Earth-Science Reviews 238 (2023) 104355

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

A review of practical models of sand transport in the swash zone

W. Chen[a,*], J.J. van der Werf[a,b], S.J.M.H. Hulscher[a]

[a] Department of Marine and Fluvial Systems, University of Twente, Drienerlolaan 5, 7522 NB Enschede, the Netherlands
[b] Unit of Marine & Coastal Systems, Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands

ARTICLE INFO

Keywords:
Sediment transport
Wave-swash interaction
Beach evolution
Practical model
Swash zone

ABSTRACT

The swash zone largely influences nearshore hydrodynamics and morphodynamics through dissipating or reflecting wave energy and controlling whether sediment will be stored on the upper beach or returned to the inner surf zone. It is a region where active beach accretion and erosion occur and beach protection measures such as sand nourishments are often placed. Hence, proper prediction of swash zone beach evolution is required to evaluate beach management scenarios. This paper describes the advances related to swash zone sand transport processes and morphodynamics. We discuss the effects of a variety of physical processes and factors (e.g. bore turbulence, pre-suspended sediment advection, wave-swash interactions, infragravity waves, in−/exfiltration, pressure gradient and bed slope) on sand transport in the swash zone. We then focus on practical models of swash zone sand transport which are appropriate for predicting longer term (days to years) beach evolutions. Three types of practical models, i.e. empirical sand transport formulae, sand transport distribution methods and equilibrium models, are identified. The strengths and limitations of these practical models are discussed. The empirical sand transport formulae include the intra-swash formulae and swash-averaged formulae. The intra-swash formulae are more physics-based and can take physical processes into account more explicitly. However, upscaling of them for modelling sand transport and morphological changes over tidal cycles or longer term is problematic due to the difficulty in obtaining reliable and accurate instantaneous swash hydrodynamics(e.g. flow velocities) and due to the error propagation. Swash-averaged formulae can be more suitable for predicting longer-term morphological changes while they still require better parameterisations of important physical processes (e.g. wave-swash interactions). Sand transport distribution methods generally work reasonably well for beach erosion under energetic wave conditions whereas they have the inability to predict the beach recovery under mild wave conditions. Equilibrium models show a potential for predicting the beach evolution under both erosive and accretive conditions well. The equilibrium slope appears to be an essential factor that largely determines the performance of the equilibrium models. This equilibrium slope should depend on wave conditions and sediment characteristics, and a quantitative relationship between them needs further research in order to make the equilibrium models more predictive.

1. Introduction

The swash zone is often referred to the part of the beach where the sediment bed is alternatively exposed and submerged by uprush (waves propagating up the beach) and backwash (waves running down the beach) on wave group time scales (Fig. 1). It is a narrow and dynamic region featured by unsteady flows, high turbulence, rapid boundary layer growth and decay, large sediment transport rates and fast bed level changes (Puleo et al., 2000; Masselink and Puleo, 2006; Brocchini and Baldock, 2008; Chardón-Maldonado et al., 2016). The swash zone plays an important role in sediment exchange between sea and land, which substantially affects the evolution of the beach (Larson et al., 2004; Puleo et al., 2017). In addition to the cross-shore physical processes, longshore sand transport occurring in the swash zone can account for a large portion of the total littoral drift (Kamphuis, 1991; Smith et al., 2003; Masselink and Puleo, 2006; Puleo et al., 2020). Hence, predictions of swash sand transport are necessary for forecasting coastal morphodynamics. Sand transport in the swash zone is determined by the highly complicated swash hydrodynamics, sediment characteristics and the beach morphology. Predicting sand transport in the swash zone is difficult partly due to the difficulty in measuring and predicting flow velocities and sand concentration in the shallow, intermittent and

* Corresponding author.
E-mail addresses: w.chen-6@utwente.nl (W. Chen), Jebbe.vanderWerf@deltares.nl (J.J. van der Werf), s.j.m.h.hulscher@utwente.nl (S.J.M.H. Hulscher).

https://doi.org/10.1016/j.earscirev.2023.104355
Received 2 November 2022; Received in revised form 4 February 2023; Accepted 6 February 2023
Available online 12 February 2023

turbulent flows (Puleo et al., 2017).

Despite the importance of both cross-shore and long-shore swash sand transports for beach morphodynamics, the longshore processes have received less attention than the cross-shore processes (Chardón-Maldonado et al., 2016). There are some empirical formulae (e.g. Bagnold, 1963; Coastal Engineering Research Center, 1984; Kamphuis, 2002; Larson and Wamsley, 2007; Jiang et al., 2011) available for calculating the longshore sand transport in the swash zone. Jackson et al. (2017) tested three existing formulae (Bagnold, 1963; Coastal Engineering Research Center, 1984; Kamphuis, 2002) by comparing the calculated longshore transport rates (using direct measurements of longshore current velocities) with measured rates in the swash zone of an estuarine beach. The Bagnold (1963) sediment transport formula is based on the horizontal component of wave motion and the longshore current velocity. The Coastal Engineering Research Center (1984) formula is based on the longshore component of wave power and Kamphuis (2002) equation includes wave period, a beach slope and grain size term. Jackson et al. (2017) found that estimates with the Bagnold (1963) formula matched better than the other two formulae because of using the direct measurements of longshore current velocities. Nevertheless, the existing longshore swash sand transport formulae have not been extensively validated due to a limited amount of laboratory and field tests of longshore swash processes (Puleo and Torres-Freyermuth, 2016). A brief review of the longshore swash sand transport can be found in Bakhtyar et al. (2009). Further study is required on the longshore swash motions and longshore swash sediment transport. Considering the facts that (i) most of the research related to sand transport in the swash zone deals with the aspects of cross-shore sand transport processes; (ii) the cross-shore sand transport plays a crucial role in shoreline accretion and erosion (Masselink and Puleo, 2006), the rest of this review is confined to cross-shore swash processes.

A lot of research has been conducted to investigate the intra-swash hydrodynamics and beach evolution within a swash event (short temporal durations) by means of field tests, laboratory experiments and detailed numerical models (e.g., Pritchard and Hogg, 2005; Zhu and Dodd, 2013; Inch et al., 2015; Wu et al., 2016; Briganti et al., 2018; van der Zanden et al., 2019; Pintado-Patiño et al., 2021). The swash motion time scale ranges from seconds on calm and reflective beaches to minutes on energetic and dissipative beaches (Hughes et al., 1997; Butt and Russell, 1999; Masselink and Puleo, 2006). The studies related to intra-swash events can to a certain extent help with the development of parameterizations of small-scale processes and upscaling to longer temporal scales. Nevertheless, upscaling of small-scale processes is still fraught with difficulties due to error propagation. Modelling of the coastal beach evolution at longer time scales (storm scale to even years) is required for evaluating coastal management scenarios (Roelvink et al., 2019). Even though depth-resolved and phase-resolved numerical models (e.g., OpenFOAM) might be capable of accurately simulating the hydrodynamics and bed level changes within one or several swash events (e.g. García-Maribona et al., 2021), these detailed models are extremely computationally expensive and are thus inapplicable for practical engineering purposes on the time scale of months to years.

The coastal hydro-morphodynamic evolution involving waves at larger temporal scales (days to years) is mostly studied using morphodynamic models in which short wave dynamics and their effects are considered in a wave-averaged sense (i.e. averaged over the short wave time scale) (Brocchini and Baldock, 2008). Some examples of the short wave-averaged morphodynamic models are SBEACH (Larson and Kraus, 1989), Delft3D (Lesser et al., 2004), UNIBEST-TC (Ruessink et al., 2007), CSHORE (Kobayashi, 2009) and XBeach (Roelvink et al., 2009). These are referred to as practical or engineering morphodynamic models. Herein, practical sand transport models refer to the models that can be applied in combination with these practical morphodynamic models which only provide wave-averaged hydrodynamics, allowing predictions of the morphological change in the swash zone over a time span of days to years. This review paper focusses on these practical sand transport models, as these are a key element of numerical models to predict coastal morphodynamics in support of coastal engineering and management. Note that the shoreline motion in the wave-averaged models is computed only at wave-averaged level. Even though the short wave variations on the group scale (short wave envelope) and associated long waves are resolved in XBeach surfbeat mode, swash motions at reflective beaches dominated by incident band wave energy are not accurately accounted for (Van Dam, 2019; de Beer et al., 2021). Therefore, complex wave dynamics in the swash zone like wave-swash interactions and run-up height are difficult to be explicitly and/or accurately computed in the wave-averaged models (Memmola et al., 2020). This problem directly affects the predictions of sand transport in the swash zone since swash hydrodynamics, such as flow velocity, are important input for many empirical sand transport models.

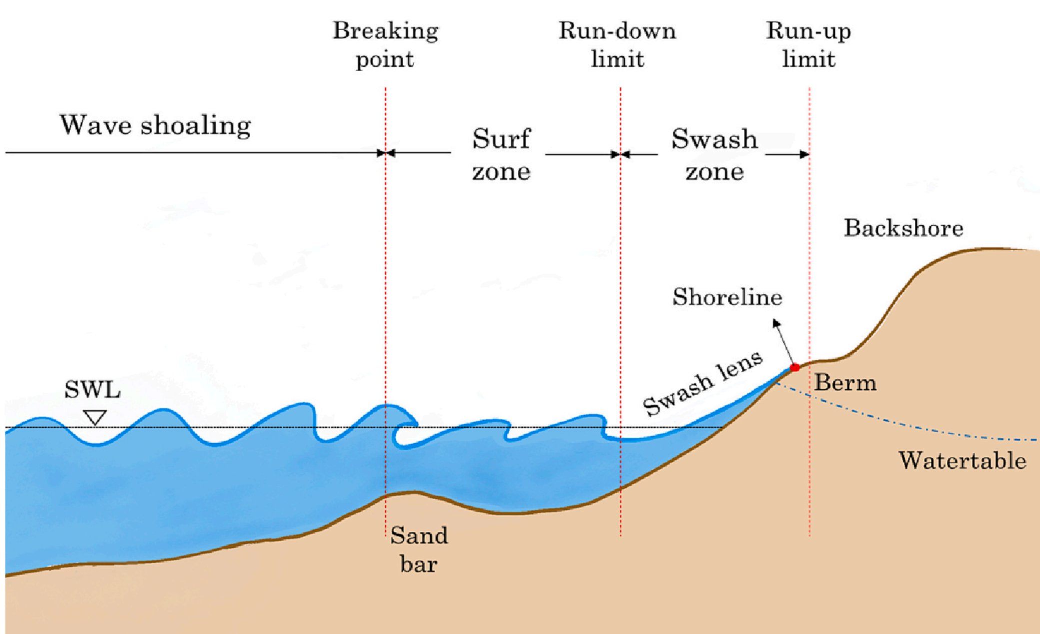

Fig. 1. Schematic of the beach profile including the surf and swash zones.

Practical cross-shore swash sand transport models have been proposed by taking into account the wave mechanics and transport processes in a highly schematic way (e.g. Larson and Kraus, 1989; Walstra and Steetzel, 2003; Van Rijn, 2009; Johnson et al., 2012; Roelvink and Otero, 2017) or by combining empirical sand transport formulae with a semi-analytical or analytical model to provide input of swash hydrodynamics (e.g., Brocchini and Peregrine, 1996; Baldock et al., 2007). These practical swash sand transport models have their own strengths and weaknesses, which will be critically reviewed in this paper.

Several review papers related to the swash zone have been published so far. For example, Elfrink and Baldock (2002) reviewed the dominant hydrodynamic forcing and sediment transport mechanisms in the swash zone. Brocchini and Baldock (2008) discussed the advances in modelling swash zone dynamics with a focus on the influence of surf-swash interaction on nearshore hydrodynamics as well as morphodynamics and proposed methods for modelling swash zone processes at different temporal and spatial scales. Only one practical sand transport model (i.e. Baldock et al., 2007 probabilistic-deterministic model) was mentioned in Brocchini and Baldock (2008). Bakhtyar et al. (2009) presented a review of modelling intra-swash sediment transport in the swash zone. Advantages and disadvantages of different types of numerical models (i.e., based on Nonlinear Shallow Water Equations, Boussinesq-type equations and Navier-Stokes equations) are reviewed. These numerical models are mainly used to simulate the hydrodynamics in the swash zone. In order to model the beach profile changes, relationships between the sediment transport and the hydrodynamics are needed. However, the sediment transport models are only very briefly mentioned in Bakhtyar et al. (2009). Briganti et al. (2016) reviewed the work on the numerical modelling of swash zone dynamics, in which a comparative analysis of the performance of different numerical models in predicting the swash zone hydrodynamics is presented. However, this review paper is focused only on the phase-resolving methods. Chardón-Maldonado et al. (2016) reviewed the advances on understanding small-scale hydrodynamics and sediment transport processes from 2004 until 2015. Additionally, the advances in the measurement instrumentation and measuring techniques for flow and sediment concentration were also presented. These publications provide reviews on basic swash hydrodynamics, sediment transport mechanisms, laboratory/field data and numerical models with different focuses. However, a comprehensive review of the practical swash sediment transport models does not exist.

Therefore, the objective of this paper is to provide a comprehensive and critical review on the cross-shore swash zone sediment transport processes and the existing practical transport models, which will promote the further development and application of swash sand transport models. This review paper is focused on: (1) describing the cross-shore transport processes and morphodynamics in the swash zone at sandy beaches; (2) reviewing and summarizing the applicability and limitations of existing practical swash sand transport models and (3) proposing future research directions on practical swash zone sand transport modelling. This review paper does not address longshore swash sand transport, detailed theories for hydrodynamics nor methods of phase-resolving numerical models.

This paper is organized as follows: Section 2 describes the sand transport processes and morphodynamics in the swash zone. In Section 3, we introduce existing practical swash sand transport models. Analytical swash hydrodynamic models, and strengths and shortcomings of these practical models are discussed in Section 4. Finally, Section 5 summarizes the main findings and presents future perspectives with the aim of improving the prediction of swash sand transport.

2. Swash zone sand transport processes

Energetic wave conditions in the swash zone on sandy beaches result in sheet flow and suspended sediment transport (van der Zanden et al., 2019). The sand transport processes in the swash zone are governed by beach morphology and hydrodynamics including swash flow velocities (e.g. Jensen et al., 2003; Masselink and Puleo, 2006; Brocchini and Baldock, 2008; Pintado-Patiño et al., 2021), bed shear stress (Conley and Griffin, 2004; Masselink et al., 2005; Barnes and Baldock, 2007; Puleo et al., 2012; Inch et al., 2015), bore collapse-induced turbulence (e.g., Puleo et al., 2000; Butt et al., 2004; Zhang and Liu, 2008; Kikkert et al., 2012), wave-swash interactions, infragravity waves (e.g., Hughes et al., 1997; Butt and Russell, 1999; Hughes et al., 2014; Bertin et al., 2018; Matsuba and Shimozono, 2021), in−/exfiltration and (horizontal and vertical) pressure gradients (e.g., Nielsen et al., 2001; Karambas, 2003; Barnes et al., 2009; Othman et al., 2014). Fig. 2 provides a schematic overview of processes that can play a role in sand transport in the swash zone. The effects of these hydrodynamics on swash sand transport processes are described in this section.

2.1. *Suspended load and sheet flow*

The swash flows are characterized by high free stream velocities during both the uprush and backwash (Elfrink and Baldock, 2002). When the water movement exerts sufficiently large shear stress on the sand, the particles will be mobilized. The sheet flow layer is the thin layer (as shown in Fig. 2) with a thickness of a few centimetres and high sand concentration (100–1600 kg/m^3) above the bed driven by intergranular and sediment-flow interaction forces (Dohmen-Janssen et al., 2001; Ribberink et al., 2008). Suspended particles transported at higher elevations without any contact with the bed and are supported by turbulent diffusive forces.

Sheet flows characterized by high sediment concentration and large transport rates play an important role in the overall swash zone sediment transport budgets (Horn and Mason, 1994). The sheet-flow layer can be divided into an upper sheet flow layer and a pick-up/deposition layer, which are above and below the still-water bed level (Ribberink et al., 2008). Laboratory measurements (Lanckriet et al., 2014; Puleo et al., 2016) showed that the vertical concentration profiles of the sheet flow layer during isolated swash events had a similar vertical distribution to those under purely horizontal oscillatory sheet flows as measured in flow tunnels. However, measurements during a wave-group induced swash cycle presented in van der Zanden et al. (2015) showed a different behavior of the vertical concentration profiles where a pick-up layer is not obvious due to the effect of horizontal sediment advection. Alsina et al. (2018) found that the vertical structure of the sand concentration in the sheet flow layer is predominantly controlled by horizontally advected sediment if the swash events are dominated by the high-frequency short waves, while the sheet flow layer is mainly controlled by the local vertical exchange of sediment if the swash events are dominated by the low-frequency wave group motion. This is in accordance with van der Zanden et al. (2015). The behavior of the latter is similar to oscillatory sheet flow. Furthermore, van der Zanden et al. (2019) found that the thickness of the sheet flow layer during wave-group induced swash events is relatively large compared to previous observed oscillatory sheet flows (e.g. Hassan and Ribberink, 2005) and observations of the sheet flow layer under non-breaking waves (e.g., Schretlen, 2012; van der Zanden et al., 2017) with similar flow velocities and grain size. This indicates that the relation between the sheet flow dynamics and the free-stream velocity in the swash zone is different from that under oscillatory flows and under non-breaking waves. The difference can be explained by the contribution of additional processes to the sheet layer growth in the swash zone. For example, landward sand advection within the swash, bore turbulence and wave-swash interactions can increase the sheet flow layer thickness (Lanckriet and Puleo, 2015; van der Zanden et al., 2015; van der Zanden et al., 2019). The sheet flow layer becomes thickest during the late stage of the backwash (Alsina et al., 2018; Pintado-Patiño et al., 2021) and immediately reduces after the arrival of the next incoming bore (Alsina et al., 2018). The transport rates related to the sheet flow reach the maximum during initial uprush in a dam break-induced swash event due to large flow velocities (Chardón-Maldonado et al., 2016).

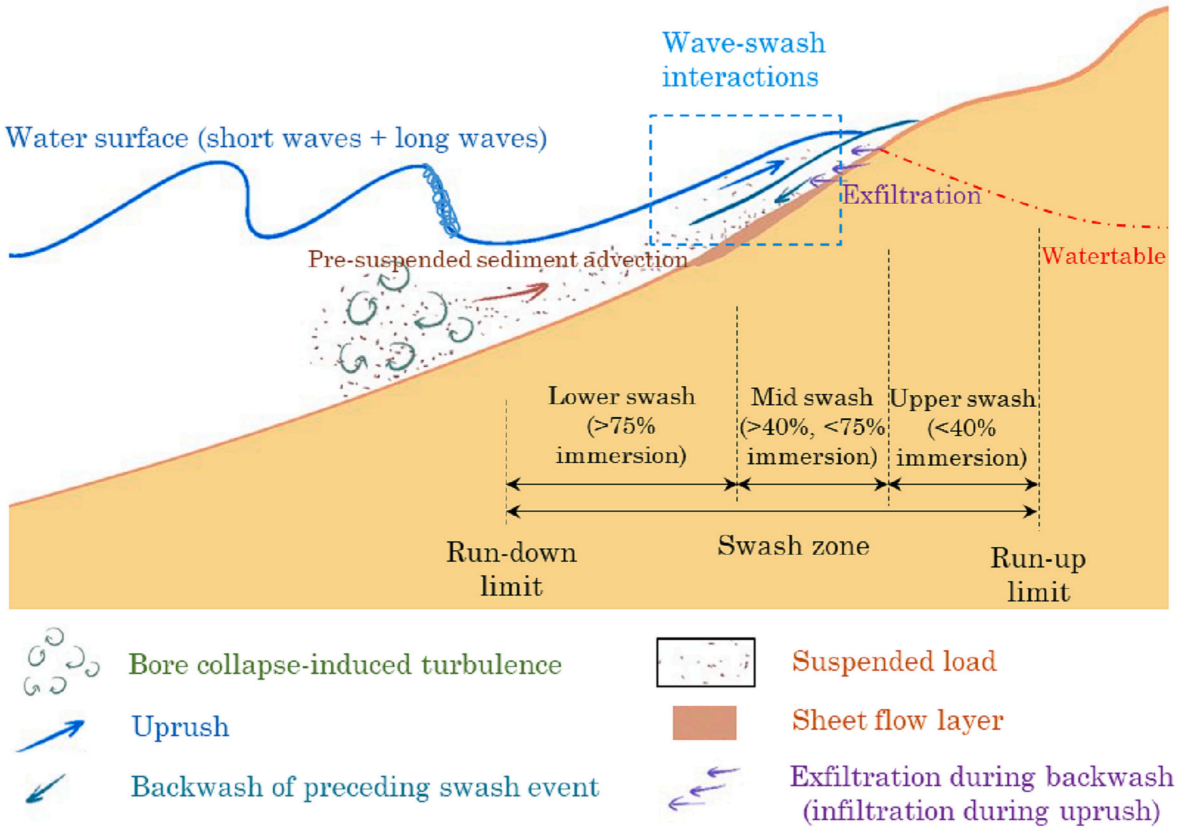

Fig. 2. Schematic overview of physical processes in the swash zone. The lower, mid and upper swash zones are defined following Aagaard and Hughes (2006) and van der Zanden et al. (2019).

Suspended sediment concentration during the uprush can reach or exceed 100 kg/m^3 (Cáceres and Alsina, 2012; Ruju et al., 2016; van der Zanden et al., 2019; Pintado-Patiño et al., 2021), which is much higher than concentrations generally occurring in the surf zone (e.g. Wang et al., 2012) and the sediment suspension extends across the water column (Chardón-Maldonado et al., 2016). The large suspended sediment concentrations within the water column combined with rapid and turbulent flows in the swash zone lead to large suspended sediment transport rates (Elfrink and Baldock, 2002; Ruju et al., 2016). Sediment suspension in the swash zone does not only depend on the local conditions but is also affected by cross-shore advection (Alsina et al., 2009; van der Zanden et al., 2019). In the lower and mid swash zones, local vertical velocity fluctuations generated by coherent eddies can play a role in the process of sand suspension (Aagaard and Hughes, 2006). These coherent eddies may originate from a) bore collapse, b) 'downbursting' at the leading edge of swash bores and c) large shear at the swash front. In addition to local conditions, laboratory experiments by Alsina et al. (2009) showed that about 25% of the pre-suspended sediment outside the swash zone stirred up by the bore reaches the mid-swash zone, which indicates that the cross-shore advection of sediment (see Fig. 2) can contribute to the sand transport processes in the swash zone. The suspended sand concentration at a particular location is maximum during the initial phase of uprush due to bore turbulence and large bed shear stress. Then, it decreases rapidly after the concentration peak and continues to decrease more gradually to zero as the water depth increases until the end of uprush. The concentration increases gradually as the flow accelerates during backwash and reaches a maximum during the mid and late stage of backwash due to large flow velocities (Osborne and Rooker, 1999; Butt and Russell, 1999). However, this pattern can be affected by wave-swash interactions which will be discussed in more depth in Section 2.3.

2.2. Sand transport during the uprush and backwash

The relative importance of suspended sand transport and sheet flow transport varies temporally and spatially within a swash event. Large instantaneous suspended sediment transport fluxes and sheet flow fluxes at a given location in the swash zone occur during the initial uprush when the bore arrives (Butt et al., 2004;O'Donoghue et al., 2016; Pintado-Patiño et al., 2021). Instantaneous sediment fluxes are derived from the production of the velocity and sediment concentration profiles (e.g. Masselink et al., 2005; Butt et al., 2009; Chardón-Maldonado et al., 2016). Then the sediment flux decays rapidly during the remaining uprush and reduces to zero a bit earlier than the flow reversal (Puleo et al., 2000; O'Donoghue et al., 2016). Therefore, the contribution of both transport types is similar near the flow reversal. Even though the near-bed sediment flux is much larger than the sediment flux in the upper layers, the suspended sediment transport rate (depth-integration of the suspended sediment flux above the sheet flow layer) contributes more to the total sand transport than the depth-integrated sheet flow (from the bed to the top of the sheet layer) during most of the uprush due to the disproportionate vertical range for integrating (Puleo et al., 2016; Ruju et al., 2016; Pintado-Patiño et al., 2021). The difference in the magnitudes of sand transport rates between these two transport modes decreases in the onshore direction (Pintado-Patiño et al., 2021). Contrary to estimates suggesting a dominance of suspended sand transport rate, van der Zanden et al. (2019) found that the sheet flow transport dominates during the uprush with the sheet flow transport rates exceeding suspended sand transport rates by a factor of two to five. This difference may be related to strong variations of the bore impact on the beach influenced by wave conditions, and cross-shore locations. In Puleo et al. (2016) and Pintado-Patiño et al. (2021), the monochromatic waves and dam-break-driven swash were applied respectively. These wave conditions can result in very different uprush bore kinematics than those in van der Zanden et al. (2019) in which bichromatic waves with a phase modulation were applied and wave capture occurred. The merged uprush bore propagating over a dry bed is expected to induce high bed shear stresses and can cause large sheet flow transport. The difference can also be caused by different methods of sediment transport measurement as well as instrumentation. During the backwash, the sheet flow transport rates generally exceed the suspended load transport rates or both transport modes are generally of similar magnitude (Horn and Mason, 1994; Puleo et al., 2000; Puleo et al., 2014a; Ruju et al., 2016). However, larger beach steepness enhances the sediment advection and turbulence near the run-down limit during the backwash, in which case the suspended load transport rates can be dominant over the sheet flow (Pintado-Patiño et al., 2021).

Whether the swash zone accretes or erodes will depend on the balance between onshore sand transport during the uprush and offshore sand transport during the backwash (Butt et al., 2004). For an accreting beach, the uprush sand transport would dominate, while for cases where a beach is in an eroding state, backwash sand transport would have to dominate. Due to the asymmetry of the uprush and backwash flows, the total sand transports during the uprush and backwash are also different. Many field and laboratory studies (Conley and Griffin, 2004; Aagaard and Hughes, 2006; Masselink and Russell, 2006; Butt et al., 2009; Tinker et al., 2009; Masselink et al., 2009; Puleo et al., 2012; Puleo et al., 2014b; Pintado-Patiño et al., 2021) have shown that the maximum uprush velocities generally are either similar to or slightly larger than the maximum backwash velocities within an entire swash cycle. On the other hand, it is generally found that the duration of the backwash is longer than that of the uprush (Conley and Griffin, 2004; Masselink and Puleo, 2006). As a consequence, the velocity skewness tends to be negative, which would bias the offshore net sand transport if velocity-based sand transport models (e.g. Bailard, 1981) are applied to the swash zone (Puleo et al., 2003; Masselink and Puleo, 2006; Hughes and Moseley, 2007; Chardón-Maldonado et al., 2016). If this were the full case, a beach could never accrete. Masselink and Russell (2006) already showed that the beach experienced progressive accretion even though the velocity skewness was mainly directed offshore. Therefore, other mechanisms should also exist to enhance the uprush transport. These mechanisms can be associated with the bore turbulence, rapid flow acceleration at the start of uprush, advection of pre-suspended sediment, flow infiltration and wave-swash interactions.

The bore turbulence seaward of the base of the swash zone enhances the sediment entrainment which is subsequently advected up the beach by uprush (Jackson et al., 2004; Chardón-Maldonado et al., 2016). Moreover, the rapid flow acceleration at the initial phase of uprush can lead to thinner boundary layer and larger bed shear stress or induce a horizontal pressure gradient, enhancing mobilization of sediment particles and onshore sand transport (Drake and Calantoni, 2001). The influence of sediment advection is important especially for fine sediment (Masselink and Puleo, 2006). The flow infiltration during the uprush can reduce the boundary layer and increase the bed shear stress, promoting the onshore sediment transport (Conley and Inman, 1994; Masselink and Puleo, 2006; Bakhtyar et al., 2009). At the same time, the infiltration induces a downward pressure gradient increasing the effective weight of sediment particles, which impedes the sediment mobilization (Butt et al., 2001). On the contrary, the exfiltration during the backwash reduces the bed shear stress and effective weight of sediment. Dominance of the effect of the boundary modification or the stabilizing/destabilizing forcing depends on the grain size (Bakhtyar et al., 2009). For coarser sediments ($D_{50} > 0.4 - 0.6$ mm), in−/exfiltration overall favors onshore transport and for finer sediment ($D_{50} < 0.2$ mm) it favors offshore transport (Karambas, 2003; Karambas, 2006; Butt et al., 2007; Masselink and Puleo, 2006; Bakhtyar et al., 2009), but the effect of in−/exfiltration on sand transport is relatively small compared to gravel (Masselink and Puleo, 2006).

2.3. Wave-swash interactions

Wave-swash interactions (also termed swash-swash interactions) can further complicate swash zone sand transport processes. Three types of wave-swash interactions are defined by previous studies, i.e. wave capture, weak wave-backwash interaction and strong wave-backwash interaction (Elfrink and Baldock, 2002; Erikson et al., 2005; Hughes and Moseley, 2007; Cáceres and Alsina, 2012; Chardón-Maldonado et al., 2016; Alsina et al., 2018), see Fig. 3.

Wave capture occurs when the second wave captures the preceding one during uprush (Cáceres and Alsina, 2012). The wave capture is less efficient than a single undisturbed uprush event in mobilizing sand particles and this could be because the presence of a water layer from the previous uprush reduces the bed shear stress and/or turbulence levels near the bed (Alsina et al., 2018). Barnes et al. (2009) and Baldock et al. (2014) suggested that the cross-shore location of wave capture largely affects sand transport since the interaction location determines whether the swash propagates over a dry bed (higher bed shear stress) or over a previous smaller uprush (smaller bed shear stress). It is also observed by van der Zanden et al. (2019) that the wave capture occurring further seaward leads to higher mobilization of sediment within the swash zone. Weak wave-backwash interaction happens when the backwash has less momentum than the incoming wave that continues to propagate landward. In contrast, strong wave-backwash interaction occurs when the backwash has similar or larger momentum than the incoming wave, leading to a stationary bore (hydraulic jump) or offshore flow (Cáceres and Alsina, 2012; Cáceres and Alsina, 2016; van der Zanden et al., 2019). The type of wave-backwash interaction and interaction location, depending on wave conditions and beach morphology, affects the direction of sand transport as well as the magnitude (Cáceres and Alsina, 2016). The weak wave-backwash interaction reduces seaward advection of sediment (Alsina et al., 2018) and usually leads to onshore sand transport (Cáceres and Alsina, 2012). The strong wave-backwash interaction typically results in hydraulic jumps, enhancing turbulence intensity (Alsina et al., 2018). Therefore, this type of interaction is effective in mobilizing sediment and increases sheet flow layer thickness and suspended sand concentrations (Hughes and Moseley, 2007; van der Zanden et al., 2019). The resulted stationary bore by the strong wave-backwash interaction prevents the run-up from advancing along the foreshore. Once the incoming bore energy is depleted, the remaining energy of the backwash prevails and transports the resuspended sand offshore (Cáceres and Alsina, 2016). Hence, the strong wave-backwash interaction generally promotes the offshore sand transport at the intra-swash time scale (Cáceres and Alsina, 2012; Cáceres and Alsina, 2016; Alsina et al., 2018). Overall, both field and laboratory studies (Blenkinsopp et al., 2011; van der Zanden et al., 2019) indicate that stronger wave-swash interactions tend to increase the transport potential of a swash event leading to more dynamic morphological changes. The degree of the wave-swash interaction can be quantified by the ratio of the period of individual swash events T_s and the period of incident waves T. The effect of wave-swash interactions on the foreshore slope change was initially analysed and quantified by Kemp (1975) in which he suggests that the elimination or reduction of the backwash (by collision) will promote the onshore movement of bed material. Later, Holland and Puleo (2001) found based on field observations that the beach profile tends to adjust until an equilibrium state is achieved such that the swash duration and the incident wave period are nearly equal ($\frac{T_s}{T} = 1$). Brocchini and Baldock (2008) provided a formula which relates the ratio of the swash duration and the incident wave period to the offshore wave conditions and beach slope, given as follows:

$$\widehat{T} = 2\left(\frac{2}{\pi}\right)^{\frac{1}{4}}\left(\frac{K^2 H_0}{gT^2\gamma^2}\right)^{\frac{1}{4}} \tag{1}$$

where K is an empirical factor that depends on beach type; H_0 and T are the deep water wave height and wave period respectively; γ is the beach

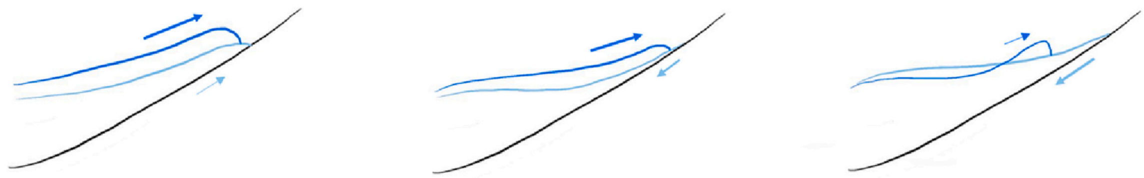

Fig. 3. Schematic of wave-swash interactions with the light blue curve representing the initial swash motion and the dark blue curve being the subsequent swash motion. The arrows indicate the direction and scale of each flux (adapted from Cáceres and Alsina, 2012).

slope. A ratio smaller than 1 indicates little or no wave-swash interaction and larger values of the ratio indicate more intensive interaction, while it cannot be used to distinguish the interaction type.

The imbalance between the landward uprush sand transport and seaward backwash transport results in a swash-averaged net sand transport, which is closely associated with morphodynamics in the swash zone.

2.4. Morphodynamics

The morphological equivalent of the swash zone is the beach face which is a relatively steep region of the beach profile between the berm and the low tide level (Masselink and Puleo, 2006). Swash morphodynamics are driven by the combination of the sediment mobilized and redistributed within the swash zone and the sediment pre-mobilized in the inner surf zone and imported/exported at the seaward boundary of the swash zone (Jackson et al., 2004; Pritchard and Hogg, 2005; Alsina et al., 2009). The rates of morphodynamic change differ over different time scales. At the time scale of individual swash events, the most dynamic morphological changes often occur in the lower swash zone and around the initial shoreline, controlled by the bed saturation condition, rapid flow acceleration after bore collapse and backwash flow momentum (van der Zanden et al., 2019; Pintado-Patiño et al., 2021). van der Zanden et al. (2019) found that the intra-swash morphological changes in the swash zone are mainly caused by a sediment redistribution within the swash zone, which suggests that the advection of pre-suspended sediment induced by bore turbulence and/or wave-swash interactions through the surf-swash boundary plays a minor role at intra-swash time scale. This is in contradiction with previous field observations (e.g. Jackson et al., 2004) and numerical results (e.g. Pritchard and Hogg, 2005) which indicated the importance of pre-suspended sediment for bed level change in the swash zone. The difference with the field observations might be related to the definition of the offshore boundary of the swash zone. In Jackson et al. (2004), the offshore boundary is close to the location where the bore collapse occurs while in van der Zanden et al. (2019) the offshore boundary is defined at the run-down limit which is more landward. Another possible cause is that the degree of wave-swash interactions on natural beaches due to random waves (including infragravity waves) can be stronger, thereby resulting in larger pre-suspended sediment loads. The differences with the numerical results may be associated with the effects of wave-swash interactions on the sand transport that are not taken into account in the numerical model. van der Zanden et al. (2019) also emphasized that the sand exchange between the surf and swash zones becomes increasingly important at swash-averaged and longer time scales.

Many field studies (e.g. Puleo et al., 2000; Turner et al., 2008; Masselink et al., 2009; Blenkinsopp et al., 2011; Puleo et al., 2014b) show that the bed level changes of a few individual events can be larger than the net bed level change over a tidal cycle with most individual swash events displaying little or no net bed level change. Additionally, net bed level change per swash event is found to be nearly normally-distributed with similar numbers of erosion and accretion events (Blenkinsopp et al., 2011; Puleo et al., 2014b). The bed levels of some individual events in Puleo et al. (2014b) vary by ±20 mm while the net bed level change over a tidal cycle is <5 mm. Moreover, Turner et al. (2008) found the standard deviation of wave-by-wave bed level changes was large with the largest bed level accretion/erosion per wave being 18 mm and − 26 mm respectively whereas the mean bed level change per swash event was of the order of one grain diameter only. This highlights the difficulty in predicting morphological changes in the swash zone over larger time-scales by addressing event-by-event sand transport as small errors can accumulate, thereby potentially resulting in unrealistic results. However, for a beach undergoing rapid storm, the net bed level change can be much larger than that of intra-swash bed level change (Holland and Puleo, 2001) and the distribution of event-scale bed level change would be skewed (Puleo et al., 2014b). Field tests (Masselink et al., 2009; Blenkinsopp et al., 2011; Puleo et al., 2014b) suggested that a few events may ultimately result in net bed level changes over tidal cycles. Therefore, the concept of a "typical" event (e.g. ensemble-averaging) from irregular-wave forced swash events may not be sufficient to predict the net long-term bed level change. The deterministic-probabilistic approach (e.g. Baldock et al., 2007) provides an option to predict the longer term morphological change in the swash zone taking the randomness of swash motions into account. Over the time scale of a tidal cycle or a storm, long waves can play an important role in governing the net bed level changes especially at dissipative beaches by controlling the number, location and timing of wave-backwash interactions along the swash zone and by increasing the wave breaking area (Cáceres and Alsina, 2016). Tides affect the morphological changes by changing water levels and by changing the water table position further influencing in−/exfiltration (Almeida et al., 2020).

The Dean number ($\Omega = \frac{H_0}{w_s T_p}$, where H_0 is the deep water wave height, T_p is the peak wave period and w_s is the sediment settling velocity) which is originally introduced by Gourlay and Meulen (1968) has been applied to predict the erosive or accretive tendency of a beach under a given wave climate (Dean, 1973; Wright et al., 1985; Dalrymple, 1992) with $\Omega < 3.2$ indicating beach accretion and $\Omega > 3.2$ indicating erosion (Kraus et al., 1991). This parameter is further developed by Hattori and Kawamata (1980) by taking the effect of beach slope on the net sediment transport in the surf zone into account. However, these criteria do not work well for the swash zone (António et al., 2023). Laboratory experiments in Eichentopf et al. (2020) have demonstrated the importance of the beach equilibrium concept and the initial morphology of a wave condition for determining the overall tendency of beach evolution in the swash zone even under rapidly varying conditions of storm sequences. When the beach slope is steeper than the equilibrium slope, the backwash moves more sand than the uprush, resulting in offshore net sand transport and flatter beach slope. If the beach slope is flatter than the equilibrium gradient, the uprush moves more sand than the backwash, inducing onshore net sand transport and steeper beach slope. Morphological change continues for both cases until a new equilibrium beach profile is achieved (Masselink and Puleo, 2006). The equilibrium beach profile is affected by the sand characteristics and wave forcing (Yates et al., 2009; Baldock et al., 2017; Eichentopf et al., 2020; Almeida et al., 2020) regardless of the initial profile morphology. How far the initial profile is away from the equilibrium state significantly affects rates of beach change and sand transport (Wright and Short, 1984; Eichentopf et al., 2020; Almeida et al., 2020; António et al., 2023). Larger disequilibrium leads to faster changes of beach profiles. However, how to reasonably determine the equilibrium beach profile over event-type time scales (e.g. over a tidal cycle or during a storm) for the swash zone still remains unclear.

3. Practical models of sand transport in swash zone

Practical models of swash sand transport depend on parameterizations of small-scale processes, and can be divided into three categories, i.e. empirical sand transport formulae, sand transport distribution methods and the equilibrium concept model. The empirical transport formulae (e.g. Shields type and energetics type formulae) often relate the sand transport rates to the flow velocity to some power. In some wave-averaged models, such as Delft3D, the swash zone is not modelled. In order to take the swash beach evolution into account in the wave-averaged morphodynamic models, the sand transport distribution methods are employed to calculate the bed level change in the swash zone. This type of distribution method basically distributes the calculated sand transport in one or several wet grid cells located in the surf zone given by wave-averaged models upwards until the run-up limit following some simple distribution functions. The effects of hydrodynamic factors (e.g. bed shear stress) on the sand transport are not explicitly modelled. The equilibrium concept model computes or corrects the sand transport based on the difference between the local slope and the equilibrium slope. These practical models of swash sand transport are reviewed in this section.

3.1. Empirical sand transport formulae

Empirical sand transport formulae consist of simple equations, which require short computational time and can be easily implemented in coastal morphodynamic models. These empirical sand transport formulae can be classified as related to intra-swash or swash-averaged conditions and parameters.

3.1.1. Intra-swash formulae

Intra-swash formulae calculate sand transport by relating instantaneous sand transport rates to the instantaneous flow velocity or the bed shear stress. Several sand transport formulae have been developed based on the energetics-based sand transport formulae proposed by Bagnold (1966) and Bailard (1981) or Shields-type formulae developed by e.g. Meyer-Peter and Müller (1948) and have been applied to the swash zone in several field studies (e.g., Masselink and Hughes, 1998; Puleo et al., 2000; Butt and Russell, 2005; Aagaard and Hughes, 2006; Masselink and Russell, 2006; Karambas, 2006; Hughes et al., 2007; Masselink et al., 2009). Since uprush and backwash sand transport processes differ, these formulae require different empirical transport efficiency constants for linking measured velocities and sand transport rates during uprush and backwash phases in the swash zone (Nielsen, 2002), and the uprush coefficients are usually larger than backwash coefficients. Different estimates of the empirical constants are given by different studies, which can be caused by different measurement locations within the swash zone (Aagaard and Hughes, 2006) and/or by inaccurately measured velocity time series due to rapid bed level changes (Puleo et al., 2014b). Nielsen (2002) adapted a sand transport formula (Nielsen, 1992) for steady flow to predict swash sand transport. The Nielsen (2002) formula takes the different transporting efficiencies of the uprush and backwash flows in a swash zone into account by incorporating a local acceleration and a phase lag between free stream velocity and sediment concentration, without using different values for the transport efficiency coefficients. However, the use of local acceleration results in a significant underestimation of the uprush sand transport during which the acceleration is mainly negative (Baldock et al., 2005; Othman et al., 2014). Pintado-Patiño et al. (2021) applied a sheet flow layer model to predict the sand transport of dam-break-driven swash events and a reasonable agreement was found between measured and estimated total sand transport. In this sheet flow layer model, the sediment concentration profile within the sheet flow layer is approximated with the formula of O'Donoghue and Wright (2004) in which the sheet flow layer thickness is determined using the approach by Lanckriet and Puleo (2015). The velocity inside the sheet layer is approximated using an exponential law (Soulsby and Damgaard, 2005).

It is worth mentioning that all above-mentioned intra-swash empirical transport formulae require the input of time series of swash flow velocities which cannot be provided by short wave-averaged models. In order to enable practical applications of these formulae, (semi-) analytical models based on the ballistic theory are often applied to calculate swash flow velocities. In most circumstances waves break as they approach the shore and form a turbulent bore in their final approach to the shoreline (Hibberd and Peregrine, 1979). Shen and Meyer (1963) developed a ballistic swash model which is an analytical solution to the one-dimensional and depth-averaged Non-Linear Shallow Water equations. Peregrine and Williams (2001) extended the Shen and Meyer (1963) solution across the entire swash zone. However, the Shen and Meyer (1963) and Peregrine and Williams (2001) solutions cannot properly describe the internal swash zone hydrodynamics, for example, they under-predicted the swash flow depth due to underestimates of the mass and momentum from the breaking bore (Guard and Baldock, 2007). Zeng and Liu (2022) developed a simple approximate explicit analytical solution for the internal swash hydrodynamics that can be solved immediately and with a good accuracy using an improved seaward boundary condition proposed by Guard and Baldock (2007). The previously mentioned solutions are only applicable for frictionless swash hydrodynamics and do not take wave-swash interactions into consideration. The bed friction plays an important role in determining the bed shear stress and therefore affects swash sand transport (Puleo and Holland, 2001). Hughes and Baldock (2004) extended the Shen and Meyer (1963) ballistic swash model by combining it with a quadratic friction law and a semi-empirical function calculating the swash flow depths. This model does not take wave-swash interactions into consideration and may thus be less applicable for gently sloping beaches. Erikson et al. (2005) proposed a model describing swash motions by modifying the ballistic model accounting for the interactions between uprush and backwash above the still water shoreline and within the swash zone. The momentum is calculated for both the uprush and backwash at the point where the fronts meet. A new velocity following collision is determined from the average of the uprush and backwash momentums. This improved ballistic swash model requires the inputs of wave heights and arrival times at the still water shoreline. However, this model was only validated for predicting the maximum run-up length and its capability of predicting the internal swash velocities and water depths still remains unknown. Moreover, the model does not take the wave-swash interactions into account if the interaction location is below the initial water shoreline.

The Nielsen (1992, 2002) intra-swash sand transport formula was later applied in the probabilistic-deterministic model proposed by Baldock et al. (2007) to predict cross-shore beach profile change in the swash zone under random waves. The swash hydrodynamics are calculated using the swash model of Baldock and Holmes (1997) which is based on ballistic theory. The input to the swash model is the height of the incident bore at the initial shoreline, and a friction coefficient which is calculated following Hughes (1995). Bore heights in the inner surf zone are well described by a Rayleigh distribution (Baldock et al., 1998), which is consistent with the Rayleigh distributed run-up under random waves (e.g. Nielsen and Hanslow, 1991). In Baldock et al.'s model, the total transport is determined for a series of Rayleigh distributed bore heights, H_b, ranging from H_{bmin} to H_{bmax}, with the net transport at any location weighted by the respective probability of occurrence for that bore height as follows:

$$q_{total} = \sum_{H_{bmin}/H_{brms}}^{H_{bmax}/H_{brms}} q_{net} \frac{2H_b}{H_{brms}} exp\left[-\left(\frac{H_b}{H_{brms}}\right)^2\right] \Delta\left(\frac{H_b}{H_{brms}}\right) \quad (2)$$

in which q_{net} may be time-averaged net sand transport, or retained as a discrete transport volume, depending on the modelling framework (Baldock et al., 2007). q_{net} is taken positive for onshore transport and negative for offshore transport; H_{brms} is the root-mean-square bore height at the run-down position determined by the surf zone wave transformation model; H_{bmin} was set to $H_{brms}/5$, with $H_{bmax} = 2.4H_{brms}$. This model has been validated for uprush transport only (berm overtopping conditions) and is not yet a full and good predictive tool for beach morphology (Baldock et al., 2007). Baldock et al. (2008) later formulated a similar parametric model using well-established formulae for wave run-up, wave run-up distributions and the Nielsen (1992) sediment transport formula. This model was applied to predict the total overwash transport into and infilling the estuary entrance and compares well with field observations. Nevertheless, further validation of this parametric model against more field data is required (Baldock et al., 2008). The fundamental assumption of this model is that a representative bore height can provide a sufficient description of the nearshore processes, which means that this model neglects the effects of wave grouping and long waves on the hydrodynamics and sand transport. Thus, this model is likely to be more applicable on reflective beaches. Moreover, the pre-suspended sediment advection and wave-swash interactions are not taken into account.

Some studies (e.g., Masselink and Russell, 2006; Hughes et al., 2007; Masselink et al., 2009) showed that the intra-swash sand transport formulae do not work well for the swash zone in terms of the magnitude and even the direction of the swash sand transport, especially for the upper swash zone, even though the measured swash hydrodynamics were applied directly in the formulae. Some improvements have been made for the intra-swash sand transport formulae by for example including bore turbulence (Pritchard and Hogg, 2005; Aagaard and Hughes, 2006), using friction factors dependent on flow phase (Pedrozo-Acuna et al., 2006; Barnes et al., 2009) or including an in−/exfiltration model (Turner and Masselink, 1998; Karambas, 2006). These improved formulae can have reasonable predictive capability of the sand transport rate and direction for simple swash events within the time scale of hours. However, when they are up-scaled for modelling sand transport and morphological change over tidal cycles or longer term, they are not necessarily more accurate than the swash-averaged model presented in the following section because small errors tend to accumulate in long-term (days to years) simulations (Masselink et al., 2009). Nevertheless, these intra-swash sand transport formulae are more physics-based and provide, as such, a basis for the development of swash-averaged sand transport formulae.

3.1.2. Swash-averaged formulae

Swash-averaged sand transport formulae predict sand transport over a timescale which is much longer than swash period. Larson et al. (2004) developed a sediment transport formula to predict the net transport rate over many swash cycles. This formula for the time-averaged net transport q_{net} was derived based on integration of the Madsen (1993) formula for the instantaneous bed load transport rate over a swash cycle. The shear stress in the Shields parameter is assumed proportional to the local velocity squared, reducing the problem to estimating the flow velocity (with an appropriate friction coefficient). By applying the ballistic theory (Shen and Meyer, 1963) and the relationship between the run-up limit and the swash front velocity, the sand transport formula was simplified as

$$q_{net} = K_c 2\sqrt{2}R^{\frac{3}{2}}\left(1-\frac{z}{R}\right)^2 \times \frac{tan\phi_m}{tan^2\phi_m - \left(\frac{dz_b}{dx}\right)^2}\left(\frac{dz_b}{dx} - tan\beta_e\right) \quad (3)$$

where R is the run-up limit and can be calculated using empirical equations (e.g. Mayer and Kriebel, 1994); β_e is the equilibrium beach gradient; z is the elevation above the location where the swash starts and z-axis points upwards; z_b is the bottom elevation and the z_b-axis is taken positive downwards; x-axis points offshore. Note that q_{net} is positive for offshore transport; ϕ_m is the friction angle (about 30°). K_c is a calibration factor and Larson et al. (2004) suggested that the value of K_c might depend on sediment grain size and the ratio between the incident wave period and the swash period. This ratio implicitly takes the wave-swash interactions into account considering the wave-swash interactions may lead to a period for the characteristic swash cycle that is different from the incoming wave period. There is an overall good agreement between the predicted and observed erosive beach profiles measured by Kubota et al. (1994, 1997, 1999). However, Larson et al. (2004) did not propose an empirical equation for calculating K_c due to limited data. The equilibrium slope (β_e) is specified based on the field measurements by Kubota et al. (1999). However, it remains unknown how to determine the value of the equilibrium slope of the swash zone when measurements are not available. The Larson et al. (2004) formula is only applicable for calculating the net sand transport and updating the beach profile above the still water level and there is no coupling to the rest of the profile. Zhang et al. (2020) later coupled the swash zone and surf zone together to predict the entire beach evolution. Nevertheless, this coupled model is only validated with measured erosive conditions and it still remains unclear if the Larson formula also works well for predicting beach accretion.

In CSHORE, a wave-averaged numerical model that predicts nearshore hydrodynamics and beach evolution (Kobayashi, 2009), a sand transport model for suspended load and bed load is formulated by relating the sediment transport rates to the time-averaged swash flow velocity and water depth in combination with sand movement probability, sediment suspension probability and wet probability (Kobayashi, 2016). The cross-shore variations of the wet probability and the mean and standard deviation of the water depth and cross-shore velocity are predicted by a time-averaged probabilistic model. Johnson et al. (2012) showed that the CSHORE model provided overall satisfactory estimates of storm-induced beach erosion but under-predicted the magnitude of upper beach erosion.

3.2. Sand transport distribution methods

As mentioned in Section 1, wave-averaged models cannot provide detailed wave dynamics in the swash zone; they even do not include the swash zone. Sand transport distribution functions for the swash zone have been developed, which can be implemented with morphological models to simulate longer-term (days to years) beach profile evolutions. Field-based shape functions describing the distribution of cross-shore sand transport across a beach profile have been proposed by previous studies (Weir et al., 2006; Aagaard and Hughes, 2006; Tinker et al., 2009). Weir et al. (2006) used field measurements of berm profile evolution to develop a swash zone shape function including three shape types (with one sub-type). However, this shape function only describes the form of the sand transport distribution while does not provide the actual magnitudes of the sediment transport rates. Therefore, it can only be used to qualitatively model the berm growth. Aagaard and Hughes (2006) proposed a simple sediment transport shape function which relates the net suspended sediment transport rate to the percentage of immersion by fitting the field data collected at dissipative beaches. Later, Tinker et al. (2009) presented a field-based shape function of the time-averaged depth-integrated suspended sediment flux in the surf zone and the swash zone. This shape function does not represent a total load transport function since the bed load transport is not included. The shape functions proposed by Aagaard and Hughes (2006) and Tinker et al. (2009) have not been implemented in a morphological model and not been validated for predicting the longer-term beach profile evolution using field and/or laboratory data. Nevertheless, some sand transport distribution methods have been applied in the widely-used wave-averaged morphological models including SBEACH, CROSMOR, UNIBEST-TC and Delft3D to model the swash sand transport by distributing the sand transport rate from the landside boundary of the surf zone in the wave-averaged models landward up to the maximum run-up height making use of different functions. These models have been validated using the measured beach profiles from the field and laboratory tests and are introduced in more detail in the following section.

3.2.1. Linear distribution method implemented in SBEACH model

SBEACH is a predictive engineering model for simulating macroscale changes of the beach profile (Larson and Kraus, 1989). The cross-shore net sand transport rates are calculated using the empirical distribution relationships developed based on large-scale lab experiments for four different zones of the beach profile, i.e. pre-breaking zone, breaker transition zone, broken wave zone and swash zone. The broken zone encompasses the main part of the surf zone and the transport rate was demonstrated to be closely related to the energy dissipation per unit volume. The predicted sand transport is proportional to the difference between the present and calculated equilibrium wave energy dissipation. The direction of the net sand transport is determined by the criterion that is based on the deep-water wave steepness and the dimensionless fall velocity. The transport rate distribution in the swash zone is approximated by linear decay with distance from the landward limit of the surf zone, which means that the transport rate is linearly extended from the end of the surf zone to the runup limit. The surf zone is arbitrarily ended at a depth of 0.3–0.5 m. SBEACH has been tested by comparing computed and measured beach profiles using lab experiment and field data. The model can predict the berm size during accretive events reasonably well, but fails to adequately describe the profile shape in the swash zone and underestimates the erosion above 0 m MSL due to the crude sand transport model in the swash zone (Larson and Kraus, 1989; Simmons et al., 2019).

3.2.2. Triangular-shape distribution method implemented in CROSMOR model

The CROSMOR model is a cross-shore profile model. The wave-averaged net total sediment transport outside the swash zone in the CROSMOR model is calculated as the sum of the net bed load and net suspended load transport rates. The instantaneous bed load transport rate is calculated using empirical formulae (e.g., Van Rijn, 2007a, 2007b, 2007c) and then the net bed load transport rate is determined by wave-averaging of the instantaneous transport rate. The net suspended load transport is calculated as the sum of the wave- and the current-related components (Van Van Rijn, 1993; Van Rijn, 2007a, 2007b, 2007c). The wave-related suspended load transport is calculated using the approach proposed by Houwman and Ruessink (1996). The current-related suspended load transport are computed based on the wave-averaged current velocity profile and the sediment concentration profile which can be obtained by solving the vertical advection-diffusion equation. A prescribed reference concentration that is often formulated as a function of the wave-averaged bed shear stress due to current and wave conditions, is applied at a near-bed reference level. The complicated hydrodynamics and sand transport processes in the swash zone are not explicitly modelled but are schematized. First, the model user needs to set a minimum water depth (typical values of 0.1 to 0.2 m), based on which the last wet grid point can be determined by interpolation after each time step. The upper end of the swash zone is determined by the run-up point which can be calculated using empirical formulae (e.g. Stockdon et al., 2006). Following that, the modelled total erosion (or accretion) area in the swash zone defined between the last wet grid point and the run-up point is given by,

$$A_E = q_l \Delta t / [(1-p)\rho_s] \tag{4}$$

in which q_l is the cross-shore wave-averaged net sand transport rate at the last wet grid cell; Δt is the time step; p represents the porosity of bed material and ρ_s is the sediment density. It is assumed that the erosion or accretion in the swash zone has a triangular shape as shown in Fig. 4. With the erosion (or accretion) area known, the maximum erosion (or accretion) depth can be derived. Finally, it is possible to calculate the bed level change in the swash zone between the last wet grid point and the run-up point for each time step as follows (for detailed information, reference is made to Van Rijn, 2009):

$$\Delta z(x) = \begin{cases} \dfrac{x - x_l}{0.8L_s} d_e, \; 0 < x - x_l < 0.8L_s \\ \dfrac{L_s + x_l - x}{0.2L_s} d_e, \; 0.8L_s \le x - x_l \le L_s \end{cases} \tag{5}$$

in which Δz is the bed level change; x_l is the x coordinate of the last wet grid cell and the x-axis points onshore; L_s is the horizontal distance between the last wet grid point and the uprush point; d_e is the maximum erosion or accretion depth. Onshore net sand transport at the last wet grid will lead to beach accretion and offshore net sand transport will cause erosion in the swash zone. The bed level of the profile including the swash zone is updated each time step.

3.2.3. Sand transport rate distribution method implemented in UNIBEST-TC model

The UNIBEST-TC model is a parametric cross-shore model in which wave-averaged hydrodynamic equations, sediment transport and bed level evolution are coupled together (Ruessink et al., 2007; Van Rijn et al., 2011). Similar methods to those used in the CROSMOR model are applied in UNIBEST-TC model to compute the sand transport rates outside the swash zone. The sand transport in the swash zone is obtained also in a schematized way but is different from the approach adopted in the CROSMOR model. A transition point in the UNIBEST-TC model is determined using $h_{min} = g(T_p/T_{dry})^2$, in which T_{dry} has to be set by the user. The basic transport formulae are assumed to be valid seaward of the transition point and additional corrections need to be made for the region landward of the position. The sediment transport rate at the transition point is then distributed over the dry part of the beach up to the significant runup point. The transport rate at any position landward of the last wet grid point is expressed as a fraction of the transport rate at the transition point, depending on the local bed level. The fraction of the transport rate at a certain level above the still water line is assumed to be associated with the relative volume of water (RCV) which passes this level (see Walstra and Steetzel, 2003). The modified transport rate is computed according to:

$$q_{x,i} = RCV\left(\frac{z_i}{z_s}\right) q_{ref} \tag{6}$$

in which

$$RCV\left(\frac{z_i}{z_s}\right) = exp\left(-2\left(\frac{z_i}{z_s}\right)^2\right) - \sqrt{2\pi}\,\frac{z_i}{z_s}\left[1 - erf\left(\sqrt{2}\,\frac{z_i}{z_s}\right)\right] \tag{7}$$

$$erf\left(\sqrt{2}\,\frac{z_i}{z_s}\right) = \frac{2}{\pi}\int_0^{\sqrt{2}\,\frac{z_i}{z_s}} exp\left(-x^2\right) dx \tag{8}$$

where z_i is the vertical coordinate relative to the transition point; q_{ref} is the sand transport at the wet-dry transition point; z_s is the significant wave runup height relative to the vertical position of the transition point. Based on the distributed sand transport rate, the bed level evolution can be computed.

3.2.4. Erosion flux distribution method implemented in Delft3D model

Delft3D has been widely used to model the beach evolution (e.g., Van Rijn et al., 2007; Lesser, 2009). To model the erosion of the dry beach, the erosion flux at a wet grid is distributed evenly to the adjacent dry cells. A user-defined factor ThetSD determines the fraction of the erosion to be distributed. If the ThetSD equals 1 all erosion that would occur in

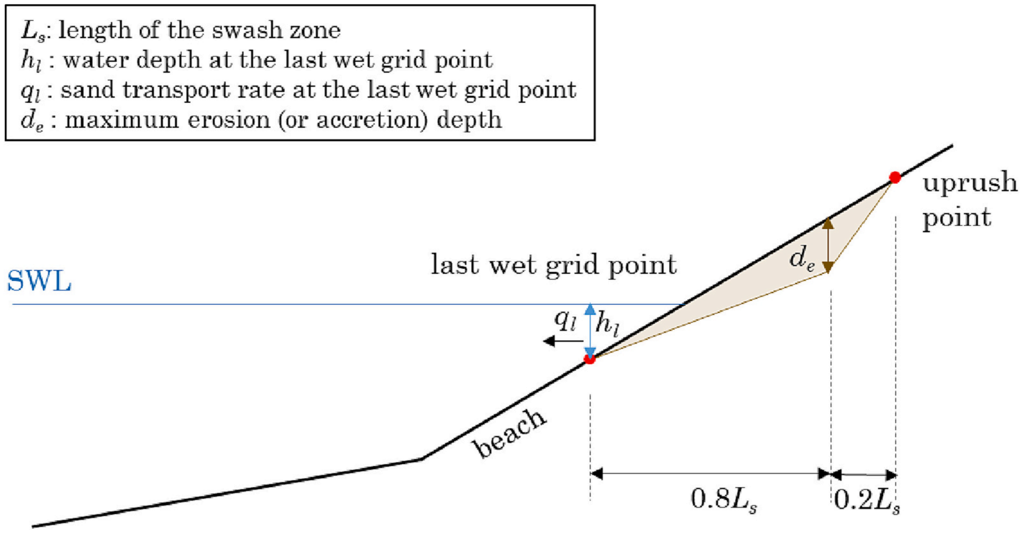

Fig. 4. Bed level changes in the swash zone (adapted from Van Rijn, 2009).

the wet cell is assigned to the adjacent dry cells. The wet and dry cells are defined as those cells at which the local water depth is larger and smaller respectively than the threshold depth for computing sediment transport. This scheme is considered to be too simple and requires further improvement (Van Rijn et al., 2011).

Van Rijn et al. (2011) compared the computed morphological development given by CROSMOR, UNIBEST-TC and Delft3D models with experimentally measured beach evolution at three different scales of identical flume tests (Grüne et al., 2008; Deltares/Delft Hydraulics, 2008; Caceres et al., 2009). Results indicated that the CROSMOR and UNIBEST-TC distribution models can simulate the beach erosion reasonably well while Delft3D model systematically over-predicted the erosion of the upper beach which is caused by the applied simple dry-bed procedure. However, none of the three models works well for accretive conditions and the performance of the Delft3D is even worse.

3.3. Equilibrium model

The above mentioned distribution models are capable of predicting beach erosion due to storms but generally fail to properly predict wave-driven recovery. The so-called Bermslope model was introduced by Roelvink and Otero (2017) in XBeach (Roelvink et al., 2009) to address this problem. XBeach was originally developed to model the hydrodynamics and morphological evolution of coastal sandy beaches on the time scale of storm events. The surfbeat approach is a default approach in the XBeach model, solving the wave action balance equation on the short wave group time scale making use of parameterization of wave nonlinearities. The motions of long waves are modelled by solving the nonlinear shallow water equations. The basic idea of the Bermslope model is to nudge the predicted beach profile towards an equilibrium beach profile based on the difference between the local and the equilibrium beach slopes. In computational cells where the simulated ratio of wave height/water depth (H/h) > 1 in surfbeat mode, the Bermslope model performs a correction on the simulated sand transport:

$$q_{swash} = q - f_{swash}|q|\left(\frac{\partial z_b}{\partial x} - bermslope\right) \tag{9}$$

$$q = u_{sed}hc \tag{10}$$

where q is the computed sediment transport; f_{swash} is a calibration factor; $\frac{\partial z_b}{\partial x}$ is the instantaneous local bed slope and *bermslope* is the prescribed equilibrium (target) swash slope; u_{sed} is the depth-averaged sediment advection speed; c is the depth-averaged concentration which can be obtained by solving the advection-diffusion equation.

The Bermslope model improved the model's ability to predict berm growth and the characteristic steep slope. However, this model failed to capture the erosive response to episodic storm conditions and continued to predict accretion during energetic conditions (Van Dam, 2019). Therefore, to overcome the shortcoming of the Bermslope model, Van Dam (2019) improved the Bermslope model by introducing a new factor (as a replacement of f_{swash} in Eq. (9)) that is dependent on the wave conditions using the concept of morphodynamic beach states (Wright and Short, 1984):

$$fac_{BS} = \frac{f_{swash}}{2}\left[cos\left(\frac{\Omega - \Omega_{min}}{\Omega_{max} - \Omega_{min}}\pi\right) + 1\right] \tag{11}$$

$$fac_{BS}(\Omega \le \Omega_{\min}) = f_{swash} \text{ and } fac_{BS}(\Omega \ge \Omega_{\max}) = 0. \tag{12}$$

where Ω is the Dean number (Dean, 1973); Ω_{min} (recommended as 2.0) defines the threshold value for reflective (accretive) conditions that correspond to the prescribed equilibrium *bermslope* and Ω_{max} (recommended as 4.0) is the threshold for storm conditions that correspond to (severe) erosion and profile flattening. For extreme storm conditions (high Ω values), Eq. (11) does not modify the computed sand transport q (i.e. $fac_{BS} = 0$ according to Eq. (12)). For intermediate conditions, the value of fac_{BS} decreases from f_{swash} gradually as Ω increases. Even though the surfbeat approach implemented in XBeach resolves the long waves and runup and rundown of long waves, it does not account for the incident band wave energy which can dominate at reflective beaches. A new run-up formula was developed based on the Stockdon et al. (2006) formula, taking into account the contribution of incident band waves to the run-up height and was implemented in XBeach. Following that, a re-distribution of the sediment transport was performed over the upper swash zone up to the modified significant wave run-up height, which accounted for incident band swash-induced sediment transport that is not resolved in XBeach surfbeat mode. This method keeps the distribution shape of the calculated sand transport rates by XBeach but extends the shape over the modified runup range using linear interpolation as illustrated in Fig. 5. The modified Bermslope model by Van Dam (2019) is calibrated and validated using a multi-decade dataset of monthly beach profile surveys at Narrabeen beach in Australia (Turner et al., 2016). This model significantly improved the prediction of the beach profile evolution. However, the equilibrium slope in the model is set as a constant value of the observed swash slope during calm conditions. When observations are not available, the determination of the equilibrium slope remains a problem and the equilibrium swash slope should

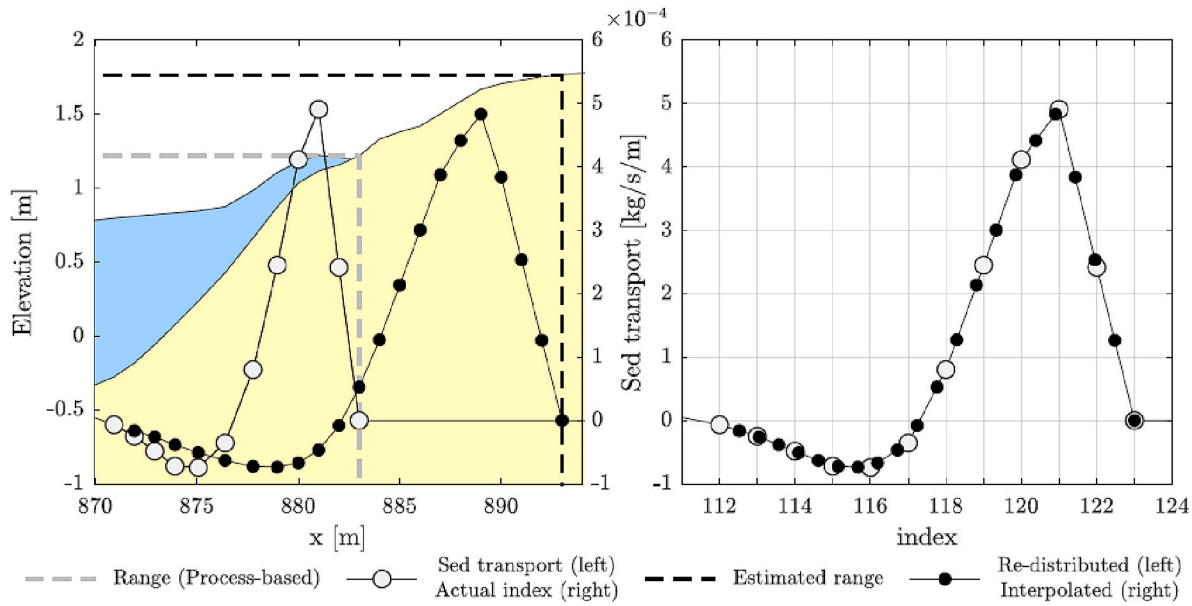

Fig. 5. *Re*-distribution of the computed sand transport rates by XBeach (white dots) from the range between the 1 m depth contour and the last wet cell (indicated by the grey dashed line) given by XBeach to the estimated range up to the significant runup height (black dashed line) calculated using empirical runup equations. The interpolation of sediment transport rates is shown in the right panel (Van Dam, 2019).

vary with wave conditions and sediment characteristics instead of a constant value. Kombiadou et al. (2021) also applied the Bermslope model (Roelvink and Otero, 2017) to simulate the shorter-term (45 days) morphodynamics of a reflective beach under storm conditions and its subsequent recovery using the XBeach surfbeat approach. After calibration, the model generally works well in terms of erosion during storms as well as in terms of berm growth and beach recovery during mild wave conditions. The model analysis demonstrates that the model performance is sensitive to the prescribed equilibrium slope, which highlights the importance of reasonably determining the equilibrium slope.

4. Discussion

4.1. The influence of different physical processes on swash zone sand transport

Beaches adapt to wave forcing over multiple time scales (intra-swash/hours/days/months/years) and the relative importance of physical factors or processes, including bore turbulence, pre-suspended sediment advection, wave-swash interactions, infragravity waves, in−/exfiltration, pressure gradient and bed slope, can be different at different time scales and different morphological conditions. Additionally, these processes can interact with each other. Knowledge of the overall effects of these processes is important for successful modelling of the sand transport in the swash zone.

The bore collapse-induced turbulence during the uprush may reach the bottom when the bore height is larger than half the local water depth and increase the bed shear stress (Fredsøe et al., 2003), promoting sand mobilization and increasing the sheet flow layer thickness (Lanckriet and Puleo, 2015; van der Zanden et al., 2015). The bore turbulence is expected to be greater at steeper slopes which have narrower surf and swash zones resulting in more intensive energy dissipation (Butt et al., 2007). The more intensive bore turbulence may lead to stronger pre-suspended sediment advection, which can further affect the magnitude and direction of sand transport in the swash zone. This could be one reason that the energetics-type models are more acceptable for gently-sloping beaches while less accurate for steep beaches. Based on the data of large-scale flume experiments, van der Zanden et al. (2019) highlighted the importance of pre-suspended sediment advection across the surf-swash boundary for bed level changes in the swash zone over multiple events and even larger time scales. The effects of bore turbulence and pre-suspended sand advection can be included in the practical sand transport models by defining a fixed or time-varying sand transport rate at the seaward boundary of the swash zone. The bore turbulence and pre-suspended sediment advection are affected by the offshore wave conditions and wave-swash interactions. Quantification and parameterization of the contribution of the pre-suspended sediment advection to the sand transport in the swash zone require further investigations.

Many studies (e.g. Blenkinsopp et al., 2011; Cáceres and Alsina, 2012; Alsina et al., 2018) have demonstrated the significance of wave-swash interactions for swash morphodynamics. The beach slope is a key parameter affecting the degree of wave-swash interactions (Osborne and Rooker, 1999; Alsina et al., 2012; António et al., 2023). Infragravity waves are found to be generally predominant at gently sloping dissipative beaches (e.g., Beach and Sternberg, 1991; Butt and Russell, 1999; Masselink et al., 2005; Miles et al., 2006). The infragravity waves control the number of wave-backwash interactions along the swash zone and type of such interaction (Cáceres and Alsina, 2016). Alsina et al. (2012) found based on large-scale flume tests that a more dissipative swash zone (gentler slope) promotes a larger number of wave-swash interaction while reduces the magnitude and frequency of larger backwashes, which leads to a reduction of total offshore suspended sand transport over the time scale of 500 waves. This is consistent with the field observations in Almeida et al. (2020) and the laboratory results in António et al. (2023). Additionally, both field study (Osborne and Rooker, 1999) and laboratory studies (Alsina and Cáceres, 2011; Cáceres and Alsina, 2012) showed that incident bores and wave-swash interactions occurring in the trough of infragravity waves generate high suspended sediment concentrations (see, for instance, Fig. 6 in Osborne and Rooker, 1999 and Fig. 11 in Cáceres and Alsina, 2012). Water depths are lowered locally in the trough of infragravity waves and therefore the turbulence induced by the wave-swash interactions can suspend more sand there. A proper parameterization of the effects of wave-swash interactions would help improve the practical modelling of the sand transport in the swash zone. This parameterization should depend on the wave period, beach slope, wave groupiness and infragravity wave phase.

The grain size has a significant influence on the infiltration and exfiltration of water across the beach face (Turner and Masselink, 1998). Moreover, the beach groundwater level also controls the degree of infiltration or exfiltration influencing sediment mobility on the bed and beach morphology (Bakhtyar et al., 2011; Briganti et al., 2016). The infiltration and exfiltration can affect the swash sand transport mainly by (1) modifying the bed shear stress, (2) changing the effective weight of sand particles (Baldock and Nielsen, 2010; Kranenborg et al., 2023). The dominance of these two mechanisms depends on the grain size, which has been mentioned in Section 2.2. Overall, the effect of in−/exfiltration is more significant for gravel beaches than sandy beaches which this paper is focused on (Bakhtyar et al., 2009). The grain size also controls the influence of pressure gradients on the sand transport.

Kranenborg et al. (2023) showed that the vertical pressure gradient which is closely related to in−/exfiltration has a significant effect on the effective submerged weight of sediment particles with the submerged weight of sediment reduced by 40% during the latter stages of the backwash. The contribution of the force induced by the horizontal pressure gradient over a sloping bed in the swash zone is an order of magnitude smaller than the total force (gravity, bed shear stress and pressure gradient) (Barnes et al., 2009). There is still some dispute on the contribution of horizontal pressure gradient. Lanckriet and Puleo (2015) suggested significant effects of the horizontal pressure gradient on sheet flow layer thickness while the measurements at a sandy beach with $D_{50} = 0.25$ mm presented in van der Zanden et al. (2019) do not reveal any evidence for horizontal pressure gradient on sheet flow layer growth, which is to some extent consistent with the findings in Othman et al. (2014). Othman et al. (2014) indicated that including the effect of horizontal pressure gradients improved the predictions of sediment transport for gravel ($D_{50} = 2.65$ mm) but not for fine sand ($D_{50} = 0.22$ mm). The pressure gradient reduces the total transport prediction by 3% for fine sand and by 18% for gravel, which implies that the overall effect of pressure gradient on the sand transport might be much less significant than the effect of wave-swash interactions considering the wave-swash interactions can change the magnitude and direction of the sand transport.

4.2. Strengths and shortcomings of the practical transport models

The strengths and shortcomings of the existing practical models of swash sand transport are summarized in Table 1. Supplementary material (excel file) is provided, listing recent studies which contain laboratory or field datasets that can be used to validate practical swash sand transport models. This tabular form is selected and extended from the supplementary material provided by Chardón-Maldonado et al. (2016).

The empirical intra-swash sand transport formulae are not only applied in combination with practical morphodynamic models but are also used in phase-resolving models (e.g. Pritchard and Hogg, 2005; Zhu and Dodd, 2015; Kranenborg et al., 2022) to predict the short-term (intra-swash/multiple swash events) bed level changes. The phase-resolving models which focus on intra-swash processes can be used to assist in understanding the importance of some hydrodynamic processes for sand transport in the swash zone (such as bore turbulence, pre-suspended sediment advection) (e.g. Pritchard and Hogg, 2005) and to check the difference in erosion/deposition patterns of the swash zone using different sand transport formulae (e.g. Zhu and Dodd, 2013). This can help with the development and improvement of parameterisations of some important physical processes and therefore improvement of practical predictive models of swash zone sand transport. However, the existing intra-swash sand transport formulae are difficult to upscale for longer term simulations especially due to the similar magnitudes of net sand transport over some extreme individual swash events and over tidal cycles (Masselink et al., 2009; Chardón-Maldonado et al., 2016) as well as rapid and large fluctuations of the net sand transport of individual swash events over longer time periods (hours to tidal time scale) (Turner et al., 2008; Masselink et al., 2009; Blenkinsopp et al., 2011). The potentially high significance of individual swash events indicates that a sand transport model needs to accurately calculate the net sand transport of every single swash event in order to successfully predict the net sand transport and longer term (days to years) beach profile evolutions. Even though the (semi-) analytical models provide possibilities to estimate the swash hydrodynamics that are required by these intra-swash sand transport formulae for practical applications, these simple models have their specific applicable conditions, as indicated in Section 3.1.1, and care should be taken to apply them for predicting the swash sand transport and beach evolutions. Furthermore, the detailed transport formulae are sensitive to small errors of flow velocities for single swash events, which can continuously accumulate over longer term periods especially if the morphodynamic feedback is included in the model and finally result in significant deviations between the real and predicted beach evolutions. Using the analytical swash models, or even the phase-resolving numerical models, for individual events and applying these to random waves over longer time scales has not been readily achieved and/or fully validated. The swash-averaged sand transport formulae compute the sand transport at a timescale that is much longer than the swash period, usually derived based on time averaging of the intra-swash sand transport formulae introducing parameterizations of some small-scale physical processes. This type of sand transport formulae may be relatively more appropriate and convenient for the long-term (days to years) prediction of beach evolutions (Thieler et al., 2000; Kobayashi, 2009) since they do not require the input of time-series of flow velocities and depths which are difficult to obtain and they are less sensitive to the uncertainties of small-scale physical processes. Additionally, the swash-averaged formulae are easier to be implemented in wave-averaged coastal morphodynamic models. However, simplifications due to a limited understanding of complex processes, for instance, the wave-swash interactions, can limit the accuracy and applicability of the sand transport model for a wide range of beach conditions. For example, in the Larson sand transport formula (Eq.(3)), the effects of grain size, friction and wave-swash interactions were lumped together into one calibration factor K_c, which indicates that the value of K_c can be site-specific and require calibration for different beach conditions, making the Larson model less predictive.

The sand transport distribution methods parameterize the sand transport processes in a higher degree of simplification compared to empirical swash transport formulae. It is worth noting that these distribution methods are closely related to the net sand transport rate at the surf-swash transition. The choice or changes of sand transport formulae applied outside the swash zone may have a direct influence on the modelled swash zone sand transport. In the CROSMOR model, the suspension enhancement factor (sef) is introduced as a calibration factor which ranges from 1 to 2. Varying the value of this factor will affect the net sand transport rate at the surf-swash transition, in which way the effects of wave collision and bore-collapse turbulence on sand transport are implicitly taken into account. The sef factor should be related to beach slopes in the swash zone (Van Rijn, 2009; Van Rijn et al., 2011). However, the relationship between the value of the sef-factor and the beach slope is still not available yet, and requires future research to make the practical swash transport model implemented in CROSMOR model more predictive. The distribution method implemented in UNIBEST model is fairly simple without introducing additional calibration factors but still works well for erosive conditions. The erosion distribution approach of Delft3D model is too crude and requires significant improvement in the future (Van Rijn et al., 2011). These distribution methods are generally capable of predicting the beach erosion under storm conditions relatively well and they only require a few input parameters such as run-up height, which can be obtained using empirical run-up formulas, more easily than time series of flow velocities that are used in empirical intra-swash transport formulae. However, the distribution methods compute the sand transport or bed level changes in the swash zone in highly schematized ways based on little physics,

Table 1
Overview and pros and cons of existing practical swash zone sand transport models.

Name	Category	Main input	Validation/validated parameters	Pros	Cons
Intra-swash sand transport formulae (Masselink and Hughes, 1998; Nielsen, 2002; Puleo et al., 2003; Butt et al., 2004; O'Donoghue and Wright, 2004; Karambas, 2006; Aagaard and Hughes, 2006)	Empirical sand transport formulae	• time series of free stream velocity • time series of water depth • empirical constants for uprush and backwash • friction coefficient	• Laboratory measurements (Roelvink and Reniers, 1995; Yamamoto et al., 1996; Pintado-Patiño et al., 2021) /net sand transport rate; vertical profile of sediment concentration; • field measurements (Masselink and Hughes, 1998; Puleo et al., 2000; Puleo et al., 2003; Butt and Russell, 2005; Masselink and Russell, 2006; Hughes et al., 2007; Aagaard and Hughes, 2006; Masselink et al., 2009) / net sand transport rates; total sand transport amounts; bed level changes	• Physical processes (e.g. flow acceleration, bore turbulence, in−/exfiltration) can be taken into account more explicitly than other types of sand transport models. • extensive verification	• accurate time series of swash hydrodynamics are difficult to obtain • upscaling to longer term (days/weeks/ years) would be problematic
Probabilistic-parametric model (Baldock et al., 2007)	Empirical sand transport formulae/ Equilibrium model	• equilibrium slope • bore height • friction coefficient	• laboratory measurements in Baldock and Holmes (1997) / bed level changes; eroded or accreted volumes within the swash zone • field measurement by Weir et al. (2006) / cumulative sediment overwash volume	•good estimates of uprush sand transport • Randomness of runup induced by irregular waves is taken into account.	•difficult to accurately predict net swash sand transport over complete swash cycles • equilibrium slope requires calibration
Larson et al. (2004) swash-averaged sand transport formula	Empirical sand transport formulae/ Equilibrium model	• equilibrium slope • a calibration factor Kc • run-up height	• field measurement in Larson et al. (2004) / net sand transport rate; bed level changes • laboratory data from Kraus et al. (1994) / bed level changes	• The required input of run-up height is relatively easier to obtain than time series of swash flow velocities and flow depths. • reasonable prediction of beach erosion	•Kc and equilibrium slope require calibration • only applicable for predicting beach profile evolution above the still water level •applicability for beach accretion remains unknown
Swash sand transport formula implemented in CSHORE model (Kobayashi, 2009)	Empirical sand transport formulae	• mean and standard deviation of the water depth and velocity in the swash zone • bottom friction factor • wet probability of the water depth	• field measurements (Johnson et al., 2012; Kalligeris et al., 2020)/ volume change; recession of profile contours; landward progression of erosion; bed level changes	• qualitatively reasonable estimates of storm-induced full beach profile erosion evolution	• poor predictive capability of upper beach profile evolution
Linear distribution method implemented in SBEACH model (Larson and Kraus, 1989)	Sand transport distribution method	• sand transport rate at the landward limit of the surf zone • run-up height	• Laboratory experiments (Larson and Kraus, 1989)/ bed level changes • Field measurements (Larson and Kraus, 1989; Simmons et al., 2019)/ bed level changes	• This model has approximately optimum performance with default parameter sets, which means that this model does not require much calibration.	• fail to adequately predict the beach profile evolution above the still water level
Triangular-shape distribution method implemented in CROSMOR model (Van Rijn, 2009)	Sand transport distribution method	• sand transport rate in the last wet grid • sef factor • run-up height	laboratory experiments from Caceres et al. (2009), Grüne et al. (2008) and Deltares/Delft Hydraulics (2008) / bed level changes	•good performance on predicting beach evolution under erosive conditions	•cannot predict beach recovery under accretive conditions well •sef factor requires calibration
Sand transport rate distribution method implemented in UNIBEST-TC model (Walstra and Steetzel, 2003)	Sand transport distribution method	• sand transport rate in the transition point • run-up height	laboratory experiments from Caceres et al. (2009), Grüne et al. (2008) and Deltares/Delft Hydraulics (2008) / bed level changes	•good performance on predicting beach evolution under erosive conditions	•cannot predict beach recovery under accretive conditions well
Erosion flux distribution method implemented in Delft3D model (DELFT3D-Flow, 2021)	Sand transport distribution method	• sand transport rate in the last wet grid	laboratory experiments from Caceres et al. (2009), Grüne et al. (2008) and Deltares/Delft Hydraulics (2008) / bed level changes	•reasonable predictions of beach evolution under erosive conditions • simple to apply	•cannot predict beach recovery under accretive conditions well
Bermslope model (Roelvink and Otero, 2017)	Equilibrium model	• run-up • equilibrium slope • sand transport rates in the swash zone • calibration factor f_{swash}	field measurements (Turner et al., 2016; Roelvink et al., 2019; Kombiadou et al., 2021) / bed level changes	•good predictions of beach evolutions under both erosive and accretive wave conditions	•difficult to determine the equilibrium slope

which can limit their applicability and predictability. Furthermore, they have the inability to predict the beach recovery under mild wave conditions.

The surfbeat approach implemented in XBeach resolves long waves. However, incident band swash motions become more important at reflective beaches where the swash sand transport is governed by complex processes such as bore collapse, flow acceleration, in−/exfiltration and swash flow asymmetry. These processes were not accounted for in the original XBeach model formula, which results in the failure of the XBeach model in predicting the beach recovery. The Bermslope model has been developed based on the equilibrium concept to capture and predict the beach recovery and berm growth. In the Bermslope model, the complex processes that govern the swash zone sand transport are not explicitly taken into account, but are implicitly considered through the difference between the instantaneous local slope and the equilibrium slope and the calibration factor f_{swash}. This model generally predicts the beach evolution under both erosive and accretive conditions well. It is worth noting that the equilibrium slope is also included in the Larson et al. (2004) formula and Baldock et al. (2007) probabilistic-deterministic model. Even though they are derived based on Shields type sand transport formulae, they can also be regarded as equilibrium models, since both of them contain the equilibrium slope. The equilibrium slope is an essential parameter in the equilibrium models. Roelvink et al. (2019) recommended to use the average actual slope of the final beachface under study as the equilibrium slope. However, observations are not always available and a calibration of the equilibrium slope is needed. Moreover, the equilibrium swash slope is not constant but changes with wave conditions and sediment characteristics. The quantitative relationship between them requires future research to make the equilibrium models more predictive.

5. Conclusions and future perspectives

This paper reviews recent progress in practical swash zone sand transport modelling. Despite a better understanding of the complicated and dynamic swash system thanks to a range of field, laboratory and numerical modelling studies, the existing practical swash sand transport models are still insufficient in terms of description of the physical processes and validation. The main findings and future perspectives based on the detailed literature review are summarized as follows.

- The importance of different physical processes and factors for swash morphodynamics can vary over time scales and beach states. For example, (a) despite some contradictions over the importance of pre-suspended sediment advection for the intra-swash morphodynamics, the effect of pre-suspended advection is important for long-term morphological changes; (b) the presence of long waves dominates over short waves at dissipative beaches, and controls the number and type of wave-backwash interactions along the swash zone; (c) the bore turbulence is expected to have a larger effect on sand transport at steeper slopes; (d) the effect of in−/exfiltration is less significant for fine sand than for coarse sand.
- There is a general consensus on the importance of wave-swash interactions for swash sand transport. However, a proper parameter to distinguish the type of wave-swash interactions still does not exist. More detailed measurements under controlled conditions are required for the development of a parameterization of wave-swash interactions.
- Upscaling the empirical sand transport formulae for predicting the sand transport and morphological change over longer time scales such as tidal cycles is still a major challenge. The swash-averaged sand transport formulae are more suitable than the intra-swash formulae for predicting long-term beach evolutions. The swash-averaged empirical equations can be improved by including processes such as wave-swash interactions, pre-suspended sediment advection and in−/exfiltration.
- For equilibrium models, the equilibrium slope is a key parameter that significantly affects the model performance. Existing equilibrium models usually use a constant observed slope of the beach under study or a calibrated constant value. However, the equilibrium slope should vary with wave conditions and sediment characteristics instead of being a constant value. A robust formula for a variable equilibrium swash slope can potentially improve the model accuracy. Therefore, determination of the equilibrium swash slope requires further investigation.
- Existing practical swash zone sand transport models all have their limitations (see Table 1). In order to develop and/or improve a practical model that is applicable for a wide range of conditions, an extensive validation of the practical model over different time scales and different beach states is needed. For example, the datasets listed in the supplementary material can be used for the model validation. Improvements of parameterization of small-scale processes (e.g., bore turbulence, wave-swash interactions, etc.) require both experimental work and phase-resolving modelling. Phase-resolving numerical models, which have been focused on specific small-scale swash processes, are valuable for practical modelling of swash zone sand transport, since they can help highlight and improve our understanding of the important processes that control the sand transport processes in the swash zone.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgement

This work is part of the Shaping the Beach project (2018-2023) funded by NWO-TTW research project (no. 16130). The authors thank Anne de Beer and Robert McCall for their useful suggestions. We wish to also thank Tom Baldock, the anonymous reviewer and Christopher Fielding (the Editor) for the insightful comments which helped to improve the original manuscript considerably.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2023.104355.

References

Aagaard, T., Hughes, M.G., 2006. Sediment suspension and turbulence in the swash zone of dissipative beaches. Mar. Geol. 228, 117–135. https://doi.org/10.1016/j.margeo.2006.01.003.

Almeida, L.P., Almar, R., Blenkinsopp, C., Senechal, N., Bergsma, E., Floc'h, F., Caulet, C., Biausque, M., Marchesiello, P., Grandjean, P., Ammann, J., Benshila, R., Thuan, D.H., da Silva, P.G., Viet, N.T., 2020. Lidar observations of the swash zone of a low-tide terraced tropical beach under variable wave conditions: The Nha Trang (Vietnam) COASTVAR experiment. J. Mar. Sci. Eng. 8, 302. https://doi.org/10.3390/JMSE8050302.

Alsina, J., Cáceres, I., 2011. Sediment suspension events in the inner surf and swash zone. Measurements in large-scale and high-energy wave conditions. Coast. Eng. 58, 657–670.

Alsina, J., Cáceres, I., Brocchini, M., Baldock, T., 2012. An experimental study on sediment transport and bed evolution under different swash zone morphological conditions. Coast. Eng.

Alsina, J.M., Falchetti, S., Baldock, T.E., 2009. Measurements and modelling of the advection of suspended sediment in the swash zone by solitary waves. Coast. Eng. 56, 621–631. https://doi.org/10.1016/j.coastaleng.2009.01.007.

Alsina, J.M., van der Zanden, J., Cáceres, I., Ribberink, J.S., 2018. The influence of wave groups and wave-swash interactions on sediment transport and bed evolution in the

swash zone. Coast. Eng. 140, 23–42. https://doi.org/10.1016/j.coastaleng.2018.06.005.
António, S.D., Van der Werf, J., Horstman, E., Cáceres, I., Alsina, J., Zanden, J.Van, Der, Suzanne, J.M.H., 2023. Influence of beach slope on morphological changes and sediment transport under irregular waves. In Preparation.
Bagnold, R.A., 1966. An Approach to the Sediment Transport Problem from General Physics. US Government Printing Office, Washington, DC.
Bagnold, R.A., 1963. Mechanics of marine sedimentation. The Sea 3, 507–528.
Bailard, J.A., 1981. Energetics Total load sediment transport model for a plane sloping beach. J. Geophys. Res. Ocean. 86, 2035–2043.
Baldock, T.E. and Holmes, P., 1997. Swash hydrodynamics on a steep beach. In Coastal Dynamics-Proceedings of the International Conference, pp. 784-793. ASCE.
Bakhtyar, R., Barry, D.A., Li, L., Jeng, D.S., Yeganeh-Bakhtiary, A., 2009. Modeling sediment transport in the swash zone: a review. Ocean Eng. 36, 767–783. https://doi.org/10.1016/j.oceaneng.2009.03.003.
Bakhtyar, R., Brovelli, A., Barry, D.A., Li, L., 2011. Wave-induced water table fluctuations, sediment transport and beach profile change: Modeling and comparison with large-scale laboratory experiments. Coast. Eng. 58 (1), 103–118. https://doi.org/10.1016/j.coastaleng.2010.08.004.
Baldock, T., Birrien, F., Atkinson, A., Shimamoto, T., 2017. Morphological hysteresis in the evolution of beach profiles under sequences of wave climates-part 1; observations. Coast. Eng. 128, 92–105. https://doi.org/10.1016/j.coastaleng.2017.08.005.
Baldock, T.E., Grayson, R., Torr, B., Power, H.E., 2014. Flow convergence at the tip and edges of a viscous swash front—experimental and analytical modeling. Coast. Eng. 88, 123–130. https://doi.org/10.1016/j.coastaleng.2014.02.008.
Baldock, T.E., Holmes, P., Bunker, S., Van Weert, P., 1998. Cross-shore hydrodynamics within an unsaturated surf zone. Coast. Eng. 34 (3–4), 173–196. https://doi.org/10.1016/S0378-3839(98)00017-9.
Baldock, T.E., Hughes, M.G., Day, K., Louys, J., 2005. Swash overtopping and sediment overwash on a truncated beach. Coast. Eng. 52, 633–645. https://doi.org/10.1016/j.coastaleng.2005.04.002.
Baldock, T.E., Nielsen, P., 2010. Discussion of “effect of seepage-induced nonhydrostatic pressure distribution on bed-load transport and bed morphodynamics” by Simona Francalanci, Gary Parker, and Luca Solari. J. Hydraul. Eng. 136, 77–79.
Baldock, T.E., Son, P.K., Manoonvoravong, P., Barnes, M.P., Alsina, J.M., 2007. Probabilistic-deterministic modelling of swash zone morphology. Coast. Sediment.’ 07, 272–285.
Baldock, T.E., Weir, F., Hughes, M.G., 2008. Morphodynamic evolution of a coastal lagoon entrance during swash overwash. Geomorphology 95, 398–411. https://doi.org/10.1016/j.geomorph.2007.07.001.
Barnes, M.P., Baldock, T.E., 2007. Direct bed shear stress measurements in laboratory swash. J. Coast. Res. 641–645.
Barnes, M.P., O’donoghue, T., Alsina, J.M., Baldock, T.E., 2009. Direct bed shear stress measurements in bore-driven swash. Coast. Eng. 56, 853–867. https://doi.org/10.1016/j.coastaleng.2009.04.004.
Beach, R.A., Sternberg, R.W., 1991. Infragravity driven suspended sediment transport in the swash, inner and outer-surf zone. In: Coastal Sediments ’91., pp. 114–128.
Bertin, X., de Bakker, A., van Dongeren, A., Coco, G., André, G., Ardhuin, F., Bonneton, P., Bouchette, F., Castelle, B., Crawford, W.C., Davidson, M., Deen, M., Dodet, G., Guérin, T., Inch, K., Leckler, F., McCall, R., Muller, H., Olabarrieta, M., Roelvink, D., Ruessink, G., Sous, D., Stutzmann, É., Tissier, M., 2018. Infragravity waves: from driving mechanisms to impacts. Earth-Sci. Rev. 177, 774–799. https://doi.org/10.1016/j.earscirev.2018.01.002.
Blenkinsopp, C.E., Turner, I.L., Masselink, G., Russell, P.E., 2011. Swash zone sediment fluxes: field observations. Coast. Eng. 58, 28–44. https://doi.org/10.1016/j.coastaleng.2010.08.002.
Briganti, R., Dodd, N., Incelli, G., Kikkert, G., 2018. Numerical modelling of the flow and bed evolution of a single bore-driven swash event on a coarse sand beach. Coast. Eng. 142, 62–76. https://doi.org/10.1016/j.coastaleng.2018.09.006.
Briganti, R., Torres-Freyermuth, A., Baldock, T.E., Brocchini, M., Dodd, N., Hsu, T.J., Jiang, Z., Kim, Y., Pintado-Patiño, J.C., Postacchini, M., 2016. Advances in numerical modelling of swash zone dynamics. Coast. Eng. 115, 26–41. https://doi.org/10.1016/j.coastaleng.2016.05.001.
Brocchini, M., Baldock, T.E., 2008. Recent advances in modeling swash zone dynamics: influence of surf-swash interaction on nearshore hydrodynamics and morphodynamics. Rev. Geophys. 46, 1–21. https://doi.org/10.1029/2006RG000215.
Brocchini, M., Peregrine, D.H., 1996. Integral flow properties of the swash zone and averaging. J. Fluid Mech. 317, 241–273. https://doi.org/10.1017/S0022112096000742.
Butt, T., Russell, P., 2005. Observations of hydraulic jumps in high-energy swash. J. Coast. Res. 21, 1219–1227.
Butt, T., Russell, P., 1999. Suspended sediment transport mechanisms in high-energy swash. Mar. Geol. 161, 361–375. https://doi.org/10.1016/S0025-3227(99)00043-2.
Butt, T., Russell, P., Miles, J., Turner, I., 2007. Sediment transport processes in the swash zone of sandy beaches. J. Coast. Res. 636–640.
Butt, T., Russell, P., Puleo, J., Miles, J., Masselink, G., 2004. The influence of bore turbulence on sediment transport in the swash and inner surf zones. Cont. Shelf Res. 24, 757–771.
Butt, T., Russell, P., Turner, I., 2001. The influence of swash infiltration-exfiltration on sediment transport. Coast. Eng. 42, 35–52. https://doi.org/10.2208/prohe.47.1327.
Butt, T., Tinker, J., Masselink, G., O’hare, T., Russell, P., 2009. Field observations of sediment fluxes in the inner-surf and swash zones. J. Coast. Res. 25, 991–1001. https://doi.org/10.2112/08-1044.1.
Cáceres, I., Alsina, J.M., 2016. Suspended sediment transport and beach dynamics induced by monochromatic conditions, long waves and wave groups. Coast. Eng. 108, 36–55. https://doi.org/10.1016/j.coastaleng.2015.11.004.
Caceres, I., Grüne, J., Van Rijn, L., Sanchez-Arcilla, A., Ahmari, A., Ribberink, J., 2009. Mobile-bed tests: the sands project. In: Coastal Engineering 2008: (In 5 Volumes). . World Scientific, pp. 2622–2632.
Cáceres, I., Alsina, J.M., 2012. A detailed, event-by-event analysis of suspended sediment concentration in the swash zone. Cont. Shelf Res. 41, 61–76. https://doi.org/10.1016/j.csr.2012.04.004.
Chardón-Maldonado, P., Pintado-Patiño, J.C., Puleo, J.A., 2016. Advances in swash-zone research: small-scale hydrodynamic and sediment transport processes. Coast. Eng. 115, 8–25. https://doi.org/10.1016/j.coastaleng.2015.10.008.
Coastal Engineering Research Center, 1984. Shore Protection Manual US Army Corps of Engineers. US Government Printing Office, Washington, DC.
Conley, D.C., Griffin Jr., J.G., 2004. Direct measurements of bed stress under swash in the field. J. Geophys. Res. Ocean. 109 https://doi.org/10.1029/2003JC001899.
Conley, D.C., Inman, D.L., 1994. Ventilated oscillatory boundary layers. J. Fluid Mech. 273, 261–284. https://doi.org/10.1017/S002211209400193X.
Dalrymple, R.A., 1992. Prediction of storm/normal beach profiles. J. Waterw. Port, coastal, Ocean Eng. 118, 193–200. https://doi.org/10.1061/(ASCE)0733-950X(1992)118:2(193).
de Beer, A.F., McCall, R.T., Long, J.W., Tissier, M.F.S., Reniers, A., 2021. Simulating wave runup on an intermediate–reflective beach using a wave-resolving and a wave-averaged version of XBeach. Coast. Eng. 163, 103788 https://doi.org/10.1016/j.coastaleng.2020.103788.
Dean, R.G., 1973. Heuristic models of sand transport in the surf zone. In: Proc. 1st Australian Conf. Coastal Eng, pp. 209–214.
DELFT3D-Flow, 2021. DELFT3D-Flow User Manual, Deltares.
Deltares/Delft Hydraulics, 2008. HYDRALABIII-SANDS; data report flume experiments. Delft, The Netherlands.
Dohmen-Janssen, C.M., Hassan, W.N., Ribberink, J.S., 2001. Mobile-bed effects in oscillatory sheet flow. J. Geophys. Res. Ocean. 106, 27103–27115. https://doi.org/10.1029/2000JC000513.
Drake, T.G., Calantoni, J., 2001. Discrete particle model for sheet flow sediment transport in the nearshore. J. Geophys. Res. 106, 859–878. https://doi.org/10.1029/2000JC000611.
Eichentopf, S., van der Zanden, J., Cáceres, I., Baldock, T.E., Alsina, J.M., 2020. Influence of storm sequencing on breaker bar and shoreline evolution in large-scale experiments. Coast. Eng. 157, 103659 https://doi.org/10.1016/J.COASTALENG.2020.103659.
Elfrink, B., Baldock, T., 2002. Hydrodynamics and sediment transport in the swash zone: a review and perspectives. Coast. Eng. 45, 149–167. https://doi.org/10.1016/S0378-3839(02)00032-7.
Erikson, L., Larson, M., Hanson, H., 2005. Prediction of swash motion and run-up including the effects of swash interaction. Coast. Eng. 52, 285–302. https://doi.org/10.1016/j.coastaleng.2004.12.001.
Fredsøe, J., Sumer, B.M., Kozakiewicz, A., Chua, L.H.C., Deigaard, R., 2003. Effect of externally generated turbulence on wave boundary layer. Coast. Eng. 49, 155–183. https://doi.org/10.1016/S0378-3839(03)00032-2.
García-Maribona, J., Lara, J.L., Maza, M., Losada, I.J., 2021. An efficient RANS numerical model for cross-shore beach processes under erosive conditions. Coast. Eng. 170, 103975 https://doi.org/10.1016/j.coastaleng.2021.103975.
Gourlay, M.R., Meulen, T., 1968. Beach and dune erosion tests, Delft Hydraulics Laboratory, Rep.no.M935/M936. Deltares (WL).
Grüne, J., Schmidt-Koppenhagen, R., Wang, Z., 2008. Cross-shore beach evolution large-scale laboratory tests with irregular waves. In: Proc. of the 2nd Intern. Conf. on the Application of Physical Modelling to Port and Coastal Protection (CoastLab 2008), Bari.
Guard, P.A., Baldock, T.E., 2007. The influence of seaward boundary conditions on swash zone hydrodynamics. Coast. Eng. 54, 321–331. https://doi.org/10.1016/j.coastaleng.2006.10.004.
Hassan, W.N., Ribberink, J.S., 2005. Transport processes of uniform and mixed sands in oscillatory sheet flow. Coast. Eng. 52, 745–770. https://doi.org/10.1016/j.coastaleng.2005.06.002.
Hattori, M., Kawamata, R., 1980. Onshore-offshore transport and beach profile change. Coast. Eng. 1980, 1175–1193.
Hibberd, S., Peregrine, D.H., 1979. Surf and run-up on a beach: a uniform bore. J. Fluid Mech. 95 (2), 323–345.
Holland, K.T., Puleo, J.A., 2001. Variable swash motions associated with foreshore profile change. J. Geophys. Res. 106, 4613–4623. https://doi.org/10.1029/1999JC000172.
Horn, D.P., Mason, T., 1994. Swash zone sediment transport modes. Mar. Geol. 120, 309–325. https://doi.org/10.1016/0025-3227(94)90064-7.
Houwman, K.T., Ruessink, B.G., 1996. Sediment Transport in the Vicinity of the Shoreface Nourishment of Terschelling. Dep. of Physical Geography, The Netherlands.
Hughes, M.G., 1995. Friction factors for wave uprush. J. Coast. Res. 1089–1098.
Hughes, M.G., Aagaard, T., Baldock, T.E., 2007. Suspended sediment in the swash zone: heuristic analysis of spatial and temporal variations in concentration. J. Coast. Res. 23, 1345–1354. https://doi.org/10.2112/05-0531.1.
Hughes, M.G., Aagaard, T., Baldock, T.E., Power, H.E., 2014. Spectral signatures for swash on reflective, intermediate and dissipative beaches. Mar. Geol. 355, 88–97. https://doi.org/10.1016/j.margeo.2014.05.015.
Hughes, M.G., Baldock, T.E., 2004. Eulerian flow velocities in the swash zone: field data and model predictions. J. Geophys. Res. C Ocean. 109, 1–11. https://doi.org/10.1029/2003JC002213.

Hughes, M.G., Masselink, G., Brander, R.W., 1997. Flow velocity and sediment transport in the swash zone of a steep beach. Mar. Geol. 138, 91–103. https://doi.org/10.1016/S0025-3227(97)00014-5.

Hughes, M.G., Moseley, A.S., 2007. Hydrokinematic regions within the swash zone. Cont. Shelf Res. 27, 2000–2013. https://doi.org/10.1016/j.csr.2007.04.005.

Inch, K., Masselink, G., Puleo, J.A., Russell, P., Conley, D.C., 2015. Vertical structure of near-bed cross-shore flow velocities in the swash zone of a dissipative beach. Cont. Shelf Res. 101, 98–108. https://doi.org/10.1016/j.csr.2015.04.006.

Jackson, N.L., Masselink, G., Nordstrom, K.F., 2004. The role of bore collapse and local shear stresses on the spatial distribution of sediment load in the uprush of an intermediate-state beach. Mar. Geol. 203, 109–118. https://doi.org/10.1016/S0025-3227(03)00328-1.

Jackson, N.L., Nordstrom, K.F., Farrell, E.J., 2017. Longshore sediment transport and foreshore change in the swash zone of an estuarine beach. Mar. Geol. 386, 88–97. https://doi.org/10.1016/j.margeo.2017.02.017.

Jensen, A., Pedersen, G.K., Wood, D.J., 2003. An experimental study of wave run-up at a steep beach. J. Fluid Mech. 486, 161–188. https://doi.org/10.1017/S0022112003004543.

Jiang, A.W., Hughes, M., Cowell, P., Gordon, A., Savioli, J.C., Ranasinghe, R., 2011. A hybrid model of Swash-Zone. Coast. Eng. Proc. 1, 29. https://doi.org/10.9753/icce.v32.sediment.29.

Johnson, B.D., Kobayashi, N., Gravens, M.B., 2012. Cross-Shore Numerical Model CSHORE for Waves, Currents, Sediment Transport and Beach Profile Evolution. U.S. Army Corps of Engineers, Washington, DC.

Kalligeris, N., Smit, P.B., Ludka, B.C., Guza, R.T., Gallien, T.W., 2020. Calibration and assessment of process-based numerical models for beach profile evolution in southern California. Coast. Eng. 158, 103650 https://doi.org/10.1016/j.coastaleng.2020.103650.

Kamphuis, J.W., 2002. Alongshore transport rate of sand. In: Coastal Engineering 2002: Solving Coastal Conundrums. World Scientific, pp. 2478–2490.

Kamphuis, J.W., 1991. Alongshore sediment transport rate distribution. In: Coastal Sediments. ASCE, pp. 170–183.

Karambas, T.V., 2006. Prediction of sediment transport in the swash-zone by using a nonlinear wave model. Cont. Shelf Res. 26, 599–609. https://doi.org/10.1016/j.csr.2006.01.014.

Karambas, T.V., 2003. Modelling of infiltration-exfiltration effects of cross-shore sediment transport in the swash zone. Coast. Eng. J. 45, 63–82. https://doi.org/10.1142/S057856340300066X.

Kemp, P.H., 1975. Wave Asymmetry in the Nearshore Zone and Breaker Area. In: Hails, J., Carr, A. (Eds.), Nearshore Sediment Dynamics and Sedimentation. Wiley-Interscience, pp. 47–67.

Kikkert, G.A., O'Donoghue, T., Pokrajac, D., Dodd, N., 2012. Experimental study of bore-driven swash hydrodynamics on impermeable rough slopes. Coast. Eng. 60, 149–166. https://doi.org/10.1016/j.coastaleng.2011.09.006.

Kobayashi, N., 2016. Coastal sediment transport modeling for engineering applications. J. WaterwPort, Coastal, Ocean Eng. 142, 1–23. https://doi.org/10.1061/(asce)ww.1943-5460.0000347.

Kobayashi, N., 2009. Documentation of Cross-Shore Numerical Model CSHORE 2009. Center for Applied Coastal Research, Newark.

Kombiadou, K., Costas, S., Roelvink, D., 2021. Simulating destructive and constructive morphodynamic processes in steep beaches. J. Mar. Sci. Eng. 9, 1–19. https://doi.org/10.3390/jmse9010086.

Kranenborg, J.W.M., Campmans, G.H.P., Jacobsen, N.G., van der Werf, J.J., Reniers, A.J.H.M., Hulscher, S.J.M.H., 2022. Depth-resolved modelling of intra-swash morphodynamics induced by solitary waves. J. Mar. Sci. Eng. 10, 1175. https://doi.org/10.3390/jmse10091175.

Kranenborg, J.W.M., Pauli, T., Jacobsen, N.G., Van der Werf, J.J., António, S.D., Campmans, G.H.P., Reniers, A.J.H.M., Hulscher, S.J.M.H., 2023. Measurements and modelling of pore-pressure gradients in the swash zone under large-scale laboratory bichromatic waves. Submitted.

Kraus, N.C., Larson, M., Kriebel, D.L., 1991. Evaluation of beach erosion and accretion predictors. In: Coastal Sediments. ASCE, pp. 572–587.

Kraus, N.C., Smith, J.M., Sollitt, C.K., 1994. SUPERTANK Laboratory Data Collection Project, Volume 1: Main Text. Vicksbg. Mississippi Coast. Eng. Res. Cent. No. CERC-9.

Kubota, S., Hida, Y., Takezawa, M., 1994. Two dimensional change of swash slope. In: Proceedings of the International Conference on Hydro-Technical Engineering for Port and Harbor Construction, Yokosuka, Japan, pp. 1193–1209.

Kubota, S., Katori, S., Takezawa, M., 1999. Relationship between on-offshore sediment transport rate on the beach face and wave energy. In: Coastal Sediments. ASCE, pp. 447–462.

Kubota, S., Naito, A., Matsumura, T., Takezawa, M., 1997. Field observations of topography change on an artificial beach face due to on-offshore transport. In: Pacific Coasts and Ports'97. Proceedings, pp. 325–330.

Lanckriet, T., Puleo, J.A., 2015. A semianalytical model for sheet flow layer thickness with application to the swash zone. J. Geophys. Res. Ocean. 120, 1333–1352. https://doi.org/10.1002/2014JC010378.

Lanckriet, T., Puleo, J.A., Asce, M., Masselink, Gerd, Turner, I.L., Conley, D., Blenkinsopp, C., Russell, P., 2014. Comprehensive field studyof Swash-Zone processes. II: Sheet flow sediment concentrations during Quasi-Steady Backwash. J. Waterw Port, Coastal, Ocean Eng. 140, 29–42. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000209.

Larson, M., Kraus, N.C., 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change; Report 1: Empirical Foundation and Model Development. Department of the Army US Army Corps of Engineers, Washington, DC.

Larson, M., Kubota, S., Erikson, L., 2004. Swash-zone sediment transport and foreshore evolution: field experiments and mathematical modeling. Mar. Geol. 212, 61–79. https://doi.org/10.1016/j.margeo.2004.08.004.

Larson, M., Wamsley, T.V., 2007. A formula for longshore sediment transport in the swash. In: Coastal Sediments'07, pp. 1924–1937.

Lesser, G.R., 2009. An approach to medium-term coastal morphological modelling. Doctoral Thesis. Delft University of Technology, Delft, The Netherlands.

Lesser, G.R., Roelvink, J.A., van Kester, J.A.T.M., Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. Coast. Eng. 51, 883–915. https://doi.org/10.1016/j.coastaleng.2004.07.014.

Madsen, O., 1993. Sediment transport on the shelf. In: 'Sediment Transport Workshop Proc. DRP TA1)', CERC, Vicksburg, Mississippi, USA.

Masselink, G., Evans, D., Hughes, M.G., Russell, P., 2005. Suspended sediment transport in the swash zone of a dissipative beach. Mar. Geol. 216, 169–189.

Masselink, G., Hughes, M., 1998. Field investigation of sediment transport in the swash zone. Cont. Shelf Res. 18, 1179–1199. https://doi.org/10.1016/S0278-4343(98)00027-2.

Masselink, G., Puleo, J.A., 2006. Swash-zone morphodynamics. Cont. Shelf Res. 26, 661–680. https://doi.org/10.1016/j.csr.2006.01.015.

Masselink, G., Russell, P., 2006. Flow velocities, sediment transport and morphological change in the swash zone of two contrasting beaches. Mar. Geol. 227, 227–240. https://doi.org/10.1016/j.margeo.2005.11.005.

Masselink, G., Russell, P., Turner, I., Blenkinsopp, C., 2009. Net sediment transport and morphological change in the swash zone of a high-energy sandy beach from swash event to tidal cycle time scales. Mar. Geol. 267, 18–35. https://doi.org/10.1016/j.margeo.2009.09.003.

Matsuba, Y., Shimozono, T., 2021. Analysis of the contributing factors to infragravity swash based on long-term observations. Coast. Eng. 169, 103957 https://doi.org/10.1016/j.coastaleng.2021.103957.

Mayer, R., Kriebel, D.L., 1994. Wave runup on composite-slope and concave beaches. In: Coastal Engineering 1994. ASCE, Kobe, Japan, pp. 2325–2339.

Memmola, F., Coluccelli, A., Russo, A., Warner, J.C., Brocchini, M., 2020. Wave-resolving shoreline boundary conditions for wave-averaged coastal models. Ocean Model 153. https://doi.org/10.1016/j.ocemod.2020.101661.

Meyer-Peter, E., Müller, R., 1948. Formulas for bed-load transport. In: IAHSR 2nd Meeting, Stockholm, Appendix 2. IAHR.

Miles, J., Butt, T., Russell, P., 2006. Swash zone sediment dynamics: a comparison of a dissipative and an intermediate beach. Mar. Geol. 231, 181–200. https://doi.org/10.1016/j.margeo.2006.06.002.

Nielsen, P., 2002. Shear stress and sediment transport calculations for swash zone modelling. Coast. Eng. 45, 53–60. https://doi.org/10.1016/S0378-3839(01)00036-9.

Nielsen, P., 1992. Coastal Bottom Boundary Layers and Sediment Transport. S. https://doi.org/10.1142/1269.

Nielsen, P., Hanslow, D.J., 1991. Wave runup distributions on natural beaches. J. Coast. Res. 1139–1152.

Nielsen, P., Robert, S., Møller-Christiansen, B., Oliva, P., 2001. Infiltration effects on sediment mobility under waves. Coast. Eng. 42, 105–114. https://doi.org/10.1016/S0378-3839(00)00051-X.

O'Donoghue, T., Kikkert, G.A., Pokrajac, D., Dodd, N., Briganti, R., 2016. Intra-swash hydrodynamics and sediment flux for dambreak swash on coarse-grained beaches. Coast. Eng. 112, 113–130. https://doi.org/10.1016/j.coastaleng.2016.03.004.

O'Donoghue, T., Wright, S., 2004. Concentrations in oscillatory sheet flow for well sorted and graded sands. Coast. Eng. 50, 117–138. https://doi.org/10.1016/j.coastaleng.2003.09.004.

Osborne, P.D., Rooker, G.A., 1999. Sand re-suspension events in a high energy infragravity swash zone. J. Coast. Res. 15, 74–86.

Othman, I.K., Baldock, T.E., Callaghan, D.P., 2014. Measurement and modelling of the influence of grain size and pressure gradient on swash uprush sediment transport. Coast. Eng. 83, 1–14. https://doi.org/10.1016/j.coastaleng.2013.09.001.

Pedrozo-Acuna, A., Simmonds, D.J., Otta, A.K., Chadwick, A.J., 2006. On the cross-shore profile change of gravel beaches. Coast. Eng. 53, 335–347. https://doi.org/10.1016/j.coastaleng.2005.10.019.

Peregrine, D.H., Williams, S.M., 2001. Swash overtopping a truncated plane beach. J. Fluid Mech. 440, 391–399. https://doi.org/10.1017/S002211200100492X.

Pintado-Patiño, J.C., Puleo, J.A., Krafft, D., Torres-Freyermuth, A., 2021. Hydrodynamics and sediment transport under a dam-break-driven swash: an experimental study. Coast. Eng. 170 https://doi.org/10.1016/j.coastaleng.2021.103986.

Pritchard, D., Hogg, A.J., 2005. On the transport of suspended sediment by a swash event on a plane beach. Coast. Eng. 52, 1–23. https://doi.org/10.1016/j.coastaleng.2004.08.002.

Puleo, J., Lanckriet, T., Conley, D., Foster, D., 2016. Sediment transport partitioning in the swash zone of a large-scale laboratory beach. Coast. Eng. 113, 73–87. https://doi.org/10.1016/j.coastaleng.2015.11.001.

Puleo, J.A., Beach, R.A., Holman, R.A., Allen, J.S., 2000. Swash zone sediment suspension and transport and the importance of bore-generated turbulence. J. Geophys. Res. Ocean. 105, 17021–17044. https://doi.org/10.1029/2000jc900024.

Puleo, Jack A., Blenkinsopp, C., Conley, D., Masselink, G., Turner, I.L., Russell, P., Buscombe, D., Howe, D., Lanckriet, T., McCall, R., 2014. Comprehensive field study of swash-zone processes. I: Experimental design with examples of hydrodynamic and sediment transport measurements. J. WaterwPort, Coastal, Ocean Eng. 140, 14–28.

Puleo, J.A., Cristaudo, D., Torres-Freyermuth, A., Masselink, G., Shi, F., 2020. The role of alongshore flows on inner surf and swash zone hydrodynamics on a dissipative beach. Cont. Shelf Res. 201, 104134.

Puleo, J.A., Holland, K.T., 2001. Estimating swash zone friction coefficients on a sandy beach. Coast. Eng. 43, 25–40. https://doi.org/10.1016/S0378-3839(01)00004-7.

Puleo, J.A., Holland, K.T., Plant, N.G., Slinn, D.N., Hanes, D.M., 2003. Fluid acceleration effects on suspended sediment transport in the swash zone. J. Geophys. Res. Ocean. 108 https://doi.org/10.1029/2003JC001943.

Puleo, J.A., Krafft, D., Pintado-Patiño, J.C., Bruder, B., 2017. Video-derived near bed and sheet flow sediment particle velocities in dam-break-driven swash. Coast. Eng. 126, 27–36. https://doi.org/10.1016/j.coastaleng.2017.04.008.

Puleo, J.A., Lanckriet, T., Blenkinsopp, C., 2014. Bed level fluctuations in the inner surf and swash zone of a dissipative beach. Mar. Geol. 349, 99–112. https://doi.org/10.1016/j.margeo.2014.01.006.

Puleo, J.A., Lanckriet, T., Wang, P., 2012. Near bed cross-shore velocity profiles, bed shear stress and friction on the foreshore of a microtidal beach. Coast. Eng. 68, 6–16. https://doi.org/10.1016/j.coastaleng.2012.04.007.

Puleo, J.A., Torres-Freyermuth, A., 2016. The second international workshop on swash-zone processes. Coast. Eng. 115, 1–7. https://doi.org/10.1016/j.coastaleng.2015.09.007.

Ribberink, J.S., van der Werf, J.J., O'Donoghue, T., Hassan, W.N.M., 2008. Sand motion induced by oscillatory flows: sheet flow and vortex ripples. J. Turbul. 9, 1–32. https://doi.org/10.1080/14685240802220009.

Van Rijn, L.C., 1993. Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Amsterdam.

Van Rijn, L.C., 2007a. Unified view of sediment transport by currents and waves. II: Suspended transport. J. Hydraul. Eng. 133, 668–689. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:6(668).

Van Rijn, L.C., 2007b. Unified view of sediment transport by currents and waves. III: Graded beds. J. Hydraul. Eng. 133, 761–775. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:7(761).

Roelvink, D., McCALL, R., Costas, S., Van der Lugt, M., 2019. In: Controlling Swash Zone Slope Is Key To Beach Profile Modelling, pp. 149–157. https://doi.org/10.1142/9789811204487_0014.

Roelvink, D., Otero, S.C., 2017. Beach berms as an essential link between subaqueous and subaerial beach/dune profiles. Geotemas (Madrid) 79–82.

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006.

Roelvink, J.A., Reniers, A., 1995. LIP 11D Delta Flume Experiments. Delft Hydraulics, Delft.

Ruessink, B.G., Kuriyama, Y., Reniers, A.J.H.M., Roelvink, J.A., Walstra, D.J.R., 2007. Modeling cross-shore sandbar behavior on the timescale of weeks. J. Geophys. Res. Earth Surf. 112 https://doi.org/10.1029/2006JF000730.

Ruju, A., Conley, D., Masselink, G., Puleo, J., 2016. Sediment transport dynamics in the swash zone under large-scale laboratory conditions. Cont. Shelf Res. 120, 1–13. https://doi.org/10.1016/j.csr.2016.03.015.

Schretlen, J.L.M., 2012. Sand transport under full-scale progressive surface waves. Doctoral Thesis. University of Twente.

Shen, M.C., Meyer, R.E., 1963. Climb of a bore on a beach part 3.Run-up. J. Fluid Mech. 16, 113–125. https://doi.org/10.1017/S0022112063000628.

Simmons, J.A., Splinter, K.D., Harley, M.D., Turner, I.L., 2019. Calibration data requirements for modelling subaerial beach storm erosion. Coast. Eng. 152, 103507 https://doi.org/10.1016/j.coastaleng.2019.103507.

Smith, E.R., Wang, P., Zhang, J., 2003. Evaluation of the CERC formula using large-scale model data. In: Engineer Research and Development Center Vicksburg MS Coastal and Hydraulicslab, Vicksburg, Mississippi.

Soulsby, R.L., Damgaard, J.S., 2005. Bedload sediment transport in coastal waters. Coast. Eng. 52, 673–689. https://doi.org/10.1016/j.coastaleng.2005.04.003.

Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger, A.H., 2006. Empirical parameterization of setup, swash, and runup. Coast. Eng. 53, 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005.

Thieler, E.R., Pilkey, O.H., Young, R.S., Bush, D.M., Chai, F., 2000. The use of mathematical models to predict beach behavior for U.S. Coastal engineering: a critical review. J. Coast. Res. 16, 48–70.

Tinker, J., O'Hare, T., Masselink, G., Butt, T., Russell, P., 2009. A cross-shore suspended sediment transport shape function parameterisation for natural beaches. Cont. Shelf Res. 29, 1948–1960. https://doi.org/10.1016/j.csr.2009.03.011.

Turner, I.L., Harley, M.D., Short, A.D., Simmons, J.A., Bracs, M.A., Phillips, M.S., Splinter, K.D., 2016. A multi-decade dataset of monthly beach profile surveys and inshore wave forcing at Narrabeen,Australia. Sci. Data 3, 1–13. https://doi.org/10.1038/sdata.2016.24.

Turner, I.L., Masselink, G., 1998. Swash infiltration-exfiltration and sediment transport cal flow rates of net. J. Geophys. Res. 103, 30813–30824.

Turner, I.L., Russell, P.E., Butt, T., 2008. Measurement of wave-by-wave bed-levels in the swash zone. Coast. Eng. 55, 1237–1242. https://doi.org/10.1016/j.coastaleng.2008.09.009.

Van Dam, T., 2019. Numerical Modelling of Beach Recovery. Master Thesis. Delft University of Technology.

van der Zanden, J., Alsina, J.M., Cáceres, I., Buijsrogge, R.H., Ribberink, J.S., 2015. Bed level motions and sheet flow processes in the swash zone: observations with a new conductivity-based concentration measuring technique (CCM+). Coast. Eng. 105, 47–65. https://doi.org/10.1016/J.COASTALENG.2015.08.009.

van der Zanden, J., Cáceres, I., Eichentopf, S., Ribberink, J.S., van der Werf, J.J., Alsina, J.M., 2019. Sand transport processes and bed level changes induced by two alternating laboratory swash events. Coast. Eng. 152, 103519 https://doi.org/10.1016/j.coastaleng.2019.103519.

van der Zanden, J., van der A, D.A., Hurther, D., Cáceres, I., O'Donoghue, T., Hulscher, S.J.M.H., Ribberink, J.S., 2017. Bedload and suspended load contributions to breaker bar morphodynamics. Coast. Eng. 129, 74–92. https://doi.org/10.1016/J.COASTALENG.2017.09.005.

Van Rijn, L.C., 2007. Unified view of sediment transport by currents and waves. I: Initiation of. J. Hydraul. Eng. 133, 649–667. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:6(649).

Van Rijn, L.C., 2009. Prediction of dune erosion due to storms. Coast. Eng. 56, 441–457. https://doi.org/10.1016/j.coastaleng.2008.10.006.

Van Rijn, L.C., Tonnon, P.K., Walstra, D.J.R., 2011. Numerical modelling of erosion and accretion of plane sloping beaches at different scales. Coast. Eng. 58, 637–655. https://doi.org/10.1016/j.coastaleng.2011.01.009.

Van Rijn, L.C., Walstra, D.-J.R., van Ormondt, M., 2007. Unified view of sediment transport by currents and waves. IV: Application of morphodynamic model. J. Hydraul. Eng. 133, 776–793.

Walstra, D.J.R., Steetzel, H., 2003. Description of improvements in the UNIBEST -TC model: Upgrade of UNIBEST-TC version 2.04 to 2.10. Delft Hydraulics, Delft, The Netherlands.

Wang, P., Yuan, W., Min, L., 2012. Measuring and modeling suspended sediment concentration profiles in the surf zone. J. Palaeogeogr. 1, 172–192. https://doi.org/10.3724/SP.J.1261.2012.00013.

Weir, F.M., Baldock, T.E., Hughes, M.G., 2006. Berm development and lagoon closure on a gently sloping beach. In: Coastal Dynamics 2005: State of the Practice, pp. 1–11.

Weir, F.M., Hughes, M.G., Baldock, T.E., 2006. Beach face and berm morphodynamics fronting a coastal lagoon. Geomorphology 82 (3–4), 331–346.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118. https://doi.org/10.1016/0025-3227(84)90008-2.

Wright, L.D., Short, A.D., Green, M.O., 1985. Short-term changes in the morphodynamic states of beaches and surf zones: an empirical predictive model. Mar. Geol. 62, 339–364. https://doi.org/10.1016/0025-3227(85)90123-9.

Wu, L., Feng, D., , T.S.-C.E, 2016, undefinedcollab, 2016, 2016. Laboratory measurements of sediment flux and bed level evolution in the swash zone. Taylor Fr. 58, 1650004. https://doi.org/10.1142/S0578563416500042.

Yamamoto, Y., Horikawa, K., Tanimoto, K., 1996. Prediction of shoreline change considering cross-shore sediment transport. In: Coast. Eng.Proc.1996. ASCE, Orlando, Florida, United States.

Yates, M.L., Guza, R.T., O'reilly, W.C., 2009. Equilibrium shoreline response: observations and modeling. J. Geophys. Res. Ocean. 114 https://doi.org/10.1029/2009JC005359.

Zeng, J., Liu, H., 2022. An approximate explicit analytical solution for the frictionless swash hydrodynamics with an improved seaward boundary condition. Coast. Eng. 174, 104127. https://doi.org/10.1016/j.coastaleng.2022.104127.

Zhang, J., Larson, M., Ge, Z.P., 2020. Numerical model of beach profile evolution in the nearshore. J. Coast. Res. 36, 506–520. https://doi.org/10.2112/JCOASTRES-D-19-00065.1.

Zhang, Q., Liu, P.L.-F., 2008. A numerical study of swash flows generated by bores. Coast. Eng. 55, 1113–1134. https://doi.org/10.1016/j.coastaleng.2008.04.010.

Zhu, F., Dodd, N., 2015. The morphodynamics of a swash event on an erodible beach. J. Fluid Mech. 762, 110–140. https://doi.org/10.1017/jfm.2014.610.

Zhu, F., Dodd, N., 2013. Net beach change in the swash zone: a numerical investigation. Adv. Water Resour. 53, 12–22. https://doi.org/10.1016/j.advwatres.2012.10.002.