ONLINE COUPLING OF SPECTRAL AND NON-HYDROSTATIC MODELS FOR WAVE SIMULATION FROM OFFSHORE TO NEARSHORE

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KEY POINTS:

- *An online, one-way coupling between the SWAN phase-averaged, spectral wave model and the SWASH time domain, multi-layered non-hydrostatic flow model has been developed.*
- *The coupling is obtained: (i) forcing the SWASH seaward boundaries by the action density spectra computed by SWAN; (ii)sharing the wave-induced setup calculated by SWAN at the grid-point level.*
- *The coupling efficiency has been evaluated through comparison with unidirectional random wave runup laboratory data.*

1 INTRODUCTION

A wide range of well established numerical models are now routinely used in coastal engineering studies. Phase-averaged spectral models are fundamentally based on linear theory, with non linear processes represented via ad hoc parametric submodels, and are thus best suited for simulating wave propagation from offshore to nearshore. Better representation of nonlinear waves in the nearshore is sought for with use of time-domain models, such as non-linear shallow water (NLSW) equations, Boussinesq-type (BT) and non-hydrostatic (NH) models. Although the NLSW equations can be used to simulate effectively broken waves and wave runup on a dry bed, they cannot correctly represent the onset of breaking. On the other hand, after a high effort has been addressed in the last two decades to improve the dispersion and nonlinear properties of both BT (*Madsen & Fuhrman,* 2010) and NH multi-layered models (*Zijlema & Stelling*, 2008), in principle they can now accurately represent wave propagation from offshore. However, such models are still excessively time-consuming to be considered for use in large-scale practical engineering problems. Therefore, the much cheaper phase-averaged approach is currently used to compute wave propagation from offshore, providing offshore boundary conditions to a phase-resolving model running in the nearshore.

The above procedure is currently carried out manually, with use of distinct codes for the spectral and the phase-resolving models. Higher efficiency is expected to be achieved by online coupling the two models, resulting in one code and one executable, for seamlessly simulating wave evolution from generation to runup and land inundation. Developing an online coupling between the phase-averaged SWAN (Simulating WAves Nearshore, *Booij, et al.* 1999) and the time-domain SWASH (Simulating WAves till Shore, *Zijlema et al.* 2011) models, both open source, is the main aim of this work.

Herein, results of the coupled-model are compared with laboratory data of unidirectional random wave runup carried out on a gentle, smooth and impermeable slopes (*Mase,* 1989). Furthermore, comparisons are presented with *McCabe et al.* (2010, 2011) findings obtained with a coupled SWAN – NLSW model.

2 COMPONENT MODELS

SWAN is a third generation wave spectral model, which solves the spectral action balance equation with sources and sinks. The model can account for shoaling, refraction, partial diffraction, generation by wind, whitecapping, three- and four-wave nonlinear interactions, bottom friction and depth-induced wave breaking (*Booij, et al.* 1999*; Holthuijsen,* 2007). Recently, the model has been extended to improve the modeling of triads wave-wave interactions (*Booij, et al.* 2009) and depth-induced wave breaking (*Salmon, et al.* 2015).

SWASH is a multi-layered, non-hydrostatic model, based on a reasonable and efficient approximation of the RANS equations (*Zijlema et al.* 2011). The numerical implementation is based on an explicit, momentum conserving, second order finite difference method for staggered grids. Acceptable frequency dispersion can be achieved by using only a few layers, due to the Keller-box scheme used for the approximation of the vertical gradient of the non-hydrostatic pressure. Depth-induced wave breaking is represented by reducing the model to the NLSW equation (*Smit et al.* 2013), taking advantage of the shock-capturing property of the model. Wetting and drying is handled with the robust *Stelling & Duinmeijer* (2003) algorithm.

3 COUPLING PROCEDURE

A single code was implemented, where SWAN (version 41.01) is the master model and SWASH (version 3.14) subroutines are packed into a library called inside the SWAN main time loop. It is a one-way coupling, not taking into account the feedback of the phase-resolving model to the action balance equation model.

The model components run sequentially in time on structured Cartesian meshes, with SWAN acting on a larger domain extended up to offshore, whereas the SWASH domain is located in the nearshore and includes the emerging beach terrain. The coupling takes place at the seaward SWASH open boundary, where: (i) the spectra computed by SWAN are prescribed; (ii) wave trains are synthesized by a single summation method (*Miles,* 1989), which produces a quasi-homogeneous wave variance (*Miles & Funke,* 1989), using a weakly reflective boundary condition; (iii) the horizontal velocity normal to the boundary, computed using the linear theory, is prescribed (*Zijlema, et al.* 2011, *Smit et al,* 2013). Furthermore, wave-induced setup calculated by SWAN integrating the 1D equation forced by the radiation stresses is passed to the SWASH domain.

4 APPLICATION

Model results have been compared with four of the random wave runup laboratoty tests on a model beach by *Mase* (1989), with bed slope 1:20 and water depth at the wavemaker d_{wm}=0.45m. A Pierson-Moscowitz spectrum was imposed at the wavemaker, with values of significant wave height H_{wm}, and peak period T_p as reported in Tab. 1, where representative wave length at the wavemaker, L_{wm}, related depth-to-wavelength ratio, $(d/L)_{wm}$, and equivalent deepwater significant wave height H_{dw} and wavelength L_{dw} are also shown. The numerical model is set-up along a one-dimensional flume of length 25 m, with horizontal resolution and time step shown in Tab. 1. SWASH was run for a duration of 1200 s, with spin-up time of 300 s.

	H_{dw}' (m)	H_{wm} (m)	K_s (-)	T_p (s)	L_{dw} (m)	L_{wm} (m)	$(d/L)_{wm}$ (-)	Δx (m)	Δt (s)	Breaker type
TEST A	0.0477	0.0495	1.037	2.50	9.758	4.998	0.111	0.020	0.002	Plunging
TEST B	0.0639	0.0618	0.968	2.00	6.245	3.884	0.086	0.020	0.002	Spilling
TEST C	0.0793	0.0734	0.930	1.67	4.337	3.120	0.069	0.015	0.001	Spilling
TEST D	0.0990	0.0914	0.915	1.25	2.440	2.122	0.047	0.010	0.001	Spilling

Tabella 1. Parameters of incident waves for the Mase (1989) tests. K_s is the shoaling coefficient based on linear wave theory.

SWAN, SWASH and SWAN + SWASH model runs were carried out. Following *McCabe et al.* (2011), the SWAN model is run without nonlinear interactions (quadruplets and triads) and bottom friction, but activating whitecapping and depth-limited breaking (*Battjes & Janssen,* 1978). The lower and upper boundaries in frequency space, subdivided in 200 frequencies, are generally chosen equal to $0.5f_p$ and $3f_p$, respectively, $f_p=1/T_p$ being the peak frequency. However, in the coupled model simulations using SWASH with one layer, a lower value for the upper limit is chosen, in the range $(2\div2.5)f_p$, in order to introduce only accurate harmonics in the phase-resolving model. In fact, based on an approximate dispersion relation, using one layer, SWASH is accurate up to a kd=2.9 for primary waves (k = wave number), with a relative error in the normalized wave celerity $c/(gd)^{1/2}$ of at most 3%. Finally, a $cos^{800}(\theta)$ directional distribution is used.

The SWASH model is run throughout the entire domain using four different configurations for each test cases: (i) one vertical layer, (ii) the same as (i) including incident bound waves (*Rijnsdorp et al.* 2014) at the wavemaker boundary, (iii) two and (iv) three vertical layers. The default values for the maximum steepness parameter (α=0.6) and the persistence parameter (β=0.3), found after calibration by *Smit et al.* (2013), were set in the, so called, hydrostatic front approximation, used to simulate depth-induced wave breaking with few layers. Furthermore, a threshold value of 0.1 mm was set in each run to represent the minimum inundation depth, while turbulence and bottom friction are neglected.

Finally, the SWAN+SWASH model is run by using five different random seeds for the generation of time series at the SWASH open boundary, in order to take account for sensitivity of runup to the random input phases, and choosing six or seven coupling points, with values of H_{m0}/d (as computed by SWAN) in the range 0.1–0.6. In these cases, the SWASH model is run with one and two layers, with a total of 250 runs.

4.1 Results and discussion

Comparison between the measured and calculated runup statistics $R_{2\%}$, $R_{1/10}$ and $R_{1/3}$ will be shown by using the relative error, $(R_{Model} - R_{Mase})/R_{Mase}$. Fig. 1 shows relative errors between experimental data and SWASH runs (panel P_1), SWAN+SWASH run using SWASH with one (panel P_2) and two layers (panel P_3).

Although the effect of increasing the number of layers is apparent, more layers should be chosen to ensure adequate modeling of the phase differences between the representative wave components, including shorter waves. Furthermore, results using one layer are most affected by the so-called evanescent modes, especially for the lower peak period. On the other hand, the largest errors appear when two layers are used.

The accuracy of the coupled model with the less computationally expensive configurations was checked running SWASH using one and two layers. It is shown that the error can be strongly reduced with proper choice of the coupling point, while attaining remarkable alleviation of the computational effort. On the other hand, because of error variability depending on both wave conditions and model configurations, it does not appear that a best-unique coupling location can be defined. However, with respect to the most important $R_{2\%}$ statistic, it seems that a common value of $H_{m0}/d \approx 0.50\text{-}0.55$ could be chosen for Tests B, C e D, while a lower value of $H_{m0}/d \approx 0.3$ appears to be optimal in Test A, for SWAN + 1layer-SWASH. On the other hand, a similar, but less evident, common behavior might be observed in case of the SWAN+ 2layers-SWASH coupling, where optimal values seem to be $H_{m0}/d \approx 0.55\text{-}0.60$ and 0.3, respectively, for Tests B, C, D and Test A. All these values are less than $H_{m0}/d \approx 0.65$ obtained by *McCabe et al.* (2011) with a SWAN+NLSW model. This is probably due to SWASH still being able to represent some degree of wave dispersion compared to the non-dispersive NLSW formulation.

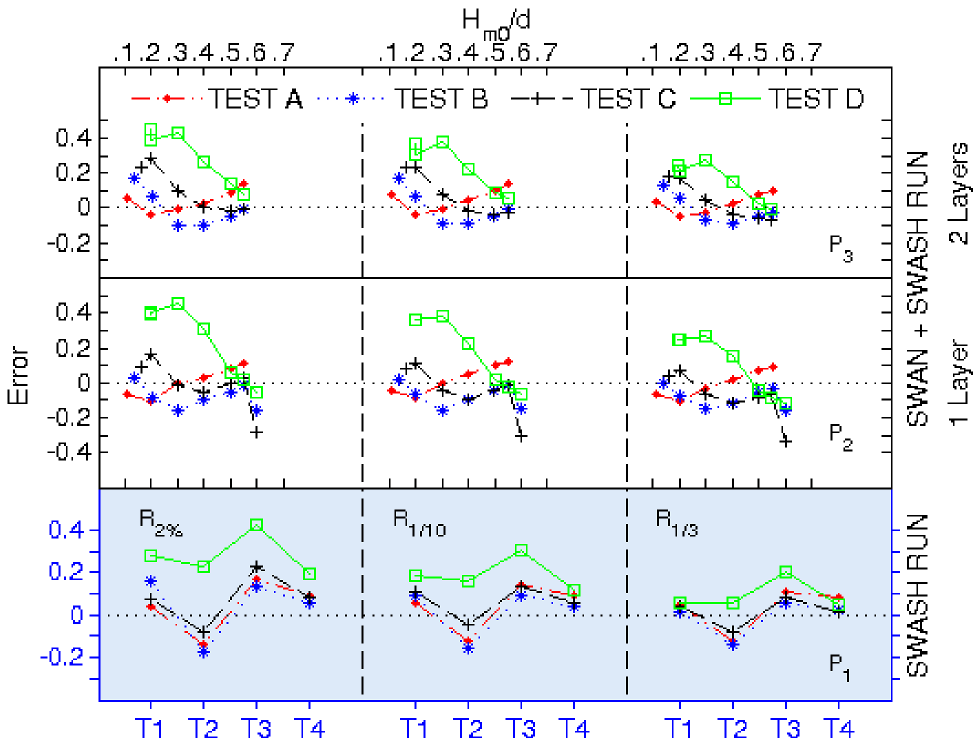

Figura 1. Error in runup statistics ($R2\%$, $R_{1/10}$, $R_{1/3}$), compared with Mase's (1989) laboratory results: SWASH run throughout the domain (panel P_1); SWAN + SWASH with 1 layer (panel P_2) and 2 layers (panel P_3). In panel P_1: T1 = run with single layer, T2 = single layer plus bound waves at wavemaker; T3 = two layers, and T4 = three layers. Panel P_2 and panel P_3 represent errors as a function of the nonlinear parameter H_{m0}/d. Errors are computed as mean values resulting from 5 randomly phased wave trains prescribed as boundary conditions of SWASH, generated from the same action density spectrum computed by SWAN.

On balance, for the wave conditions analyzed, simulations are shown to be reasonably accurate even with SWASH used throughout for sufficiently large peak periods, and in a broader peak period range with the coupled model.

5 CONCLUSIONS

In this study, an online, one-way coupling between the SWAN and SWASH models has been introduced. Numerical results indicate a fairly good agreement of computed runup statistics with data from unidirectional random wave laboratory tests. The coupled model proved effective in reducing the SWASH domain extent, thus reducing the overall modeling effort, while retaining outcomes' accuracy, suggesting that it can be a comprehensive and valuable tool for both engineering and scientific purposes. The choice of the optimal coupling point is found to be dependent on both the wave conditions and the model configuration.

Finally, it should be emphasized the importance of both nonlinear effects and spectral wave model accuracy in very shallow water, where instabilities might arise due to wave-maker algorithm characteristic, which is based on linear wave theory and horizontal bottom, and because of increased wave reflection. Therefore, further evaluations can be made including the contribution of incident (bound) infragravity-waves at the coupling point. On the other hand, different SWAN configurations as to triplet interactions and depth-induced breaking modeling (*Salmon et al.* 2015), might be used to improve the results.

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