Department for Environment Food and Rural Affairs

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Dealing with sandy coasts – new methods from SANTOSS research project

Project: SC060027

Flood and Coastal Erosion Risk Management Research and Development Programme

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Miranda Kavanagh

Director of Evidence

Executive summary

Many activities within coastal management, science and engineering need to consider the impact of the movement of sediments in the coastal zone, due to natural processes or as a result of engineering or other works. This report presents the results of a research project to improve our understanding of aspects of sediment (primarily sand) transport in the coastal zone. The results are interpreted and adapted to meet practical needs, and reported in a way that is intended to be comprehensible by typical end-users. The report is aimed at coastal managers, engineers and scientists working in the Environment Agency, Department for Environment, Food and Rural Affairs (Defra), local authorities, harbour authorities, energy providers and engineering consulting firms. Within the Environment Agency it may also be of interest to scientists, policy-makers, asset management staff, and those with an interest in the take-up of research.

Activities that might be assisted by this report include planning, assessment and design of coastal defence management; wind farms and other nearshore technology; harbour and marina developments; and dredging and reclamation, including beach nourishment and use of control structures.

The research project SANTOSS, run by a consortium of UK and Dutch universities with funding from UK and Dutch research councils, aimed to improve our understanding and predictive capability of sand movement in the coastal zone. The Environment Agency commissioned HR Wallingford to represent its interests (and those of Defra) on the User Group of the project, to interpret the research results in practical terms, and to produce this report to disseminate the research results for practical purposes.

The project was primarily concerned with the "sheet-flow" regime of sand transport. This occurs at the sea bed under the action of very large storm waves, which produce a slurry of water-sand mixture at the sea bed which is swept back and forth by the wave velocities, and carried by tidal, wave- or wind-driven currents that carry the slurry of sand with them, or by asymmetries in the wave motion that result in a net drift of sand. These sheet-flow conditions are not well understood, and yet they carry vastly more sand than occurs over a rippled sea bed. Although such extreme storm conditions are rare, they can have a disproportionate impact on the long-term sand transport, and hence on the shape of beaches and the adjacent sea bed. The sediment transport formula developed here applies equally to moderate conditions (rippled beds) and extreme conditions (sheet flow).

The research was conducted with laboratory experiments, together with numerical modelling. The main outputs are summarised below.

Outputs of the SANTOSS research project

- A database of sediment transport under waves and currents in large-scale laboratory facilities, comprising measurements reported in the scientific literature and new data collected in the project.
- Better understanding of the processes involved, derived from the experiments and from development of detailed numerical models.
- A new formula for predicting sediment transport rates, based on new knowledge from the measurements and models.
- Papers and reports describing these findings.

The report describes the aspects of research which have a direct bearing on practical management, science and engineering issues, and explains how they can be used.

In summary, these are:

- When carrying out desk studies of coastal issues, a new formula (the SANTOSS formula) is available as MATLAB code to calculate the transport rate of sand. It includes processes not considered in most previous formulae, and hence is expected to give more accurate and realistic estimates especially in the shallow nearshore region where waves become steep and forward-leaning as they approach breaking.
- A large database of laboratory observations of suspended sediment transport rates under large simulated wave conditions is available. If the sediment and wave conditions at a study site match those in the database, the latter can be consulted to give direct estimates of sediment behaviour for coastal studies requiring such information.
- If physical modelling is run in connection with a coastal study, be aware that oscillating water tunnels may underestimate net sediment transport rates by up to a factor of two compared with equivalent measurements in large (near full-scale) wave flumes and, for certain cases with fine sand, even the direction of transport can be reversed. The tunnels do, however, give more accurate simulations of the near-bed behaviour than could be produced in *small* wave flumes.
- If a large field measurement campaign is done as part of a coastal study, it would be useful to take detailed measurements of wave orbital velocities, to obtain measures of the asymmetries in velocity and acceleration required as inputs to the SANTOSS sediment transport formula.
- When advocating numerical modelling, make use of the SANTOSS sediment transport formula at the heart of coastal profile models or coastal area models for studies in which its *strengths* are appropriate and its *limitations* are not important. Integrating the formula into such models is best tackled by modellers familiar with the individual models. The strengths and limitations are specified in the report.

The new SANTOSS formula has advantages over older methods in that it covers a wide range of wave, current and sediment conditions, is based on a large dataset, can handle extreme (sheet-flow) as well as moderate (rippled-bed) conditions, and incorporates a wide range of physical processes.

The report serves a second function in that it describes, in terms aimed at coastal managers, physical processes involved in the near-shore zone, types and capabilities of coastal numerical models, and descriptions and capabilities of sediment transport prediction methods.

Acknowledgements

The SANTOSS research project was funded by the UK Engineering and Physical Sciences Research Council and Dutch Technology Foundation STW for participating universities in the UK and the Netherlands respectively.

The research was carried out by the Universities of Aberdeen (Professor T O'Donoghue, Dr L Campbell, D van der A), Bangor (Professor A G Davies, Dr J Malarkey), Liverpool/Plymouth (Dr Shunqi Pan, Dr Ming Li), and Twente (Associate Professor J Ribberink, Dr J van der Werf, J Schretlen), with input from Dr R Uittenbogard of Deltares.

The Environment Agency funded HR Wallingford Ltd (Professor R L Soulsby) to represent its interests (and those of Defra) on the User Committee of the SANTOSS project, and to produce this report to disseminate the research results for practical purposes.

I would like to thank Dr N Beech for his valuable contribution to Section 1, and Dr N Beech and Mr S Jenkinson for their helpful comments on the content and style of the report. I would also like to thank Dr S Surendran and Eleanor Heron for their advice as project managers for the Environment Agency.

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1 Are you involved with coastal management?

1.1 Introduction

Many activities within coastal management, science and engineering need to consider the impact of the movement of sediments in the coastal zone, due to natural processes or as a result of engineering or other works. This report presents the results of a research project to improve our understanding of aspects of sediment (primarily sand) transport in the coastal zone. The results are interpreted and adapted to meet practical needs, and reported in a way that can be comprehended by typical end-users.

The recently completed research project SANTOSS, run by UK and Dutch universities with funding from UK and Dutch research councils, aimed to improve our understanding and predictive capability of sand movement in the coastal zone. The main outputs of the project were: a database of sediment transport under waves and currents in large-scale laboratory facilities, comprising pre-SANTOSS measurements from the literature and new data collected in the project; better understanding of the processes involved, derived from the experiments and from development of detailed numerical models; a new formula for predicting sediment transport rates, based on the new knowledge from measurements and models, and papers and reports describing these findings. Those wishing for more detail than is given in this report should refer to the publications by the research team listed in Appendix B.

The Environment Agency commissioned HR Wallingford to represent its interests (and those of the Department for Environment, Food and Rural Affairs, Defra) on the User Group of the project. One aim was to interpret and adapt the results of the research and report it in a way that could be comprehended by typical end-users, which is the purpose of this report. The detailed objectives and outcomes of the SANTOSS project are presented in Section 2. Further sections set out the way in which the research outcomes can be applied to coastal management, science and engineering studies.

The report is aimed at coastal managers, engineers and scientists working in the Environment Agency, Defra, local authorities, harbour authorities, energy providers and engineering consulting firms. Within the Environment Agency it may also be of interest to scientists, policy-makers, asset management staff, and those with an interest in the take-up of research. The report is aimed at two kinds of reader: those who would like to understand the processes of coastal sediment transport better, and wish to judge in general terms whether the SANTOSS research (in particular the new formula) is relevant to their responsibilities; and those who might need to choose and then make use of a sediment transport formula (for example, in their own numerical modelling). Some of the detail supplied for the latter kind of reader can be skipped by the former, and this is indicated in the relevant sections.

1.2 Types of activity dealt with by this report

Tables 1.1 to 1.4 indicate the importance of sandy bed behaviour to various industry activities, considered under four generic headings:

- coastal defence management;

- wind farms and other nearshore technology;
- harbour and marina developments;
- dredging and reclamation, including beach nourishment/use of control structures.

Each table suggests some issue/factors that further define that particular activity and lists the stages that make up the activity from planning/study through to post-construction monitoring. For each stage the table then indicates the relevance of sandy bed behaviour, and hence the potential importance of the new research using a high, medium or low score.

Although sandy bed behaviour (and SANTOSS) might be important to a given stage of work, it does not follow that detailed analysis involving the use of the models/algorithms (classical and novel) would be undertaken at that stage, the analysis possibly being deferred to later stages of the project or derived from earlier work. The tables indicate the relevance of sandy bed behaviour to each stage of work and not necessarily the likelihood of the technology being applied at that stage.

Table 1.1 Coastal defence management *for beach nourishment/beach control structures see Table 1.4	**Issues/factors:** • coast protection • flood defence • nearshore sandbanks • linear defence • maintenance • beach management, reprofiling, recycling, etc*
Stages:	**Relevance**
Shoreline Management Plan	high
Coastal defence strategy	high
Project Appraisal Report (PAR)	high
Environmental assessment	high
Outline design	high
Detailed design	medium
Construction	low
Post-construction monitoring	medium

Table 1.2 Wind farms and other nearshore technology	**Issues/factors:** • movement of sandbanks • impacts on shoreline
Stages:	**Relevance**
Planning	high
Feasibility study	high
Environmental assessment	high
Outline design	high
Detailed design	medium
Construction	low
Post-construction monitoring	medium

Table 1.3 Harbour and marina developments	**Issues/factors:** • siltation • impacts on coastal processes
Stages:	**Relevance**
Planning	high
Feasibility study	high
Environmental assessment	high
Outline design	high
Detailed design	medium
Construction	medium
Post-construction monitoring	medium

Table 1.4 Dredging and reclamation, including beach nourishment/use of control structures (See also Table 1.1)	**Issues/factors:** • sediment plumes • beach profile response
Stages:	**Relevance**
Planning	high
Feasibility study/PAR	high
Environmental assessment	high
Outline design	high
Detailed design	medium
Construction	medium
Post-construction monitoring	medium

If your work encompasses any of these issues, the report might help you to find better approaches to them.

The structure of the report moves from the general to the particular: first describing the users and activities, then the issues, approaches used, models, sediment transport, and finally the new methods developed by the SANTOSS projects. It is hoped that this structure will allow the reader to decide quickly whether the report is relevant to his/her responsibilities and, if so, to appreciate more easily how the new research results might assist in practical coastal management.

A glossary of terms used and a list of symbols can be found after the reference list at the end of this report.

2 The SANTOSS project

2.1 Research objectives

The SANTOSS research project, funded jointly by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Dutch Research Council STW, was run by a consortium of UK and Dutch researchers from the Universities of Aberdeen, Liverpool (subsequently Plymouth), Bangor and Twente plus Deltares.

The project was concerned with the "sheet-flow" regime of sand transport. This occurs at the sea bed under the action of very large storm waves, which exert such high oscillatory water velocities at the sea bed that sea-bed ripples cannot exist and are washed flat. Instead, a slurry of water-sand mixture a few millimetres or centimetres deep (the sheet-flow) is swept back and forth by the wave velocities. Usually there are currents (tidal or wave- or wind-driven) that carry the slurry of sand with them, or there are asymmetries in the wave motion that result in a net drift of sand. These sheet-flow conditions are not well understood, and yet they carry vastly more sand than occurs over a rippled sea bed.

Although such extreme storm conditions are rare, they have a disproportionate impact on the long-term (say, annually averaged) sand transport. In turn, these create major changes in the shape of beaches and the adjacent sea bed. The dominant contribution of sheet-flow conditions to annual sediment transport has been demonstrated by De Leeuw (2005) for water depths between eight and 20 metres on the Dutch shoreface. These depths do not, however, delimit the applicability of the SANTOSS research, which covers a much wider range of depths (see Section 7.3 for limits of applicability).

The aims of the project were:

- to establish a new model for sand transport in wave and wave-plus-current sheet-flow conditions;
- to implement the new model within a general sand transport model for use by coastal engineering practitioners.

At an early stage, and partly in response to a request from the User Group, the remit of the project was extended to encompass cases with rippled beds, presence of currents, and (partially) the surf zone, as described in Sections 5.2 and 7.1.

2.2 Work undertaken and achievements

The research project met its objectives, and the following work was achieved:

- Large-scale laboratory experiments were performed to measure sediment transport rates under sheet-flow conditions, concentrating on a recently recognised physical process (known as acceleration skewness, see glossary), characteristic of forward-sloping waves approaching breaking.
- Experiments over fixed beds in the oscillating water tunnel provided new understanding of the hydrodynamic processes, which were made use of in the formulation of the new SANTOSS sediment transport formula (below).
- Twin large-scale laboratory experiments were performed in a very large wave flume in Germany and in a Dutch oscillating water tunnel to

investigate the differences between sediment transport in the two kinds of facility. These experiments showed that sediment transport rates measured in the tunnel were smaller than those measured in the (more fully realistic) wave flume by about a factor of two and, for certain cases with fine sand, even the direction of transport was reversed.

- Existing numerical 1DV models of hydrodynamics and sediment transport at a point at Bangor, Liverpool and Twente Universities and Delft Hydraulics were enhanced, tested and compared, and applied to investigate various physical processes.
- Methods of characterising a wave with acceleration skewness and velocity skewness in terms of commonly available wave parameters were specified (Malarkey 2008).
- Existing formulae for waves with acceleration skewness were reviewed and tested against new SANTOSS data and earlier data in the SANTOSS database, and their performance ranked (Van der A 2009).
- A new method (the SANTOSS formula) was developed to predict sediment transport rates under a wide range of conditions, based on the detailed SANTOSS results.

2.3 Outputs

The main outputs from the project are summarised below.

Outputs of the SANTOSS research project

- A database of sediment transport under waves and currents in large-scale laboratory facilities, comprising pre-existing measurements reported in the scientific literature and new data collected here.
- Better understanding of the processes involved, derived from the experiments and from development of detailed numerical models.
- A new formula for predicting sediment transport rates, based on new knowledge from the measurements and models.
- Papers and reports describing these findings.

The new formula is the most readily applicable output for practical purposes, and figures the most prominently in this report, although other outputs are touched on.

For many applications, the new transport formula must be embedded into a numerical model of a coastal site. This is best achieved by engineers and scientists who routinely develop and operate such models at specialist firms, or at civil engineering consultancy firms who have coastal modelling expertise.

In addition, the project furthered our understanding of wave and sediment processes, and provided new detailed measurements and enhanced research-level models. However, only results with direct practical application are presented in this report. The improved understanding of physical processes gained from numerical models (which is considerable) is not described here, as it is more relevant to academic research than direct practical use. Those wishing for a more detailed account of the research results can obtain them from the project publications, or from the project website, or by contacting a member of the research team.

A list of publications produced by the project is given in Appendix B. Copies of papers and reports can be obtained from Professor O'Donoghue (contact details given below).

Further details about the SANTOSS project, and access to the database, can be found on the project website:

http://www.santoss.utwente.nl/

or, if the website is no longer available, by contacting the project's Principal Investigator for the UK:

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2.4 Physical processes dealt with by SANTOSS

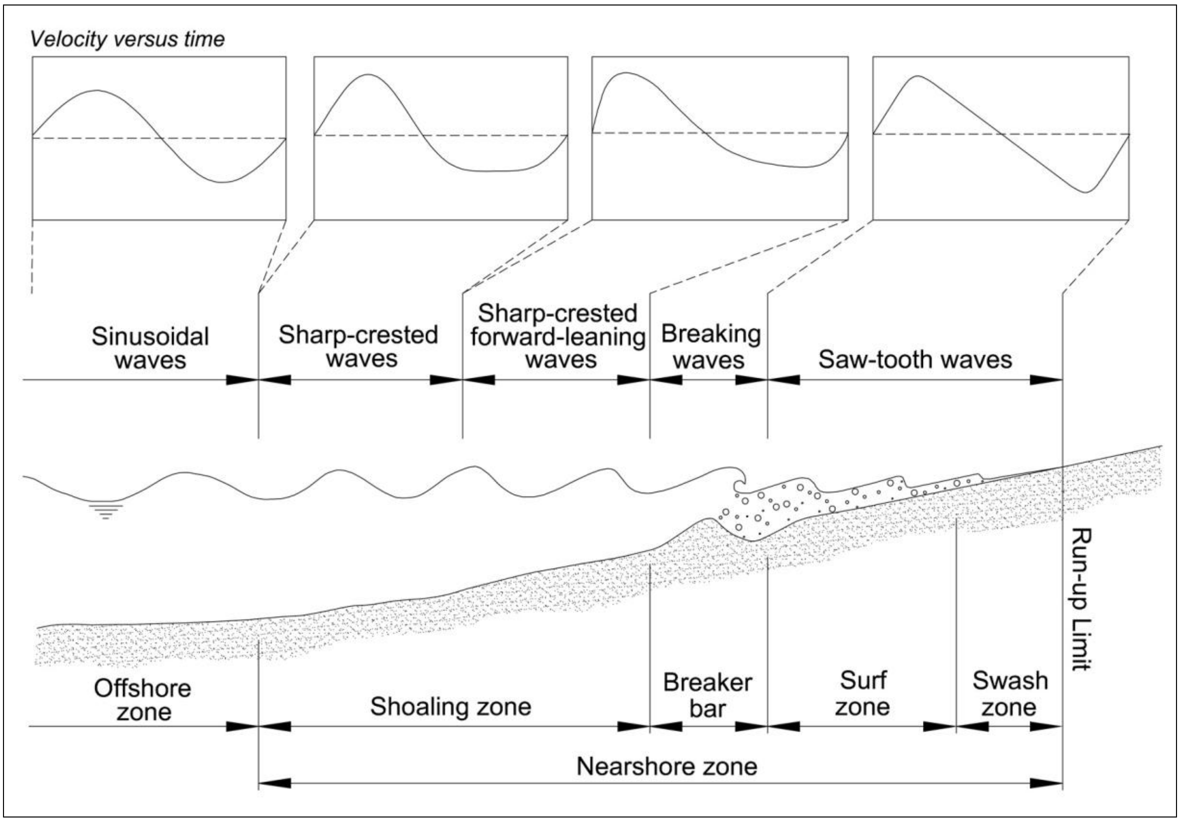

Figure 2.1: Schematic of wave transformation in a vertical slice taken at right-angles to the coastline. The shape of waves at the surface changes as they move into shallower water, and orbital velocity at the sea bed changes correspondingly. Upper panels show velocity variations with time through one wave cycle, with onshore velocities shown positive.

The SANTOSS research is mainly concerned with the movement of sediment (primarily sand) by waves approaching the coast, together with associated wave-driven and tidal currents. The transformation of waves as they approach the coast is shown schematically in Figure 2.1, which is a sketch of a vertical slice through the water column taken at right angles to the shoreline. The zones shown do not have rigorous definitions, and the boundaries are blurred (see, for example, Horikawa 1988; Mangor 2001), so this figure should not be treated as definitive. The upper part of Figure 2.1 portrays the variation in wave-induced (orbital) velocity at the sea bed through one wave cycle for different characteristic wave shapes. These shapes are characterised by two statistical measures of skewness, firstly applied to the time-series through the wave-cycle of the orbital velocity, and secondly to the time-series of the acceleration (not shown in Figure 2.1).

In deep water offshore (say deeper than 10 to 20 metres), the wave shape at the water surface is approximately sinusoidal, so that it is symmetrical vertically and horizontally. The orbital velocity is also sinusoidal and symmetrical.

As the wave travels into shallower water, the crest becomes sharper and the trough becomes flatter. Onshore velocity induced at the bed under the crest is greater than offshore velocity under the trough, but lasts for a shorter time. In SANTOSS terminology, these waves have "non-zero velocity skewness". The net effect is to drive sediment towards the shore.

As the wave travels into even shallower water, the crest starts to travel faster than the trough, so that the wave leans forward. The wave is still sharp-crested (more so than before) and is now also forward-leaning. Orbital velocity rises more quickly between a trough and the succeeding crest than it drops between crest and succeeding trough. In SANTOSS terms, a forward-leaning wave has "non-zero acceleration skewness". A combination of effects due to this skewness enhances the net shoreward movement of sediment (Van der A 2010, Van der A *et al.* 2008, 2009, 2010).

Eventually, the wave front leans forward so far that the wave breaks by spilling, plunging or surging, depending on the steepness of the beach. The broken wave then travels through the surf zone onto the beach as a series of bores having a roughly saw-tooth shape, which again are forward-leaning. The energy released in the breaking process makes the water turbulent and it may also contain entrained air. Turbulence from breaking enhances the movement of sediment here. The bores decrease in height up the beach as their energy is dissipated through the turbulence. Finally, the waves surge up the beach in the swash zone, which is the zone where the beach is alternately wet and dry as waves run up and fall back.

SANTOSS concentrated on the zone where waves approach the break-point, just outside the surf zone, in which the wave crest starts to lean forward as a result of the retarding effect of shallowing water depths; the project excluded breaking waves inside the surf zone and wave run-up area of the swash zone. The SANTOSS formula differs from many earlier coastal sediment transport formulae, in that it takes account of acceleration skewness in forward-leaning waves, as well as sharp-crested effects.

The formula is designed to deal with rippled beds and sheet flow, and with currents, such as the long-shore currents generated when waves approach the coast obliquely, and tidal currents. Further to seaward, the waves do not feel the effect of the sea bed so strongly, the sea bed is likely to be covered in ripples instead of being flat with sheet-flow sediment transport as it is in the surf and swash zones, and the asymmetry of the waves is small. The SANTOSS formula is still applicable here, and takes account of phase-lag effects due to the ripples.

In the surf and swash zones, where there is intense turbulence, the SANTOSS formula is not directly applicable because most of the research was done in oscillating water tunnels which do not generate the turbulence due to wave breaking. However, it can be applied here by including an existing suspension model which takes account of the extra turbulence.

The applicability of SANTOSS research is discussed further in Section 7, and illustrated in Figure 7.1.

3 Approaches to coastal issues in sandy areas

3.1 Study methods

Issues in coastal areas are usually tackled using one or more of the following methods:

- desk study (assembling information, performing simple calculations);
- site visit, field measurements and local knowledge;
- experience of similar issues at similar sites;
- physical modelling;
- numerical modelling.

Many studies start with a combination of the first three methods, because they are relatively quick and cheap (provided that the field measurements are only basic at this stage). This allows the major issues and processes to be identified and prioritised. If necessary, physical and/or numerical modelling can be performed, possibly backed by an extensive field measurement campaign, to provide a more detailed assessment but at greater cost.

A summary of the strengths and weaknesses of these approaches is given by Van Os *et al.* (2004). Guidelines on the use of physical modelling for sediment-related studies (Soulsby and Sutherland 2010) were prepared as part of the EU research project HYDRALAB III.

3.2 Approaches to using SANTOSS outputs for coastal issues

The SANTOSS outputs are most readily applicable to numerical modelling, but they can also influence desk studies, field measurements and physical modelling in the following ways.

- Desk studies: use of the SANTOSS database of pre-SANTOSS and new sediment transport measurements (see Section 2.3 for availability). If the sediment and wave conditions at a study site match those in the database, the latter can be consulted to give direct estimates of sediment behaviour for coastal studies requiring such information.
- Field measurements: when specifying the measurements needed at the study site, if possible, measure the velocity and acceleration asymmetries in wave orbital velocities (see Section 2.4) or derive them from real-time surface elevations at a number of key locations around the site, since these are used in the SANTOSS formula. Although methods of deducing them from standard wave parameters are provided as part of the formulation, direct on-site measurements are preferable.
- Physical modelling: be aware that measurements of sediment response to wave orbital motions in oscillating water tunnels do not represent all the

physical processes found in real waves, and can significantly underestimate the sediment transport rate compared with measurements in large wave flumes. However, the tunnels do overcome some of the scaling issues associated with *small* wave flumes.

- Numerical modelling: use of the new SANTOSS sediment transport formula at the heart of coastal numerical models (see Section 4) of sediment transport and morphological evolution of the sea bed, especially where velocity and acceleration asymmetries are important (see Section 7.2).

- Detailed investigations for a limited number of cases: use one of the detailed point models (see Section 5), such as the POINT-SAND “practical” model of University of Twente or the “research-level” models of Bangor University or Liverpool University, at selected locations at the study site. These models are not available for general use, and the relevant researchers would need to be commissioned to run them.

Sections 4, 5 and 6 elaborate on the use of the SANTOSS formula in numerical modelling applications. The terms morphology, morphodynamics and morphodynamic model used in these sections are defined in the glossary.

4 Coastal numerical models

4.1 Classes of numerical model

It is important to distinguish two broad classes of numerical model used on coasts: coastal models and point models.

Two classes of numerical model

Coastal models predict the horizontal distribution of water levels, currents, waves, sediment transport (and possibly changes in sea-bed morphology) over an extended study area. The SANTOSS formula could be applied at every point within the study area of a coastal model.

Point models predict the vertical distribution of current velocity, suspended sediment concentration and hence suspended sediment flux at a single point. Time-varying bedload transport rates are also predicted. The total sediment transport rate is obtained from the wave-averaged sum of the bedload transport rate and the depth-integrated suspended sediment flux. The results may be presented as an algebraic sediment transport formula. The SANTOSS formula is an example of the latter type.

The physical processes of tides, waves, wind, sediment transport and consequent changes to the coastline, beaches and sea bed (morphodynamics) are dealt with by coastal models based on grids in one or two horizontal dimensions (and possibly also the vertical dimension) which can be tailored to specific sites. These are bespoke models, and the code is usually not available publicly. For some applications it is sufficient simply to compute the distribution patterns of sediment transport, while in others the further step of interpreting these in terms of morphodynamic change of the coastline, beach and/or seabed is needed.

At each grid point of a coastal model it is necessary, when addressing issues involving sediments or morphodynamics, to have a means of predicting the magnitude and direction of movement of sediment in response to the current and waves at that grid point. This introduces the second class of model, which has a grid of points in the *vertical*, and assumes that everything (water depth, current, wave and sediment characteristics) is constant in the two horizontal dimensions. This point model predicts the *vertical* variation from sea bed to water surface in current velocity and suspended sediment concentration via a set of equations relating sediment behaviour to current and wave conditions. Velocity and concentration are combined to give the suspended transport rate of sediment and movement of sediment at the bed (bedload transport).

A distinction is sometimes made between “research-level models”, which contain a wealth of detail on physical processes but are relatively slow to run, and “practical models” in which the physical processes are simplified for the model to run quickly.

In principle, a “research-level” point model could be embedded at every grid point of a coastal model. However, these are generally too slow computationally to be practicable in a coastal model where they must be run many millions of times. For example, a fast point model might take a few seconds to run for each input condition. If such a model were used in a coastal model with 100,000 grid points, for every minute over a 24-hour simulation, it would require a computer run lasting about 5,000 days, without even considering the time for computing the changing current and wave fields! Thus much faster methods are needed, and in most cases a simple algebraic formula (or set of formulae) is used as an approximation to the full simulation of a point model.

Research-level point models were used by the Universities of Bangor and Liverpool, and at Deltares, in the SANTOSS project to explore physical processes and gain understanding. A "practical" point model, the POINT-SAND model, was developed at University of Twente, which runs faster than research-level models. However, the project partners also recognised the need for a much faster alternative, which became the SANTOSS sediment transport formula.

4.2 Coastal models

In addition to the two broad classes of numerical model, coastal models can be subdivided into three classes.

Three subdivisions of coastal models

Coastal plan-shape models predict changes in the shape of the shoreline as viewed from above, in response to wave action. The SANTOSS model is not primarily intended for this kind of model.

Coastal profile models predict changes in the shape of the beach and seabed as seen in a vertical slice, in response to wave and current action. They extend through the surfzone and a little way offshore, and usually assume a shoreline, underwater contours and wave conditions which are nearly uniform in the alongshore direction. The SANTOSS model is designed for this type of model, although it has not been calibrated for use in the surfzone.

Coastal area models predict changes in the shape of the seabed in an extended offshore area in response to wave and current action. They do not model the surfzone or swashzone in detail. The SANTOSS model is usable in this type of model, although its special capabilities of dealing with the skewnesses associated with strongly shoaling waves are not essential in deeper water.

The usual sequence of computation in a morphodynamic coastal model is common to all three classes of model, although some steps are omitted or simplified in coastal plan-shape models. The sequence of operations is shown in flowchart in Figure 4.1.

First, the distribution over the study area of wave height and direction is computed using a wave model run repeatedly for a series of input waves that represent the full wave climate in terms of wave periods, heights and directions.

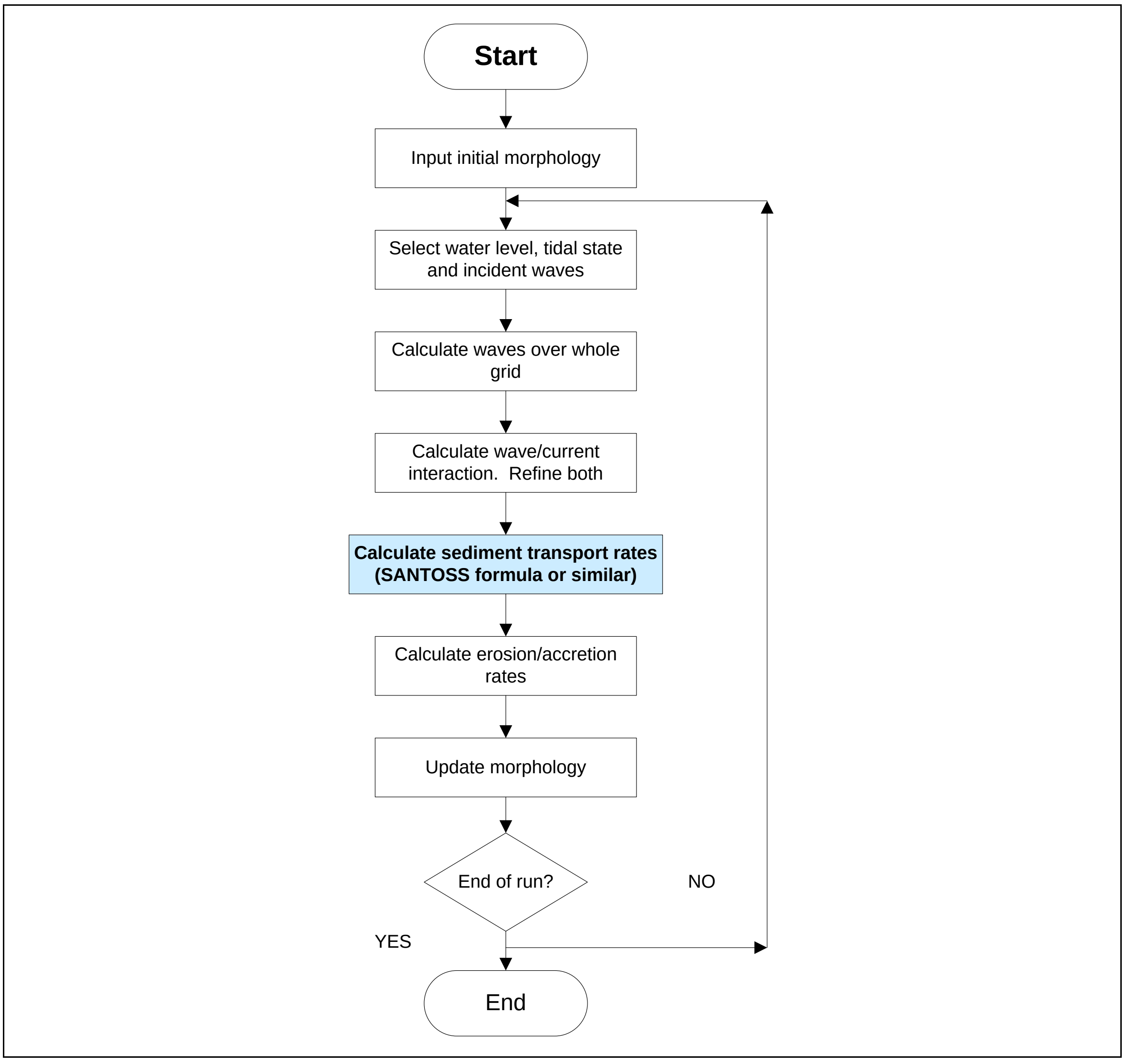

Figure 4.1: Flowchart of general procedure for a morphodynamic coastal model (Southgate and Brampton, 2001)

Secondly, the distribution of water levels and current velocities throughout the modelled area is computed using a flow model, time-stepping through a time-interval appropriate to the study. For example, in a tidal area a single representative tidal cycle might be modelled, which could be a mean tide or a spring tide. Usually the model has to be "wound up" for three tidal cycles, with the third taken as being the representative cycle. In a more detailed approach, half a lunar month of tides might be run to include a full spring-neap cycle. The effect of wind on the water surface might also be included in the flow model. In an interactive model, waves and currents are allowed to influence each other via a number of mechanisms. An iterative approach is usually used, alternating between the wave and flow models.

Thirdly, having computed flow and wave fields, the distribution of sediment transport can be computed. At its heart will be a sediment transport formula, of which there are a number to choose from (see Section 5), with the SANTOSS formula being the most recent. The sediment transport formula (SANTOSS or similar) is represented by the box "Calculate sediment transport rates".

The final stage at each time-step is to calculate the net erosion or accretion rates at each gridpoint, based on whether the sediment transport rate out of a grid cell is greater or smaller than the rate into the cell, followed by an update of the bed morphology. At the next time-step of the model, the current and wave distributions must be re-calculated, because the bed morphology has changed.

As an illustration of the types of coastal issues tackled by numerical models, a range of studies performed using a coastal profile or area model is presented in Appendix C.

More detailed descriptions of the three classes of coastal model are given by Southgate and Brampton (2001), together with guidance on how to choose them, set them up and decide what runs to perform, and how to interpret the outputs bearing in mind sources of uncertainty. A step-by-step guide is given. Descriptions of the three classes of coastal model, adapted from those given by Southgate and Brampton (2001), are summarised below.

4.2.1 Coastal plan-shape models

In these models, beach morphology is represented by a single contour representing the shoreline, and such models are therefore often referred to as “one-line” models. Changes in the position of this contour, together with other parameters such as wave conditions, currents and sediment transport rates, are functions of coastwise distance and time, and so these models are one-dimensional. The model predicts changes in the beach and nearshore seabed plan-shape. The beach profile along a line perpendicular to the shoreline is usually assumed to be unchanging with time.

This type of model generally uses a longshore sediment transport formula to compute changes in the shoreline. These give the long-shore transport integrated across the surf-zone. The SANTOSS formula is not primarily intended for this kind of model, partly because it is not designed for breaking waves, and partly because the integration would need to be done point by point.

Applications for which a coastal plan-shape model is appropriate include those where the (horizontal) shape of the beach itself is the most important feature, rather than the underwater (vertical) shape of the near-shore sea bed or behaviour of offshore features such as sandbanks or navigation channels. These include: response of the beach plan-shape to coast defence measures such as groynes, offshore (detached) breakwaters and artificial reefs; response to other engineering works that interrupt the longshore flow of sediment, such as harbour extensions, river training walls and submerged water intake tunnels; and response to extraction of sand or aggregate from offshore areas.

These models run quickly for each wave input, and hence can be run economically with hourly or three-hourly offshore wave sequences over many years (possibly synthesised), and for a wide range of design options or variants on the wave climate.

Some examples of proprietary coastal plan-shape models are BEACHPLAN, UNIBEST-CL+ and LITPACK-LITLINE.

4.2.2 Coastal profile models

Coastal profile models are also one-dimensional, but the axis runs seawards, perpendicular to the coastline. Figure 2.1 illustrates the layout of such a model. Cross-shore models predict the changing levels of the beach and nearshore seabed profile, but usually there is only limited representation of the effects of longshore transport or longshore morphology variations, often none at all. All such models predict beach profile changes, and the movement of sediment perpendicular to the contours.

This is the kind of model that the SANTOSS formula is primarily designed for. Coastal profile models concentrate on cross-shore sediment transport processes, which would be strongly influenced by the velocity and acceleration skewnesses included in the SANTOSS formula (but not in some other formulae). However, the SANTOSS formula is tailored to non-breaking waves, because these are simulated in the oscillatory water tunnels that were the primary source of data in its development. Extrapolating its use into the surf zone or the swash zone is less reliable. Nonetheless, the broken waves behave like bores propagating up the beach, which are well represented as saw-tooth (acceleration-skewed) waves, so that in this respect the SANTOSS model has some of the right properties.

Coastal profile models simulate the net shoreward movement of sand due to wave velocity (and perhaps acceleration) asymmetry, and the seaward movement of sand in the surf zone due to the undertow generated as a result of wave breaking. These result in a convergence of sand at the point of wave breaking, which generates a breaker bar (see Figure 2.1). These models are primarily designed to simulate the generation, migration and erosion of breaker bars, which on many coastlines world-wide provide coast protection by dissipating the wave energy. However, breaker bars are less common (or less pronounced) around the UK coast than in other parts of the world because of the large tidal range experienced over much of our coastline. This effectively means that as the tide rises and falls, the point of wave breaking moves up and down the beach too rapidly for a well-defined bar to form in any one place.

Applications for which a coastal profile model would be appropriate include those in which the shoreline is almost straight or gently curving, because these models assume that alongshore variations in the beach profile and offshore wave properties are small. They are slower computationally than coastal plan-shape models, but much faster than coastal area models. They are designed to give simulations over a period of hours to days (a typical storm or inter-storm period), and many of these models give spurious results if they are run over much longer timespans.

The models can be used for issues involving the "health" of beaches such as effects of beach or shoreface nourishments, the effect of wave reflection by a new seawall on the beach in front of the wall, effect on the beach profile of changes in wave climate (for example, as a result of lowering or migration of an offshore sandbank), stability of beach levels through which pipelines or cables are to be run, and for military applications such as amphibious landings. However, as noted, their results should be treated with caution if the model is used to simulate beach profile evolution over more than a few days. In some of these models the position of the waterline is fixed, so that they cannot simulate a net advance or retreat of the shoreline. Some models include swash-zone processes, but others omit them.

Some examples of proprietary coastal profile models are COSMOS, UNIBEST-TC and LITPACK-LITPROF.

4.2.3 Coastal area models

In some situations, for example the circulation of sediment in the shelter of an island, headland or breakwater, currents and sediment transport pathways are not shore-parallel or shore-normal but have significant components in two dimensions. The simplifications made in the two types of model described above mean that they would be unlikely to produce accurate results in these circumstances. A digital representation of the initial morphology of the beach and/or nearshore is required together with boundary conditions for the hydrodynamic 'forcing', such as incident wave conditions.

The SANTOSS formula is also suitable for this kind of model. If the SANTOSS model is implemented in both a coastal profile model and a related coastal area model they will have the virtue of consistency.

An important distinction between individual coastal area models is the kind of computational grid they employ. At its simplest, a uniform square (or rectangular) grid of points can be placed over the “wet” part of the study area. Such grids allow the governing differential equations to be written in a finite-difference form for solution fairly easily. However, they do not usually fit the shape of a complex shoreline closely, nor allow higher resolution to be used in areas of greater interest. The fitting can be improved by a modification known as a cut-cell approach used along the shoreline, and higher local resolution can be achieved by nesting a finer grid, or by an adaptive quad-tree approach in which large cells are successively subdivided automatically where needed as the model run progresses. An alternative approach to fitting the shoreline closely and varying the resolution is to use a curvilinear orthogonal grid, which is effectively a squashed and curved version of a square grid. The most flexible approach is to use a mesh of triangular elements of varying shapes and sizes which can be fitted closely to the shoreline and refined at will in areas of interest. The penalty is greater complexity in handling the differential equations, and hence longer run times.

The computational speed of coastal area models is slower than plan-shape or profile models, because of their greater complexity, especially if a fully three-dimensional version is used. Even two-dimensional, depth-averaged coastal area models compute faster than real time by only a small factor, and three-dimensional models often run slower than real time.

Some examples of proprietary coastal area models are PISCES/TELEMAC, DELFT3D-Online and MIKE 21 CAMS.

A useful overview of morphological models, including a table showing the models, their owners, the sediment transport models they use, and references to papers with greater detail is given by Van Rijn *et al.* (2005, p.80).

5 Sediment transport prediction at a point

The new SANTOSS formula is designed to predict the sediment transport rate and direction at a single point on the sea bed. The "point" represents a small area of the sea-bed sufficient to cover many ripples (if present). Coastal numerical models of all three types make use of such a predictor at each grid point of the model. They treat the "point" as being applicable to the size of a grid-cell (which may cover many square metres), over which conditions are assumed to be uniform. The transport formula or model is computed at each grid point for each time-step of the coastal model during a run, totalling many millions of computations. While accuracy is important, impacting directly on the accuracy of morphodynamic predictions of the models, it is essential that the predictor is computationally efficient. This is required to ensure that computer simulations of days, months or years of real time can be performed within a reasonably short computation time (a few days at most).

Two subdivisions of point models

Sediment transport formulae are methods of calculating the sediment transport rate (possibly divided into bedload and suspended transport) direct from algebraic equations. One "formula" may consist of several equations, usually based on a mixture of physics and calibration against data. They are the quickest method computationally, and hence the best suited to repeated computation in morphodynamic coastal numerical models, although less strongly based in physics than the gridded models. The SANTOSS formula is an example, with physics well-represented through a large number of equations.

Sediment transport point models are models with a vertical grid of points (usually closer spaced near the bed), and a grid of points in time (usually around 100 points per wave cycle) in which a set of physical and empirical equations are solved to give mean and oscillatory profiles of velocity, suspended sediment concentration and suspended sediment flux. The flux is integrated through the depth and over a wave cycle to yield the mean suspended sediment transport rate and direction. This can be added to the mean bedload transport over a wave cycle to give the total sediment transport rate and direction. "Research-level" models can include a wide range of detailed physical processes, but may take a few minutes to run for each individual input. "Practical" models are quicker, and may not include time stepping through the wave cycle. However, the distinction is blurred.

Sometimes the names "formula" and "model" are used interchangeably. The new SANTOSS method is called a model by its developers, but is classed as a formula (albeit comprising a large number of equations) in the present report. There are many different options for the formula or point model, and the output of the coastal model will depend on which one is used. Some previously existing formulae and models are described below, followed by a description of the SANTOSS formula.

5.1 Some previous sediment transport formulae and models

Only formulae and point models which are used in well-known coastal models, or which are recent contenders with similar features to the SANTOSS model are listed here. They all apply to transport of sand (or in some cases gravel) by a combination of currents and waves, although treatment of the waves varies between methods. In the present context, the current is treated as being steady, which in practice is an adequate assumption for slowly varying currents such as tidal and wave-driven currents. The mathematical formulations are not given here, but can be found in the referenced papers. Some of them are summarised, with the formulations, by Soulsby (1997).

Section 5.1 can be skipped by those who do not need to compare alternative sediment transport formulae themselves.

5.1.1 Bijker formula

The earliest sediment transport formula for combined currents and waves was devised by Bijker (1967), and is still widely used. It was based on novel measurements and theory for wave-current interaction. The theory was used to modify an existing sediment transport formula for current alone to introduce the additional stirring effect of the waves on the sediment. It was originally calibrated for non-breaking waves, but is often applied in the surf zone by simply multiplying the results by five. This is an approximation, indicating the magnitude of the additional stirring produced by the turbulence generated by wave breaking.

5.1.2 Bailard formula

One of the most widely used methods is the Bailard (1981) formula, which was developed from the energetics arguments proposed successively by researchers such as Bagnold, Inman and Bowen. The general approach is that the work done in transporting sediment is assumed to be a fixed proportion of total energy dissipated by the waves and current. It was originally devised for cross-shore transport and longshore transport in the surf zone. The efficiency factors it contains were calibrated only against longshore transport measurements, although the same values are widely used for cross-shore transport calculations. Although Bailard only expounded his formula as part of a more general paper on a model of beaches, it became popular with numerical modellers because it is computationally efficient, and it takes account of: bedload and suspended load transport; waves and currents at any angle, including the effects of wave velocity asymmetry (but not acceleration asymmetry); and bed slopes in any direction. Results of tests of the formula as part of a European research project are described by Soulsby (1997, pp.181-182).

5.1.3 Soulsby-Van Rijn formula

This simple formula (Soulsby, 1997, pp.183-185) was devised by applying an adapted method developed by Grass (1981) to include wave effects in a steady-flow sediment transport formula developed by Van Rijn (1984). A free coefficient was then calibrated against a set of curves plotted by Van Rijn (1993) using outputs from his TRANSPOR model (see below). Despite its simplicity, it captures many of the features of sediment transport by combined waves and currents. However, it does not include the effects of velocity-asymmetry or acceleration-asymmetry, nor of boundary-layer streaming (see glossary). The formula applies to non-breaking waves.

5.1.4 SedFlux model and ParaSedFlux formula

The SedFlux model is a "practical" sediment transport point model, which is gridded in the vertical but not in time. It has been released in successive stages during its development, namely SedFlux2000 (Damgaard *et al.,* 2001), SedFlux2004 (Soulsby and Dunn, 2005), and SedFlux2007 (Soulsby and Obhrai, 2007). The SedFlux model predicts the magnitudes and directions of bedload, suspended load and total load transport rates for sand or shingle (gravel), together with suspended sediment concentrations at specified heights, in response to forcing by combined waves and currents. Waves are assumed to be sinusoidal for the suspended sediment transport (no effects of velocity or acceleration skewness), but can include velocity skewness (but not acceleration skewness) in the bedload component. One version of the model includes the gravitational effects on bedload (but not suspended) transport of a sloping sea bed in which the slope can be in any direction relative to the directions of the current and waves.

The model itself is too computationally demanding to use at every grid point and every time-step of a coastal numerical model, so an algebraic formulation was devised which captures the processes embodied in SedFlux2007 in a much more computationally efficient form (Soulsby, 2009). The SedFlux2007 model was run for a large number of sets of input data, in which values of input parameters were varied systematically to provide 858 synthetic data points. These were used to develop a parameterisation formula named ParaSedFlux, which comprises 37 linked algebraic equations.

5.1.5 TRANSPOR model

Van Rijn (1993) and Van Rijn (2001, 2005) devised a point model developed in stages first as TRANSPOR (provided on a diskette insert in Van Rijn 1993), and successively as TRANSPOR2000, and TRANSPOR2004. For the latter, Van Rijn (2005) says:

"*TRANSPOR2004 includes predictors for the bed load and suspended load components in wave-current flows. The suspended load predictor incorporates....the 'wave-related' component of the transport which depends on the correlation between the intra-wave flow and suspension processes...The bedload transport rate is obtained by time-averaging (over the wave period) the instantaneous...transport rates from a quasi-steady bed-load formula approach. The predicted bed-load results are within a factor of 2 or 3 of measured values*." Further details can be found in Van Rijn (2005).

The TRANSPOR2004 model compares favourably with experimental data, but it is slower to run than methods expressed purely as algebraic formulae, because it makes integrations in space through the water column and in time through a wave cycle.

Van Rijn (2007) updated the TRANSPOR2004 model as a unified model of sediment transport, which includes sediments with fractions in the clay and silt ranges, as well as sand and gravel, and deals with the effects of cohesion associated with fine sediments.

5.1.6 STPQ3D model

STPQ3D is a quasi-3D numerical point model that calculates the non-cohesive sediment transport in combined waves and currents. It involves numerical solution of equations describing the wave and current velocity, turbulence generated and erosion, turbulent diffusion and settling of sediment over a vertical grid of points and throughout the wave period. STPQ3D accounts for: waves and currents at arbitrary angles, breaking waves, plane/ripple-covered bed, uniform/graded bed material or shingle, effect of bed slope and effect of streaming. The main outputs are the time-varying and time-averaged profiles of bed and suspended load in two directions. To use it in a coastal area model requires a large number of input combinations to be run in advance, and then time- and space-dependent results obtained by multi-variable interpolation in the resulting table of outputs.

5.1.7 Previous formulae accounting for acceleration skewness

Since about 2000 it has been recognised that the physical process of acceleration skewness had hitherto been omitted from sediment transport predictors. A wave with a “saw-tooth” surface profile (see Figure 2.1) is known to transport sediment strongly shorewards, yet previous prediction methods would have predicted zero transport. Hence, a process promoting onshore transport was missing. Six formulae which include acceleration-skewness effects are listed by Ribberink *et al.* (2010), and their performance is compared with the new SANTOSS formula (see Section 7.2). These are the formulations by Drake and Calantoni (2001), Hoefel and Elgar (2003), Watanabe and Sato (2004), Silva *et al*. (2006), Nielsen (2006) and Gonzalez-Rodriguez and Madsen (2007). The acceleration effects are introduced in various ways, depending on the nature of the formulation. Ribberink *et al*. (2010) give further details of the methods, and these are elaborated together with full details of the intercomparison by Van der A (2009). The effect of acceleration skewness typically doubles the effect of velocity skewness. We show in Section 7.3 that the new SANTOSS formula is more accurate than the above formulae.

5.2 The SANTOSS sediment transport formula

The SANTOSS formula is described in detail in a SANTOSS project report by Ribberink *et al.* (2010). In this report it is referred to as the SANTOSS transport model, using “model” in the sense of the point models defined here in Section 4.1. In the present report it is called the SANTOSS formula, to emphasise that it is expressed as a series of algebraic formulae, rather than as a vertically gridded numerical model. In fact, the SANTOSS model as presented by Ribberink *et al.* (2010) comprises 80 linked equations. A summary of these equations is given in Appendix D of the present report.

Appendix D can be skipped by those who do not intend to make use of the SANTOSS formula themselves.

It is unlikely that many practitioners, other than numerical modellers, will use the formula themselves, but they can gain a feel for the methodology from Appendix D. In practice, the formula will usually be coded as a subroutine within a coastal model (see Section 4.2). A MATLAB-code of the SANTOSS transport model (version 2.07) is available on request from the University of Twente (email: r.h.buijsrogge@utwente.nl, or by contacting Professor O’Donoghue at University of Aberdeen, see Section 2.3).

The SANTOSS model predicts sediment transport by bedload and suspended modes of transport within the thin wave boundary layer just above the sea bed. It does not include suspended transport above this layer. Some methods of including this are advocated by by Ribberink *et al.* (2010), by making use of existing methods for suspended sediment transport (such as methods by Van Rijn or Bijker). In doing so, it is essential that only the suspended load above the wave boundary layer is computed, to avoid “double-counting”. The results which are given in subsequent sections of this report, and also by Ribberink *et al.* (2010), do not include any additional suspended load above the wave boundary layer. Under some circumstances (primarily cases with strong currents), the total transport may be a factor of two to ten times that predicted by the SANTOSS formula, although such cases are outside of the primary remit of the SANTOSS project. Extending the SANTOSS results to encompass cases with strong suspension outside the wave boundary layer would ideally require additional research to specify a reference concentration at the top of the boundary layer. Nonetheless, because the SANTOSS formula better predicts sediment transport in the bottom layer, and uses existing methods above this, the resulting values of total transport will generally be an improvement on earlier methods.

Incorporating the influence of gravity on the transport in cases where the sea bed has a significant slope (which can be an important stabilising factor in morphodynamic models) is also touched upon by Ribberink *et al.* (2010), but has not been tested. The method advocated for introducing slope-effects (Apsley and Stansby, 2008) was designed for transport by steady currents, and its extension to wave-dominated conditions would require further research.

6 Methodology for applications

6.1 Who might use the SANTOSS formula, and how

The new formula can be used in a number of ways, depending on the type of study, the stage within that study, and the level of detail required from the answers.

In the early stages of a project or investigation, a non-specialist might wish to make some initial order-of-magnitude calculations of sediment transport, using a spreadsheet or a limited number of calculations on a computer. A spreadsheet can be devised by making use of the equations in Appendix D. This is not a small task, in view of the large number of equations that have to be coded in, but once it has been done and thoroughly tested, it should be a relatively simple job to adapt the spreadsheet for subsequent projects.

Alternatively, and probably preferably, the MATLAB code which is freely available (see Section 5.2) can be obtained and implemented on a computer. The code provided to operate the SANTOSS formula would need to be embedded in additional project-specific MATLAB code. This requires a MATLAB licence and an operator who is familiar with MATLAB. However, this approach removes the need for programming the formula, and guarantees answers that are exactly as the originators intended.

At a higher level of complexity, the formula needs to be embedded within a coastal model of the sorts described in Section 4.2. This requires access to one of the proprietary models, and (importantly) a modeller who is thoroughly familiar with that model. These types of application are best undertaken by a specialist consultancy firm. The most reliable method of embedding the model is to obtain the MATLAB code, and either interface it directly with the main model code, or convert it to the language used to code the main model. In the latter case, it is essential to carry out a comprehensive comparison with outputs from the MATLAB code for a range of inputs which includes all the possible branches in the code.

Whichever approach is used, to run the model for a specific project will require a set of inputs for each condition required, and some intermediate calculations to convert these to the inputs used by the SANTOSS formula, including calculations of the various measures of wave orbital velocity used by the formula. Some guidance is given below.

The sub-sections 6.2 to 6.4 can be skipped by those who do not intend to make use of the SANTOSS formula themselves.

6.2 Inputs needed

The primary inputs required are:

- water depth h;
- (possibly) magnitude and direction of bed slope;
- water temperature and salinity;
- significant wave height H_s;
- a measure of wave period - either the mean period T_m or peak period T_p;
- wave propagation direction φ_w;

- current speed –depth-averaged current $\overline{\mathrm{U}}$ or current $U(z)$ at fixed height z;
- current direction φ_c;
- median (and 90 per cent finer) grain diameters of the sea bed sediment d_{50} (and d_{90});
- density ρ_s of the sediment.

These can be obtained as specified “design” conditions (like a set of storm conditions with specified return periods), or as values obtained from a coastal numerical model.

The recommended conversions (Ribberink, personal communication) from irregular wave parameters to the regular wave inputs required for the SANTOSS formula are $H = H_s$ and $T = T_p$.

Care must be taken to use a consistent convention for directions. In field work, it is usual to express directions in the compass convention, in degrees clockwise of North. Wave directions follow the convention for wind, namely the direction they *come from*, but currents follow the “ship’s head” convention of direction *going to*. However, numerical models (and the SANTOSS formula) usually work in mathematical (Cartesian) coordinates, expressing directions all as *going to*, measured in radians anti-clockwise of the x-axis (which is often East-directed). Thus, data taken from field data must be converted to the mathematical convention before being input to the SANTOSS formula, and the output sediment transport directions converted back to compass convention if necessary. Currents and waves derived from coastal numerical models will usually already be in the correct convention for use with the SANTOSS formula. These considerations apply to the use of any type of sediment transport predictor.

Assuming the mathematical convention is used, the angle φ between current and wave, required in SANTOSS formula calculations, is given by $\varphi = \varphi_c - \varphi_w$.

6.3 Intermediate calculations required

The SANTOSS formula requires inputs which are in the above list, or which can be derived from them:

- Density ρ and kinematic viscosity ν of the water can be derived from the temperature and salinity by standard methods (for example Soulsby, 1997).
- Relative density of sediment $s = \rho_s/\rho$.
- Height above sea bed of the top of the wave boundary layer δ is derived from wave parameters (see below). Ribberink (personal communication) advised that using a constant height of z = 0.2 m instead of $z = \delta$ introduces errors of only a few percent. For practical purposes this could be a simpler option, provided the depth is greater than (say) one metre.
- Current velocity vector at the top of the wave boundary layer $\vec{u}_\delta$. Ribberink *et al.* (2010) advocate use of a fully 3D coastal numerical model which resolves the wave boundary layer, or a 3D sub-model with a depth-averaged coastal numerical model. Both approaches make heavy demands on computation time. A less intensive approach suggested by Ribberink (personal communication) is to assume a logarithmic velocity profile shape, using an increased apparent roughness due to wave influence. This approach would only be valid in situations with progressive waves plus mean current with no influence of undertow or return flow and wind.

6.4 Calculating wave orbital velocity

The movement of sediment by waves is mainly effected through the horizontal orbital velocities they generate just above the sea bed. As described in Section 2.4, the bottom velocities in deep water are well approximated by a sinusoidal variation with time and can be calculated quite accurately using linear (Airy) theory. An approximation to this method of calculation is given by Equations (D.51) to (D.54) of Appendix D. Some alternative methods of calculation were compared by Soulsby (2006), who found that the presence of a current can significantly modify the orbital velocity through the current-inclusive wave dispersion relation.

The more elaborate description of the wave orbital velocity, including velocity and acceleration skewness, required for the SANTOSS formula must then be obtained (as recommended by Ribberink *et al*. 2010) from the paper by Elfrink *et al.* (2006), who analysed a large set of field observations from three sites to obtain empirical expressions for velocity amplitudes, half-periods of crest and trough, and asymmetries of accelerating and decelerating phases. The inputs are H, T, h and local bed slope. Hence if bed slope is known as an input, it can be used in these calculations and makes a significant difference to the velocity signature. An alternative version of the Elfrink *et al.* (2006) formulation was derived by Malarkey (2008) as part of the SANTOSS project. Further manipulation of these quantities to yield the parameters required as inputs by the SANTOSS formula is detailed in Appendix A of the report by by Ribberink *et al.* (2010).

7 Advantages and limitations of the SANTOSS formula

7.1 Assessing the merits of models

The merits of point models and formulae of sediment transport for practical applications in the coastal zone can be assessed in terms of the following criteria:

- Under what conditions is it applicable?
- How versatile is it?
- How easy is it to use?
- How fast is it computationally?
- How robust is it for all combinations of inputs?
- How accurate is it, compared with observations?
- What is its track record?

All these criteria play a role in deciding whether a method is well-suited to a particular application. They are discussed further below, in the context of the SANTOSS formula.

7.2 Conditions of applicability

When assessing models and formulae one can ask, for example, is it most applicable in deep or shallow water? Does it apply to mud, sand or shingle? Does it handle forcing by waves or currents or both? The conditions of applicability of the model or formula can then be compared with the conditions relevant to individual studies.

Figure 7.1 shows the zones of wave transformation taken from Figure 2.1, with the relative applicability of the SANTOSS formula shown qualitatively by the width of the bar at the bottom. For comparison, the relative applicabilities of two representative alternative formulae described in Section 5.1 are also shown. The Bailard formula is calibrated for longshore transport in the surf zone, but is less reliable for cross-shore transport, and for use further offshore. In contrast, the ParaSedFlux formula is intended for use in offshore waters and becomes progressively less applicable as the waves shoal and break.

In the offshore zone, the SANTOSS formula is applicable, but so are many previous methods. It can handle the boundary layer streaming in the offshore and shoaling zones, which many other formulae cannot.

In the shoaling zone, the SANTOSS formula is still applicable for sharp-crested waves (which some methods do not include), and also for sharp-crested, forward-leaning waves (which many methods do not include).

No simple sediment transport formula, including the SANTOSS formula, is really suited to the actual point of breaking, where not only can vertical velocities (downwards and upwards) become important, and turbulence and air entrainment are intense, but the shape of the sea bed is often far from simple. Inside the surf zone, the SANTOSS formula can handle the forward-leaning, saw-tooth wave shape, but only includes the effect of the breaking-induced turbulence in an approximate fashion.

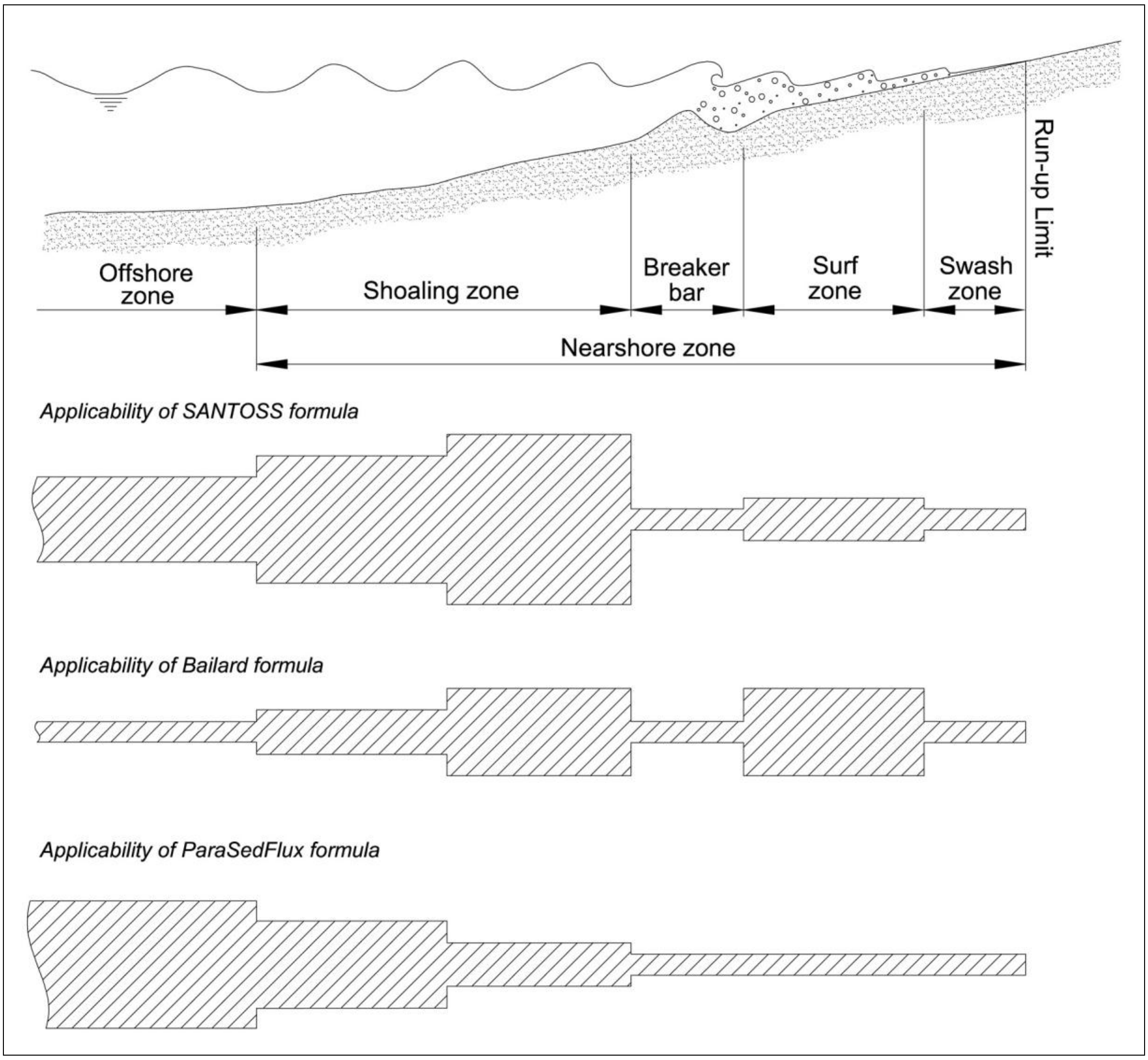

Figure 7.1: Applicability of SANTOSS formula in different zones. Width of shaded bar indicates (qualitatively) degree of applicability. In reality, applicability varies smoothly, not in steps. For comparison, applicability of two different formulae is shown.

In the swash zone, the bed is alternately wet and dry, and percolation of water through the sea bed becomes important, so the SANTOSS formula (in common with almost all other formulae) is not well suited.

The effect of currents also varies with the zones shown in Figure 7.1. Through the offshore and shoaling zones, tidal currents parallel to the coast may be important, and in the shoaling, breaking and surf zones, wave-generated longshore currents may be important. The SANTOSS formula is able to handle both of these. In the surf zone, an offshore-directed undertow may be generated in the lower part of the water column. This is not easily dealt with by the SANTOSS formula, or indeed by any formulae.

7.3 Versatility

When assessing models/formulae one can ask, for example, does it only apply to a restricted range of conditions, or to all the conditions found in coastal waters? If it is well suited to one set of conditions (such as in the surf zone) it might not work well in others (such as deeper waters), in which case if the study area encompasses many different conditions, different models/formulae might be needed in different zones. This can lead to incompatibilities, and in turn to anomalous morphodynamic responses at the borders of the zones.

As shown in Figure 7.1 and described above, the SANTOSS formula is most readily applicable to the shoaling zone, where its capabilities for dealing with velocity and acceleration skewness come to the fore, and it can also be applied successfully further offshore, but it is less well suited to the surf zone.

In terms of types of sediment handled, the SANTOSS formula is designed for relatively well-sorted fine and medium sand with median grain diameter d_{50} in the approximate range 0.1 to 1.0 mm, although its use could possibly be extended to coarser sediments (untested as yet). Of the alternative formulae listed in Section 5.1, the Bijker, Bailard and Soulsby-Van Rijn formulae are similarly intended for fine and medium sand. The TRANSPOR2004, SedFlux/ParaSedFlux and STPQ3D models can handle shingle transport, and the latest version of TRANSPOR2004 is designed to include very fine (including cohesive) sediments. Some of these models are also designed to include the effects of widely graded sediments (for instance, specified by two or more of d_{10}, d_{50} and d_{90}), whereas the SANTOSS model is intended for well-sorted sediments specified mainly by a single grainsize (d_{50}, plus a weak dependence on d_{90}).

All the models mentioned are “equilibrium” models, in that they are intended to apply to study areas in which the currents, waves, depths and bed materials vary only slowly in space and time (they are nearly uniform and steady). If any of these vary rapidly in time or space, different approaches are required which are generally much more computer-intensive. The need for a non-equilibrium approach becomes progressively greater for finer sediments. Modelling methods also exist for adapting equilibrium formulae to non-equilibrium conditions, which provide a useful compromise between the equilibrium and fully non-equilibrium methods.

In addition, the SANTOSS outputs are not well suited to (nor were they intended for) cases with:

- highly mixed sediments, such as mixed sand and gravel;
- biologically active areas, where organisms can affect the mobility of the sediments (both negatively and positively);
- areas with strongly bi-modal wave spectra (for example, with similar energies in the swell band and wind-sea band of frequencies);
- areas with strong wave reflection, such as from the toe of a backing sea wall;
- areas with crossing waves.

Most alternative sediment transport predictors are not well suited to these conditions.

7.4 Ease of use

When assessing models/formulae one can ask, for example, is it a single, simple algebraic formula, a large set of inter-related formulae, an iterative scheme, or a fully gridded model? Could it be used on a pocket calculator, or in a spreadsheet, or does it require numerical solution by computer over a grid of points in space and/or time? Can it be used by a non-specialist, or does it require a specialist in sediment transport or numerical modelling? Does it require input data which are not readily available?

In order to deal with processes such as ripple effects, velocity skewness and acceleration skewness, the SANTOSS formula is necessarily more complicated to programme than simpler formulae. Similarly, the amount of information required for inputs is greater than for simpler formulae. However, the "practical" vertically-gridded models require just as much input information, and more complicated programming. "Research-level" models are even more difficult to programme and run, and are sometimes unstable. A single run of the latter type of model requires significant attention and run-times, and it is not clear whether the decreasing ease of use brings corresponding improvements in accuracy.

The SANTOSS set of equations is too complicated to use on a pocket calculator. It could in principle be implemented in a spreadsheet, but is most readily usable as a computer code (see Section 6). Given the MATLAB code, it could be used for preliminary calculations by a non-specialist, but full detailed implementation is best handled by a specialist.

7.5 Computational speed

When assessing models/formulae one can ask, for example, could it be applied at every grid point and every time-step of coastal model, to cover an adequate number of runs, of adequate duration, within an acceptable computational time (such as a few days of continuous computing)?

Despite major advances in computing speed in recent decades, the computing time needed to model a study area remains a limiting factor. Increases in speed are rapidly exploited in terms of greater grid resolution, more advanced numerical methods, longer runs, 3D instead of 2D models, and greater numbers of cases requiring modelling - especially if sensitivity tests or stochastic results are required.

The speeds of the various models and formulae mentioned here have not been compared in a formal sense. This would require the same wide range of inputs to be run and timed on the same computer. However, in view of the algebraic nature of the SANTOSS set of equations, it is likely to be sufficiently efficient computationally to be implemented in coastal profile models and coastal area models without causing a problem with run lengths.

7.6 Robustness

When assessing models/formulae one can ask, for example, can it be relied on to give reasonable answers for all the inputs under which it might be run? Is it prone to causing computational errors which halt a run?

The testing described by Ribberink *et al*. (2010) (see below) covered a wide range of input conditions and the formula was well-behaved in every case. As far as is known, it does not cause computational errors or give answers which are grossly unrealistic.

7.7 Accuracy

When assessing models/formulae one can ask, for example, how do its predictions compare with (well-controlled) laboratory measurements? How do they compare with (less well-controlled, but more realistic) field measurements?

The accuracy of prediction of sediment transport rates is much poorer than for many other branches of science and engineering; it is nearer to the accuracy of weather forecasting than of structural design. A level of agreement between predictions and observations of around 70 per cent of predictions lying within a factor-of-two of observed values is considered good. This level of agreement between models and data is unlikely to be much bettered in the near future, because the agreement of *data* with data between repeat experiments is no better than this.

7.7.1 Comparison with laboratory measurements

The SANTOSS formula was tested by Ribberink *et al.* (2010) against the dataset of 206 experimental sediment transport measurements assembled as part of the project. The overall results are shown in Table 7.1. These are all good performance figures, by the standards of sediment transport. When used with internally predicted ripple heights and wavelengths (as would be needed in practical applications), the formula performs a little less well than when used with experimentally observed ripple dimensions. The comparison for steady currents (which the SANTOSS formula was not originally intended for) is particularly impressive.

Table 7.1: Performance of SANTOSS formula against laboratory data

Data-set	**N**	**% within factor 2**	**% within factor 5**
All waves (+ current)[1]	206	77	93
All waves (+ current)[2]	206	65	85
Steady current (no waves)	137	87	99

[1] with observed ripple dimensions
[2] with predicted ripple dimensions
N = no. of cases tested

The accuracy of the SANTOSS formula can also be gauged from Figure 7.2, comparing calculated and measured sediment transport rates. Different classes of wave condition are distinguished by different colours. Data points lying between the pair of dashed lines represent predictions that are accurate to within a factor of two of the corresponding observed value.

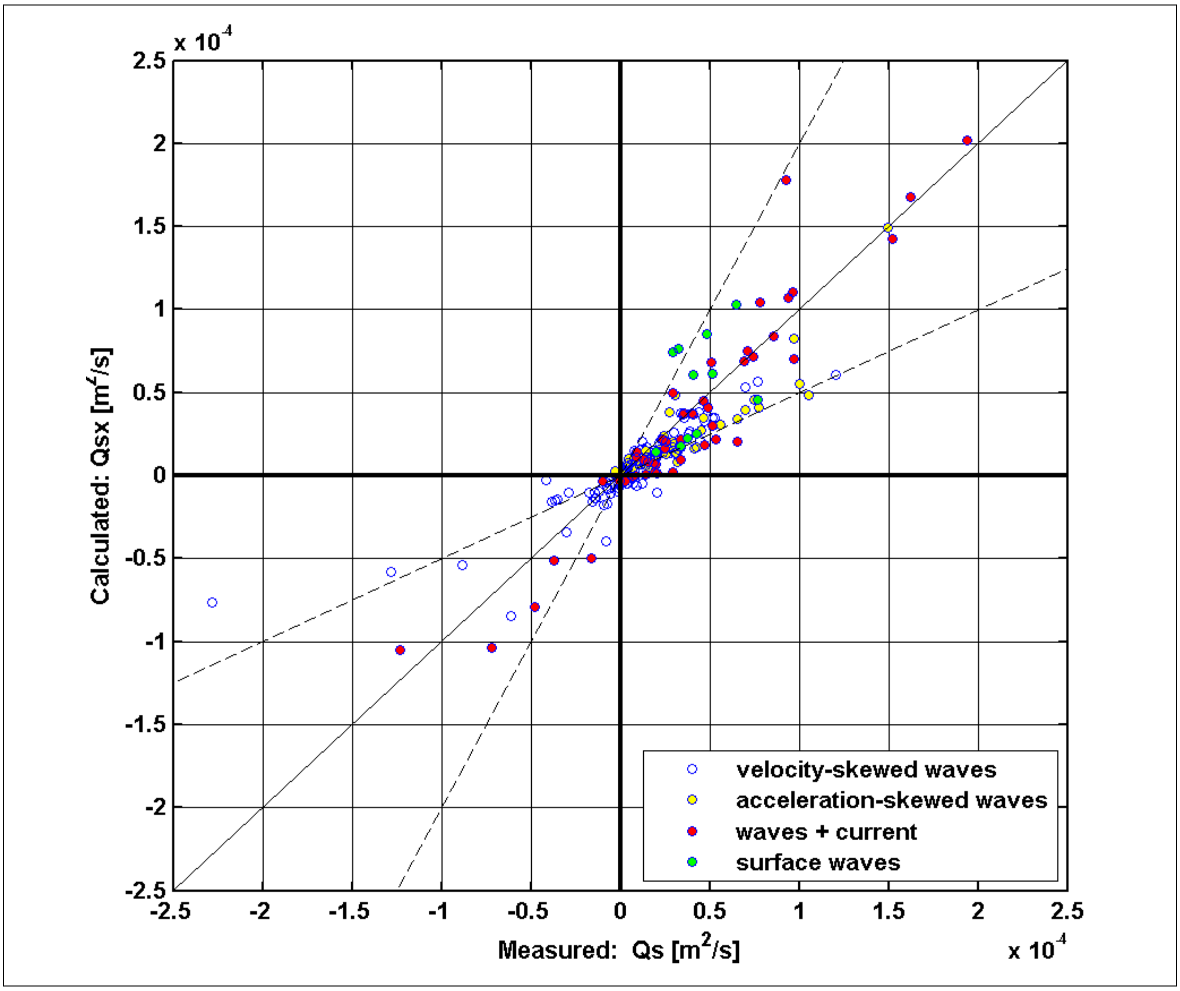

Figure 7.2: Model performance for all surface waves with or without a co-linear current and with predicted ripple dimensions (Ribberink *et al*., 2010)

7.7.2 Comparison with field measurements

Apart from the tests of accuracy described above, no independent tests have been performed as yet. Ideally, some tests of prediction capability would be made against field observations of sediment transport. However, field data of transport rates are not reliable, as most of the transport predicted by the SANTOSS formula takes place in a very thin layer above the bed where it is difficult to make measurements in the sea. Hence field observations could not be regarded as a primary standard against which to judge prediction formulae. The same problem is common to tests of other coastal sediment transport formulae.

A second approach to testing the formula is to implement it in a coastal profile model such as the COSMOS or UNIBEST-TC models. Then, predictions of changes in bed morphology for a known sequence of wave inputs can be compared with observed bed changes from laboratory or field measurements. This approach depends on other aspects of the coastal profile model, such as wave transformation, being accurate; nevertheless it can provide a comparative measure of the performance of the SANTOSS formula against other formulae. This approach is perfectly feasible, and such tests are planned for the future.

7.7.3 Comparison with other formulae

Ribberink *et al.* (2010) made comparisons with the performance of six other sediment transport formulae published between 2001 and 2007 (see Section 5.1.4). All of these included the acceleration skewness effects, but in different ways. When tested against a set of 55 laboratory data from three sources, all of which used acceleration-skewed wave velocities, the SANTOSS formula performed appreciably better than all the previous methods (Table 7.2).

A further comparison was made by Ribberink *et al.* (2010) with two more general sediment transport formulae. These are the bedload formula of Nielsen (2006), and the bedload component of the formula of Van Rijn (2007). The Van Rijn formula does not include acceleration-skewness effects in its standard form, but a similar method to that of Nielsen was suggested by Van Rijn, which was applied in this comparison. Taking the full 206 cases in the SANTOSS database, the SANTOSS formula again performed appreciably better than the other two methods (Table 7.2).

Table 7.2: Comparison of SANTOSS formula with other methods

Formula	N	% within factor 2	% within factor 5
SANTOSS formula[1]	55[2]	78	98
Drake & Calatoni (2001)	55	13	30
Hoefel & Elgar (2003)	55	36	89
Watanabe & Sata (2004)	55	71	91
Silva *et al*. (2006)	55	69	91
Nielsen (2006)	55	64	89
Gonzalez-R & Madsen (2007)	55	24	64
SANTOSS formula[1]	206[3]	77	93
Nielsen (2006)	206	52	72
Van Rijn (2007)	206	42	77

[1] with observed ripple dimensions
[2] tests against 55 laboratory data with acceleration-skewed waves
[3] tests against 206 laboratory data for all kinds
N = no. of cases tested
Both datasets contain some cases with waves plus current

7.7.4 Comparison with benchmark tests

A widely-used benchmark test for sediment transport models is the set of curves presented by Van Rijn (1993) which show sediment transport rates predicted by his original TRANSPOR model for 55 wave and current inputs. It is not claimed that these curves represent “perfect” accuracy, but they provide a standard basis against which other models and formulae can be compared.

A comparison is made in Figure 7.3 of predictions of the SANTOSS formula for these standard inputs (Ribberink *et al*., 2010) with those of TRANSPOR model. Inspection of the two sets of curves shows they have broadly similar characteristics. In particular:

- for the current-only (H = 0 m) curve, sediment transport increases with current speed above a threshold value of about 0.4 $m.s^{-1}$;
- the addition of waves enables sediment to be transported by current speeds below 0.4 $m.s^{-1}$;
- adding progressively larger waves increases transport above the current-only curve, most strongly for weak currents and less so for strong currents.

However, the curves differ because the SANTOSS model only includes suspended sediment within the wave boundary layer, whereas the TRANSPOR model includes suspension throughout the water depth. Comparing the curves:

- at the strongest current speed (2.0 m.s^{-1}) the SANTOSS transport (within the wave boundary layer) is only about a tenth of the TRANSPOR transport (throughout the depth);
- for lower currents the proportion is greater (about 50 per cent for H = 0, current = 0.4 m.s^{-1}).

For consistency with the benchmark case, the acceleration and velocity skewnesses were set to zero for the SANTOSS model in these tests.

7.8 Track record

In common with all new methods, the SANTOSS formula starts life with no track record in practical applications. But this is not a good reason to be loath to use it. Many practitioners understandably prefer to stick with methods that have a long track record. However, this can put a long delay into the trialling and eventual acceptance of new methods. Since the new methods are likely to be better in some ways than the older methods, it is desirable that they should be trialled early on, possibly in parallel with a longer-established method. This approach would ideally apply to all new methods, including the SANTOSS formula.

The SANTOSS team argue that the new formula is superior to older methods because:

- The model is developed and validated for a wide range of wave (+ current) conditions and grain sizes, as well as current only-conditions, using a large number of datapoints, and handles sheet-flow and rippled-bed conditions.
- The model combines a number of physical processes, namely: i) it is a semi-unsteady model (contrary to most of the existing descriptions) which includes the influence of phase-lag effects for ripples as well as for sheet flow); ii) wave shape effects (saw-tooth, velocity-asymmetry) are accounted for; and iii) some specific progressive surface wave effects are accounted for. The combined incorporation of these physical processes is the main reason for the better performance of the model compared to existing ones.

This makes a good case for its early adoption in relevant studies.

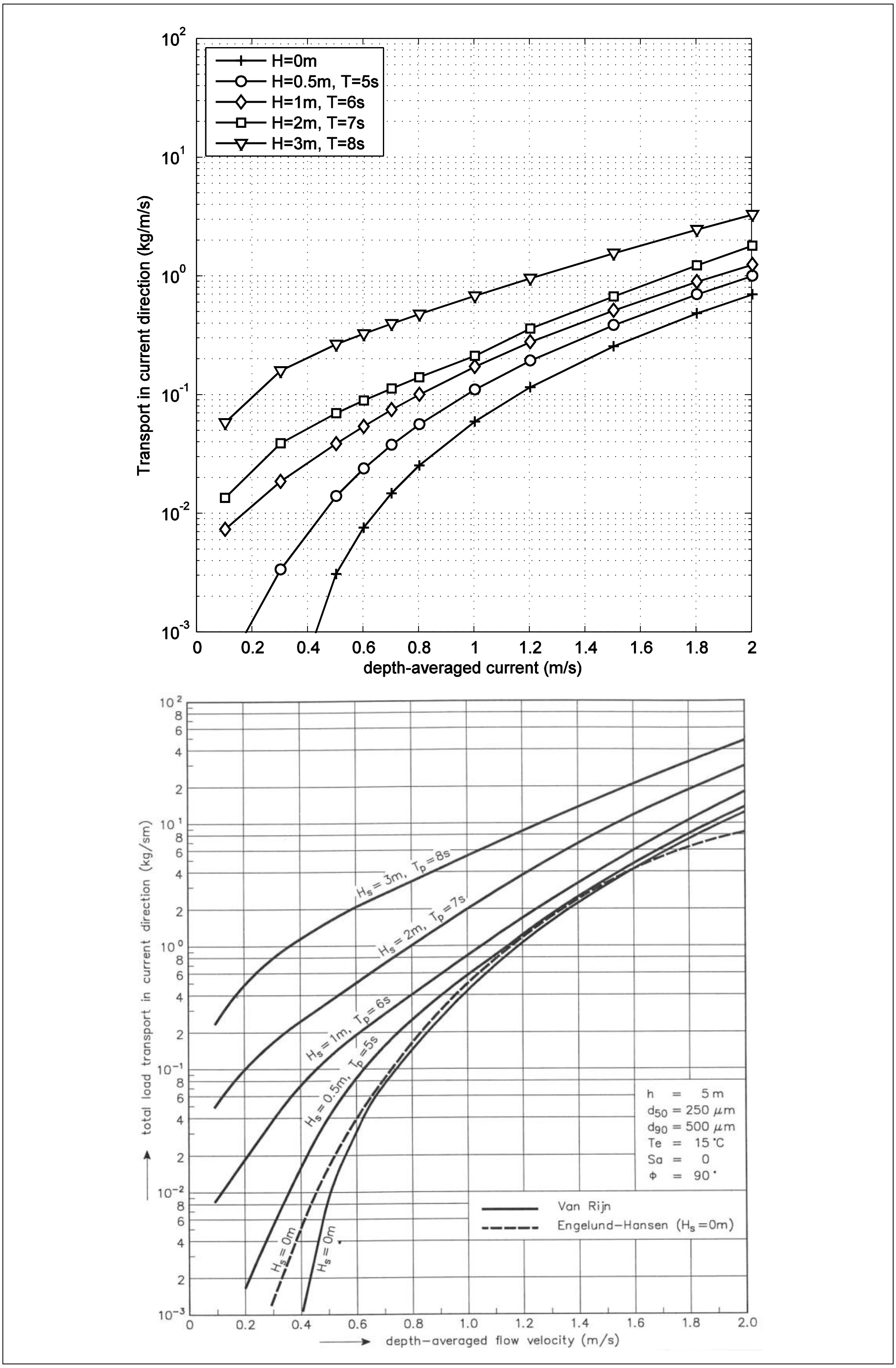

Figure 7.3: Transport rate as a function of current velocity and wave height and period. Sediment size d_{50} = 0.25 mm and water depth h = 5 m. Upper: SANTOSS formula (reproduced from Ribberink *et al*., 2010). Lower: TRANSPOR model (reproduced from Van Rijn, 1993)

8 Related research projects

Various research projects, partly or wholly funded by the Environment Agency, have been running in parallel with the SANTOSS project. The most relevant of these, and their connections with the SANTOSS research, are described below. The descriptions are largely drawn from websites of the projects.

8.1 LEACOAST and LEACOAST2 project

The EPSRC-funded research project LEACOAST was a collaborative venture between the University of Liverpool and University of East Anglia. It aimed to improve understanding of interactive coastal processes and morphology changes produced by construction of shore-parallel breakwaters in UK tidal conditions. The project focussed on modelling and measuring the hydrodynamics and morphological changes during storm events. Use was made of an existing Liverpool morphological computer model, which was enhanced to include the effect of over-topping and reflective porous structures. Field data were gathered from two typical embayments at Sea Palling in Norfolk, UK where nine shore-parallel segmented breakwaters have resulted in the formation of low-water tombolos and salients, as well as impacts on the beaches down-drift. Existing data on waves, currents and transient bathymetric changes collected from a central embayment in the United Kingdom Coastal Research Facility (UKCRF) by earlier EPSRC-sponsored research were used in the modelling component. The project was also supported by HR Wallingford, Halcrow, Environment Agency, Defra and a number of academic partners.

The research continued until 2008 in the EPSRC-funded LEACOAST2 project, with additional partners University of Plymouth, Proudman Oceanographic Laboratory and British Oceanographic Data Centre, who were sub-contracted to the project for field measurements and data management, as well as end-users Halcrow Maritime and HR Wallingford. HR Wallingford and Halcrow were funded by Defra and the Environment Agency to develop generic design guidance for detached breakwaters in a macro-tidal environment, drawing on information from the companion EPSRC-funded project and comprehensive numerical modelling carried out by HR Wallingford. The LEACOAST2 projects focused on time and space-scales appropriate for shoreline management plans, and on providing results of generic value for the UK coastal environment.

Further details can be found at the websites:

http://www.research.plymouth.ac.uk/cerg/leacoast/

http://www.research.plym.ac.uk/cerg/leacoast2/

The objectives of the LEACOAST(2) projects were both broader and narrower than the SANTOSS project. They were broader in that they included field measurements and applications of coastal area models to a wide study area, whereas the SANTOSS research focussed on wave and sediment processes at a single point. But they were narrower in that LEACOAST only dealt with schemes involving shore-parallel breakwaters for coast protection, whereas the SANTOSS research can be applied to a much wider range of projects. Potentially, the SANTOSS formula can be incorporated into the kind of coastal area models used in the LEACOAST project, although with some caveats for the Sea Palling study area concerning the extreme three-dimensionality of the problem, and effects of wave reflection, neither of which the SANTOSS formula is ideally suited for.

8.2 Beach Management Manual

The *Beach Management Manual* was published in 1996. Since that date, research and experience has progressed considerably prompting an update to the manual. The second edition of the *Beach Management Manual* draws on latest good practice, including international experience, and places beach management in the context of developments such as Shoreline Management Plans. Other sustainability, habitat and biodiversity issues are also addressed, as well as changes in legislation.

The updated manual includes the latest information on state-of-art methods, guidance and information on beach monitoring and maintenance, evaluation of the state and performance of a beach, design, procurement, execution and the after-care of beach improvement schemes.

This revision is timely, not least because of increasing concerns about climate change. Sea levels are predicted to rise and increased storminess is predicted to cause greater problems in maintaining adequate defences against coastal flooding and erosion.

The new version of the manual outlines the results of recent research (in the UK and beyond) and summarises the experiences of a large number of beach management and recharge schemes carried out since 1996. For example, new information is available on the strategies, quantities and types of sediment needed for the long-term maintenance of a beach, valuable for optimising management practices.

The project started in April 2008, funded by the Environment Agency, Natural England, BIRSE, Pevensey Coastal Defence Ltd, SCOPAC, Van Oord and CIRIA Core, and run by a consortium led by Halcrow with Royal Haskoning and HR Wallingford.

Further details and the revised guide can be found at the website: http://www.ciria.org/service/research_information (research & information/projects/RP787).

The updated manual makes mention of the SANTOSS research, but, because it is as yet untried in practical applications, the manual will not yet recommend its use – it will be treated as a promising new development.

8.3 Guide to the Management of Toe Structures

In 1986 toe scour was identified as the most common cause of seawall failure. Since that time there has been some research into aspects of toe scour, but there is no guidance on the management of toe structures and sediment levels at the toe. An essential part of putting this new knowledge into good practice is delivering it in the form of a guide to the management of the toe of coastal defences. This guide will complement the revised *Beach Management Manual*.

The *Guide to the Management of Toe Structures* (Environment Agency project SC070056) will give practical guidance to asset managers and engineers on the prediction of toe scour at coastal structures and the options available for mitigating its effects. It will introduce new knowledge gained from recent research and translate it into good practice. Furthermore it will address important aspects of performance-based risk assessment for toe structures in line with Environment Agency developments in asset management and planning.

The SANTOSS research is not ideally suited to applications involving toe scour, because wave reflection from a coastal structure (such as a seawall) is an important process influencing scour, and this is not presently included in the SANTOSS formula.

It is possible that the SANTOSS methodology could be adapted in future to deal with wave reflection, in which case it would become suitable.

The SANTOSS formula could be used in its present form for planning purposes and project appraisal to assess an otherwise healthy beach profile at a seawall, to better understand the conditions of draw down which lead to exposure of the wall; that is, to consider the condition before toe scour becomes an issue.

The report *Toe Structures for Coastal Defences – a Management Guide* is expected to be available in the summer of 2011.

9 Conclusions and recommendations

9.1 Conclusions

The SANTOSS project has developed a new sediment transport formula that includes processes which had often been overlooked previously. The project demonstrated the benefits of joint funding by research councils in different EU states, and of harmonious collaborative working between Dutch, Scottish, Welsh and English universities.

The following objectives were achieved by the research team:

- Large-scale laboratory experiments were performed in an oscillating water tunnel to measure sediment transport rates for simulated acceleration-skewed waves under sheet-flow conditions (Van der A, 2010; Van der A *et al.*, 2008, 2009, 2010). The effect of acceleration skewness was found to significantly enhance transport in the direction of wave propagation.
- Corresponding experiments were performed in a very large wave flume to investigate the differences between sediment transport rates in the two kinds of facility (Schretlen, 2010). They showed greater transport in the flume by a factor of two for medium sand, and the negative transport of fine sand observed in tunnels was positive in the flume.
- Experiments over fixed beds in the oscillating water tunnel provided new understanding of the hydrodynamic processes, which were made use of in the formulation of the new SANTOSS sediment transport formula.
- A database of sediment transport measurements was assembled from earlier laboratory experiments at large scale, together with the new data from the SANTOSS laboratory experiments (Van der Werf *et al*., 2009).
- Existing “research-level” numerical 1DV models of hydrodynamics and sediment transport at a point were enhanced, tested and compared, and applied to investigate various physical processes.
- Methods of characterising a wave with acceleration skewness and velocity skewness in terms of commonly available wave parameters were specified (Malarkey, 2008).
- Existing formulae for waves with acceleration skewness were reviewed and tested against new SANTOSS data and pre-existing data in the SANTOSS database, and their performance ranked (Van der A, 2009).
- A new sediment transport formula incorporating all the above effects was devised (Ribberink *et al*., 2010). This improved the prediction performance compared with six recent sediment transport models which include the acceleration-skewness effect, when tested against a database of laboratory observations of transport rate for acceleration-skewed waves. The improvement can be quantified as increasing the proportion of predictions lying within a factor-of-two of observed values from between 13 and 71 per cent of predictions for the earlier models to 78 per cent for the SANTOSS model. Similarly, the proportion of predictions lying within a factor-of-five of

observed values increased from between 30 and 91 per cent of predictions for the earlier models to 98 per cent for the SANTOSS model (Table 7.2).

- In a more general sense, the SANTOSS formula compared well with two "general purpose" models when tested against a large and varied database. The improvement can be quantified as increasing the proportion of predictions lying within a factor-of-two of observed values from 42-52 per cent of predictions for the other models to 77 per cent for the SANTOSS model. Similarly, the proportion of predictions lying within a factor-of-five of observed values increased from 64-72 per cent of predictions for the other models to 93 per cent for the SANTOSS model (Table 7.2).

9.2 Evaluation

The SANTOSS project produced outputs of value in practical applications. Of these, the new sediment transport formula is potentially the most readily applicable to coastal projects. It is well suited for use in the wave-shoaling zone, and is also suitable for the offshore zone. The new formula has advantages over older methods in that it covers a wide range of wave, current and sediment conditions, is based on a large dataset, can handle extreme (sheet-flow) as well as moderate (rippled-bed) conditions, and incorporates a wide range of physical processes. The formula has not been calibrated or tested in the surf zone, and no recommendations are given by the research team for its application here. The SANTOSS formula could be used here if a separate suspension model (such as the established Bijker or Van Rijn models) was added, including an allowance for breaking-induced turbulent mixing.

The formula has been validated for sand in the size range 0.13-0.46 mm (and under steady currents alone for 0.19-3.8 mm), but by extrapolation it would probably be usable for sand grains in the range 0.1 mm up to a few millimetres. In common with most methods it is not suitable for cohesive sediments, bio-active sediments, very widely-mixed sediment sizes, or shingle. The formula is demonstrably more accurate than rival formulae. It is expected to be fast enough to use efficiently in coastal profile models and coastal area models (not yet tested). Further testing against field data (subjects to caveats on accuracy of data), and in coastal profile models is desirable. Useful extensions to cover the case of breaking waves (surf zone) and suspension above the wave boundary layer could be made.

The results have been interpreted in terms of their potential use in tackling issues in coastal management, science and engineering through methods including desk studies, field measurements, physical modelling and numerical modelling.

9.3 Recommendations

i. Consider making use of the SANTOSS database and sediment transport formula in coastal studies involving sandy sediments, most particularly for beach profile evolution (for example, in coastal profile models) and secondarily for evolution of offshore morphology (for example, in coastal area models).

ii. Consider extending the specification of coastal field measurements to include detailed measurement of wave orbital velocities to obtain asymmetries in velocity and acceleration that can be used in the SANTOSS sediment transport formula.

iii. When advocating physical modelling, be aware of the advantages of scaling of oscillating water tunnels, but also of their limitations in measuring sediment transport rates compared with large wave flumes.

iv. When advocating numerical modelling, consider making use of the SANTOSS sediment transport formula at the heart of coastal profile or area models for studies in which its *strengths* are appropriate and its *limitations* are not important. Integrating the formula into such models is best tackled by modellers familiar with the individual models.

v. The greatest *strength* of the SANTOSS formula compared with previous methods lies in its treatment of wave-induced sediment transport in the strongly shoaling zone lying seawards of the wave breakpoint. It is appreciably more accurate than previous methods in this zone, and also performs well in zones further offshore.

vi. In the surf zone, a *limitation* is that transport is likely to be underestimated if the SANTOSS formula is applied exactly as specified in Appendix D. This could be largely remedied by adding a suspended sediment model.

vii. A further *limitation* is that the SANTOSS formula does not include suspended transport at heights above the sea bed that lie outside the wave boundary layer (say higher than 0.2 m). In cases of fine sand with a strong current, this could comprise 90 per cent of the transport, although this has not been quantified for typical coastal wave conditions with a longshore current. For such cases, other methods for computing suspended load would be needed. The total transport predicted would then be at least as good, and probably better, than would be the case if older methods were used for transport in the lower layer.

viii. Extensions of the SANTOSS formulation to include effects of wave breaking, and suspended sediment throughout the water depth (via non-equilibrium methods), are possible subjects for future research.

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VAN DER WERF, J.J., SCHRETLEN, J.J.L.M., RIBBERINK AND J.S., O'DONOGHUE, T., 2009. Database of full-scale laboratory experiments on wave-driven sand transport processes. *Coastal Engineering*, 56, 726-732.

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List of symbols

$\hat{a}$	horizontal excursion amplitude of the free stream orbital flow
c	wave propagation speed
d_g	orbital diameter of horizontal grain motion
d_α	grain diameter of sediment for which α % is finer
D^*	dimensionless grain diameter
D_s^*	dimensionless grain diameter of suspended sediment
f_δ	current friction factor
f_w	wave friction factor
f_{wc}	friction factor for wave crest
f_{wt}	friction factor for wave trough
f_{wRe}	friction factor for wave Reynolds stress
$f_{w\delta}$	combined wave-current friction factor
$f_{w\delta c}$	combined wave-current friction factor for the wave crest
$f_{w\delta t}$	combined wave-current friction factor for the wave trough
g	gravity acceleration
h	water depth
H	wave height
k_{sw}	wave roughness height
$k_{s\delta}$	current roughness height
L	wave length
m	calibration constant for sediment load
m_η	coefficient in ripple height formula
m_λ	coefficient in ripple length formula
n	power in sediment load formula

n_η coefficient in ripple height formula

n_λ coefficient in ripple length formula

p calibration parameter for ripple roughness

P_c phase lag parameter for the wave crest

P_t phase lag parameter for the wave trough

q_s sand transport rate in volume per unit time and width (excluding pores)

r_c stirring height of sediment during wave crest

r_t stirring height of sediment during wave trough

R wave velocity skewness parameter

s relative density of sediment (= ρ_s / ρ)

T wave period

T_c wave period for wave crest (including mean current)

T_t wave period for wave trough (including mean current)

T_cu time length of accelerating part of wave crest (including mean current)

T_tu time length of accelerating part of wave trough (including mean current)

$\tilde{T}_c$ wave period for wave crest

$\tilde{T}_\mathrm{t}$ wave period for wave trough

$\tilde{T}_\mathrm{cu}$ time length of accelerating part of wave crest

$\tilde{T}_{tu}$ time length of accelerating part of wave trough

$T_{c,sw}$ wave period for wave crest (surface waves)

$T_{\mathrm{t,,sw}}$ wave period for wave trough (surface waves)

$u_x(t)$, $u_y(t)$ instantaneous horizontal velocity vector at time t

$\hat{u}$ characteristic amplitude of horizontal orbital velocity in the free stream

$\hat{u}_\mathrm{c}$ maximum wave crest velocity (free stream)

$\hat{u}_\mathrm{t}$ maximum wave trough velocity (free stream)

$\tilde{u}_{c,r}$	representative velocity for wave crest (free stream)
$\tilde{u}_{t,r}$	representative velocity for wave trough (free stream)
$\vec{u}_{\delta}$	mean current velocity vector at level $z = \delta$ above the bed
$u_w(t)$	horizontal orbital velocity (free stream)
$\vec{u}_c$	combined wave-current velocity vector at maximum (wave crest) orbital velocity (free stream)
$\vec{u}_t$	combined wave-current velocity vector at minimum (wave trough) orbital velocity (free stream)
$\vec{u}_{c,r}$	combined wave-current representative velocity vector for wave crest (free stream)
$\vec{u}_{t,r}$	combined wave-current representative velocity vector for wave trough (free stream)
$\hat{\dot{u}}_c$	maximum magnitude of the flow acceleration to the wave crest
$\hat{\dot{u}}_t$	maximum magnitude of the flow acceleration to the wave trough
w_s	settling velocity of suspended sediment
$\hat{w}$	vertical orbital velocity amplitude
x	horizontal spatial coordinate (in wave propagation direction)
y	horizontal spatial coordinate normal to wave propagation direction
z	level above the bed
α	weighting factor for combined friction factor wave + current
α_w	factor in expression for wave Reynolds stress
α_r	calibration coefficient phase-lag parameter for ripple regime
α_s	calibration coefficient phase-lag parameter for sheet-flow regime
β	wave acceleration skewness parameter
δ_{sc}	sheet-flow layer thickness for the wave crest
δ_{st}	sheet-flow layer thickness for the wave trough

δ	level above the bed at which the mean current velocity is imposed
ΔT, ΔT_c, ΔT_t	extension/reduction of half-cycle period (general, crest, trough)
ε	calibration factor for level of vertical orbital velocity above the bed
ζ	ratio of maximum horizontal grain-velocity at the bed and maximum horizontal orbital velocity in the free stream
η	ripple height
$\vec{\theta}_c$	non-dimensional representative bed shear stress vector (Shields parameter) for the wave crest
$\vec{\theta}_t$	non-dimensional representative bed shear stress vector (Shields parameter) for the wave trough
$\vec{\theta}_{c,sw}$	non-dimensional representative bed shear stress vector (Shields parameter) for the wave crest (surface waves)
$\vec{\theta}_{t,sw}$	non-dimensional representative bed shear stress vector (Shields parameter) for the wave trough (surface waves)
θ_{wRe}	non-dimensional wave Reynolds stress (Shields)
θ_w	non-dimensional maximum bed-shear stress (Shields) for waves based on $\hat{u}$ and f_w
θ_{cr}	critical Shields number (for initiation of motion)
λ	ripple length
μ	calibration factor for wave roughness height in case of fine sands
ν	kinematic viscosity of water
ξ_0	product of wave number and water depth (k_0h) at deep-water
ξ	product of wave number and water depth (kh)
ρ	density of water
ρ_s	density of sand
σ	calibration factor for combined wave-current friction coefficient
τ_{wRe}	wave Reynolds stress

φ angle between direction of mean current and the direction of wave propagation (x-axis)

φ_c direction of mean current

φ_w direction of wave propagation (x-axis)

Φ non-dimensional sand transport rate

Ψ sediment mobility parameter

Ω_c non-dimensional sediment load entrained from the bed during the wave crest

Ω_t non-dimensional sediment load entrained from the bed during the wave trough

Ω_{cc} part of the non-dimensional sediment load entrained during the wave crest that is also transported during the wave crest

Ω_{tt} part of the non-dimensional sediment load entrained during the wave trough that is also transported during the wave trough

Ω_{ct} part of the non-dimensional sediment load entrained during the wave crest that is transported during the following wave trough

Ω_{tc} part of the non-dimensional sediment load entrained during the wave trough that is transported during the following wave crest

Glossary

Acceleration skewness: A measure of the effects of asymmetrical accelerations of the water near the sea bed due to wave motions.

Bathymetry: A detailed measure of the seabed morphology defined either by underwater contours (isobaths) or by a grid of water depths.

Bedload transport rate: The rate at which sediment moves in contact with the bed, by grains rolling, hopping and sliding. Measured as mass or volume of sediment transported across one metre of the sea bed (perpendicular to the direction of transport) per second (units kg m^{-1} s^{-1} or m^2 s^{-1} respectively).

Bed shear-stress: The time-varying friction with the sea bed generated by currents and/or waves. Related to the depth-averaged current speed, or the wave orbital velocity, via a quadratic friction law.

Boundary-layer streaming: A process in which the interplay of vertical and horizontal wave-induced velocities within the thin frictional layer at the sea bed cause a net flow of water in the direction of wave propagation. This can be a key factor in determining the net transport of sediment over a wave-cycle. Also known as mass transport.

Coastal area models: Models that predict changes in the shape of the seabed in an extended offshore area in response to wave and current action. Do not model the surf zone or swash zone in detail.

Coastal models: Models that predict the horizontal distribution of water levels, currents, waves, sediment transport (and possibly changes in sea-bed morphology) over an extended study area.

Coastal plan-shape models: Models that predict changes in the shape of the shoreline as viewed from above, in response to wave action.

Coastal profile models: Models that predict changes in the shape of the beach and sea bed as seen in a vertical slice, in response to wave and current action. Extend through the surf zone and a little way offshore. Usually require shoreline, underwater contours and wave conditions to be nearly uniform in the alongshore direction.

Mass transport: See boundary-layer streaming.

Morphodynamics: The evolution of the morphology over time (hours to decades).

Morphodynamic model: A numerical model that is capable of simulating the changing shape of the shoreline and/or the sea bed.

Morphology: The shape of the shoreline and the underwater contours of the sea bed, sometimes alternatively known as the bathymetry or the topography.

Orbital velocity: The oscillatory velocity associated with waves. At heights between the sea bed and water surface there are horizontal and vertical components of velocity, which reduce in magnitude with depth below the water surface. For sediment transport, it is the horizontal component just above the sea bed which is most important.

Oscillating water tunnel: A laboratory facility comprising a rectangular cross-section closed duct, in which the horizontal component of near-bed wave orbital velocity is simulated by driving water to and fro using a piston in another part of the facility.

Point models: Detailed models that predict the vertical distribution of current velocity, suspended sediment concentration and hence suspended sediment flux at a single point. The time-varying bedload transport rates are also predicted. The total sediment transport rate is obtained from the wave-averaged sum of the bedload transport rate and the depth-integrated suspended sediment flux.

Practical point models: Sediment transport point models which are quicker than research-level models because they contain more heavily parameterised physics, and may not include time stepping through the wave cycle.

Research-level point models: Sediment transport point models which include a wide range of detailed physical processes, but may take a few minutes to run for each individual input.

Sediment transport formulae: Methods of calculating the sediment transport rate (possibly divided into bedload and suspended transport) direct from algebraic equations. One "formula" may consist of several equations, usually based on a mixture of physics and calibration against data.

Sediment transport point models: see point models.

Sheet flow: The condition of the sea bed in which very strong wave or current flows obliterate ripples and form a dense slurry of sand and water.

Skewness: A measure of departures from symmetry in wave orbital motions. See acceleration skewness, velocity skewness.

Suspended sediment flux: The product of instantaneous velocity and suspended sediment concentration. Varies with height above the sea bed and with time through a wave cycle. Integration through a wave cycle and through the water depth yields the suspended sediment transport rate.

Suspended sediment transport rate: The rate at which sediment moves when suspended above the bed. Measured as mass or volume of sediment transported across one metre of the sea bed (perpendicular to the direction of transport) per second (units kg m^{-1} s^{-1} or m^2 s^{-1} respectively).

Topography: See bathymetry.

Total sediment transport rate: The rate at which sediment moves by bedload and suspended transport. Given by the (vector) sum of the bedload and suspended transport rates. Measured as mass or volume of sediment transported across one metre of the sea bed (perpendicular to the direction of transport) per second (units kg m^{-1} s^{-1} or m^2 s^{-1} respectively).

Velocity skewness: A measure of the effects of asymmetrical velocities of the water near the sea bed due to wave motions.

Appendix A. Contractual arrangements with HR Wallingford

The aims of the Environment Agency-funded work by HR Wallingford stated in the Environment Agency's C2G Business Justification were as follows:

In this section, clearly state what the project is seeking to achieve. All Objectives must be SMART (Specific, Measurable, Achievable, Relevant, Time bound).	
Objective 1	The overall objective is to represent the interests of Defra and the Agency in an externally-funded university research project aimed at developing improved knowledge about sand movement by waves in the sea through new experiments and numerical modelling. This ultimately benefits the design and appraisal of coastal flood defence schemes.
Objective 2	The proposed work provides an interface between the academic researchers (funded by research councils) and the users who can benefit from the improvements, providing that the project is steered appropriately.
Objective 3	The project will enable Defra and Environment Agency to be represented on the steering committee.
Objective 4	The purpose of this work is to ensure that the research proceeds in the most useful way for their needs, and to interpret and adapt the results of the research and report it in a way that can be comprehended by typical end-users.
Objective 5	A further objective is to develop a benefits and implementation plan to ensure that the sand transport research has a clear take-up route by practitioners.

The following work was undertaken by HR Wallingford.

Attending annual User Meetings, and in some cases Research Meetings as well, commenting on the usability of the research and proposing ways of making the results more readily usable by practitioners (re Obj. 1,2,3).

Reading reports and papers, giving practical feedback to the researchers (re Obj. 2,4).

Reporting to Environment Agency and Defra on progress with the project, in detail after each User Meeting, and by brief formal reports for administrative purposes (re Obj. 1,2,3).

Discussing with Environment Agency the most appropriate way of reporting the project's research results in a way which most benefits practical end-users, including the Environment Agency (re Obj. 4,5).

Evaluating the final SANTOSS model in terms of practical usability, versatility and ease of use (re Obj. 4,5).

Writing final report (re Obj. 4,5).

Appendix B. Publications from SANTOSS project

This list was supplied by the SANTOSS research team on 22/2/2010.

JOURNAL Publications

Van der A, D.A., O’Donoghue, T., Ribberink, J.S. (2010). Measurements of sheet-flow transport in acceleration-skewed oscillatory flow and comparison with practical formulations. *Coastal Engineering,* 57, 331-342.

Hassan, W.N.M., Ribberink, J.S. (2009). Modelling of sand transport under wave-generated sheet flow with a RANS diffusion model. *Coastal Engineering*, DOI: 10.1016/J.coastaleng.2009.08.009.

Van der Werf, J.J., Schretlen, J.L.M., Ribberink, J.S. & O'Donoghue, T. (2009). Database of full-scale laboratory experiments on wave-driven sand transport processes.*Coastal engineering*, 56(7), 726-732, DOI: 10.1016/j.coastaleng.2009.01.008.

Ming Li, Pan, S. & O’Connor, Brian A. (2008). A two-phase numerical model for sediment transport prediction under oscillatory sheet flows. *Coastal Engineering*, 55, 1159-1173.

Ribberink, J.S., Werf, J.J. Van der, O’Donoghue, T. & Hassan, W.N.M. (2008). Sand Motion induced by oscillatory flows: sheet flow and vortex ripples. *Journal of Turbulence*, 9(20), 1-32.

Van der Werf, J.J., Magar, V., Malarkey, J., Guizien, K. & O'Donoghue, T. (2008). 2DV Modelling of sediment transport processes over full-scale ripples in regular asymmetric oscillatory flow. *Continental Shelf Research*, 28(8), 1040-1056.

O'Donoghue, T., Ribberink, J.S. & Werf, J.J. Van der (2007). Insights on wave-generated sand transport processes from large-scale laboratory experiments (In Chinese). *Renmin zhujiang* (Pearl River), 2007(1), 10-15.

CONFERENCE papers

Van der A, D.A., Ribberink, J.S., Werf, J. J. Van der & O’Donoghue, T. (accepted). New practical model for net sand transport induced by non-breaking waves and currents. *32nd ICCE 2010, Shanghai*.

Schretlen, J.L.M., Ribberink, J.S. & O’Donoghue, T. (accepted). Boundary layer flow and sand transport under full-scale surface waves. *32nd ICCE 2010, Shanghai*.

Kranenburg, W.M., Ribberink, J.S. & Uittenbogaard, R.E. (accepted). Numerical reproduction of recent experiments on sand transport under full-scale surface waves. *32nd ICCE 2010, Shanghai*.

Van der A, D.A., O’Donoghue, T. & Ribberink, J.S. (accepted). Effects of acceleration skewness on oscillatory boundary layers and sheet-flow sand transport. *European IAHR conference, Edinburgh, 2010*.

Van der A, D.A., O’Donoghue, T. & Ribberink, J.S. (2009). Sheet-flow sand transport processes in oscillatory flow with acceleration skewness. *Proc. Coastal Dynamics ’09*, World Scientific, Tokyo, Japan, pp 1-15.

Schretlen, J.L.M., Ribberink, J.S. & O'Donoghue, T. (2009). Measurements and modelling of sand transport under full-scale surface waves, *Proc. Coastal Dynamics 2009*, World Scientific, Tokyo, Japan, pp. 1-13.

Schretlen, J.L.M., Werf, J.J. Van der, Ribberink, J.S., Kleinhans, M.G., Zuijderwijk, W.M. & O'Donoghue, T. (2009). New high-resolution measurements of wave boundary layer flow under full-scale surface waves. World Scientific, *Proc. 31st ICCE, Hamburg*, Germany, pp. 1559-1571.

Van der A, D.A., O’Donoghue, T., Davies, A. G. & Ribberink, J.S., (2009). Effects of acceleration skewness on rough bed oscillatory boundary layer flow. World Scientific, *Proc. 31st ICCE, Hamburg*, Germany, pp. 1583-1595

Schretlen, J.L.M., Werf, J.J. Van der, Ribberink, J.S., Uittenbogaard, R.E. & O'Donoghue, T. (2008). Surface wave effects on sheet-flow sand transport. London: Taylor & Francis Group, *Proc. River, Coastal and Estuarine Morphodynamics, RCEM* 2007, September 2007, Enschede, The Netherlands, Vol I, pp. 329-335.

O’Donoghue, T. & Ribberink, J.S. (2007). Laboratory experiments and the development of wave-driven sand transport models. In: P.M. Rowinski (Ed.), Transport Phenomena in Hydraulics, E-7 (401) (Publications of the Institute of Geophysics - Series E: Water Resources, 0138-0133) (pp. 177-195). Warsaw, Poland: Institute of Geophysics, Polish Academy of Sciences.

Campbell, L.J., O'Donoghue, T. & Ribberink, J.S. (2007). Wave boundary layer velocities in oscillatory sheet flow. World Scientific, *Proc. 30th ICCE*, September 2006, San Diego, USA. Vol. 3, pp. 2207-2219.

Rijn, L.C. van, Ruessink, B.G., Grasmeijer, B.T., Werf, J.J. Van der & Ribberink, J.S. (2007). Wave-related transport and nearshore morphology. ASCE, *Proc. Coastal Sediments `07*, May 2007, New Orleans, Louisiana, Vol I, pp. 1-14.

Werf, J.J. Van der, Ribberink, J.S. & O'Donoghue, T. (2007). Development of a new practical model for sand transport induced by non-breaking waves and currents. ASCE, *Proc. Coastal Sediments `07*, May 2007, New Orleans, Louisiana, Vol I, pp. 42-55.

Campbell, L. J., O’Donoghue, T. & Ribberink, J.S. (2006). Wave boundary layer velocities in oscillatory sheet flow. World Scientific, *Proc. 30th ICCE*, pp. 2207-2219.

O'Donoghue, T., Ribberink, J.S. & Werf, J.J. Van der (2006). Insights on wave generated sand transport processes from large-scale laboratory experiments. Guangdong Economy Publishing House, *Proc. Second International Conference on Estuaries and Coasts*, Guangzhou, China, Nov 2006, Vol. I, pp. 131-139.

PhD Theses

Van der A, D.A. (2010) *Effects of acceleration skewness on oscillatory boundary layers and sheet flow sand transport.* PhD Thesis. University of Aberdeen.

Schretlen, J.L.M. (in preparation). *Sand transport processes under full-scale surface waves*. PhD Thesis. University of Twente.

SANTOSS Reports

Schretlen, J.L.M. (in preparation). *Full-scale surface wave experiments*. SANTOSS_UT_IR4. University of Twente.

Ribberink, J.S., Van der A, D. & Buijsrogge, R.H. (2010). *SANTOSS transport model, A new formula for sand transport under waves and currents.* SANTOSS_UT_IR3. University of Twente and University of Aberdeen.

Van der A, D.A., (2009). *Intercomparison of sand transport formulae for acceleration skewed flows*. SANTOSS_AU_IR6. University of Aberdeen.

Van der A, D.A. (2008). *AOFT-Santoss-Series-D Experiments*. SANTOSS_AU_IR5. University of Aberdeen.

Van der A, D.A. (2008). *AOFT-Santoss-Series-C Experiments*. SANTOSS_AU_IR3. University of Aberdeen.

Campbell, L.J., O'Donoghue, T. (2008). *AOFT-Santoss-Series-B Experiments*. SANTOSS_AU_IR4. University of Aberdeen.

Malarkey, J. (2008). *A review of freestream descriptions and velocity and acceleration skewness.* Centre for Applied Marine Sciences, Bangor University, CAMS Rep. 2008-5 (SANTOSS report UWB_IR2).

Campbell, L.J. (2007). *AOFT-Santoss-Series-A Experiments*. SANTOSS_AU_IR2. University of Aberdeen

Werf, J.J. Van der (2007). *Development of a new practical model for net sand transport induced by non breaking waves and currents.* Civil Eng. & Man Res. Reports 2007R-009 / WEM-006 (Int. rep. 1568-4652). Water Engineering & Management (WEM).

Schretlen, J.L.M. & Werf, J.J. Van der (2006). *SANTOSS Database, Existing data from experiments in oscillatory flow tunnels and large wave flumes.* Report SANTOSS_UT_IR1. Civil Engineering & Management Research Report (Int. rep. 2006R-008/WEM-009). UT Universiteit Twente.

Campbell, L.J. (2005). *An overview of practical sand transport modelling*. SANTOSS_AU_IR1, University of Aberdeen.

Appendix C. Examples of Coastal Numerical Model applications

APPLICATIONS OF COSMOS AND PISCES/TELEMAC SEDIMENT TRANSPORT MODELS AT HR WALLINGFORD

Type of application	**Nature of project**	**Location UK**	**Location O/seas**	**Model COSMOS**	**Model PISCES**
Sediment transport pathways	Erosion of dynamic sand headland threatening roads, pipelines, housing		Kuwait	X	X
Beach stability and evolution	Threat to waterfront hotel and beach development from hurricanes		West Indies	X	
Beach stability and evolution	Coastal protection works		Italy	X	
Beach stability and evolution	Proposed renourishment		Malta	X	
Beach stability and evolution (Software sale + training)	Assessment of coastline protection schemes		Italy	X	
Beach stability and evolution	Water frontage development	Scarborough		X	X
Beach stability and evolution	Submerged breakwater design		Italy	X	
Sediment transport pathways	Sand bypassing, coastal nourishment with dredged material		Israel	X	X
Scour and shoreline impacts	Restriction of river mouth to aid self-scour of navigation channel		Italy		X
Sediment transport pathways and seabed evolution	Tidal reclamation		South Korea		X
Coastal impacts	Foreshore reclamation	Sussex			X
Harbour sedimentation	Harbour development		Namibia		X
Sediment transport pathways	Harbour designs	N Ireland			X
Bar development	Navigability of river mouth		Nigeria		X
Coastal impacts	Proposed new harbour	Gt Yarmouth			X
Coastal impacts	Nourishment	Harwich			X
Loss of sediment from beach	Design of artificial beach		Kuwait		X
Coastal impacts	Offshore reefs	E Anglia			X
Sediment transport pathways	New access channel to port		Vietnam		X
Sediment transport pathways	Harbour entrance	Chichester			X
Sediment transport pathways	Entrance to inlet	Walton/Naze			X
Sediment transport pathways	Coastal strategy study	Poole Bay			X
Channel sedimentation	Port rehabilitation		El Salvador		X
Channel stability	Effect of new bridge piers	Poole			X
Channel sedimentation	Port rehabilitation		India		X

Appendix D. SANTOSS sediment transport model formulation

The following description is taken from the report by Ribberink *et al.* (2010). For the present purpose, it has been shortened to omit some of the explanatory and derivation material. The original report gave formulations for two versions of the model: one which is applicable to the type of flow found in laboratory oscillatory water tunnels (for comparisons with measurements made during and before the SANTOSS project), and one which is applicable to flows with a free surface. Only the latter is relevant to practical applications at study sites, so only that version is given here. Anyone wishing to make use of the model is advised to read the original report by Ribberink *et al.* (2010) for more background detail. Note that a list of symbols and a glossary of terms can be found after the reference list in the present report.

Appendix D can be skipped by those who do not intend to make use of the SANTOSS formula themselves.

General

The new transport formulation is formed by extending and modifying the semi-unsteady model concept of Dibajnia and Watanabe (1998). In summary, the transport calculation with the new model can be described as follows:

i. Sediment loads stirred up during the wave crest and wave trough are calculated separately based on representative bed shear stresses for crest and trough.
ii. The magnitude of a phase-lag parameter determines the proportions of these loads which are transported during i) the same half-cycle as they were generated, and ii) during the next half-cycle.
iii. The phase-lag parameter is calculated as the ratio of stirring height and settling distance during each half-cycle.
iv. The Shields parameter for each half-cycle is calculated using a quadratic friction formula with input of the combined wave-current velocity at the edge of the wave boundary layer.

Velocities

The near bed velocity at the edge of the wave boundary layer, $z = \delta$, due to combined wave-current motion be defined as follows:

$$\vec{u}(t) = \vec{u}_\delta + \vec{u}_w(t) \tag{D.1}$$

with $\vec{u}_\delta$ the current velocity vector and $\vec{u}_w(t)$ the free-stream orbital velocity vector.

Consider the wave propagating in the x-direction and the current making an angle φ with the orbital velocity vector (Figure D.1).

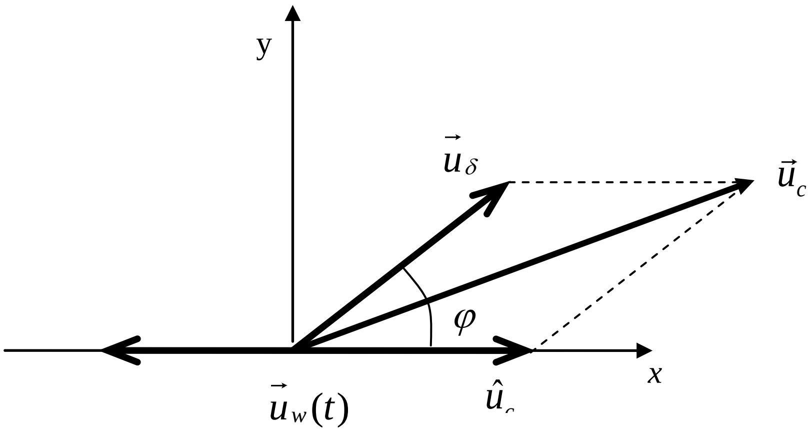

Figure D.1: Illustration of wave and current velocity vectors $\vec{u}_w(t)$ and $\vec{u}_\delta$. The vector $\vec{u}_c$ is the resultant velocity vector at maximum orbital velocity.

Assuming an arbitrary wave shape, the velocity in the *x*- and *y*-directions is given by:

$$u_x(t) = |u_\delta| \cos\varphi + u_w(t) \tag{D.2}$$

$$u_y = |u_\delta| \sin\varphi \tag{D.3}$$

Consider the wave shape as in Figure D.2, and define the combined wave-current velocity vectors at times of maximum and minimum orbital velocity as:

$$\vec{u}_c = \{u_{cx} \ , \ u_{cy}\} = \{\hat{u}_c + |u_\delta|\cos\varphi, \ |u_\delta|\sin\varphi\} \tag{D.4}$$

$$\vec{u}_t = \{u_{tx} \ , \ u_{ty}\} = \{-\hat{u}_t + |u_\delta|\cos\varphi, \ |u_\delta|\sin\varphi\} \tag{D.5}$$

where $\hat{u}_c$ and $\hat{u}_t$ are the peak crest and trough orbital velocity respectively (both are positive quantities). A characteristic orbital velocity amplitude $\hat{u}$ and the characteristic orbital excursion amplitude $\hat{a}$ for the full wave cycle are calculated in the following way:

$$\hat{u} = \sqrt{\frac{2}{T}\int_0^T u_w^2(t)\,dt} \tag{D.6}$$

$$\hat{a} = \frac{\hat{u}T}{2\pi} \tag{D.7}$$

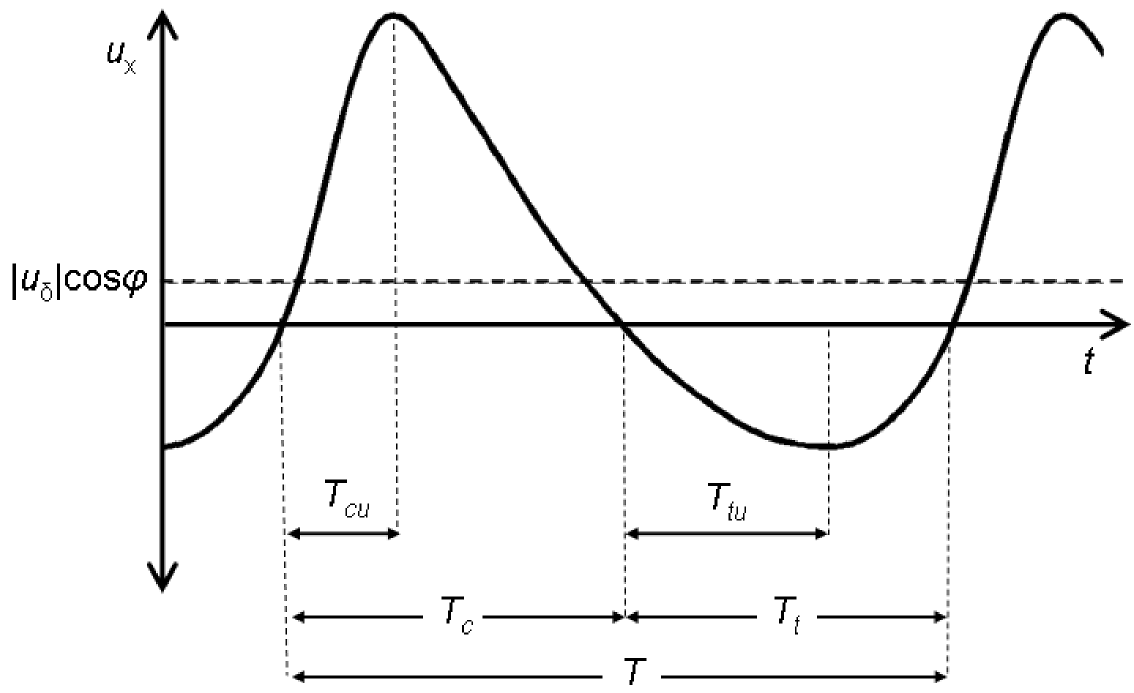

Figure D.2: Velocity time series in wave direction. T_c and T_t are the crest and trough periods, T_{cu} and T_{tu} are the crest and trough acceleration time lengths.

For the calculation of the sediment load and the transport during each half-cycle of the wave, we use a representative horizontal orbital velocity for the wave crest $\tilde{u}_{c,r}$ and for the wave trough $\tilde{u}_{t,r}$, defined as a root-mean square velocity assuming a sinusoidal wave shape as follows:

$$\tilde{u}_{c,r} = \hat{u}_c \frac{1}{2}\sqrt{2} \tag{D.8}$$

$$\tilde{u}_{t,r} = \hat{u}_t \frac{1}{2}\sqrt{2} \tag{D.9}$$

Similar to Equations D.4 and D.5, combined wave-current velocity vectors can be written for the two half-cycles:

$$\vec{u}_{c,r} = \{u_{c,rx}\ ,\ u_{c,ry}\} = \{\tilde{u}_{c,r} + |u_\delta|\cos\varphi,\ |u_\delta|\sin\varphi\} \tag{D.10}$$

$$\vec{u}_{t,r} = \{u_{t,rx}\ ,\ u_{t,ry}\} = \{-\tilde{u}_{t,r} + |u_\delta|\cos\varphi,\ |u_\delta|\sin\varphi\} \tag{D.11}$$

For *velocity-skewed* waves the crest velocity is larger than the trough velocity. This asymmetry is expressed in the velocity skewness parameter *R*, defined as:

$$R = \frac{\hat{u}_c}{\hat{u}_c + \hat{u}_t} \tag{D.12}$$

Moreover, the duration of the crest half-cycle T_c is smaller than the duration of the trough half-cycle T_t. A mean current component in wave propagation direction will lead to an extension of the crest period and a reduction of the trough period as shown in Figure D.2.

For *acceleration-skewed* waves (saw-tooth shape due to forward leaning waves) an acceleration skewness parameter β is used, based on the maximum magnitudes of the flow acceleration to the wave crest $\hat{\dot{u}}_c$ and to the wave trough $\hat{\dot{u}}_t$:

$$\beta = \frac{\hat{\dot{u}}_c}{\hat{\dot{u}}_c + \hat{\dot{u}}_t} \tag{D.13}$$

Moreover, for acceleration-skewed waves the acceleration time length of the crest T_{cu} is generally shorter than the acceleration time length for the trough T_{tu}, see Figure D.2.

In the new transport model the periods T_c, T_t, T_{cu}, T_{tu} are calculated on the basis of standard shapes for velocity-skewness (second-order Stokes) and for acceleration skewness (saw-tooth). This makes it possible to calculate the above-mentioned time-lengths on the basis of known wave period T, velocity-skewness parameter R and acceleration-skewness parameter β (see Appendix A of Ribberink *et al.* 2010 for more details).

Sediment grains move with the wave during the wave crest and against the wave during the wave trough (Lagrangian motion). In this way they experience a longer crest period $T_{c,sw}$ (= T_c + ΔT_c) and a shorter trough period $T_{t,,sw}$ (= $T_t - \Delta T_t$).

The extension/reduction ΔT of the half-cycle period depends on the ratio of the wave propagation velocity c and the horizontal grain displacement during the half wave-cycle (orbital diameter) d_g and can be written as:

$$\Delta T = \frac{d_g}{c} \tag{D.14}$$

Assuming a sinusoidal wave shape for the half-cycle horizontal grain motion the crest-period extension and trough period reduction can be written as follows (see Appendix B of Ribberink *et al.* 2010 for the derivation):

$$\Delta T_c = \frac{d_g}{c} = \left\{ \frac{c}{\zeta \hat{u}} \pi - 2 \right\}^{-1} T \tag{D.15}$$

During the wave trough, the period and orbital diameter are reduced and the following similar expression follows:

$$\Delta T_t = \frac{d_g}{c} = \left\{ \frac{c}{\zeta \hat{u}} \pi + 2 \right\}^{-1} T \tag{D.16}$$

Here ζ is the ratio of the horizontal grain-velocity amplitude and free-stream velocity amplitude, calibrated on the basis of measurements in a large wave flume as $\zeta = 0.55$ (Schretlen 2010).

The wave propagation velocity is calculated using an explicit formulation given by Soulsby (1997), see Equations D.50 to D.54. The Lagrangian half-cycle wave periods are calculated using Equations D.15 and D.16:

$$T_{c,sw} = T_c + \Delta T_c \tag{D.17}$$

$$T_{t,sw} = T_t - \Delta T_t \tag{D.18}$$

A vertical orbital velocity is present which affects the settling velocity of the grains. The following expressions for the vertical orbital velocity amplitude at elevation z near the bed $\hat{w}(z)$ are based on second-order Stokes wave theory, with h the water depth and H the wave height:

$$\hat{w}_1(z) = \frac{\pi H}{T}\frac{z}{h} \qquad \text{(first order)} \tag{D.19}$$

$$\hat{w}_2(z) = \hat{w}_1 2(2R-1) \qquad \text{(second order)} \tag{D.20}$$

The maximum amplitude (for $R \neq 0.5$) can be calculated with:

$$\hat{w}(z) = \frac{1}{8}\hat{w}_1\sqrt{64 - \frac{\left(-\hat{w}_1 + \sqrt{\hat{w}_1^2 + 32\hat{w}_2^2}\right)^2}{\hat{w}_2^2}} + \hat{w}_2 \sin\left(2\arccos\left(\frac{1}{8}\frac{-\hat{w}_1 + \sqrt{\hat{w}_1^2 + 32\hat{w}_2^2}}{\hat{w}_2}\right)\right) \tag{D.21}$$

Bed shear stress

The magnitudes of the total (non-dimensional) bed shear stress under the wave crest and trough are calculated through the Shields parameters:

$$|\theta_\mathrm{c}| = \frac{\frac{1}{2} f_{\mathrm{w\delta c}} |u_{\mathrm{c,r}}|^2}{(s-1)gd_{50}} \tag{D.22}$$

$$|\theta_\mathrm{t}| = \frac{\frac{1}{2} f_{\mathrm{w\delta t}} |u_{\mathrm{t,r}}|^2}{(s-1)gd_{50}} \tag{D.23}$$

with s the sediment specific gravity, $s = \rho_\mathrm{s}/\rho_\mathrm{w}$, where ρ_s is the sand density and ρ_w the water density, g the acceleration due to gravity and d_{50} the median grain-size of the sand bed. The x and y components of the (vector) Shields parameters are:

$$\theta_{cx} = |\theta_\mathrm{c}|\frac{u_{\mathrm{c,r}x}}{|u_{\mathrm{c,r}}|} = |\theta_\mathrm{c}|\frac{\left(\tilde{u}_{\mathrm{c,r}} + |u_\delta|\cos\varphi\right)}{|u_{\mathrm{c,r}}|} \tag{D.24}$$

$$\theta_{cy} = |\theta_\mathrm{c}|\frac{u_{\mathrm{c,r}y}}{|u_{\mathrm{c,r}}|} = |\theta_\mathrm{c}|\frac{(|u_\delta|\sin\varphi)}{|u_{\mathrm{c,r}}|} \tag{D.25}$$

$$\theta_{tx} = |\theta_\mathrm{t}|\frac{u_{\mathrm{t,r}x}}{|u_{\mathrm{t,r}}|} = |\theta_\mathrm{t}|\frac{(-\tilde{u}_{\mathrm{t,r}} + |u_\delta|\cos\varphi)}{|u_{\mathrm{t,r}}|} \tag{D.26}$$

$$\theta_{ty} = |\theta_\mathrm{t}|\frac{u_{\mathrm{t,r}y}}{|u_{\mathrm{t,r}}|} = |\theta_\mathrm{t}|\frac{(|u_\delta|\sin\varphi)}{|u_{\mathrm{t,r}}|} \tag{D.27}$$

Following Ribberink (1998), the combined wave-current friction factor at crest and trough are calculated as the linear combination of the wave friction factor (at crest and trough) and the current friction factor (see also Madsen and Grant 1976):

$$f_{\mathrm{w\delta c}} = \alpha f_{\delta} + (1-\alpha)\, f_{\mathrm{wc}} \tag{D.28}$$

$$f_{\mathrm{w\delta t}} = \alpha f_{\delta} + (1-\alpha)\, f_{\mathrm{wt}} \tag{D.29}$$

with

$$\alpha = \frac{\sigma |u_{\delta}|}{\sigma |u_{\delta}| + \hat{u}} \tag{D.30}$$

Factor σ is a calibration factor for wave + current conditions, calibrated as $\sigma = 3$.

The wave friction factor under the wave crest is defined as:

$$\begin{aligned} f_{\mathrm{wc}} &= 0.00251\exp\left[5.21\left(\frac{\left(\frac{2T_{\mathrm{cu}}}{T_{\mathrm{c}}}\right)^{2}\hat{a}}{k_{\mathrm{sw}}}\right)^{-0.19}\right] && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} > 1.587 \\ f_{\mathrm{wc}} &= 0.3 && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} \le 1.587 \end{aligned} \tag{D.31}$$

and under the trough is:

$$\begin{aligned} f_{\mathrm{wt}} &= 0.00251\exp\left[5.21\left(\frac{\left(\frac{2T_{\mathrm{tu}}}{T_{\mathrm{t}}}\right)^{2}\hat{a}}{k_{\mathrm{sw}}}\right)^{-0.19}\right] && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} > 1.587 \\ f_{\mathrm{wt}} &= 0.3 && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} \le 1.587 \end{aligned} \tag{D.32}$$

The current-related friction factor is calculated assuming a logarithmic velocity profile:

$$f_{\delta} = 2\left[\frac{0.4}{\ln\left(30\delta / k_{\mathrm{s}\delta}\right)}\right]^{2} \tag{D.33}$$

The current roughness height is based on grain roughness extended with additional mobile-bed roughness for the presence of the sheet-flow layer in the following way:

$$k_{\mathrm{s}\delta} = \max\{3d_{90}, d_{50}[\mu + 6(\langle|\theta|\rangle - 1)]\} + p.\eta^{2} / \lambda \tag{D.34}$$

The wave roughness height is provided with additional form roughness if wave ripples are present:

$$k_{\mathrm{sw}} = \max\{d_{50}, d_{50}[\mu + 6(\langle|\theta|\rangle - 1)]\} + p.\eta^2/\lambda \tag{D.35}$$

with

$$\mu = \begin{cases} 6 & \text{if } d_{50} \le 0.15 \text{ mm} \\ \left[6 + \left(10^3 d_{50} - 0.15\right)\frac{(1-6)}{(0.20-0.15)}\right] & \text{if } 0.15 \text{ mm} < d_{50} < 0.20 \text{ mm} \\ 1 & \text{if } d_{50} \ge 0.20 \text{ mm} \end{cases} \tag{D.36}$$

where p = 0.4 (calibration parameter) and d_{50} is in metres,

with the mean absolute Shields parameter according :

$$\langle|\theta|\rangle = \frac{\frac{1}{2} f_\delta |u_\delta|^2}{(s-1)gd_{50}} + \frac{\frac{1}{4} f_{\mathrm{w}} \hat{u}^2}{(s-1)gd_{50}} \tag{D.37}$$

The bed roughness for the sheet-flow regime is solved iteratively since the Shields parameter also depends on the bed roughness (Ribberink 1998). Here $\hat{u}$ is determined according Equation D.6, which for second order Stokes waves becomes:

$$\hat{u} = \sqrt{\frac{1}{2}\hat{u}_{\mathrm{c}}^2 + \frac{1}{2}\hat{u}_{\mathrm{t}}^2} \tag{D.38}$$

where for sinusoidal and acceleration skewed flow $\hat{u} = \hat{u}_{\mathrm{c}} = \hat{u}_{\mathrm{t}}$.

The 'total' wave friction factor f_{w} as used in Equation D.37 is based on Swart (1974)

$$\begin{aligned} f_{\mathrm{w}} &= 0.00251\exp\left[5.21\left(\frac{\hat{a}}{k_{\mathrm{sw}}}\right)^{-0.19}\right] && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} > 1.587 \\ f_{\mathrm{w}} &= 0.3 && \text{for} \quad \frac{\hat{a}}{k_{\mathrm{sw}}} \le 1.587 \end{aligned} \tag{D.39}$$

To take account of surface-wave effects, the wave Reynolds stress θ_{wRe} (Equation D.49) is added to the x-components of the bed shear stress (Equations D.24 and D.26) to enhance the crest x-component and reduce the trough x-component of the Shields parameter, while the y-components (Equations D.25 and D.27) are unchanged:

$$\theta_{\mathrm{c}x,\mathrm{sw}} = \theta_{\mathrm{c}x} + \theta_{\mathrm{wRe}} \tag{D.40}$$

$$\theta_{\mathrm{c}y,\mathrm{sw}} = \theta_{\mathrm{c}y} \tag{D.41}$$

$$\theta_{\mathrm{t}x,\mathrm{sw}} = \theta_{\mathrm{t}x} + \theta_{\mathrm{w_{Re}}} \tag{D.42}$$

$$\theta_{\mathrm{t}y,\mathrm{sw}} = \theta_{\mathrm{t}y} \tag{D.43}$$

and

$$\vec{\theta}_{\mathrm{c,sw}} = \left\{\theta_{\mathrm{c}x,\mathrm{sw}}, \theta_{\mathrm{c}y,\mathrm{sw}}\right\} \tag{D.44}$$

$$\vec{\theta}_{\mathrm{t,sw}} = \left\{\theta_{\mathrm{t}x,\mathrm{sw}}, \theta_{\mathrm{t}y,\mathrm{sw}}\right\} \tag{D.45}$$

The magnitude of crest and trough bed shear stress is now:

$$\left|\theta_{\mathrm{c,sw}}\right| = \sqrt{\theta_{\mathrm{c}x,\mathrm{sw}}^2 + \theta_{\mathrm{c}y,\mathrm{sw}}^2} \tag{D.46}$$

$$\left|\theta_{\mathrm{t,sw}}\right| = \sqrt{\theta_{\mathrm{t}x,\mathrm{sw}}^2 + \theta_{\mathrm{t}y,\mathrm{sw}}^2} \tag{D.47}$$

The wave Reynolds Shields parameter is:

$$\theta_{\mathrm{w\,Re}} = \frac{\tau_{\mathrm{wRe}}}{\rho_w (s-1) g d_{50}} \tag{D.48}$$

in which the wave Reynolds stress is calculated from:

$$\tau_{\mathrm{w\,Re}} = \rho \frac{f_{\mathrm{w\,Re}}}{2c} \alpha_w \hat{u}^3 \tag{D.49}$$

with $\hat{u}$ determined by Equation D.6 and $\alpha_w = 4/(3\pi) = 0.424$.

The friction coefficient $f_{\mathrm{wRe}} = f_{\mathrm{w}\delta}$ (combined wave current friction, making no distinction between crest and trough), is again defined as:

$$f_{\mathrm{w}\delta} = \alpha f_\delta + (1-\alpha) f_{\mathrm{w}}$$

using again the Equations D.33 and D.39 for both friction factors and the Equations D.34 to D.36 for the roughness height.

The wave propagation speed c can be calculated from:

$$c = \frac{L}{T} \tag{D.50}$$

with L given by the explicit approximation to the wave dispersion relation quoted by Soulsby (1997, p.71):

$$\xi_0 = \frac{4\pi^2 h}{g T^2} \tag{D.51}$$

For $\xi_0 \leq 1$:

$$\xi = \sqrt{\xi_0}(1 + 0.2\xi_0) \tag{D.52}$$

For $\xi_0 > 1$:

$$\xi = \xi_0 \left(1 + 0.2 \exp\left(2 - 2\xi_0\right)\right) \tag{D.53}$$

and

$$L = \frac{2\pi h}{\xi} \quad \text{(D.54)}$$

For the case in which a mean current is the only driving mechanism for sand transport the expressions reduce as follows:

$$|\theta_c| = |\theta_t| = \frac{\frac{1}{2} f_\delta u_\delta^2}{(s-1)gd_{50}} \quad \text{(D.55)}$$

with x and y components:

$$\theta_{cx} = |\theta_c| \cos\varphi \quad \text{(D.56)}$$

$$\theta_{tx} = |\theta_t| \sin\varphi \quad \text{(D.57)}$$

Transport

The dimensionless net transport is now calculated using the following 'velocity-load' formulation (in which the loads Ω are scalars):

$$\vec{\Phi} = \frac{\vec{q}_\mathrm{s}}{\sqrt{(s-1)gd_{50}^3}} = \frac{\sqrt{|\theta_\mathrm{c}|}T_\mathrm{c}\left(\Omega_\mathrm{cc} + \frac{T_\mathrm{c}}{2T_\mathrm{cu}}\Omega_\mathrm{tc}\right)\frac{\vec{\theta}_\mathrm{c}}{|\theta_\mathrm{c}|} + \sqrt{|\theta_\mathrm{t}|}T_\mathrm{t}\left(\Omega_\mathrm{tt} + \frac{T_\mathrm{t}}{2T_\mathrm{tu}}\Omega_\mathrm{ct}\right)\frac{\vec{\theta}_\mathrm{t}}{|\theta_\mathrm{t}|}}{T} \quad \text{(D.58)}$$

in which $\vec{\theta}_c = \vec{\theta}_{c,sw}$, $\vec{\theta}_t = \vec{\theta}_{t,sw}$, $T_c = T_{c,sw}$ and $T_t = T_{t,sw}$ are given by Equations D.44, D.45 and D.15 to D.18.

There are four contributions to the net sand transport:

- Ω_{cc} represents the sand load that is entrained during the wave crest period and transported during the crest period,
- Ω_{ct} represents the sand load that is entrained during the wave crest period and transported during the trough period,
- Ω_{tt} represents the sand load that is entrained during the wave trough period and transported during the trough period,
- Ω_{tc} represents the sand load that is entrained during the wave trough period and transported during the crest period

The load contributions are calculated in the following manner:

$$\Omega_\mathrm{cc} = \begin{cases} \Omega_\mathrm{c} & \text{if} \quad P_\mathrm{c} \le 1 \\ \dfrac{1}{P_\mathrm{c}}\Omega_\mathrm{c} & \text{if} \quad P_\mathrm{c} > 1 \end{cases} \quad \text{(D.59)}$$

$$\Omega_\mathrm{ct} = \begin{cases} 0 & \text{if} \quad P_\mathrm{c} \le 1 \\ \dfrac{(P_\mathrm{c}-1)}{P_\mathrm{c}}\Omega_\mathrm{c} & \text{if} \quad P_\mathrm{c} > 1 \end{cases} \quad \text{(D.60)}$$

$$\Omega_{tt} = \begin{cases} \Omega_t & \text{if} \quad P_t \le 1 \\ \dfrac{1}{P_t}\Omega_t & \text{if} \quad P_t > 1 \end{cases} \tag{D.61}$$

$$\Omega_{tc} = \begin{cases} 0 & \text{if} \quad P_t \le 1 \\ \dfrac{\left(P_t - 1\right)}{P_t}\Omega_t & \text{if} \quad P_t > 1 \end{cases} \tag{D.62}$$

The sand loads are described as:

$$\Omega_c = \begin{cases} 0 & \text{if } \left|\theta_c\right| \le \theta_{cr} \\ m\left(\left|\theta_c\right| - \theta_{cr}\right)^n & \text{if } \left|\theta_c\right| > \theta_{cr} \end{cases} \tag{D.63}$$

$$\Omega_t = \begin{cases} 0 & \text{if } \left|\theta_t\right| \le \theta_{cr} \\ m\left(\left|\theta_t\right| - \theta_{cr}\right)^n & \text{if } \left|\theta_t\right| > \theta_{cr} \end{cases} \tag{D.64}$$

where m and n are coefficients calibrated from a large dataset as m = 9.41 and n = 1.2.

The critical Shields number determined by (Soulsby 1997):

$$\theta_{cr} = \frac{0.3}{\left(1 + 1.2D^*\right)} + 0.055\left(1 - \exp\left(-0.02D^*\right)\right) \tag{D.65}$$

in which:

$$D^* = \left(\frac{(s-1)g}{\nu^2}\right)^{1/3} d_{50} \tag{D.66}$$

with ν the kinematic viscosity of water.

The phase lag parameters are calculated from:

$$P_c = \begin{cases} \alpha_r \dfrac{\eta}{2\left(T_c - T_{cu}\right)w_s} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha_s \dfrac{\delta_{sc}}{2\left(T_c - T_{cu}\right)w_s} & \text{if } \eta = 0 \text{ (sheet flow regime)} \end{cases} \tag{D.67}$$

$$P_t = \begin{cases} \alpha_r \dfrac{\eta}{2\left(T_t - T_{tu}\right)w_s} & \text{if } \eta > 0 \text{ (ripple regime)} \\ \alpha_s \dfrac{\delta_{st}}{2\left(T_t - T_{tu}\right)w_s} & \text{if } \eta = 0 \text{ (sheet flow regime)} \end{cases} \tag{D.68}$$

Herein α_s and α_r are coefficients calibrated from a large dataset as $\alpha_s = 8$ and $\alpha_r = 9.3$.

The settling velocities during crest and trough are now corrected with the vertical orbital velocity at level $z = r$ above the bed as follows:

$$
\begin{aligned}
w_{s,c} &= w_s + \hat{w}(r_c) \\
w_{s,t} &= w_s - \hat{w}(r_t) \;\; (\geq \; 0)
\end{aligned}
\tag{D.69}
$$

With :

$$
r_c = \begin{cases} \varepsilon\eta & \text{if } \; \eta > 0 \text{ (ripple regime)} \\ \varepsilon\delta_{sc} & \text{if } \; \eta = 0 \text{ (sheet flow regime)} \end{cases}
\tag{D.70}
$$

$$
r_t = \begin{cases} \varepsilon\eta & \text{if } \; \eta > 0 \text{ (ripple regime)} \\ \varepsilon\delta_{st} & \text{if } \; \eta = 0 \text{ (sheet flow regime)} \end{cases}
\tag{D.71}
$$

Factor ε is a coefficient calibrated from a large data-set as $\varepsilon = 3$.

The ripple height η and ripple length λ are based on O'Donoghue *et al.* (2006):

$$
\frac{\eta}{\hat{a}} = m_\eta n_\eta \left(0.275 - 0.022\psi_{max}^{0.42}\right)
\tag{D.72}
$$

$$
\frac{\lambda}{\hat{a}} = m_\lambda n_\lambda \left(1.97 - 0.44\psi_{max}^{0.21}\right)
\tag{D.73}
$$

where

$$
m_\eta = \begin{cases} 0.55 & \text{if } d_{50} \leq 0.22\,\text{mm} \\ 0.55 + \dfrac{0.45\left(10^3 d_{50} - 0.22\right)}{\left(0.30 - 022\right)} & \text{if } 0.22\,\text{mm} \leq d_{50} < 0.30\,\text{mm} \\ 1 & \text{if } d_{50} \geq 0.30\,\text{mm} \end{cases}
\tag{D.74}
$$

$$
m_\lambda = \begin{cases} 0.73 & \text{if } d_{50} \leq 0.22\,\text{mm} \\ 0.73 + \dfrac{0.27\left(10^3 d_{50} - 0.22\right)}{\left(0.30 - 022\right)} & \text{if } 0.22\,\text{mm} \leq d_{50} < 0.30\,\text{mm} \\ 1 & \text{if } d_{50} \geq 0.30\,\text{mm} \end{cases}
\tag{D.75}
$$

The following smooth transition from ripple-regime to flat bed/sheet-flow regime is used:

$$
n_\eta = n_\lambda = \begin{cases} 1 & \text{if } \psi_{max} \leq 190 \\ \dfrac{1}{2}(1 + \cos\left\{\pi \dfrac{\left(\psi_{max} - 190\right)}{\left(240 - 190\right)}\right\} & \text{if } 190 < \psi_{max} < 240 \\ 0 & \text{if } \psi_{max} \geq 240 \end{cases}
\tag{D.76}
$$

and:

$$
\psi_{max} = \frac{\hat{u}_c^2}{\left(s-1\right) g d_{50}}
\tag{D.77}
$$

The sheet-flow layer thickness δ_{si} is determined according the formula of Dohmen-Janssen (1999):

$$\frac{\delta_{si}}{d_{50}} = \begin{cases} 25.08\left|\theta_{wi}\right| & \text{if } d_{50} \leq 0.15 \text{ mm} \\ \left[25.08 + \left(10^3 d_{50} - 0.15\right)\frac{(13-25.08)}{(0.20-0.15)}\right]\left|\theta_{wi}\right| & \text{if } 0.15 \text{ mm} < d_{50} < 0.20 \text{ mm} \\ 13\left|\theta_{wi}\right| & \text{if } d_{50} \geq 0.20 \text{ mm} \end{cases} \qquad \text{(D.78)}$$

where $i = c,t$.

The empirical constant for fine sand ($d_{50} \leq 0.15$ mm) is adjusted from 35 to 25.08 in order to compensate for the increased mobile roughness for fine sand.

The fall velocity of suspended sand is computed using the formula of Soulsby (1997):

$$w_s = \frac{\nu}{0.8 d_{50}}\left(\sqrt{10.36^2 + 1.049 D_s^{*3}} - 10.36\right) \qquad \text{(D.79)}$$

in which:

$$D_s^* = \left(\frac{(s-1)g}{\nu^2}\right)^{1/3} 0.8 d_{50} \qquad \text{(D.80)}$$

Thus the median grain diameter of the suspended sand is assumed to be 80 per cent of the median grain diameter of the sand bed. For strongly non-uniform sediments, a better approach recommended by Ribberink (personal communication) is to split the mixture into fractions and use the mean settling velocity of the suspended fractions (with $w_s < 0.8u_*$).

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