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Applicability of Smoothed Particle Hydrodynamics for estimation of sea wave impact on coastal structures

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ABSTRACT

The present work describes the validation of an SPH-based technique for wave loading on coastal structures. The so-called DualSPHysics numerical model has been used for the scope. The attention is focused on wave impact on vertical structures and storm return walls. For vertical quay walls, the numerical results have been compared with analytical and semi-empirical solutions. Later on, the wave impact on storm return walls has been modelled and the results have been compared with experimental data. Regular and random waves have been simulated. Despite the model limitations (e.g. lack of an active wave absorption system), good agreement is achieved with the formulae predictions and experimental results which proves that DualSPHysics model is becoming an alternative to some classical approaches and can be used as complementary tool for the preliminary design of coastal structures.

1. Introduction

The design of coastal defences requires proper assessment of actions exerted by sea waves on structures, such as run-up heights, overtopping flow rates and velocities, and wave forces and pressures. For hard structures (e.g., quay walls and breakwaters), these values represent boundary conditions that can be used to assess local damage and overall structural stability. Wave forces can be generally characterised and measured by physical and/or numerical modelling. Analytical or semi-empirical formulations can also help for the purpose. In recent years, new building technologies and the latest standards for environmental safety and public use of coastal zones have encouraged designers to seek new solutions and more complex layouts than those traditionally used as coastal defences. For example, limiting the height of storm return walls that are built on top of existing coastal structures often is necessary to protect coastal areas from flooding and to keep them attractive and accessible at the same time. Scenarios such as this one require engineers to explore different solutions parapet or curve-shaped walls and stilling water basins that are integrated within the urban architecture. Application of existing analytical or empirical formulas to such cases is not always possible, as they may have different hydraulic boundary conditions and structural layouts. Although physical model tests can provide the data needed by designers, physical modelling can be very time consuming and expensive. Numerical modelling offers a useful and complementary tool to assess the effects of sea wave impact on coastal structures.

Traditional empirical methods to predict wave forces on dikes and return walls (e.g., Goda, 1974; Kortenhaus et al., 1999; Takahashi et al., 1994) were developed from physical model experiments largely focused on deep-water wave conditions and simple geometries. However, in cases such as Belgian coastal defences, the additions of new crest elements on existing sea dikes or quay walls are used as countermeasures against wave forces. For example, construction of storm return walls on top of existing quay walls is planned for Zeebrugge Harbour to protect the boroughs that are located in low-lying areas next to the harbour. New storm return walls either with or without parapets may be built on the top of the existing sea dikes in the Blankenberge Marina. However, not much of the existing data is applicable to these cases due to the peculiar geometries and hydraulic conditions of these harbours. The storm return walls will be built at a certain distance from the seaward edge of the dike crest, which will create a sort of crest berm over which the waves will propagate and transform before reaching the wall. The influence of the length and elevation of this crest berm coupled with the storm return wall has not yet been comprehensively analysed. Previous studies (e.g., Trouw et al., 2012; Van Doorslaer et al., 2012a, 2012b; Verwaest et al., 2010) did not provide a complete and general description of the problem, and they were often restricted to particular geometries or boundary conditions. Thus, the behaviour of these new storm return walls under wave attacks must be characterised for proper design of coastal

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defences. Recent events struck the entire coast of the North Sea such as the storm “Xaver” occurred in the night between 5th and 6th December 2013 and hit the coasts of the Northern Countries confirming how important a proper re-design of the existing sea dikes is.

While semi-empirical approaches or physical model results have been useful for the design of coastal structures, numerical modelling is a powerful tool that can be used to solve complex problems in the fields of engineering and science. Its main advantage is its ability to simulate any scenario without building expensive physical models. Numerical models do not suffer from scale effects, and numerical simulations can provide physical data that can be difficult or even impossible to measure in a real model. Hardware development has reduced the computational cost, which once was a bottleneck for numerical modelling. Finally, numerical modelling can reduce the number of physical tests required, which translates to significant savings in money and time.

Traditional computational fluid dynamics (CFD) techniques such as volume-of-fluid methods (VOF) have been used to study wave-structure interactions (Kleefsman et al., 2005) and to design breakwaters (Higuera et al., 2013; Vanneste and Troch, 2012). However, Eulerian numerical methods, such as those based on the finite volume technique, require expensive mesh generation and have severe technical challenges associated with implementing conservative multi-phase schemes that can capture the nonlinearities within rapidly changing geometries. Thus, the emergence of meshless schemes has provided a much needed alternative, and meshfree methods, such as Monte Carlo methods (Geeraerts et al., 2009) or the particle finite element method (PFEM) (Oñate et al., 2011), are becoming popular.

Developed originally for astrophysics in the 1970s (Lucy, 1977), the meshless Smoothed Particle Hydrodynamics (SPH) method has been developed rapidly during the last decade due to its applications in engineering. This method uses particles to represent a fluid, and these particles move according to the governing dynamics. When simulating free-surface flows, the Lagrangian nature of SPH allows the domain to be multiply-connected with no need for a special treatment of the surface; this property makes the technique ideal for studying violent free-surface motion (Violeau, 2012).

SPH has been used to describe a variety of free-surface flows, including wave propagation over a beach, plunging breakers, impact on structures, and dam breaks. Monaghan (1994) presented the first attempt to study free-surface flows. Monaghan also studied the behaviour of gravity currents (Monaghan, 1996), solitary waves (Monaghan et al., 1999) and wave arrival at a beach (Monaghan and Kos, 1999). Later, the model was applied to the study of wave-structure interactions (Colagrossi and Landrini, 2003). Gómez-Gesteira and Dalrymple (2004) used SPH to study the classical dam break problem in three dimensions. Within the field of coastal engineering, Gotoh et al. (2004) and Shao (2005) used SPH to study the wave-breakwater interaction, and Khayyer and Gotoh (2009) used it to predict wave impact pressure due to sloshing waves. More recently, Ren et al. (2014) validated SPH model results by comparing them to other available numerical results and to experimental data for wave damping over a porous seabed with different levels of permeability. St-Germain et al. (2014) used SPH to investigate the hydrodynamic forces induced by the impact of rapidly advancing tsunamis. SPH also was successfully used for other engineering applications, such as to simulate free-surface flows encountered in Pelton turbines (Marongiu et al., 2010) and to study a real spillway in France that connects the reservoir of a river dam to a valley with a complex bottom shape (Lee et al., 2010).

The DualSPHysics code (Crespo et al., 2011; Gómez-Gesteira et al., 2012a, 2012b), which was developed to use SPH for real engineering problems, includes software that can be run on either CPUs or GPUs (graphics cards with powerful parallel computing). GPUs offer greater computing power than CPUs, and they are an affordable option to accelerate SPH modelling. Therefore, the simulations conducted in this study were executed using a GPU card installed on a personal computer. DualSPHysics is open source and can be freely downloaded from www.dual.sphysics.org. The first rigorous validation of the GPU implementation of DualSPHysics code was presented in Crespo et al. (2011), and more details about the implementation of DualSPHysics can be found in Domínguez et al. (2011, 2013a, 2013b). In addition, the computation of forces exerted by large waves on the urban furniture of a realistic promenade was presented in Barreiro et al. (2013). That study presented a very preliminary analysis of the accuracy of the model when simulating hydraulics loadings (e.g., hydrostatic force, dam break, etc.), and it illustrated the abilities of DualSPHysics to handle complex geometries in a straightforward way. However, only qualitative results for wave impacts on a real coastal structure were presented. In addition, Ren et al. (2014) and St-Germain et al. (2014) used previous versions of DualSPHysics in their studies, and Altomare et al. (2014) used DualSPHysics code to study the run-up on a real armour block coastal breakwater.

The goal of the present study was to demonstrate the accuracy of DualSPHysics to quantify the sea wave forces on coastal defences such as storm return walls. Several validation test cases are presented and compared with solutions proposed in the literature and with experimental data. Relatively short time series of regular waves and random waves were considered. An absorption model is not used in DualSPHysics, but the modelling can be considered to be accurate because the scope of the work was not to reproduce very long times series of sea waves in the numerical flume but rather to focus on identified short wave groups or wave trains.

2. SPH method

SPH is a Lagrangian and meshless method in which the fluid is discretised into a set of particles. Each of these particles is a nodal point for which physical quantities (such as position, velocity, density, and pressure) are computed as an interpolation of the values of the neighbouring particles. The contribution of the nearest particles is weighted according to distance between particles, and a kernel function (W) is used to measure this contribution depending on the inter-particle distance that is defined using a smoothing length (h). The smoothing length is a characteristic length used to define the area of influence of the kernel.

The mathematical fundamentals of SPH are based on integral interpolants, thus any function F can be computed by the integral approximation:

$$F(\mathbf{r}) = \int F(\mathbf{r}')W(\mathbf{r}-\mathbf{r}', h)d\mathbf{r}' \tag{1}$$

The kernel functions must have several properties (Monaghan, 1992), such as positivity inside the area of interaction, compact support, normalization, and monotonic decrease with distance. One kernel option is the quintic kernel described by Wendland (1995), for which the weighting function vanishes for inter-particle distances greater than $2\,h$. It is defined as:

$$W(q) = \alpha_D \left(1-\frac{q}{2}\right)^4 (2q+1) \qquad 0 \le q \le 2 \tag{2}$$

where $q = r/h$ and $\alpha_D = 7/(14\pi h^2)$ are the normalization constants in two dimensions and $\alpha_D = 21/(16\pi h^3)$ is the normalization constant in three dimensions.

The function F in Eq. (1) can be expressed in a discrete form based on the particles. Thus, the approximation of the function is interpolated at particle a, and the summation is performed over all particles within the region of compact support of the kernel:

$$F(\mathbf{r}_a) \approx \sum_b F(\mathbf{r}_b)W(\mathbf{r}_a-\mathbf{r}_b, h)\frac{m_b}{\rho_b} \tag{3}$$

where the volume associated with the neighbouring particle b is m_b/ρ_b and m and ρ are the mass and density, respectively.