NEW SUSPENDED SAND CONCENTRATION MODEL FOR BREAKING WAVES

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INTRODUCTION

Coastal area modelling suites such as Delft3D, MIKE21 and Telemac are powerful process-based modelling suites that couple hydrodynamic modules with sediment transport and morphodynamic modules to simulate complex coastal environments. However, such modelling suites (as well as other process-based models) are often considered to be inefficient and unsuitable for simulating medium- to long-term morphodynamics. A common view held in existing literature is that extending small-scale process-based morphology models for simulation of long-term morphodynamics is unsuitable, due to the various theoretical (e.g. robustness of sediment transport models) and practical (e.g. computational costs) limitations. In particular, a lack of knowledge of sediment transport processes and how they relate to hydrodynamics makes the application of short-term models to long-term coastal evolution challenging. Even the state-of-the-art morphodynamic suites consist of relatively simple physics, relying instead on numerous semi-empirical parameterizations, which are often poorly supported by measured data and/or physical process understanding. The improvement of sediment transport models could therefore shed valuable insights into poorly understood physical phenomena and serve as a stepping-stone in the bridging of theoretical knowledge gaps that currently hinder the more effective use of such morphodynamic models in medium- to long-term simulations.

EXISTING SAND TRANSPORT MODELS

Numerous studies have reported that wave breaking is responsible for relatively larger amounts of sediment entrainment in the surf zone than alternative mechanisms, with suspended sand concentration (SSC) being considerably higher in the surf zone under breaking conditions than non-breaking conditions. The greater levels of SSC observed under breaking conditions is attributed to turbulent kinetic energy (TKE) that is injected into the water column at the ‘plunging point’ (cross-shore point where the wave plunges - near breaker bar crest), which entrains sediment. Accurately modelling the sediment concentration induced by wave breaking is essential in attaining realistic sediment transport rates, and in modelling the resulting morphological changes.

A thorough evaluation study was carried out for 6 existing reference concentration (C_0) formulae under field-scale breaking wave conditions, identifying numerous limitations in the models studied. Common limitations observed in *all* existing models evaluated in this study could be largely put under two categories: 1) inapplicability to multiple cross-shore zones, 2) inability to replicate the high levels of breaking-induced SSC found in the breaking zone.

Models that are only applicable to one cross-shore zone (e.g. breaking zone) have very limited uses in a practical sense. If such models are to be incorporated into morphodynamic models, they will need to be adept in reproducing sediment concentration/transport patterns in multiple cross-shore zones. Also, as SSC is highest in the breaking zone, under breaking conditions, large discrepancies between measured and predicted SSC in the breaking zone (which were observed to be up to an order of 10^1 kg/m^3; see Fig.1) would result in unrealistic transport rates and resulting morphodynamic predictions.

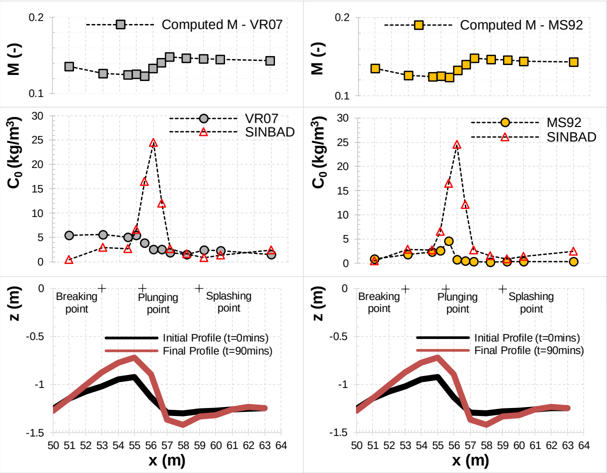

Figure 1 - Computed Mixing parameter *M*, reference concentration C_0 and measured cross-shore profile evolution from SINBAD experiments (van der Zanden et al., 2017). collected under large-scale regular plunging waves. z=0 at surface; x=0 at wave paddle. Left plots show the performance of the model of Van Rijn (2007) and Right plots show the performance of the model of Mocke et al., (1992). ALL figures used herein are reprinted and modified from Lim et al. (2020) with permission from Elsevier.

Several models related the C_0 to the sand pickup rate or Shields Parameter (i.e. assumed that suspension occurred when exerted bed shear exceeded critical bed shear). Such models were adept in reproducing SSC in the shoaling zone where there was no external (breaking-induced) TKE, but performed poorly in the breaking zone, particularly around the plunging point (see around x=55.5-56m in Fig.1), where breaking-induced TKE is highest. This was because these formulations were based on the implicit assumption that the sediment entrainment was only forced by local TKE generated by bed shear; neglecting the external TKE generated by strong breaking-induced vortices.

This limitation was addressed in more recent studies that incorporated the measured near-bed TKE (k_b) into the C_0 formulae, modifying the bed-shear-driven transport parameters to include the external TKE. Though latest studies (e.g. van der Zanden et al., 2017) have indicated strong relationships between near-bed TKE and reference concentration/sediment pickup, there are also inherent limitations. Such models are highly sensitive to the accuracy and magnitude of measured or modelled k_b. This led to the k_b-driven models showing varied performance under regular and irregular breaking conditions (where k_b was found to vary by a factor of 1.1-1.3 between regular and irregular breakers). It is also very challenging to accurately measure and/or model k_b, making it difficult to use these models widely in morphodynamic models.

NEW SAND TRANSPORT MODEL

A new practical model was developed to be able to adeptly tackle these commonly observed limitations. A unique and novel method of modelling the cross-shore distribution of C_0 was proposed, driven in-part by a novel empirical relationship between the local water depth and reference concentration. The local water depth (d) was found to have a strong inverse relationship with C_0, particularly in the shoaling and breaking zones (Fig.2). The local water depth was lowest around the bar crest (where wave breaking generally occurs) where corresponding SSC was highest. It was proposed that by incorporating the inverse water depth ($1/d$) into the proposed formula, the cross-shore distribution of C_0 could be captured well.

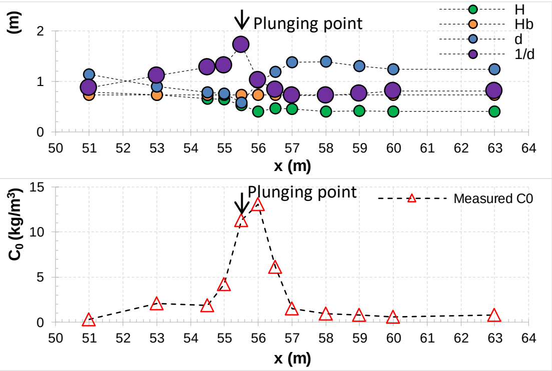

Figure 2 - Cross-shore distributions of local wave height (H), breaker height (H_b), local water depth (d), and inverse water depth ($1/d$) compared against cross-shore distribution of measured reference concentration (C_0).

Additional benefits of using the (inverse) water depth in the formulation is that it takes into consideration the location, evolution and migration of the breaker bar and bottom profile. This is important as the evolution and migration of the breaker bar can have significant effects on the wave breaking location, local wave heights, wave plunging intensity and resulting magnitude of SSC to name a few. Key parameters including the grain diameter and wave climate were also incorporated to enhance the model's applicability to a wide range of different conditions (e.g. with varying grain sizes and low and high energy weather conditions). Finally, gravitational acceleration was included to account for the grain settling forces.

The new C_0 model showed very good agreement with measured data (RMSE range 0.36-1.79kg/m^3) in the shoaling, breaking and inner surf zones, when validated against 119 tests cases from 4 high-resolution field-scale datasets. Fig.3 indicates that even at plunging point, where all other tested models were found to underpredict to varying degrees (e.g. Fig.1), the proposed model accurately replicated the measured reference concentration. This high level of accuracy in predictions was maintained even when the breaker bar was fully developed and wave plunging intensity highest. There was however some discrepancy between measured and computed C_0 just after the plunging point - see x=56m in Fig.3. The bottom panel of Fig.3 shows that at x=56m is where the bar trough is - i.e. where the water depth suddenly increases. As 1/d is one of the driving parameters in the L19 formula, the sudden increase in depth is reflected in the decrease in corresponding C_0. On the contrary however, measured C_0 increases at this point and SSC peaks. As turbulent vortices, injected at wave plunging, continue to travel obliquely downwards and in the direction of wave propagation (i.e. from x=55.5-56m), more sand is agitated into suspension. The TKE generated by the large vortices also enhance vertical sediment mixing. This enhanced mixing is well-modelled by the mixing parameter of L19 in the top panel of Fig.3. The peak in SSC at x=56m is also partially attributed to the effects of horizontal advection transporting TKE and suspended sediment to/from adjacent regions. These effects are not incorporated into the L19 model, sometimes leading it to slightly under-predict immediately shoreward of the plunging point. Overall, however the new L19 model performs very well, with good applicability to shoaling, breaking and inner surf zones. It is also particularly adept in reproducing the high levels of SSC found in the breaking zone under breaking wave conditions.

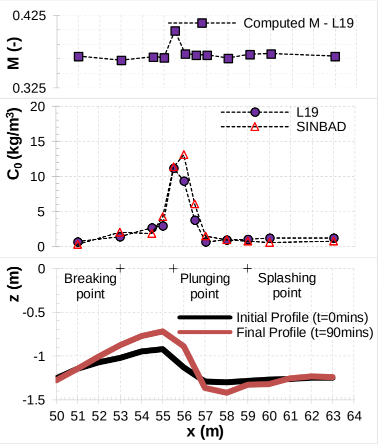

Figure 3 - Computed Mixing parameter M, reference concentration C_0 and cross-shore profile evolution from SINBAD experiments (z=0 at surface; x=0 at wave paddle) collected under large-scale regular plunging waves. Plot shows performance of newly proposed L19 model.

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