RUN-UP, BOUNDARY LAYERS AND SHEAR STRESSES BENEATH SHOALING TSUNAMIS

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BACKGROUND AND INTRODUCTION
While the tsunami propagation, run-up and inundation has received considerable attention in literature, the associated boundary layer dynamics and induced sediment transport have received relatively little attention. Recently, Williams and Fuhrman (2016) simulated a series of tsunami scale boundary layers, emphasizing that they are simultaneously both current- and wave-like due to their long duration yet unsteady nature. They viewed the tsunami as a time varying current, something that has also been done by Larsen et al. (2017) and Larsen et al. (2018) in studies of tsunami-induced scour around monopile foundations. This approach is valid sufficiently far off-shore, but nearshore, the effects of the free-surface will inevitably become important.While difficult due to the large scales involved, the run-up and inundation can likewise be studied experimentally (Sriram et al. 2016). In this work the run-up process of full-scale tsunamis will be simulated in deail using CFD, which can naturally resolve shorter dispersive waves, wave breaking and boundary layer dynamics.

MODEL VALIDATION
The present simulations are performed within the OpenFOAM environment, with the newly stabilized turbulence closure model of Larsen and Fuhrman (2018) and Fuhrman and Larsen (2018). To demonstrate that the model is capable of propagating a properly scaled tsunami an experiment of Sriram et al. (2016) is first simulated. The studied wave is a single wave (elongated soliton type) with a wave height H=0.12 m and a period of T=30 s. The wave propagates 251.5 m before reaching a slope of S=1/6. It should be noted that the period of this model scale wave is much longer than those typically used when studying model scale wind waves. Fig. 1 shows an excellent match between the experimental and modelled surface elevations, η, at both 60 and 225 m from the wave paddle. It can be seen that, as the wave propagates, the non-linearity grows and at x=225 m (Fig. 1b) the wave is starting to disintegrate into solitons.

RUN-UP
Following the validation the model is used to simulate a total of 14 full-scale tsunamis propagating on an initial flat bed before running up constant slope regions. The tsunamis are represented both as single waves and leading depression N-waves (summation of a negative and a positive single wave) and the slopes are systematically varied.

The run-up heights will be shown to match reasonably well those predicted using a combined existing analytical and empirical expressions.

From the highly resolved numerical simulations it will be shown that the tsunami run-up can appear as:
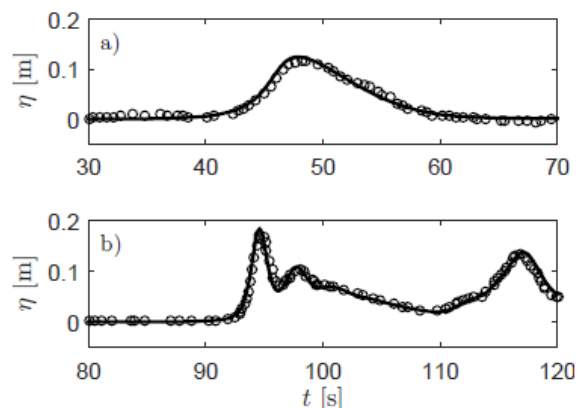

Figure 1 - Comparison of experimental by Sriram et al. (2016) (o) and numerical (-) surface elevation at a) x=60 m and b) x=225 m.

(1) "Tide-like". Here the tsunami surface elevations are almost horizontal and the inundation speeds are relatively low. This scenario only happened at very steep slopes, which were seen almost as a vertical wall by the tsunamis essentially causing a standing wave.
(2) "Breaking bore". During shoaling the tsunami fronts steepen, and the front of the tsunamis start splitting, similar to that shown in Fig. 1. The short waves cannot maintain their shapes during shoaling, however, and break at a distance to the shore. This turned the tsunamis into breaking bores. In these cases the inundation speeds were very high.
(3) "Undular bore turning into a breaking bore". In cases with very mild slopes, the tsunamis developed many shorter waves, turning the whole front into an undular bore. During shoaling these waves could not sustain the shape and broke at a distance to the shore, again turning the tsunami into a breaking bore.
(4) "Undular bore". By maintaining a steep slope and extending the flat part of the domain, such that the tsunami propagated far in shallow water it was possible to create a scenario where an undular bore developed, and did not loose all it's energy before reaching the shore.

By comparing two cases with identical initial wave shape and slope it was possible to assess the importance of the shorter waves riding on the larger main tsunami wave. In Fig. 2 snapshots of the surface elevations of single waves running up a slope of S=1/30 are shown. In the case propagating the furthest (Fig. 2b) an undular bore is clearly visible at the front, while in Fig. 2a the wave has not propagated far enough for an undular bore to develop. The final run-up height of the two cases are however very similar as previously hypothesized by Madsen et al. (2008).
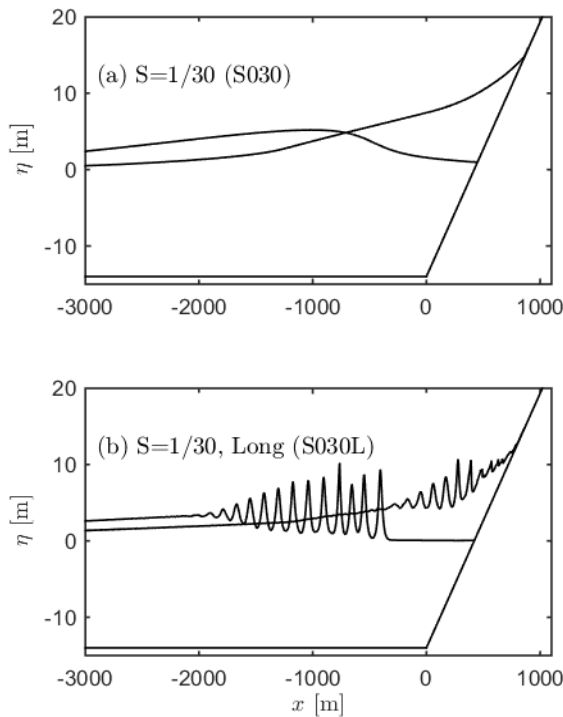
Figure 2 – Comparison of run-up of single waves on a 1/30 slope.

It will also be shown that the inundation speeds are similar, but the local flow velocities in the crest of the shorter waves may be substantially higher compared to the case without short waves.

BOUNDARY LAYERS AND BED SHEAR STRESSES

The boundary layers beneath the tsunamis will be shown to grow in time, reaching a maximum thickness just before flow reversal. After flow reversal a new boundary layer forms and grows. The boundary layer thicknesses, δ, will be shown ranging from spanning a small proportion of the water depth to spanning the entire depth. A new engineering approach for predicting bed shear stress, taking into account the temporal development of the boundary layer thickness, will be presented. Fig. 3 shows free stream velocities, u_0, surface elevations, predicted and modelled boundary layer thicknesses, modelled and predicted friction velocity, U_f, using both a standard Manning approach and the new approach, for an N-wave running up a slope of S=1/100. It can be seen that there is good agreement between both the modelled and predicted boundary layer thickness and friction velocity. Furthermore, only the new approach is able to capture the high friction velocity beneath the steep tsunami front, where the boundary layer will not have had much time to grow thereby creating higher velocity gradients and in turn bed shear stress. The new approach is formulated such that it can easily be implemented in potential flow models, potentially improving their sediment transport predictive capabilities.
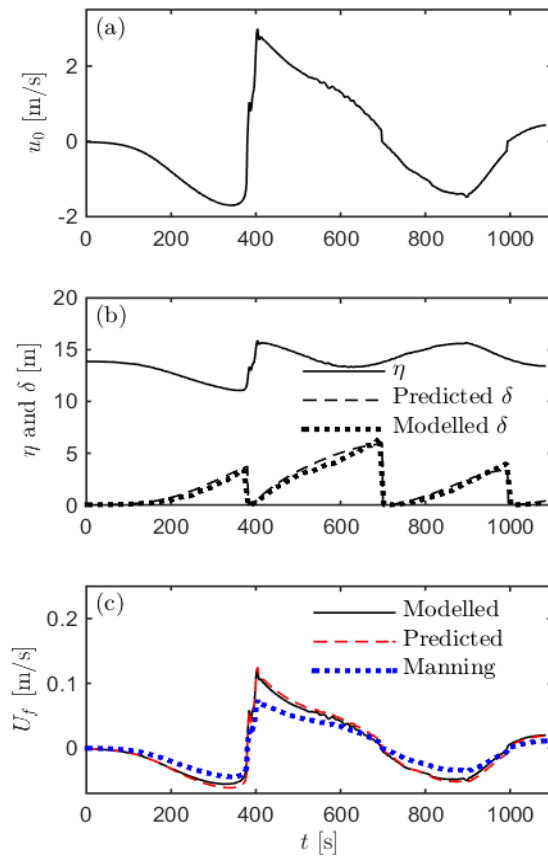

Figure 3 – Time series of (a) free stream velocities, (b) surface elevations and boundary layer thickness and (c) friction velocity, for an N-wave on a 1/100 slope.

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