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Ensuring numerical stability of wave propagation by tuning model parameters using genetic algorithms and response surface methods

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ABSTRACT

The effectiveness of a Metamodel-Embedded Evolution Framework for model parameter identification of a Smoothed Particles Hydrodynamic (SPH) solver, called DualSPHysics, is demonstrated when applied to the generation and propagation of progressive ocean waves. DualSPHysics is an open-source code that provides GP-GPU acceleration, allowing for highly refined simulations. The automatic optimization framework combines the global-convergence capabilities of a Multi-Objective Genetic Algorithm (MOGA) with Response Surface Method (RSM) based on a Kriging approximation. The proposed Metamodel-Embedded Evolutionary framework is used to find the set of SPH model parameters that ensures an accurate reproduction of a 2^{nd} order Stokes wave propagating in a numeric flume tank. In order to demonstrate the consistency of the obtained results, the optimum set of parameters found by the framework is finally used to reproduce other 2^{nd} and 3^{rd} order Stokes waves propagating over the same flume tank.

1. Introduction

One of the major complexities in the study of coastal and ocean engineering process consists in the necessity of modeling small scale phenomena, such as boundary layer flows and turbulence, for physical systems involving large scale problems such as wave run-up, wave breaking, fluid-structure interaction (FSI) and coastal flooding. As is typical in numerical problems, two conflicting tasks need to be tackled: on one hand prediction models must rely on accurate physics description; on the other hand the computational burden of the numerical model needs to suit engineering requirements.

The ability to correctly reproduce a certain wave field is one of the fundamental requirements for prediction tools. Many theories have been formulated over the past years to model different wave types, but the complexity of analytic models restricts their practical utility. In the past 20 years easier accessibility of high performance computing allowed application of Computational Fluid Dynamics (CFD) techniques to coastal engineering problems.

In this respect different numerical methods have been presented for the solution of wave propagation problems. One successful application has been presented by Zijlema et al. (2011), who developed a time-domain, depth-averaged, non-hydrostatic model for free surface waves based on Non-Linear Shallow Water (NLSW) equations for large domain applications. NLSW equations are a simplified form of the Navier-Stokes equations, assuming depth-integrated free-surface flows. This model has been widely used for the prediction of coastal engineering problems, such as wave transformation and propagation over small sloped beaches, wave breaking, wave run-up and wave overtopping of coastal defenses (see for instance Suzuki et al. (2011), Smit et al. (2014) and Suzuki

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et al. (2017)). Kennedy et al. (2000), Madsen et al. (2002) and Fuhrman and Madsen (2008) presented a Boussinesq model in which non-linearities and wave dispersion are retained in the solution of depth integrated N-S equations.

Limitations of Boussinesq and NLSW in computing vertical flow characteristics and accurately reproducing phenomena such as wave flow through porous structures, have been overcome by using fully 3D, unsteady Navier-Stokes (N-S) models for the solution of pressure, velocity and turbulence characteristics. N-S models are applicable to a wide range of coastal structures of complex geometry, both permeable and impermeable. Among N-S techniques, the most popular models are based on an Eulerian flow description, in which fluid motion equations are written considering a specific fixed location in the fluid domain. VOFbreak (Austin and Schlueter, 1982), FLOW-3D (see e.g. Bayon et al., 2016) and IHFOAM (Higuera et al., 2013) are some examples of N-S Eulerian models. The most relevant flaw of these models is represented by time consuming mesh generation processes, often required for complex geometries. Moreover Eulerian approaches present severe technical challenges associated with implementing conservative multi-phase schemes able to capture the non-linearities within rapidly changing geometries. A second family of N-S techniques consists in meshless models in which the wave field is specified through a Lagrangian approach and the tracking of free surface is an intrinsic property of the fluid discretization in unit elements or particles. Among Lagrangian meshless models, Smoothed Particle Hydrodynamics method (SPH) has recently gained significant popularity in the coastal engineering field (Violeau, 2012). In SPH, the fluid is discretized into a set of particles. Each of these particles is a nodal point where physical quantities (e.g. position, velocity, density, pressure) are computed as an interpolation of the values of the neighboring particles.

In this paper we employ a SPH-based model (DualSPHysics, see Crespo et al., 2015) to reproduce different progressive waves on a flat-bottom 2D tank ending with a sloped beach. DualSPHysics is an open-source code based on the Smoothed Particle Hydrodynamics (SPH) method. It has been derived from the SPH formulation implemented in the open-source code SPHysics (Gomez-Gesteira et al. (2012a)). DualSPHysics has been mainly used to study wave transformation and breaking at detailed scale close to the shoreline. Many studies recently demonstrated the validity of this method. Barreiro et al. (2013), Vacondio et al. (2013), Rota et al. (2014), Altomare et al. (2014, 2015a, 2017) are some of the many examples available in literature. The particle formulation of SPH methods is particularly suitable for modeling coastal processes especially in the surf and swash zones characterized by strong non-linearities such as run-up and wave breaking. The computational burden required for large domain simulations becomes unbearable, hence the *GP-GPU* acceleration implemented in DualSPHysics, allows for feasible computational requirements as demonstrated by Valdez-Balderas et al. (2013) and Vacondio et al. (2014).

In general, any numerical model requires a preliminary validation study in which numerical predictions are compared to analytic results or experiments. This stage gives the chance to calibrate numerical models by opportunely tuning parameters in order to increase their fidelity in the description of each specific problem. A major complexity in properly tuning SPH model parameters is due to their dependence on the particular problem that needs to be solved. Considering the physical and mathematical meaning of each parameter, this paper proposes an innovative method, based on data mining, for the calibration of the model setting that better suits a specific problem. The problem under investigation is the propagation of a wave train in a tank. In particular the numerical calibration process is applied to minimize the error between the computed and the theoretic 2^{nd} order Stokes wave profile. To achieve this target, a two-step computational framework for parameter calibration has been set up based on a combination of a Multi-Objective Optimization Algorithm and a Response Surface Method (RSM).

As outlined by Simpson et al. (2008) the improvements in computational resources are nowadays used to add complexities to the solution of particular problems. High-fidelity models are created to fill the gap between numerical simulations and physical observations. RSM (also referred to as *metamodels* or *surrogate models*) represent a less computationally expensive emulator of the original function under study. So they play a key role in reducing computational effort when a large number of function evaluations are needed. For a comprehensive review of surrogate-based technique applications in water resources problems and related issues the reader is referred to Razavi et al. (2012) and Brunetti et al. (2017).

The paper is organized as follows: theoretic background on Stokes waves and wavemaker theory is provided in Section 2. The Section 3 describes the formulation of the DualSPHysics solver, highlighting the physical and mathematical meaning of each of the analyzed model parameters. The optimization-based calibration framework is described in Section 4 in all its parts: the Multi-Objective Optimization Algorithm (4.1), the RSM (4.2) and the formulation of the objective function (4.3). Results obtained by the proposed approach are presented and discussed in Section 5.

2. Physical and theoretical backgrounds of wave generation and propagation

The parameter identification is carried out on a second order Stokes wave. This wave theory is able to model a wide range of wave amplitudes $\frac{H}{gT^2}$ and depth ratios $\frac{d}{gT^2}$; it is a widely employed model for ocean engineering problems. Moreover, the non-linear theory at the basis of their mathematical formulation allows for steep waves modeling. The wave profile $\eta(x,t)$ is obtained considering a 2D potential flow assumption:

$$\eta(x,t) = a\cos(kx-\omega t) + ka^2 \cdot \frac{\cosh(kd)[2+\cosh(2kd)]}{4\sinh^3(kd)} \cdot \cos[2(kx-\omega t)] \tag{1}$$

Where d is the water depth, H the wave height and T the wave period. The non linear wave profile is obtained by superimposing two harmonics of frequency ω and 2ω, solutions of the first and second order problems respectively. Non linear Stokes wave theory is generally valid for deep water for $\frac{H}{d} \ll 1$ and $Ur \ll 10$, where Ursell number Ur is defined as follow:

$$Ur = \frac{HL^2}{d^3} \tag{2}$$

In the context of a wave flume, progressive waves are generated using a piston-type wavemaker (see e.g. Dean and Dalrymple, 1991). The ratio between the expected wave height and the imposed stroke S of the wavemaker is theoretically provided by Eq. (3).

$$\frac{H}{S} = \frac{2(cosh(2kd)-1)}{\sinh(2kd)+2kd} \tag{3}$$

3. Smoothed particle hydrodynamics for numerical modeling of progressive waves

SPH method basically develops in two phases: a kernel