μm. A particle size of 250 μm was used in most computations. Values of 200 μm and 300 μm were used in the sensitivity computations.
The effective current-related bed-roughness was assumed to be in the range of 0.01 to 0.1 m; the effective wave-related bed-roughness was assumed to be in the range of 0.01 to 0.05 m.

It is known that the net cross-shore transport rates in the nearshore zone are the result of a delicate balance of the various onshore and offshore-directed transport components. Most of these transport components cannot yet be represented with sufficient accuracy. Therefore, a detailed sensitivity study (based on 18 computations) was performed varying the most important input and model parameters to come up with variation ranges of the net transport rates rather than present absolute values.

The results of this sensitivity study for profile 76 (Noordwijk) are presented in the following.

Cross-shore and longshore transport rates at depth of 20 m in profile 76

The yearly-averaged total cross-shore transport component based on the Delft Hydraulics model is onshore-directed and varies predominantly in the range of 0 to 10 m^3/m^1/year (see Figure 4.6.2). The upper limit is mainly related to the contribution of the density gradient. The cross-shore transport component is dominated by tide-induced, wind-induced and density-induced currents in combination with the wave motion acting as a stirring mechanism. Especially, the wind-induced currents (dominant southwesterly winds) and the density-induced currents yield onshore-directed velocities and hence transport rates.

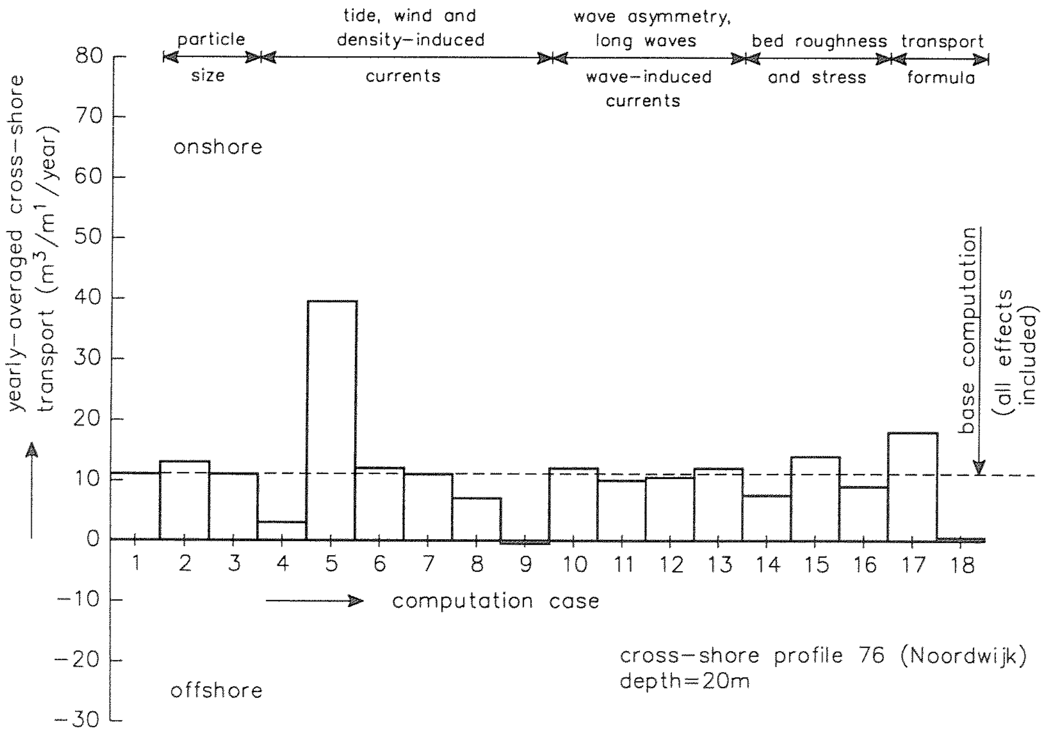


Figure 4.6.2 Effect of model and input parameters on yearly-averaged total cross-shore transport rate at depth of 20 m, profile 76 (Noordwijk)

The yearly-averaged total longshore transport component based on the Delft Hydraulics model is northward directed and varies predominantly in the range of 10 to 40 m^3/m^1/year. The lower limit is related to reduced tidal current velocities. The upper limit is related to a relatively small particle-diameter.

The computation based on the Bailard-Bagnold model is comparable to the 1989-computations by Roelvink and Stive (1989a) showing a cross-shore transport component of about 0 m^3/m^1/year, which is somewhat smaller than the value of 3 m^3/m^1/year (excl. pores) reported by Roelvink and Stive. The longshore component according to the BB-computation is 32 m^3/m^1/year which is much larger (factor 8) than the value of 4 m^3/m^1/year (excl. pores) reported by Roelvink and Stive. This later discrepancy is most probably related to the use of a more symmetric tidal cycle by Roelvink and Stive.

Based on the results of the sensitivity analysis, the contributions of the various hydrodynamic processes to the cross-shore transport rates can be estimated.
The wave velocity asymmetry effect, the bound long wave effect, the LH-streaming effect and the reduced return current effect do not contribute to the cross-shore transport rate at a depth of 20 m. The contribution of the fluid density gradient effect to the cross-shore transport rate at 20 m is about 5 to 15 m^3/m^1/year, depended on the location along the coast (5 m^3/m^1/year near Scheveningen and 15 m^3/m^1/year near Callantsoog).

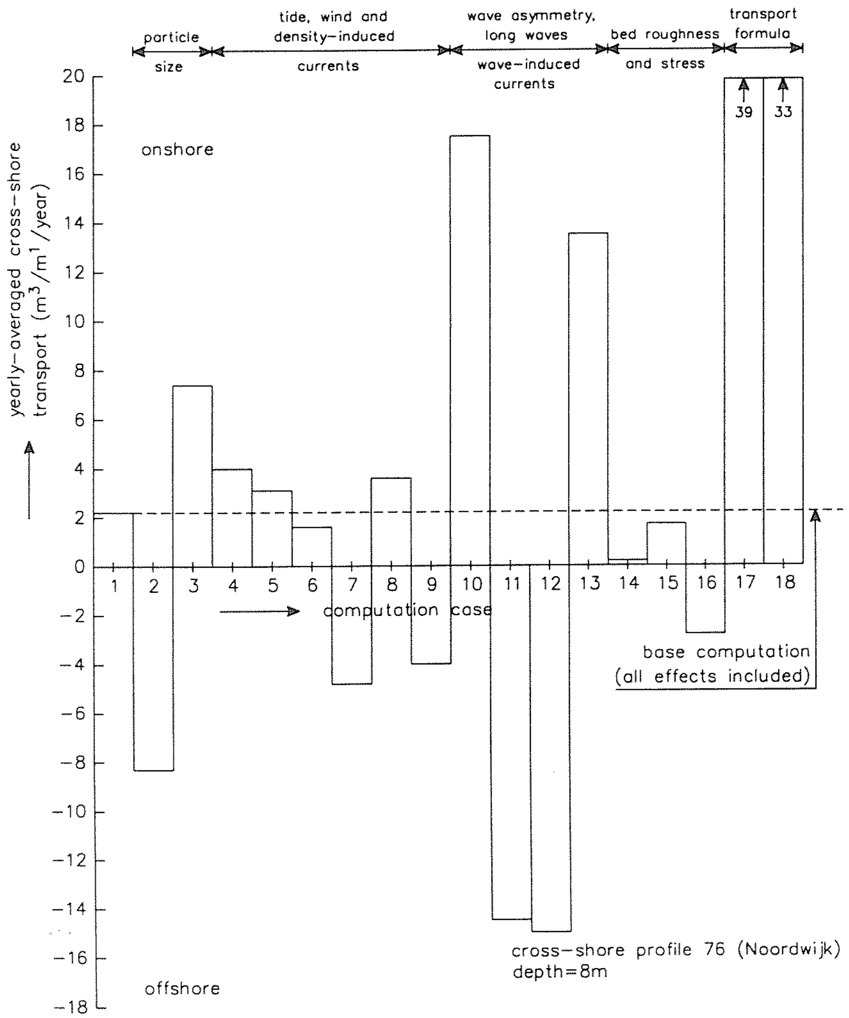


Figure 4.6.3 Effect of model and input parameters on yearly-averaged total cross-shore transport rate at depth of 8 m, profile 76 (Noordwijk)

Cross-shore and longshore transport at depth of 8 m in profile 76

The results of the sensitivity computations are discussed in the following.

The yearly-averaged total cross-shore transport component based on the Delft Hydraulics model varies predominantly in the range of -10 to + 10 m^3/m^1/year (see Figure 4.6.3). Onshore (LH-streaming, wave velocity asymmetry, density gradient) as well as offshore (long waves, undertow) transport processes do occur. All transport components are important. Relatively fine sediment material may result in relatively large offshore-directed transport, whereas relatively coarse sediment material may result in onshore-directed transport. Overall, there is a slight tendency for a net onshore transport.

The yearly-averaged total longshore transport component based on the Delft Hydraulics model is northward directed and varies predominantly in the range of 10 to 50 m^3/m^1/year. The lower limit is related to relatively small mean velocities and no wind effects. The upper limit is related to relatively fine sediment material.

The computation based on the Bailard-Bagnold model is comparable to the 1989-computations by Roelvink and Stive (1989a) showing a cross-shore transport component of about 33 m^3/m^1/year, which is somewhat larger than the value of 20 m^3/m^1/year (excl. pores) reported by Roelvink and Stive. The longshore component according to the BB-computation is about 5 m^3/m^1/year which is somewhat larger (factor 2) than the value of 2 m^3/m^1/year (excl. pores) reported by Roelvink and Stive. This later discrepancy is most probably related to the use of a more symmetric tidal cycle by Roelvink and Stive.

The effect of wave velocity asymmetry, the bound long waves, the LH-streaming, the reduced return current and the fluid density gradient to the cross-shore transport rate is in the range of 5 to 25 m^3/m^1/year.

Further research of the various cross-shore transport processes is strongly recommended, given the relatively large variation ranges of the cross-shore transport components. Quantitative results can be obtained by studying the backfilling of small dredged trenches at the -20 m and -8 m depth contours.

Best estimates of yearly-averaged transport rates at depth of 20 and 8 m in profiles 14, 40, 76 and 103

Based on all available computations, a best estimate (including variation ranges) of the yearly-averaged transport rates at a depth of 20 m and 8 m in 4 cross-shore profiles along the coast is given in the following table. The net transport vectors are shown in Figure 4.6.4.

Cross-shore profile	Yearly-averaged total load transport (m^3/m^1/year) (all values, excluding pores)			
	Cross-shore		Longshore	
	Depth = 20 m	Depth = 8 m	Depth = 20 m	Depth = 8 m
14 Callantsoog	3 ± 5	0 ± 5	45 ± 20	90 ± 40
40 Egmond	10 ± 5	0 ± 5	35 ± 15	80 ± 35
76 Noordwijk	5 ± 5	0 ± 5	20 ± 10	50 ± 30
103 Scheveningen	0 ± 5	0 ± 5	15 ± 10	40 ± 25

+ north/onshore; - south/offshore

The present results are compared to those of Roelvink and Stive (1989a). They presented computed and calibrated transport rates; the calibrated values were obtained by applying a multiplier of 0.5 to the cross-shore transport rates and a multiplier of 2 to the longshore transport rates.

The calibrated longshore transport rates of Roelvink and Stive are of the order of 5 to 10 m^3/m^1/year which is considerably smaller (factor 2 to 10) than the present results. The results of Roelvink and Stive fall outside most of the present variation ranges. A net southward longshore transport rate at a depth of 8 m in profile 40 (Egmond) was computed by Roelvink and Stive. The calibrated net onshore transport rates of Roelvink and Stive are of the order of 1 to 3 m^3/m^1/year at a depth of 20 m and fall within most of the present variation ranges. The net onshore transport rates of Roelvink and Stive at a depth of 8 m are of the order of 10 m^3/m^1/year which is significantly larger than the present results indicating a zero transport over the 8 m depth contour.

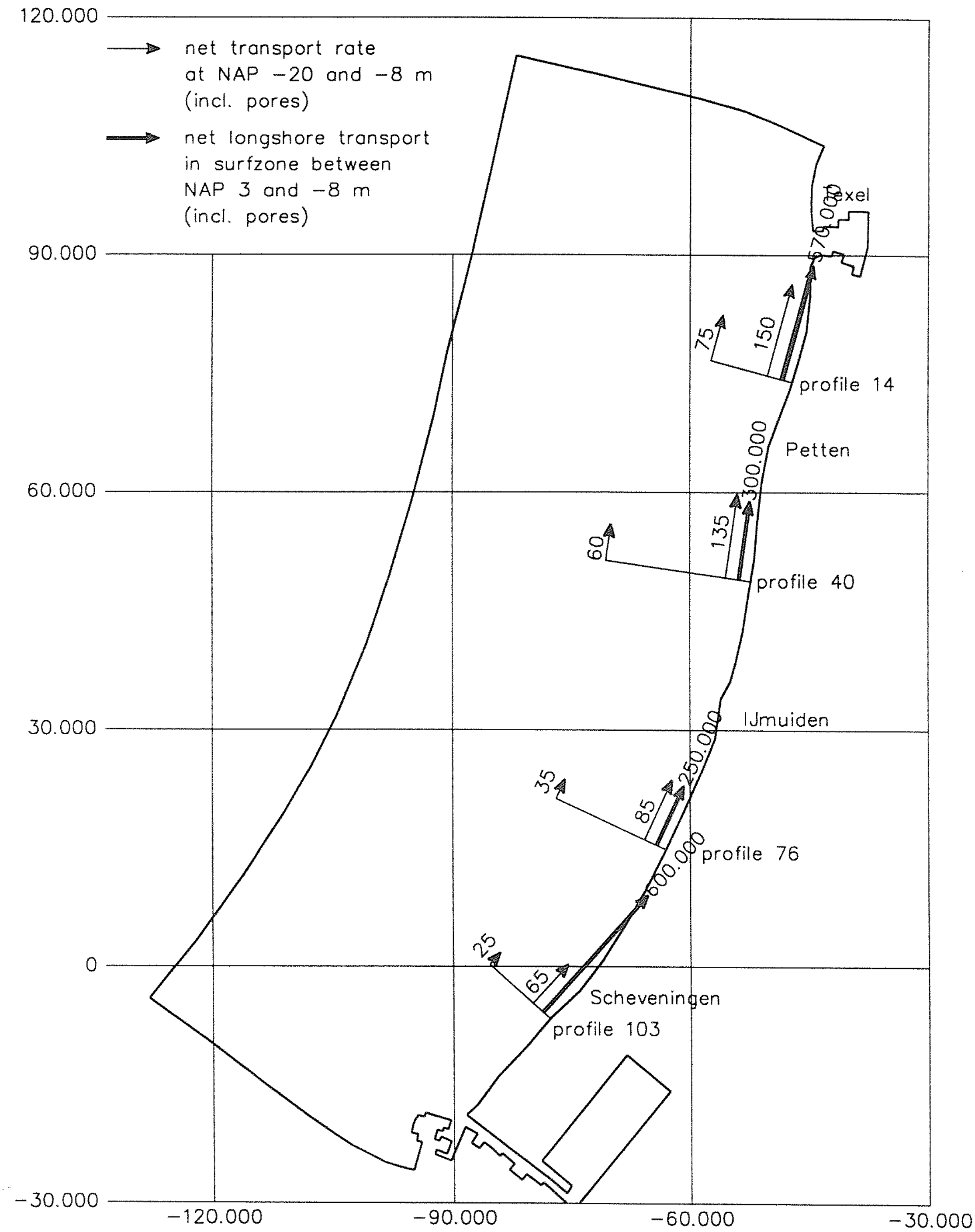


Figure 4.6.4 Net sediment transport vectors along Dutch coast (incl. pores)

4.6.3 Yearly-averaged longshore transport rates in the surf zone (3 m/-8 m)

Longshore transport rates in profile 76

First, the results of the sensitivity computations for profile 76 (Noordwijk) are discussed.

In all, 19 computations were made varying input parameters and model processes for a smooth (longterm-averaged) bed profile without breaker bars.
In all computations the net longshore transport rate is in the northward longshore direction. Generally, the northward transport rates are about 2 to 3 times as large as the southward transport rates.
The base computation yields a net longshore transport of about 250.000 m^3/year in profile 76 (excluding pores) for a smooth (time-averaged) bed profile. The cross-shore distribution of the longshore transport rate shows a large transport peak in the shallow surf zone near the shoreline.

About 60% to 70% of the total integrated longshore transport does occur in the inner surf zone with a width of about 200 m.

The total load transport consists of two components: bed load and suspended load transport. In longshore direction the suspended load transport is the dominant mode of transport at all locations.

The net longshore transport is most strongly affected by the:

- wave climate,
- depth-averaged longshore current,
- presence of breaker bars,
- bottom slope,
- particle diameter.

The effect of minor changes in the wave climate on the net longshore transport rate was found to be rather small in profile 76, but a significant effect was found for profile 40 (Egmond), where the coastline orientation is relatively small (7° to 8°).

The net longshore transport rate was found to be strongly dependent on the accuracy of the computed longshore current. A 50%-decrease of the current velocities results in a decrease of the net longshore transport rate by a factor 3 to 4. The accuracy of the wave-induced longshore velocities predicted by the UNIBEST-model is largely unknown, because of a lack of measured data for verification of the model. The model has been calibrated in the sense that realistic (right order of magnitude) velocities are computed.

The presence of breaker bars results in an increase of the net longshore transport rate of about 50% to 60%. About 60% of the total integrated longshore transport rate is found to occur in the inner surf zone with depths between 0 and 4 m.

The bottom slope in the surf zone (line trough -1 m and -8 m N.A.P.) has a significant effect on the net longshore transport process. Increasing the bottom slope from about 0.005 to 0.01 yields an increase of the transport rate by a factor of 2. Steepening of the cross-shore profile results in more intensive breaking closer to the shoreline and hence larger wave-induced current velocities and transport rates.

Best estimates of net longshore transport rates in the surf zone

Based on all available computations, a best estimate (including variation ranges) of the net longshore transport rate in the surf zone of 9 cross-shore profiles along the coast is given in the following table. The variation ranges for the sections with a relatively small coastline-orientation (< 10°) are found to be rather large (± 100%).

Cross-shore profile	Coastline orientation (°)	Steepness of profile* (-)	Yearly-averaged longshore transport integrated over the surf zone upto -8 m NAP (m^3/year, excluding pores)		
			North (positive)	South (negative)	Net
14	18°	0.008	680.000	-340.000	340.000 (± 50%)
28	7°	0.008	580.000	-290.000	290.000 (± 100%)
40	8°	0.008	360.000	-180.000	180.000 (± 100%)
47	10°	0.006	300.000	-150.000	150.000 (± 75%)
68	21°	0.005	300.000	-150.000	150.000 (± 50%)
76	26°	0.005	300.000	-150.000	150.000 (± 50%)
92	37°	0.006	380.000	-190.000	190.000 (± 50%)
103	40°	0.008	720.000	-360.000	360.000 (± 50%)
108	41°	0.012	760.000	-380.000	280.000 (± 50%)

* Profile steepness is slope of line through -1 m and -8 m NAP contours

The net transport vectors are shown in Figure 4.6.4.

Finally, the influence of structures is noted. The present results are valid for a natural coast without the presence of structures like harbour dams and groynes. Groynes which are present in the sections 0.4 to 31 km and 97 to 115 km (from Den Helder), have a blocking effect on the sediment materials transported along the shore. The degree of blocking depends on the cross-shore length of the groynes and the height of the groynes.

The harbour dams near Hoek van Holland and IJmuiden extend considerably beyond the surf zone resulting in an almost full blocking of the total longshore transport process.
No attempt was made to evaluate in detail the effect of the structures on the longshore transport rates. Further research using 3D-models is required to estimate the effect of long dams on the local transport rates.

4.6.4 Morphological behaviour of cross-shore profile

Early attempts to model the profile development of beaches by using 2DV-models were made by Roelvink and Stive (1989b) and by others.

Roelvink and Brøker (1993) discuss the simulated bed profile evolutions of various 2DV-profile models. The computed bed evolutions are the result of successive computations of hydrodynamics, sediment transport rates and bed level changes.

In case of regular waves over an initially smooth bed profile, a bar is produced by the models at the position where the onshore-directed transport rates under the non-breaking waves turn into offshore-directed transport rates inside the surf zone. The mechanisms just shoreward of breaker point are essential for the bar evolution.

In case of irrregular waves a relatively steep bed profile tends to be reshaped into a profile with more gentle slopes. The bar formation is not as pronounced as in the regular wave case. The sediment transport appeared to be very sensitive to even small humps in the bed. The observed relatively large initial offshore transport is not very well reproduced. Furthermore, the modelled evolutions do not represent the erosion at the steep dune front (dune and swash zone phenomena). The models generally show far too large cross-shore transport gradients in the zone landward of the breakpoints of the highest waves. Landward of the breaker bar the offshore-directed transport decreases too quickly as a result of underprediction of the undertow. The strong sensitivity of the suspended sediment transport to the strength of the undertow causes errors in the transport rates and gradients.

The models operate best in the central part of the surf zone where the waves are spilling breakers and the conditions have a quasi-uniform character.
At present stage of research the models can only be used for short-term modelling of the cross-shore processes.

An example of computed bed levels based on the UNIBEST-model is given in Figure 4.6.5 for the LIP-1B experiment with irregular waves. The measured data show the generation of a breaker bar approximately at x = 130 m, which is not represented by the model.
Further research of breaker bar generation is strongly recommended.

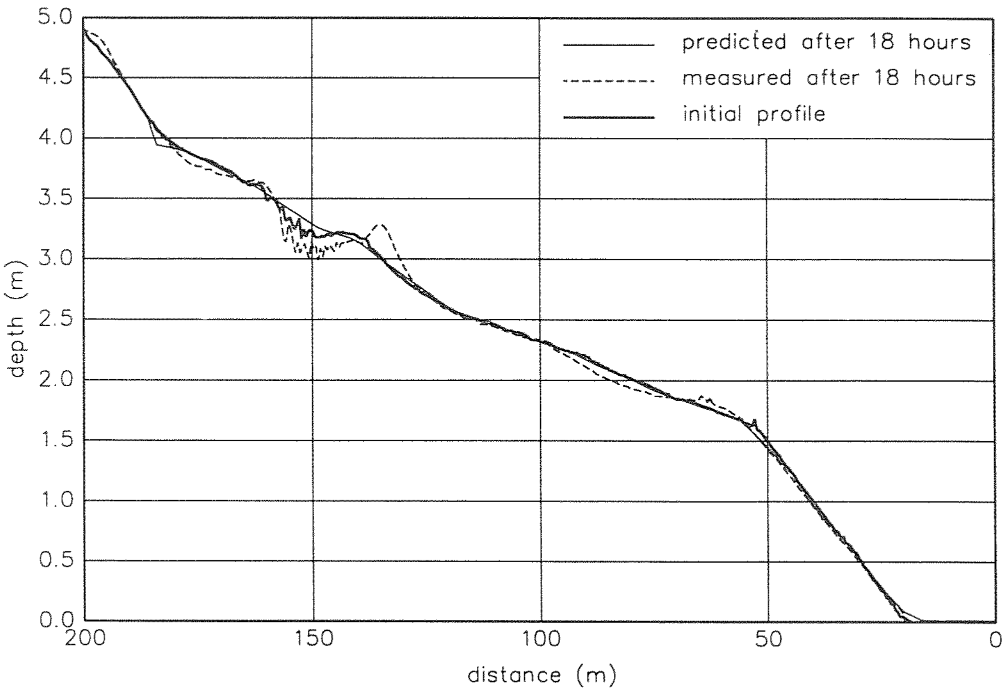


Figure 4.6.5 Measured and computed bed level evolution for LIP-1B experiment based on UNIBEST-model

4.6.5 Further research

Further research should be focussed on:

- Generation, migration and degeneration of major breaker bars using 2DV and 3D mathematical models; flume and field studies are required for a better understanding of the physical processes involved and verification of the models.

- Measument and modelling of net yearly-averaged sand transport rates at the -20 m and -8 m depth contours by analyzing the backfilling of small dredged trenches at various locations along the coast.

- Measurement and modelling of wave-induced longshore transport rates in the surf zone at various locations along the coast.

5 Behaviour-related research and long-term modelling

5.1 Introduction

Behaviour-related models describe the behaviour of morphological features or systems using relatively simple expressions formulated to represent the phenomena at the larger scales of interest. Hence, the basic phemenological behaviour of the system is described neglecting unnecessary details. All process-related information and additional empirical information is represented by coefficients, parameterized functional relationships or by stripped process-based submodels. An overview is given by De Vriend et al (1993).

Behaviour-related research of the closed coastal systems has had only limited attention in the Coastal Genesis Project, compared to the process-related research.

The following types of models are herein discussed:

- statistical models,
- parametrization models,
- advection-diffusion models,
- multi-line models.

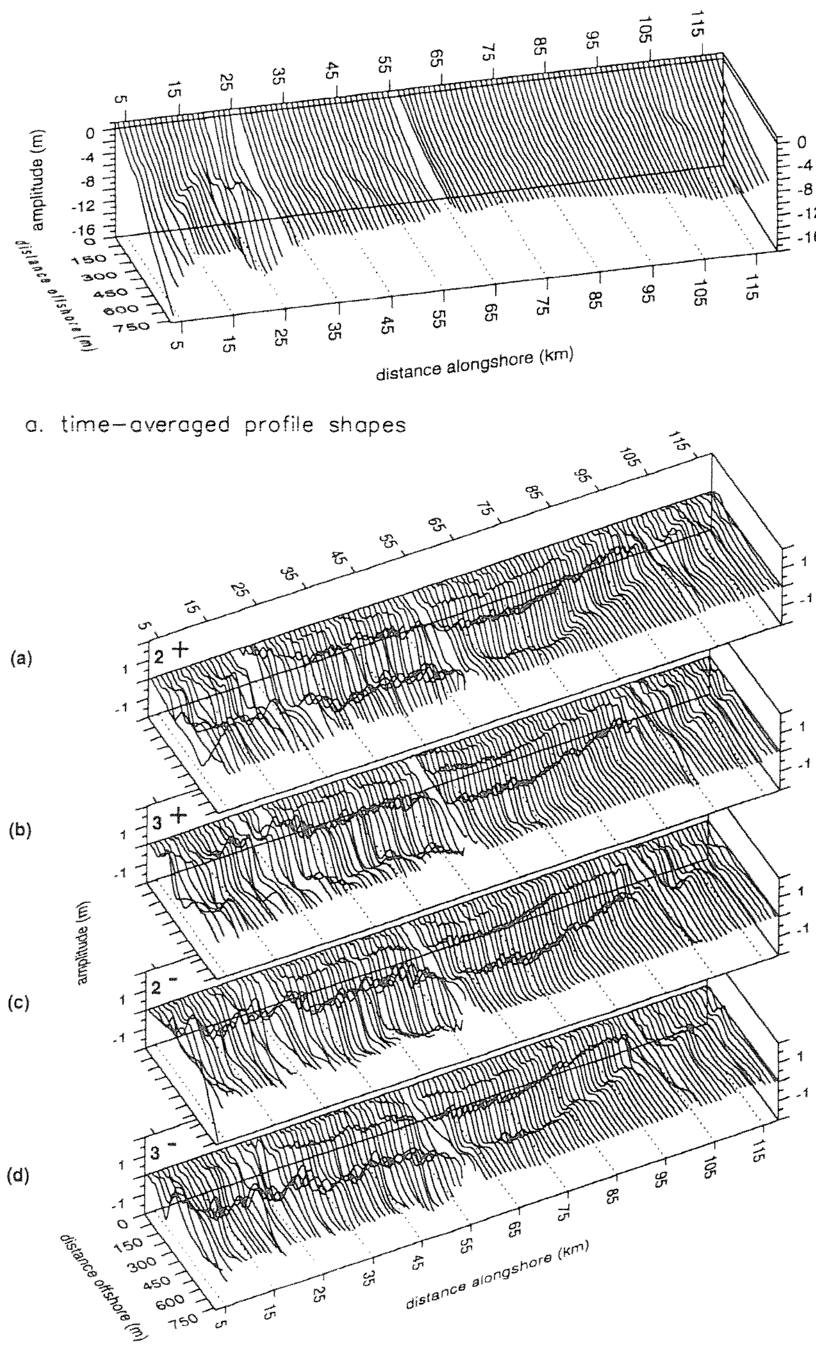
5.2 Statistical models

The statistical models considered herein are extrapolation models and empirical orthogonal function (EOF) models.

Extrapolation (linear or non-linear) is a widely applied method, which has however severe limitations. For example, linear regression analysis is a purely statistical operation without any physical basis unless the physical processes involved are proven to behave as a linear system in time. The predictive ability is determined to a large extent by the length of the data record as compared to the forecast period.
Rijkswaterstaat (1994c, d) has used linear and non-linear extrapolation techniques to determine yearly-averaged sand volume changes of small-scale and large-scale sections along the coast of The Netherlands.
Kops and Van de Graaff (1993) also used statistical methods to study the behaviour of the coastline near Egmond.

The basic idea of the EOF-models is to map a data set onto an orthogonal set of spatial functions, which are derived from the eigenfunctions of the covariance matrix. Each spatial function has its own time-evolution function and contains a certain part of the variance of the data, indicated by the corresponding eigenvalue.
This method has been used by Wijnberg and Terwindt (1994) to study the behaviour of the cross-shore profiles of the Dutch coast between Den Helder and Hoek van Holland in the period between 1964 and 1990. The analysis showed the presence of distinct regions with different large-scale coastal behaviour. The boundaries between these regions were found to

be quite sharp and related to coastal structures (harbour dams of IJmuiden, Hoek van Holland, seawall of Petten). The results are given in terms of the position of the shoreline, the shape of the mean profile and the bar development (see for example Figure 5.2.1).



a. time-averaged profile shapes

b. secondary morphology (bar systems) represented by second and third empirical eigen functions

Figure 5.2.1 Time-averaged cross-shore profiles and bar systems along the central Dutch coast

5.3 Parametrization models

The parametrization models are based on simple input-output relationships between the driving variables of the hydrodynamic system and the response of the morphological system; each defined scale may have its own parametrization model. The selection of variables strongly depends on the dominant physical processes involved.
The existing models may be used to predict the type of beach, the shape of the cross-shore profile and the morphological regime (erosional or accretional events). An overview is given by Kroon (1994). The existing coastal parametrization models can be divided into two groups: environmental parameters and surf-similarity parameters.
The Dean-number defined as the ratio of the wave height and the product of fall velocity and wave period, is generally used as an environmental parameter characterizing the beach type and state. The significant wave height in deep water or that at the breaker line is commonly used to characterize the wave conditions.
The surf-similarity parameter defined as the ratio of the wave steepness and the beach slope is indicative for the local hydrodynamics like the local breaker type, the relative breaker height and the presence of low-frequency motions.

The coastal parameters are poorly defined in case of a barred cross-shore profile. Another problem is the effect of the tidal range, which is not included in the parameters. The differences in time scales of rapid erosional and slow deposition events are also not represented by the parametrization models.

Kroon (1994) studied the morphological behaviour of the swash bar in the inner surf zone near Egmond. The existing parametrization models could not be used to describe the morphological development of the swash bar, because the mean water depth is missing in these models. This latter variable is of essential importance in tide-dominated conditions. It was found that swash bars do occur for a relative wave height (H_s/h) smaller than 0.4 at the boundary of the swash zone. The swash bar migrates landward resulting in beach accretion during the flood periods with water levels exceeding the crest level of the bar. The swash bar is eroded during high-energy conditions with relative wave heights larger than 0.4.

Kroon (1994) also studied the morphological behaviour of the breaker bars in the outer surf zone near Egmond, Katwijk and Zandvoort, The Netherlands. The bars were found to migrate in a seaward direction. The lifetime of the bars near Egmond is of the order of 25 years and about 10 years near Katwijk and Zandvoort. The bars may respond on every single storm event and migrate in a seaward or a landward direction on the event time-scale. These opposite directions may be caused by the three-dimensional crescentic planform of the bars or by the dominance of different processes in adjacent coastal zones. On a long-term time-scale the outer bar migrates in seaward direction as a net result over all the storm events. Major changes in the outer bar configuration like the final degeneration of the bar in the outer surf zone corresponds with high-energy storm events. Kroon (1994) introduced a storm parameter defined as the ratio of the storm duration and the interval between two storm events and found that bar degeneration may occur for a storm parameter larger than 0.7, see Figure 5.3.1.

The results show that the seaward migration of the bars in the outer surf zone is a continuous process up to a crest position at 0.75 of the surf zone width. The bar crest remains at that position until a high-energy storm event ($S > 0.7$) causes the bar to move further offshore with a simultaneous decrease of the bar height (decay).

The knowledge of the physical processes related to the nearshore generation, seaward migration and degeneration further offshore of the breaker bars is still at an early stage of development. So far, the behaviour of breaker bars has been studied, using a 2DV-approach in cross-shore direction; the effect of 3D-circulation patterns has been almost fully neglected. Further research of breaker bar behaviour should have high priority, focussing especially on 3D-circulation patterns. The available international data of cross-shore profiles including bar features in different conditions (sediment size, tidal range, type of wave energy) should be further analyzed.

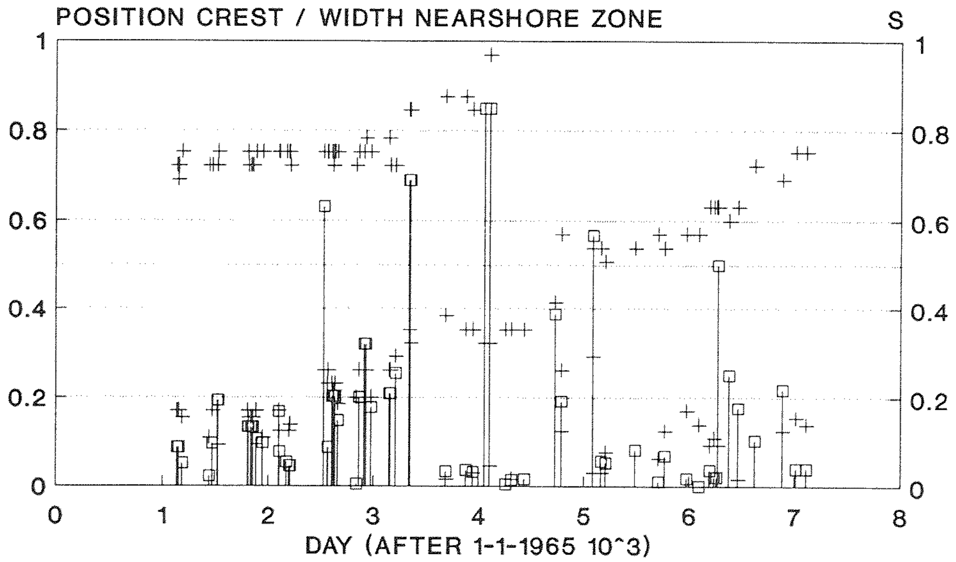


Figure 5.3.1 Dimensionless positions of the bar crest and storm parameter in time, Egmond, The Netherlands (+ position crest/width nearshore zone, □ storm parameter)

5.4 Advection-diffusion type models

The behaviour of a morphological feature or system can, in principle, be simulated by using an advection-diffusion type of model formulated in terms of the local bed level as a function of the horizontal coordinates and time.

All process-related and empirical knowledge has to be represented by the advection and diffusion-related coefficients. Source terms can be used to represent effects related to human interference (nourishment, mining etc.).

A typical result of a diffusion-type profile model is shown in Figure 5.4.1 for the long-term evolution of an underwater profile nourishment (De Vriend et al, 1993). The diffusion coefficient was fitted by using the results of a 2DV-profile model (UNIBEST-model). The diffusion concept was tested against the results of process-based models at various time-scales, ranging from seasons to decades. In all cases, a rather good agreement was found for roughly the same spatial distribution of the diffusion coefficient; large in the active zone and decreasing to almost zero at the shoreface zone.

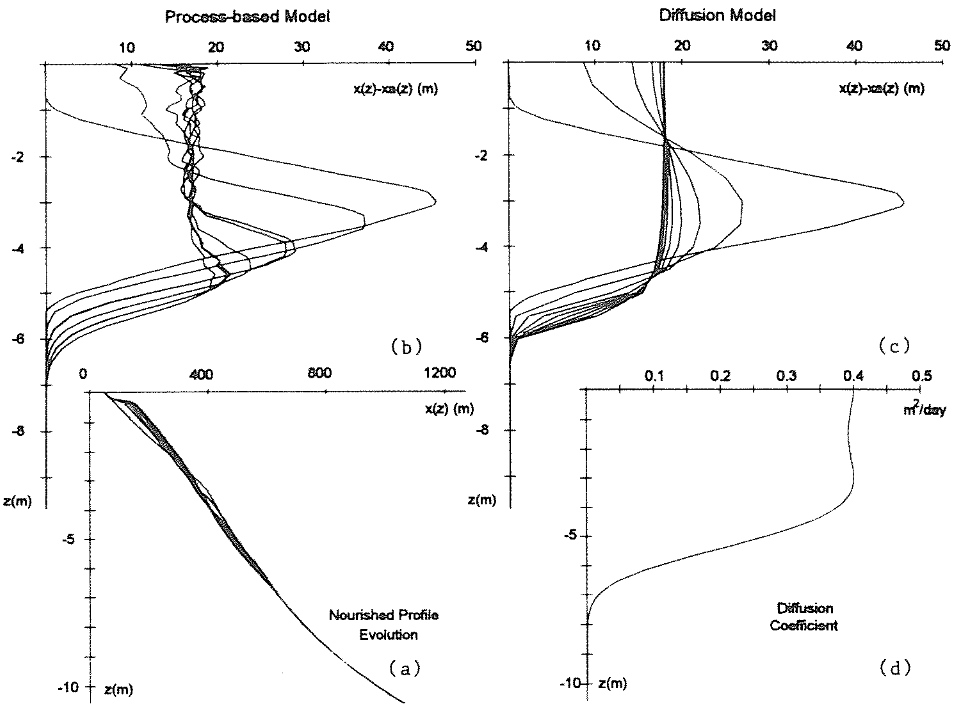


Figure 5.4.1 Cross-shore profile evolution based on diffusion-type model and 2DV-profile model (UNIBEST)

5.5 Multi-line models

Multi-line models have been developed by many researchers (see De Vriend et al, 1993). The basis of most multi-line models is the concept of equilibrium shoreface profiles. Often, the long-term averaged cross-shore profile is taken as the equilibrium profile. Basic assumptions of the equilibrium profile concept are: no net sediment movement seaward of the "closure depth" location and no effect of breaker bars on the long-term profile shape. A critical review of the equilibrium profile concept is given by Pilkey et al (1993).

Recently, Stive and De Vriend (1994) used a multi-line model for a uniform coastline schematizing the cross-shore profile into three line segments for the active zone between the dune front and the 5 m depth contour, the middle shoreface zone between the 5 m and 12 m depth contours and the lower shoreface zone between the 12 m and 18 m depth contours and tilting around the foot point at 18 m depth. The cross-shore profile is assumed to act as a system of hinged line segments. The dune face and the upper shoreface maintain their shape relative to the mean sea level, while obeying the mass balance equation. The detailed dynamics of the active zone (bar migration) is disregarded. The lower shoreface is assumed to be subject to changes induced solely by cross-shore transport at the upper end of the lower shoreface zone. A cross-shore transport formulation is used to determine the net wave-related and current-related transport rates including the effect of bottom slope.
The model concept was tested with reasonable success against the observed behaviour of the central Dutch coast considering a hindcast over the last century and another over the subboreal evolution of the profile, see Figure 5.5.1.

An important conclusion from this application is that the bottom slope effect on the transport process is only relevant at geological time scales and that the profile evolution at the engineering time scale (100 years) can be determined from a static sediment balance. Hence, the dynamic coupling between the profile characteristics, the hydrodynamics and the sediment transport can be neglected on a time scale of 100 years.

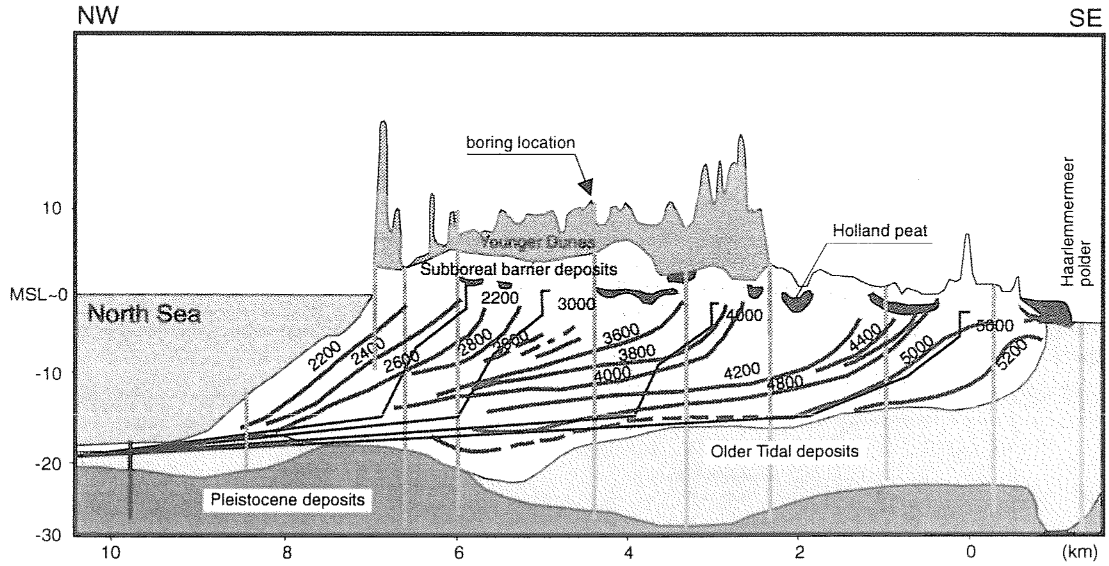


Figure 5.5.1 Long-term cross-shore profile evolution of the central Dutch coast

Following the approach of Stive and De Vriend (1994) a multi-line sediment budget model was used by Van Rijn (1994) to hindcast the sand volume changes along the Dutch coast during the period 1964-1992 and to forecast the coastline changes and sediment budgets (including nourishment) for the period 1995 to 2050. The model concept is shown in Figure 5.5.2. The effect of sea level rise is represented by a modified Bruun-rule. The net yearly-averaged cross-shore and longshore transport rates at the -20 m and -8 m depth contours and the net longshore transport rate in the surf zone were determined from a detailed 2DV cross-shore profile model (updated UNIBEST-model).

The hindcast study was aimed at matching the observed sand volume changes in the zone between 3 m and -8 m depth contours with the longshore and cross-shore gradients of the computed sand transport rates including nourishment and dredging, using a simple sand budget model (see Figure 5.5.2). Based on this, the net longshore transport rate in the surf zone upto -8 m N.A.P. contour was found to increase from zero near Hoek van Holland to about 500.000 m^3/year near IJmuiden. North of IJmuiden the net longshore transport rate is directed southward in section 35-55 km and northward again in section 0-35 km. The net southward longshore transport process is related to the presence of the harbour dams of IJmuiden reducing the wave energy coming from south-west directions.

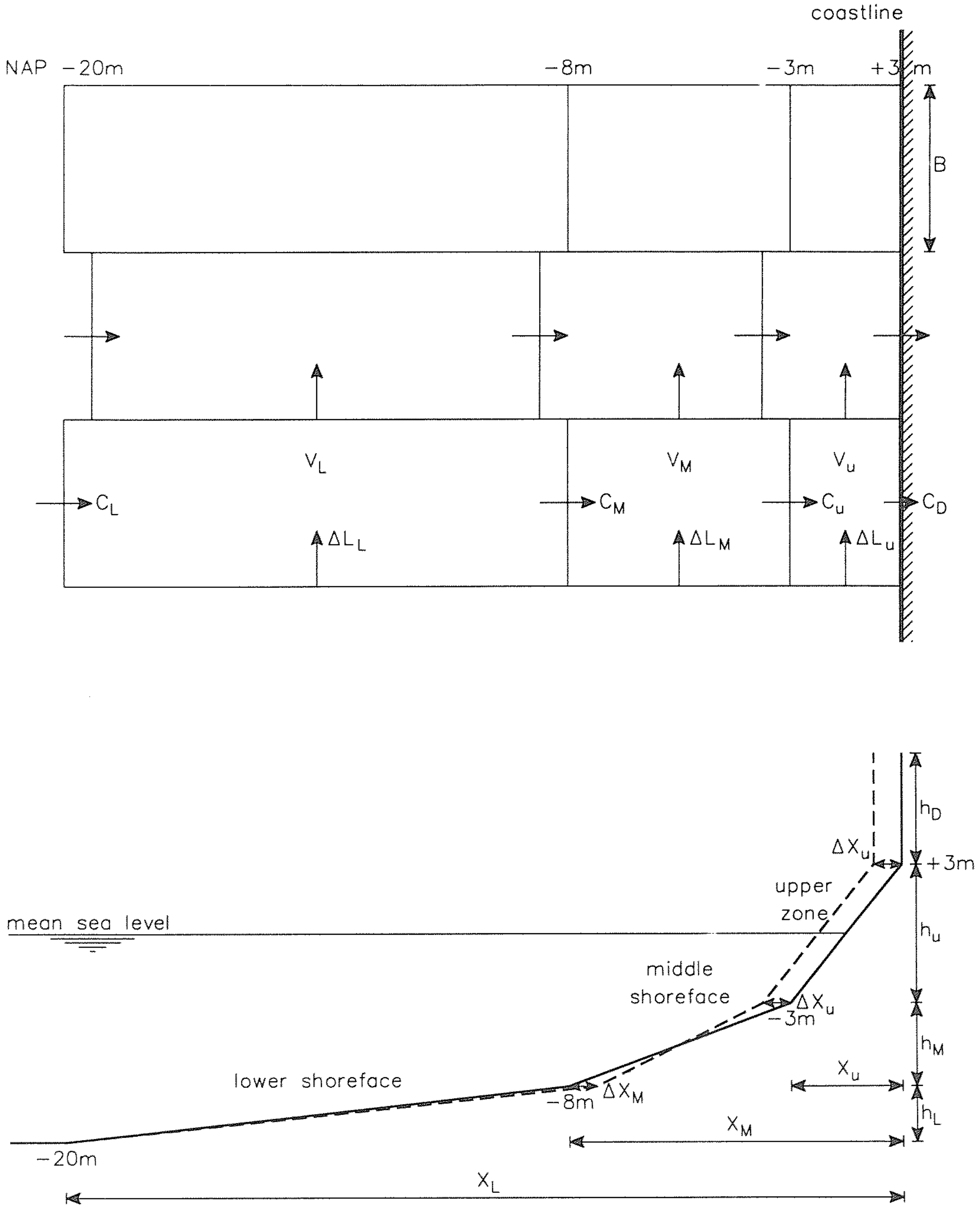


Figure 5.5.2 Multi-line sediment budget model
(X = cross-shore distance, h = height, V = volume, B = width, C = cross-shore transport rate, ΔL = gradient of longshore transport rate)

5.6 Further research

Further research should be focussed on:

- Implementation of process-related submodels representing cross-shore and longshore transport processes in multi-line models.
- Representation of the effect of beach nourishment and structures in multi-line models (dynamic coupling between hydrodynamics, sediment transport and morphology).
- Analysis of available international cross-shore profile data (uniform stable coast) including bar features in different conditions (sediment size, tidal range, type of wave-energy).
- Application of advection-diffusion models for modelling of long-term morphological behaviour.

6 Recommendations for further research

6.1 Summary

The process-related research of closed coastal systems has made considerable progress in the period 1990 to 1995, as appears from the publication of four theses (Roelvink, 1993; Al-Salem, 1993; Van de Meene, 1994 and Kroon, 1994) and many reviewed journal papers.

High-frequency wave propagation in uniform coastal zones using parametric and probabilistic wave-energy models was extensively studied resulting in a better understanding of the surf zone wave mechanics and of the limitations of the available formulations (wave breaking and wave asymmetry).

Low-frequency wave propagation with emphasis on bound-long waves related to short wave groups has had considerable attention resulting in a leading role in international research. A mathematical model for long waves has been developed and calibrated using laboratory and field data. The hypothesis that bar formation is to an important extent related to bound long waves is not supported by the present results; the long waves generally have a destructive effect on bar formations.

The mean current field and its vertical structure in cross-shore direction has been studied extensively by performing large-scale (LIP-experiments) and small-scale flume experiments and by mathematical modelling with 2DV-profile models. Streaming and undertow models have been developed and improved. Considerable progress has been made, but the models are not yet sufficiently accurate. Information of wave-induced currents is not sufficiently available, especially for barred profiles.
Wave-current interaction is considerably better understood than before. A set of useful parameterized models is available to estimate the near-bed velocities and bed-shear stresses in wave-current systems.

Sand transport research was aimed at deriving predictive and practical formulations for bed-load and suspended load transport in breaking and non-breaking wave conditions with or without a current superimposed. A new model for total load transport has been developed and used to estimate the yearly-averaged transport rates in the nearshore zone. A leading international role was played, as appears from the published theses and reviewed journal papers.
The effect of sediment size, irregular waves and breaking waves on the sand transport processes are still at an early stage of understanding, especially for barred cross-shore profiles. Field data of sand concentrations and transport rates are urgently needed.

Integrated modelling shows that the 2DV profile models are robust and effective tools with respect to diagnostic modelling, but the models are not yet capable of describing the generation, migration and degeneration of breaker bars. Information of three-dimensional circulation patterns along uniform coasts is missing. The wave mechanics in the swash zone should be better understood and implemented in the models.

Physical processes which still are at an early stage of understanding, are:

Wave and currents
- wave velocity aymmetry, especially in breaking waves of barred profiles;
- wave breaking and energy dissipation, especially in breaking waves over barred profiles;
- break-point forced long waves in the surf zone;
- wave-induced cross-shore and longshore currents over barred profiles (lag effects);
- wave-inducing streaming in non-breaking waves;
- vertical structure of velocities and turbulence in nearshore zone;
- apparent roughness of rippled and plane beds in wave-current systems.

Sediment transport
- bed-load and suspended load transport processes (magnitude and direction) in field conditions;
- effect of unsteady flow phenomena on bed-load transport processes of fine sediments in irregular waves;
- effect of wave velocity asymmetry on suspended load transport processes;
- sediment concentrations and wave-related transport rates over plane sloping beds in non-breaking and breaking waves;
- effective roughness of rippled beds.

Morphology
- generation, migration and degeneration of major breaker bars (including effect of underwater nourishment);
- behaviour of swash bars in relation to coastline changes;
- behaviour of offshore sand ridges (sediment source for nourishment?).

Behaviour-related research has had only limited attention compared with process-related research. Statistical models have been used succesfully to study cross-shore profile characteristics and coastline changes.
Bar behaviour has been studied by parameter analysis; predictive results have however not been obtained.
Multi-line models have been used to hindcast observed data (JARKUS) of sand volume changes (sand budgets) for the coastline between Den Helder and Hoek van Holland and to forecast nourishment volumes required to ensure a stable coastline for the coming 50-years (including sea-level rise). The effects of structures and nourishment should be better represented by the models.

6.2 Basic research objectives

The primary research task for the coming years is a better understanding of the large-scale sand budget of the surf zone between Den Helder and Hoek van Holland. This requires more accurate information of:

- the total net longshore transport at the boundaries of the surf zone (cross-shore profile near Den Helder),
- the total cross-shore transport at the boundaries of the budget area (across -8 m depth contour along the coast).

Both transport components are now estimated to be about 0.5 million m³/year. These values should be verified by performing field experiments in combination with diagnostic mathematical modelling.

The *longshore transport* rates should be measured in the following characteristic cross-shore profiles:

- between Callantsoog and Den Helder to evaluate the sediment loss to the Waddenzee,
- north of Scheveningen to evaluate the sediment loss from the eroding sections between Hoek van Holland and Scheveningen,
- near Egmond where the northward and southward longshore transport components are of the same order of magnitude (net zero transport).

The *cross-shore transport* rates should be measured in the central sections north and south of IJmuiden:

- near Egmond at -8 m and -20 m N.A.P. contour,
- near Noordwijk at -8 m and -20 m N.A.P. contour.

Some of the erosion problems along the Dutch coast may be solved by engineering measures, as follows:

- *Underwater nourishment in shoreface zone*
  The erosion in the outer surf zone and in the middle and lower shoreface zones and the associated profile steepening can be eliminated by underwater nourishment. In the coastal section between Hoek van Holland and Scheveningen this can be achieved by using the (unpolluted) sandy materials dredged from the main channels near the harbour of Rotterdam (total amount of about 2 to 4 million m³/year), which are now dumped at "Loswal Noord" outside the active coastal zone.

- *Construction of artificial breaker bars*
  Major breaker bars are missing in the eroding sections north of Callantsoog and south of Scheveningen, whereas the bottom slopes in these sections are relatively steep. As a result, wave breaking will occur in shallower depths closer to the shore increasing sediment suspension and longshore transport. Sediments are eroded from between the groynes in these coastal sections by undertow and rip currents which is intensified by strongly plunging breaking waves.

  A possible solution attacking the cause of the erosion problems rather than eliminating the symptoms may be the construction of artificial breaker bars in the outer surf zone to increase the wave energy dissipation further offshore. The breaker bars may be constructed of sandy materials (dredged in deeper waters) creating a nearshore sand buffer as well as a wave breaking structure. A sand buffer in the sections north of Callantsoog may also contribute to the sediment demand of the Waddenzee, because of erosion and deposition processes related to longshore tidal currents which may eventually result in reduction of the coastal erosion.
  Based on bar dimensions in adjacent sections, about 3 to 5 million m³ is required to cover a longshore distance of 10 km.

An alternative solution may be the construction of a long detached underwater breakwaters of stones and concrete blocks.

- *Long dam near Den Helder*
  It is beyond any doubt that future generations will take back the land that has been eroded by the sea. In this respect it might be interesting to study the morphological consequences of a long south-west oriented dam near Den Helder (Plan Schoorl) with the objective to reclaim land for reasons of safety, recreation and living. The presence of a dam will affect the position and size of the tidal channels and the outer ebb delta, whereas also the southwestern part of the island of Texel may be affected. Exploring studies should be initiated as a prelude to future developments showing our bright outlook on social issues for generations to come.

To be able to evaluate these ideas, basic knowledge of hydrodynamic and sand transport processes in relation to bar behaviour is of essential knowledge. Furthermore, (quasi)three-dimensional mathematical models should be available to study the morphological consequences of this type of human interference in a rather complicated system with accelerating and decelerating longshore tidal currents, circulation zones downstream of dams, inflow and outflow of tidal inlets in combination with shoaling, refracting and breaking waves. This will be further discussed in the following sections.

6.3 Process-related research

The most important hydrodynamic and associated morphological processes in the shoreface zone are:

- near-bed wave velocity asymmetry in shoaling and breaking waves,
- breaking-induced near-bed cross-shore return currents (undertow),
- breaking-induced longshore currents,
- tide, wind and density-induced mean currents,
- wave-induced streaming in boundary layer (Longuet-Higgens streaming),
- free and bound low-frequency waves,
- cross-shore and longshore bed-load and suspended load transport,
- generation, migration and degeneration of bars.

Morphological evolution of the bed is related to gradients of sediment transport rates and hence to gradients of the hydrodynamic variables.
A key point is the relative contribution of the cross-shore and longshore transport rates (both in magnitude and direction), which may strongly affect the morphological behaviour of the breaker bars. It may explain the difference in regularity and size of the bars along the coast. North of IJmuiden the position of the bars is rather irregular with a longshore coherence (same position and size of the bars) of about 2 km. South of IJmuiden the longshore coherence is of the order of 10 km; the bars seem to behave as being part of one large-scale two-dimensional bar system.
South of IJmuiden (near Bloemendaal) the net northward longshore transport rate is found to be relatively large (about 300.000 m^3/year) and reasonably constant, particularly from profile 70 km onwards. This may prevent the generation and growth of local disturbances in bar behaviour and hence the bars remain relatively small and can, therefore, migrate at

a faster rate. Small local differences in the cross-shore transport rates are smoothed out by the dominant longshore transport processes.
North of IJmuiden the net longshore transport rate is found to be relatively small (order of 100.000 m^3/year), but the gradients are relatively large. The net transport direction may even vary from southward to northward over short periods and small scales due to variations in the wave climate, having a large effect on the transport processes in this part of the coast, where the coastline orientation is relatively small. In these latter conditions the effect of the cross-shore transport processes on the bar variability may be relatively important resulting in larger but slower migrating bars. Irregularity will be enhanced by local differences in longshore and cross-shore transport rates.

Transport processes in lower and middle shoreface zone (-8/-20 m N.A.P.)

The net yearly-averaged cross-shore transport rates at the -20 m and -8 m N.A.P. contours consist of onshore and offshore-directed components, which are of the same order of magnitude.
In deeper water (depth of 20 m) the net transport rates are dominated by the tide-, wind- and density-induced mean currents in combination with the waves as stirring agent; the wave velocity asymmetry, the bound long waves and the near-bed return current hardly contribute to the net transport rate.
At a depth of 8 m all transport components are significant; the net transport rate was however found to be about zero (with variation ranges of $\pm$ 5 m^3/m^1/year).
The sand transport processes in deeper water take place in a rather thin layer close to bed (say lowest 1 m of the depth), where bed load and suspended load transport are equally important. Direct measurement of fluid velocities and sand concentrations will not yet be feasible at the highest level of accuracy, especially during rough weather conditions, because the required instruments will most probably not be available in the coming 5 years.
As an alternative solution, it is proposed to determine the transport rates from the morphological development of small trenches (length of 100 m, width of 10 m, depth of 2 m) dredged parallel and perpendicular to the shore at a depth of 20 m and 8 m and acting as sand traps. The bed profiles should be sounded regularly over a time period of 1 to 2 years. Simultaneous measurement of fluid pressures, fluid velocities and densities (and sand concentrations, if possible) at stations on both sides of the trenches should be carried out throughout the year. The hydrodynamic data will be used as input data for the models to compare computed transport rates and measured transport rates; the latter being derived from the backfilling of the trenches.

Sensitivity analysis using the models has shown that the transport processes of relatively fine sediments are rather sensitive to the composition and size of the sediments and the effective roughness of the small-scale bed forms (dunes, rippes, flat bed). Field evidence suggests that these parameters may vary considerably along the cross-shore profile. The effect of particle size and effective bed roughness should be studied in detail in the large-scale wave tunnel. Furthermore, the instruments required for measuring sand concentrations and fluid velocities in the high-concentration range should be studied in the wave tunnel with the aim to develop operational instruments for field conditions.

Transport processes in the surf zone (3/-8 m N.A.P.)

The net yearly-averaged longshore transport integrated over the surf zone width was determined by using a one-dimensional mathematical model (Van Rijn et al, 1994). In all computations the net integrated longshore transport rate was found to be directed northward. Generally, the northward transport rates are about 2 times as large as the southward transport rates. About 60% to 70% of the total width-integrated longshore transport does occur in the inner surf zone (width of 200 to 300 m, upto -4 m N.A.P.). The suspended load transport is the dominant mode of transport.

Based on analysis of the sensitivity computations, the net longshore transport rate was found to be most strongly affected by:

- longshore current velocity,
- presence of breaker bars,
- bottom slope,
- wave climate.

The wave-induced longshore current velocity was found to be an important parameter for the longshore transport process. The contributions of the wind-induced and tide-induced velocities were found to be of less importance, because most of the longshore transport is found to occur in the inner surf zone (width of about 200 to 300 m) near the shore, where the tide- and wind-induced currents are relatively small.

The accuracy of the wave-induced longshore velocities predicted by the applied models is largely unknown, because of a lack of measured data for verification of the model. The model has been calibrated in the sense that realistic (right order of magnitude) velocities are computed. The results of the sensitivity analysis show that the longshore transport rate is strongly dependent on the accuracy of the predicted velocities. A 50%-decrease of the current velocities results in a decrease of the net longshore transport rate by a factor of 3 to 4. The major part of this decrease does occur in the inner surf zone.

The effect of breaker bars present at various locations along the coast was studied by performing computations for two specific profiles as measured in 1985 and 1975. The presence of breaker bars results in an increase of the net longshore transport rate of about 50% to 60%. The cross-shore distribution of the longshore transport rate for the 1985-profile shows (three) peaks in the transport rate at the bar locations (outer bar, inner bar and swash bar). About 60% of the total integrated longshore transport rate is found to occur in the inner surf zone (width of about 300 m) with depths between 0 and 4 m.

The bottom slope herein defined as the slope of the imaginary line through the -1 m N.A.P. and the -8 m N.A.P. depth contours has a significant effect on the net longshore transport process. Increasing the bottom slope from about 0.005 to 0.01, yields an increase of the transport rate by a factor 2. Steepening of the cross-shore profile results in more intensive wave breaking closer to the shoreline and hence larger wave-induced current velocities and transport rates.

The wave climate is of dominant importance for the longshore transport rate because of the generation of the longshore current and the stirring action of the waves.

The results of sensitivity computations show that small changes in the wave climate (percentage of occurrence for each wave direction) may have a large effect on the net longshore transport rate in those sections where the coastline orientation is small ($< 10°$) such as in the sections near Egmond (profile 40 km). This was simulated by assuming a change of $5°$ of the local coastline orientation near Egmond. Using the wave climate of 1989, the net longshore transport rate was reduced from about 400.000 m^3/year to about 20.000 m^3/year (factor 20). Under these conditions, it might be argued whether a yearly-averaged wave climate is sufficiently representative. A better approach may be the simulation of the actual measured wave records over a number of years and subsequent averaging of the transport rates over the same period.

Based on the above-given considerations, it is proposed to perform field experiments focussing on the longshore current velocities and longshore transport rates in the inner surf zone (upto -4 m N.A.P.). As the suspended load transport is dominant in the surf zone, this parameter can be determined with sufficient accuracy by measuring the suspended sand concentrations and the fluid velocities using the recently built Acoustic Sand Transport meter (ASTM), simultaneously at 5 elevations above the bed. This instrument should be deployed from a permanent measurement station in the inner surf zone to ensure accurate determination of the measurement elevations and in-situ calibration with pumped samples. Direct measurement of the longshore transport rates in the outer surf zone (large depths, higher waves) requires the use of a large and robust platform, which is most probably not available. To overcome this problem, it is proposed to measure longshore velocities from stand-alone tripods deployed in the outer surf zone. Using the data of these instruments, the longshore transport rates can be determined by the available mathematical models, verified by the data measured in the inner surf zone.
Other hydrodynamic processes to be studied in the inner surf zone are: near-bed wave velocity asymmetry under breaking waves, wave-induced near-bed return currents and low-frequency wave phenomena.
A crucial aspect of the surf zone dynamics is the role of the breaker bars on the wave energy dissipation, wave-induced longshore velocities and hence the longshore transport rates. As the bars are highly dynamic in the inner surf zone, the morphological development of the bars should be known on the time-scale of the most dynamic events (storms), which implies regular pre and post-storm soundings. Most of these requirements can be satisfied by using a mobile research platform such as the CRAB (Coastal Research Amphibious Buggy) in use at the Duck field research facility in the USA (Birkemeier and Mason, 1984). The CRAB is used for accurate surveys of the nearshore zone. The surveys are conducted from the beach out to water depths of 6 m in wave heights up to 2 m (moderate storms). Other uses are bed material sampling and deployment of underwater instrumentation.

The mechanics of breaking waves and associated transport processes should be further studied in wave flumes focussing on the relative contributions of the transport components related to wave asymmetry and breaking-induced return currents.

6.4 Mathematical modelling research

One of the most basic features of the hydrodynamic and sediment transport processes in the coastal zone is *three-dimensionality*, which is caused by the existence of different types of driving forces related to tide, wind, wave, density-difference and Coriolis-effects acting in the lower and middle shoreface as well as in the surf zone where the breaking waves are dominant.
Even at a uniform beach with oblique incoming waves a cross-shore undercurrent is generated in combination with a longshore drift current. Very close to the bed in the wave-boundary layer onshore-directed streaming may occur due to an unbalance of the local shear stresses. Longshore variability of breaker bars may result in the generation of localized seaward-going currents, known as rip currents which are fed by the longshore currents. These rip currents spreading out in the deeper surf zone in combination with adjacent landward-going surface currents (mass transport) can be interpreted as horizontal circulation cells moving gradually along the coast.
The morphological development of the shoreface, beach and dune face in this battlefield of waves and currents is generally known as coastal behaviour.

Simulation and prediction of coastal behaviour at a certain level of accuracy require the use of mathematical models representing the basic hydrodynamic and sediment transport processes. Essentially, the models are the reflection of our knowledge of the physical processes.

In recent years a range of useful mathematical model concepts has been developed, which can be classified into two broad categories:

- process-related models,
- behaviour-related models.

A primary research task for the coming years is the further development of both process-related and behaviour-related models along parallel lines in time.

As regards the process-related models, the highest priority should be given to the operationalization and validation of a (quasi)-3D mathematical model with the objective to describe the yearly-averaged transport patterns in complicated systems like tidal inlets and adjacent coastal zones (for example the Marsdiep-channel) including the effect of man-made structures like long (harbour) dams. The knowledge of cross-shore processes has reached a stage that it is possible and feasible to go to quasi or full 3D modelling of currents and sediment transport. Research related to morphological predictions over longer time scales using 3D-models may have a lower priority compared to operationalization and validation of the physical processes involved.

Research should be focussed on:

- formulation of equations,
- implementation of submodels,
- evaluation of numerical schemes,
- pre- and post-processing techniques.

The 2DV-coastal profile models should be further developed with the emphasis on the generation, migration and degeneration of major breaker bars in the surf zone, which requires a better description of:

- wave asymmetry in breaking waves,
- mean current field in breaking waves,
- streaming in the wave boundary layer,
- bed-shear stresses in combined currents and waves,
- particle size variations (multi fraction approach).

Sensitivity studies should be performed, focussing on:

- input and boundary conditions,
- model parameters (physics).

Schematization of the time-varying input conditions needs further attention by studying:

- representative tide and wave conditions,
- chronology of events,
- worst case events.

The relative importance of the various physical processes should be studied by diagnostic modelling in relation to laboratory and field data.

As regards the behaviour-related models, the emphasis should be put on the sediment budget and coastline models with the objective to obtain large-scale and long-term predictions.
The relative importance of the different types of driving forces and their time scales should be studied to identify the dominant processes of the larger scales. Based on this, it can be decided whether simple parametric input-output models or stripped process-related models are most valuable for long-term modelling.

An attempt should be made to evaluate the possible merites of two-dimensional advection-diffusion schemes formulated in terms of the bed level (and associated coefficients) as the basic variable for the description of long-term morphological behaviour.

6.5 Summary

In summary, coastal research should be performed along the following lines:

Physical processes

Objective	:	Longshore and cross-shore transport over the -20 m and -8 m N.A.P. contours. Longshore transport in the surf zone (3 m/-8 m N.A.P. contours).

Transport at -8 m and -20 m N.A.P. contours

Field experiments	:	Dredging of small trenches parallel and normal to shore. Measurements of fluid velocities and fluid pressures on both sides of the trenches. Locations: near Egmond and Noordwijk.
Laboratory experiments	:	Effect of particle size and irregular waves on net bed-load transport. Effect of small-scale bed forms on hydraulic roughness.

Longshore transport in surf zone

Field experiments	:	Measurement of fluid velocities and sand concentrations using ASTM from permanent station in inner surf zone (upto -4 m N.A.P.). Measurement of fluid velocities and pressures from stand-alone frames in the outer surf zone. Monitoring of bar behaviour using CRAB. Locations: Callantsoog, Egmond, Noordwijk.
Laboratory experiments	:	Mechanics of breaking waves and associated processes in relation to bar behaviour.

Mathematical modelling

Objectives	:	Yearly-averaged transport pattern near tidal inlets including the effect of long (harbour) dams to feed the sediment budget models. Effects of underwater nourishment in outer surf zone and middle shoreface zone. Behaviour of major (artificial) breaker bars.

Process-related models

3D coastal area models	:	Formulation of equations. Implementation of submodels. Evaluation of numerical schemes. Pre- and post-processing techniques. Sensitivity analysis.
2DV coastal profile models	:	Validation of physical processes — wave asymmetry, — mean currents and streaming, — roughness and bed-shear stresses, — particle size variation (multi-fractions), — generation, migration of bars.

	Diagnostic modelling and sensitivity analysis — relative importance of processes, — comparison with measured data, — geometrical schematization, — input and boundary conditions. Input schematization — representative conditions (tide, waves), — chronology of events, — worst case events (catastrophic events).

Behaviour-related models

Coastline models, :	Multi-line approach and line-segment approach
Sediment budget models,	Process and scale analysis
Bed-level advection-diffusion models	Integration of stripped-process models (1D network models) and empirical phemenological models (transient evolution to equilibrium) and/or multi-line models
	Analysis of international cross-shore profile data under different conditions (parametrization model).

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