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Journal of Hydraulic Research

ISSN: 0022-1686 (Print) 1814-2079 (Online) Journal homepage: http://www.tandfonline.com/loi/tjhr20

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To cite this article: Leo C. Van Rijn Consultant, Jan S. Ribberink Associate Professor, Jebbe Van Der Werf Engineer & Dirk J.R. Walstra Senior Engineer (2013) Coastal sediment dynamics: recent advances and future research needs, Journal of Hydraulic Research, 51:5, 475-493, DOI: 10.1080/00221686.2013.849297

To link to this article: http://dx.doi.org/10.1080/00221686.2013.849297

Journal of Hydraulic Research Vol. 51, No. 5 (2013), pp. 475–493
http://dx.doi.org/10.1080/00221686.2013.849297

Vision paper

Coastal sediment dynamics: recent advances and future research needs

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ABSTRACT
This vision paper discusses the advances made over the last three decades in coastal sand transport and morphodynamics, and the research needs for the coming decades. The prime focus of the paper is on the relationship between the transport of sand particles and fluid motions in the coastal environment based on laboratory and field experiments as well as mathematical modelling. The paper mainly focuses on two main issues: (1) better understanding of sediment transport processes in the coastal zone and (2) the development of improved practical engineering sand transport formulae and morphodynamic models.

Keywords: Coastal modelling; coastal processes; morphodynamics; sediment transport; waves

1 Introduction

The motion of coastal sediment particles under the influence of tide, wind and wave-driven processes is a complex but intriguing problem that is far from being solved. The formidable task is to merge laboratory experiments, field observations and theoretical developments, and to provide scientific insights and engineering solutions of coastal sediment problems. Over many decades, researchers and engineers inspired by coastal sediment phenomena have conducted field and laboratory experiments to learn more about coastal sediment dynamics. Their efforts have resulted in a wealth of papers and documents published in journals, conference and symposium proceedings over the last 50 years.

The last three decades have been particularly fruitful in advancing the fundamental understanding of coastal processes. At the beginning of the 1980s, the knowledge of sediment concentrations under shoaling and breaking waves in the surf zone was rather scarce. The lead author of this paper recalls his efforts to gain information on coastal sand transport by collecting water-sediment samples under breaking waves on a Tunesian beach during his summer vacation in 1980 using small limonade bottles taken from the hotel. Since then, many more ambitious (field and laboratory) experiments have been completed and sand transport models have been developed by coastal researchers in the USA, Japan and Europe trying to systematically unravel the complex coastal sediment transport problem.

This vision paper describes the progress we have made in recent decades and explores the future research needs of the dynamics of sand particles in the coastal environment. The nature of the relationship between the transport of sand particles and fluid motions in the coastal environment is the prime focus of this paper. Two main research approaches are discussed aimed at: (1) better understanding of sediment transport processes in the coastal zone and (2) the development of improved practical engineering sand transport and morphodynamic models. Although

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Received 7 September 2013; accepted 24 September 2013/Open for discussion until 30 April 2014.

ISSN 0022-1686 print/ISSN 1814-2079 online
http://www.tandfonline.com

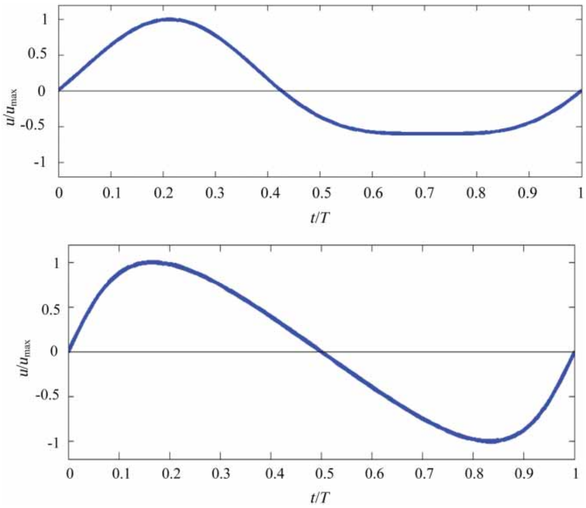


Figure 1 Time series of horizontal near-bed orbital velocity showing velocity skewness on the shoreface before wave breaking (upper) and acceleration skewness in the surf zone (lower)

the emphasis is on sand transport mechanics, the application of sand transport formulations in morphodynamic models is also briefly discussed.

2 State-of-the-art of coastal sediment dynamics

2.1 *Wave forcing and transport regimes*

When short gravity waves approach the shore they deform due to the influence of the changing water depth. In the outer surf zone, the wave crest gets higher and the wave crest period shorter, whereas the wave trough gets smaller and the wave trough period longer, see also Fig. 1 (upper). This wave deformation is referred to as wave skewness. Moving shoreward waves become steeper and then most of them break, after which the remaining waves have a sawtooth shape with a relatively steep wave front, which is called wave asymmetry (forward leaning waves). Further shoreward the swashzone is developed which is dominated by the uprush and backswash. Wave skewness and asymmetry also appear in the near-bed orbital velocity, where it is commonly referred to as velocity skewness and acceleration skewness (Fig. 1).

As sand transport is nonlinearly related to the near-bed velocity, waves are able to generate a net sand flux in the cross-shore direction (on- and offshore). We call this phenomenon the wave-related sand flux $\tilde{u}\tilde{c}$ as it is due to the interaction between the oscillating component $\tilde{u}$ of the flow and the sand concentration $\tilde{c}$. The wave-related sand transport component is generally computed as the vertical integral of $< \tilde{u}\tilde{c} >$, where the brackets indicate wave-averaging. Waves also induce net currents, notably wave boundary layer streaming and breaking-induced cross-shore and longshore currents (Fig. 2). These net currents are also able to transport sand particles, and we refer to this component as the current-related transport, which follows from the vertical integral of uc, where u is the time-averaged fluid velocity and c is the time-averaged sand concentration.

The cross-shore sand transport, in particular the wave-related component, is not fully understood due to the complex interaction processes between the flow, suspended sand and the seabed, occurring in the wave boundary layer of the thickness of the order of centimetres. We can identify two distinct transport regimes depending on the particle mobility number $\psi_{\max} = (U_{\max})^2/[(s-1)gD_{50}]$, where $U_{\max}$ is the maximum orbital velocity, $s = \rho_s/\rho$ the relative sand density ($\approx$ 2.65), ρ_s the sand density, ρ the water density, g the acceleration due to gravity and D_{50} the median grain

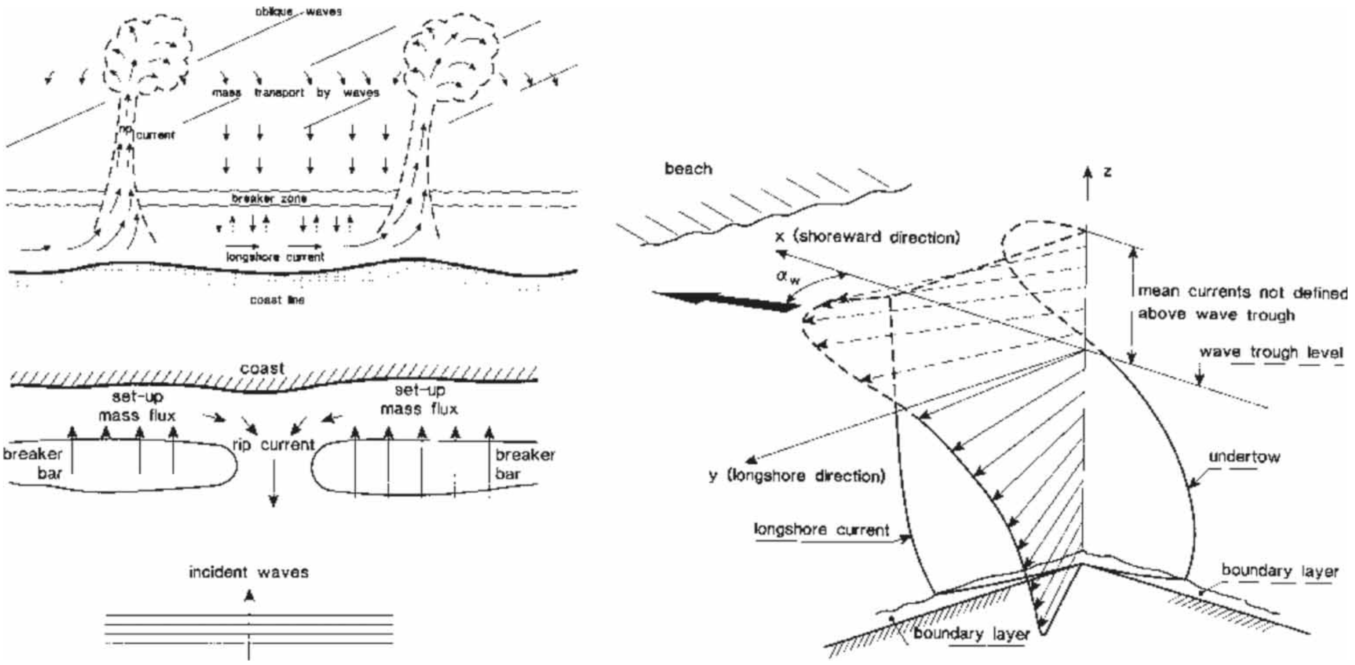


Figure 2 3D flow velocity pattern in surf zone size. These regimes are: (1) rippled-bed regime at $\psi_{\max} < 190$ and (2) flat-bed, sheet-flow regime at $\psi_{\max} > 240$ (Traykovski *et al*. 1999, O'Donoghue and Wright 2004a, 2004b). The transition between these two occurs in the range $190 < \psi_{\max} < 240$. The flat-bed sheet-flow regime is observed for larger orbital velocities (storm waves in relatively shallow water) and for fine sands ($\psi_{\max} > 240$ or Shields' parameter $\Theta > 0.8$). The wave-related sand transport is then confined to a thin layer with a thickness of the order of 1 cm near the bed, the sheet-flow layer, with large sand concentrations (10–60% by volume). Flow and sand dynamics over rippled beds differ strongly from flat-bed oscillatory flows (Ribberink *et al*. 2008), especially for relatively steep, vortex ripples with ripple steepness $\eta/\lambda > 0.1$, where η is the ripple height and λ the ripple length. In this later case, flow separation and coherent vortex motions dominate the entrainment, transport and resettling of sand grains.

Due to the complexity of the dynamic interactions near the seabed, understanding and modelling of sand transport rely heavily on experimental research in both field and laboratory conditions. In Sections 2.2–2.4, we focus on results from large-scale laboratory experiments as performed in large oscillatory flow water tunnels and large wave channels (Fig. 3). In oscillatory flow water tunnels, the near-bed sediment dynamics in wave bottom boundary layer (WBBL) can be investigated relatively easily at full scale and in great detail. Large-scale wave flumes are less suitable for this type of detailed research but on the other hand they enable a better reproduction of the wave-induced flows, including the relatively small vertical orbital velocities and mean flows (streaming). Therefore, both types of experiments are important and complementary.

2.2 *Sheet-flow transport in the WBBL*

Many new insights on the sand transport processes at oscillatory sheet-flow conditions have been gained in the recent decades. This progress can mainly be attributed to extensive laboratory investigations in oscillatory flow tunnels in Japan, the UK and in the Netherlands (Dibajnia and Watanabe 1992, O'Donoghue and Wright 2004b, Ribberink and Al-Salem 1994). In contrast to earlier sand transport formulas

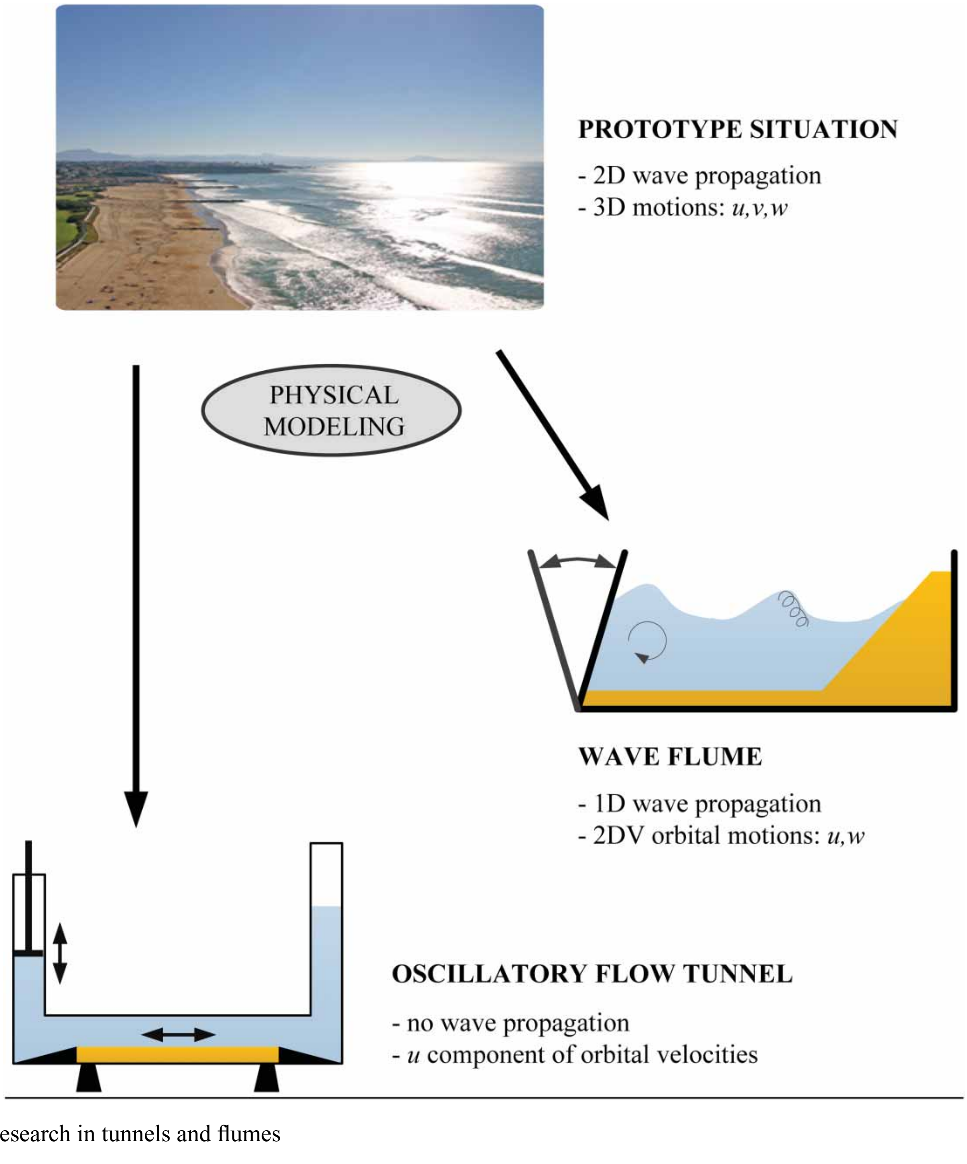


Figure 3 Laboratory research in tunnels and flumes

(Bagnold 1963, Bailard 1981), the experiments showed that the net sand transport under skewed and asymmetric oscillatory flows cannot always be linearly related to the third-order moment of the horizontal orbital velocity U near the sea bed $\langle U^3 \rangle$ (Van der Werf *et al.* 2009). More recent wave tank experiments extended these insights to sheet flows under skewed progressive surface waves (Dohmen-Janssen and Hanes 2002). Detailed measurements inside the bottom boundary layer and sheet-flow layer with new measuring techniques such as conductivity concentration metre (CCM based on electrical conductivity measurement; Ribberink and Al-Salem 1994, McLean *et al.* 2001) gave new insight in the sheet-flow dynamics. In addition to this experimental research, process-based modelling with single-phase and two-phase flow models have also contributed to the interpretation of the observed sheet-flow phenomena and net sand transport behaviour (Dong and Zhang 1999, Davies *et al.* 2002).

The sheet-flow layer is a thin near-bed region in the lower part of the WBBL with a typical two-layer structure, consisting of a pick-up layer below the original "no flow" bed level and an upper sheet-flow layer above. The immobile bed level fluctuates due to sand pick-up and deposition each half-wave cycle, and as a result both sheet-flow layers show opposite concentration variations due to vertical sediment exchange between the layers (Ribberink and Al-Salem 1994, McLean *et al.* 2001, Dohmen-Janssen and Hanes 2002, O'Donoghue and Wright 2004a, 2004b). Combined intra-wave velocity and concentration measurements reveal that although suspension is present above the sheet-flow layer, the bulk of the sand flux along the bed is concentrated in the sheet-flow layer. This happens even when a net current is added to the oscillatory flow and also for fine sand in the suspension regime under progressive surface waves (Ribberink *et al.* 2008, Schretlen 2012).

Skewness of the near-bed oscillatory flow velocity, as occurring on the shoreface (Fig. 1), often leads to a net sand transport in the direction of the high positive velocity ("onshore" direction). This is caused by the nonlinear relation between the sediment transport (q_s) and velocity (U) resulting in: $\langle q_s \rangle \sim \langle U^3 \rangle$, which exists for medium and coarse sand (Ribberink and Al-Salem 1994, Dibajnia and Watanabe 1998). However, for fine sand and large orbital flow velocities the sheet-flow layer may be relatively thick (up to 2 cm) and the sand concentrations show an increasing phase lag with the time-dependent velocity. Sediments entrained from the bed during one half-cycle do not resettle to the bed before flow reversal, being still in the water column during the next half-cycle and transported in the opposite direction. In velocity-skewed oscillatory flows, with relatively large velocities and large sand entrainment during the onshore part of the wave cycle, this phase-lag effect can lead to a net sand transport in the offshore direction (Ribberink and Chen 1993, O'Donoghue and Wright 2004a, 2004b, Hassan and Ribberink 2005).

Asymmetric or forward leaning waves, as occurring in the surf zone (Fig. 1), lead to acceleration skewness of the near-bed oscillatory flow (Hoefel and Elgar 2003, Elfrink *et al.* 2006). Detailed boundary layer measurements in a large-scale flow tunnel over fixed rough beds show a distinct asymmetry in the turbulence intensities and (bed) shear stresses between the high-acceleration positive flow and its low-acceleration negative counterpart (Van der A *et al.* 2011). This asymmetry is the main cause for a net sand transport in the direction of highest acceleration (="onshore" direction; Watanabe and Sato 2004, Van der A *et al.* 2010, Ruessink *et al.* 2011, Silva *et al.* 2011). Again, the phase-lag phenomenon may play an important role for fine sands but now in enhancing positive net transport, which is in marked contrast to its negative effect in velocity-skewed flow.

In parallel with insightful studies in oscillatory flow tunnels, complementary sheet-flow experiments were carried out under large-scale progressive surface waves in a large-scale wave channel (Ribberink *et al.* 2000, Dohmen-Janssen and Hanes 2002). It has been found that the net sand transport under skewed surface waves is generally more onshore directed than in flow tunnels. Later flume experiments of Schretlen (2012) revealed that although the time-dependent sheet-flow dynamics are very similar to that in oscillatory flow tunnels, the offshore net transport of fine sand occurring in tunnels is not observed in wave channels. Furthermore, under comparable velocity-skewed oscillatory flows in wave channels the net transport is directed onshore rather than offshore as in the oscillatory tunnels. An important hydrodynamic difference between tunnels and wave channels is the (relatively small) offshore-directed mean flow in the "tunnel" WBBL (streaming). In oscillatory water tunnels, velocity-skewed flows induce a small "offshore"-directed mean flow near the bed due to the time-dependency of the turbulent stresses during the wave cycle (Ribberink and Al-Salem 1994, Davies and Li 1997, Scandura 2007, Gonzalez-Rodriguez and Madsen 2011). Also, acceleration-skewed oscillatory flows generate a similar negative streaming close to the bed (Van der A *et al.* 2011). Under progressive surface waves a competing "onshore" directed streaming component exists due to the presence of vertical orbital velocities and a net vertical momentum exchange between the free stream and the wave boundary layer (wave Reynolds stress; Longuet-Higgins 1953, Trowbridge and Madsen 1984a, 1984b). Schretlen *et al.* (2011) carried out detailed flow measurements in the WBBL and in the sheet-flow layer under large-scale skewed waves in the large wave channel in Hannover Grossen Wellenkanal (GWK) (see also Schretlen 2012). In these "mobile bed" conditions the wave-averaged mean flow (streaming) above the sheet-flow layer appeared to be more onshore directed than in comparable oscillatory (tunnel) sheet flows. Most of the (onshore directed) net transport is concentrated in the deeper parts of the sheet-flow layer (pick-up layer) and is mainly current related. In this layer, an onshore mean current is induced by erosion depth asymmetry, i.e. the deepest immobile bed layers are only eroded and transported during the onshore part of the wave cycle when the largest orbital velocities occur.

Process-based boundary layer models, especially single-phase models consisting of a Reynolds-averaged Navier–Stokes (RANS) model for the hydrodynamics and an advection–diffusion (AD) model for the sand concentrations have been very helpful in providing physical explanations for the net sediment transport behaviour in the sheet-flow regime as observed in the laboratory experiments. Using different turbulence closures, these 1 dimensional vertical (DV) models have been employed successfully for explaining grain-size effects, phase-lag effects, effects of wave skewness, asymmetry and wave–current interaction (Davies and Li 1997, Guizien *et al.* 2003, Holmedal and Myrhaug 2006, Hassan and Ribberink 2010, Blondeaux *et al.* 2012). With a suitable reference concentration formulation (Fredsoe and Deigaard 1992, Zyserman and Fredsøe 1994) these models, sometimes combined with a separate bedload formula, also form a useful practical tool for quantitative predictions of the net transport rate in the sheet-flow regime (Davies *et al.* 2002, Ruessink *et al.* 2009, Fuhrman *et al.* 2013). Kranenburg *et al.* (2012, 2013) use two different single-phase boundary layer models, a purely "oscillatory flow version" and a "progressive surface wave version", the latter also including the important advective terms in the momentum and concentration equations. It is shown that with this type of models a good qualitative and quantitative reproduction of mean flows (streaming) as well as of net sand transport rates for skewed waves as measured in wave tunnels and in wave channels, including also the interesting fine sand cases, can be obtained (Fig. 4). More detailed investigations with these models confirm the important role of onshore wave streaming (due to wave Reynolds stress effect) for the net sand transport under progressive surface waves and reveal the importance of horizontal sediment advection. Under progressive surface waves the near-bed sediment flux is not only controlled by the local flow/sediment conditions (vertical entrainment and deposition) but can also be affected by horizontal advection of sediment from neighbouring locations which are earlier or later in the wave phase. Horizontal intra-wave gradients in this advective sediment flux cause increased sediment concentrations under the wave crest and decreased concentrations under the trough and finally lead to an additional onshore net sediment transport component. This advection process is directly related to the net horizontal Lagrangian displacement of sediment particles in onshore direction and is especially significant in the case of fine sand when phase-lag effects exist (Kranenburg *et al.* 2013).

Two-phase flow models, with separate momentum equations for water and sand (Asano 1990), provide a better physical basis and a more realistic continuous representation of the sheet-flow layer dynamics than single-phase models. These two-phase models include the (fluctuating) immobile bed level and the suspension layer above. Different closure models are used for inter-granular stresses (Dong and Zhang 1999, Amoudry *et al.* 2008). Although much conceptual uncertainty still exists and calibration is required, two-phase flow models appear to be a useful tool for reproducing a number of important sheet-flow characteristics and net sand transport rates in flow tunnels. Kranenburg (2013) shows that grain-size effects and progressive surface wave effects on streaming and sand flux inside the sheet-flow layer can be reproduced in a satisfactory way for skewed waves.

2.3 *Sand transport over rippled beds in the WBBL*

Measurements of the flow field around ripples in full-scale velocity-skewed oscillatory flow conditions (Sato 1987, Clubb 2001, O'Donoghue and Clubb 2001, Thorne *et al.* 2002, Van der Werf 2006, Van der Werf *et al.* 2007) show the development of a strong vortex at the lee side of the ripple during the onshore-directed half-wave cycle, when the highest velocities occur. After the on–offshore flow reversal, this vortex is transported over the ripple crest in the offshore direction. During the offshore

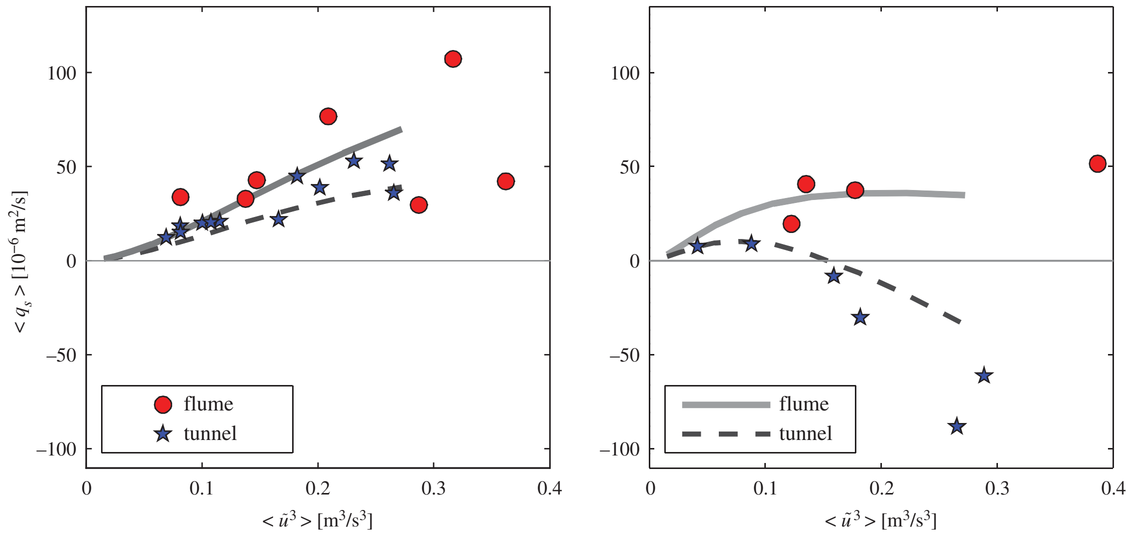


Figure 4 Comparison between computed net transport rates (lines) and measured net transport rates (symbols) for skewed oscillatory flows (tunnel) and surface waves (flume) for increasing near-bed orbital velocity ($\langle \tilde{u}^3 \rangle$) and for two grain sizes; left plot is for medium sand (0.2 mm) and right plot is for fine sand (0.13 mm).
Source: Kranenburg (2013)

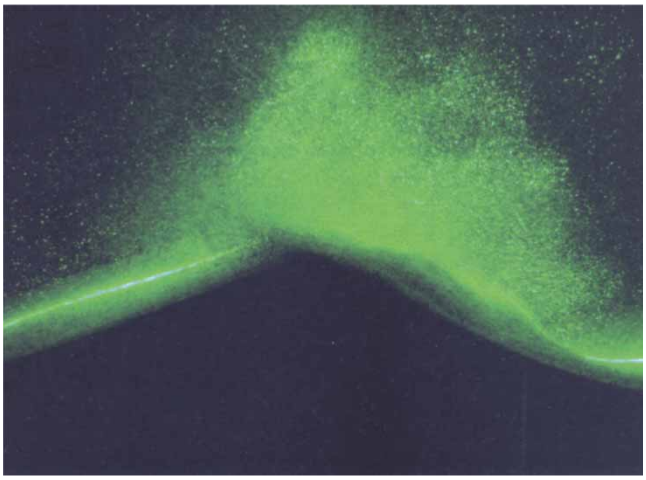


Figure 5 Sand particles in suspension near ripple crest (Van der Werf 2006)

half-wave cycles, velocities are lower due to the velocity skewness, and a similar but less strong vortex develops on the other side of the ripple. After the off–onshore flow reversal, this vortex is also transported over the ripple crest but now in the onshore direction. This process of oscillatory vortex shedding leads to a boundary layer dominated by coherent vortex motions extending up to approximately two ripple heights above the ripple crest.

The vortices are often strong enough to bring sand grains into suspension and to generate a near-bed transport layer dominated by suspended sand (Fig. 5). The measurements confirm that waves induce secondary mean current cells on both sides of the ripples directed upwards on both ripple flanks towards the crest. Van der Werf *et al.* (2006) showed that the wave- and ripple-averaged concentration profile in a near-bed layer of approximately three ripple heights thick can generally be described as an exponentially decaying function of the distance above the ripple crest. Exponential concentration profiles are associated with diffusive processes with a height-independent sand diffusivity. However, suspended sand concentrations above rippled beds are largely controlled by coherent advective processes associated with lee-side vortices. Therefore, Nielsen (1992) argued that both advective and diffusive mechanisms are involved in the sand entrainment process and that a combined description of these processes is required.

Van der Werf *et al.* (2007) have combined the measured particle velocities and concentrations to obtain the intra-wave vector sand flux field. The authors found that the highest wave-averaged fluxes occur near the ripple surface along the side slopes and are directed upward toward the ripple crest. This reflects the upward flow along both ripple flanks which is continuously present during both half-wave cycles. Due to the velocity skewness, the negative flux at the onshore ripple flank is dominant as the lee-side vortex is much stronger here and traps more sediment than its counterpart on the offshore flank. Furthermore, Van der Werf *et al.* (2007) demonstrated that both wave- and current-related flux components are important for the total flux. The current-related flux dominates near the ripple surface, while the wave-related flux dominates at higher elevations (up to one ripple height above the ripple crest level). Both flux components are higher above the onshore than above the offshore ripple flank, reflecting velocity skewness. Further analysis of these detailed flux and ripple-shape data showed that the total net sand transport under these skewed oscillatory flows is negative (“offshore”) and consists of a positive bedload component and a negative net suspended sand transport of similar magnitude (Ribberink *et al.* 2008). New powerful acoustic instruments are now available to simultaneously measure the flow, concentration and hence the sand flux fields around ripples (Hurther and Thorne 2011) promising new details on transport mechanisms.

Early modelling of the flow and sand concentrations around ripples was done by Malarkey and Davies (2002) and Davies and Thorne (2005). Li and O’Connor (2007) applied a 3D RANS model of the full water column to study sediment transport above rippled beds under the action of combined waves and currents (co-linear and normal). They showed that a current considerably influences vortex dynamics and associated sand transport processes. In particular, the vortices generated under combined effect of waves and currents tend to stay low in the trough area of the ripple and are ejected earlier than those in the waves-alone case at both the ripple crest and trough, which leads to concentration peaks at different phases and with different magnitudes. Van der Werf *et al.* (2008) have shown that two different boundary layer models (2DV $k-\omega$ turbulence closure model and a discrete-vortex particles-tracking model) can reproduce the time-dependent velocities and suspended sand concentration above vortex ripples which are controlled by vortex generation and shedding. The process-based models confirm offshore-directed time- and ripple-averaged horizontal velocity (streaming) close to and below the ripple crest, the near-bed region of exponential decay in the time- and ripple-averaged concentrations and the net offshore-directed net suspended sand flux. The latter was found to be consistent with the measured total net offshore sand transport once the onshore bedload transport was taken into account, which demonstrates the importance of models being able to predict bedload transport rates as well.

Penko *et al.* (2013) have presented a 3D boundary layer model that solves the unfiltered Navier–Stokes and AD equation. They show that while flow statistics of the 2DV plane from the 3D simulation are in good agreement with the observations from wave flume experiments, the 2DV analysis does not show the three-dimensionality of the vortex generation, dissipation and suspended sediment concentration. The simulated suspended sediment reveal significant variations in concentration in the cross-flow direction, and using different methods to calculate the vertical profile of time- and spatially-averaged sediment fluxes give an order of magnitude difference. This difference may be attributed to the cross-flow variation in the hydrodynamics caused by vortices dissipating non-uniformly due to the random turbulent fluctuations. The results suggest that while a 2DV plane may be sufficient to obtain a general idea of the hydrodynamics over vortex ripples, 3D analysis is necessary for a complete understanding of sediment transport.

2.4 *Suspended sand transport under breaking waves*

Breaking waves in the surf zone generate an additional sediment stirring effect, caused by the breaking-induced flows and enhanced turbulent kinetic energy in the water column. This additional stirring effect is observed during several experimental laboratory studies for different types of wave breaking (e.g. spilling or plunging waves). Wave breaking-induced turbulence may also interfere, often in an intermittent way, with the WBBL turbulence and lead to increased bed shear stresses and additional bedload transport, pick-up and turbulent mixing of suspended sediments.

In the recent decades a large number of laboratory flume studies over fixed beds focused on the important hydrodynamics under breaking waves in the water column, above the bottom boundary layer. Only few studies involved some examination of the effects of breaking-induced turbulence on the boundary layer and bed shear stress. They were carried out in an oscillatory flow tunnel using artificial grid-turbulence (Fredsoe *et al.* 2003) or in small-scale wave flumes with low Reynolds number wave conditions. The dynamics of coherent structures induced by breaking waves can be visualized and quantified nicely with particle imaging velocimetry (PIV) techniques.

The results of a recent large-scale flume experiment with breaking waves (CROSSTEX) have shown that near-bed sediment suspension dynamics has an intermittent character that strongly correlates with local breaking wave turbulence and also with strong pressure gradients and sediment advection from other locations (Scott *et al.* 2009, Yoon 2011, Yoon and Cox 2012). Measurements of suspended sediment fluxes during CROSSTEX show that these suspension events near the bed are highly relevant for the beach profile changes. The character of turbulence related to breaking waves is significantly different for spilling and plunging breakers and the timing of increased turbulence intensity reaching the bed is probably crucial for the direction of an additional wave-related suspended sediment flux (Scott *et al.* 2009, Van Thiel de Vries 2009).

Sediment advection with the undertow and/or through long wave motions (Scott *et al.* 2009) may play a role in the surf zone or from the swash into the inner surf zone (Alsina and Cacares 2011). This means that suspended sediment transport is no longer only determined by local vertical pick-up and deposition processes and local hydrodynamics but also by incoming sediment fluxes from neighbouring locations with different hydrodynamics.

Some models for inner surf zone and swash applications account for horizontal and/or vertical advection of suspended sediment by using shallow-water flow equations (including bore effect) combined with depth-integrated suspension models for the intra-wave suspended sediment concentration (Kobayashi and Johnson 2001, Reniers *et al.* 2013). Li and O'Connor (2007) use an intra-wave 3D RANS boundary layer model for sediment suspension over rippled beds including wave-breaking effects and show the influence of timing of surface-generated turbulence reaching the bed during certain phases of the wave cycle. Christensen *et al.* (2000) also use an intra-wave RANS model and show, although turbulence levels are generally overprediced, that the model is able to predict the correct net transport direction, i.e. onshore transport for plunging breakers and offshore transport for spilling breakers. Bakhtyar *et al.* (2010) report some first experiences with an intra-wave two-phase RANS flow/sediment model for the inner surf and swash zone. Suzuki *et al.* (2007) use an intra-wave Large Eddy Simulation (LES) model together with a sediment pick-up function. They reproduce the intermittency of the suspension process and show the existence of noticeable sediment pick-up areas in the surf zone. In general, the advanced models show qualitative agreement with observed sediment dynamics in the surf zone and are useful tools to interpret measurements and to study the surf zone dynamics.

2.5 *Sand transport in field conditions*

Field studies of sand transport in the surf zone of sandy beaches have been conducted over many decades. The pioneering work in the USA was done by Kana (1979) and Kraus (1987) using mechanical samplers employed by the authors themselves standing in the water. These early attempts gave a first impression of the magnitude of the sand concentrations generated by breaking waves in the surf zone. Later, various permanent field stations consisting of piers running into the sea have been built in the USA (Duck) and in Japan (HORS). Various dedicated field experiments combining electronic instruments and mechanical samplers for calibration purposes have been carried out resulting in extensive databases on hydrodynamics, sediment concentrations and bed forms. Many papers have been published presenting the results of these studies.

A significant milestone in the field work was the experimental campaign completed at the Duck pier between 1995 and 1998 in the USA (Miller 1999). Measurements of velocities and suspended sediment concentration were performed at about 10 positions across the barred beach of Duck in waves up to 3.5 m to provide an estimate of the suspended load transport. The bed sediments consisted of fine to medium sand (0.15–0.3 mm). The overall bed slope in the surf zone between the shoreline and the 5 m depth contour was about 1–40. The velocity and concentration measurements were taken by means of instruments attached to the lower boom of a track-mounted crane (sensor insertion system, SIS) on the deck of the field research pier. The SIS was able to place instrumentation on the bottom at depths up to 9 m, up to 15 m away from the pier pilings. Using data records of about 8 min, about 10 cross-shore positions could be sampled. The vertical array of instruments consisted of eight optical concentration sensors and four electromagnetic current metres. The lowest (bottom) concentration sensor was about 3 cm above the bed. The depth-integrated longshore suspended sand transport at each position was computed by multiplying the instantaneous concentration times the instantaneous longshore velocity and

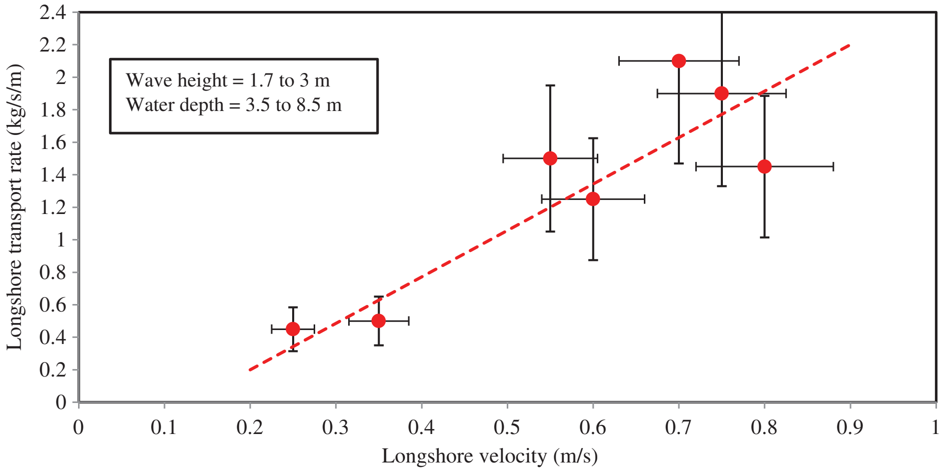


Figure 6 Longshore sand transport in surf zone of Duck (USA)

time-averaging the products. Some results of longshore transport are shown in Fig. 6.

Similar field experiments have also been performed in Europe (Great Britain, The Netherlands, Denmark and France). The most significant study in Europe was the COAST3D-field experiment in the period from 1995 to 2000 (Grasmeijer 2002, Van Rijn *et al.* 2002). The experiments were performed at two contrasting sites: (1) a quasi-uniform (2D) stretch of the Dutch coastline (Egmond) and (2) a fully 3D site (Teignmouth) on the UK coast. A large-scale vehicle (WESP) with trailer was built to measure instantaneous velocities and suspended sand concentrations at various locations in the surf zone of Egmond during moderate wave conditions (minor storm events). The trailer was equipped with electromagnetic, acoustic and optical instruments. Some results from the sandy (0.2–0.3 mm) Egmond site deserve some detailed discussion. The near-bed concentrations were found to vary between 1 kg/m^3 at low wave conditions and 10 kg/m^3 during minor storm events, when the maximum longshore suspended transport was found to be about 0.15 kg/s/m and was dominated by the current-related transport component (Fig. 7). Estimates of the bedload transport were found to be relatively small. Detailed analysis of the instantaneous data shows that during storm events the mean (time-averaged) transport components are the dominant modes of suspended transport in the beach zone, both in the cross-shore and in the longshore direction. The oscillatory transport component in the longshore direction is dominated by the far infragravity range (shear waves), but the contribution of this component to the total longshore transport was negligibly small (order of 5%). The oscillatory transport component in the cross-shore direction was also dominated by the gravity and infragravity ranges (< 100 s) and were relatively large (35% of the total cross-shore transport rate). The wave-related high-frequency suspended transport in the cross-shore direction was predominantly onshore directed and relatively small compared with the current-related transport, except for low wave conditions.

Due to the hard work and commitment of many field workers in the USA, Japan and Europe we now have much deeper

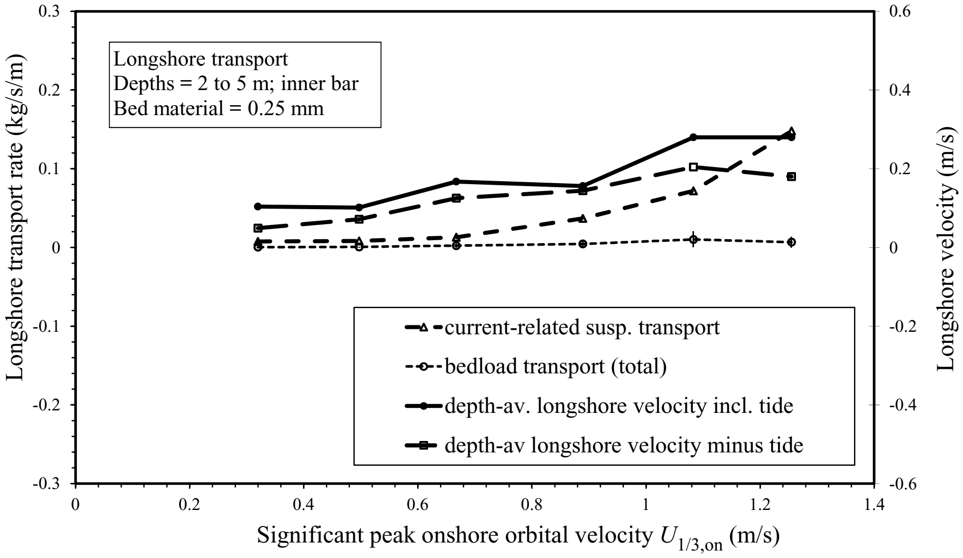


Figure 7 Longshore sand transport in surf zone of Egmond (The Netherlands)

understanding of the sand transport processes in the surf zone of sandy beaches. The available data have been used by modellers to improve and calibrate the existing sand transport formulae of morphodynamic models (Van Rijn 2007a, 2007b).

2.6 *Practical sand transport modelling*

2.6.1 *Approaches*

In recent years, a substantial body of field- and laboratory-based research has been devoted to measuring sand transport processes induced by waves and currents, and as a result some predictive approaches for the net, wave-averaged sand transport have been developed. Generally, these approaches can be divided into two classes: (1) process-based numerical models and (2) parameterized (engineering) formulae.

Process-based models represent many of the detailed physical processes involved in sand transport by waves and currents, and resolve the vertical and sometimes also the horizontal structure of the time-dependent intra-wave velocity and sand concentration fields. Such models are often restricted to specific flow and sand conditions, require relatively long computation times and are therefore generally not implemented in coastal morphodynamic models. However, process-based models have added significantly to the understanding of flow and sand transport processes and by this to the development of practical sand transport models. Parameterized engineering sand transport formulae on the other hand consist of a set of relatively simple equations often covering a wide range of flow and sand conditions. They require short computation times and can be implemented easily in coastal morphodynamic models.

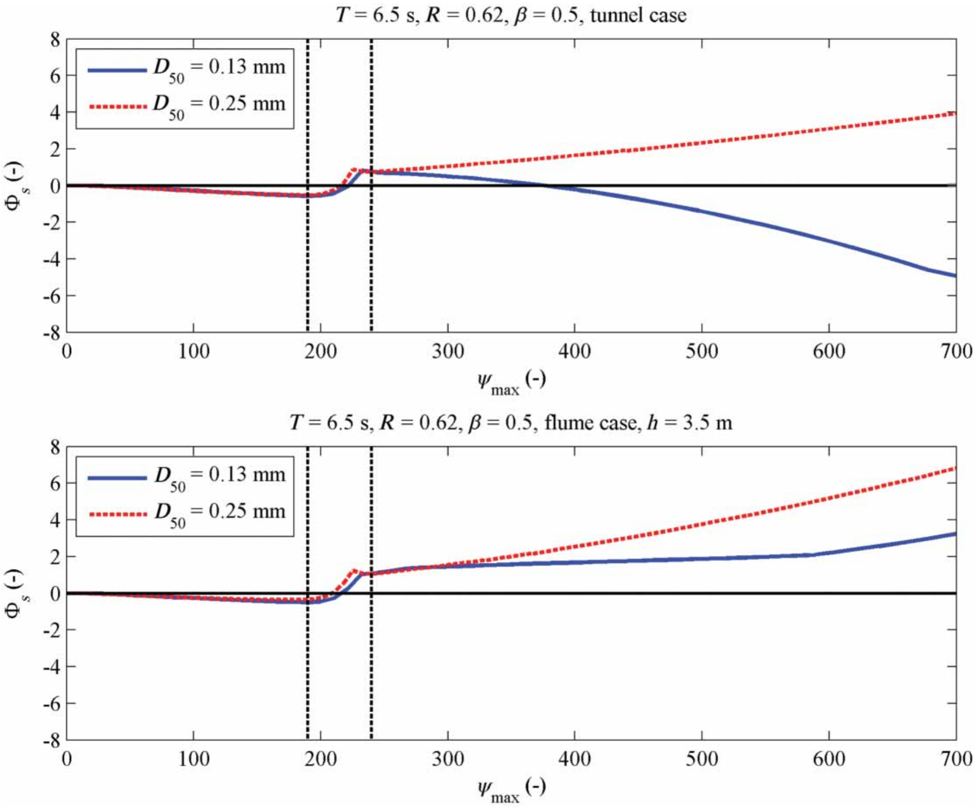
Coastal morphodynamic modelling systems (e.g. Delft3D, Telemac and Mike) solve the wave-averaged flow and AD equations to determine the time-averaged suspended sand concentration field. Vertical integration of the product of the resulting flow and suspended sand concentrations gives the time-averaged current-related suspended transport. This type of modelling involves the specification of an enhanced sediment mixing coefficient due to the waves effect, which can be obtained by empirical equations (Van Rijn 2007a, 2007b) or by using a $k-\varepsilon$-type turbulence closure model. Furthermore, the bed boundary condition (i.e. a reference concentration) should be also specified (Zyserman and Fredsøe 1994, Van Rijn 2007a, 2007b). The near-bed transport which takes place mainly in the wave boundary layer, i.e. the wave-related suspended transport and the bedload transport, is computed by these modelling systems using empirical sand transport formulae (see below and Section 2.7).

2.6.2 *Practical formulae for near-bed sand transport*

Practical (parameterized) sand transport relationships for the coastal environment are generally semi-empirical formulae which can be classified as related to time-averaged, quasi-steady or semi-unsteady conditions and parameters. Based on approaches used for fluvial sediment transport, time-averaged formulae predict sand transport at a timescale that is much longer than the wave period, using wave-averaged values of velocity and sand concentration. The Bijker (1971) formula is an example of a widely-used time-averaged transport formula, in which waves act as stirring agent for the current-related transport (suspended load and bedload). In the time-averaged formulae, the total net transport is always in the direction of the mean current and the wave-related transport component is not taken into account. This approach applies mostly to the longshore direction where tide, wind and wave-driven processes are dominant.

Quasi-steady formulae calculate intra-wave sand transport, with the assumption that the instantaneous sand transport relates only to the (local) instantaneous forcing parameter, either the flow velocity or the bed shear stress. Commonly-used quasi-steady formulae predict non-zero net transport resulting from velocity skewness, as occurs under Stokes-type waves (Bailard 1981, Ribberink 1998, Soulsby and Damgaard 2005, Van Rijn 2007a, 2007b, Wang 2007). However, most formulas do not account for transport resulting from acceleration skewness, as occurs under sawtooth-shaped waves (Watanabe and Sato 2004, Van der A 2010). Formulae that do account for both velocity and acceleration skewness have mostly been developed for sheet-flow conditions (Nielsen 2006, Gonzalez-Rodriguez and Madsen 2007, Suntoyo *et al.* 2008). Quasi-steady formula do not apply to lower energy conditions when the bed is generally covered with ripples. The assumption of quasi-steadiness only holds for conditions for which the reaction time of sand particles is short relative to the wave period. In other words, the pick-up and settling of sand particles must take place in a much shorter time than the wave period. This assumption is not the case for fine sand sheet-flow conditions (Dohmen-Janssen 1999, O'Donoghue and Wright 2004a, 2004b, Van der A 2010) and rippled-bed conditions (Van der Werf *et al.* 2007), where phase-lag effects can significantly affect the magnitude and sometimes even the direction of the net transport rate.

Semi-unsteady formulae have been developed to account for phase-lag effects in sheet-flow conditions (Dibajnia and Watanabe 1992, Camenen and Larson 2007), rippled-bed conditions (Nielsen 1988, Van der Werf *et al.* 2006) and for both sheet-flow and ripple conditions (Silva *et al.* 2006, 2011, Van Rijn 2007a, 2007b). Van der A *et al.* (2013) present the newest practical model for the net sand transport induced by non-breaking waves and currents (SANTOSS-model). This model is based on Dibajnia and Watanabe's (1992) semi-unsteady half-cycle concept, and it has bed shear stress as the main forcing parameter and includes phase-lag effects for rippled beds and fine sand. The formula differentiates itself from other semi-unsteady half-cycle-type formulae through explicit inclusion of progressive surface wave effects (Kranenburg 2013), as well as the effects of velocity skewness and acceleration skewness. Moreover, it is based on a large amount of experimental data for a wide range of conditions.


$T = 6.5$ s, $R = 0.62$, $\beta = 0.5$, tunnel case

$T = 6.5$ s, $R = 0.62$, $\beta = 0.5$, flume case, $h = 3.5$ m

Figure 8 Non-dimensional cross-shore sand transport as function of wave mobility number based on SANTOSS-model; onshore = positive and offshore = negative. Upper panel: purely horizontal orbital flow (oscillatory flow in wave tunnel). Lower panel: real free surface (skewed and asymmetric) waves

It should be noticed that a significant shortcoming of all transport formulas discussed above is that they are based on considerations related entirely to oscillatory flows and non-breaking surface waves. The performance of these formulas for breaking wave conditions, with additional stirring processes in the WBBL, is still unknown. Figure 8 shows the non-dimensional cross-shore sand transport $\Phi_s = \langle q_s \rangle / [(s-1)^{0.5} g^{0.5} D_{50}^{1.5}]$ as function of the wave mobility number $\psi_{\max} = (U_{\max})^2 / [(s-1) g D_{50}]$, as computed by the SANTOSS-model for regular non-breaking waves. This model includes all effects discussed in Sections 2.2 and 2.3. Two sand sizes have been used: $D_{50} = 0.13$ and 0.25 mm. Other settings are kept constant: wave period $T =$ 6.5 s, degree of velocity skewness $R = U_{\max}/(U_{\max} + U_{\min}) =$ 0.62, and degree of acceleration skewness $\beta = 0.5$ (i.e. there is no acceleration skewness). Figure 8 shows two cases: purely horizontal orbital flow (as present in a wave tunnel, Fig. 3) and real free surface waves at a depth of 3.5 m (as present in a large-scale wave flume, Fig. 3). The vertical dashed black lines indicate the transport regimes: ripples, transitional and sheet-flow.

In the case of purely horizontal orbital motion (upper panel) the transport rates are generally offshore directed (negative) in the ripple regime ($\psi_{\max} < 190$) due to phase-lag effects between sand concentrations and velocities related to lee-side vortices that are ejected at around the moment of flow reversal. Net transport rates are increasingly onshore directed in the sheet-flow regime ($\psi_{\max} > 240$), but become offshore directed again for the fine sand in the high mobility regime due to phase-lag effects. The net transport rates of real waves in the sheet-flow regime are much larger due to (i) vertical advection of sand, (ii) the onshore-directed Longuet-Higgins streaming and (iii) onshore Lagrangian drift of sand particles. For both the coarse and the fine sand, the net transport is in the onshore direction in the sheet-flow regime. The net transport rates of the fine sand are smaller due to larger phase lags between the velocities and concentrations. Figure 8 clearly shows that onshore and offshore-directed transport processes result in a complex behaviour of the net transport rate. Rather detailed models are required to simulate these processes with sufficient accuracy.

2.7 *Morphodynamic models*

The development of morphodynamic models for large-scale coastal areas began around the 1980s. At that time depth-averaged and time-dependent flow models became increasingly available. These models were coupled to simplistic wave models and sand transport formulae to compute flow, wave and sediment transport fields for typical wave climates. These results were integrated over the tidal cycle to obtain tide-averaged transport rates which were upscaled to short-term time scales (up to a year). The waves were assumed to stir up the sediments from the bed into suspension and the currents were assumed to carry the sediments through the coastal environment. This representation generally is sufficiently adequate for the longshore direction, where tide, wind and wave-driven processes are dominant. Wave-related transport components due to the oscillatory fluid motions in the cross-shore direction were almost completely neglected at that time. Hence, onshore and offshore-directed transport components could not be modelled at all. Over time, these deficiencies were gradually resolved and nowadays we have powerful morphodynamic models which can compute both longshore and cross-shore transport components over medium-term time scales (up to five years). Also, more sophisticated process-based models have shown, in recent years, the capability (after calibration) to produce realistic evolution of coastal morphology in applications covering time scales ranging from years to decades (Hibma *et al.* 2005, Jones *et al.* 2007, Brown and Davies 2009, Lesser 2009, Ruggiero *et al.* 2009, Tung *et al.* 2012, Walstra *et al.* 2012) and even to centuries (Dastgheib *et al.* 2008, Van der Wegen and Roelvink 2008).

In such models morphology evolves as a result of interrelations between hydrodynamics (waves and currents), sediment transport and the morphology itself. Although some models have approximations for the wave-related transport components due to the oscillatory fluid motions in the cross-shore direction, this transport component is usually not incorporated in large-scale coastal applications. The main reason for this is that the predictive capabilities in the upper shoreface are limited and would typically require a 3D (or at least Quasi 3D) description of the hydrodynamics. Especially in longer-term simulations (5–10 years), small misbalances between onshore–offshore-directed transports cause gradual erosion/accretion of the upper shoreface that eventually will dominate the solution. Besides model uncertainties, Walstra *et al.* (2013) showed that input reduction (i.e. reduced set of forcing conditions to reduce computational time) can dramatically affect long-term predictions, even to such an extent that even the main morphological characteristics are no longer reproduced.

The modelling of nearshore bar dynamics on time scales covering the lifecycle of the bars (decade) requires a rather accurate balance between onshore and cross-shore transports. With a cross-shore process-based model, Roelvink *et al.* (1995), Pape *et al.* (2010) and Walstra *et al.* (2012) were able to capture the essential parts of the long-term morphological bar response for different sites. However, to obtain realistic results at each site, a significant calibration effort was required. Here, we summarize the most recent results of the Walstra *et al.* (2012) study, which is based on a cross-shore profile model. The model applied was used to identify the mechanisms that govern the medium-term bar dynamics covering the period 1984–1987 with some measured data estimates of bar crest positions.

The net offshore migration of four bars was reasonably well represented after 377 days (Fig. 9d), but the bar amplitude was under-estimated (Fig. 9e). P1 (red) refers to the most offshore bar position and P4 (black) refers to the most nearshore bar position. Measured bar data (crest position in Fig. 9d and bar height in Fig. 9e) at three times are also indicated. The model qualitatively captured most of the high resolution fluctuations The predicted temporal evolution of the profile is characterized by relatively short (1–5 days) offshore migration periods, during wave events with offshore H_{rms} larger than about 2 m; however, not all high-wave events resulted in offshore bar migration. Note, for example, one of the largest wave events (offshore $H_{\mathrm{rms}} = 3.6$ m at $t = 195$ days). Gradual onshore migration occurred during periods of mostly just or non-breaking moderately energetic wave conditions (typically offshore $H_{\mathrm{rms}} < 1.5$ m), which can last for several weeks to months.

Apparently, much of the cross-shore behaviour of sand bars can be described with relatively simple physics, where undertow, wave asymmetry, longshore current and bed-slope effects are the dominant mechanisms. Moreover, the application showed that certain aspects of cross-shore morphodynamics can be captured with a relatively simple expression for oscillatory sediment transport included in the bedload only. However, the applicability is restricted to the barred nearshore part of the profile and the model requires heavy calibration for different sites. This is partly due to the assumption of long-uniformity that forms the basis for any cross-shore profile model, but is probably primarily due to the fact that not all processes are included or that the presently included processes are not sufficiently accurate. As detailed transport formulations are now becoming available it is believed that these can be used to substantially improve the generic applicability of morphodynamic models and to expand their validity across the entire cross-shore profile.

3 Vision on future research needs

Our vision on the future needs (coming decade) for coastal sand transport and associated morphodynamics can be formulated as follows:

- Research focusing on sand transport processes in shoreface (non-breaking waves), surf zone (breaking waves) and in swash conditions employing field and controlled laboratory experiments which are to be supported by detailed process-based hydrodynamic and sediment modelling.
- Development of universal database of fluid velocities, sediment concentrations and sand transport rates along sandy beaches in the field and in laboratories.
- Development of improved practical sand transport models using data from various laboratory and field experiments (databases) and new insights from sand transport process research.
- Detailed validation of morphodynamic models with improved sand transport models to predict longshore and cross-shore transport and associated coastal morphology over medium- and long-term time scales.

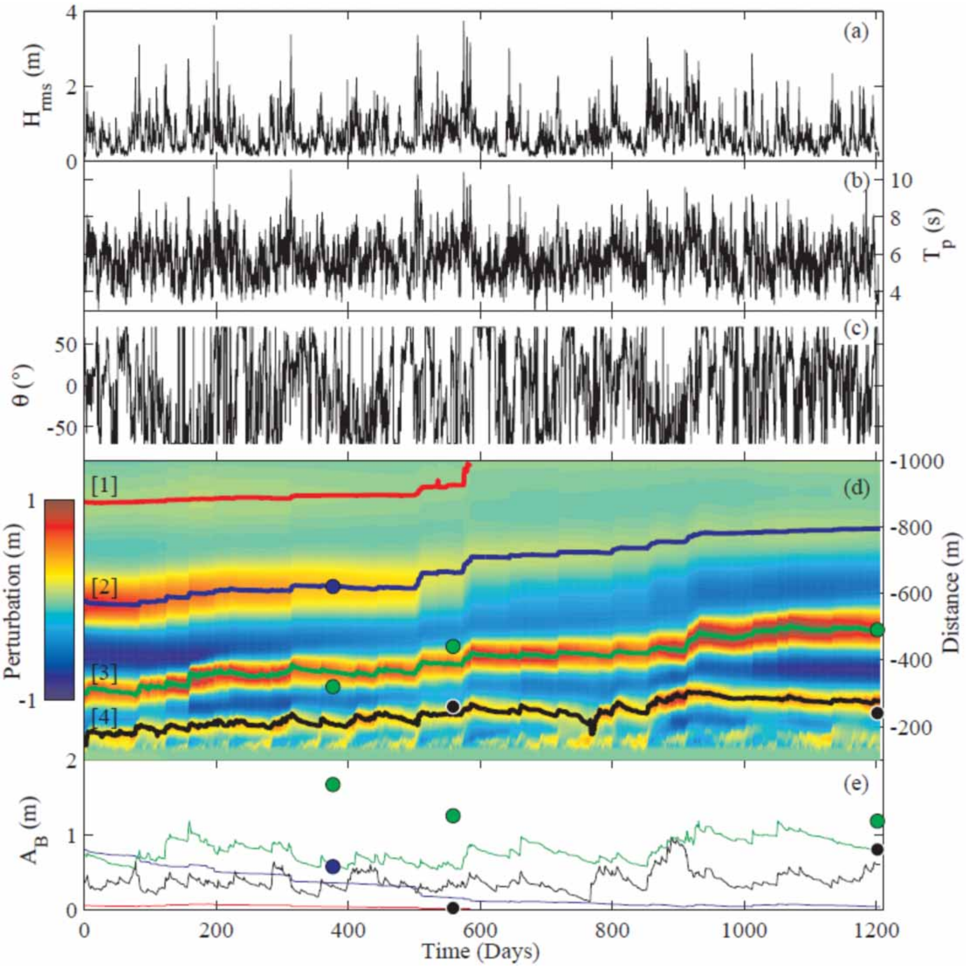


Figure 9 Time series of (a) offshore root-mean-square wave height H_{rms}, (b) offshore peak wave period T_p, (c) offshore incident wave angle θ, (d) time stack of predicted profile perturbation (deviations of mean profile) and indication of bar crests [1–4] and (e) predicted and three measured (coloured dots) bar amplitudes A_B. Reprinted from *Coastal Engineering*, Vol. 60, D.J.R. Walstra, A.J.H.M. Reniers, R. Ranasinghe, J.A. Roelvink, B.G. Ruessink, *On bar growth and decay during interannual net offshore migration*, pp. 190–200. Copyright 2012 with permission from Elsevier

3.1 *Sand transport process research*

In Table 1 an overview is given of sand transport processes in different coastal areas which are still insufficiently known and can be considered as future research priorities.

3.1.1 *Laboratory and field experiments*

Many small-scale laboratory experiments on sand transport under (non)breaking waves have been performed and published. Most of the data refer to the ripple regime under relatively low-amplitude waves (< 0.2 m). Presently, several medium-scale and large-scale wave flumes are available to study the full transport regime with ripples and sheet flow under real waves up to 2 m high. These facilities should preferably be used in future experiments to extend our knowledge of sediment transport processes under progressive surface waves.

Collections of large-scale sediment data from oscillatory flow tunnels are still valuable for future research, due to their great level of measurement detail of near-bed processes and the wide parameter ranges of these data (Van der Werf *et al.* 2009). With awareness that the flow dynamics of surface waves are not fully represented in flow tunnels, they can still play a useful role to support research on sediment dynamics in WBBLs.

A range of sophisticated instruments is available to measure the oscillatory flow velocities and the sand concentrations within the whole flow depth from the bed to the water surface. Further development and application of new non-intrusive measuring techniques such as PIV and acoustic velocity profiling for unraveling wave-mean, oscillatory and turbulent sand flux components is recommended. Moreover, new innovative measuring techniques, with higher spatial and temporal resolution than CCM are required to obtain improved data and better insight into different sediment flux components in the sheet-flow layer and in the bedload layer around ripples. It is extremely important to include sufficient measurement points over the water depth to derive depth-integrated total transport rates. This applies especially to the cross-shore transport processes where the transport direction near the bed may be opposite to that near the surface.

Table 2 shows presently available data sets of depth-integrated sand transport based on detailed velocity and concentration measurements in medium-scale and large-scale wave flume experiments. Until now only few experiments have been done

Table 1 Research topics in coastal sediment dynamics

Coastal area	Research topics
Shoreface	• The vertical structure of sediment flux components (mean, oscillatory and turbulent) under non-breaking waves in sheet-flow and rippled-bed conditions • Sediment dynamics (i) under non-breaking waves with strong superimposed mean currents (under an angle), (ii) under shoaling waves offshore of the breaker bar (non-uniform flow, sloping beds) and (iii) for grain-size mixtures (sorting) • Advection of suspended sediments, Lagrangian motion under progressive non-breaking surface waves • Time-history effects of suspended sediments (irregular waves and wave groups/long waves)
Surf zone	• Suspended sediment dynamics under breaking waves around the breaker bar in the outer surf zone (advection versus pick-up and deposition) • Near-bed sediment dynamics in the WBBL under spilling and plunging breakers • Vertical structure of suspended sediment flux components (mean, oscillatory and turbulent) in inner the surf zone • Coherent flow structures and intermittent sediment stirring under breaking waves
Beach	• Sediment pick-up/deposition versus advection in the swash zone along the beach • Grain–size sorting and bed-slope effects in the swash • Turbulent bore influence on bed shear stress and sediment pick-up • Percolation influence on sediment pick-up and deposition

Table 2 Experimental data on sand transport in medium-scale and large-scale wave flumes and in field conditions

	Regular laboratory waves		Irregular laboratory waves		Irregular field waves	
Type of sand	Non-breaking	Breaking	Non-breaking	Breaking	Non-breaking	Breaking
Fine sand 0.15–0.20 mm	D2002		R1995	T2009		M1999
	B2011		G2002	Y2010		G2002
	S2012		B2011			
Medium sand 0.20–0.5 mm	S2012		H2011	AC2011		AH2010

R1995 = Roelvink and Reniers (1995); D2002 = Dohmen-Janssen and Hanes (2002); B2011 = Baldock *et al.* (2011); S2012 = Schretlen (2012); Y2010 = Yoon and Cox (2010); T2009 = Van Thiel de Vries (2009); M1999 = Miller (1999); G2002 = Grasmeijer (2002); AC2011 = Alsina and Cacares (2011); AH2010 = Aagaard and Hughes (2010); H2011 = Hurther and Thorne (2011).

in these types of facilities. These datasets are recommended for future research but should also be extended with additional large-scale experiments in complementary parameter ranges.

3.1.2 *Process-based sand transport modelling*

Numerical modelling of detailed sediment and hydrodynamics is generally useful (i) for the interpretation of experimental results, (ii) to put new experimental insights in a wider perspective and (iii) to support the development of practical sand transport models. Further exploration of the use of modern 3D Navier–Stokes Solvers on intra-wave time scales with RANS and LES techniques for turbulence modelling together with AD models for suspended sediment is recommended. This type of numerical modelling can be used to investigate the near-bed suspension dynamics and transport around ripples and in sheet flows, but can also be explored for the suspension dynamics in the water column as induced by strong superimposed currents and breaking waves. Improved modelling of wave-breaking hydrodynamics in the water column and its interaction with the near-bed WBBL hydrodynamics seems to be crucial for adequate process-based modelling of sediment dynamics in surf zone and swash conditions. For better understanding of bedload and sheet-flow processes, two-phase flow models, but also more detailed Lagrangian discrete particle modelling with one-way and two-way coupling (Drake and Calantoni 2001), should further be improved.

3.2 *Open international databases*

Nowadays, fully automatic operating tripods with sophisticated electronic optical and acoustic instrumentation are placed in coastal environments to measure instantaneous fluid velocities and sand concentrations at various elevations above the sand bed. These instruments provide a wealth of information of basic coastal sand transport parameters. It is therefore extremely important to take an initiative to develop an international (open) database of sediment transport and corresponding hydrodynamic data. The sediment transport data should not only contain local data of sediment concentrations and fluid velocities but also bulk data of longshore transport rates (net longshore transport integrated over the surf zone).

During the past decades a vast amount of money has been spent by universities and research institutes on field experiments in the surf zones of the USA, Japan and Europe. However, most of the data obtained are not accessible to the international coastal community of students, engineers and researchers. This should drastically change. Without a database of high-quality data, there can be no major progress on coastal sediment transport. The database should not be filled with time series of crude data, but only with validated, high-quality data sets of longshore and cross-shore transport rates of typical wave events (of about 30 min) of sites all over the world. The availability of such a database would greatly enhance the improvement and calibration of existing sediment transport prediction methods.

3.3 *Development and validation of practical sand transport models*

In the presently existing practical sand transport models "bedload type" formulas are generally used for the integrated sand flux near the bed. It is assumed that near the sea bed the sand transport is only a function of the local flow/bed conditions and is not affected by neighbouring locations. At higher elevations above the bed this is no longer valid and suspension models are used (AD), which are able to take into account sediment advection effects. Different ideas still exist about which near-bed layers should be included and about the definition of bedload. Some researchers use a bedload formula only for bedload below the sheet-flow layer, the sheet flow itself is treated as suspension (Davies *et al.* 2002). Others include the transport in the sheet-flow layer in the bedload formula (Ribberink 1998, Van Rijn 2007a, 2007b). The new SANTOSS formula (Van der A *et al.* 2013) represents all transport in the wave boundary layer, including the wave-related suspension for rippled beds. In future research more clarity should be obtained about the validity of the "local" transport formula concept, especially for non-uniform flow conditions as occurring around breaker bars and in the swash.

Uncertainty still exists about the importance of the wave-related suspended sediment transport component under different types of breaking waves and how to model this flux. At which levels above the bed (in and above the WBBL) is the wave-related suspended sediment flux component a relevant contribution to the total net sediment flux? Indications exist that onshore net transport under plunging breakers is caused by an onshore wave-related suspension flux (not confined to the WBBL) that dominates over the offshore-directed current-related suspension flux by the undertow. More experimental insight is necessary in this transport component, and how to incorporate it in practical sand transport models. For the validation of presently existing practical sand transport models and for future new sand transport model concepts the presently available datasets are too limited and new measurements in the field and in controlled laboratory conditions are strongly required. Measuring only net sand transport rates through the measurement of bed-profiles is too limited for further model development. Further insights are required in the vertical distribution of the various sediment flux components above the sea bed as well as in their horizontal distribution along the sea bed. The instruments to do this are now available.

New sand transport and sand flux measurements in controlled and schematized conditions of large wave flumes are especially useful to obtain reliable sand transport validation data for specific wave conditions (breaking waves, irregular waves, wave groups, skewed/asymmetric waves), for specific sand transport regimes and grain sizes (rippled beds, sheet flow), specific coastal areas (shoreface, surf zone, swash) and for near-bed measurements requiring a high level of detail and accuracy.

Field data are generally less controlled, accurate and detailed than the laboratory data but have the great advantage that they are able to provide validation material from the real world in which the sediment transport processes are full scale and controlled by many driving mechanisms at the same time, such as (random) waves, wave-driven mean currents, tidal currents and bed slope-induced gravity effects. Long shore as well as cross-shore transport component should be measured simultaneously. A big problem of field measurements still is the accurate determination of the measurement level close to the bed, as this requires the use of sophisticated instruments with accurate vertical control (in millimetres).

Field data of sand transport during breaking and non-breaking wave conditions are scarce (Table 2) and urgently needed to better estimate the transport during these events. Most field data now available (Table 2) refer to the longshore component of suspended sand transport in conditions with breaking waves, when the time-averaged current-related transport mode is dominant. Field data of the various cross-shore components of suspended transport are still very scarce. Furthermore, the nature of the underlying transport processes (turbulent structures; wave shape effects) during non-breaking and breaking wave conditions need to be studied in much more detail. The focus should be on depth-integrated transport rates including the sheet-flow layer and covering a wide range of conditions (different sand sizes, spilling and plunging breaking waves, small and large depths).

3.4 *Development and validation of morphodynamic models*

The development of morphodynamic models will partly be influenced by improvements in the sub-models. For example, improved transport models such as discussed in the previous sections need to be implemented and thoroughly tested. The incorporation of improved sub-models or the inclusion of more processes does not imply that a morphodynamic model also improves. Ruessink *et al.* (2007) have shown that the reduction in the number of processes accounted in the model can actually result in improved and more robust model predictions. Furthermore, different sub-models need to be compatible (e.g. inclusion of detailed transport formulations that require intra-wave orbital velocities is only relevant if the wave model can provide these). Therefore, by definition the development of a morphodynamic model lags behind the development of the sub-models.

In recent years there has been a shift from the development of morphodynamic models towards innovative and new types of applications. Especially studies that aim to reproduce field-based empirical formulations are worth mentioning. For example, it has been shown that morphodynamic models can reproduce the equilibrium relationship between tidal prism and the cross-sectional channel area (Tung *et al.* 2012). Another example is the comparison of various types of (simulated) synthetic delta's with field observations. Recently, the ability of morphodynamic models to consider multiple sediment fractions and therefore also the prediction of the stratigraphy has been used to validate the models on observed stratigraphic records (Geleynse *et al.* 2011).

The time scales on which morphodynamic models are applied are also increasing. Two decades ago state-of-the-art morphodynamic models were applied for weeks to months, which has increased to years and decades for standard applications and even millennia for highly schematized configurations. Besides the increase of computational power, new upscaling techniques are being developed, which hold the promise of routine morphodynamic forecast to centuries or more. However, little is known about the influence that these upscaling techniques have on the quality of the predictions. All morphodynamic upscaling techniques utilize the difference in characteristic time scale of the hydrodynamics and the associated morphological response. For example, the hurricane impact on a barrier island occurs on the same time scale as the hydrodynamic forcing, whereas the morphological response of a prograding delta occurs on the time scales of millennia. A first step to identify the errors associated with morphodynamic modelling was made by Ranasinghe *et al.* (2011). This was further extended by Borsboom *et al.* (2013) in which the limits of morphodynamic upscaling were also shown through an analytical stability analysis. However, this study also showed that errors introduced by the numerical solution schemes are typically of similar or greater magnitude.

All morphodynamic models require some kind of input filtering for the hydrodynamic boundary conditions. Recently Walstra *et al.* (2013) showed that this input filtering or input reduction can have a dramatic impact on the model predictions. More research is required to test the impact of input filtering on waves, tides and fluvial input for different environments.

Based on the above considerations we believe that the future development of morphodynamic models should focus on:

1. Inclusion and testing of improved sub-models of sand transport.
2. Detailed validation by: (1) direct reproduction of laboratory and field data and (2) the reproduction field-based empirical relations and observations (e.g. stratigraphic records). We suggest making a clear distinction between these hard (1) and soft (2) validation efforts. Although hard validations are relevant and need to be repeated for each new model, the soft validation should receive more attention as it is more closely related to required model outcomes (e.g. long-term impact of sea level rise). Furthermore, validation standards (benchmarks) should be developed.
3. Development and testing of innovative modelling techniques that increase the computational efficiency. This should focus both on improved (faster and more accurate) numerical solution scheme's and improving or combining morphodynamic acceleration techniques. For the latter also guidelines should be developed of which acceleration techniques are most appropriate for specific physical environments or types of applications. The same holds for input reduction as no proper guidelines are available, especially for long-term (i.e. decades or longer) simulations.

Notations

D_{50} = median particle sand size (m)
c = time-averaged sediment concentration (kg/m^3)
$\tilde{c}$ = oscillatory component of sediment concentration (kg/m^3)
g = gravity acceleration (m/s^2)
H = wave height (m)
q_s = sediment transport rate (kg/m/s)
s = ρ_s/ρ = relative density (–)
R = velocity skewness (–)
T = wave period (s)
U = instantaneous velocity (m/s)
$\tilde{u}$ = oscillatory component of fluid velocity (m/s)
β = acceleration skewness (–)
ρ = fluid density (kg/m^3)
ρ_s = sediment density (kg/m^3)
η = ripple height (m)
λ = ripple length (m)
Φ_s = dimensionless transport rate (–)
Θ = Shields mobility parameter (–)
ψ = mobility parameter (–)

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