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Experiences with SWASH on modelling wave propagation over vegetation: comparisons with lab and field data

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ABSTRACT: The vegetation capacity to protect the coasts from wave action is becoming more important and attractive due to ongoing sea level rise and increasing storminess. In addition, it is a quite environmentally friendly way. Quantifying the vegetation effect in wave propagation will be relevant for coastal management. A non-hydrostatic wave model based on the nonlinear shallow water equations, SWASH, offers opportunities to quantify the wave dissipation effect in vegetation fields. However, limited applications of SWASH addressing this subject can be found in the literature and therefore it is important to enhance the existing knowledge on the model behaviour. In this research, in order to understand the characteristics of the SWASH model further, the model is applied to reproduce the significant wave height (H_s) evolution over vegetation fields measured in flume experiments and in field campaign. Overall, SWASH performed very well in reproducing the H_s evolution measured both in the laboratory and in the field. In the case of flume data, the statistical scores MBE, RMSE and MRE, showed that the SWASH performance clearly improved when increasing the number of vertical layers assumed in the simulations. In the case of field data, considering a vegetation factor (V_f) between 0.1 and 0.5, that represents the overall effect of scarcely known numerical vegetation parameters, led to a fairly good SWASH performance in modelling the H_s evolution over vegetation.

Keywords: Wave propagation, Vegetation, SWASH model, Wave dissipation, Model-data comparisons.

RESUMO: A capacidade da vegetação de proteger a costa da acção das ondas é cada vez mais importante e atractiva, devido ao aumento do nível do mar assim como das tempestades. Além disso, é uma abordagem ecológica de protecção costeira. A quantificação do efeito da vegetação na propagação de ondas torna-se relevante para a gestão costeira. Um modelo de ondas não hidrostático baseado nas equações não lineares de águas pouco profundas, o SWASH, possibilita quantificar o efeito de dissipação das ondas em campos de vegetação. No entanto, existem ainda, na literatura, poucas aplicações do SWASH a este fenómeno, e portanto, é particularmente importante aumentar o conhecimento sobre o comportamento deste modelo. Nesta investigação, para compreender melhor as características do SWASH, este foi aplicado na reprodução dos resultados de altura significativa de onda (H_s) sobre vegetação, obtidos num canal de ondas e numa campanha de campo. No geral, o SWASH teve um bom desempenho

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na simulação da H_s obtida tanto no laboratório como no campo. No caso dos dados de laboratório, os valores estatísticos MBE, RMSE e MRE indicam claramente que o desempenho do SWASH melhorou ao aumentar o número de camadas verticais considerado nas simulações. Na aplicação a dados de campo, ao considerar um factor de vegetação (V_f) entre 0,1 e 0,5, que representa o efeito geral de parâmetros numéricos da vegetação com pouca informação disponível, levou a um razoável desempenho do SWASH na simulação da H_s.

Palavras-chave: Propagação de ondas, Vegetação, Modelo SWASH, Dissipação de ondas, Comparações Modelo-Dados.

1. INTRODUCTION

Important losses of vegetation species affecting the coastal environments have occurred due to coastal erosion and human activities. Vegetation can protect the coasts from erosion and floods by dissipating the energy of waves and currents. The interest in understanding the coastal vegetation capability is growing, since the foreseen sea level rise and increasing storminess would increase the load on coastal structures. The use of vegetation and the design of vegetation-based structures are being increasingly considered for coastal management/protection, since those may lead to efficient and economical solutions with low environmental impact.

Wave propagation over vegetation is a quite complex process that is dependent on both vegetation and hydrodynamic characteristics. Therefore, a comprehensive numerical modelling will be useful in order to estimate waves in and behind vegetation fields.

The SWASH (Simulating WAves till SHore) is an open source phase-resolving wave model, based on the nonlinear shallow water equations, including non-hydrostatic pressure (Zijlema *et al.*, 2011). SWASH has been successfully used in a variety of studies with different purposes. Smit *et al.* (2013) applied SWASH to flume experiments proving the model capacity to solve the relevant near-shore wave processes. Using SWASH for impermeable coastal structures in shallow foreshores, Suzuki *et al.* (2017) obtained accurate mean wave overtopping discharges. Zhang *et al.* (2018) showed a good capacity of SWASH to compute the vertical distribution of wave-induced longshore currents, by simulating laboratory data.

SWASH can simulate the wave dissipation by vegetation due to the implementation of drag, inertia and porous effect in Suzuki *et al.* (2019). However, there are only few applications of the SWASH model to the propagation of waves over vegetation. Cao *et al.* (2016) verified the SWASH results of wave height evolution with field data observed in the mangrove forests along the South China Sea. They also analysed the importance of vegetation numerical parameters to the vegetation-induced run-up reduction. Dao *et al.* (2018) applied the SWASH model for better understanding the wave damping provided by wooden fences, in the Mekong Delta coasts. They analysed how transmitted wave height varied with the nonlinearity of incident waves.

It is clear the importance of comparing the SWASH model results with measured data. In this work, the SWASH model (version 5.01) is applied to reproduce the wave height evolution over vegetation measured in the flume experiments of Løvås (2000) and in the field campaign of Vo-Luong and Massel (2006). Løvås (2000) performed physical model experiments of wave propagation over kelp seaweed to estimate the field conditions along the Jæren coastline, Southwestern Norway. Løvås (2000) found that the presence of kelp modifies substantially the local hydrodynamics. Vo-Luong and Massel (2006) carried out field measurements of wave propagation through Can Gio mangrove forest, Southern Vietnam. Vo-Luong and Massel (2006) found that wave breaking and wave interaction with vegetation are the dominant energy dissipation processes in such conditions.

The main objective of the present paper is to assess the performance of the SWASH model to simulate the wave propagation over vegetation. The secondary objectives are to assess: a) the influence of the number of vertical layers applied in modelling the laboratory data and b) the range of values of vegetation factor (V_f) in modelling the field data.

After the introduction in the current section 1 of this paper, the characteristics of the vegetation model in SWASH are presented in the section 2. The sections 3 and 4 cover, respectively, the analysis and results for the flume data and field data cases. The conclusions follow in section 5.

2. VEGETATION MODEL IN SWASH

The SWASH model (Zijlema *et al.*, 2011) is an open source phase-resolving wave model for simulating unsteady free-surface and rotational flows till the shore. SWASH is based on the nonlinear shallow water equations, including a non-hydrostatic pressure term. Considering a 2D domain with horizontal and vertical Cartesian coordinates x and z, the governing equations are (Suzuki *et al.*, 2019):

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uu}{\partial z}=-g\frac{\partial \zeta}{\partial x}-\frac{\partial q}{\partial x}-\frac{1}{\rho}F_x \quad (2)$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial ww}{\partial z}=-\frac{\partial q}{\partial z}-\frac{1}{\rho}F_z \quad (3)$$

where t is the time, $u(x, z, t)$ is the velocity in the horizontal direction, $w(x, z, t)$ is the velocity in the vertical direction, g is the gravitational acceleration, ρ is the fluid specific mass, $q(x, z, t)$ is the non-hydrostatic pressure (normalized by ρ), and F_x and F_z represent body and surface forces in the horizontal and vertical directions, respectively.

The vegetation model implemented in SWASH considers forces acting on cylinders (plants or stems) based on the Morison equation (Morison *et al.*, 1950).

If cylinders are vertical, only the force in the horizontal direction F_x is considered. The force acting on vertical cylinders per unit volume is given by:

$$F_x=\frac{1}{2}\rho C_D h_\nu b_\nu N_\nu u|u|+\rho(1+C_m)h_\nu A_\nu N_\nu\frac{\partial u}{\partial t} \quad (4)$$

where C_D is the bulk drag coefficient, h_v is the cylinder height, b_v is the cylinder diameter, N_v is the number of cylinders per horizontal area, u is the horizontal velocity due to wave motion, C_m is the added-mass coefficient and A_v is the area of the base of a single cylinder ($A_v = (\pi/4)\, b_v^2$). Note that the first and second terms in the right-hand side of Equation 4 are, respectively, the drag and inertia forces acting on the vegetation. Then, F_x given by Equation 4 is implemented in Equation 2 as follows:

$$(1-\frac{h_\nu}{h}A_\nu N_\nu)\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial wu}{\partial z}+g\frac{\partial \zeta}{\partial x}+\frac{\partial q}{\partial x}+\frac{1}{2}C_D\frac{h_\nu}{h}b_\nu N_\nu u|u|$$

$$+(1+C_m)\frac{h_\nu}{h}A_\nu N_\nu\frac{\partial u}{\partial t}=0 \quad (5)$$

where h_v/h is the ratio between h_v and the water depth h. The first and last terms in the left-hand side of Equation 5 represent, respectively, the inertia acting onto the clear fluid and the inertia of water displacement due to vegetation.

Vertical force acting on cylinders (plants or stems) F_z and porosity effect are also implemented in SWASH code, however those were not used in the present simulations.

Note that, for simplicity, vegetation model in SWASH assumes rigid cylinders (plants or stems), so any realistic vegetation motion in time that would represent changes in the C_D, h_v or A_v of individual cylinders is neglected.

3. ANALYSIS AND RESULTS: FLUME DATA CASE

The SWASH model is used to replicate the wave propagation over kelp seaweed (*Laminaria hyperborea*) measured in the flume experiments of Løvås (2000).

The laboratory tests of Løvås (2000) simulated, in 1:10 scale, the field conditions along the Jæren beaches of southwestern Norway. The experiments were carried out in a wave flume at SINTEF, Trondheim (Løvås and Tørum, 2001). The beach slopes were made with sand. Artificial plants were designed and prepared from a plastic liquid to replicate real kelp plants sampled in the field. The artificial plants had 10 cm high stipes and 10 cm long fronds with a corresponding full-scale surface area of approximately 0.6 m^2 and were uniformly distributed representing a full-scale plant density of 12 plants/m^2 (Dubi and Tørum, 1994; Dubi, 1995; Løvås and Tørum, 2001). The laboratory wave tests were taken in both situations with and without vegetation to analyse the different effects.

The Figure 1 schematizes the computational domain used in SWASH (Mendez and Losada, 2004). It illustrates the bottom (black thin line), the kelp field area (grey shaded area) and the water level considered in the SWASH runs (blue line). Figure 1 also shows the ten wave gauge locations (vertical black thick lines): the wave gauge at $x \sim 1$ m ("offshore") and the other nine along the 1:30 surf zone beach slope.

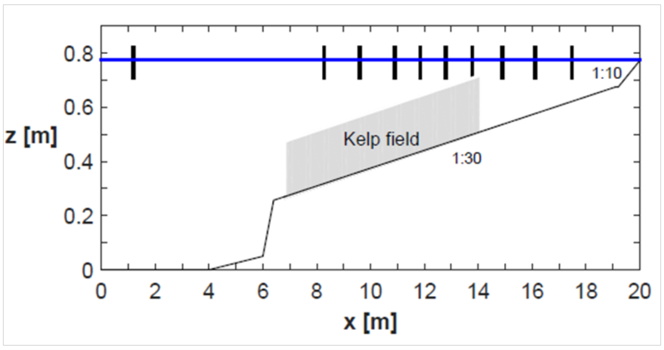

Figure 1. Schematization of the SWASH computational domain for Løvås (2000) experiments (Mendez and Losada, 2004).

The SWASH model was run in nonstationary mode. The computational grid was a regular one with calculation grid size uniformly set as $\Delta x = 0.1$ m. At the boundary ($x = 0$ m) the water depth (h) was of 0.77 m (Figure 1). The waves were generated by a Joint North Sea Wave Project (JONSWAP) frequency spectrum with peak enhancement parameter $\gamma = 7.0$ (Løvås and Tørum, 2001). Runs were taken for two different forcing spectral wave conditions: a) significant wave height

H_s = 0.125 m with peak wave period T_p = 3.5 s and b) H_s = 0.220 m with T_p = 2.5 s. Since the wave generation in the experiments had no means to suppress spurious waves nor to absorb reflected waves (Løvås and Tørum, 2001), weakly reflective boundary and added second order bound long wave generation were not considered. The hydrostatic front approximation (HFA) approach for depth-induced wave breaking was considered with maximum steepness parameter α = 0.6 and persistence parameter β = 0.3 (Smit *et al.*, 2013). The total simulations time was 30 min with time step of 0.001 s. Non-hydrostatic pressure was included with the Keller-box numerical scheme for the vertical pressure gradient.

SWASH runs were taken for two different vertical discretizations: a) only one vertical layer and b) two vertical layers with equidistantly distributed thicknesses.

Consistent with the Løvås (2000) flume tests, a 7.27 m long area of cylinders (kelp field) was considered in SWASH (Figure 1) with cylinder height h_v = 0.2 m, cylinder diameter b_v = 0.025 m and number of cylinders per horizontal area N_v = 1200 units/m^2 (Mendez and Losada, 2004). A constant bulk drag coefficient C_D of 0.15 and 0.20 was considered, respectively, for the H_s = 0.125 m with T_p = 3.5 s and H_s = 0.220 m with T_p = 2.5 s runs (Ma *et al.*, 2013).

SWASH runs were taken for both situations with and without kelp vegetation field.

The Figure 2 shows the results of H_s evolution obtained in the SWASH runs along with the flume measured data by Løvås (2000).

The Figure 2 shows an overall good performance of SWASH in simulating the evolution trend and magnitude of H_s flume data for all runs. The magnitude of H_s results over vegetation estimated by SWASH is underestimated by SWASH for the case with forcing H_s = 0.220 m and T_p = 2.5 s with one vertical layer (top blue dashed line).

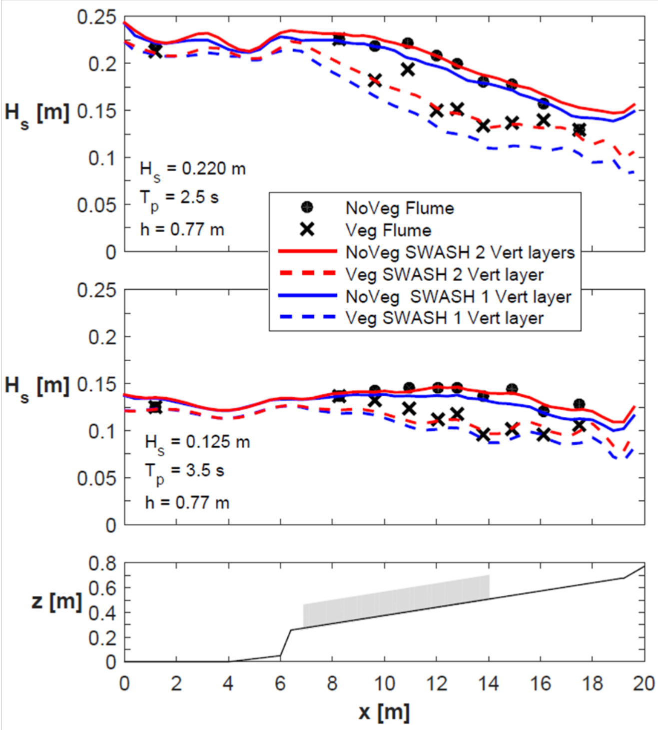

Figure 2. SWASH modelled and flume measured (Løvås, 2000) significant wave height (H_s) evolution.

To analyse further the SWASH performance for simulations considering one or two vertical layers, the differences between numerical results and measured data were quantified through the mean bias error (MBE), the root mean square error (RMSE) and the mean relative error (MRE) statistical parameters (Table 1).

The MBE, RMSE and MRE values (Table 1) show a general improvement of the SWASH performance when increasing from one to two the considered vertical layers in the simulations, especially for the runs with vegetation. This improvement happens for all runs with exception for the case with forcing H_s = 0.220 m and T_p = 2.5 s without vegetation (continuous red and blue lines, Figure 2 on top) where the SWASH performance barely changed.

Table 1. Statistical scores between SWASH and flume (Løvås, 2000) H_s results.

Run			MBE [m]	RMSE [m]	MRE
H_s = 0.220 m, T_p = 2.5 s	NoVeg	2 vert layers	0.005	0.009	6.6 %
		1 vert layer	-0.003	0.009	6.7 %
	Veg	2 vert layers	-0.007	0.012	8.0 %
		1 vert layer	-0.025	0.027	24.7 %
H_s = 0.125 m, T_p = 3.5 s	NoVeg	2 vert layers	0.001	0.005	4.4 %
		1 vert layer	-0.006	0.009	7.5 %
	Veg	2 vert layers	-0.004	0.008	6.7 %
		1 vert layer	-0.011	0.013	11.5 %

It is clear that the MBE, RMSE and MRE values improved for SWASH runs with vegetation, in both sea states (dashed lines, Figure 2), when considering two vertical layers instead of one, and hence a better SWASH behaviour was achieved in reproducing the H_s evolution over vegetation measured in the flume experiments.

In terms of computational time, while the four runs assuming a single vertical layer took about 2 min in total to be completed, the runs with two vertical layers took approximately 7 min.

4. ANALYSIS AND RESULTS: FIELD DATA CASE

The SWASH model is applied to model the wave propagation through mangrove forest measured in Nang Hai, Can Gio mangrove forest, Southern Vietnam (Vo-Luong and Massel, 2006).

The Vo-Luong and Massel (2006) field campaign took place in Can Gio mangrove forest which lies in a delta. The specific studied site, Nang Hai, is located at a sheltered area of the Dong Tranh estuary that is more influenced by waves. The field measurements were carried out during 16 days, from January to February 2005. The field data was measured along a transect parallel to wave direction and across mixed mangrove trees (*Avicenia* sp. and *Rhizophora* sp.). Pressure sensors were used to measure the free surface elevation through the mangrove forest in selected tidal levels. During the field campaign, multiple time series data were collected at a single pressure sensor location for each selected tidal level.

The Figure 3 shows the used SWASH computational domain: the bottom (black line), the mangrove forest area (grey shaded area) and the two tidal levels considered (blue lines). Also illustrated are the locations of the pressure sensors (black squares).

During the field campaign, the wave height at the boundary (x = 0 m) was, in general, about 0.35-0.4 m" (Vo-Luong and Massel, 2006).

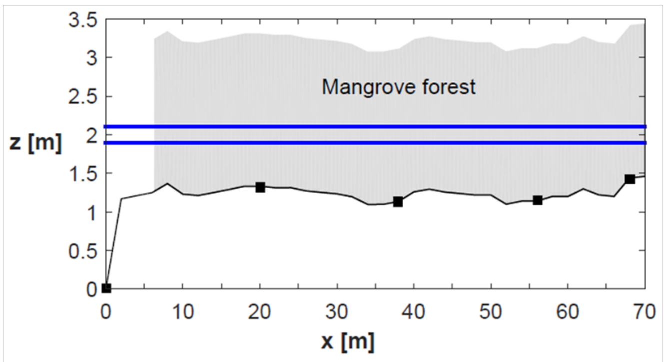

Figure 3. Schematization of the SWASH computational domain for Vo-Luong and Massel (2006) field experiments (Vo-Luong and Massel, 2008).

SWASH was run in nonstationary mode using a 70 m long regular computational grid with uniform discretization Δx = 0.1 m. At the boundary, forcing waves generated via a JONSWAP spectrum with H_s = 0.4 m and T_p = 1.2 s (Vo-Luong and Massel, 2008). SWASH was run for two tidal levels correspondent to: a) $h_{x=0}$ = 2.1 m and b) $h_{x=0}$ = 1.9 m (Figure 3 and Figure 4). The boundary was set to weakly reflective and with added second order bound long wave generation. The HFA approach for depth-induced wave breaking was considered with α = 0.6 and β = 0.3. The total simulations run time was of 30 min with a time step of 0.001 s. Non-hydrostatic pressure was included with the Keller-box scheme. Two vertical layers were assumed with equidistantly distributed thicknesses.

Regarding the vegetation parameters, the cylinders area (mangrove forest) extends from x = 6 m to x = 70 m (Suzuki *et al.*, 2012) in the SWASH domain (Figure 3) and the cylinder height was taken constantly higher than the water depth (h_v = 2 m) as the mangroves are usually emergent (Cao *et al.*, 2015). Since detailed field values of b_v, N_v and C_D are not available, and due to their complex spatial and time variability, it was used for simplicity the vegetation factor $V_f = b_v \times N_v \times C_D$, which represent the overall effect of these vegetation numerical parameters (Suzuki *et al.*, 2012).

SWASH was run for 2 constant and fixed values of V_f throughout the group of cylinders (mangrove forest): a) V_f = 0.1 and b) V_f = 0.5.

The Figure 4 shows the results of H_s evolution for both the SWASH runs and the field measured data (Vo-Luong and Massel, 2008). The field H_s values (black diamonds) at a single location correspond to the multiple time series field data that were collected and analysed for each tidal level at the same pressure sensor (Vo-Luong and Massel, 2006; Vo-Luong and Massel, 2008; Suzuki *et al.*, 2012; Cao *et al.*, 2015).

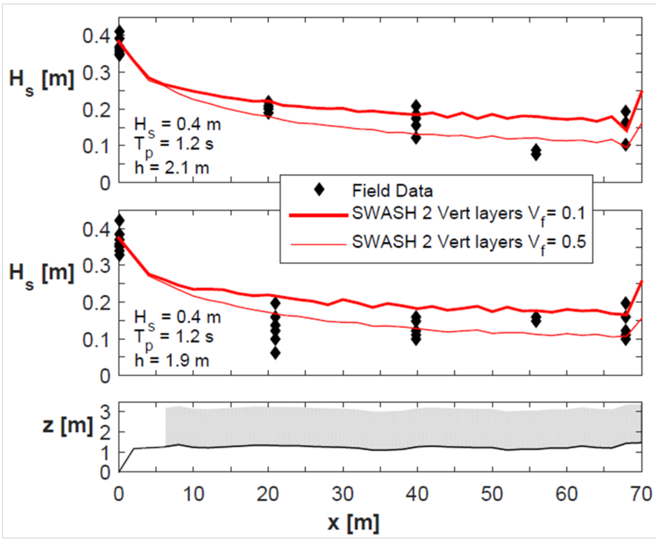

Figure 4. SWASH modelled and field measured (Vo-Luong and Massel, 2008) significant wave height (H_s) evolution.

The Figure 4 shows a general good performance of SWASH in simulating the H_s evolution through vegetation measured in the field for both tidal levels. Analysing the results of SWASH runs (Figure 4), it can be seen that a fairly good performance of SWASH in modelling the field measured data for the two tidal levels can be obtained by considering a V_f value between 0.1 and 0.5.

5. CONCLUSIONS

In the present paper, the SWASH model is applied to reproduce the significant wave height (H_s) evolution over vegetation measured in flume experiments (Løvås, 2000) and in the field (Vo-Luong and Massel, 2006).

SWASH had an overall good performance in simulating the evolution of H_s flume data measured by Løvås (2000). For situations with kelp seaweed, a clear improvement of the SWASH performance, quantified by the MBE, RMSE and MRE parameters, occurred when increasing from one to two the number of vertical layers assumed in the simulations.

SWASH had a general good performance in modelling the H_s evolution through mangrove forest measured in the field (Vo-Luong and Massel, 2006), for both considered tidal level conditions. The results of SWASH runs indicate that taking a vegetation factor (V_f) between 0.1 and 0.5, which represents the overall effect of scarcely known numerical vegetation parameters, a fairly good SWASH performance can be achieved for both tidal levels.

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