SMART BOUNDARY CONDITIONS FOR NUMERICAL MODELLING OF HURRICANE INDUCED STORM SURGE

Ludovico Cipollone, University of L'Aquila, ludovico.cipollone@graduate.univaq.it
Davide Pasquali, University of L'Aquila, davide.paquali@univaq.it
Daniele Celli, University of L'Aquila, daniele.celli@.univaq.it
Carmine Di Nucci, University of L'Aquila, carmine.dinucci@.univaq.it
Marcello Di Risio, University of L'Aquila, marcello.dirisio@.univaq.it

INTRODUCTION

Cyclones represent a natural event characterized by a system of winds rotating inwards to an area of low barometric pressure, with an anticlockwise (northern hemisphere) or clockwise (southern hemisphere) circulation (Wang, 2012).

Extreme weather caused by such phenomena in coastal areas can lead to environmental damages, coastal defense issues (Celli et al., 2019), coastal flooding, and in some cases the loss of human life (Quader et al., 2017). The increase in the intensity of strong tropical cyclones worldwide (Elsner, 2020), and the growing attention on climate change effects, turn the spotlight on this phenomenon. It has also been observed that these phenomena are not unusual in the Mediterranean area and are referred to as Medicane (Tous et al., 2013). The most recent event is Medicane "Apollo" which affected the east coast of Sicily at the end of October 2021.

Since the effects of cyclones may cause an increase in coastal hazards, an early warning system must be implemented. This kind of tool can be used in a short term for hazard monitoring and facilitating public education and awareness of risk assessment and defining long-term strategies for climate change adaptation.

Many operational warning systems rely on complex numerical hydrodynamic models to provide surge and flood forecasts (Pasquali et al., 2015).

Numerical simulations are usually carried out by defining the pressure and wind field representing the given cyclone to force the numerical model. The large extension of the domains of interest and the complexity of the phenomenon make the numerical models characterized by high computational costs.

A possible approach could be reducing the dimension of the numerical grid but in this case, the solution would be influenced by the boundary conditions.

This research work aims to propose a novel analytical approach able to describe hurricane-induced storm surge (modeling both temporal and spatial variations) useful to define reliable boundary conditions to be used within hydrodynamic simulations with reduced domain dimensions, hence reducing the computational costs of detailed numerical simulations.

THE ANALYTICAL MODEL

The proposed method aims to reproduce the free surface elevation induced by cyclones' pressure field, relying on the theory of linear dynamic systems (e.g., Di Risio et al., 2017).

With this hypothesis, the free surface elevation induced by a pressure field depends only on the instantaneous response function. Then, by using the convolution integral, i.e., by applying the superposition of effects principle, the system response to duration impulse is obtained.

The instantaneous impulsive response functionhas been formulated through the dimensionless analytical model proposed by Le Mehaute (Le Mehaute, 1996).

The wave motion can be formulated with a potential function if the hypothesis of irrotational flow is assumed. The resolution of the Laplace equation allows then to obtain the free surface (η) evolution in cylindrical coordinate and dimensionless form as follows:

$$\eta*(r^*,t^*) = \int_0^\infty J_0(k^*r^*)H_I(k^*)\sigma^* sin(\sigma^* t^*)k^*dk^* \qquad (1)$$

where η^* (=η/d, being d the water depth) is the dimensionless free surface elevation, J_0 is the Bessel function of the first kind and order zero, r* (=r/d) is the dimensionless radial coordinate, σ^* (=$\sigma\sqrt{d/g}$) is the dimensionless angular frequency, g is the gravity acceleration), k* (=*kd*) is the dimensionless wavenumber, t* (=$t\sqrt{g/d}$) is the dimensionless elapsed time.
The function H_I aims to describe the effect of the impulse pressure acting on the free surface:

$$H_I = \int_0^R r^* J_0(k^*r^*)p(r^*)dr^* \qquad (2)$$

To describe the free surface elevation induced by cyclones, it is possible to use to the formulation proposed by Holland (Holland 2008) that reads as follows:

$$p(r) = p_{drop}\left(1 - e^{-\frac{A}{r^B}}\right) \qquad (3)$$

where $p_{drop} = p_n - p_c$ (p_c is the absolute pressure at the Cyclone's center and p_n is the absolute atmospheric pressure) is the amplitude of the pressure anomaly at the cyclone's eye, A and B are scaling parameters, and r is the radial distance expressed in kilometers from the cyclone's eye.

If a finite duration (Δt) impulse pressure, starting at t=0, acting on the surface is considered, the free surface elevation can be estimated by the convolution integral:

$$\tilde{\eta}(r,t) = \int_0^{\Delta t} d\tau \int_0^{\infty} J_0(k^* r^*) H_I(k^*) \sigma^* sin\big(\sigma^*(t^* - \tau)\big) k^* dk^* \quad (4)$$

where Δt (=$\Delta t \sqrt{g/d}$) is the dimensionless duration of the impulse.

Indeed, the whole cyclone path can be discretized in time as a succession of impulse pressure of duration Δt moving in space.

PRELIMINARY RESULTS

A sensitivity analysis was been performed for evaluating values of the numerical parameters to be used to evaluate the integral of Equation (1) so that $\delta k^* = 0.001$ and $k^*_{max} = 0.3$. First an instantaneous impulse has been considered, then a finite duration impulse and third the actual path of the cyclone has been included into the method.

Numerical evaluation of Equation (1) and (4) have been performed using a 10th-order Gaussian quadrature algorithm.

To consider the contribution due to the displacement in space of the pressure field, the radial spatial coordinate cannot be further used. Hence, two coordinate transformations must be applied. The first one allows to write the radial response function in a cartesian system moving with the cyclone and a second one so that the response function could be written in a global cartesian reference frame.

Wave pattern induced by a standing impulse of 50 s (p_{drop} = 5.5 kPa, A=23 m^B, B=1.5) are shown in Figure 1

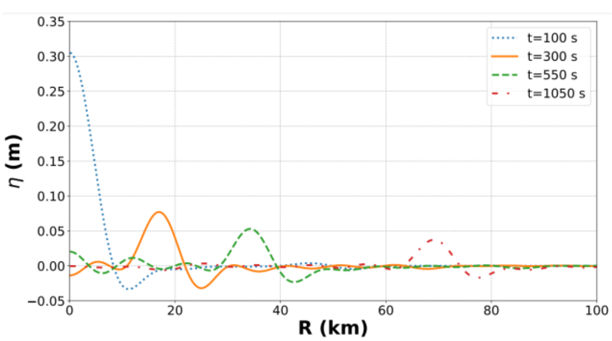

Figure 1 Wave pattern induced by a pressure impulse with duration of 50 s.

Wave pattern induced by a moving cyclone discretized by means of pressure impulses with a duration of 50 s (p_{drop} = 5.5 kPa, A=23 m^B, B=1.5, Vx = 35 km/h, Vy = 0 km/h) are shown in figure 2.

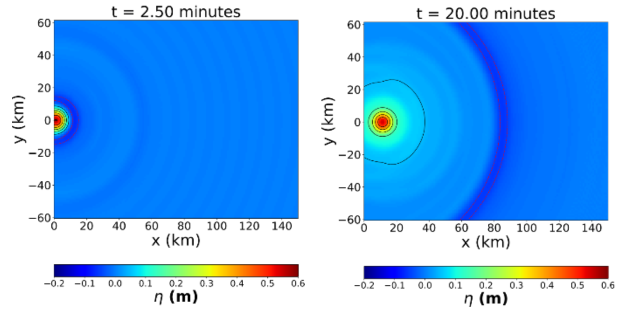

Figure 2 Wave patter induced by a moving cyclone.

The proposed model has been applied to define the analytical boundary conditions for a series of numerical experiments carried out by means of Delft3D-FLOW numerical model. Numerical results will be shown and discussed during the conference.

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