

Modelling tsunamis with a non-hydrostatic version of the MOHID model

João. C. Silva (1), António A. Pires Silva (1), Paulo. C. Leitão (2) and Adélio. J. Silva (2)

- (1) CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av Rovisco Pais, 1.
joao.c.da.silva@ist.utl.pt.
- (2) HIDROMOD, Rua Rui Teles Palhinha, nº 4, 1º. 2740-278, Porto Salvo.

Abstract: Recent studies suggest the propagation and run-up of tsunamis can be strongly influenced by dispersion due to non-hydrostatic effects, which can result in up to 60% higher values of coastal run-up than the ones calculated by hydrostatic models. In this communication the validation of a non-hydrostatic version of MOHID model is presented. This version features a newly introduced pressure correction method. The validation process is based in the benchmarking methodology proposed by NOAA (<http://nctr.pmel.noaa.gov/benchmark/>), for numerical models aimed at the study of tsunami events. It consisted in running a battery of tests, with increasingly complex geometries, with the objective of comparing the numerical results with their analytical solutions, laboratory data or field data. These results include snapshots of the wave propagation, time series of surface elevations and inundation maps. Field (Tohoku tsunami), lab and analytic results are compared with MOHID results run in non-hydrostatic and hydrostatic mode.

Keywords: tsunami, MOHID, non-hydrostatic, NOAA.

1. INTRODUCTION

On 26 December 2004 the Boxing Day tsunami took the lives of over 225 000 people in countries around the Indian Ocean. This catastrophe strengthened the interest in the development of plans to mitigate the effects of future tsunamis in countries or regions susceptible to this kind of phenomena. These concerns are also shared by Portugal which through the Portuguese civil protection agency (Autoridade Nacional de Proteção Civil) tasked the company Hidromod, lda to delimit potential inundation areas of several regions of the Portuguese coast in the case of a tsunami event.

Traditionally this kind of studies have been mainly developed with the aid of hydrostatic models such as COMCOT, MOHID, TUNAMI-N2 and COMMIT/MOST. In this type of models the vertical accelerations are neglected and the hydrostatic approximation is applied to the vertical momentum equation. This is a valid approximation when the wavelength of the disturbance is much larger than the height of the water column, which often holds true for the case of tsunamis generated by submarine earthquakes.

However, studies following the Boxing Day tsunami suggest the evolution and run-up of tsunamis can be strongly influenced by dispersion due to non-hydrostatic effects. This can result in up to 60% higher values of coastal run-up than the ones calculated by models based on the non-linear shallow water equations (NSWE) (Cui *et al.* 2012), for example.

For the aforementioned reasons it was decided that this was a good opportunity to evaluate the added value of introducing non-hydrostatic capabilities in the MOHID modelling system.

Theias (2005) was the first to introduce a non-hydrostatic approach in MOHID following a method proposed by Casulli & Zanolli (2002). However, this method assumes a hydrostatic approach for the surface layer, which may result in an important limitation in some situations. To overcome this, a Keller-box approach was proposed by Stelling (Stelling & Zijlema, 2003) (Cui *et al.* 2012) in order to compute the non-hydrostatic pressure correction applied to a single layer (2D flow). This method showed to be very promising and was included in MOHID by Leitão (Leitão, 2016).

To determine whether this non-hydrostatic version of MOHID was reliable the model was submitted to a comprehensive validation process from which some of the results are presented below.

2. METHODOLOGY

The validation process of the non-hydrostatic model was based on a benchmarking methodology proposed by North American organization NOAA (National Oceanic and Atmospheric Administration) designed for wave propagation models and applied to the simulation of tsunamis. The methodology is detailed in Synolakis *et al.* (2007).

All laboratory results and data used for setting up the tests in the numerical models can be found in NOAA's centre for tsunami research website, at <http://nctr.pmel.noaa.gov/benchmark/>.

The bathymetries used in the numerical models were for the most part created based on the available descriptions of the laboratory experiments. For the test cases with more complex geometries, namely the Monai Valley experiment and Tohoku tsunami the resources were found online in NOAA's centre for tsunami research website for the first case and requested to the Korean Ocean Research and Development Institute (KORDI) for the second.

The initial conditions of solitary waves, namely elevation and velocity, were calculated using their respective equations presented in either Archambeau *et al.* (1999) or Staroszczyk (2011), depending on which profile fitted better the measured solutions and whether higher order equations were necessary to ensure the model's stability.

Each test case was ran in both the hydrostatic and non-hydrostatic versions of MOHID and the obtained results were compared with their respective analytic solution or recorded data (depending on the type of test) and are presented along with the spatial and time steps used in their simulations.

3. MODEL VALIDATION RESULTS AND ANALYSIS

3.1. Analytical benchmarking

In this battery of tests solitary waves of varying relative amplitude (A/h) were propagated along a constant depth channel.

In Fig. 1 and Fig. 2 are presented the results of the simulations for relative amplitudes of 0.125 and 0.5, respectively. As can be observed, the non-hydrostatic model is much more capable at maintaining the phase, amplitude and shape of the analytical solution than the hydrostatic model.

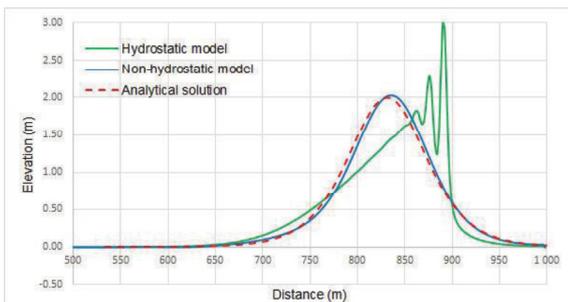


Fig. 1. Propagation of a solitary wave on a flat bottom channel. $A/h=0.125$; spatial step=2 m; time step=0.05 s.

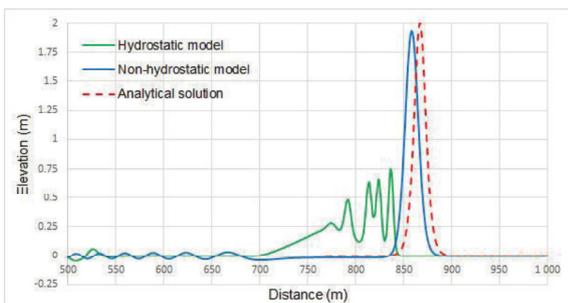


Fig. 2. Propagation of a solitary wave on a flat bottom channel. $A/h=0.5$; spatial step=2 m; time step=0.01 s.

3.2. Laboratory benchmarking – Solitary wave on a simple beach

The objective of this set of tests was to reproduce the laboratory results obtained for the propagation of a solitary wave of varying relative amplitudes on a constant depth channel adjoining a sloping beach with a slope of 1:19.85.

In Figure 3 to Figure 5 are presented the results obtained for the propagation of a breaking wave with relative amplitude of 0.3. As can be observed, the hydrostatic model struggles to reproduce the wave profile obtained from the laboratory results and underestimates the maximum run-up. On the other hand, the non-hydrostatic model satisfactorily reproduces the maximum run-up and wave profile evolution for all cases except the instant shown in Figure 4. This suggests that the wave breaking module still needs further development.

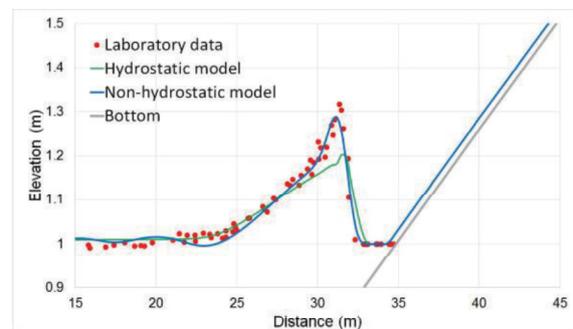


Fig. 3. Time evolution of a breaking wave with $A/h=0.3$, for $T=20$. Spatial step=3 m. Time step=0.01 s.

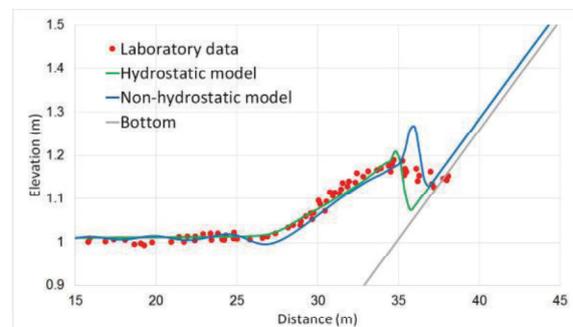


Fig. 4. Time evolution of a breaking wave with $A/h=0.3$, for $T=25$. Spatial step=3 m. Time step=0.01 s.

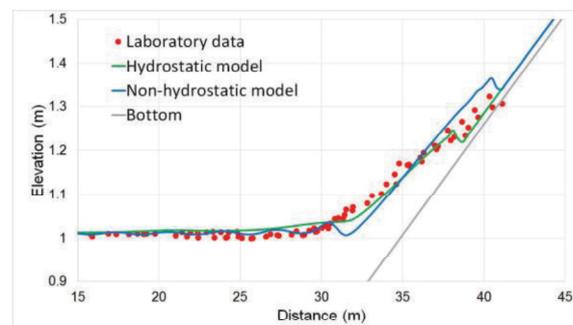


Fig. 5. Time evolution of a breaking wave with $A/h=0.3$, for $T=30$. Spatial step=3 m. Time step=0.01 s.

3.3. Laboratory benchmarking – Solitary wave on a conical island

In this set of tests solitary waves of varying relative amplitude were propagated on a wave tank with a conic island at its centre. The island had the shape of a truncated, right circular cone with diameters of 7.2 m at the toe and 2.2 m at the crest. Its vertical height was approximately 62.5 cm with a slope of 1:4 on its beach face. The objective of the experiments was to study the run-up process of a tsunami.

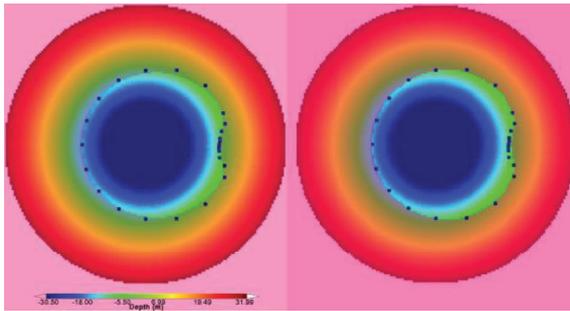


Fig. 6. Comparison of the maximum run-up around the conical island, for $A/h=0.181$, between the computed results for the non-hydrostatic (left) and hydrostatic (right) models and measured data (blue squares).

In Fig. 6 are presented the maximum run-up values around the conical island for a solitary wave of $A/h=0.181$, obtained using a 100:1 bathymetry of the physical model on a computational grid, a spatial step of 5 m and a time step of 0.01 s. Looking at the maximum run-up, at the front of the island the simulated results are well adjusted with the recorded data for both models. At the back side of the island the hydrostatic model underestimates the maximum run-up while the non-hydrostatic model has a good adjustment.

3.4. Laboratory benchmarking – Tsunami run-up onto a complex three dimensional beach, Monai Valley

This test was based on experimental data obtained in a wave tank modelled after Monai Valley, Japan, which was built in order to study the extreme run-ups observed near the village of Monai during the 1993 Okushiri tsunami. The detailed model bathymetry, imposed wave as well as a video of the experiment are hosted in NOAA's centre for tsunami research website.

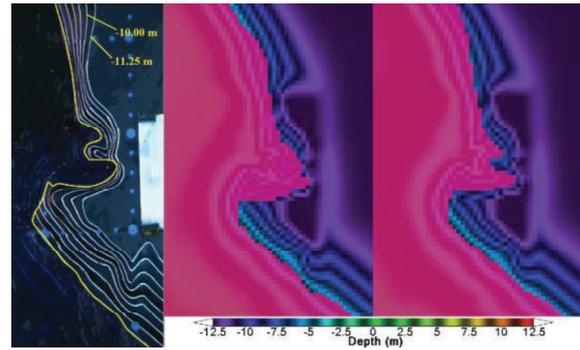


Fig. 7. Comparison of a screenshot of the Monai Valley experiment (left), with the maximum run-up-values obtained from the non-hydrostatic model (centre) and the hydrostatic model (right).

The bathymetry used in the numerical simulations was scaled by a factor of 100:1 in relation to the physical model. The spatial resolution in the x and y directions was of 1.4 m and the time step was 0.01 s.

Looking at the inundation maps in Fig. 7, in the video of the experiment the maximum observed run-up value is of approximately 10 m (in relation to the initial water level). When compared to the numerical models, the non-hydrostatic model produces the more accurate result with a simulated maximum run-up of 10.15 m against the 8.17 m simulated by the hydrostatic model.

3.5. Field benchmarking – Tohoku earthquake and tsunami

The Tohoku tsunami (Japan) was modelled using the hydrostatic version of MOHID by researchers at KORDI with the objective of studying its propagation and inundation as well as to examine MOHID's applicability for this type of simulations. The simulation conditions are detailed in Hyun *et al.* (2013). In order to replicate the study results a request was made to KORDI for the supply of tidal gauge data, fault parameters for generation of the initial water level condition and bathymetry. The initial water displacement was calculated following the fault plane model proposed by Okada (1985).

The simulated inundation maps for the Sendai plane, presented in Fig. 8, show no relevant differences between the hydrostatic and non-hydrostatic versions of MOHID. The observable and computed results seem to be fairly well matched, with inundation areas being mainly overestimated by the numerical models in the sections that present bigger disparities. The agreement between observable and computed data could be potentially improved by using a higher resolution numerical grid with topography that contemplated the pre-existing structures, such as buildings and sea walls.

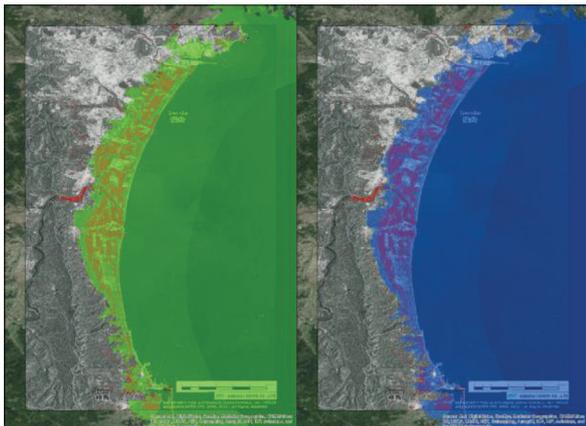


Fig. 8. Comparison of the observed inundated areas (red dots) with the inundation maps generated by the non-hydrostatic (left) and hydrostatic (right) models, for the Tohoku tsunami. The observed inundated areas were reproduced from RADARSAT satellite images hosted by Kokusai Kogyo Co., Ltd. (2011).

4. CONCLUSIONS

From the overall good results obtained for all the simulated test cases it may be concluded that the non-hydrostatic model appears to provide realistic solutions.

When compared to the hydrostatic version of MOHID, the non-hydrostatic model displayed much better results in the tests where the vertical acceleration component was more relevant, in particular the test cases for the higher values of relative amplitudes. In the experiments that were more similar to real tsunami events the difference between models was less dramatic. This can be explained by the fact that tsunami waves' propagation in the open sea can be approximated to the shallow water equations, which assume a small vertical velocity of the fluid (nearly hydrostatic). However, looking at the simple beach, conical island and Monai Valley experiments the non-hydrostatic model was consistently better at estimating the maximum run-up values. This is particularly relevant since the run-up is an important factor in the planning of mitigation measures against tsunami events.

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